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Cinemática Interna e a Relação $L-\sigma$ das Galáxias HII

Tese de Doutorado

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Resumo

Galáxias HII representam uma subclasse das galáxias anãs que atrevessam um surto de formação estelar intenso (fenômeno *starburst*). Elas têm sido observadas ao longo das últimas décadas por serem ótimos laboratórios para testar modelos astrofísicos e por serem consideradas “velas padrão” promissoras, através da correlação existente entre suas dispersões de velocidades (σ) e a luminosidade das linhas de Balmer (L)

Uma forma de investigar a origem de σ e melhor compreender a física que está por trás da relação $L-\sigma$, é através do estudo da cinemática interna das regiões *starburst*, que representam as unidades de formação estelar em galáxias HII. Neste trabalho estudamos a cinemática interna da região HII gigante dominante em II Zw 40, uma galáxia HII prototípica. Investigamos o comportamento dinâmico do gás ionizado nesta região em níveis de detalhes sem precedentes. Ao fazermos isto, estendemos o estudo da cinemática de regiões HII gigantes em galáxias do Grupo Local às galáxias HII mais distantes (12 Mpc). Isto foi possível através do grande poder de resolução do telescópio Gemini e do seu instrumento GMOS/IFU. Investigamos a região através de diagramas de diagnóstico cinemáticos, que nos permitiram identificar e quantificar as propriedades cinemáticas de subregiões como superbolhas em expansão, o núcleo cinemático dominante e o campo turbulento global. Estendemos a análise interpretativa dos diagramas de diagnóstico como ferramenta para uso na identificação de propriedades comuns desses sistemas. Verificamos que o núcleo dominante é aquele que apresenta a dispersão de velocidades característica da região e é obtido do perfil de linha

integrado, pondo vínculos na interpretação sobre a origem do σ supersônico verificado nesses sistemas.

A relação $L-\sigma$ das galáxias HII foi estudada separadamente para uma amostra de 120 objetos com larguras de linha medidas em alta resolução espectral, combinada a um conjunto de dados espectrofotométricos tomados da literatura. Isso nos permitiu investigar os efeitos sistemáticos que afetam a relação, como a não-Gaussianidade dos perfis de linha, a evolução do *starburst* e a metalicidade. Verificamos que as galáxias que apresentam perfis de linha aproximadamente Gaussianos são aquelas que melhor seguem a relação. Estas representam portanto uma classe mais homogênea do ponto de vista cinemático e definem a propriedade básica das galáxias HII alvos da relação $L-\sigma$. Por outro lado, verificamos através da técnica estatística Análise de Componentes Principais, que outros parâmetros independentes, indicadores do estágio evolutivo do *starburst*, como a largura equivalente $H\beta$ ($W_{H\beta}$) ou a razão de ionização $[OIII]/[OII]$, e indicador da metalicidade (O/H), contribuem significativamente para o estreitamento da relação, pois juntamente com σ predizem mais precisamente o parâmetro dependente L ($\delta \log L \sim 0.20$). Recalibrarmos a relação empírica $L-\sigma$ -O/H, previamente apresentada como o indicador de distâncias das galáxias HII, considerando um número de galáxias que dobra a amostra anteriormente analisada e fornecemos um conjunto alternativo de relações que podem ser usadas, com maior precisão e simplicidade, para determinar distâncias de galáxias HII a altos *redshifts* com interesses cosmológicos.

Abstract

HII galaxies represent a subclass of dwarf galaxies that are undergoing a burst of intense star formation (starburst phenomenon). They have been observed over the last decades because they are excellent laboratories for testing astrophysical models and are considered promising “standard candles” through the correlation between its velocity dispersion (σ) and Balmer line luminosities L .

One way to investigate the origin of σ and better understand the physics behind the L - σ relation, is by studying the internal kinematics of the starburst regions, which represent units of star formation in HII galaxies. In this work we studied the internal kinematics of the main giant HII region in II Zw 40, a prototypical HII galaxy. We have investigated the dynamic behavior of the ionized gas in this region at levels of unprecedented detail. By doing this, we extend the study of kinematics of giant HII regions in the Local Group galaxies to more distant HII galaxies (12 Mpc). This was possible through the great resolving power of the Gemini telescope and its instrument GMOS/IFU. We investigated the region through diagnostic kinematic diagrams, which allowed us to identify and quantify the kinematic properties of subregions such as superbubbles undergoing expansion, the dominant kinematic core and the global turbulent field. We extend the interpretative analysis of diagnostic diagrams as a tool for use in the identification of common properties of these systems. We found that the dominant core is one

that shows the velocity dispersion characteristic of the region and is obtained from the integrated line profile, constraining interpretations of the origin of supersonic σ found in these systems.

The $L-\sigma$ relation of HII galaxies was studied separately for a sample of 120 objects with line widths measured in high spectral resolution, combined with a set of spectrophotometric data taken from literature. This allowed us to investigate the systematic effects that affect the relationship, such as the non-Gaussianity of the line profiles, evolution of the starburst and metallicity. We found that the galaxies which have nearly Gaussian line profiles are the ones that better follow the relationship. They represent a more homogeneous class in terms of kinematics and define the key property of the HII galaxies targets of the $L-\sigma$ relation. Furthermore, we verified through Principal Component Analysis technique, that other independent parameters, indicators of the evolutionary stage of the starburst, as the $H\beta$ equivalent width ($W_{H\beta}$) or the ionization ratio [OIII]/[OII], and indicator of the metallicity (O/H), contribute significantly to reduce the scatter of the relationship, because together with σ they predict more precisely the dependent parameter L ($\delta \log L \sim 0.20$). We recalibrated the $L-\sigma$ -O/H empirical relation, previously presented as the distance indicator of the HII galaxies, considering a number of galaxies which doubles the sample analyzed in the past and we provided an alternative set of empirical relations that can be used alternatively, with greater accuracy and simplicity, to determine distances of HII galaxies at high redshifts with interests cosmological.

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"The scientist does not study nature because it is useful; he studies it because he delights in it, and he delights in it because it is beautiful. If nature were not beautiful, it would not be worth knowing, and if nature were not worth knowing, life would not be worth living."

– Jules H. Poincaré

Capítulo 1

Introdução

1.1 Galáxias HII

Na procura por galáxias com linhas de emissão no Observatório Astrofísico de Tonantzintla (México), Guillermo Haro identificou um objeto peculiar que apresentava linhas de emissão nebulares intensas e nenhum contínuo visível (Haro 1951). Devido ao seu perfil estelar e suas propriedades espectrais, Haro classificou provisoriamente esse objeto como nebulosa planetária, mas reconheceu a necessidade de mais observações a fim de classifica-lo corretamente. Harlow Shapley, no *Harvard Announcement Card 1110*¹, sugere que este objeto, com coordenadas próximas à periferia do aglomerado de galáxias de Coma, poderia ser uma galáxia tais como as descritas por Carl Seyfert com forte emissão nuclear (Seyfert 1943). Entretanto, Mayall (1951)

¹O HAC 1110 foi gentilmente digitalizado pelo Harvard-Smithsonian Center for Astrophysics a pedido do autor e publicado no endereço eletrônico <http://www.cfa.harvard.edu/iau/services/HACs.html>

através de medições de velocidades radiais confirmou que o objeto deveria pertencer a Via Láctea (Galáxia) e assim classificou-o como uma nebulosa planetária². Possivelmente motivado pelas descobertas de Seyfert (Seyfert 1943), Haro continuou sua busca por galáxias peculiares e em 1956 já havia identificado um bom número desses objetos corretamente como “galáxias azuis com emissão nuclear”, caracterizados pela forte emissão de radiação ultravioleta de seus núcleos (Haro 1956a). Haro fazia levantamentos espectroscópicos na região espectral de H α da série de Balmer (6563Å), através de prisma objetivo acoplado a um telescópio Schmidt. Usava também uma técnica desenvolvida por Humason & Zwicky (1947), observando grandes áreas do céu com placas fotográficas em várias bandas fotométricas. Desse modo, eles selecionavam objetos que apresentavam diferenças de intensidades relativas peculiares nas diferentes bandas fotométricas (Haro 1956b).

Posteriormente Zwicky (Zwicky 1964) introduziu o termo “galáxias compactas” ao classificar galáxias que eram dificilmente distinguidas de estrelas nas placas do “Palomar Sky Survey”. Uma fração desses objetos também apresentava linhas de emissão intensas.

Hoje a maioria dos trabalhos sobre **galáxias HII** referem-se àquelas encontradas nas listas de galáxias compactas com linhas de emissão e excesso no ultravioleta, produzidas por Haro (1956a), Zwicky et al. (1966), Markarian (1967) e em levantamentos (*surveys*) como o Tololo Survey (Smith et al. 1976) e o University of Michigan Survey (MacAlpine & Williams 1981). Porém objetos que hoje chamamos de galáxias HII ou “blue compact galaxies” (BCGs) representam apenas uma fração dos objetos dessas listas. Os demais objetos

²H 4-1, 12h59m27,8s +27d38m11s (J2000).



Figura 1.1: Imagem da região central de 30 Doradus, região HII gigante localizada na Grande Nuvem de Magalhães. O aglomerado estelar ionizante R 136 é visto acima do centro da imagem. (ESA/NASA, ESO e Danny LaCrue).

são normalmente galáxias nucleares ativas, espirais normais com formação estelar nuclear e regiões HII em galáxias espirais próximas, todas apresentando propriedades observadas similares às galáxias HII, isto é, a presença marcante de uma população estelar jovem produzindo um continuo azul intenso e linhas de emissão do gás nebuloso ionizado. Por opção, nesse texto usarei o termo “galáxia HII” embora “galáxia azul compacta” refere-se ao mesmo tipo de objeto. A diferença na nomenclatura é consequência do método de detecção desse tipo de objeto. Galáxias HII foram historicamente encontradas e identificadas a partir de levantamentos de prisma objetivo devido às suas fortes linhas de emissão, como as linhas da série de Balmer, enquanto que as BCGs foram detectadas por serem compactas e azuis em levantamentos fotográficos. Ambos nomes enfatizam uma propriedade típica desses objetos e são encontrados na literatura.

Recentemente, devido aos avanços dos grandes programas de levantamentos de galáxias como o Sloan Digitized Sky Survey (SDSS) e 2dF Galaxy Redshift Survey (2dFGRS), o número de galáxias identificadas como galáxias HII cresceu bastante, ainda que estas estejam sendo estudadas mais frequentemente em amostras de grandes números, com o objetivo principal de caracterizar as propriedades físicas da população (Kniazev et al. 2004; Izotov et al. 2006; Papaderos et al. 2006). Outros levantamentos como o KPNO International Spectroscopy Survey (KISS) também têm produzido listas de galáxias com linhas de emissão, tipicamente galáxias HII, aumentando o número identificado desses objetos, e mais ainda, com suas propriedades físicas determinadas (Melbourne & Salzer 2002).

Atualmente podemos classificar as galáxias HII como um subgrupo de galáxias anãs atravessando um período de formação intensa de estrelas (fenômeno “starburst”), dando origem a um espectro óptico dominado por linhas nebulares de emissão sobrepostas a um contínuo azul relativamente fraco. Seus espectros ópticos são muito similares aos de regiões HII gigantes³, como por exemplo a região 30 Doradus localizada na Grande Nuvem de Magalhães (Figura 1.1), a maior galáxia satélite da Via Láctea. Destacam-se as linhas de hidrogênio da série de Balmer ($H\alpha$, $H\beta$, $H\gamma$), as linhas proibidas de oxigênio [$OIII$] $\lambda\lambda 4959, 5007$, [$OIII$] $\lambda 4363$ e [OII] $\lambda\lambda 3726, 3729$, nitrogênio [NII] $\lambda 6548, 6583$ e enxofre [SII] $\lambda\lambda 6716, 6731$. Todas estas representando

³Embora não haja uma definição rígida sobre o que é uma região HII gigante, uma propriedade marcante que as diferencia das regiões HII ditas normais, é que aquelas apresentam larguras de linhas de emissão indicando velocidades supersônicas. Como não há nenhuma região HII gigante na Galáxia, esse objetos são também chamados de regiões HII gigantes extragalácticas.

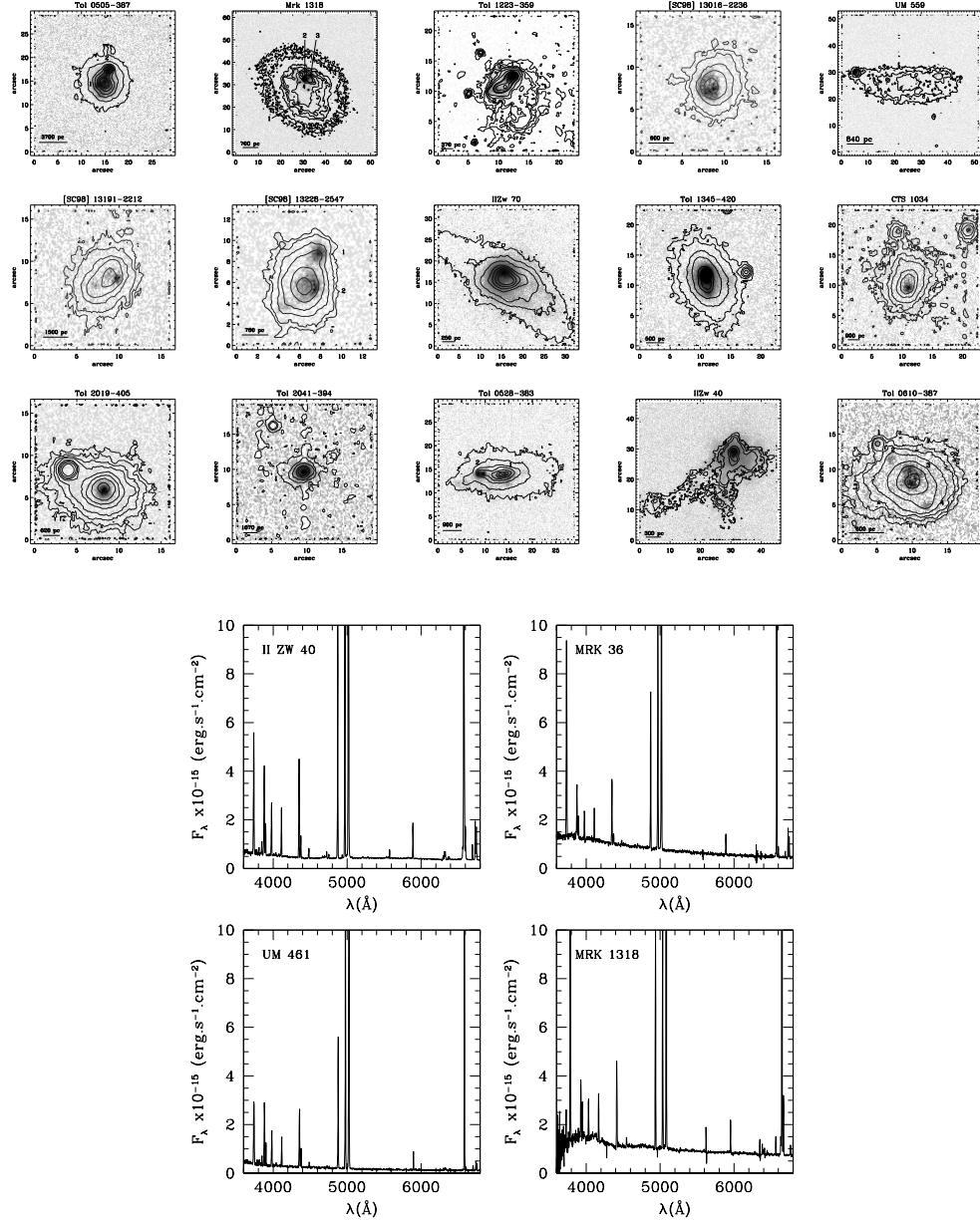


Figura 1.2: (*painéis superiores*) Imagens em banda estreita centrada em $H\beta$ (figuras gentilmente cedidas por Patricio Lagos e originais do trabalho Lagos et al. (2007)). Os números sobre as imagens indicam regiões distintas possivelmente associadas a superaglomerados. (*painéis inferiores*) Espectros ópticos de algumas galáxias HII típicas.

transições eletrônicas de elementos do gás ionizado. Algumas imagens e espectros ópticos de galáxias HII típicas são apresentadas na Figura 1.2.

Galáxias HII são também caracterizadas por apresentarem baixa abundância química e uma taxa alta de formação estelar, alimentada por grande conteúdo de gás (Sargent & Searle 1970; Searle & Sargent 1972). A Figura 1.3 apresenta a distribuição calculada da abundância de oxigênio, dada pela razão numérica O/H para uma amostra de 875 galáxias HII obtida do SDSS. Dado que a abundância de oxigênio solar é de $12 + \log(O/H)^4 \sim 8,7$ (Scott et al. 2009), podemos ver que a maioria das galáxias HII apresenta abundâncias cerca de 4,5 vezes menor do que a do Sol, algumas chegando a ser 50 vezes⁵ mais deficiente neste elemento, como a galáxia recordista I Zw 18 com $12 + \log(O/H) \sim 7,2$ (Skillman & Kennicutt 1993), não presente na amostra da Figura 1.3. Sargent e Searle levantaram as hipóteses dessas galáxias estarem formando suas primeiras gerações de estrelas ou que a formação estelar ocorre em surtos (*bursts*), separados por longo período de quietude (*quiescence*). Ambas hipóteses estão baseadas na idéia de que essas galáxias não poderiam manter as taxas típicas atuais de formação estelar durante escalas de tempo cosmológicas, pois teriam consumido todo o seu gás e produzido assim um maior enriquecimento químico. Atualmente a segunda hipótese é mais aceita, uma vez que se observa nessas galáxias uma população estelar velha subjacente (Telles & Terlevich 1997; Westera et al. 2004).

Estruturalmente essas galáxias apresentam superaglomerados com mi-

⁴Para o Sol $\log N_H = 12,00$ onde o valor $12 + \log(O/H) = 8,7$ corresponde a cerca de 2000 átomos de H para 1 de O.

⁵Valor dependente da abundância adotada para o Sol.

lhares de estrelas de alta massa ($> 20M_{\odot}$) concentrados em um pequeno volume (10^1 - 10^2 parsecs), embebidos em grande conteúdo de gás. R 136 em 30 Doradus é um exemplo típico desses superaglomerados (Figura 1.1).

Galáxias HII são objetos chaves para o entendimento do processo de formação de galáxias e formação estelar massiva em gás de baixa metalicidade. Elas também podem ser usadas para testes de modelos de evolução química e oferecem a possibilidade de determinação da abundância de hélio primordial (Y_p) a partir de uma extração às condições químicas iniciais (Figura 1.4), uma vez que é verificada a existência de relações entre as abundâncias de oxigênio (O/H) e nitrogênio (N/H) com a abundância de hélio nesses sistemas (Pagel et al. 1992; Izotov et al. 1994, 1997; Izotov & Thuan 1998). O estudo do impacto no meio interestelar em consequência da formação estelar massiva pode ainda restringir a taxa de Supernovas, a função de massa inicial e a dependência química dos ventos de estrelas Wolf-Rayet.

Um outro tópico importante a ser melhor investigado sobre esses objetos e que será tema deste trabalho, trata da interpretação da correlação empírica entre a luminosidade das linhas de Balmer e as largura de linhas de emissão do gás ionizado que indicam movimentos supersônicos. Correlações como esta foram primeiramente encontradas para regiões HII gigantes por Melnick (1979), Terlevich & Melnick (1981), Melnick et al. (1987) e estendidas para galáxias HII por Melnick et al. (1988) e Telles & Terlevich (1993). Esses autores argumentam que, assim como a relação Tully-Fisher para galáxias espirais e o plano fundamental das galáxias elípticas servem como indicadores de distâncias extragalácticas e usadas na determinação da constante de Hub-

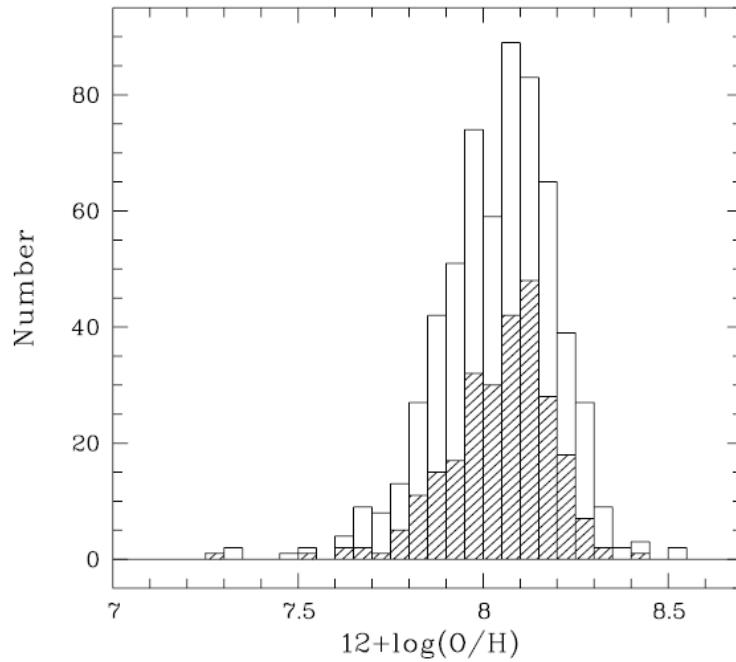


Figura 1.3: Distribuição de metalicidade para uma amostra de 875 galáxias com linhas de emissão (ELGs), tipicamente galáxias HII com temperaturas eletrônicas medidas. O histograma aberto representa a distribuição de metalicidade para 612 galáxias com $\delta \log (O/H) \leq 0,2$ dex (média=8,04, $\sigma=0,16$, mediana=8,06). O histograma hachurado representa a distribuição de metalicidade para 263 galáxias com $\delta \log (O/H) \leq 0,1$ dex (média=8,05, $\sigma=0,14$, mediana=8,07). Figura extraída do trabalho de Kniazev et al. (2004).

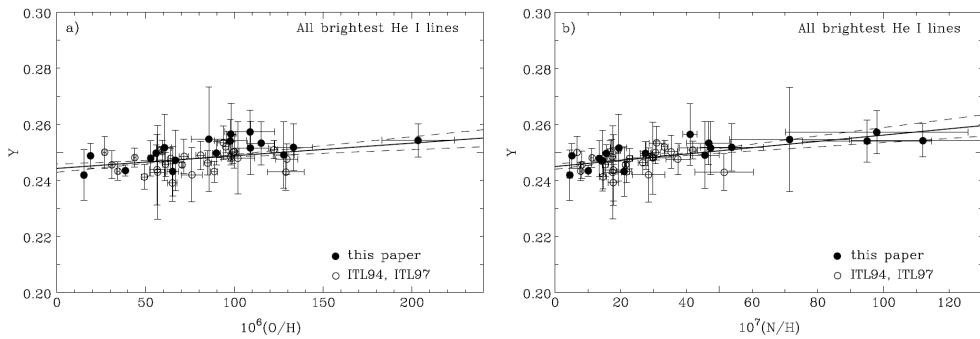


Figura 1.4: Relações lineares entre a fração de massa de hélio Y e a abundância de oxigênio O/H (a) e nitrogênio N/H (b) para uma amostra de 45 galáxias HII. As extrapolações as condições iniciais $O/H = 0$ e $N/H = 0$ fornecem coeficientes lineares $Y_p=0,244\pm0,002$ e $Y_p=0,245\pm0,001$, respectivamente (linhas sólidas). As linhas tracejadas apresentam os ajustes desviados $\pm 1 \sigma$. Figura extraída do trabalho de Izotov & Thuan (1998) e os dados presentes nele referenciados.

ble (H_0), as relações paramétricas encontradas para galáxias HII podem servir como uma ferramenta adicional.

1.2 Relações Paramétricas de Galáxias

Ainda que não se compreenda completamente a origem física que está por trás das relações empíricas verificadas para sistemas galácticos, o ajuste dessas relações e suas aplicações como ferramenta cosmológica para determinação de distâncias extragalácticas têm mostrado ser de fundamental importância na cosmologia moderna observational, beneficiada por telescópicos modernos com alto poder de resolução e eficiência. Aqui faremos uma breve introdução sobre as relações paramétricas “clássicas” de galáxias ditas normais, isto é, galáxias espirais e galáxias elípticas, utilizadas atualmente para a determinação de distâncias cosmológicas e em seguida mostraremos porque as galáxias HII são candidatas a se tornarem alvos para a aplicação de um método alternativo, contornando o problema dos limites de aplicabilidade dos métodos clássicos.

1.2.1 Relação Tully-Fisher

A relação Tully-Fisher é uma correlação empírica entre a magnitude absoluta de uma galáxia espiral “late-type” e sua velocidade de rotação $M_{\text{abs}}\text{-}V_{\text{rot}}$. A velocidade de rotação é usualmente determinada de observações rádio da emissão de 21cm do hidrogênio neutro (H_I) ou de curvas de rotação derivadas de observações no óptico e é o parâmetro independente da distância. Embora o conceito tenha sido usado de maneira variada, por exemplo, por

Öpik (1922) e Roberts (1969) por várias décadas, foi o trabalho de Tully & Fisher (1977) que mostrou o potencial da correlação como um poderoso indicador de distâncias extragalácticas.

Após a aplicação inicial da relação Tully-Fisher usando fotometria na banda B de galáxias espirais, foi logo mostrado que haviam duas grandes vantagens em usar fotometria no infra-vermelho próximo ao invés de comprimentos de ondas ópticos: (1) As incertezas em decorrência da absorção interestelar tanto na nossa Galáxia como na galáxia observada seriam muito reduzidas; e (2) a emissão infra-vermelha é dominada por estrelas gigantes “late-type” cujas luminosidades fornecem melhores medidas da história de formação estelar global da galáxia. Luminosidades em bandas ópticas são mais afetadas pela formação estelar recente. Como resultado a dependência da morfologia da galáxia com a razão massa-luminosidade é显著antemente reduzida (Aaronson & Mould 1983). Aaronson e Mould também mostraram que a inclinação da relação é dependente do comprimento de onda, com seu valor crescendo do azul para o infra-vermelho e que o espalhamento para a relação no infra-vermelho era menor, tornando-a um melhor indicador de distância.

Embora não haja uma base física firme para a relação Tully-Fisher, vários grupos tentaram recuperar os parâmetros físicos usando simulações numéricas cosmológicas. Por exemplo, Steinmetz & Navarro (1999) usaram simulações padrão de matéria escura fria⁶ em alta resolução. Eles mostraram que

⁶O nome matéria escura vem do fato deste tipo de matéria não ser detectado através da radiação eletromagnética, enquanto que o termo fria expressa a sua propriedade prevista pelo modelo de apresentar velocidades baixas se comparadas a da luz. No modelo de matéria escura fria, as estruturas que poderão dar origem às galáxias crescem de maneira

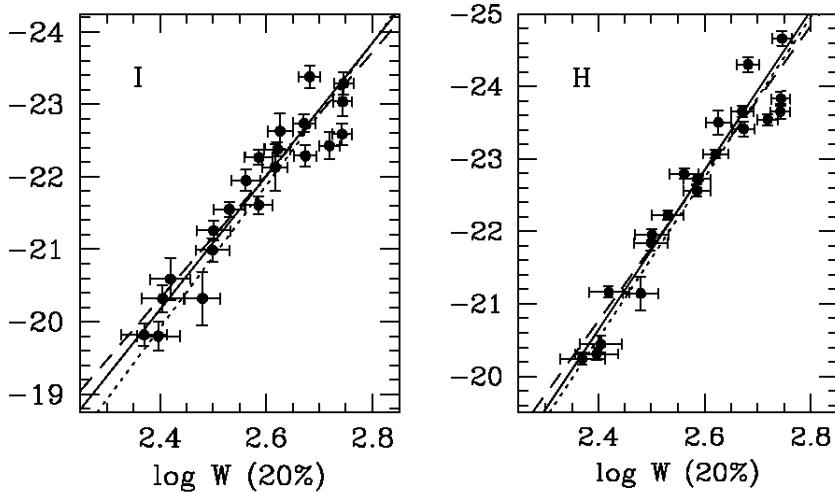


Figura 1.5: Relações Tully-Fisher nas bandas I e H para galáxias espirais com distâncias determinadas usando estrelas Cefeidas. As linhas sólidas representam ajustes lineares bivariados ($I = -9,24 (\log W_{20} - 2,5) - 21,12$, RMS = 0,36; $H = -11,03 (\log W_{20} - 2,5) - 21,74$, RMS = 0,36), enquanto que as linhas tracejadas e pontilhadas representam os ajustes direto e inverso respectivamente. W_{20} são as larguras em km s^{-1} do perfil de HI (21 cm) medidas a 20% do pico de HI. Figuras originais do artigo de Sakai et al. (2000).

a inclinação da relação Tully-Fisher pode ser reproduzida em um modelo hierárquico, sugerindo que a relação Tully-Fisher é uma consequência direta da equivalência cosmológica entre massa e velocidade de rotação, que foi também a conclusão de Mo et al. (1998). Por outro lado, Eisenstein & Loeb (1996) argumentaram que como o espalhamento da relação prevista em modelos é maior do que o observado, em razão das variações nas histórias de formação, a relação Tully-Fisher é uma consequência dos processos subsequentes auto-regulatórios de formação estelar (“*feedback*”) que regulam a dinâmica do gás, e não um resultado direto das condições cosmológicas iniciais.

Um trabalho importante sobre a relação Tully-Fisher e sua aplicação como indicador de distância extragaláctica é do Projeto Chave do Telescópio Espacial Hubble (“ H_0 Key Project”). Sakai et al. (2000) calibraram relações Tully-Fisher no óptico e no infra-vermelho próximo usando distâncias determinadas a partir da relação período-luminosidade de estrelas Cefeidas (método primário) presentes nas galáxias da amostra de calibração. Assim, relações paramétricas de galáxias, como por exemplo a relação Tully-Fisher, podem ser chamadas de indicadores de distâncias secundários. Calibrações das relações Tully-Fisher nas bandas fotométricas I e H para galáxias calibradoras locais podem ser vistas na Figura 1.5. A distância d de uma galáxia pode ser determinada tendo observado seu fluxo ou magnitude aparente m em uma banda fotométrica e o parâmetro que é independente da distância, no caso da relação Tully-Fisher, a velocidade de rotação. Calcula-se então

hierárquica, com os pequenos objetos colapsando primeiro e se fundindo a outros de forma a produzirem objetos cada vez mais massivos.

o parâmetro intrínseco, luminosidade ou magnitude absoluta M , a partir da relação calibrada⁷. Distâncias de aglomerados em unidades de milhões de parsecs (Mpc) são determinadas pela média das distâncias calculadas de suas galáxias membros, aplicando-se a equação do módulo de distância,

$$m - M = 5 \log d + 25.$$

Para cada aglomerado determinada-se portanto um valor da constante de Hubble através da Lei de Hubble⁸,

$$v = \frac{H_0}{d},$$

onde v é a velocidade de recessão do aglomerado determinada a partir do desvio espectral para o vermelho (*redshift*) médio das suas galáxias membros, $z = v/c$ e c é a velocidade da luz. Novamente, uma média dos valores de H_0 é calculada fornecendo um valor final e sua incerteza.

1.2.2 O Plano Fundamental

Acredita-se que galáxias elípticas normais representam uma família de objetos que podem ser descritos por um número pequeno de parâmetros físicos. Para esses objetos, espera-se que as velocidades internas estejam correlacionadas com a energia de ligação do sistema, como causa do equilíbrio

⁷A relação Tully-Fisher calibrada na banda I final, usada para determinação de distâncias e a constante de Hubble é aquela combinando galáxias calibradoras locais (Figura 1.5) e galáxias de aglomerados distantes, $I = -(10.00 \pm 0.08)(\log W_{50} - 2.5) - 21.32$ (Sakai et al. 2000).

⁸Fórmula aproximada usada para galáxias até redshifts intermediários, isto é $z \leq 0,5$, onde os efeitos de segunda ordem devido a aceleração do Universo são desprezíveis

dinâmico e o teorema do virial. Assumindo que a luz traça a massa de modo similar para todas as galáxias elípticas, uma correlação entre dispersão de velocidades (σ) e luminosidade (L) é consequentemente esperada. Desse modo, a relação Faber-Jackson para as galáxias elípticas $L-\sigma$ (Faber & Jackson 1976) é análoga a relação Tully-Fisher para galáxias espirais. A relação Faber-Jackson permitiu usar galáxias “early-type” também como “velas padrão” para medir distâncias de aglomerados, medir a constante de Hubble e mapear o campo de velocidade peculiar próximo.

A introdução do brilho superficial por Dressler et al. (1987) resultou em um aprimoramento da relação Faber-Jackson, reduzindo o espalhamento da relação em 50%. A relação $D_n-\sigma$ junta os observáveis tamanho e brilho superficial, definindo D_n como o diâmetro dentro do qual o brilho superficial é igual a algum valor fixo. Para galáxias com curvas de luz de crescimento similares, D_n é uma função bem definida do diâmetro a meia luz, D_e , e brilho superficial médio, $\langle I \rangle_e$, dentro de D_e , tal que $D_n = f(D_e, \langle I \rangle_e)$.

Simultaneamente, Djorgovski & Davis (1987) anunciaram uma relação “fundamental” entre o raio efetivo r_e , σ e $\langle I \rangle_e$. Ambos grupos especularam que $D_n-\sigma$ era uma projeção de perfil de um “plano fundamental”,

$$r_e \propto \sigma^\alpha \langle I \rangle_e^\beta,$$

onde $\alpha \approx 1,2$ e $\beta \approx -0,85$ Djorgovski & Davis (1987).

Mais recentemente, Jorgensen et al. (1996) mostraram que o plano fundamental de galáxias “early-type” segue a relação

$$r_e \propto \sigma^{1,24} \langle I \rangle_e^{-0,82},$$

usando 224 galáxias “early-type” em 11 aglomerados. Galáxias elípticas e S0

parecem seguir a mesma relação, ambas com espalhamento muito pequeno. No aglomerado de Coma, por exemplo, o espalhamento é apenas 14% em r_e (i.e., distância).

Enquanto os detalhes da base física por trás das relações empíricas permanecem desconhecidos, a idéia geral de galáxias “early-type” em equilíbrio dinâmico com população estelar homogênea é uma aproximação razoável para o plano fundamental observado. Com a suposição de que galáxias “early-type” formam uma família homóloga, a combinação do teorema do virial e o plano fundamental implica que as razões M/L são fortemente correlacionadas com seus parâmetros estruturais,

$$M/L \propto \sigma^{0,49} r_e^{0,22} \sim M^{1/4},$$

Portanto, quando relações $D_n-\sigma$ ou o plano fundamental são usados como indicadores de distância, deve-se fazer algumas suposições: (1) A razão M/L se relaciona com os parâmetros estruturais da galáxia da mesma forma para todas as galáxias; e (2) galáxias “early-type” têm população estelar (idade, etc.) similar para uma dada massa de galáxia. O requisito principal para o uso do plano fundamental como um indicador de distância secundário, é que a inclinação e o espalhamento da relação média em aglomerados distantes, sejam similares aos de amostras locais de calibração. Apesar das incertezas por trás da origem e universalidade do plano fundamental, sua validade como um indicador de distância tem sido empiricamente estabelecida e consistentemente reafirmada Jorgensen et al. (1996); Kelson et al. (2000).

Na Figura 1.6 são mostradas as relações plano fundamental e $D_n-\sigma$ para galáxias em Leo I, Virgo e Fornax. As distâncias desses aglomerados de galáxias são obtidas através de medidas de estrelas Cefeidas. Fixando a

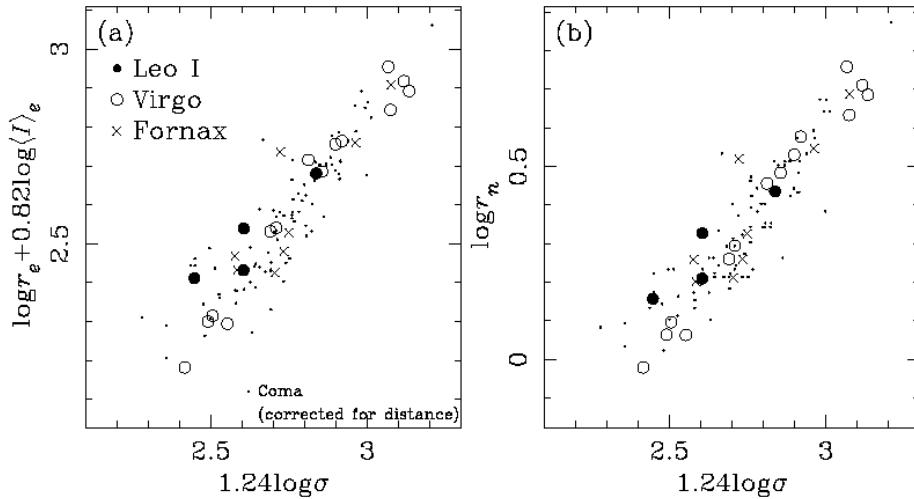


Figura 1.6: Relações Plano fundamental (a) e D_n - σ (b) em Leo I, Virgo e Fornax. O brilho superficial $\langle I \rangle_e$ e o raio efetivo r_e estão nas unidades L_\odot pc $^{-2}$ e kpc respectivamente. É apresentada a amostra de Coma, original de Jorgensen et al. (1995a,b). Figura original do trabalho de Kelson et al. (2000) (*H₀ Key Project*).

inclinação do plano fundamental, encontrada por Jorgensen et al. (1996), o ponto zero é definido como $\gamma \equiv \log r_e - 1,24 \log \sigma + 0,82 \log \langle I \rangle_e$. De maneira semelhante o ponto zero da relação D_n - σ é definido como $\delta \equiv \log r_n - 1,24 \log \sigma$, onde r_n é o raio dentro do qual o brilho superficial médio da galáxia é de 19,6 mag arcsec $^{-2}$ na banda Gunn r (Jorgensen et al. 1995a). Os pontos zero γ e δ obtidos para o *H₀ Key Project* (Kelson et al. 2000) foram $-0,173 \pm 0,013$ e $-2,395 \pm 0,011$ respectivamente.

Os pontos zero do plano fundamental e D_n - σ relacionam explicitamente o tamanho angular θ_e ou θ_n a uma escala métrica. Comparando pontos zero de um plano fundamental ou D_n - σ métrico ($\log r_e$ ou $\log r_n$) com os de

relações angulares ($\log \theta_e$ ou $\log \theta_n$) de aglomerados distantes, pode-se inferir diretamente as suas distâncias em Mpc, através das equações

$$\log d = \gamma_a + \gamma - 3$$

ou

$$\log d = \delta_a + \delta - 3,$$

onde γ_a e δ_a são os pontos zeros das relações de aglomerados. Dessa maneira as relações plano fundamental e $D_{n-\sigma}$ são usadas para inferir distâncias extragalácticas e na determinação da constante de Hubble $H_0 = vd$.

1.2.3 Relações $L-\sigma$ e $R-\sigma$ para Galáxias HII

Terlevich & Melnick (1981) analisaram as relações entre luminosidade $H\beta$, tamanho, larguras das linhas de emissão e abundâncias de elementos pesados de uma amostra de 25 regiões HII gigantes e galáxias HII. Eles concluíram que as relações $Luminosidade \propto \sigma^4$ e $Tamanho \propto \sigma^2$, válidas para sistemas gravitacionalmente ligados como galáxias elípticas, bojos de galáxias espirais e aglomerados globulares, são também válidas para regiões HII gigantes e galáxias HII. Além disso, eles verificaram que o espalhamento da relação $L-\sigma$ é explicado em parte por um efeito de metalicidade, sugerindo que regiões HII gigantes e galáxias HII são sistemas de uma família de pelo menos dois parâmetros. Posteriormente, grupos independentes (Hippelein 1986; Roy et al. 1986) confirmaram a validade dessas relações para regiões de formação intensa de estrelas de alta massa, onde a emissão nebulosa indica movimentos supersônicos⁹. Mais tarde, Melnick et al. (1988) calibraram

⁹ $\sigma \geq c_{HII} = (2kT_{HII}/m_H)^{1/2} = 12,85 \text{ km s}^{-1}$ para $T_{HII} = 10^4 \text{ K}$; onde k é a constante

a relação $L_{\text{H}\beta}\text{-}\sigma$ incluindo a razão O/H como um segundo parâmetro para uma amostra de 49 galáxias HII e a utilizaram como indicador de distância extragaláctica.

A semelhança entre as relações $L\text{-}\sigma$ e $R\text{-}\sigma$ encontradas para galáxias HII e galáxias elípticas sugere que a largura das linhas de emissão em galáxias HII representa a dispersão de velocidades do sistema gás-estrelas dominado pelo potencial gravitacional total, e assim os valores de σ refletem a massa total do sistema. Telles (1995) mostrou que galáxias HII definem um espécie de “plano fundamental” similar ao definido por galáxias elípticas (Figura 1.7).

As relações empíricas para galáxias espirais (seção 1.2.1) e elípticas (seção 1.2.2) como indicadores de distâncias, não podem ser aplicadas às galáxias em altos *redshifts* ($z > 0,5$), devido aos efeitos sistemáticos de evolução da população estelar com o tempo cosmológico (*look-back time*). Portanto, mesmo que seja possível medir os parâmetros observacionais com a nova geração de telescópios em terra e espaciais, ainda não está claro se será possível aplicar essas técnicas para determinar com precisão distâncias de galáxias em $z > 0,5$ (Melnick et al. 2000). Por outro lado, a técnica desenvolvida por Melnick et al. (1988) para obter distâncias extragalácticas através da relação $L_{\text{H}\beta}\text{-}\sigma$ para galáxias HII revelou-se uma ferramenta cosmológica poderosa, porém recebeu pouca atenção na literatura. Uma justificativa para seu uso é que, apesar de serem objetos de baixa massa, suas luminosidades bolométricas são dominadas por uma ou mais componentes *starburst*, fazendo com que suas luminosidades por unidade de massa sejam muito altas, tornando esses objetos possíveis de serem observados a distâncias de

de Boltzmann, m_H é massa do átomo de hidrogênio.

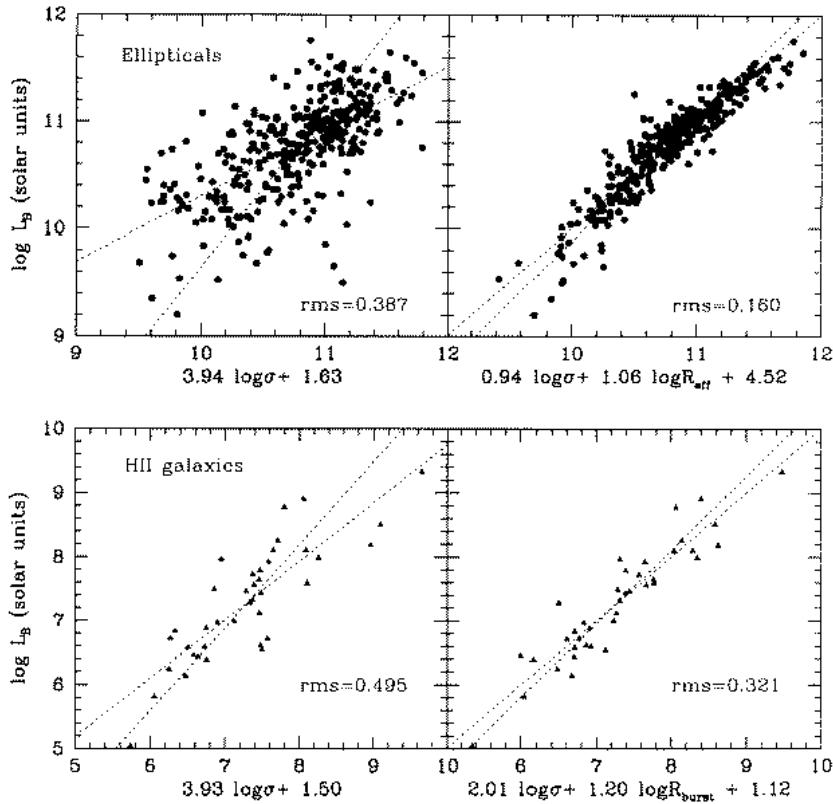


Figura 1.7: (*painel superior*) Gráfico logarítmico da luminosidade B de galáxias HII (triângulos) e Elípticas (círculos) versus larguras de linhas. (*painel inferior*) Correlação entre o raio linear e a dispersão de velocidade. As linhas pontilhadas mostram os ajustes lineares direto e inverso para galáxias HII e galáxias elípticas (Telles 1995).

interesse cosmológico. Além disso, Melnick et al. (2000) argumentam que, ao selecionar galáxias HII com as mais intensas linhas de emissão (i.e. com as maiores larguras equivalentes), estamos selecionando efetivamente as regiões de formação estelar mais jovens, dentro de um limite estreito de idade do *starburst* (Copetti et al. 1986).

Apesar da validade da relação estar confirmada, ainda não foi possível usar efetivamente as calibrações atuais como um indicador de distâncias extragalácticas com precisão comparada a relação Tully-Fisher ou o plano fundamental, devido à falta de dados de alta qualidade para a amostra de calibração, as incertezas quanto a eficiência de um segundo parâmetro e a ausência de limites para aplicação do método. A única tentativa para o Universo Local se resume ao trabalho precursor de Melnick et al. (1988), com a determinação da distância ao aglomerado de galáxias de Virgo (15 ± 2 Mpc) e da constante de Hubble ($H_0 = 89 \pm 10$ km s $^{-1}$ Mpc $^{-1}$). A presença significativa de galáxias HII no Universo distante justifica o esforço em se compreender melhor a sua relação $L-\sigma$ e os efeitos sistemáticos envolvidos. Phillips et al. (1997) mostraram que um número significativo dessas galáxias habitam o campo a profundidades típicas da imagem “Hubble Deep Field” (Williams et al. 1996), isto é $0,4 < z < 1$. Em um trabalho seguinte Guzmán et al. (1997) mostram que estas galáxias de fato concordam com a relação $L-\sigma$ previamente calibrada para o Universo Local. Em trabalho mais recente, Siegel et al. (2005) inferem o parâmetro cosmológico densidade da matéria (Ω_m) a partir de distâncias estimadas de novas galáxias típicas HII das amostras de Pettini et al. (2001) e Erb et al. (2003) ($2,17 < z < 3,39$), usando ainda a calibração de Melnick et al. (1988), que pode sofrer de efeitos sistemáticos ainda

não contemplados e que discutiremos mais profundamente neste trabalho.

1.3 Movimentos Internos em Galáxias HII

Vários mecanismos de alargamento dos perfis das linhas de emissão têm sido propostos para explicar as larguras de linhas supersônicas em regiões HII gigantes e galáxias HII. Esses mecanismos se dividem principalmente em dois grupos: modelos gravitacionais e modelos onde o alargamento das linhas é consequência da injeção de energia mecânica pelas estrelas massivas.

Em modelos gravitacionais (Terlevich & Melnick 1981), os perfis de linha Gaussianos observados, estão supostamente relacionados com os movimentos virializados dentro de regiões HII. Pelo Teorema do Virial

$$2K + U = 0, \quad (1.1)$$

onde K e U são as energias cinética e potencial do sistema, respectivamente. Para uma distribuição esférica de massa M , de densidade $\rho(r)$ qualquer e raio R ,

$$K = \frac{1}{2}M\langle V_{RMS}^2 \rangle \quad (1.2)$$

e

$$U = -C \frac{GM^2}{R}, \quad (1.3)$$

onde C é uma constante que depende do perfil de densidade¹⁰, $\langle V_{RMS}^2 \rangle$ a

¹⁰Para uma distribuição esférica de massa com densidade uniforme ($\rho = \text{constante}$), $U = -\frac{3}{5}\frac{GM^2}{R}$. Para uma galáxia esférica com brilho superficial $\Sigma(r)$ seguindo a Lei de Vaucouleurs $\log \Sigma(r) = -Ar^{1/4} + B$, onde A e B são constantes arbitrárias e $M/L = \text{constante}$, $U = -0,33\frac{GM^2}{R_e}$ (Fish 1964), onde R_e é o raio efetivo — o raio de um círculo que compreende a metade da luz da galáxia.

velocidade quadrática média das partículas e G a constante universal da gravitação. Como observamos na linha de visada apenas a componente radial da dispersão de velocidades (σ_{obs}) e assumimos uma distribuição de velocidades isotrópica, temos que

$$\langle V_{RMS}^2 \rangle = 3\sigma_{obs}^2. \quad (1.4)$$

Portanto, substituindo em (1.1) as equações (1.2) e (1.3), e considerando a equivalência (1.4), temos

$$3M\sigma_{obs}^2 = C \frac{GM^2}{R},$$

que pode ser reescrita na forma

$$\sigma_{obs} = \sqrt{\frac{C}{3}} \sqrt{\frac{GM}{R}}.$$

Assim, para diversos sistemas reais que se aproximam do equilíbrio dinâmico podemos considerar como válida a relação

$$\sigma_{vir} \sim \sqrt{\frac{GM}{R}}. \quad (1.5)$$

Para uma relação massa-luminosidade constante ($M/L = \text{constante}$) pode-se mostrar a partir de (1.5) que

$$L \propto R\sigma^2.$$

Para sistemas com M/L e brilhos superficiais constantes, L depende apenas da área pela qual a energia é liberada, assim temos que

$$L \propto R^2.$$

Logo chegamos as seguintes relações de escala

$$L \propto \sigma^4 \quad (1.6)$$

e

$$R \propto \sigma^2. \quad (1.7)$$

O principal argumento contrário a validade das relações (1.6) e (1.7) em sistemas como regiões HII gigantes e galáxias HII é que nestes casos a dispersão de velocidades considerada é a do gás e não das estrelas, que podem ser consideradas as partículas do sistema descrito acima. O argumento se justifica porque é esperado que para o gás com propriedades colisionais e velocidades supersônicas, essas relações não se mantenham, já que a energia se dissiparia através de choques entre partes da nuvem em escalas relativamente curtas de tempo $t \sim R/\sigma$. Alguns mecanismos têm sido propostos na tentativa de explicar as relações de escala ($L-\sigma$ e $R-\sigma$) verificadas e as larguras de linha supersônicas observadas.

O *Cometary Stirring Model* (CSM) (Tenorio-Tagle et al. 1993) propõe que em um aglomerado recém formado, um grupo de estrelas de baixa massa produzindo ventos e apresentando dispersão de velocidades $\sigma_* \sim (GM/R)^{1/2}$, dada pelo potencial gravitacional de acordo com o Teorema do Virial (equação 1.1), irá agitar o gás remanescente, colocando-o em um movimento turbulento médio $\sigma_{\text{gás}} \sim \sigma_*$. A agitação do gás nesse caso, é causada por passagens sucessivas de estrelas e seus ventos estelares supersônicos, gerando os chamados choques “cometários” ou *bow shocks*. Este representaria, portanto, o “agente estabilizador”, que seria responsável por repor a energia dissipada e manter o gás em movimento supersônico. A partir de algumas considerações

geométricas, propriedades dos ventos e a transferência de momento ao gás, o modelo permite estimar a luminosidade do aglomerado L_{aglo} como função da dispersão de velocidades do gás e constantes fundamentais, através da equação

$$L_{aglo} = \frac{4c\sigma^4}{9G} = 0,5 \times 10^8 L_\odot \left(\frac{\sigma_{\text{gás}}}{10 \text{ km s}^{-1}} \right)^4. \quad (1.8)$$

Vale notar que (1.8) é independente da velocidade do vento v_* ou da sua luminosidade L_* , representando assim um modelo analítico gravitacional. A equação (1.8) se manterá válida enquanto os ventos guiados radiativamente dominarem os *bow shocks* e a luminosidade estelar. Desta maneira o modelo reproduz a relação de escala $L \propto \sigma^{~4}$ observada, especialmente para galáxias HII.

Scalo & Chappell (1999) mostraram que é possível reproduzir relações de escala observadas em regiões *starburst* através um modelo analítico que considera o balanço entre a injeção de energia cinética devido aos ventos estelares e a dissipação, dado pela equação

$$\frac{d(\sigma^2/2)}{dt} = \frac{\dot{N}_* E}{\rho} - \frac{1}{2} a \sigma^3 N_{\text{nuv}}, \quad (1.9)$$

onde \dot{N}_* é a taxa de formação estelar por unidade de volume, E é a energia cinética média injetada pelas estrelas, ρ a densidade média da região, a a seção de choque entre nuvens ou fragmentos e N_{nuv} o número de nuvens por unidade de volume. Aqui, N_{nuv} é considerado como sendo determinado pela produção por ventos, criando subestruturas discretas, e a destruição via colisões. Lida da esquerda para a direita, a equação (1.9) diz que a dispersão de velocidade, σ , que é observada através das larguras de linha de uma região, é controlada pela injeção de energia cinética média pelos ventos

como função da taxa de formação estelar (\dot{N}_\star), menos um termo dissipativo ($\sigma^2/2\tau_{\text{col}}$) devido às colisões entre nuvens, onde τ_{col} é a escala de tempo de colisão, $\tau_{\text{col}} \sim (N_{\text{nuv}} a \sigma)^{-1}$. A partir de algumas considerações idealizadas os autores mostram que em uma situação de equilíbrio, $d(\sigma^2/2)/dt = 0$, é válida a relação de escala

$$\sigma = \left(\frac{2\dot{E}\mu_{\text{nuv}}}{\rho^2} \right)^{1/3}, \quad (1.10)$$

onde μ_{nuv} é a densidade de coluna média através das nuvens e $\dot{E} = N_{\text{nuv}} E$ é a taxa de energia total injetada pelas estrelas por unidade de volume, que pode ser escrita em termos da luminosidade mecânica L_K em erg s⁻¹ ($\dot{E} \sim L_K/R^3$). Escrevendo o segundo componente de ρ do denominador da equação (1.10) em termos da densidade de coluna média de toda a região, $\rho = \mu/R$, temos que

$$\sigma \sim \left(\frac{L_K/R^2}{\rho} \frac{\mu_{\text{nuv}}}{\mu} \right)^{1/3}. \quad (1.11)$$

Entretanto, para que esta relação possa ser comparada com as observações e assim testar o modelo, deve-se conhecer como que L_K se relaciona com a luminosidade radiativa L_* . Uma hipótese aceitável para as fontes da energia cinética são os ventos de estrelas massivas $L_{\text{vent}}(m) \propto \dot{M}V_\infty^2$, onde \dot{M} é a taxa de perda de massa e V_∞ é a velocidade terminal do vento, ambos para uma dada massa estelar m . Assim, para se obter uma relação entre L_{vent} e L_* deve-se ponderar, portanto, as contribuições relativas de estrelas de diversas massas de uma população para L_{vent} e L_* , o que implica adotar um espectro de massa, ou seja, uma função de massa inicial. Para um espectro de massa na forma de lei de potência $n(m) = Am^{-\gamma}$, onde o parâmetro $\gamma > 1$ é uma condição bem razoável e A uma constante arbitrária, uma

relação $L_{\text{vent}} \propto L_*^\delta$ é esperada. O expoente δ varia entre 1,3 e 1,6 para uma população estelar típica de aglomerados jovens com presença significativa de estrelas massivas. Adotando $\delta = 1,5$ a equação (1.11) pode ser reescrita fazendo $L_K = L_{\text{vent}} = L_*^{1,5}$, na forma

$$L_* \sim \left(\frac{\rho}{\mu_{\text{nuv}}/\mu} \right)^{2/3} R^{4/3} \sigma^2. \quad (1.12)$$

Se considerarmos a aproximação M/L e brilho superficial constantes (i.e. $L \propto R^2$), temos para esse modelo a relação de escala $L \propto \sigma^6$, que não pode ser descartada, ainda que não concorde tão bem com os resultado convergentes – $L \propto \sigma^{-5}$ para regiões HII gigantes e $L \propto \sigma^{-4}$ para galáxias HII. Este pode ser considerado portanto, um modelo típico não-gravitacional, ou seja, em que o principal mecanismo físico responsável pela dispersão de velocidades global da gás na região de formação estelar é a transferência de momento dos ventos estelares para o gás remanescente.

Os modelos apresentados acima pretendem explicar os movimentos globais do gás em regiões de formação estelar, especialmente regiões HII gigantes e galáxias HII, considerando várias hipóteses simplificadoras. Entretanto existem outros modelos que procuram explicar a dinâmica de bolhas, também chamadas de cavidades ou mesmo *shells*, que são muito presentes nesses ambientes como consequência nítida da evolução estelar. A física envolvida nesses modelos é bem mais complexa e trata de processos termodinâmicos e transferência radiativa, como por exemplo a hidrodinâmica de gás em expansão, condução de calor, ondas de choque, dissipação de energia, ionização e resfriamento radiativo. Essas bolhas, inicialmente de efeito localizado da ordem de raios estelares a poucas dezenas de parsecs, fatalmente adquirirão escalas de tamanho compatíveis com as regiões *starburst* ($\sim 10^2$ pc), em

consequência especialmente da ocorrência de Supernovas, e possivelmente guiarão a dinâmica do gás em um estágio final. A partir dos anos 60 surgiram os primeiros modelos que descrevem a evolução de bolhas remanescentes da fase Supernova das estrelas massivas (Shklovskii 1962; Woltjer 1970). Posteriormente Castor et al. (1975) e Weaver et al. (1977) propuseram um modelo para a evolução das bolhas circumstelares criadas por ventos de estrelas tipo O. Estes modelos têm sido extrapolados para o processo expansão global do gás em regiões *starburst*, sob efeito combinado dos ventos de estrelas massivas e Supernovas, oriundos de superaglomerados (McCray & Kafatos 1987; Maíz-Apellániz et al. 1999; Yao et al. 2006). Eles prevêem relações de escala envolvendo o tempo t , a luminosidade mecânica L_K , o raio da bolha R e a sua velocidade de expansão V_{exp} , porém pouco dizem sobre a dispersão supersônica global do gás observada. Veremos no Capítulo 3 que essas bolhas podem ser estudadas em galáxias HII e regiões HII gigantes em detalhes, através de espectroscopia bidimensional, a fim de testar a validade desses modelos.

Modelos de alargamento de linha diferentes consideram a ação combinada de várias bolhas e filamentos, como subestruturas interactuantes que dificilmente são resolvidas espacialmente pelas observações (Dyson 1979; Tenorio-Tagle et al. 1996). Chu & Kennicutt (1994) e Melnick et al. (1999) mostraram em estudos cinemáticos de 30 Doradus, que a soma dessas estruturas complexas em expansão produz linhas de emissão com um perfil simples aproximadamente Gaussiano ($\sigma \sim 22 \text{ km s}^{-1}$). Entretanto, as assimetrias nos perfis podem ser explicadas por componentes fracas, sendo comum a presença de uma componente subjacente larga ($\sigma \sim 40 - 50 \text{ km s}^{-1}$), possivelmente as-

sociada a ação dos ventos de estrelas massivas. Eles concluem que a energia cinética dessas bolhas e filamentos em expansão é várias vezes maior que a energia de ligação gravitacional da região. Apesar das evidências dessas estruturas interactuantes em regiões HII gigantes, esses mecanismos de alargamento também não explicam as correlações $L-\sigma$ e $R-\sigma$ observadas.

A persistência desses vários modelos dinâmicos, considerados como hipóteses viáveis na literatura presente, mostra o quão desconhecido é o assunto que trata da origem da dispersão de velocidades encontrada em regiões de formação intensa de estrelas como regiões HII gigantes e galáxias HII, primeiramente investigada por Smith & Weedman (1970, 1972).

1.4 Objetivos

Este trabalho tem como objetivo central investigar a cinemática das regiões HII gigantes e galáxias HII. Para isso atacamos o problema por duas frentes: (1) investigando a cinemática interna de uma região HII gigante que habita a galáxia II Zw 40, prototípica da classe das galáxias HII, nos beneficiando da técnica moderna de espectroscopia bidimensional (Unidade de Campo Integrado) com alta resolução espacial; e (2) investigando a relação $L-\sigma$ para uma amostra de 120 galáxias HII do Universo Local a partir de dados espetrofotométricos e medidas de larguras das linhas de emissão em espectros por nós observados em alta resolução espectral. Também queremos verificar a possibilidade do uso da relação de escala $L-\sigma$ observada para esses objetos como indicador de distâncias extragalácticas, a partir do estudo dos efeitos sistemáticos que afetam os parâmetros derivados L e σ .

No Capítulo 2 descreveremos a metodologia de trabalho, incluindo a nossa estratégia observacional e uma apresentação didática das ferramentas de análise de dados que utilizaremos. Nos dois Capítulos seguintes, Capítulos 3 e 4, apresentaremos os trabalhos independentes redigidos para publicação. O primeiro artigo foi aceito pela revista *Astrophysical Journal* em fevereiro de 2009 e trata da cinemática interna da região HII dominante na galáxia II Zw 40. O segundo, que será submetido à mesma revista em setembro de 2009, trata da relação $L-\sigma$ para as galáxias HII e seus efeitos sistemáticos. Ambos trabalhos foram idealizados e formatados de forma padrão para a publicação em revista científica, contendo uma introdução dos temas específicos, os resultados e análise dos dados, discussões e sumário das conclusões. Todos os dados utilizados nesta Tese estão apresentados em tabelas e figuras descritas nos artigos de forma auto-consistente. Qualquer referência aos dados, feitas nos Capítulos 2 e 5, serão portanto direcionadas aos artigos. Os resultados de cada trabalho são complementares para o entendimento da cinemática de galáxias HII e da relação $L-\sigma$, e serão apresentados de forma concisa no Capítulo 5.

Capítulo 2

Metodologia

Neste capítulo apresentaremos a motivação para o uso da espectroscopia unidimensional e bidimensional, como estratégia observacional a fim de obtermos dados relevantes para o nosso estudo das galáxias HII. Esses dados foram usados nos trabalhos desenvolvidos nos Capítulos 3 e 4. Assim, neles estão contidas informações complementares, bem como mais detalhes técnicos das observações, características dos instrumentos, procedimentos de redução dos dados e de seleção da amostra de galáxias. O presente capítulo tem a intenção de apresentar de forma didática a metodologia de trabalho, preenchendo a lacuna deixada pela exposição do trabalho nos capítulos seguintes, que estão formatados adequadamente para publicação em revistas científicas. Possíveis redundâncias de informação podem ocorrer quando tornarem-se necessárias sua apresentação em ambos capítulos.

2.1 Espectroscopia Unidimensional: Coudé e FEROS

Quando falamos em espectroscopia unidimensional queremos dizer que temos a informação da luz difratada de apenas “uma componente espacial”, mais precisamente, de uma única região delimitada do objeto. Por exemplo, podemos ter a luz integrada em uma tira estreita que tem a largura da fenda do espetrógrafo, como é o caso do espetrógrafo Coudé, e que correspondente a projeção da fenda sobre o objeto¹. Ou mesmo, a luz captada por uma fibra óptica em espetrógrafos de fibra única, como é o caso do espetrógrafo FEROS (*Fiber-fed Extended Range Optical Spectrograph*), que capta a luz de uma região delimitada, correspondente a projeção da seção reta da fibra sobre o campo de estudo. Com apenas uma observação como essas temos o estudo espectroscópico unidimensional, pois não temos a informação de como os espectros nas regiões adjacentes se comportam.

2.1.1 Espectros

Aqui apresentaremos a metodologia observacional da espectroscopia unidimensional feita com os espetrógrafo Coudé e FEROS instalados nos telescópios

¹Como a largura da fenda normalmente é da ordem da resolução espacial, frequentemente limitada pela turbulência atmosférica (*seeing*), diz-se que há somente uma componente espacial (x ou y) amostrada. Ainda assim o campo observado de um espetrógrafo Coudé, por exemplo, não é estático e gira conforme o telescópio acompanha o objeto no céu. Em exposições longas precisamos reposicionar continuamente o objeto sobre a fenda, e portanto o que obtemos de fato é um espetro que integra a luz de uma área projetada do objeto.

1,6m do Laboratório Nacional de Astrofísica - MCT (LNA/Brasil) e nos telescópios 1,52m e 2,2m do European Southern Observatory (ESO/Chile), respectivamente.

Com o objetivo de obter um espectro da região de formação estelar dominante nas galáxias, posicionamos a fenda (Coudé) ou a fibra (FEROS) dos espectrógrafos sobre sua região mais brilhante. É razoável pensar que esta região, com intenso fluxo óptico, corresponda ao evento principal de formação estelar nessas galáxias, já que nessa faixa de comprimento de onda encontram-se várias das linhas mais intensas do gás nebuloso que acusam a presença do *starburst* (toda Série de Balmer, $[\text{OII}]\lambda\lambda 3726, 3729$, $[\text{OIII}]\lambda 4363$ $[\text{OIII}]\lambda\lambda 4959, 5007$, $[\text{NII}]\lambda\lambda 6548, 6584$, $[\text{SII}]\lambda\lambda 6716, 6731$, $\text{HeI } \lambda 7065$ e $[\text{ArIII}]\lambda 7136$).

A Figura 2.1 mostra um exemplo do espectro de UM 499 reduzido do Coudé e a nossa estratégia observacional com este instrumento. Posicionamos a fenda, de largura correspondendo a 1 segundo de arco ($1''$), sempre de forma a cobrir a região mais brilhante da galáxia. Este caso é bem ilustrativo por se tratar nitidamente de uma galáxia *starburst* nuclear clássica. É nítido que regiões dos braços da galáxia, que também apresentam formação estelar intensa, poderão ter seus espectros sensibilizados no detector (CCD²), entretanto, ao extraímos os espectros definimos uma abertura de integração da luz que ficasse limitada a região central mais brilhante. Os espectros obtidos com o espectrógrafo Coudé foram calibrados em comprimento de onda e também em fluxo.

Procedimento semelhante foi feito nas observações com o FEROS. Na

²Charge-Coupled Device

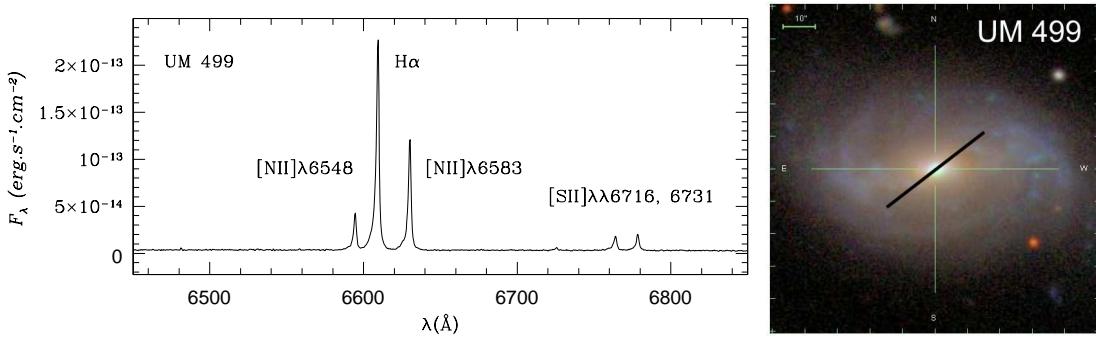


Figura 2.1: Exemplo de espectro reduzido do espectrógrafo Coudé e imagem exemplificativa da galáxia UM 499 (SDSS *Finding Chart Tool*) mostrando a posição típica da fenda ($1''$), cobrindo a região mais brilhante da galáxia. Não foi relevante a direção exata da fenda sobre a galáxia uma vez que o espectro é extraído de uma abertura englobando apenas a região central mais brilhante.

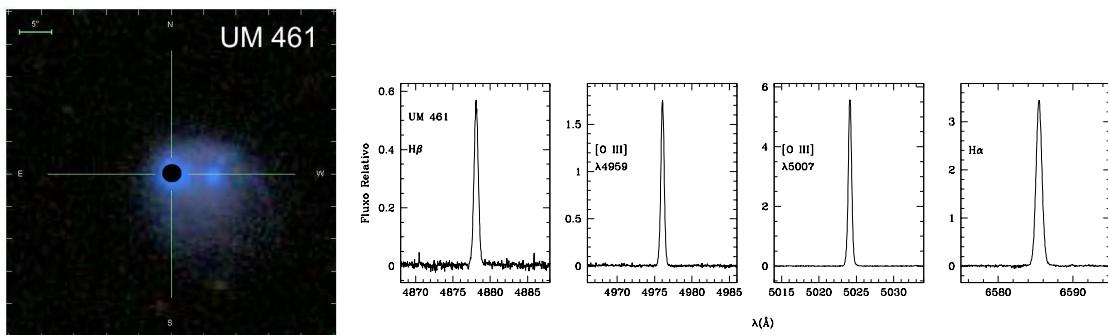


Figura 2.2: Exemplo de espectro (*echelle*) reduzido do espectrógrafo FEROS e imagem exemplificativa da galáxia UM 461 mostrando com um círculo preto a posição da fibra ($2,7''$) sobre o objeto. Posicionamento da fibra sempre sobre a região mais brilhante da galáxia.

Figura 2.2 mostramos um espectro reduzido de UM 461 e a estratégia de posicionamento da fibra óptica do instrumento sobre o objeto. Neste caso típico de uma galáxia HII podemos ver que existem mais de uma região de formação estelar na galáxia, que poderiam em princípio terem seus espectros tomados separadamente, entretanto mantivemos o critério de posicionar sempre a fibra sobre o *starburst* dominante. Os espectros FEROS são espectros *echelle* capazes de cobrir uma grande faixa espectral (3700-8600Å), pois o espectro é dividido em várias ordens para ocupar grande parte da área do CCD simultaneamente. Os espectros FEROS foram calibrados apenas em comprimento de onda.

Aqui vale notar que nossa estratégia de observação com o FEROS foi pioneira no ano 2000 quando começamos a usar este instrumento para observação de galáxias *starburst*. O FEROS é um instrumento projetado especialmente para observação de estrelas e assim não era utilizado normalmente para observações de galáxias. Este instrumento foi usado inicialmente acoplado ao telescópio 1.52m, onde ocorreram a maioria das nossas observações, e posteriormente foi instalado no telescópio 2.2m, ambos pertencentes ao consórcio do ESO. Graças a alta eficiência do instrumento pudemos em muitos casos fazer apenas uma exposição de 1800 ou 3600 segundos das nossas galáxias, obtendo uma razão sinal-ruído (S/N) nas linhas de emissão, adequada às nossas necessidades de medição. Com isso obtivemos a maior amostra de galáxias HII com larguras de linhas de emissão medidas e na mais alta resolução ($R=48000$) já estudada.

No Apêndice A é apresentado em ordem de ascensão reta o catálogo de perfis de linhas com todas as galáxias observadas. Para galáxias observadas

com o FEROS, são apresentados os perfis das quatro linhas nebulares medidas, H β , [OIII] $\lambda\lambda$ 4959, 5007 e H α , e para as galáxias observadas com o Coudé são apresentados os perfis de H α . Em seguida é apresentado uma comparação lado a lado dos perfis H α de galáxias que foram observadas com os dois instrumentos.

2.2 Espectroscopia Bidimensional: GMOS/ IFU (Gemini)

A espectroscopia bidimensional tem mostrado ser a técnica ideal para o estudo da cinemática de regiões de formação estelar (Bordalo, Plana, & Telles 2009, e referências nele contidas). Principalmente porque estes objetos apresentam subestruturas ($\sim 10^1$ pc) que só podem ser observadas com alto poder de resolução espacial. Por outro lado, é importante mapeá-las por uma área compatível com o tamanho da região ($\sim 10^2$ pc) para que se procure uma compreensão global dos movimentos internos. Durante mais de 30 anos esses estudos se limitaram às regiões HII gigantes em galáxias do Grupo Local, utilizando basicamente a espectroscopia Fabry-Perot e múltiplas observações de fenda longa a fim de cobrir grande parte do objeto. Entretanto, com o alto poder de resolução espacial alcançado na Era presente, dos telescópios de 10 metros, e seus instrumentos super eficientes, utilizando por exemplo, arranjos de fibras óticas e microlentes, pôde-se estender este estudo às galáxias mais distantes, a fim de estudar melhor a cinemática em escalas espaciais relativamente pequenas ($\sim 10^2$ pc), como núcleos de galáxias ativas e regiões de formação estelar em galáxias *starburst*. No que diz respeito a cinemática das

regiões HII gigantes em galáxias HII fora do Grupo Local, o trabalho apresentado no Capítulo 3 (Bordalo et al. 2009) é um dos primeiros na literatura, se beneficiando do instrumento GMOS/IFU instalado no telescópio Gemini Norte (Havaí/EUA).

As vantagens do uso da técnica de Unidade de Campo Integrado (IFU) são várias. Em primeiro lugar, pode-se cobrir um intervalo espectral bem maior do que normalmente se obtém com a espectroscopia Fabry-Perot, possibilitando a medição de várias linhas espectrais, para inferência das condições físicas na região, além da criação de mapas sintéticos, que podem ser integrados em intervalos de comprimento de onda específicos. Além disso, a observação de vários pontos da nebulosa é feita simultaneamente através de um arranjo de fibras óticas com microlentes em suas pontas, ajustadas ao plano focal do telescópio, reduzindo o problema de variações fotométricas ou variações do instrumento entre uma exposição e outra, como ocorre na técnica de múltiplas observações de fenda longa. Por outro lado, a aplicação da técnica resulta em um volume de dados impressionante, que merece uma atenção especial na sua redução e análise, para que se obtenha a informação desejada. Este “pacote” de dados que resulta de uma única observação é chamado normalmente de cubo de dados, uma vez que a informação está presente em três dimensões – duas coordenadas espaciais, x e y , mais a coordenada espectral λ – formando o cubo com os vetores de dados x , y e λ . Por esse motivo esta técnica é também chamada de “espectroscopia 3D”, sem que isso se confunda com o limite da informação espacial bidimensional.

2.2.1 Cubo de Dados

A Figura 2.3 mostra uma imagem sintética de como está distribuída a informação em um cubo de dados do instrumento GMOS/IFU. Cada elemento hexagonal (*spaxel*) representa uma unidade do campo para o qual se registrará um espectro. A forma hexagonal dos *spaxels* corresponde ao desenho da microlente instalada na ponta da fibra ótica que leva a luz até o aparato óptico (espectrógrafo propriamente dito). No GMOS/IFU este elemento colocado no plano focal do telescópio apresenta um diâmetro efetivo de $0,2''$. Como o campo apresenta $20 \times 25 = 500$ lentes destinadas ao objeto alvo temos um campo total³ para uma única observação de $3,5'' \times 5''$.

Os dados apresentados na Figura 2.3 referem-se ao campo central da galáxia II Zw 40, nosso objeto de estudo no Capítulo 3. Para que pudéssemos cobrir uma área significativa da região HII gigante naquela galáxia fizemos seis exposições deslocadas em ascensão reta e declinação em forma de cruz, centrada no *starburst* dominante (ver Figura 1 do Capítulo 3). As exposições foram todas de 300 segundos e não alcançamos S/N nas linhas suficiente em regiões muito afastadas do núcleo (*core*). Por isso nosso estudo se concentrou no campo central e adjacências próximas, $\sim 300 \times 300 \text{ pc}^2$.

Com esses dados reduzidos de ruído de leitura (Bias) e Campo Plano (Flat Field), e calibrados em comprimento de onda, é possível construir mapas sintéticos monocromáticos da região, isto é, mapas que representam a emissão de uma única linha de emissão, somando uma “fatia” $\Delta\lambda$ do cubo onde cai, por exemplo, a linha de H α , gerando o mapa de H α da região (Figura 2.3,

³O GMOS/IFU também possibilita a observação de um campo de $7'' \times 5''$ no modo *two-slit*.

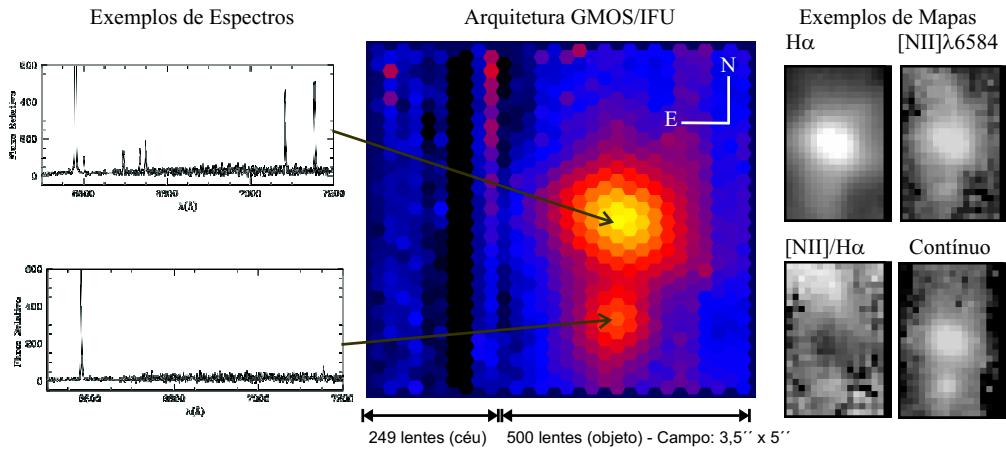


Figura 2.3: (*esquerda*) Exemplos de espectros reduzidos de elementos do campo distintos, (*centro*) arquitetura do campo GMOS-N/IFU mostrando campo central de II Zw 40 e (*direita*) exemplos de mapas monocromáticos ($H\alpha$ e $[NII]$ 6584Å), derivado ($[NII]/H\alpha$) e integrado no contínuo.

direita). A partir de mapas como este podemos fazer operações aritméticas como soma, subtração, multiplicação e divisão de mapas monocromáticos, sem que seja necessária sua calibração fotométrica, uma vez que todos foram observados simultaneamente e através de áreas iguais (*spaxels*). Para estudos que necessitam maior precisão espetrofotométrica sobre uma maior faixa espectral, deve-se atentar para a difração atmosférica, efeito que para grandes distâncias zenitais (Z) se torna mais evidente e deve ser corrigido (ver Lagos 2008, para um tratamento criterioso deste efeito). A massa de ar (X) nas nossas seis observações variou de 1,121 a 1,214 ($X = \sec Z$). Para nosso estudo em intervalos espetrais relativamente curtos (~ 500 Å) esse efeito não representou um problema, ainda que não estivéssemos interessados em precisão espetrofotométrica.

2.3 Larguras de Linhas

As relações de escala apresentadas na seção 1.3 envolvem o parâmetro independente da distância σ , comumente chamado de dispersão de velocidades. Entretanto, a hipótese de que as larguras de linhas em galáxias HII fornecem uma medida fidedigna da sua dispersão de velocidade interna,vem do fato desses sistemas apresentarem perfis das linhas de emissão aproximadamente Gaussianos. Isso é aceitável para a grande maioria dos objetos, inclusive quando observados com alta resolução espectral. Apesar disso, alguns objetos apresentam perfis contendo asas ou extensões proeminentes e até mesmo múltiplas componentes com intensidades de emissão compatíveis entre si, indicando a presença significativa de uma componente sistêmica.

A forma com que estimamos a dispersão de velocidades neste trabalho foi através de ajustes Gaussianos simples ou em múltiplas componentes. Usamos as rotinas SPLOT em IRAF (*Image Reduction and Analysis Facility*) preferencialmente para ajustes simples, e a rotina PAN (*Peak Analysis*) em IDL (*Interface Description Language*), para o ajuste de múltiplas componentes. A largura de linha do perfil Gaussiano ajustado ao perfil observado (FWHM_{obs}) é então convertida em $\sigma_{\text{obs}} = \text{FWHM}_{\text{obs}}/\sqrt{8 \ln 2}$ e este corrigido dos alargamentos instrumental (σ_{inst}) e térmico

$$\sigma_{\text{térm}} = \sqrt{\frac{kT_e}{m}},$$

assumindo distribuição Maxwelliana das velocidades, onde k é a constante de Boltzmann⁴, T_e a temperatura eletrônica⁵ em Kelvin e m a massa do

⁴ $k = 1,38065 \times 10^{-23} \text{ J K}^{-1}$

⁵Cálculo para T_e (OIII) será apresentado na Seção 2.5.2.

átomo⁶. Para os dados do FEROS que apresentam alta resolução ($\sigma_{\text{inst}}=2,5 \text{ km s}^{-1}$) também corrigimos as dispersões de velocidade derivadas das linhas do hidrogênio do alargamento devido as suas transições de estrutura fina, $\sigma_{\text{ef}}=3,20 \text{ km s}^{-1}$ para H α e $2,40 \text{ km s}^{-1}$ para H β (García-Díaz et al. 2008). A dispersão de velocidades não térmica (σ_{nt}) e que chamaremos também simplesmente de σ é portanto dada pela expressão

$$\sigma_{\text{nt}}^2 = \sqrt{\sigma_{\text{obs}}^2 - \sigma_{\text{inst}}^2 - \sigma_{\text{ef}}^2 - \sigma_{\text{térm}}^2}.$$

O fato das amostras de galáxias HII representarem amostras heterogêneas no que diz respeito a cinemática, é interessante na óptica da investigação sobre a origem dos movimentos internos nesses sistemas. Este foi nosso foco no trabalho apresentado no Capítulo 3 e por isso demos maior atenção as peculiaridade dos perfis de linha. Assim, procedemos análises de perfis de linha oriundos de regiões internas a região HII gigante de II Zw 40, usando as metodologias de deconvolução em múltiplas componentes Gaussianas e medidas de forma de perfil através dos estimadores de assimetria (*skewness*) e curtose (*kurtosis*).

Pela ótica do uso da relação $L-\sigma$ com indicador de distância a medida de largura de linha deve ser robusta. Assim um método que seja demasiadamente trabalhoso ou que necessite de alta qualidade do espectro observado (altos S/N e resolução espectral), pode inviabilizar seu uso como indicador de distância de galáxias realmente distantes. Portanto, deve-se por um lado obter uma medida robusta do parâmetro derivado da largura de linha, σ , e por outro analisar quais galáxias podem ser usadas como alvos e que devem seguir a relação com medidas robustas. Este foi nosso foco no trabalho

⁶ $m_{\text{H}} = 1,66054 \times 10^{-27} \text{ kg}$ e $m_{\text{O}} = 2,65686 \times 10^{-26} \text{ kg}$

apresentado no Capítulo 4. Apesar disso, demos atenção também às peculiaridades dos perfis de linha de cada galáxia, a fim de caracterizar a amostra do ponto de vista cinemático. Para isso, desenvolvemos um método semi-quantitativo de classificar as galáxias em função da forma de seus perfis espectrais, através de medidas dos estimadores de assimetria e curtose.

Em seguida (Seção 2.3.1) apresentamos nossa metodologia de cálculo dos estimadores de assimetria e curtose dos perfis de linha, que serviu a ambos trabalhos (Capítulos 3 e 4) e posteriormente (Seção 2.4) apresentaremos brevemente a metodologia de construção dos diagramas de diagnóstico cinemático que foram utilizados na análise dos dados de II Zw 40 no Capítulo 3.

2.3.1 Assimetria e Curtose

Enquanto que a média e o desvio padrão são medidas de localidade e espalhamento da distribuição, a assimetria (ou distorção) e a curtose são medidas adimensionais da sua forma. Na astronomia o uso da média (centróide) e desvio padrão de distribuições como histogramas e perfis espectrais são mais comuns, pois são parâmetros que normalmente estão associados às grandezas físicas (comprimento de onda em espectros eletromagnéticos ou tempo em séries temporais). Entretanto, estimadores de assimetria e curtose podem ser úteis fornecendo uma medida de quão próximos da distribuição Normal são os perfis observados. Esta pode também servir como uma análise complementar à deconvolução em múltiplas componentes. Usamos portanto esses estimadores para nos auxiliar na classificação das galáxias em função dos seus perfis de linha. Para um perfil de linha espectral real que apresenta duas dimensões, isto é, comprimento de onda (λ) e fluxo (y) os quatro primeiros

momentos centrais podem ser escritos nas formas

$$\begin{aligned} \text{média} &= \mu = \frac{\sum \lambda \cdot y}{\sum y}, \\ \text{desvio padrão} &= \sigma = \sqrt{\frac{1}{\sum y} \sum (\lambda - \mu)^2 \cdot y}, \\ \text{assimetria} &= \xi = \frac{1}{\sum y} \frac{\sum (\lambda - \mu)^3 \cdot y}{\sigma^3}, \\ \text{curtose} &= \kappa = \frac{1}{\sum y} \frac{\sum (\lambda - \mu)^4 \cdot y}{\sigma^4}. \end{aligned}$$

Vale lembrar que a assimetria de uma Gaussiana é igual a 0, significando ser uma distribuição perfeitamente simétrica, enquanto a curtose⁷ tem valor 3. Assimetrias positivas indicam que o perfil apresenta asa proeminente à direita ou para comprimentos de ondas mais vermelhos, enquanto que assimetrias negativas indicam asas proeminentes azuis (Figura 2.4). Curtoses maiores que 3 indicam perfis pontiagudos, ou leptocúrticos. Esses perfis acusam a presença de asas extensas e em nosso caso de estudo podem indicar a presença de componentes subjacentes (fracas) largas. Valores de curtose menores que 3 indicam perfis achatados, ou platicúrticos. Estes perfis estão normalmente associados àqueles perfis em que duas componentes de intensidades compatíveis estão convolvidas.

Como os estimadores são calculados numa região espectral, para usarmos o método para perfis de linha reais e em seguida podermos compara-los uns com outros consistentemente, precisamos definir uma metodologia de cálculo fixa para todos os espectros. Por exemplo, podemos delimitar a região de integração em λ que engloba o perfil de linha, definindo o intervalo no qual

⁷ Alguns livros definem a curtose da Gaussiana como 0 fazendo $\kappa' = \kappa - 3$, assim curtoses positivas indicam perfis leptocúrticos enquanto que as negativas platicúrticos

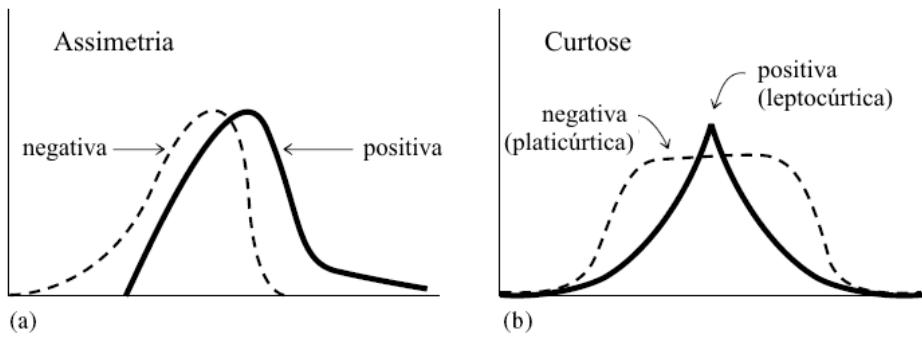


Figura 2.4: Exemplos de distribuições em que a assimetria (a) e a curtose (b) são significativamente diferentes da distribuição normal ou Gaussiana.

o fluxo do pico da linha cai a um dado percentual. Isso nos garante que os valores dos estimadores podem ser comparados entre si e que suas diferenças relativas são intrínsecas e podem nos auxiliar na caracterização dos perfis de linha. O ideal seria que essa janela de integração contemplasse grande parte das asas da linha, entretanto isso na prática não é possível. Devido o S/N nas asas serem menores, a janela em λ definida deve garantir que estamos integrando numa região onde o ruído não altera significativamente o valor dos estimadores para todos os perfis. Alguns perfis que tiveram suas asas mais amostradas poderiam ter estimadores mais precisos (ou absolutos com respeito a Gaussiana). Entretanto, a comparação do seus estimadores com daqueles de perfis não tão bem amostrados seria tendenciosa. Essa foi a base de nossa metodologia para calcularmos os estimadores de forma dos perfis de linha. Forneceremos mais detalhes sobre este procedimento e a forma como classificamos as galáxias usando essas medidas no Capítulo 4. Alguns exemplos de perfis H α são apresentados na Figura 2.5 e mostram algumas, e não toda a variedade de forma de perfis de linha das galáxias da nossa

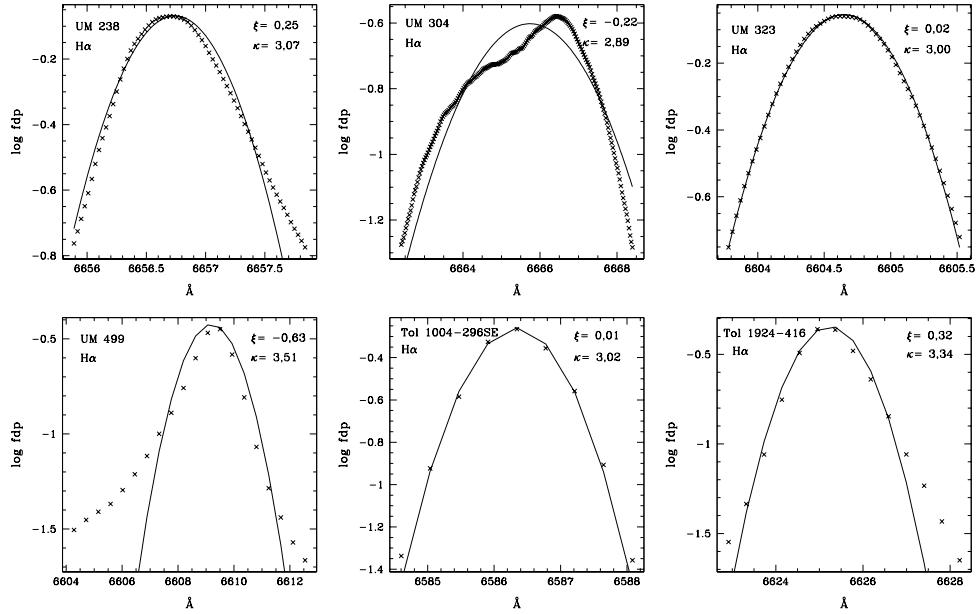


Figura 2.5: Exemplos de perfis $\text{H}\alpha$ com seus valores dos estimadores de assimetria e curtoza. (*painéis superiores*) Perfis observados com o FEROS com resolução espectral de $0,13\text{\AA}$ ($\text{FWHM}_{\text{inst}}$). (*painéis inferiores*) Perfis observados com o Coudé ($\text{FWHM}_{\text{inst}}=0,90\text{\AA}$). As janelas de integração foram definidas como contendo a emissão até 20% do valor de pico para os espectros FEROS e 5% para os espectros Coudé.

amostra. Os perfis estão graficados em mono-log para que as peculiaridades nas suas formas sejam melhor visualizadas. As linhas sólidas representam as Gaussianas ajustadas aos perfis, que nesta escala toma forma de uma parábola.

2.4 Diagramas de Diagnóstico Cinemático

Os diagramas de diagnóstico cinemático vêm sendo usados há não muito tempo na literatura e devem se tornar ferramentas necessárias para o estudo da cinemática de regiões *starburst* em geral num futuro próximo, especialmente em função do desenvolvimento de novos instrumentos de campo integrado como o GMOS/IFU do Gemini (Muñoz-Tuñón et al. 1995). Não mais que 10 trabalhos, incluindo o nosso apresentado no Capítulo 3, foram desenvolvidos desde 1996 usando esta técnica (Yang et al. 1996; Muñoz-Tuñón et al. 1996).

Trata-se de graficar os observáveis intensidade (I), largura de linha (FWHM ou σ) e a velocidade radial (V) nas três formas possíveis, isto é, $I-\sigma$, $I-V$ e $V-\sigma$. As três medidas podem ser obtidas, por exemplo, através de ajustes simples Gaussianos automatizados a cada perfil de linha dos espectros campo. Assim podemos mapear como esses três valores variam sobre a face da nebulosa e se apresentam alguma relação sistemática entre si. Os trabalhos precedentes têm mostrado que essas relações existem, fornecendo pistas sobre a origem dos movimentos internos e servindo de contrapartida observational para o confronto com modelos teóricos de formação e evolução de superaglomerados. É de fato uma técnica robusta uma vez que podemos usar ajustes

simples aos perfis de linha para obtermos uma indicação dos observáveis e diagnosticar propriedades cinemáticas interessantes, como bolhas em expansão (*shells*), campo turbulento do *core* e *outflows*. Em seguida podemos investigar essas subregiões através de técnicas mais refinadas como a deconvolução em múltiplas componentes dos perfis de linha e estimadores de assimetria e curtose. Com dados GMOS/IFU é possível inclusive confrontar os resultados da cinemática com as condições físicas simultaneamente, algo que fizemos em II Zw 40 ainda que limitado à qualidade dos nossos dados, investigando o perfil de densidade eletrônica e de abundância de oxigênio em sua região central (ver Figuras 3 e 4 do Capítulo 3). Alguns diagramas obtidos da região NGC 604 em M33 analisada nos trabalhos precursores estão apresentados na Figura 2.6. Algumas tendências nesses gráficos são facilmente notáveis. (i) Altas dispersões de velocidades ocorrem em regiões de menor intensidade (diagrama $I-\sigma$) e (ii) neste caso parece existir uma dispersão de velocidades característica da região, $\sigma_0 \sim 17 \text{ km s}^{-1}$, agindo como um limite inferior para σ . (iii) Ainda é possível identificar bandas inclinadas (setas verticais $I-\sigma$) que os autores acreditam estar associadas às bolhas evoluindo no meio interestelar. (iv) A região mais brilhante apresenta valores de σ característicos encontrados em toda a região HII. (v) As variações de velocidade radial tendem a serem maiores em regiões de baixa intensidade (diagrama $I-V$).

Apenas o trabalho de Muñoz-Tuñón et al. (1996) buscou explicar padrões característicos formados no plano $I-\sigma$ através de um modelo de formação de superaglomerados e evolução de bolhas no meio interestelar. Após a análise feita em II Zw 40 propomos através de exemplos esquemáticos algumas for-

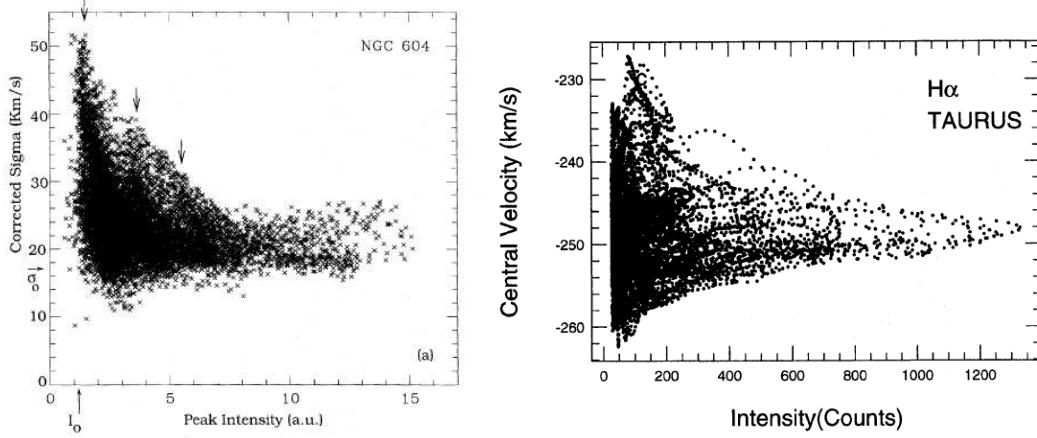


Figura 2.6: (esquerda) Diagrama $I-\sigma$ de NGC 604 (Muñoz-Tuñón et al. 1996). As setas verticais indicam as figuras identificadas pelos autores como *bandas inclinadas*, I_0 o limite mínimo de intensidade de pico da linha para medida confiável de σ e $\sigma_0=17 \text{ km s}^{-1}$ o limite inferior aproximadamente constante em todo intervalo de intensidades. Dispersão de velocidade corrigida (σ_{cor}) no eixo y se refere a correção pelo alargamento térmico e instrumental ($\sigma_{\text{cor}}^2 = \sigma_{\text{obs}}^2 - \sigma_{\text{térm}}^2 - \sigma_{\text{inst}}^2$). (direita) Diagrama $I-V$ de NGC 604 (Yang et al. 1996). Ambos trabalhos foram feitos usando a linha de H α e com o interferômetro imageador TAURUS instalado no telescópio 2,5 m Isaac Newton do Observatório Roque de Los Muchachos em La Palma, Ilhas Canárias/Espanha.

mas de interpretar os movimentos internos em regiões HII gigantes, incluindo idéias próprias e argumentos compilados de trabalhos anteriores. Parte dessas idéias estão publicadas no artigo apresentado no Capítulo 3 inclusive em seu apêndice. A idéia é que o conjunto desses diagramas possam vir a ser usados como modelos para ajudar na identificação de propriedades cinemáticas interessantes em regiões HII gigantes observadas através de espectroscopia bidimensional. Não nos estenderemos mais aqui neste ponto já que outros detalhes técnicos da metodologia são apresentados nas Seções 2 e 3.5 do artigo supracitado.

2.5 Espectrofotometria e Condições Físicas

Foi proposto que parte do espalhamento na relação $L-\sigma$ deve estar associado à existência de um segundo parâmetro (Terlevich & Melnick 1981; Melnick et al. 1987, 1988; Telles & Terlevich 1993). Um dos parâmetros investigados por este grupo foi a abundância química dado pela a razão O/H. No trabalho apresentado no Capítulo 4 testaremos esta hipótese de posse de uma amostra que dobra o número de galáxias das amostras anteriores e de dados espectrofotométricos mais homogêneos e de mais alta qualidade. Não só estudamos o impacto do parâmetro O/H mais de outras condições físicas que serão apresentadas a seguir.

Toda a espectrofotometria apresentada neste trabalho foi compilada da literatura. Aqui ressaltamos a importância do trabalho de Kehrig, Telles, & Cuisinier (2004, daqui em diante KTC) para o trabalho a ser apresentado no Capítulo 4. Ambos trabalhos foram planejados inicialmente pelo

Dr. Eduardo Telles com o intuito de alcançar uma amostra significativa de galáxias HII com dados espectrofotométricos e de larguras de linhas. Essas galáxias são em sua maioria equatoriais e do hemisfério sul (ver Tabela 1 do Capítulo 4). Obtivemos dados espectrofotométricos ópticos do trabalho de KTC para 91 das 120 galáxias e regiões de galáxias da nossa amostra Coudé + FEROS com larguras de linhas medidas. KTC observaram com espectroscopia de fenda longa e em alguns casos extraíram mais de um espectro por galáxia, para diferentes regiões de emissão separadas espacialmente. Nas galáxias em que foi usada esta metodologia tomamos os fluxos das regiões de maior fluxo. A largura da fenda usada foi de $2''$. A fim de completarmos os dados espectrofotométricos para o maior número possível de galáxias da nossa amostra compilamos dados e resultados diretos de trabalhos recentes com metodologias semelhantes a KTC e que serão referenciados em momento oportuno no Capítulo 4.

A espectrofotometria possibilita a medida de fluxo calibrado (em $\text{erg s}^{-1} \text{cm}^{-2}$) das linhas de emissão, que por sua vez nos permitem derivar as condições físicas dos berçários de formação estelar. Condições físicas em galáxias HII e regiões de formação estelar em geral é um tópico vasto na literatura, especialmente no que diz respeito às metodologias para a obtenção dos indicadores como, abundância química, temperatura eletrônica, densidade eletrônica, temperatura de ionização, conteúdo de poeira, dentre outros. Não é nosso foco neste trabalho entrar no mérito de cada um desses indicadores nem em detalhes da física que estão por trás dos cálculos para obtenção deles. Quando necessitarmos de argumentos físicos específicos para darmos suporte às nossas interpretações de como e porque esses parâmetros

podem afetar a relação $L-\sigma$, os faremos em momento oportuno no Capítulo 4. Entretanto, a fim de obtermos os dados relevantes para o nosso estudo utilizaremos cálculos clássicos que ainda são frequentemente usados e serão apresentados a seguir. De posse desses dados iremos analisá-los conjuntamente com nossos resultados vindos dos perfis de linha e que fornecem informações sobre a dinâmica desses sistemas. Todos esses resultados serão apresentados no Capítulo 4.

A partir dos dados de fluxos de linha calculamos os seguintes parâmetros físicos: coeficiente de extinção $H\beta$, temperatura e densidade eletrônica, a razão de ionização $[OIII]/[OII]$ e a abundância de oxigênio dado pela razão O/H. A largura equivalente de $H\beta$ será também usada e foi extraída diretamente dos trabalhos referenciados.

2.5.1 Extinção

A poeira é o principal ingrediente do meio interestelar responsável pela extinção da luz óptica na linha de visada do objeto observado devido aos processos de espalhamento e absorção. Para que possamos usar propriamente os fluxos das linhas de emissão dos espectros calibrados precisamos corrigi-los do efeito da extinção. Para regiões de formação estelar o método normalmente usado é o Decremento de Balmer. O parâmetro padronizado que mede a quantidade de extinção, não só na galáxia estudada, mas em toda linha de visada é o coeficiente de extinção $H\beta$, $C(H\beta)$, definido como

$$I(H\beta) = F(H\beta) \times 10^{C(H\beta)}, \quad (2.1)$$

onde F é o fluxo observado e I o fluxo corrigido da extinção. Assumindo como conhecidas a função de extinção interestelar $f(\lambda)$ e algum processo físico capaz produzir razões das intensidades em linhas constantes, como $I(\lambda)/I(\text{H}\beta)$, podemos obter $C(\text{H}\beta)$ através da relação

$$\frac{I(\lambda)}{I(\text{H}\beta)} = \frac{F(\lambda)}{F(\text{H}\beta)} \times 10^{C(\text{H}\beta)f(\lambda)},$$

onde

$$f(\lambda) = \frac{C(\lambda)}{C(\text{H}\beta)} - 1. \quad (2.2)$$

As razões de intensidade entre as linhas da Série de Balmer podem ser relativamente bem estimadas para ambientes como regiões HII, fornecendo os seguintes valores para o Caso B (10^4K): $I(\text{H}\alpha)/I(\text{H}\beta) = 2,87$ e $I(\text{H}\gamma)/I(\text{H}\beta) = 0,466$ (Osterbrock 1989). Assim, as razões observadas com por exemplo $F(\text{H}\gamma)/F(\text{H}\beta)$ e $F(\text{H}\alpha)/F(\text{H}\beta)$ podem ser medidas e usadas para se calcular a quantidade de extinção dada por

$$C(\text{H}\beta) = \frac{\log \left(\frac{F(\text{H}\alpha)}{2,87F(\text{H}\beta)} \right)}{f(\text{H}\beta) - f(\text{H}\alpha)}$$

ou

$$C(\text{H}\beta) = \frac{\log \left(\frac{F(\text{H}\gamma)}{0,466F(\text{H}\beta)} \right)}{f(\text{H}\beta) - f(\text{H}\gamma)}.$$

Como a função de extinção interestelar é normalmente padronizada em $\text{H}\beta$, temos $f(\text{H}\beta)=0$ e $f(\lambda) < 1$ para $\lambda > \text{H}\beta(4861\text{\AA})$ e $f(\lambda) > 1$ para $\lambda < \text{H}\beta$, indicando que a extinção interestelar é maior em comprimentos de onda mais azuis, tornando o espectro “avermelhado”, daí o nome também usado para a extinção de avermelhamento interestelar. Em nosso estudo usamos a função de extinção de Whitford (1958) conforme padronizada por Lequeux et al. (1979). Entretanto, uma forma analítica também usada para essa curva é

que reproduz valores muito próximos aos publicados por Lequeux et al. (1979) é apresentada na forma

$$f(\lambda) = 3,15854 \times 10^{-1,02109\lambda} - 1,$$

onde λ está em unidades de μm (Izotov et al. 1994). Obtendo o valor de $C(\text{H}\beta)$, qualquer coeficiente de extinção $C(\lambda)$ pode ser calculado através da equação 2.2, e seu fluxo corrigido $I(\lambda)$, da mesma forma que na equação 2.1 para $\text{H}\beta$.

2.5.2 Abundância O/H

A temperatura eletrônica (T_e) e as abundâncias iônicas O^+ e O^{++} podem ser derivadas de forma satisfatória a partir das linhas proibidas de $[\text{OII}]\lambda 3727$, $[\text{OIII}]\lambda\lambda 4959,5007$ e $[\text{OIII}]\lambda 4363$. Uma forma clássica usada para a determinação de T_e é através da razão

$$R \equiv \frac{(4959 + 5007)}{4363},$$

entre intensidades de linhas do [OIII] e por isso também chamada de $T_e(\text{OIII})$. Como as linhas 4959 e 5007Å são normalmente presentes nos espectros, é a presença ou não da linha 4363Å que determina a viabilidade de se aplicar o método- T_e (ou direto) para derivar a abundância de oxigênio em regiões HII em geral. É sabido que T_e é diferente em zonas de baixa e alta ionização em regiões HII. Como as intensidades das linhas proibidas são fortemente dependentes da T_e é importante que se leve em consideração as variações de T_e nessas zonas para que se obtenha valores precisos das abundâncias iônicas. Em muitos casos não é possível a observação simultânea das linhas

de diagnóstico para a determinação direta da temperatura em zona de mais baixa ionização, como pro exemplo $T_e(\text{OII})$, assim é normalmente assumida uma função analítica relacionando a temperatura dessas duas zonas. Neste trabalho usaremos as expressões fornecidas em Pagel et al. (1992) e baseadas nos modelos de fotoionização de Stasińska (1990). Obtemos $T_e(\text{OIII})$ diretamente dos espectros a partir da expressão

$$t = T_e(\text{OIII}) = \frac{1,432}{\log R - 0,85 + 0,03 \log t + \log(1 + 0,0433xt^{0,06})},$$

onde t está em unidades de 10^4K , $x=10^{-4}N_e t_2^{-1/2}$, N_e é a densidade eletrônica em cm^{-3} e

$$t_2 \equiv T_e(\text{OII}) = \frac{2t}{1 + 0,8t}.$$

Usamos a razão de linhas [SII] $\lambda 6717/\lambda 6731$ sensível a N_e inserindo seus valores na rotina TEMDEN do pacote NEBULAR do IRAF. Esta rotina calcula N_e com base em um modelo atômico de cinco níveis (Shaw & Dufour 1995). As abundâncias iônicas puderam então ser calculadas a partir das expressões

$$12 + \log(\text{O}^{++}/\text{H}^+) = \log \frac{4959 + 5007}{\text{H}\beta} + 6,174 + \frac{1,251}{t} - 0,55 \log t$$

e

$$12 + \log(\text{O}^+/\text{H}^+) = \log \frac{3727}{\text{H}\beta} + 5,890 + \frac{1,676}{t_2} - 0,40 \log t_2 + \log(1 + 1,35x),$$

e a abundância total de oxigênio fazendo

$$\frac{\text{O}}{\text{H}} = \frac{\text{O}^+ + \text{O}^{++}}{\text{H}^+}.$$

Em princípio a abundância de íons com mais alto grau de excitação devem ser considerados, entretanto a razão acima é uma boa aproximação já que a

abundância iônica de O⁺⁺⁺ não excede normalmente 2-3% da abundância total de oxigênio em sistemas como galáxias HII (Skillman & Kennicutt 1993). Com esse método pudemos calcular abundâncias para 51 das 91 galáxias em comum com a amostra de KTC. Estimamos também abundâncias O/H através de métodos empíricos (Pilyugin 2000; Denicoló et al. 2002) para aquelas galáxias que não tiveram suas linhas [OIII] λ 4363 observadas em KTC e para aquelas em que não encontramos suas abundâncias pelo método- T_e na literatura. Todos esses dados serão apresentados no Capítulo 4.

2.5.3 [OIII]/[OII] e $W_{\text{H}\beta}$

A largura equivalente de H β ($W_{\text{H}\beta}$) e a razão de ionização [OIII]/[OII] podem fornecer a informação sobre o estágio evolutivo e as propriedades dos aglomerados ionizantes em galáxias HII. A fim de investigar se a relação $L-\sigma$ é sensível a esses efeitos precisamos obter esses parâmetros para as galáxias da nossa amostra. $W_{\text{H}\beta}$ foram diretamente tomados dos trabalhos da literatura, enquanto que a razão [OIII] $\lambda\lambda$ 4959,5007/[OII] λ 3737 foi calculada a partir dos fluxos corrigido de avermelhamento. Em ambos casos a preferência foi para os dados de KTC, que nos forneceu 91 $W_{\text{H}\beta}$ e 88 [OIII]/[OII].

Os dados de abundância O/H apresentados nesta seção, incluindo $W_{\text{H}\beta}$ e [OIII]/[OII], serão analisados conjuntamente no Capítulo 4 através da técnica de análise por componentes principais, com o objetivo de investigar os efeitos sistemáticos sobre a relação $L-\sigma$. Buscamos por um conjunto de parâmetros independentes que pode predizer a L_{Balmer} (parâmetro dependente) do *starburst* em galáxias HII, através de um modelo de regressão múltipla, identificando um conjunto novo de indicadores de distâncias extragalácticas para

esses sistemas e calibrando os coeficientes das regressões, considerando uma amostra homogênea que dobra o número de objetos analisados em estudos anteriores.

2.6 Distâncias e Luminosidade

Para que possamos estimar as luminosidades das linhas de emissão, como por exemplo H α de interesse neste trabalho, precisamos conhecer as distâncias das galáxias de nossa amostra. As distâncias foram calculadas a partir da Lei de Hubble, através da medida de *redshift* diretamente obtida dos espectros calibrados.

A Lei de Hubble é expressa na forma,

$$D = \frac{V}{H_0},$$

onde D é a distância da galáxia, V é a velocidade de recessão das galáxias e H_0 a constante de Hubble. Primeiramente, corrigimos as velocidades radiais observadas pelos movimentos da Terra, colocando-as no referencial heliocêntrico

$$z_{\text{hel}} = z_{\text{obs}} + z_{\oplus},$$

onde z_{\oplus} é o desvio Doppler resultante, devido aos movimentos da Terra de rotação, em torno do baricentro Terra-Lua e movimento heliocêntrico. Essa correção em módulo é menor que 30 km s^{-1} . A tarefa do IRAF usada para o cálculo da velocidade heliocêntrica foi a RVCORRECT do pacote ASTUTIL. As velocidades radiais heliocêntricas

$$V_{\text{hel}} = z_{\text{hel}}c,$$

foram finalmente corrigidas com respeito ao campo de radiação cósmica em microondas (CMB)

$$V_{\text{CMB}} = V_{\text{hel}} + \delta V,$$

onde δV é a componente de velocidade na direção da galáxia observada em relação ao CMB. A componente δV é calculada usando as coordenadas do ápice no sistema de coordenadas galáctico, $l_{\text{ápice}} = 264,14^\circ$, $b_{\text{ápice}} = +48,26^\circ$ e $V_{\text{ápice}} = 371,0 \text{ km s}^{-1}$ (Fixsen *et al.*, 1996). Usamos o *NASA/IPAC Extra-galactic Database - NED*⁸ para obtermos δV de todos os objetos observados. Após essa correção calculamos as distâncias pela equação,

$$D = \frac{V_{\text{CMB}}}{71 \text{ km s}^{-1} \text{ Mpc}^{-1}}.$$

Ao longo deste trabalho apresentado no Capítulo 4 usaremos o resultado do WMAP (*Wilkinson Microwave Anisotropy Probe*) para a constante de Hubble, $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, com margem de erro de 5%. Finalmente utilizamos as D para calcularmos as luminosidades H α das galáxias através da equação

$$L(\text{H}\alpha) = 4\pi D^2 I(\text{H}\alpha).$$

2.7 Análise de Componentes Principais

A Análise de Componentes Principais (PCA) é uma técnica estatística usada para procurar pistas sobre a natureza das relações entre variáveis. Ela difere da técnica de regressão múltipla que procura estimadores ótimos entre variáveis específicas em função de outras. O primeiro ponto que merece ser

⁸<http://nedwww.ipac.caltech.edu/>

destacado é que a análise de componentes assume-se relações lineares entre as variáveis. Entretanto, a prática de substituir grandezas lineares por seus logarítmicos é um argumento normalmente aceito para a aplicação deste método dentro de certo grau de confiabilidade (Brosche 1973).

Usamos a técnica PCA no Capítulo 4 com o objetivo de compreender melhor o papel que cada parâmetro físico observado tem na estrutura global dessas galáxias. São eles a luminosidade $H\alpha$, a dispersões de velocidades, a abundância química O/H, a largura equivalente $H\beta$ e a razão de ionização [OIII]/[OII].

A técnica PCA é usada com o objetivo de reduzir o número de variáveis (em nosso caso os parâmetros físicos) e fornecer uma visão estatisticamente privilegiada de um conjunto de dados. Ela fornece também as ferramentas adequadas para identificar as variáveis mais importantes no espaço das componentes principais. Essa técnica consiste em reescrever as variáveis originais em novas variáveis denominadas componentes principais, através de uma transformação de coordenadas. Cada componente principal é uma combinação linear de todas as variáveis originais e nesta combinação cada variável terá uma importância ou peso (*loading*) diferente. As componentes principais (novos eixos de coordenadas) são ortogonais entre si e assim não correlacionadas, logo cada componente principal fornece uma informação estatisticamente diferente das outras. O processo é tal que maximiza a informação estatística para cada uma das coordenadas que são criadas. As variáveis originais têm a mesma importância, enquanto que as componentes principais têm importância estatística decrescente. Na Seção 4.3 do Capítulo 4 apresentamos de forma completa a análise feita usando esta técnica para a investigação

dos outros parâmetros independentes O/H, $W_{\text{H}\beta}$ e [OIII]/[OII], que podem explicar parte do espalhamento observado da relação $L-\sigma$, fornecendo assim subsídios para propormos modelos de regressão múltipla que poderão servir como indicadores de distância de galáxias HII.

Capítulo 3

A Cinemática da Região HII Gigante em II Zw 40

Neste capítulo apresentamos o trabalho publicado na revista *Astrophysical Journal* com base em dados de espectroscopia de campo integrado ou bidimensional, e que trata do estudo da cinemática interna da região HII gigante na galáxia II Zw 40, e que representa uma galáxia prototípica da classe das galáxias HII. A região HII gigante estudada domina as propriedades especiais desta galáxia no óptico. Desenvolvemos a técnica de análise cinemática de gás nebuloso através de diagramas de diagnóstico cinemático. Esses diagramas que contemplam os observáveis intensidade de emissão, velocidade radial e dispersão de velocidades, embora já tenham aparecido na literatura, aqui foram reinterpretados à luz dos nossos dados e estendidas suas aplicações às subregiões da região HII gigante, tornando possível a caracterização das principais propriedades cinemáticas, como o campo turbulento permeante, as bolhas em expansão e os ventos de alta velocidade não resolvidos, oriundos

possivelmente das estrelas de alta massa. Este estudo é ideal para investigarmos os mecanismos de alargamento das linhas nebulares em regiões HII e galáxias HII. Lançamos luz a questão que intriga a comunidade há tempos sobre a predominância de perfis de linha supersônicos nestes sistemas e se estes perfis podem ser usados para determinar a massa do sistema, uma vez que é aceito o equilíbrio do virial. Estudos sobre a origem dos movimentos internos nesses sistemas são cruciais para entendermos a física por trás das relações empíricas $L-\sigma$ e $R-\sigma$ para regiões HII gigante e galáxias HII estudadas por vários grupos e que ainda não é bem compreendida. O trabalho apresentado no Capítulo 4 dará continuidade a investigação aqui feita.

THE INTERNAL KINEMATICS OF THE H II GALAXY II Zw 40

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ABSTRACT

We present a study of the kinematic properties of the ionized gas in the dominant giant H II region of the well known H II galaxy: II Zw 40. High spatial and spectral resolution spectroscopy has been obtained using the Integral Field Unit mode on the Gemini Multi-Object Spectrograph instrument at the Gemini-North⁷ telescope. The observations allow us to obtain the H α intensity map, the radial velocity and velocity dispersion maps as well as estimate some physical conditions in the inner region of the starburst, such as oxygen abundance (O/H) and electron density. We have used a set of kinematics diagnostic diagrams, such as the intensity versus velocity dispersion ($I-\sigma$), intensity versus radial velocity ($I-V$), and $V-\sigma$, for global and individual analysis in the subregions of the nebula. We aim to separate the main line broadening mechanisms responsible for producing a smooth supersonic integrated line profile for the giant H II region. Bubbles and shells driven by stellar winds and possibly supernovae, covering a large fraction on the face of the nebula, are identified on scales larger than 50 pc. We found that unperturbed or “free from shells” regions showing the lowest σ values ($\sim 20 \text{ km s}^{-1}$) should be good indicators for the σ_{grav} component in II Zw 40. The brightest central region ($R \sim 50 \text{ pc}$) is responsible for σ derived from a single fit to the integrated line profile. The dominant action of gravity, and possibly unresolved winds of young ($< 10 \text{ Myr}$) massive stars, in this small region should be responsible for the characteristic H α velocity profile of the starburst region as a whole ($\sigma = 32\text{--}35 \text{ km s}^{-1}$). Our observations show that the complex structure of the interstellar medium of this galactic scale star-forming region is very similar to that of nearby extragalactic giant H II regions in the Local Group galaxies.

Key words: galaxies: individual (II Zw 40) – Galaxy: kinematics and dynamics

Online-only material: color figures

1. INTRODUCTION

H II galaxies (HIIGs) are dwarf galaxies undergoing a burst of star formation. Their extensive star-forming regions, composed of an ensemble of Super Star Clusters (SSC) and giant H II regions (GHIIRs), dominate the optical emission. HIIGs represent the simplest examples of the starburst phenomenon occurring on galactic scales. II Zw 40 is one of the most famous HIIG showing an intense starburst in its central region. Its optical spectrum is dominated by very intense emission lines of H, He, [O II], [O III], [N II], [S II], and [Ne III] superposed on a faint blue continuum, indicating that the present rate of star formation (SF) is much higher than the historical average (Sargent & Searle 1970; Searle & Sargent 1972; Terlevich et al. 1991; Walsh & Roy 1993; Kehrig et al. 2004). II Zw 40 has a sub-solar oxygen abundance of $12 + \log(\text{O/H}) = 8.07$ from the data of Kehrig et al. (2004), typical of this class. The star formation (SF) history of this galaxy has been the object of several studies, ranging from the hypothesis that the star-forming episode may be producing a first generation of stars to a scenario in which the history of SF consists of a continuous series of short bursts over

its lifetime. Near-infrared spectra have been obtained by Vanzi et al. (1996), who showed that II Zw 40 has a low supernova rate and that no nuclear starburst, as powerful as the present one, has occurred in the past gigayear. Kunth & Sargent (1981) and Vacca & Conti (1992) found Wolf-Rayet (WR) features in the optical spectrum, confirming that the central region is very young (3–6 Myr). Beck et al. (2002) found that the bright central region concentrates 75% of the thermal free–free emission and that the 75 pc region is formed by four supernebula, each powered by ~ 600 O stars. Ulvestad et al. (2007) also found no radio supernovae with powers greater than Cas A.

The initial trigger of the present SF episode is also a question that remains unanswered for this class of dwarf starbursts since most are isolated systems (Telles & Terlevich 1995; Telles & Maddox 2000). If not triggered by external agents (i.e., interactions), star formation is caused by internal processes, manifesting in a stochastic manner (Pelupessy et al. 2004). This may be the case for the subsample of low luminosity, compact objects, classified as type II H II galaxies by Telles et al. (1997), with no signs of morphological disturbances. However, the more luminous H II galaxies, classified as type I, do show some signs of extensions, fuzz, or tails in their outer envelopes, suggesting tidal origin. Over the years, only a few studies have been carried out to determine the overall dynamics of II Zw 40. HI velocity mapping reveals a complex structure with a subtle velocity gradient (Brinks & Klein 1988; van Zee et al. 1998). The southeast and northwest HI tails have reversal rotation, suggesting that most of the material is falling back toward the dynamical center. The best scenario for the formation of II Zw 40 seems to be the result of a collision between two gas-rich dwarf

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galaxies, and the current starburst occurs in the overlapping merging region (Baldwin et al. 1982).

In the early 1970's, Smith & Weedman (1970a, 1972) first discovered broad [O III] and Balmer lines in GHIIRs. These lines have widths which are broader (i.e., line of sight velocity dispersion $\sigma \sim 13\text{--}25 \text{ km s}^{-1}$) than those found in normal H II regions in the Galaxy, e.g., $\sigma \sim 5.4 \text{ km s}^{-1}$ in Orion (Münch 1958; Smith & Weedman 1970b). These high velocity widths imply gas motions a few times the speed of sound. The early detailed studies suggested that winds from WR stars should contribute to the total kinetic energy in mass motions (Smith & Weedman 1972), and that supernova remnants (SNRs) could play a significant role in the energetic balance of GHIIRs (Skillman & Balick 1984).

In the meantime, Melnick (1977) showed a correlation between the diameter and the global H α profile widths of GHIIRs. Terlevich & Melnick (1981) found $L(H\beta) \propto \sigma^4$ which led them to propose a gravitational model for the origin of the supersonic motions, due to the close similarities with the parametric relations found for systems in dynamical equilibrium, such as elliptical galaxies, globular clusters and bulges of spiral galaxies. The first extrapolation to HIIGs was done by Melnick et al. (1988), where a significant sample of galaxies was observed, including II Zw 40. Recent work also confirms the existence of the $L-\sigma$ relation for HIIGs, suggesting that GHIIRs and the star-forming regions in HIIGs belong to a single family of objects (Rozas et al. 2006; Bosch et al. 2002; Telles et al. 2001; Fuentes-Masip et al. 2000).

Several line broadening mechanisms have been proposed to interpret the supersonic widths measured in the spectra of GHIIRs and HIIGs. Dyson (1979) proposes that line profiles consist of two components: one broad line component of the shocked region, and a narrower component originated in the neighboring region which is ionized by UV photons escaping from the broad line region. The broad line emission is likely to arise near the shell of a hot (10^6 K) highly ionized, wind-driven bubble. Yorke et al. (1984) used the champagne flow model (Tenorio-Tagle 1979)—disruption of neutral clouds adjacent to H II regions—to explain the broad lines. The gravitational model (Terlevich & Melnick 1981) is based on the assumption that the dominant influence is the gravitational potential. In this model, the observed Gaussian line profiles are a direct consequence of the virialized motions of the gas plus stars complex. If one supposes a *self-gravitating* system, the standard deviation of this Gaussian profile in velocity is

$$\sigma \sim \sqrt{\frac{GM}{R}}.$$

The Cometary Stirring Model (CSM) proposed later by Tenorio-Tagle et al. (1993) improves the simpler original picture. They propose that a group of pre-main-sequence low-mass stars of a recently formed starburst move under the gravitational potential with velocity dispersion σ_{star} . These stars drive winds that stir the remaining cloud through a supersonic bow, or “cometary,” shocks, providing it with an average turbulent motion $\sigma_{\text{gas}} \sim \sigma_{\text{star}}$. This model predicts the total mechanical energy produced by the shocks and the associated line luminosity. These predictions are in agreement with the observed relation $L \sim \sigma^4$. Few attempts have been made (e.g., Östlin et al. 2004; Cumming et al. 2008), and none with a statistically significant sample, to definitely test the hypothesis of $\sigma_{\text{gas}} = \sigma_{\text{star}}$ which would strengthen the support for this model.

A skeptical view of this scenario was presented by Chu & Kennicutt (1994) in a detailed study of the GHIIR 30 Doradus in the Large Magellanic Cloud (LMC). They showed that a smooth integrated velocity profile in the inner region ($135 \times 135 \text{ pc}$) results from a complex velocity field, which demonstrates the futility of using global velocity profiles to infer the physical origin of the gas motion. The dominant contributor to the global velocity dispersion, as proposed by the authors, at least in the bright core, is the superposition of individual expanding shells. Consequently, the most important physical mechanisms would be the stellar winds from OB associations combined with champagne-type flows and possibly supernovae.

This long disagreement in the literature has also been enlightened by works favored by high spectral, spatial as well as bi-dimensional spectroscopy of GHIIRs and the nearest HIIGs. Muñoz-Tuñón et al. (1996) analyzed the velocity field of NGC 604 and NGC 588 in the galaxy M33. They show that, in both cases, the peaks of high velocity dispersions are systematically concentrated in regions of faint nebular emission. On the other hand, there is a smooth low-velocity dispersion component which permeates all regions of the nebula. They proposed a simple criterion to identify expanding shells in the intensity vs. σ diagram. This smooth low-velocity dispersion component is what one measures in the integrated spectrum of a GHIIR. Yang et al. (1996) came up with basically the same conclusions in a similar study of NGC 604. The results found by Telles et al. (2001) using Echelle long-slit spectroscopy of a small sample of HIIGs point in the same direction. Despite the complex velocity fields found in such objects, they show that the brightest knots dominate the global luminosity and velocity dispersion.

Though much effort has been spent to understand the kinematics of the gas-stars complex in GHIIRs and HIIGs, a clear picture is still absent, given the complexity of these systems. The puzzle can be noted in the follow question: *Why should one find such parametric relations in these violent environments where massive star evolution seems to play a significant, maybe dominant, role?* Here, we aim to bring some insight to this question by extending the bi-dimensional spectroscopy study of Local GHIIRs to this nearby prototypical HIIG, with comparable spatial and spectral resolution. The kinematics of the ionized gas in the very center of II Zw 40 is investigated in some detail.

II Zw 40 has coordinates R.A. $05^{\text{h}}55^{\text{m}}42\text{:}6$, DEC. $+03^{\circ}23^{\text{m}}32\text{''}$ (J2000.0), a $V=15$ mag (Telles & Terlevich 1997). It lies at a low galactic latitude of $\sim -10^\circ$. The observed radial velocity of 778 km s^{-1} and a cosmological (corrected from heliocentric to cosmic microwave background frame) recession velocity of 845 km s^{-1} , puts it at a distance of 11.9 Mpc .⁸

The paper is organized as follows. Section 2 describes the observations and reduction procedures. The results are presented in Section 3 together with full descriptive data analysis. In Section 4, we discuss our results. Finally, we give a brief summary in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

The observations of II Zw 40 were done during the run GN-2003B-Q-26 on 2003 December 26. We used the Gemini Multi-Object Spectrograph (GMOS) equipped with an Integral Field Unit (IFU) on the Gemini-North Telescope. The IFU was used in one-slit mode giving a $3.5 \times 5 \text{ arcsec}^2$ field of view. Each lens in its original hexagonal shape has $0\farcs2$ nominal size projected in the sky. In this case, the IFU directed to the science

⁸ $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is used throughout this paper.

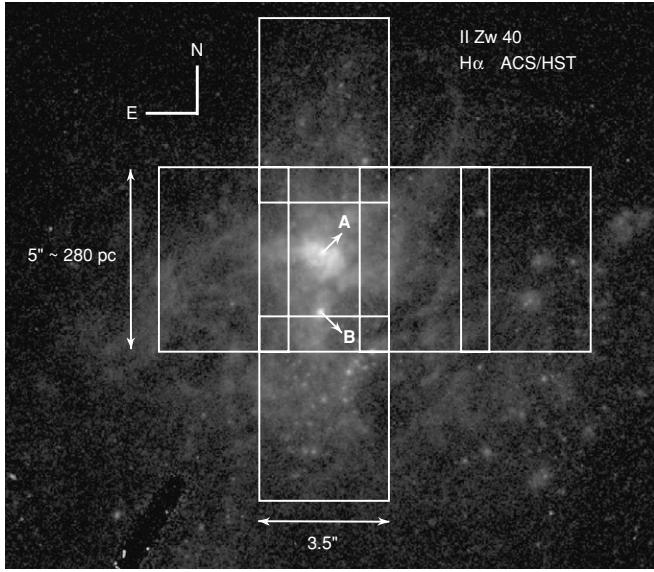


Figure 1. High-resolution H α image ($0''.027 \text{ pixel}^{-1}$) obtained with ACS/HST. The GMOS/IFU fields are shown over the central region of the galaxy (HST's archive data from the proposal 9739 by Rupali Chandar; see also Figure 1 in Vanzi et al. 2008).

target has 20×25 lenses, in a total of 500 lenses. A set of 249 lenses, 1 arcmin away from the science target, provides a sky background for subtraction during the data reduction. In order to cover a larger field, we exposed at six different offsets overlapping the fields about $1''$. Figure 1 shows the Advanced Camera for Surveys/*Hubble Space Telescope* (ACS/HST) high-resolution H α image ($0''.027 \text{ pixel}^{-1}$), with the different fields observed with GMOS/IFU shown as rectangles over the image. The GMOS/IFU data were recorded in three 2048×4608 CCDs with $13.5 \mu\text{m}$ pixel size. We used the R831 grating covering the wavelength range 5970 – 8080 \AA and providing a spectral resolution of 1.5 \AA (FWHM) at 6580 \AA , with corresponding $\sigma_{\text{inst}} = 29.0 \pm 1.0 \text{ km s}^{-1}$ ($\sigma = \text{FWHM}/2.355$). The exposure time of each field was 300 s. The seeing constantly remained subarcsecond during the observations ($\approx 0''.5$ – $0''.6$).

The basic data reduction was performed using the Gemini IRAF⁹ package developed by the Gemini Observatory staff. A CuAr spectrum was obtained in order to provide the wavelength calibration. We processed bias subtraction, dome and twilight flat field correction. Each field was calibrated in wavelength but not in flux. The final cube for each field was resampled to $0''.2$ per pixel using GFCUBE, resulting in a $16 \times 25 \times 6270$ data cube. We developed a special procedure using IRAF in order to produce the H α emission, radial velocity and velocity dispersion synthetic maps. For each data cube, we used the task FITPROFS in *onedspec* package to fit a single Gaussian profile to the H α emission line. The task provides the H α central wavelength, the FWHM, and the integrated intensity in relative counts. We run the task automatically for all spectra in the original sampling ($0''.2$ hexagonal spaxel) and resampled ($0''.2 \text{ pixel}^{-1}$) data cubes. There is no difference using either data sets, nevertheless, it is more practical for the analysis to use the resampled square pixel data cubes. We constructed FITS images using H α line

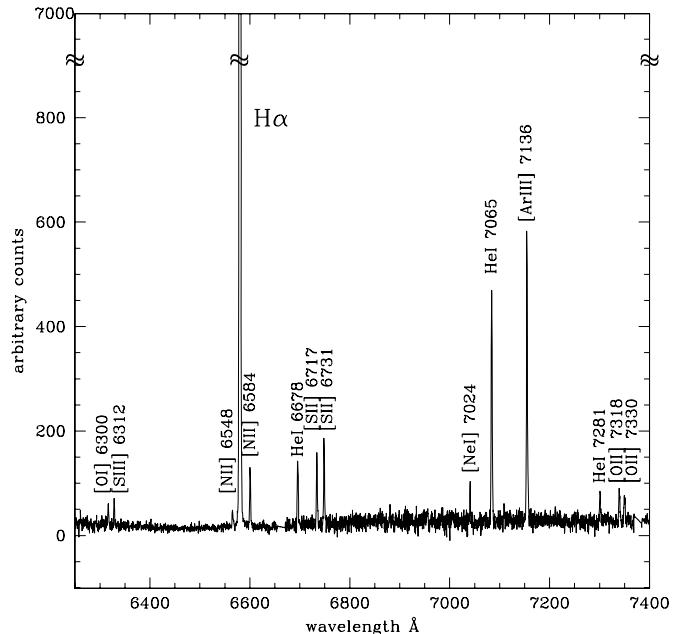


Figure 2. Single pixel spectrum on the bright core centered on knot A. The labels show most of the emission lines present on our spectrum from 6250 \AA to 7400 \AA . The y-axis has been cut to illustrate the relative intensity of the lines, in particular the much larger intensity of the H α line which is used in this work.

intensities, centers and FWHM values to build our final maps. Finally, we overlapped them to build the mosaiced field.

As an additional test, the different maps were also produced from the original data cube using the ADHOC package (Boulesteix 1999) in a parallel reduction procedure in order to check the accuracy of the data reduction. This package is designed to reduce Fabry–Perot interferometry data and is able to handle any data cube. Both reductions showed very similar maps, then we decided to use the maps produced with the IRAF routines for all our further analysis.

Figure 2 shows a spectrum of a single pixel on the brightest region on the main knot of II Zw 40 nebula (knot A). This one pixel spectrum illustrates the quality of our data, and shows that we are able to detect, resolve and measure faint lines of [O I] $\lambda 6300$, [S III] $\lambda 6312$, [N II] $\lambda\lambda 6548, 6584$, He I $\lambda 6678$, [S II] $\lambda\lambda 6717, 6731$, [Ne I] $\lambda 7024$, He I $\lambda 7065$, [Ar III] $\lambda 7136$, He I $\lambda 7281$, [O II] $\lambda\lambda 7318, 7330$, and [Ar III] $\lambda 7751$ (not shown). The peak intensity of H α in this one single pixel exceeds 7000 counts and with a total flux of 20000 counts. The S/N on the continuum around H α (which is not of interest here) is about 5 on this 1 pixel spectrum. On the fainter regions, where the line widths are still measurable, the S/N on the adjacent continuum is about 0.5, and what determines the accuracy of the line width measurement is the peak intensity over the continuum which is directly proportional to the total flux of the emission line. We estimated, therefore, a conservative minimum relative flux necessary to accurately measure a single H α line width of 300 counts ($\log F = 2.5$).

The single Gaussian fit is an operational measurement procedure. Though the major contribution comes from regions presenting line profiles well fitted by single Gaussians, some regions of the nebula show asymmetric line profiles or multiple components. These measurements can map regions of kinematic interest through line width variations, and can reveal large scale motions through variations of the line centroids across the nebula. When one has sufficient high spectral resolution the

⁹ IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

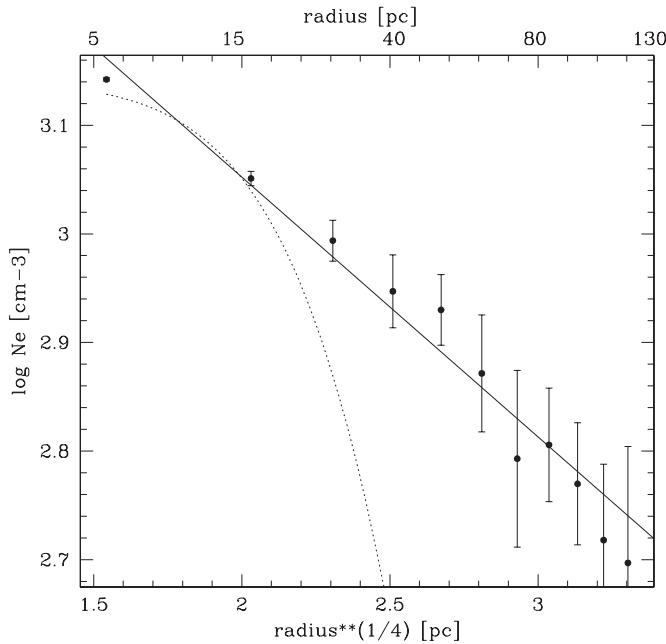


Figure 3. Electron density distribution in the central field, derived from an azimuthal fit to isointensities of the ratio of the sulfur line ($[S\text{ II}]\lambda\lambda 6717,6731$) maps. The solid line is a $r^{1/4}$ linear fit to the data. The dotted line is a Gaussian profile to represent the approximate seeing during this observation.

analysis of a single line profile can provide additional information constraining the larger and the smaller scale velocity variations.

3. RESULTS

3.1. Electron Density and Abundance Distribution

We briefly comment on the distribution of some derived physical properties before we proceed with the main topic of the kinematic properties of the starburst region in II Zw 40. We have been able to reliably measure and map the distribution of some weak lines in the central field.

Figure 3 shows the electron density (n_e) distribution derived from the ratio of $[S\text{ II}]\lambda\lambda 6717,6731$ lines (Dopita & Sutherland 2003). This plot was produced by azimuthally averaging the two-dimensional map centered on the peak distribution of the sulfur line ratio which is coincident with the peak H α line emission from knot A. First, we show that n_e is not constant and ranges from $\sim 1400 \text{ cm}^{-3}$ in the center to $\sim 500 \text{ cm}^{-3}$ about 100 pc from the center of knot A, and higher than the low-density limit of 100 cm^{-3} . It is also noticeable the good fit to a $r^{1/4}$ law (solid line) to the outer points (avoiding the dominant effect of seeing in the center represented by the dotted line), which is usually representative of the surface brightness distribution of stellar systems in dynamical equilibrium.

Figure 4 shows the oxygen abundance distribution in this central field. H α and continuum emission are also plotted as contours over the image. All pixels with H α emission less than 3.4% of the peak emission were erased. The O/H abundance was derived by applying the N2 calibrator from Denicoló et al. (2002). This is an empirical relation between the line ratio of $[N\text{ II}]\lambda 6584/\text{H}\alpha$ with the oxygen abundance. Simple closed box chemical evolution models considering the primary and secondary origin of nitrogen predict this linear correlation between nitrogen and oxygen, though dependent on the ionization parameter. Here, we simply apply the empirical

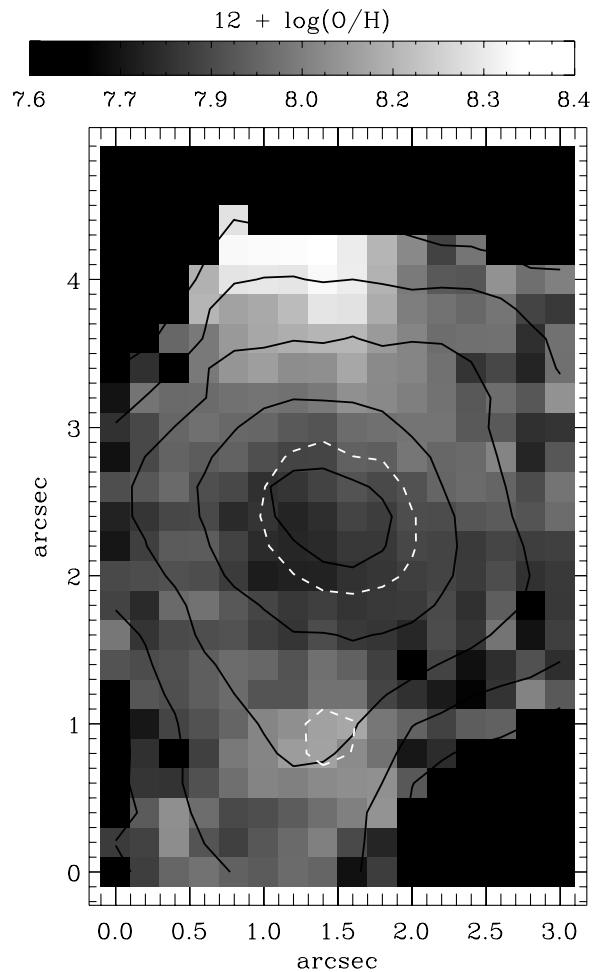


Figure 4. Oxygen abundance distribution in the central field, derived from the ratio of $[N\text{ II}]\lambda 6584/\text{H}\alpha$ (Denicoló et al. 2002). The H α emission contours at 68%, 20%, 9%, 5% and 3.4% of the peak intensity (solid lines) and the continuum emission contours (dashed lines) at 47% of its peak intensity are superposed on the image. We use a 3×3 box to smooth the pixel-to-pixel variation due to Poisson noise.

calibration of this relation. We found a lower abundance over knot A, $12 + \log(\text{O/H}) = 7.85$, a slight increase over knot B, $12 + \log(\text{O/H}) = 8.0$ and a significant increase in a region at NE of the knot A, $12 + \log(\text{O/H}) = 8.3$. The statistical error of the N2 estimator is $\delta_{(\text{O/H})} \sim 0.15$; however, relative differences between the regions should be real.

We will not explore the physical conditions analysis here any further. However, we may say that we have not found any relation between the velocity dispersion and the oxygen abundance or n_e .

3.2. The H α Integrated Line Profile

We now compare the integrated line width for the main starburst region in II Zw 40 derived here, with the inner core line width obtained with the high-dispersion fiber spectrograph FEROS (Kaufer et al. 1999), on the 1.52 m telescope (ESO).¹⁰ We combined 181 spectra from our GMOS data cube, around the inner core in a synthetic aperture of a diameter of $2.^{\prime}7$ (equivalent to 150 pc) which corresponds to the FEROS fiber diameter.

¹⁰ All the FEROS data and analysis were presented in Bordalo (2004, Ms. Sc. thesis) directed by E. Telles at Observatório Nacional—MCT/Brazil, and will be published in a forthcoming paper.

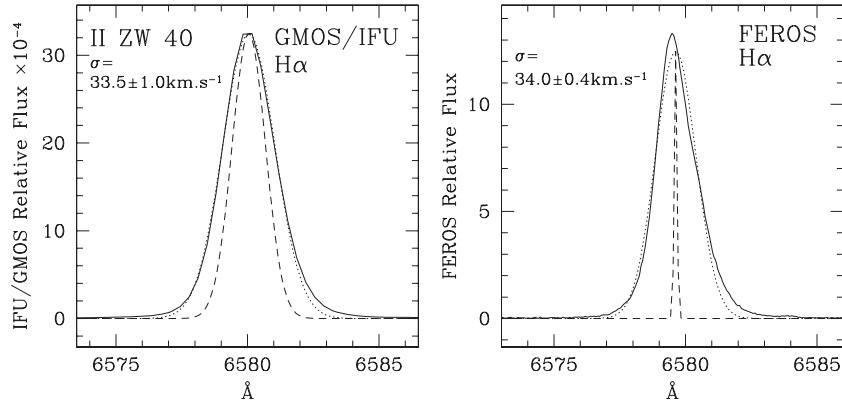


Figure 5. Line profiles derived with GMOS/IFU (left) and FEROS (right) data. The dashed lines represent the respective instrumental profiles (FWHM = 1.5 Å for the GMOS and FWHM = 0.13 Å for the FEROS). The dotted lines represent the single Gaussian fits. The velocity dispersions values derived are shown in the boxes.

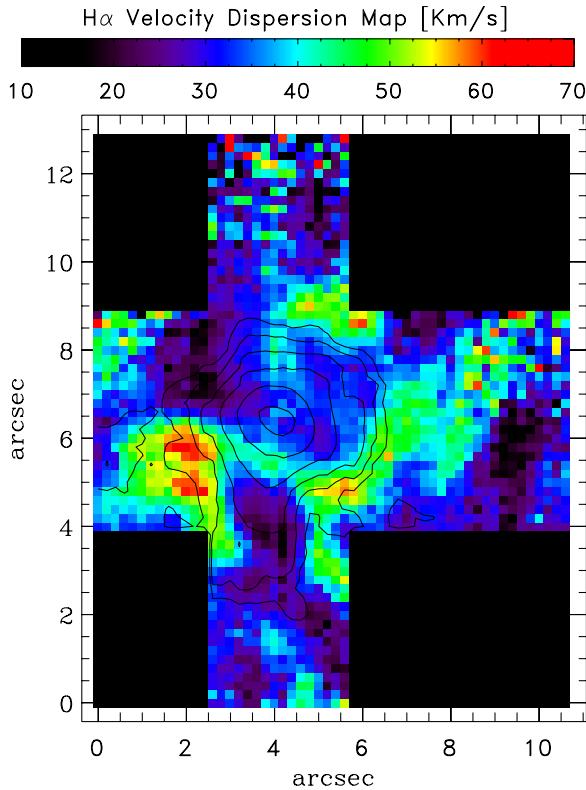


Figure 6. H α velocity dispersion map, corrected for instrumental and thermal broadening, of the inner region of II Zw 40. The contours represent 68%, 20%, 9%, 5%, 3.4%, and 2.6% of the H α peak intensity. North is up and east is left. (A color version of this figure is available in the online journal.)

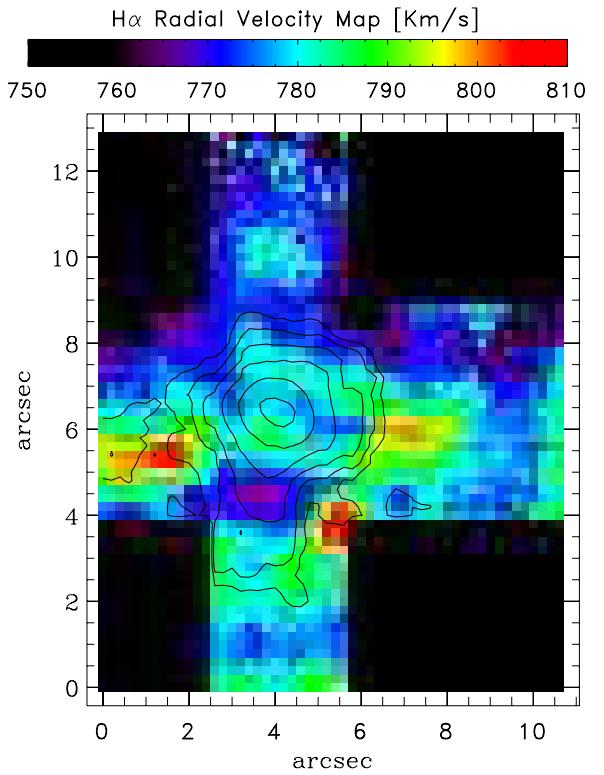


Figure 7. H α radial velocity map. The contours represent 68%, 20%, 9%, 5%, 3.4%, and 2.6% of the H α peak intensity. The recession radial velocity is not corrected by the heliocentric motion. North is up and east is left. (A color version of this figure is available in the online journal.)

Figure 5 shows the line profiles, their single Gaussian fits and the velocity dispersions derived from the data of these two very different instruments. Our simulated spectrum from GMOS/IFU data shows an observed FWHM = 2.34 Å, while the FEROS spectrum shows FWHM = 1.83 Å. After the respective instrumental broadening, and the thermal broadening corrections (for $T_e = 10^4$ K, FWHM_{th} = 0.47 Å or $\sigma_{th} = 9.1 \text{ km s}^{-1}$), the velocity dispersions derived were virtually the same, $\sigma = 34 \text{ km s}^{-1}$.

II Zw 40 presents an integrated supersonic line width with a derived high velocity dispersion reaching 34 km s $^{-1}$, which is significantly higher than 30 Dor with $\sigma = 26 \text{ km s}^{-1}$, the most

powerful GHII R of our Local Group, (Chu & Kennicutt 1994; Melnick et al. 1999).

3.3. The H α Flux Monochromatic Map

The H α flux monochromatic map is a result of the emission line intensity measurements across the observed field. We fitted single Gaussians to the H α line profiles to derive their respective total fluxes, using the procedure discussed in Section 2. The H α monochromatic (total flux from the single Gaussian fit) contour map is presented superposed on the velocity dispersion and radial velocity maps (Figures 6 and 7) in six contours levels (68%, 20%, 9%, 5%, 3.4%, and 2.6% of the peak intensity). The overall H α distribution in the synthetic map obtained from

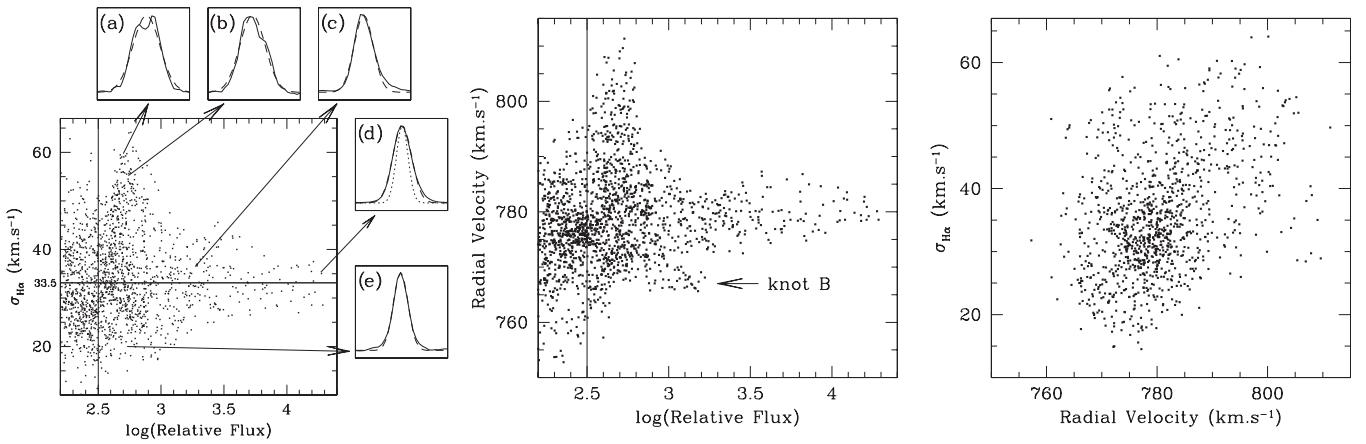


Figure 8. $I-\sigma$ (left), $I-V$ (center), and $V-\sigma$ (right) plots for the whole region observed in II Zw 40 as described in the text. The solid horizontal line in the $I-\sigma$ plot represents the σ value for the inner core ($D = 2''.7$). Characteristic individual pixel line profiles are shown in the left panel from (a) to (e). Dashed lines represent the single Gaussian fits, and the dotted line under profile (d) is the instrumental profile. The vertical solid line at $\log(\text{relative flux}) = 2.5$ represents the estimated minimum line flux to well measure a single line profile. All points with $\log(\text{relative flux}) < 2.5$ are not shown in the $V-\sigma$ plot.

GMOS/IFU agrees very well with the narrow band H α image from ACS/HST at higher resolution (Figure 1). In the HST's image it is possible to clearly resolve the two inner knots (A and B), the cavities formed by low H α emission maybe associated with superbubbles, and also some filaments. A synthetic red continuum image from our IFU data, shown here only in two contours in Figure 4, also reveals the two inner knots, separated by projected distance of $1''.6$ (~ 90 pc). However, the Northern knot (A) is responsible for virtually all the ionizing luminosity in the core of II Zw 40 (Vanzi et al. 2008).

The starburst region revealed in II Zw 40, from the morphological point of view, is also very similar to the largest and extensively studied counterparts in the Local Group, such as 30 Dor, NGC 588 and NGC 604, showing complex kinematic features, along with filamentary structure, shells, and cavities, suggesting a common physical cause (Tenorio-Tagle et al. 2006). The similarities of the properties of the ISM in GHIIRs and HIIGs were first investigated through empirical relations of integrated physical parameters (Melnick et al. 1987, 1988), particularly the fact that both exhibit supersonic motions of the warm interstellar medium (ISM). A more detailed analysis of spatially resolved properties of these structures will help us understand the interplay between the massive cluster formation and evolution with its surrounding interstellar medium on scales of tens to hundreds of parsec.

3.4. The H α Velocity Dispersion and Radial Velocity Maps

The velocity dispersion map is presented in Figure 6, with H α intensity contours superposed. The region corresponding to the brightest knot (inner 50 pc) presents a low to intermediate σ value ($25\text{--}35$ km s⁻¹). There are, at least, three well defined high-dispersion ($45\text{--}65$ km s⁻¹) regions ~ 100 pc from the brightest knot. An almost constant velocity dispersion field ($\leqslant 35$ km s⁻¹), which contains most H α contour levels, is present in a region with 100×100 pc² at NW of the brightest knot. At least two regions of low velocity dispersion ($15\text{--}25$ km s⁻¹) are also found in the field, strikingly in between regions of high dispersion. A third low-dispersion region is seen at extreme West, 300 pc far from the core, but we preferred to discard this from the analysis due to its low S/N.

The observed H α radial velocity map is shown in Figure 7. There is no sign of an overall rotation in the main starburst

region of II Zw 40 (500×500 pc²). On the other hand, discrete regions can reach high values of radial velocity, suggesting local expanding motions, although the total velocity range does not exceed 60 km s⁻¹.

3.5. Intensity- σ and Intensity-Velocity Diagrams

An efficient method to identify kinematic features in GHIIRs, detect the massive clusters, their effect on the ISM, and their star formation rates, is by the analysis of the Intensity- σ ($I-\sigma$) and Intensity-Velocity ($I-V$) diagrams (Muñoz-Tuñón et al. 1996; Yang et al. 1996; Martínez-Delgado et al. 2007).

We present, in the Appendix, a schematic illustration of these diagrams, and a brief description of how they were previously interpreted by Muñoz-Tuñón et al. (1996). We also extend the analysis of these diagrams, including $V-\sigma$, to bring additional insight to the observed bulk motions.

In Figure 8 (left panel) we show the $I-\sigma$ plot for the whole observed field. The plot for II Zw 40 shows exactly the same basic features found in previous work on GHIIRs (Muñoz-Tuñón et al. 1996; Yang et al. 1996). In general low-intensity regions have the highest σ values, while the range of σ values decreases for high-intensity regions. In the case of II Zw 40, there is a horizontal band defining a lower limit of $\sigma_0 \simeq 25$ km s⁻¹ for regions brighter than 4000 counts ($\log F = 3.6$). The horizontal line in the $I-\sigma$ plot shows the velocity dispersion of 33.5 km s⁻¹ derived from the integrated line profile with the $2''.7$ aperture (Figure 5 left panel). It is a characteristic value for II Zw 40 found in all intensity regions. The inclined bands identified by Muñoz-Tuñón et al. (1996) are also identified in the plot. High velocity dispersions reach peaks of 65 km s⁻¹ in low-intensity regions. As we will show in the following section, two inclined bands in this plot are superposed in the range $2.6 < \log F < 3.1$.

Some characteristic line profiles are also shown in Figure 8 (left panel). These are individual pixel profiles exemplifying the variety of shapes observed in different regions. Profiles (a) and (b) are the most asymmetric profiles observed. They originate close to the center of the two regions of high dispersion at SE and at SW of the brightest knot, respectively (see Figure 6). They are clearly double-peak profiles, consistent with expanding motions. Profile (c) originates in the second brightest knot and shows a prominent red wing. Profile (d) originates in the

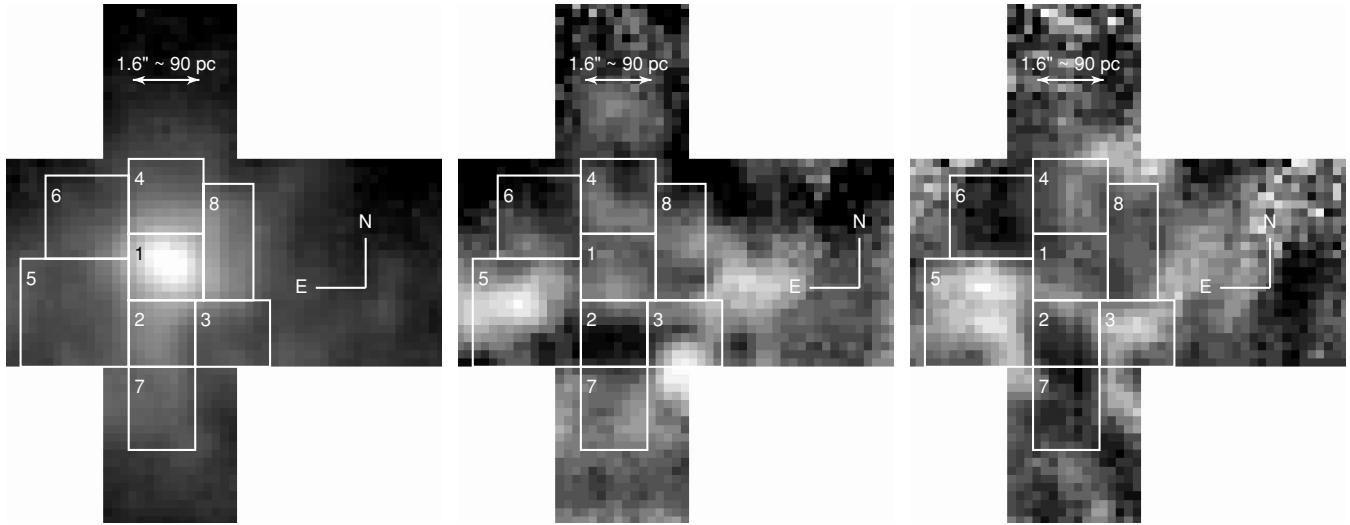


Figure 9. H α emission map (left), radial velocity map (center), and velocity dispersion map (right). The eight regions defined are drawn on each map.

brightest knot and Profile (e) comes from the lowest dispersion region.

Figure 8 (center panel) presents the I - V plot which shows the relative radial velocity variations. These motions are usually associated with the line broadening component named σ_{rad} . The physical mechanisms at play which produce these line centroid variations should be several, such as turbulence, winds, champagne flows, expanding bubbles or rotation, acting on stellar radius scales to hundreds of parsecs. However, the estimate of the contribution of these subcomponents is limited to the spatial and spectral resolution of the observations. For instance, in this work we chose to associate the action of the spatially resolved bubbles, producing the highest radial velocity variations, to the component σ_{rad} . The other mentioned mechanisms, however, should also contribute to produce the overall pattern in the I - V plot. Another line broadening component named σ_{shell} will be here associated with the unresolved expanding shells identified as responsible for an underlying broad component found in the most inner region and discussed in Section 3.7. Therefore, the position-to-position motions found in Figure 8 (center panel) contribute to the total broadening of an integrated line profile of the whole region. We do not intend to quantify precisely the contributions of the broadening components from the diagnostic diagrams. In the case of II Zw 40, the radial velocity differences are not higher than 15 km s^{-1} in the brightest central region, and the highest differences are concentrated in low H α intensity regions. We found that the discrete tails toward high-intensity values shown in Figure 8 (center panel) are associated with the presence of knot A (main tail) and B with a relative radial velocity of $\sim -13 \text{ km s}^{-1}$.

Figure 8 (right panel) shows the V - σ plot. In the case of II Zw 40, it suggests that the overall motions in the star-forming region are primarily random, instead of dominated by systematic line of sight motions. For instance, if one was observing a highly collimated outflow toward the line of sight, as a champagne flow, one should expect to see a trend in this diagram. Broad profiles from the low-density regions should be found blueshifted, while narrow profiles from high-density regions should be found redshifted, producing a pattern such as a narrow band with negative slope, not found for the whole region in Figure 8 (right panel). On other hand, the most important result shown by this diagram is that low σ ($15\text{--}25 \text{ km s}^{-1}$) regions have small radial

velocity variations, suggesting that they are close to the rest frame of the galaxy. This is the first indication that these regions may be unperturbed by massive stellar evolution.

We will try to associate the morphological features observed in the H α flux, velocity and dispersion maps with the features from these diagnostic diagrams by choosing individual regions for a more detailed analysis below.

3.6. The Kinematics of Individual Regions Revealed by Diagnostic Diagrams

The patterns shown in I - σ , I - V and V - σ plots (Figure 8) redisplay many of the features that can be observed in the maps (Figures 6 and 7). We wish to evaluate the contribution of individual features to the integrated H α line profile of II Zw 40 using the kinematic diagnostic diagrams. For this purpose, we defined eight regions with reliably measured σ and radial velocity. The choice of regions was arbitrary, but motivated by different peculiarities noted in the H α flux, radial velocity and velocity dispersion maps. The chosen regions are superposed on these maps in Figure 9.

For each chosen region, we have plotted a set of four graphs. These graphs are presented in Figure 10 in blocks of four boxes: (a) an integrated profile over the region in linear-logarithmic axes, where we also show the region number, the derived σ value, and the estimated skewness ξ and kurtosis κ of each integrated profile, (b) I - σ , (c) I - V , and (d) the V - σ plot. The vertical solid line in plots (b) and (c) shows our confidence limit in flux as described in Section 2. All references to the boxes in this section refer to Figure 10, where we quote the region number and the corresponding box letter, i.e., Box (1a) means plot (a) of Region 1 in Figure 10. The results of the analysis of the emission line shapes through ξ and κ estimates for each region will be presented in Section 3.7. A brief description of each region follows.

Region 1 was defined to cover the main and brightest H α knot (knot A) as shown by the H α map (Figure 9 left). It covers an area of $1.8'' \times 1.6''$ (equivalent to $100 \text{ pc} \times 90 \text{ pc}$). The resultant integrated profile of Region 1 is shown in Box (1a), where the dashed and dotted lines represent the instrumental profile and the Gaussian fit, respectively. The σ derived for Region 1 was 33.3 km s^{-1} which agrees with the value derived from our

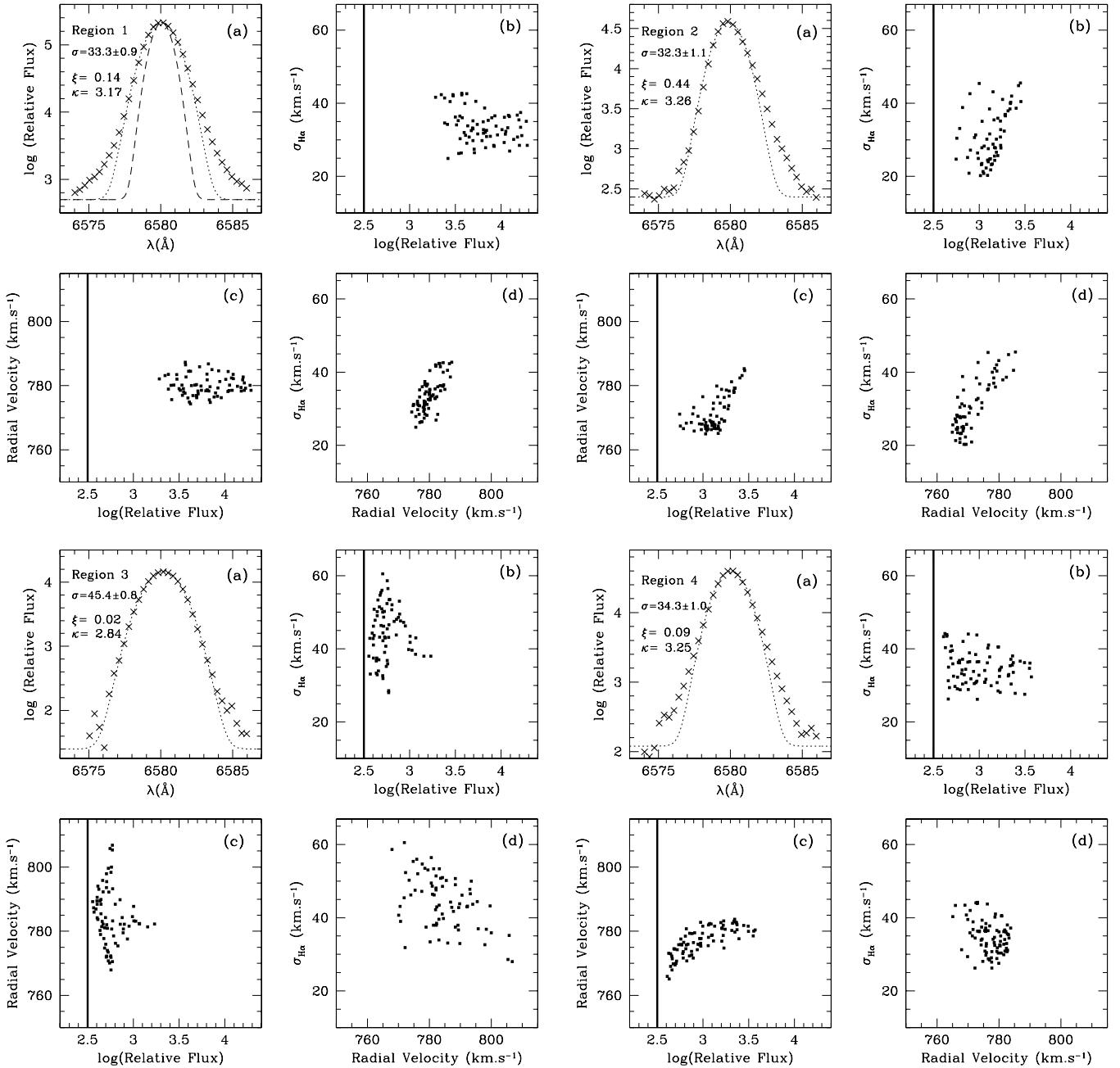


Figure 10. Panels present the four boxes discussed in the text for each region. The dashed line in Box (1a) represents the instrumental profile (FWHM = 1.5 Å). The dotted lines in all boxes represent the single Gaussian fits to the integrated profiles. Note that in linear-logarithmic axes a Gaussian takes the form of a parabola. The region number and the σ value derived are shown in Boxes (a). $I-\sigma$, $V-\sigma$, and $V-\sigma$ for each region are presented by Boxes (b), (c), and (d), respectively. The vertical solid line in Boxes (b) and (c) at $\log(\text{relative flux}) = 2.5$ represent the estimated minimum line flux to well measure a single line profile. Only Region 6 presents points with $\log(\text{relative flux}) < 2.5$, and they are not shown in Box 6b.

IFU simulated and FEROS spectra for a larger aperture (see Figure 5). Box (1b) shows that there is a well defined lower σ_0 value slightly above 25 km s⁻¹ and no high σ variations. Radial velocity variations found in Box (1c) indicates that the gas in Region 1 expands at < 15 km s⁻¹. Since the points in Box (1c) are within ~7.5 km s⁻¹ from the average recession velocity, it is likely that the rms radial velocity variation contributes to an equivalent FWHM of ~15 km s⁻¹ or $\sigma \sim 6.5$ km s⁻¹ (see Appendix). Radial velocity variations between individual pixels in Region 1, therefore, do not contribute significantly to explain the total 33 km s⁻¹ velocity dispersion. At this spatial resolution only large scale radial velocity variations can

be identified, and only these will be analyzed here (~50 pc). Box (1d) shows that most points are clustered with no apparent correlation between V and σ . We found that random motions are dominant in Region 1, instead of line-of-sight motions.

Region 2 was defined to cover the second brightest knot (knot B), south of Region 1. Region 2 covers an area equivalent to 90 pc × 90 pc. Box (2a) shows that, the integrated profile is the most asymmetric of all regions, showing a prominent red wing. This region is responsible for the red wing in the integrated profile obtained for II Zw 40 with FEROS, and also with our GMOS/IFU data (Figure 5). The reason for this asymmetry is

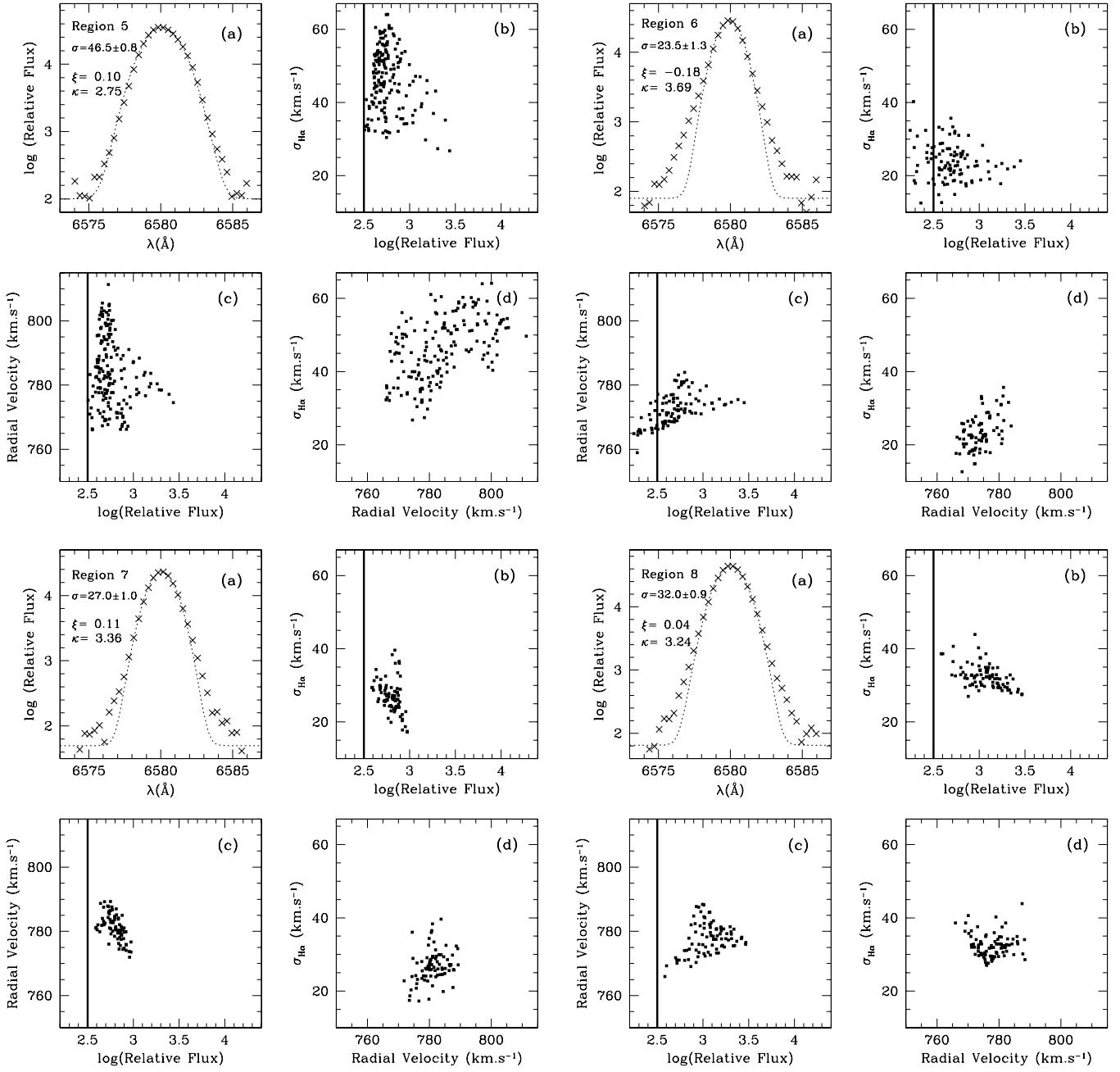


Figure 10. (Continued)

that σ reaches a local maximum in a few relative high-intensity points (North of knot B) as shown by Box (2b). Moreover, the same high-intensity points, seen in Box (2c), have the largest recession velocities, resulting in this observed red wing. As a consequence, Box (2d) shows a strong correlation pattern (see Figure 13(c)). The radial velocity motions in Region 2 contribute twice as much to the integrate line width of the region as compared with Region 1 ($\sigma \sim 13 \text{ km s}^{-1}$). The gas in Region 2 has a relative line-of-sight motion with respect to the gas in Region 1 of roughly -13 km s^{-1} . We found, however, two systematic components, one due to the relative radial motion between the two knots, and the other due to the expanding motion, as shown by the vertical band at $\log F \sim 3.2$ in Box (2c) presenting an intermediate radial velocity variation.

Region 3 covers the southwest high-dispersion region. It covers an area of $1.^{\circ}8 \times 1.^{\circ}6$ (equivalent to $100 \text{ pc} \times 90 \text{ pc}$). The expected kinematic features due to the presence of an expanding shell are seen in all boxes for this region. Box (3a) shows a symmetric broad profile with $\sigma = 45.4 \text{ km s}^{-1}$. This is actually the resulting smoothed profile obtained due to the contribution of unresolved asymmetries and multiple components as shown in 1 pixel profiles (a) and (b) of Figure 8 (left panel). Box (3b) clearly shows the inclined band indicating the presence of an expanding shell, possibly produced by an expanding bubble (see Figure 13(a)). Box (3c) confirms the expanding motion through the very high spread in radial velocity (see Figure 13(b)). The observed range of radial velocity, of about 20 km s^{-1} above and below the average recession velocity should underestimate the real radial component. This is in fact a limitation of fitting single

Gaussians to the integrated profiles. From the line splitting in individual pixels in the center of the bubble we could measure a maximum $\Delta V \sim 90 \text{ km s}^{-1}$ or a $V_{\text{exp}} \sim 45 \text{ km s}^{-1}$. We estimated the radial velocity flow component to the integrated profile shown in Box (3a) as FWHM $\sim 90 \text{ km s}^{-1}$ or $\sigma \sim 38 \text{ km s}^{-1}$ (see Appendix). Therefore, the expanding motion dominates the total broadening seen in the integrated profile of Region 3. The data points in Box (3d) show large scatter and there is not a significant trend in this plot, as seen in Region 2.

Region 4 covers an area of $1''.8 \times 1''.8$ (equivalent to $100 \text{ pc} \times 100 \text{ pc}$) and presents a field of intermediate σ and H α intensity values, north of knot A. Region 4 presents many similarities with Region 1: similar σ derived as shown in Box (4a) and similar pattern in Box (4b) showing low σ variations and a lower limit $\sim 25 \text{ km s}^{-1}$. The small radial velocity variations found in Box (4c) and a concentrated velocity dispersion distribution in (4d) indicate that there is no significant systematic motions contributing to the total line broadening, which is dominated by random motions on scales smaller than the seeing of $\sim 20 \text{ pc}$.

Region 5 is one of the most interesting regions, and covers a large area of $2''.6 \times 2''.6$ (equivalent to $150 \text{ pc} \times 150 \text{ pc}$) SE of knot A. It presents some of the broadest profiles, and it is probably associated with an expanding shell (Boxes 5a and 5b). Region 5 also presents high radial velocity spread (Box 5c) of over 40 km s^{-1} , although this may underestimate the real radial velocity component as argued above in the analysis of Region 3. Regions 3 and 5 show very similar patterns in all diagrams, suggesting that these patterns can be easily used as expanding shell diagnostics in GHIIIRs. Despite their different sizes and morphologies the two shell regions have similar kinematic properties. Some double-peak profiles seen in Region 5 are also consistent with a bubble expanding with a velocity of 45 km s^{-1} , likely to be powered by supernovae and stellar driven winds. There is not a significant trend found in Box (5d).

Region 6 was defined to cover a field containing the lowest velocity dispersion values. It covers an area of $2''.0 \times 2''.0$ (equivalent to $110 \text{ pc} \times 110 \text{ pc}$) northeast of Region 1. The observed $\sigma = 23.5 \text{ km s}^{-1}$, as shown in Box (6a), is the lowest value verified of all regions. Box (6b) also shows that a significant area presents σ values lower than knot A, though they are still supersonic. Velocity variations are also very small as shown by Box (6c). Box (6d) indicates primarily random motions. All plots suggest, therefore, that Region 6 represents a region where the mechanical energy input resulting from massive star evolution does not play a significant role to stir the gas up.

Region 7 presents a relatively low velocity dispersion field (Box 7a). It covers an area of $1''.6 \times 2''.0$ (equivalent to $90 \text{ pc} \times 110 \text{ pc}$), South of knot B. It completes the sampling of a larger low-to-intermediate dispersion field covered partially by Region 2 (Boxes 2b and 7b). Both regions are confined between the two high-dispersion bubbles, Regions 3 and 5. The H α structure in Region 7 is associated with the extended emission to the south of both knots (see Figure 9, left panel). Box (7c) shows a weak correlation of I and V with fainter emission points moving away. However, no clear correlation between radial velocity and σ is seen in Box (7d).

Region 8 covers an area from W to NW of the knot A (equivalent to $70 \text{ pc} \times 160 \text{ pc}$) with a $\sigma = 32 \text{ km s}^{-1}$ (Box 8a), similar to Region 1. It was defined to contain a field with almost constant velocity dispersion through a large range of intensities, which is shown by Box (8b). The pattern formed in Box (8b) is

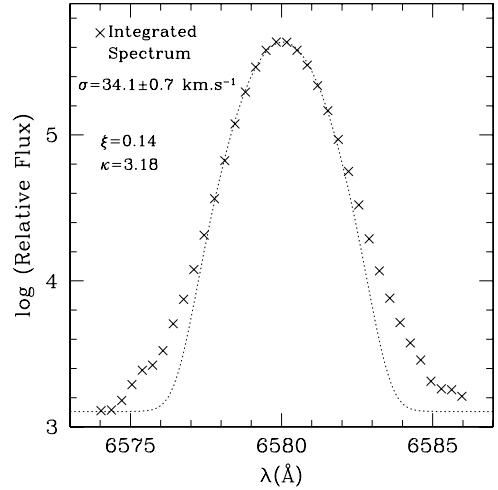


Figure 11. Fully integrated profile summing all eight regions analyzed in Section 3.6. The dotted line represents the single Gaussian fit to the profile.

not an inclined band. Region 8 does not present high velocity variations, as shown by Box (8c) and it is likely dominated by random motion inferred by the points concentrated in Box (8d). The few higher dispersion points at low intensities seen in Boxes (8b) and (8d) may be picking up a possible additional region of interest (i.e., shell) north of Region 8 (see Figure 9, right panel) which is not well mapped in our observations and is not included in the present analysis.

Our definitions of the regions favor the interpretation of the different patterns in $I-\sigma$ diagrams where kinematic features are easily identified. Thus, the patterns may be the result of different physical mechanisms. Something to have in mind here, is our spatial resolution which only permits us to identify kinematic features in scales of a tens of parsec and limited by our field size. The overall picture is that local systematic motions represent a dominant component to the observed line widths in Regions 3 and 5 which are likely associated with resolved expanding shells due to the fact that we can observe line splitting directly. Although, masked by the use of single Gaussians, they leave a signature in the diagnostic diagrams. Region 1 presents a small range of intermediate σ values which are also found in all the intensities of nebular emission across the whole extent of the star-forming region. Region 2 is turbulent with some characteristics of flow motions. Regions 4, 7, and 8 show smooth turbulent fields. Wherever we cannot observe double-peaked profiles in these regions, we cannot completely rule out a radial systematic component to the line width, possibly associated with unresolved shells; however, random motions must dominate over expansion in these cases. Finally, relatively to the other regions, Region 6 seems to be slightly affected or even unperturbed by mechanical energy input provided by massive star evolution, presenting the lowest σ values.

3.7. Making up the Integrated Velocity Profile from Individual Regions

Figure 11 shows the fully integrated line profile produced by combining all eight spectra for the regions presented in Section 3.6, with a resulting $\sigma = 34.1 \text{ km s}^{-1}$. Despite the complex medium-scale structures ($50-100 \text{ pc}$) seen in the synthetic maps (Figures 6 and 7), mainly due to the presence of asymmetries and multiple components (e.g., profiles (a) and

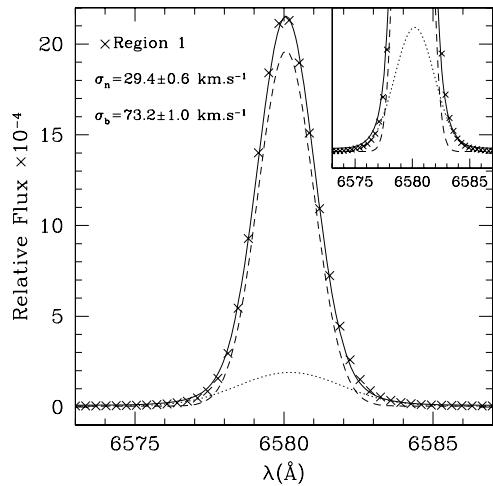


Figure 12. Integrated profile of Region 1 (same in Figure 10, Box 1a) plotted in linear axes. The profile is well fitted by two Gaussians, and the profiles are plotted. The dashed line represents the narrow component σ_n , whereas the dotted line represents the broad component σ_b . The solid line shows the resultant profile.

(b) of Figure 8, left panel), the fully integrated profile is quite smooth and symmetric.

An important result is that the velocity dispersion derived from a single Gaussian fit to the profile of Region 1 (Figure 10, Box 1a) is virtually the same as those derived from the original FEROS spectrum with an aperture of 2''.7, and the simulated spectrum with the FEROS aperture on our GMOS/IFU data (Figure 5), and the fully integrated line profile (Figure 11). Region 1 represents 10% of the total area analyzed but 49% of the total H α flux in all eight regions. In contrast, Regions 3 and 5, showing the broadest profiles, cover 33% of the total area analyzed but only contribute 14% to the total flux. Other regions, namely Regions 6 and 7, covering 25% of the total area and showing the lowest σ values only contributes 10% to the total H α flux. All the highest surface brightness regions, namely Regions 1, 2, 4, and 8, show the common values $\sigma = 32\text{--}35 \text{ km s}^{-1}$ which characterize the global kinematics of the warm gas in II Zw 40s dominant starburst region.

The aperture effect to derive the characteristic velocity dispersion of II Zw 40 is negligible if an integrated spectrum is taken with an aperture covering the brightest knot. As an example, Melnick et al. (1988) derived for II Zw 40 a $\sigma = 35.2 \pm 0.5 \text{ km s}^{-1}$ with a 6'' wide entrance slit aperture. From an observational point of view, this result is very positive. If the same is valid for most HIIGs and GHIIRs, as has been confirmed, the measured supersonic σ , introduced in the $L\text{--}\sigma$ relation, is little affected by the effects of SNRs and wind-driven bubbles where the warm gas emission is faint, and where the integrated velocity dispersion is much higher than in the central core.

We computed the skewness, ξ , and the kurtosis, or flatness factor, κ , to quantify the shape of each profile and they are included in all Boxes (a) of Figure 10. We warn that the quantitative results, especially for κ , are sensitive to the window of summation and the height of continuum. We defined a confident fixed window 6576–6584 Å to compute the ξ and κ values, since broad wings are not well mapped for the faintest profiles. Relative differences between kurtosis values are more significant than their absolute values, which should in principle be comparable with a Gaussian profile ($\xi = 0$, $\kappa = 3$). We found that most profiles have peaked shape $\kappa > 3$ (leptokurtic).

Regions 3 and 5 are significantly more flattened than the others (platykurtic). The most asymmetric profiles identified by the highest $|\xi|$ are those of Regions 2 and 6, which can be easily distinguished visually in liner-logarithmic plots in Boxes (2a) and (6a) of Figure 10. We also estimated ξ and κ values for the fully integrated profile shown in Figure 11. We can see that not only the σ but also ξ and κ values are virtually identical to those estimated from profile of Region 1 (Figure 10, Box 1a).

Since the S/N in the wings of the profile from Region 1 is much higher than the others, we were able to measure across in a larger window (6574–6586 Å) and estimate another pair of ξ and κ values for this profile, giving an idea of how sensitive the values of the higher order moments are. The estimated values derived in this spectral range are $\xi = 0.14$ and $\kappa = 4.19$, showing that the integrated profile in Region 1 is very peaked. This result indicates the presence of a broad but weaker component in the core of II Zw 40. Multicomponent Gaussian fits to the profile of Region 1 are shown in Figure 12. We used the PAN routine (Peak Analysis; Dimeo 2002) in IDL to fit two components to H α profile. We found a narrow component $\sigma_n = 29.4 \pm 0.6 \text{ km s}^{-1}$ which is not very different from σ derived from a single fit $\sigma = 33.3 \pm 0.9 \text{ km s}^{-1}$. The broad component was estimated to be $\sigma_b = 73.2 \pm 1.0 \text{ km s}^{-1}$ and its flux corresponds 18% to the flux of the narrow component. We may speculate that the broad component is associated with unresolved wind-driven shells at the core of II Zw 40 where most of the young and massive stars concentrate.

4. DISCUSSION

An important verification provided by the above results is that the H α kinematic features already found in Local Group's GHIIRs are represented in the main starburst region of II Zw 40: a prototypical H II galaxy at roughly 11.9 Mpc. In fact, one way to investigate the starburst phenomena on these galactic scales is to compare the main starburst region in II Zw 40 with the local GHIIRs studied by similar techniques.

Yang et al. (1996) found that virial motions and expanding shells contribute roughly equally to the velocity width of the integrated profile in NGC 604. Using the same methods, Muñoz-Tuñón et al. (1996) proposed an evolutionary scenario when they compared their results of NGC 604 with NGC 588. A simple model for an idealized homogeneous shell evolving in a uniform density medium suggests that younger and fast shells should have lower intensities and reach higher σ values than older ones. Hence, the authors argue that NGC 604 appears to be younger than NGC 588 based on the inclined bands associated with shells, and identified in $I\text{--}\sigma$ plots. Furthermore, NGC 604 presents a well defined lower limit ($\sigma_0 \simeq 17 \text{ km s}^{-1}$) in supersonic line width everywhere (horizontal band in $I\text{--}\sigma$ plot), while NGC 588 does not. A substantial fraction of NGC 588 presents line widths lower than the brightest region, including points showing subsonic σ values. Melnick et al. (1999) suggest that it is also the case for 30 Dor. In the Cometary Stirring Model (CSM) framework, this difference can also be understood as an evolutionary effect. A young region keeps most of the supersonic motions communicated to the leftover gas via bow shocks by the winds of low-mass stars during its early stage. As massive stars evolve, ejecting mechanical energy into the ISM, through stellar winds and supernova events, they produce shells that expand beyond the core. Shells will be destroyed by random motions of the background neighboring gas and slow down, resulting in σ even below the bright region (Tenorio-Tagle et al. 1993; Muñoz-Tuñón et al. 1996). The main point in this scenario is that

the dominant line-broadening mechanism in young GHIIRs is gravity, while turbulence by wind-driven shells and supernovae dominate in older ones.

More recently, Martínez-Delgado et al. (2007) have shown that the morphological features observed in their analysis of three-dimensional spectroscopic data of three blue compact galaxies (Mrk 324, Mrk 370, and III Zw 102), especially those in the σ versus I_{peak} diagram, look similar to the ones found in GHIIRs, with a supersonic horizontal band that extends over a large range of intensities, and inclined bands that reach high σ values at low intensity arising from large volumes surrounding the central knots. In a similar study to our own, using similar technique with Gemini GMOS/IFU, Westmoquette et al. (2007a, 2007b) looked at the properties of a young star cluster and its environment in the dwarf irregular starburst galaxy NGC 1569. Despite the fact that they decompose the profiles rather than fit a single Gaussian, the narrow components of their profiles show all properties found in these other studies including ours, namely that, it is most likely explained by a convolution of the stirring effects of massive star evolution and gravitational motions. In addition, they found that the observed lower limit ($\sigma_0 \simeq 12 \text{ km s}^{-1}$) of the narrow component is in agreement with $\sigma_{\text{virial}} = \sqrt{GM/R}$.

Here, we wish to test the hypothesis that the dominant broadening mechanism of the H α line in the core of II Zw 40 is gravity.

As shown in Figure 8 (left panel), II Zw 40 presents the lowest σ values ($\sigma \sim 20 \text{ km s}^{-1}$) in regions with faint H α emission. Here we identify Region 6 as the most significant contributor to this low σ (see Figure 10, Box 6b), which appears to present dominantly random motions, through its diagnostic diagrams. In addition, Region 6 does not seem to be affected by the neighboring superbubble of Region 5. Therefore, this region may still retain the kinematic information of the pre-existing underlying turbulent velocity field. The velocity dispersion values derived in Region 6 should not be associated with the internal velocity dispersion of individual dense molecular cloud cores or clumps (typically less than a few km s^{-1}), where individual or groups of massive stars form, but instead, they may be the result of the large-scale turbulent motions of the parent complex of diffuse molecular clouds, which gave rise to the present episode of violent star formation. Some of these clouds will form stars in short local dynamical times, while others, though dense, may not form stars. We do not intend to discuss any detailed model, but simply try to envisage a viable scenario for our conjecture of an overall underlying velocity component. Massive star clusters will form in much denser fragments (clumps or cores) of the molecular clouds whose properties are not assessed by our observations, and require density tracers (e.g., HCN) with high spatial resolution radio observations. Though, these clumps must also have relative velocities stirring up the ISM under the influence of the common gravitational potential due to the complex of stars, and gas, and possibly dark matter. The ^{12}CO ($J=1 \rightarrow 0$) traces the diffuse molecular cloud on hundreds of parsec scales. The measured CO line width of a region encompassing the entire ionized region in II Zw 40 is $\Delta V = 42 \text{ km s}^{-1}$ or $\sigma \sim 18 \text{ km s}^{-1}$ (Tacconi & Young 1987), somewhat comparable to the low σ in the ionized gas. However, these motions seem to be completely detached from the global H I velocity distribution which extends up to 5 arcmin ($\sim 6 \text{ Kpc}$) in the direction of the southern and northern tails (van Zee et al. 1998; Brinks & Klein 1988), where the line width is $W_{50} \sim 120 \text{ km s}^{-1}$ ($\sigma \sim 50 \text{ km s}^{-1}$) and has a strong

contribution by the large-scale rotation pattern of the galaxy on these scales.

The large resolved superbubble in Region 5 is very well delimited in σ and intensity maps and may not have slowed down sufficiently to be disrupted. Moreover, Region 3 also presents a well defined bubble in σ and intensity maps, which is seen as an inclined band in the diagnostic plot. Despite being smaller than the bubble in Region 5, they both show similar profile shapes, expansion velocities $V_{\text{exp}} \sim 45 \text{ km s}^{-1}$, and integrated velocity dispersions $\sigma \sim 45 \text{ km s}^{-1}$, possibly indicating similar evolutionary phase and associated with the age of knot B.

Although II Zw 40 contrasts slightly with a simple scenario for a GHIIR, in the sense that it may suffer from the composite effects resulting from the evolution of multiple stellar clusters, we can say that in the CSM context, the GHIIR in II Zw 40 is kinematically young. Some superbubbles are evolving within the core, though it does not present a constant σ or only “well behaved” Gaussian emission lines (Muñoz-Tuñón et al. 1995, 1996). However, the presence of surrounding regions showing lower σ than the core in II Zw 40 is a sign of youth. There are still unperturbed regions preserving kinematic information of the parent cloud under the dominant influence of the galaxy’s gravitational potential, ionized by diffuse UV radiation. In consonance with our conclusions, many studies about this galaxy indicate the presence of a very young starburst in its brightest region, as mentioned in the introduction.

An important resolution bias must be of concern here in order to test our hypothesis. Melnick et al. (1999) show that the supersonic integrated line profile in 30 Dor is actually due to a superposition of discrete number of clouds, small shells and filaments which are resolved on subparsec scales. In these scales, strong winds of WR, O, and B stars might be responsible for stirring up the gas around the dominant young cluster, imposing a turbulent motion higher than the one predicted only by the gravitational potential. The presence of a significant number of the very young stars in the core should be responsible partially for the difference between the σ found in Region 1 and that one found in Region 6. In fact, we found evidence of a broad component $\sigma_b \sim 73 \text{ km s}^{-1}$ in Region 1, responsible for the large wings in the integrated profile, which may be associated with unresolved inner shells. However, its contribution to the integrated profile is very small, since only 15% of the total H α flux in Region 1 comes from this component.

We can now sum up the main reasoning so far. A common framework assumes that the observed velocity dispersion (σ_{obs}) is mainly given by the contributions of gravity (σ_{grav}), thermal broadening (σ_{th}), multiple unresolved expanding shells (σ_{shell}) and systematic radial motions (σ_{rad}). Here we consider σ_{rad} as being the sum of several phenomena such as SN, expanding bubbles, champagne flows, relative motions between discrete clusters providing large scale shear, turbulence and rotation, which cause position-to-position radial velocity variations and, in extreme cases, line splitting. We detected and identified σ_{shell} only in the core, i.e., Region 1, as the weak broad component, but possibly present with different weights in the whole nebula. Indeed, we found that most profiles have peaked shape indicating the presence of faint wings or broad components, with the exception of those found in regions of bubbles, i.e., Regions 3 and 5. Once corrected for the instrumental profile, the observed velocity dispersion of a GHIIR or discrete regions inside them is therefore given by (Melnick

et al. 1999)

$$\sigma_{\text{obs}} = \sqrt{\sigma_{\text{grav}}^2 + \sigma_{\text{shell}}^2 + \sigma_{\text{th}}^2 + \sigma_{\text{rad}}^2}.$$

We fixed the thermal broadening as $\sigma_{\text{th}} = 9.1 \text{ km s}^{-1}$ due to the gas electron temperature for hydrogen at 10^4 K , causing no significant systematic error in our results. The radial velocity variations on scales larger than 50 pc can be identified here. It varies from few km s^{-1} in regions such Region 1, $\sigma_{\text{rad}} \sim 6.5 \text{ km s}^{-1}$, to $\sigma_{\text{rad}} \sim 38 \text{ km s}^{-1}$ in Regions 3 and 5 as inferred from line splitting in the center of bubbles. Region 6 seems to be “free from shells,” and it can be a good probe of $\sigma_{\text{grav}} \sim 20–25 \text{ km s}^{-1}$, posing a lower limit of velocity dispersion in II Zw 40. In fact, these values are not very different from the narrow component found in Region 1, $\sigma_n \sim 29 \text{ km s}^{-1}$, and the lower limit $\sigma_0 \sim 25 \text{ km s}^{-1}$ in the $I-\sigma$ diagnostic diagram. If indeed, the σ measured in Region 6, is unaffected by stellar evolution, and the narrow component of the Gaussian fit to the profile of Region 1 gives the same low value of σ , and additionally the low limit of overall measured σ is probing the same physical mechanism, we may suggest a common dominant line broadening cause. Gravity provides the continuous underlying source of stirring the ISM over the whole star-forming region. However, the characteristic $\sigma = 32–35 \text{ km s}^{-1}$ found over the whole starburst region of II Zw 40 and derived from a single Gaussian fit should be the result of combined sources, of the dominant action of gravity, unresolved multiple expanding shells and systematic radial motions.

5. SUMMARY

The three-dimensional spectroscopic analysis of II Zw 40, using Gemini-North GMOS/IFU, yield insights into several astrophysical questions about the structure and evolution of starburst regions, especially those associated with the birth of super star clusters and their impact on the ISM. The kinematics of the warm gas inferred from line profiles of emission lines, such as H α , imposes constraints on the theoretical models of star formation and on feedback of stellar evolution on the ISM. We have analyzed the kinematic properties of the ionized gas in II Zw 40 using diagnostic diagrams and individual region description. A summary of the main conclusions follows.

1. Electron densities in the inner starburst region range from 5×10^2 to $1.4 \times 10^3 \text{ cm}^{-3}$, somewhat higher than the common low-density regime for H II regions of 10^2 cm^{-3} . Its spatial distribution is not constant and shows a clear decline (compatible with an $r^{1/4}$ law) with a peak coincident with the H α line emission peak.
2. Oxygen abundance as inferred by the N2 calibrator in the inner $100 \times 100 \text{ pc}^2$ ranges from $12+\log(\text{O/H}) = 7.8$ to 8.4, showing lower values $12+\log(\text{O/H}) = 7.85$ associated with the dominant site of star formation, namely knot A.
3. The aperture effect to infer the characteristic velocity dispersion $\sigma = 34 \text{ km s}^{-1}$ of II Zw 40, derived from a single Gaussian fit, is negligible. All shape properties (σ , ξ and κ) of a fully integrated profile are virtually the same as those found in the profile of the brightest region.
4. The diagnostic diagrams of I versus σ , I versus V , and additionally σ versus V are powerful tools to identify the origin of internal motions in GHIIRs and also in HIIGs.
5. We found regions where stellar evolution does not seem to play a significant role stirring the gas up, and should reveal the kinematic signature of the proto-cloud that gave rise to the present starburst. In the case of II Zw 40, Region 6

northeast of the main knot poses a lower limit of $\sim 23 \text{ km s}^{-1}$ to the global velocity dispersion in the galaxy, which should provide a good estimate of σ_{grav} .

6. Despite the different sizes and morphologies, the two large shells found in Regions 3 and 5 have the same kinematic properties, with very similar patterns in all diagnostic diagrams. Both regions have smoothed integrated line profiles with $\sigma \sim 45 \text{ km s}^{-1}$ and they seem to expand at $V_{\text{exp}} \sim 45 \text{ km s}^{-1}$, contributing significantly with $\sigma_{\text{rad}} \sim 38 \text{ km s}^{-1}$ to the total width of their integrated profile.
7. The inner 50 pc and brightest region of II Zw 40 seems to be kinematically very young, where gravity seems to play an important role. Part of the difference found between $\sigma \sim 33 \text{ km s}^{-1}$ in the core and 23 km s^{-1} found in Region 6 is possibly associated with a weak broad component and a small systematic radial velocity flow component σ_{rad} . The broad component should be associated with σ_{shell} originated from multiple unresolved shells provided by stellar winds of WR and OB stars acting on few or subparsec scales.
8. The kinematic features in II Zw 40 are all remarkably similar to the ones found in supersonic GHIIRs in irregular and other star-forming galaxies powered by massive star and stellar cluster formation and evolution, suggesting that these starbursts in H II galaxies are their scaled up versions on galactic scales.

Finally, the core supersonic σ is the one producing the Luminosity– σ relation observed in GHIIRs and HIIGs. This component can be derived by simply measuring the integrated line profiles by fitting a single Gaussian on the brightest knot of the starburst, regardless of aperture size. However, we must further investigate how these derived motions precisely relate to the underlying mass distribution before we can derive absolute total galactic masses. We must also investigate, with a statistically significant sample, the possible evolutionary effects of the starburst on the observed relations, and how they can be parameterized for the use as a powerful extragalactic distance estimator applied to high redshifts.

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APPENDIX

INTERPRETING THE DIAGNOSTIC DIAGRAMS

It is convenient to emphasize the meaning of some patterns formed by the point distributions in the different diagnostic diagrams of Figure 8. These patterns are the graphical representation of the kinematic signatures observed in the two-dimensional flux, velocity and dispersion maps. The following description is valid for the methodology of fitting only single Gaussians to the emission line profiles and its limitation is emphasized when necessary. However, it is a very powerful tool for kinematic analysis provided by data cubes. Three typical patterns are of particular interest, and they are sketched in diagrams (a)–(c) of Figure 13.

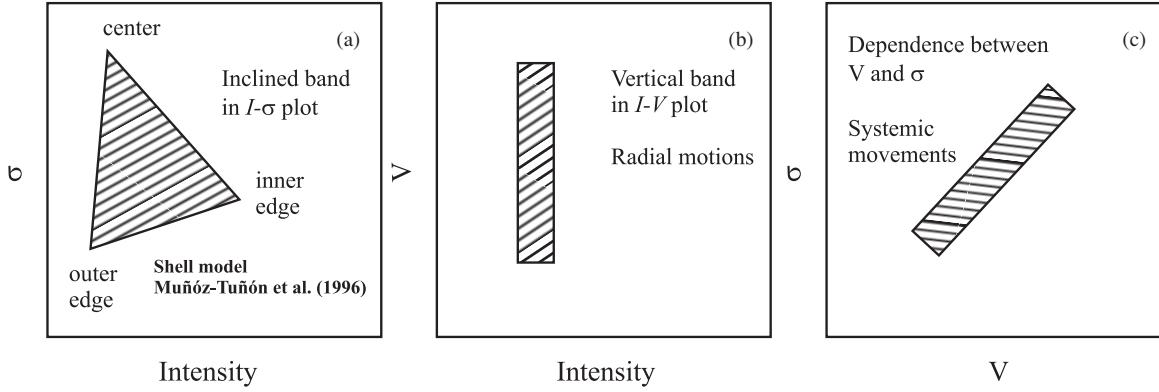


Figure 13. Schematic diagrams showing idealized patterns formed by the distribution of points discussed in the text.

Figure 13(a) shows the pattern known as the inclined band in the $I-\sigma$ diagram, previously identified by Muñoz-Tuñón et al. (1996). The authors propose that this pattern should be the result of an ideal shell evolving in the ISM. Their scenario allows the interpretation of this diagram as a diagnosis for the evolutionary state of the GHIIRs. The points defining the vertexes of the triangle should correspond to the three parts of the shell: center, inner edge, and outer edge (see their Figure 3). The velocity dispersion in the center reaches the maximum value, while the minimum value occurs in the outer edge. The inner edge presents higher intensity and higher velocity dispersion than the outer edge. Assuming that the pattern drawn in the Figure 13(a) represents a young shell, as it ages, σ at the center becomes gradually lower, as well as the difference between the intensity at the center and at the inner edge. Then, the whole figure shifts down, and the upper angle becomes smaller. Furthermore, in their scenario, older shells should present higher intensities than young ones, and should be mapped at right of the young ones in the diagram.

Figure 13(b) shows a vertical band pattern in $I-V$ diagram. This pattern indicates the contribution of resolved systematic radial movements. Abrupt velocity variations in a short intensity range should indicate a local expansion of the gas. It is expected that regions which present the inclined band pattern in the $I-\sigma$ diagram also present a well defined vertical band pattern in $I-V$ diagram. In general, any vertical variations (ΔV) can be used to quantify the component due to expanding motions in a region. We used the approximation $\text{FWHM}_{\text{rad}} \sim \Delta V$ to infer the broadening component due to radial velocity variations (σ_{rad}) for regions with almost constant σ values and nearly Gaussian emission-line profiles. However, if the emission profiles are not well represented by single Gaussians, ΔV measured in $I-V$ plot should underestimate the real component due to systematic radial expansion. As an alternative, one might try to measure the line splitting from the most asymmetric or double-peaked profile, in order to better estimate ΔV from two centroids.

Figure 13(c) shows a correlation between V and σ . This pattern indicates systematic motion with a significant component in the line of sight. The pattern drawn indicates differentiated group behavior: in this case, gas with relatively high σ is moving away from the observer. Although we have drawn the pattern with a positive slope, a region with the same systematic motions could be identified in a negative slope pattern. Such dependence should be expected in the presence of relative motions between distinct clouds of ionized gas with different internal properties. Champagne flows should reproduce the pattern like the one

shown in Figure 13(c) (see Section IIIc in Skillman & Balick 1984). The simplest pattern would be the random distribution of the points in the plane $V-\sigma$, indicating no dependence between the variables. In this latter case, it may represent isotropic expansion or turbulence, but with no privileged direction.

REFERENCES

- Baldwin, J. A., Spinrad, H., & Terlevich, R. 1982, MNRAS, **198**, 535
 Beck, S. C., Turner, J. L., Langland-Shula, L. E., Meier, D. S., Crosthwaite, L. P., & Gorjian, V. 2002, AJ, **124**, 2516
 Bordalo, V. 2004, Master's thesis, Observatório Nacional
 Bosch, G., Terlevich, E., & Terlevich, R. 2002, MNRAS, **329**, 481
 Boulesteix, J. 1999, ADHOC User's Manual <http://www-obs.cnrs-mrs.fr/adhoc/adhoc.html>
 Brinks, E., & Klein, U. 1988, MNRAS, **231**, 63
 Chu, Y.-H., & Kennicutt, R. C., Jr. 1994, ApJ, **425**, 720
 Cumming, R. J., Fathi, K., Ostlin, G., Marquart, T., Márquez, I., Masegosa, J., Bergvall, N., & Amram, P. 2008, A&A, **479**, 725
 Dimeo, R. 2005, PAN User Guide, <ftp://ftp.ncnr.nist.gov/pub/staff/dimeo/pandoc.pdf>
 Denicoló, G., Terlevich, R., & Terlevich, E. 2002, MNRAS, **330**, 69
 Dopita, M. E., & Sutherland, R. S. 2003, Astrophysics of the Diffuse Universe (Berlin: Springer)
 Dyson, J. E. 1979, A&A, **73**, 132
 Fuentes-Masip, O., Muñoz-Tuñón, C., Castañeda, H. O., & Tenorio-Tagle, G. 2000, AJ, **120**, 752
 Kaufer, A., Stahl, O., Tubbesing, S., Norregaard, P., Avila, G., Francois, P., Pasquini, L., & Pizzella, A. 1999, Messenger, **95**, 8
 Kehrig, C., Telles, E., & Cuisinier, F. 2004, AJ, **128**, 1141
 Kunth, D., & Sargent, W. L. W. 1981, A&A, **101**, L5
 Martínez-Delgado, I., Tenorio-Tagle, G., Muñoz-Tuñón, C., Moiseev, A., & Cairós, L. M. 2007, AJ, **133**, 2892
 Melnick, J. 1977, ApJ, **213**, 15
 Melnick, J., Moles, M., Terlevich, R., & Garcia-Pelayo, J.-M. 1987, MNRAS, **226**, 849
 Melnick, J., Terlevich, R., & Moles, M. 1988, MNRAS, **235**, 297
 Melnick, J., Tenorio-Tagle, G., & Terlevich, R. 1999, MNRAS, **302**, 677
 Münch, G. 1958, in IAU Symp. 8, Cosmical Gas Dynamics, ed. J. M. Burgers & R. N. Thomas (Dordrecht: Kluwer), 1035
 Muñoz-Tuñón, C., Gavryusev, V., & Castañeda, H. O. 1995, AJ, **110**, 1630
 Muñoz-Tuñón, C., Tenorio-Tagle, G., Castañeda, H. O., & Terlevich, R. 1996, AJ, **112**, 1636
 Östlin, G., Cumming, R. J., Amram, P., Bergvall, N., Kunth, D., Mrquez, I., Masegosa, J., & Zackrisson, E. 2004, A&A, **419**, L43
 Pelupessy, F. I., van der Werf, P. P., & Icke, V. 2004, A&A, **422**, 55
 Rozas, M., Richer, M. G., López, J. A., Relaño, M., & Beckman, J. E. 2006, A&A, **455**, 539
 Sargent, W. L. W., & Searle, L. 1970, ApJ, **162**, 155
 Searle, L., & Sargent, W. L. 1972, ApJ, **173**, 25
 Skillman, E. D., & Balick, B. 1984, ApJ, **280**, 580
 Smith, M. G., & Weedman, D. W. 1970a, ApJ, **161**, 33
 Smith, M. G., & Weedman, D. W. 1970b, ApJ, **160**, 65

- Smith, M. G., & Weedman, D. W. 1972, *ApJ*, **172**, 307
 Tacconi, Young 1987, *ApJ*, **322**, 681
 Telles, E., Muñoz-Tuñón, C., & Tenorio-Tagle, G. 2001, *ApJ*, **548**, 671
 Telles, E., & Terlevich, R. 1995, *MNRAS*, **275**, 1
 Telles, E., & Terlevich, R. 1997, *MNRAS*, **286**, 183
 Telles, E., Melnick, J., & Terlevich, R. 1997, *MNRAS*, **288**, 78
 Telles, E., & Maddox, S. 2000, *MNRAS*, **311**, 307
 Tenorio-Tagle, G. 1979, *A&A*, **71**, 59
 Tenorio-Tagle, G., Muñoz-Tuñón, C., & Cox, D. P. 1993, *ApJ*, **418**, 767
 Tenorio-Tagle, G., Muñoz-Tuñón, C., Pfez, E., Silich, S., & Telles, E. 2006, *ApJ*, **643**, 186
 Terlevich, R., Melnick, J., Masegosa, J., Moles, M., & Copetti, M. V. F. 1991, *A&AS*, **91**, 285
 Terlevich, R., & Melnick, J. 1981, *MNRAS*, **195**, 839
 Ulvestad, J. S., Johnson, K. E., & Neff, S. G. 2007, *AJ*, **133**, 1868
 Vacca, W. D., & Conti, P. S. 1992, *ApJ*, **401**, 543
 van Zee, L., Skillman, E. D., & Salzer, J. J. 1998, *AJ*, **116**, 1186
 Vanzi, L., Rieke, G. H., Martin, C. L., & Shields, J. C. 1996, *ApJ*, **466**, 150
 Vanzi, L., Cresci, G., Telles, E., & Melnick, J. 2008, *A&A*, **486**, 393
 Walsh, J. R., & Roy, J. R. 1993, *MNRAS*, **262**, 27
 Westmoquette, M. S., Exter, K. M., Smith, L. J., & Gallagher, J. S., III 2007a, *MNRAS*, **381**, 894
 Westmoquette, M. S., Smith, L. J., Gallagher, J. S., III, & Exter, K. M. 2007b, *MNRAS*, **381**, 913
 Yang, H., Chu, Y.-H., Skillman, E. D., & Terlevich, R. 1996, *AJ*, **112**, 146
 Yorke, H. W., Tenorio-Tagle, G., & Bodenheimer, P. 1984, *A&A*, **138**, 325

Capítulo 4

A Relação $L-\sigma$ das Galáxias HII

Neste Capítulo apresentamos o artigo que foi submetido a revista *Astrophysical Journal* e que trata do estudo da relação entre a luminosidade da linha de emissão H α e a dispersão de velocidades encontrada para galáxias HII. Compilamos neste trabalho um conjunto de dados espectrofotométricos provindos de vários trabalhos publicados na literatura para a nossa amostra de 120 galáxias HII com larguras de linha medidas em alta resolução espectral. A partir desses dados derivamos um conjunto de parâmetros físicos para cada galáxia que foram analisados através de métodos estatísticos a fim de investigar efeitos sistemáticos sobre a relação $L-\sigma$, como a não-Gaussianidade dos perfis de linha, a evolução das regiões de formação estelar e a abundância química. O trabalho procura identificar uma amostra homogênea de galáxias que melhor representa a classe das galáxias HII do ponto de vista da dinâmica interna e das suas condições físicas e que melhor seguem a relação $L-\sigma$, impondo vínculos a sua interpretação física. Apresentamos um conjunto de novas relações paramétricas que podem ser usadas como indicadores de

distâncias de galáxias HII. Este estudo é baseado em dados inéditos de perfis de linha em alta resolução, dobrando assim as amostras até hoje estudadas e usadas na calibração da relação $L-\sigma$ para as galáxias HII locais.

The $L-\sigma$ Relation of The Local HII Galaxies

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ABSTRACT

We have investigated the $L-\sigma$ relation of the HII galaxies (HIIGs) using a sample of 120 star-forming regions in these galaxies with optical spectroscopic observations. We were able to classify their nebular emission-line profiles due to our high resolution spectra. We noted peculiarities in the line profiles such as sharp lines, wings, asymmetries, and in some cases more than one component in emission. It suggests that more than one dynamical mechanism may be responsible for the observed profiles in the family of HIIGs. However, the similarity of the $L-\sigma$ relation for HIIGs with those found for virialized systems, such as normal elliptical galaxies, continue posing the intriguing question of why the gas should behave in a same manner, since other mechanisms due to star evolution, playing an important role in these starburst galaxies, contribute significantly to mechanical energy into the ISM. From a new independent set of spectrophotometric data we derived physical condition parameters and performed a principal component analysis. We have investigated the potential role of metallicity (O/H), H β equivalent width ($W_{\text{H}\beta}$) and ionization ratio [OIII]/[OII] to accounted for the observational scatter of $L-\sigma$ relation. Our results indicate that the $L-\sigma$ relation for HIIGs is more sensible to the evolution of the current starburst event (short-term evolution) occurring in these galaxies dated by $W_{\text{H}\beta}$ or the [OIII]/[OII] ratio. Long-term evolution measured by O/H can also play a potential role setting up the power of current ionizing stars. We noted that Gaussian line profile galaxies present a better correlation between the parameters L and σ , indicating that they are best suited for application of the parametric relations as extragalactic distance indicator with cosmological interest. Best fits for a homogeneous sample of 45 HIIGs provide us a set of new extragalactic distance indicators with an rms scatter compatible with observational errors $\delta \log L_{\text{H}\alpha} = 0.20$.

Subject headings: HII galaxies — starburst: parametric relation, velocity dispersion — giant HII regions: kinematics and dynamics

1. Introduction

Giant HII regions (GHIIRs) and HII galaxies (HIIGs) have been intensively studied for almost forty years not only because they are natural laboratories to test astrophysical models (Stasińska & Izotov 2003, and references therein) but also because they present tight scaling relations which can be useful as extragalactic distance estimators with relevance to cosmology (Melnick et al. 2000; Melnick 2003; Siegel et al. 2005; Plonis et al. 2009).

The correlations between nebular diameter, luminosity and velocity dispersion of the ionized gas in GHIIRs were found by Melnick (1977, 1978, 1979) and further investigated by Terlevich & Melnick (1981). Several other works from independent groups have confirmed the existence of these relations for GHIIRs in the Local Group’s magellanic irregular galaxies and in some nearby spirals but there is no agreement about the calibration coefficients (slope and zero point), mainly due to different sample selection, observational data quality and linear fit algorithms (Hippelein 1986; Melnick et al. 1987; Arsenault & Roy 1988; Fuentes-Masip et al. 2000; Bosch et al. 2002; Rozas et al. 2006). For HIIGs these studies are more scarce. The first L - σ calibration obtained by (Melnick et al. 1988, hereafter MTM) had only been confirmed by Telles et al. (2001) for a small sample of HIIGs. Both works found an RMS scatter of $\delta \log L_{\text{H}\alpha} \sim 0.30$ which is a landmark for follow up achievements. In fact, part of this observed scatter has been proposed to be associated with a second parameter, namely oxygen abundance (MTM) or core radius (Telles & Terlevich 1993).

Despite the fact that the physical origin of the observed supersonic line widths has been a topic of intense debate in the literature, with no consensus in the context of mechanical feedback, formation and evolution of Super Stellar Clusters (Terlevich & Melnick 1981; Tenorio-Tagle et al. 1993; Chu & Kennicutt 1994; Scalo & Chappell 1999; Melnick et al. 1999; Tenorio-Tagle et al. 2006; Bordalo et al. 2009), the L - σ relation remains potentially a powerful tool as an alternative empirical extragalactic distance estimator to the classical Tully-Fisher for spirals and D_{n} - σ relations for ellipticals.

In this work we present a new calibration for the L - σ relation for a homogeneous sample of local ($z < 0.1$) HIIGs, doubling the sample of MTM with velocity widths obtained from high resolution spectra. These were combined with a complete set of spectrophotometry data obtained mostly from Kehrig, Telles, & Cuisinier (2004) (hereafter KTC). These data allow us to obtain physical conditions of the nebular gas in the starburst region for most objects of our sample with velocity dispersion derived. We investigated the potential role of different systematic effects over the L - σ relation, such as age, metallicity, aperture and non-Gaussianity of the emission line profiles. We argue that the detailed study of these effects is crucial to identify a homogeneous sample for which the relation is valid, and bring light on its physical interpretation.

The paper is organized as follows. Section 2 describes the data, observations and reductions. The results are presented in §3. In §4 we present the analyzes. We present a discussion about our results in §5 and summarize the conclusions in §6.

2. Data Sample, Observations and Reductions

2.1. The Sample

We have selected most objects from the Spectrophotometric Catalogue of HII Galaxies (SCHG) (Terlevich et al. 1991, hereafter T91). It contains many galaxies from Curtis Schmidt-Thin Prism Survey of Tololo (Smith et al. 1976, Tol) and University of Michigan Survey (MacAlpine et al. 1977, UM). The SCHG also contains few galaxies from Fairall, Markarian and Zwicky lists (Fairall 1980; Markarian 1967; Zwicky et al. 1966, F80, MRK, Zw, respectively). We have also selected HIIGs from smaller surveys such as those produced by Kunth et al. (1981) (POX), Maza et al. (1991) (CTS) and Surace & Comte (1998) (SC98). Cambridge UK Schmidt galaxies (Cam) have been selected from Campbell et al. (1986). Note that some of HIIGs had their names cataloged in more than one of these lists. Additionally, we have selected some classical starburst galaxies — spiral galaxies with HII nuclear regions or simply nuclear starburst galaxies — from Montreal Blue Galaxy Survey (MBG) (Coziol et al. 1993). However, the objects NGC 6970, IC 5154, ESO 533-G 014 and MCG -01-57-017 were only presented in a private list from Roger Coziol. Nuclear starburst galaxies are also often present in HIIGs lists due to their similar optical properties (for example, UM 477 and MRK 710). Thus our sample consists of 120 starburst regions in galaxies for which we have obtained line widths from optical high spectral resolution spectroscopy.

This sample is not complete in a statistical sense. It is heterogeneous in nature comprising four order of magnitude in $H\alpha$ luminosity range. Figure 1 shows the redshift distribution of our sample. The mean of the distribution is 0.0222, whereas the median is 0.0167. The study including all these galaxies is fundamental to investigate the range of the starburst magnitude for which the $L-\sigma$ relation is valid. This is the largest sample of HIIGs ever studied in order to test and calibrate the local $L-\sigma$ relation. This has been possible due to the private agreement between the Observatório Nacional-MCT and the European Southern Observatory (ESO) for the dedicated use of the 1.52m and 2.2m telescopes at La Silla, Chile.

2.2. High Spectral Resolution Spectroscopy

HIIGs are mostly compact objects and the young starburst regions in the core of these systems dominate the main observational properties, i.e. emission line fluxes and their widths (Telles et al. 2001). More recently, Bordalo et al. (2009) have confirmed with the spatial resolved kinematics study of the prototypical HIIG II Zw 40, using 3D integral field spectroscopy, that the line width measured in the nuclear core is the same as the line width measured over the whole extent of the starburst region, indicating that this kinematic core dominates the overall dynamics.

We have decided to use the Fiber-fed Extended Range Optical Spectrograph (FEROS) installed initially on the 1.52m and, later, in 2.2m ESO telescopes at La Silla Observatory in Chile, for the first time to observe galaxies, increasing our sample to the present 120 objects. The target fiber was positioned over the brightest region (nuclear core) of the galaxies. FEROS consists of two fiber coupled to the Cassegrain focus of the telescope by micro lenses, providing a spectral resolution of $R = 48000$ ($\sigma_{\text{inst}} = 2.50 \pm 0.20 \text{ km s}^{-1}$, $\sigma = \text{FWHM}/2.355$). Each of the two fibers has a projected 2.7" entrance aperture and the target and sky are recorded simultaneously.

The echelle FEROS spectrum covers the whole optical region 3560-9200Å. We have observed 103 galaxies with this instrument in five observational runs in the period between November 2000 and April 2007. The FEROS spectra were recorded in a 2048×4096 $15\mu\text{m}$ pixel CCD. The basic reduction, extraction and dispersion calibration of the spectra were done by a pipeline routine in MIDAS (François 1999). It processes Bias and Flat Field calibration in a standard way and applies dispersion calibration to the object spectra from information of a Thorium-Argon-Neon lamp spectrum. The final spectrum is calibrated in wavelength and all 39 orders matched in a single order spectrum covering the optical range. We could measure the line widths for Balmer H β (4861 Å), H α (6563 Å) and [OIII] $\lambda\lambda 4959, 5007$ for most of the galaxies observed. Four galaxies (Tol 0226-390, CTS 1004, Cam 08-28A and CTS 1038) had not their H α widths measured due to bad pixels region presented in the CCD. An example of a wavelength calibrated FEROS spectrum is shown in Figure 2.

Additional line widths were obtained with the 1.60m telescope at Pico dos Dias Observatory (LNA/Brazil) using Coudé spectrograph and the 600 l/mm diffraction grating, resulting on a spectral resolution at 6500 Å of 0.75 Å and 0.90 Å (instrumental FWHM) when CCD 48 and CCDs 101/106 was used, respectively. These correspond to $\sigma_{\text{inst}} = 14.7$ and 17.6 km s^{-1} , respectively. We observed in the region 6400-6900 Å to obtain line width measurements of the H α line emission. The slit used was 1" for all observations. We obtained data from five observational runs between February 1997 and March 1999.

Coudé data was reduced in a standard procedure for slit spectra in CCD using IRAF¹. We used the CCDRED package for Bias and Flat Field reduction and the SPECRED package for extraction and calibration procedures. We extracted the spectra from the brightest knot of the galaxies along the slit. An example of a calibrated Coudé spectrum is shown in Figure 3.

Table 1 lists all observations including FEROS ones and observations with Coudé spectrograph. Columns 1, 2 and 3 give the galaxy name, and their coordinates (J2000). Columns 4, 5, 6 and 7 show the observation log for the Coudé spectrograph and Columns 8, 9 and 10 show the observation log for the FEROS spectrograph, describing the total exposure times, number of exposure, the detector used (only for Coudé) and date of observations, respectively. The last column 11 shows alternative names for the galaxy.

2.3. Spectrophotometry

Most of the spectrophotometric data used in this work comes from KTC with 91 objects in common with our FEROS plus Coudé sample. Their data were obtained from a Boller & Chivens spectrograph on the 1.52m ESO telescope. The spectra cover 4000Å in the optical range centered at 5700Å. They have a spectral resolution of 5Å and the entrance slit was 2 arcsec. KTC observed with long slit and in some cases they extracted more than one spectrum for a galaxy, representing different bright regions spatially separated. Additional and complementary data were obtained from recent works and the references will be cited below. Emission line fluxes and equivalent widths of permitted and forbidden line fluxes were gathered from these sources to derive the physical parameters, such as extinction coefficient, ionization ratio, electron temperature and density and oxygen abundance.

3. Results

3.1. Line Widths and Velocity Dispersions

We have measured the emission line widths from our high spectral resolution observations by fitting single Gaussians to the observed line profiles. We used SPLOT routine of IRAF positioning the cursor at both sides of the line at the same continuum intensities.

¹IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

We have just measured the FWHM of H α line from Coudé spectra. In FEROS spectra we measured line widths of H α , H β and [OIII] $\lambda\lambda 4959, 5007$ emission lines that were detected for almost all galaxies. All Gaussian FWHM measurements from spectra of both instruments are presented in Table 2.

In many cases a single Gaussian fit was not good to represent the observed profile. Some present irregularities such as prominent wings and multiple components. Therefore, we decided to visually classify galaxies depending on their line profiles using the following criterium:

- Gaussian Profile - Symmetrical lines well represented by a single Gaussian fit. These profiles occur in 62% of galaxies in our sample.
- Irregular Profile - Asymmetrical lines showing prominent wings and generally peaked. These occur in 29% of our sample.
- Profile with Components - These clearly show more than one component in emission, normally double-peak lines with similar intensities, occurring in 17% of our sample.

Our classification was done by eye comparison between the single Gaussian fit and the observed line profile, therefore it has an intrinsic subjectiveness even though interesting for early and qualitative purposes in this work. Since we have for most galaxies the four strong emission lines, we checked them all to classify the galaxy. Figure 4 presents some examples of prototypical H α profiles of the three classes defined. All galaxies were classified including those showing low signal-to-noise (S/N) in their emission line profiles, possibly introducing a bias in their classification. Some galaxies may have been classified as presenting Gaussian profiles simply because its line wings were not well sampled. The spectra from FEROS were used in priority to Coudé ones to classify those galaxies observed with both instruments. The galaxies were assigned as letter G for Gaussian and I for irregular profiles, and C for profile with components. The respective class for each galaxy are shown in the last column of Table 2. We will return to this point later in Section 4.2 using a semi-quantitative analysis to select a more homogeneous sample.

We derived the radial velocity dispersions σ from the observed FWHM presented in Table 2. The observed velocity dispersion σ_{obs} in km s $^{-1}$ were corrected by the instrumental σ_{inst} , and thermal broadening σ_{th} , assuming a Maxwellian velocity distribution of the hydrogen and oxygen atoms,

$$\sigma_{\text{th}} = \sqrt{\frac{kT_e}{m}},$$

where k is the Boltzmann constant², T_e is the electronic temperature in Kelvin and m is the mass of the atom³. We used $T_e(\text{OIII})$ presented in Table 3 to derive σ_{th} for all galaxies. For those galaxies where T_e were not directly determined or found in literature we assumed a mean value of 14000 K. For H lines from FEROS spectra we also corrected σ_{obs} by the fine structure broadening σ_{fs} : 3.20 km s⁻¹ for H α and 2.40 km s⁻¹ for H β as adopted by García-Díaz et al. (2008). The velocity dispersion of interest here and sometimes called “non-thermal” velocity dispersion, was calculated by

$$\sigma = \sqrt{\sigma_{\text{obs}}^2 - \sigma_{\text{inst}}^2 - \sigma_{\text{th}}^2 - \sigma_{\text{fs}}^2}.$$

For the FEROS, $\sigma_{\text{inst}} = 2.5$ km s⁻¹, while for Coudé, $\sigma_{\text{inst}} = 14.7$ km s⁻¹ and $= 17.6$ km s⁻¹, depending on the instrumentation used (see Section 2.2). The correction due to σ_{th} for H lines varies between 9.5 and 12.5 km s⁻¹, and for the O lines, between 2 and 3 km s⁻¹. We estimated the error in σ due to uncertainties in T_e as being $\delta\sigma_{\text{H}} < 0.3$ km s⁻¹ and $\delta\sigma_{\text{O}} < 0.1$ km s⁻¹.

The internal errors were determined as a function of the S/N calculated for the emission lines and defined as the ratio between the peak intensity and the adjacent continuum RMS. Figure 5 shows the comparisons between σ derived from the same ion considering all data. The FEROS measurements are very consistent. The RMS of a linear fit for all points are 1.96 for HII and 1.36 for [OIII] lines in km s⁻¹ (Figure 5 left and center). The comparison between FEROS and Coudé measurements also shows good agreement accept for two objects (Tol 0440-381 and UM 448) that present components in their line profiles. The observation of these objects is more sensitive to the position of the slit and fiber over the galaxy. The RMS=5.22 km s⁻¹ from a linear fit is also showed inside the box (Figure 5 right). For different ranges of S/N we selected samples of galaxies for their σ values to be compared. The selection were based on the S/N of the weaker lines of each ion (i.e. H β and [OIII] $\lambda 4959$) and their σ values were plotted in y axis against the σ values derived from the more intense line in x . The error were estimated by taking the RMS of a direct least square fit for each data set. In a similar procedure, we estimated the errors for Coudé $\sigma_{\text{H}\alpha}$ comparing sets of two ranges of S/N with $\sigma_{\text{H}\alpha}$ of galaxies observed also with FEROS. Table 4 shows the estimated errors in σ as a function of S/N for H and O lines. The σ values and their respective errors for each line are shown in Table 5.

² $k = 1.38065 \times 10^{-23} \text{ J K}^{-1}$

³ $m_{\text{H}} = 1.66054 \times 10^{-27} \text{ kg}$ e $m_{\text{O}} = 2.65686 \times 10^{-26} \text{ kg}$

3.2. Physical Conditions

Before we use line fluxes to derive physical conditions we need to infer the amount of extinction for each galaxy. Dust in starburst regions are responsible for extinction of light in line of sight due to absorption and scattering. In optical wavelength the amount of extinction can be reasonably well estimated from H recombination lines through the Balmer Decrement method. To derive $H\beta$ extinction coefficient $C_{H\beta}$ for galaxies with KTC spectrophotometry we used the theoretical ratios $H\alpha/H\beta = 2.87$ and $H\gamma/H\beta = 0.466$ for case B optically thick with $T = 10^4$ K (Osterbrock 1989). In cases where $H\alpha/H\beta$ were smaller than the theoretical value 2.87, we calculated $C_{H\beta}$ using the ratio $H\gamma/H\beta$. When ratios were $H\alpha/H\beta < 2.87$ and $H\gamma/H\beta > 0.466$ simultaneously we adopted the zero value for $C_{H\beta}$. Derredened fluxes I_λ were thus calculated by

$$I_\lambda = F_\lambda \exp[C_{H\beta}(1 + f_\lambda)],$$

where F_λ is the published fluxes corrected by atmospheric extinction and f_λ is the interstellar reddening function normalized at $H\beta$. We adopted f_λ from Whitford (1958) as normalized by Lequeux et al. (1979).

$H\beta$ equivalent widths ($W_{H\beta}$) were taken directly from KTC for 91 objects. From the same work ionization ratios $[OIII]\lambda\lambda4959+5007/[OII]\lambda3727$ (hereafter $[OIII]/[OII]$) were directly determined for 80 objects from derredened fluxes of oxygen lines.

We derived oxygen abundances for 51 objects adopting T_e -method and the standard model for a two-zone photoionized HII region. This number was limited by the number of objects with all oxygen lines available in KTC, i.e. $[OIII]\lambda\lambda4959, 5007$, $[OIII]\lambda4363$ and $[OII]\lambda3727$ lines. We did not consider those galaxies in which $[OII]\lambda3727$ fluxes were indirectly determined by KTC. Temperatures for low- and high-ionization zones were derived according to Pagel et al. (1992) using the $[OIII](\lambda\lambda4959 + 5007)/\lambda4363$ ratio and electron densities, $N_e(SII)$. $N_e(SII)$ was derived for 87 from the $[SII]\lambda6717/\lambda6731$ ratio, using TEMDEN from NEBULAR package of IRAF, based on five-level atom calculations and developed by Shaw & Dufour (1995). All $[SII]\lambda6717/\lambda6731$ ratios higher than 1.4 were fixed at this value, corresponding to a minimum $N_e(SII)$ of 27 cm^{-3} in TEMDEN task. For those galaxies where N_e were not directly determined or found in literature we assumed a mean value of 204 cm^{-3} . Oxygen ionic abundances could be derived using Pagel et al. (1992) expressions for O^{++}/H^+ and O^+/H^+ to obtain the total oxygen abundance

$$\frac{O}{H} = \frac{O^+}{H^+} + \frac{O^{++}}{H^+}.$$

Typical errors in oxygen abundances from derived by T_e -method and provided by the Monte Carlo simulations were $\delta(O/H)=0.05-0.06$.

For galaxies in KTC that could not have their abundances determined from T_e –method, or even were not present in their sample, we compiled some recent results found in literature using also the T_e –method. From most of these other works the values for $W_{\text{H}\beta}$, $[\text{OIII}]/[\text{OII}]$, $N_e(\text{SII})$ and $T_e(\text{OIII})$ were also taken. For those galaxies that we could not find oxygen abundances determined from T_e –method, mainly due to absence of the auroral $[\text{OIII}] \lambda 4363$ line, we derived O/H empirically using p-method (Pilyugin 2000) and N2 calibrator (Denicoló et al. 2002).

Firstly, we calculated both high- and low-abundance values for O/H (Pilyugin 2000, equations (4) and (6)). We only considered those values in agreement with the respective abundance regimes of the Pilyugin’s best fits, i.e. $12 + \log(\text{O/H})_{P3} < 7.95$ or $12 + \log(\text{O/H})_{P2} > 8.15$. In order to brake the degeneracy when the values were acceptable, we adopted a criterium similar to the one described in van Zee et al. (1998). Those galaxies with $\log [\text{NII}](\lambda\lambda 6548 + 6584)/[\text{OII}](\lambda 3727 \text{ blended}) > -0.8$ should have their high-abundance values assigned (P2), whereas those with $\log [\text{NII}]/[\text{OII}] < -1.05$ should have their low-abundance values assigned (P3). With this criterium we assigned 14 empirical abundance values for $12 + \log(\text{O/H})$ and all from high-abundance side. Instead of using the calibrator $[\text{NII}]/\text{H}\alpha$ provided in van Zee et al. (1998) for the turnover region, and when the Pilyugin’s values were not calculated or acceptable, we used the N2 calibrator from Denicoló et al. (2002),

$$12 + \log(\text{O/H}) = 9.12 + 0.73 \cdot \text{N2},$$

where N2 is defined as $\text{N2} = \log([\text{NII}]\lambda 6584/\text{H}\alpha)$. For this, we also used [NII] derreddened fluxes from KTC. Other 15 O/H ratios were calculated by the N2 calibrator. The uncertainties in oxygen abundances derived by both empirical methods (p-method and N2) were estimated to be $\delta(\text{O/H})=0.14$, corresponding to the RMS of least square fits between T_e -method abundances and empirical abundances derived independently.

Table 3 presents all physical parameters discussed in this section. Columns 1-5 show the galaxy name, the observed flux of $\text{H}\alpha$ ($F_{\text{H}\alpha}$), the derived logarithmic reddening parameter ($C_{\text{H}\beta}$), the equivalent width of $\text{H}\beta$ ($W_{\text{H}\beta}$), the ionization ratio $[\text{OIII}]/[\text{OII}]$, the derived electron density (N_e) and temperature (T_e), and oxygen abundance (O/H), and finally, last column shows the references to the sources of the data in the same order they appear in the table.

3.3. Distance and $\text{H}\alpha$ Luminosity

The distances (D) to all galaxies in Mpc were derived using the Hubble’s Law, $D = cz_{\text{H}}/H_0$, where z_{H} is the cosmological redshift of the galaxies and H_0 is the Hubble Constant

in $\text{km s}^{-1} \text{Mpc}^{-1}$. Heliocentric redshifts (z_{hel}) were derived from the observed redshift ($z_{\text{obs}} = \Delta\lambda/\lambda$) by removing the earth's rotational and orbital motions using the resultant velocity component from RVCORRECT routine of IRAF. This correction is smaller than 30 km s^{-1} in modulus and it was only applied to the redshifts from FEROS spectra. The uncertainty $\delta z_{\text{hel}} = 5 \times 10^{-5}$ was estimated for FEROS spectra's redshifts and $\delta z_{\text{hel}} = 1.5 \times 10^{-4}$ for Coudé spectra's redshifts. Heliocentric redshift from FEROS were used in priority to Coudé to derive distances for those galaxies observed with both instruments. We found z_{H} from z_{hel} by removing the solar motion with respect to 3K Cosmic Microwave Background (CMB). We use the NASA/IPAC Extragalactic Database - NED⁴ to obtain the resultant velocity correction (heliocentric to 3K background) for all galaxies of our sample. The distances to galaxies were calculated using $H_0=71 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The heliocentric redshifts (z_{hel}) and distances (D) for all galaxies are presented in columns 2 and 3 of Table 2.

$\text{H}\alpha$ luminosities ($L_{\text{H}\alpha}$) were therefore derived from derredened fluxes ($I_{\text{H}\alpha}$) and D ($L_{\text{H}\alpha} = 4\pi D^2 I_{\text{H}\alpha}$). We have used $\text{H}\alpha$ rather than $\text{H}\beta$ in $L-\sigma$ relation since it is more intense and relatively less affected by extinction and underlying absorption. The last column of Table 5 shows the derived $\text{H}\alpha$ luminosities for 118 galaxies for which we had reliable spectrophotometry.

The error in luminosity is very difficult to evaluate precisely since it depends on several factors. Firstly, slit spectrophotometry for extended objects suffer intrinsically on the aperture effect. In addition, individual spectrophotometric errors were not provided by KTC, instead, they provided the random error of the flux measurements of the line emissions as being in the range $5\% - 40\%$ for $F > 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$, decreasing for high intensity lines. However, they compared their results with those in T91 showing good agreement with their spectrophotometry. A point in favor of these new spectrophotometric data is their homogeneity on technique and instrumentation. In view of this, to obtain quantitative results in the analysis sections we will only consider a sample of homogeneous spectrophotometric data, i.e. luminosities derived from KTC data and only few new available data with similar techniques.

3.4. The $L-\sigma$ Relation

We present in Figure 6 (a), the $L-\sigma$ relation in logarithmic units for 116 galaxies and two starburst regions in the same galaxy Tol 1004-296 (SE and NW), all observed with FEROS and Coudé spectrographs. We also show in de same figure the $L_{\text{H}\alpha}$ (b) and σ (c) distributions

⁴<http://nedwww.ipac.caltech.edu/>

for each subsample (G, I and C), which will help the visualization of the subsample properties highlighted below. We have plotted in Figure 6 (a) as many galaxies as possible for which we could obtain spectrophotometric data from other works and from Coudé spectrophotometry. It shows the strong correlation between the nebular luminosity and its velocity dispersion. It confirms once more the existence of this relation for HIIGs, but now for a sample of more than one hundred galaxies, doubling the old samples studied in the past. Galaxies which present irregular profiles and especially those showing profiles with components are systematically concentrated in the high velocity dispersion ($\log \sigma > 1.6$) and luminosity ($\log L_{\text{H}\alpha} > 41$) regions of the L - σ plot (top right). On the other hand, galaxies showing Gaussian profile are more well distributed in this plane, though more concentrated in the regime $\log \sigma < 1.6$ (bottom left). They span from typical values of σ found for single GHIIRs, $12 - 30 \text{ km s}^{-1}$ ($1.1 < \log \sigma < 1.5$), to $\sim 60 \text{ km s}^{-1}$ ($\log \sigma \sim 1.8$). It is clear in Figure 6 (a) that galaxies showing irregularities and multiple components in their emission line profiles contributes to flatten the L - σ relation resulting on its curved shape toward high L and σ values. This behavior was in fact predicted by MTM but they only identified two galaxies that clearly disagree of the mean line (Tol 0226-390 and Tol 0242-387) due with their limited sample. These two galaxies are also presented in our sample and were in fact classified visually as I. MTM sample was restricted to those objects which present $W_{\text{H}\beta} > 30 \text{\AA}$. We will show below that this criterium seems to be also efficient to select galaxies with the most Gaussian line profiles.

In order to minimize the uncertainties due to a heterogeneous data set, we further analyze in this section the L - σ relation for those galaxies that have line-widths measured from FEROS data and spectrophotometry compiled from KTC's work. Additional 4 objects (UM 382, CTS 1027, II Zw 70 and Tol 2138-405) that have good new spectrophotometry are included. Although the number of objects decreases from 118 to 81, it still represents the largest sample ever studied in the literature.

Figure 7 shows the L - σ relation for the homogeneous sample described above including galaxies undistinguished by their emission line profiles (81 objects). The regression fits for the total sample and only for the G subsample (53 objects) are presented in Table 6. The class of ordinary least-square fits (OLS) used in this work is appropriate to problems where the intrinsic scatter dominates the errors arising from the measurement process (Isobe et al. 1990). We argue that the OLS($Y|X$) is the most appropriate to describe the L - σ relation for our data set and is the best to be compared with previous calibrations (MTM, Telles et al. 2001). A second point is that the uncertainties in σ are much smaller than in luminosity, which justify the first to be treated as an independent parameter in a direct linear regression. Nevertheless the other fits provide us an idea of maximum limits of the regression coefficients (slope and zero point).

It is clear that the $L-\sigma$ relation including only G galaxies is tighter and steeper than the one including the whole sample of HIIGs. It suggests that the Gaussianity of the emission line profiles in these systems may be associated with the nature of the $L-\sigma$ relation. Figure 8 shows the $W_{\text{H}\beta}$ distribution for each class G, I and C. Note that most G galaxies are concentrated in the region of high $W_{\text{H}\beta}$ ($> 30\text{\AA}$). Thus a sample selection criterium based on high $W_{\text{H}\beta}$ would be efficient to select also galaxies with the most Gaussian profiles. The consequences of this result to the nature of the $L-\sigma$ relation are profound. Since $W_{\text{H}\beta}$ is an age indicator of the current starburst, resultant Gaussian line profiles may be associated with the youngest systems. If the $L-\sigma$ relation for HIIGs has in fact an upper envelope described by those galaxies with zero-age and maximum $W_{\text{H}\beta}$ values, it should be populated only by HIIGs showing the most Gaussian line profiles. In Section 4.2 we will more rigorous in selecting a subsample of G galaxies with the most Gaussian line profiles by a semi-quantitative criterium in order to investigate if it has additional consequences in the slope and scatter of the $L-\sigma$ relation.

4. Data Analysis

4.1. Aperture Effects

The $L-\sigma$ relation may be in principle affected by the aperture effect in two ways. Firstly, if the observation comes from fixed-slit spectroscopy ($\sim 2''$) as in this work, nearby objects should have their fluxes underestimated and hence their luminosities too. Furthermore, extended and more compact objects, both at same distances, may suffer differentially from this effect. It may also have implications in determining their physical conditions (Kewley et al. 2005).

Multiplicity of star-forming regions and the aperture effect can also introduce a bias in σ determination — a single observation integrate light from more than one starburst region in the same galaxy. This could introduce a systematic velocity component in the integrated line profiles since Super Star Clusters and their associated GHIIRs may present relative radial velocities that would add light in a non-trivial way. If there is only a dominant starburst region, as in most cases for HIIGs, this problem is not severe and this may be the reason why the $L-\sigma$ relation exists (Telles et al. 2001). Although multiplicity does not necessarily preclude gaussianity, it seems to be usually associated with asymmetric line profiles (Bordalo et al. 2009). We have also found very compact objects presenting line profiles with multiple components (e.g. CTS 1033 shown in Figure 9). However, most of the galaxies classified as C are not compact, but extended systems frequently associated to nuclear starburst galaxies, where the systemic rotational component dominate the features in emission line profiles.

The multiplicity effect seems to be inherent in the $L-\sigma$ relation causing no strong bias, otherwise the $L-\sigma$ relation would be not verified, even in the short redshift range of our sample. The physical sizes covered by the observations span from few hundred parsecs in nearby objects (e.g. UM 461 and MRK 36), characterizing sizes of single GHIIRs, to few kiloparsecs (e.g. CTS 1008 and Cam 08-28A). In addition, multiplicity and aperture effects can be greatly reduced by selecting only the galaxies showing the most Gaussian line profiles.

4.2. Gaussian Profile Galaxies

In order to find a more homogeneous sample and, in addition, test the visual classification presented in Section 3.1, we have further adopted a semi-quantitative criterium to search for galaxies with the most Gaussian emission line profiles. These seem to be the ones that show the lower scatter in the $L-\sigma$ plane, as shown in Figure 7, and therefore deserve special attention. The quantitative estimators that we used were the skewness (ξ) and kurtosis (κ) of the emission line profiles (see Miesch, Scalo, & Bally 1999, for the use of these estimators in one-point velocity statistics of star-forming regions). These estimators are related to the third (m_3) and fourth (m_4) momenta of the distribution through the formulae

$$\xi = \frac{m_3}{s^3}$$

and

$$\kappa = \frac{m_4}{s^4},$$

where s is the standard deviation of the distribution and m_3 and m_4 their higher momenta⁵. For practical cases concerning real data spectra, where λ is the wavelength and y is the flux, the formulae for these estimators can be written by:

$$\begin{aligned} \text{mean} = \mu &= \frac{\sum \lambda \cdot y}{\sum y}, \\ \text{standard deviation} = s &= \sqrt{\frac{1}{\sum y} \sum (\lambda - \mu)^2 \cdot y}, \\ \text{skewness} = \xi &= \frac{1}{\sum y} \frac{\sum (\lambda - \mu)^3 \cdot y}{s^3}, \end{aligned}$$

⁵We used s to denote the standard deviation in order not to be confused with the velocity dispersion derived (σ).

$$\text{kurtosis} = \kappa = \frac{1}{\sum y} \frac{\sum (\lambda - \mu)^4 \cdot y}{s^4}.$$

Before we proceed the calculation of ξ and κ estimators we smoothed all FEROS spectra with a box of 11 pixels (FEROS's scale is 0.03Å/pix) using SPLOT. Since our aim was to estimate the global shape of the emission lines, the smooth procedure is very useful to eliminate high frequency noise. The most Gaussian profile galaxies were selected as the ones which met the criterium of symmetry⁶: $|\xi| < 0.1$ and $2.9 < \kappa < 3.1$. The estimators were calculated in a window centered at the mean, obtained from the single Gaussian fit (centroid), and defined as the one in which the line intensity falls to 20% of its peak value. This methodology ensures that the estimators show a good consistency between them, however the size of integration window over λ interval is somewhat a matter of definition which should be based on the quality of the data.

Only FEROS galaxies with S/N in the line greater than 30 were analyzed by this method. Emission line profiles of 49 galaxies met the above criterium of symmetry. Two examples (UM463 and [F80] 30) are presented in Figure 9 (upper panels), including their shape estimators ξ and κ . We also present the H α emission line profile of II Zw 40 ($\xi=0.18$, $\kappa=3.05$) as an example in which the criterium of symmetry was efficient to reject profiles with strong asymmetries (Figure 9 bottom right). Most estimators were calculated using H α line and only few using [OIII] 5007Å due to the presence of bad pixels or significantly lower S/N in H α . A comparison with the G subsample classified visually (Table 2) showed good agreement except for six galaxies that were previously classified as I or C, namely Tol 0104-388, Tol 0957-278, CTS 1030, CTS 1033, CTS 1037 and CTS 1039. These objects were thus visually rejected. We kept the visual classification for these galaxies since the first two objects present two intense components which are identified in the other emission lines observed, while CTS 1033 presents at least three emission components (Figure 9 bottom left). The last is a very special case in which asymmetries in the integration window are compensated resulting in estimators that mimic a symmetric profile ($\xi=-0.04$, $\kappa=3.03$). The other three objects present intense broad component not well evaluated in the integration window though they are symmetric. Thus 43 galaxies compose a more restrictive subsample of the galaxies showing the most Gaussian line profiles and they were assigned as G' in Table 2.

The need for a qualitative analysis of the emission line profiles is in fact a limitation of the method applied to our data. Since the S/N ratio is relatively low in the wings of the line, we need to limit the integration window to a fix proportion of the peak value (see above), in order to keep the consistency between the values from very different S/N lines. Nevertheless, the method provides a way to determine a homogeneous sample of galaxies based on their

⁶ $\xi=0$ and $\kappa=3$ for the Gaussian distribution.

kinematic properties.

Table 6 shows the regression fits for the $L-\sigma$ relation considering the more restrictive subsample G' . From 43 objects identified as G' , 37 had homogeneous observational data as described in Section 3.4 and were used to derive the calibration coefficients. Although this sample presents few objects in the range $1.6 < \log \sigma < 1.8$, the OLS fits show that the $L-\sigma$ is steeper than the one for the whole G subsample (53 objects). We conclude that the galaxies showing the most Gaussian line profiles show the $L-\sigma$ relation that could be identified as an upper envelope $L \propto \sigma^4$ with minimum scatter $\delta \log L_{\text{H}\alpha} = 0.29$.

4.3. The Second Parameter

Terlevich & Melnick (1981) and Melnick et al. (1988) have suggested that the dependent parameter L_{Balmer} can be predicted by σ and O/H, which should define the manifold of HIIGs. Telles & Terlevich (1993) also showed that the structural parameter namely radius of the burst should be considered as a second parameter in $L-\sigma$, acting remarkably similar to effective radius in fundamental plane of the elliptical galaxies. It is crucial to investigate the existence of an independent second parameter (or a third) in $L-\sigma$ relation not only to obtain a precise distance indicator but also to understand the physics behind this scaling relation. If the underlying relation is in fact the one between mass and luminosity, as proposed by these authors, then σ can be used properly to obtain dynamical masses of these systems with great relevance for the high redshift studies of HIIGs counterparts, such as the Lyman Break Galaxies (Lowenthal et al. 2009, and references therein).

We have used the Principal Component Analysis (PCA) to investigate the relative dependence of $L-\sigma$ relation on a possible second parameter based on our new data set, following the early analysis by MTM. Let us first analyze the largest sample possible considering the 5 parameters (variables) — $L_{\text{H}\alpha}$, σ_{H} , O/H, $W_{\text{H}\beta}$ and [OIII]/[OII]. The sample includes $n = 95$ objects with all these quantities known (Tables 3 and 5). All quantities were considered in logarithmic scales. Table 7 shows the lower half triangle of the correlation matrix. Visual analysis of Table 7 shows that the strong correlation are found between $W_{\text{H}\beta}$ and [OIII]/[OII] ($r = 0.86$) and $L_{\text{H}\alpha}$ and σ_{H} ($r = 0.82$). It is also worth noting that the correlations between $L_{\text{H}\alpha}$ and [OIII]/[OII], $L_{\text{H}\alpha}$ and $W_{\text{H}\beta}$ and σ_{H} and $W_{\text{H}\beta}$ are near zero. The correlations of O/H and $W_{\text{H}\beta}$ and O/H and [OIII]/[OII] are negative, while O/H and $L_{\text{H}\alpha}$ and O/H and σ_{H} are positive.

The first three principle components (PCs) with their loadings⁷ obtained from the correlation matrix, as well as the eigenvalues (l) and the respective individual percentages ($l/5$) of total variance (5) are presented in Table 8. Nearly 88% of the variance among the 95 sample points lies in only two dimensions. The number 2 of dimensions of the manifold can be easily verified due to the bimodal behavior of the variance (Jolliffe 2002). The two first principal components (PCI and PCII) present eigenvalues well above 1 (or $1/5=20\%$), while the others well bellow. In addition, one can estimate the confidence interval for the eigenvalue 1 using the formula $\sqrt{2l^2/(n-1)}$ which provide $l = 1.00 \pm 0.15$ (or $20 \pm 3\%$), showing that PCII with 34% and PCIII with 7.3% are well far from $l = 20 \pm 3\%$. This test is justified since in PCA all variables have (0,1)-normalization, so any PC with an eigenvalue less than 1 is not worth consideration. This also called “eigenvalue-one” criterium to decide the dimensionality of the manifold on the space parameters have gained almost universal acceptance (see Brosche (1973) and Bujarrabal et al. (1981) for the earliest papers applying PCA technique to galaxy samples).

Since PCI and PCII contain no more than 88% of the total variance and other PCs present very small eigenvalues, we show that the addition of O/H, $W_{H\beta}$ and [OIII]/[OII] does not contribute to explain the total variance of the space parameters and hence they can not be used simultaneously to reduce the scatter in the $L-\sigma$ relation. These three well known indicators of the physical conditions in star-forming regions are strongly correlated with each other and the correlations found here are in good agreement with early findings (e.g. Campbell et al. 1986). The interrelationships between them are known and of intense debate in literature (Terlevich et al. 2004; Hoyos & Díaz 2006, and references therein). It introduces a problem commonly faced by PCA technique and multiple regression known as collinearity (or multicollinearity). Multicollinearities are often indicated by large correlations between subsets of the variables which can be seen in correlation matrix for variables O/H, $W_{H\beta}$ and [OIII]/[OII] (Table 7). These three parameters are the ones that have high loadings of PCI, hence they are variables which are most closely related to PCI (Table 8). On the other hand, the high loadings in PCII identify $L_{H\alpha}$ and σ_H as the parameters most closely related to PCII.

The main result of the above analysis is that PCI can be thought of as measures of physical conditions in HIIGs, whereas PCII as measures of strength of $L-\sigma$ relation. Note that we do not invoke any prior knowledge about the physical origin of the $L-\sigma$ relation. As PCs are pairwise uncorrelated, the conclusion is that physical conditions are responsible for part of the observed scatter in $L-\sigma$ relation, though the three parameters studied here can not

⁷The loadings represent correlations between the PCs and the original variables. PCs are the new set of variables uncorrelated by definition and written as linear combinations of the original variables.

be used simultaneously to explain that. Note that σ_H presents its highest loading in PCII, which suggests that it is not a primary consequence of internal physical conditions (measured by these three parameters), and possibly not controlled by subsequent mechanical feedback processes due to massive stellar evolution. However, the weaker but real correlation between σ_H and O/H ($r = 0.47$, see Table 7) is responsible for the non-negligible loading for σ_H in PCI (0.66). It shows that O/H introduces some degree of multicollinearity as an additional independent parameter in $L-\sigma$ relation. Although a high degree of multicollinearity does not violate the assumptions of the regression model, it influences the variance of the estimated regression coefficients (partial slopes and intercept). We will present the $\sigma-Z$ relation in the context of the discussion about the internal dynamics of HIIGs in Section 5.1.

For now, we are not interested in fully predict the dependent variable $L_{H\alpha}$ based on the other parameters studied here. They present high degree of multicollinearity mainly due to $W_{H\beta}$ -[OIII]/[OII] relation. Instead, we want to identify which physical condition parameter explains more efficiently the scatter as a second independent parameter in the $L-\sigma$ relation. A possible way to further investigate the variance of the space parameters, overcoming the problem of multicollinearity in PCA, is by using only a subset of parameters, where the subset is chosen so that it does not contain or it is intended to minimize multicollinearities⁸.

Table 9 presents the results of the PCA table for the same previous sample containing 95 objects, undistinguished by their emission line profiles or $W_{H\beta}$, for the three parameter spaces: $[L_{H\alpha}, \sigma_H, O/H]$, $[L_{H\alpha}, \sigma_H, W_{H\beta}]$ and $[L_{H\alpha}, \sigma_H, [OIII]/[OII]]$. The results for $[L_{H\alpha}, \sigma_H, O/H]$ shows that in addition to $L_{H\alpha}$ and σ_H , O/H has a relative high loading in the PCI (0.61), which shows its strong relevance to explain the variance in the PCI. It results from relative higher correlation of O/H with σ_H as mentioned above. Therefore PCII only explains 27% of the total variance. On the other hand, the analysis with the subset $[L_{H\alpha}, \sigma_H, W_{H\beta}]$ shows that $W_{H\beta}$ is uncorrelated with σ_H and contributes efficiently to explain 35% of the variance in the PCII. Ionization ratio [OIII]/[OII] also presents higher contribution to PCII than O/H. Its behavior is more likely the $W_{H\beta}$ and define the first-order effect on $L-\sigma$ relation.

The residual variance 4%-5% in PCIII (Table 9) accounts for observational errors, but a fraction of it can be explained by the fact that we have analyzed a heterogeneous sample. We have not distinguished galaxies by their emission line profile. In fact, part of the large scatter in the high L and σ regime populated most by I and C galaxies (see Figure 6) may not be explained at all, since single Gaussian fits seem not to well represent the internal kinematic in these systems or the resultant line widths are not well correlated with L . In

⁸Principle Component Regression (PCR) is also a multivariate analysis appropriate to investigate problems in which multicollinearity is present (Jolliffe 2002)

addition, there must be outliers also due to photometric errors propagated to parameters that may be perturbing the PCA results. PCA is a powerful technique that can be also used to detect outliers in data sets providing robust results. In order to obtain the distance estimators presented in next section, we have investigated and detected outliers in the context of multiple regression (Appendix A).

We conclude by saying that $W_{\text{H}\beta}$ as an age estimator of the starburst in HIIGs can not be neglected in a regression model in order to obtain a distance indicator based on $L-\sigma$ relation. The ionization ratio [OIII]/[OII] acts in a similar way as $W_{\text{H}\beta}$ and can be explicitly considered in absence of $W_{\text{H}\beta}$. Finally, the results shown above do not mean that O/H can not be used as a second parameter in $L-\sigma$ relation, instead we have verified that its efficiency to reduce the scatter of $L-\sigma$ may be real but it seems to be smaller than the one using $W_{\text{H}\beta}$. Additionally, O/H introduces a higher degree of collinearity due its relationship with σ (Appendix A).

4.4. Empirical Relations

Primary luminosity dependence on σ has been evaluated by a slope of $L-\sigma$ relation considering only galaxies showing nearly Gaussian emission line profiles. For a given velocity dispersion σ and metallicity (O/H), the galaxies with the largest H β equivalent width $W_{\text{H}\beta}$ or ionization ratio [OIII]/[OII] should present also the largest Balmer luminosities $L_{\text{H}\alpha}$. On the other hand, for a given σ and $W_{\text{H}\beta}$ or [OIII]/[OII], galaxies with the lowest O/H ratio should also present the largest $L_{\text{H}\alpha}$. The results found here for $L-\sigma$ relation (Table 6) and PCA (Section 4.3), as well as in early studies (Terlevich & Melnick 1981, MTM), corroborate the same empirical model for HIIGs. Therefore, we need to obtain precise regression coefficients through multiple regressions.

Let us derive a set of empirical relations that can provide distance indicators based on the homogeneous subsample of 53 objects showing nearly Gaussian line profiles (visually classified as G) that have shown the tightest $L-\sigma$ relation (Table 6). It is possible that some I or even C galaxies would fit in a regression model increasing the statistical significance of the regression coefficients, but in general, as shown in Section 3.4, they contribute to flatten the $L-\sigma$ relation increasing its scatter especially in the regime of high L and σ values. It suggests that some of them do not share the same physical properties of the most G galaxies or the single fit procedure to derive their resultant σ is not appropriate. These objects may also suffer differentially from aperture effects (Section 4.1). The sample containing 53 objects was chosen instead of the more restrictive one (37 objects), selected by the semi-quantitative criterium (Section 4.2), since the later are not well represented in the range $1.6 < \log \sigma <$

1.8 km s⁻¹.

Multiple regression fits for 53 objects are shown in Table 10. Linear fits to the $L-\sigma$ relation for the same sample were also presented in Table 6. Note that the scatter given by the RMS of the multiple regression fits did not reduce significantly by the inclusion of a second or a third independent parameter. It is mainly due to the presence of outliers. Outliers may not introduce a significant problem in $L-\sigma$ relation (shown in Figure 7 and Table 6) because L and σ outlying measurements do not surpass the intrinsic scatter (RMS ~ 0.30). We have included O/H, $W_{H\beta}$ and [OIII]/[OII], each carrying a potential source of error. Some data were in fact compiled from different works and they may have not been obtained at exact same region in the galaxies. In Appendix A we present a full statistical analysis of detecting outliers and measuring the degree of multicollinearity of all regressions presented in Table 10 (45 objects). All eight data points deleted from the sample containing 53 objects were investigated and reported. We have shown that the presence of these outliers is mainly due to inclusion of objects with an uncertain nature, with data considered from different sources, and unusual high uncertainties in derived parameters due to low S/N spectra. Thus Table 10 also show a set of empirical relations based on a sample of 45 objects without outliers. For RMS comparison with the ones from regression models with two or three independent parameters, we also presented the linear fit OLS(Y|X) to $L-\sigma$ relation for the sample containing 45 objects free from outliers. We reproduced a new version of the early empirical model $L-\sigma$ -O/H used by MTM to derived their distance indicator with a same RMS scatter of $\delta \log L_{H\alpha} = 0.22$. Independent functional forms for $L-\sigma$ - $W_{H\beta}$ and $L-\sigma$ -[OIII]/[OII] produce virtually the same result and they are both more efficient than O/H as a second independent parameter in $L-\sigma$ relation reducing the RMS scatter to $\delta \log L_{H\alpha} = 0.20$. In addition, we present the “true” empirical model for HIIGs, $L-\sigma$ -O/H- $W_{H\beta}$ (R1) and $L-\sigma$ -O/H-[OIII]/[OII] (R2), accounting for by age and metallicity effects to predict the dependent parameter $L_{H\alpha}$. Although the scatter have not reduced significantly by the inclusion of a third independent parameter — O/H in $L-\sigma$ - $W_{H\beta} \sim 2\%$ and O/H in $L-\sigma$ -[OIII]/[OII] $\sim 3\%$ — we expect that by reducing observational errors one can measure more precisely the scatter reduction using three independent parameters to predict $L_{H\alpha}$. Note that the results for the coefficients found for samples with 53 and 45 objects are virtually the same within the standard errors. This shows the robustness of the regression fits.

It is an important result that $W_{H\beta}$ can account alone for a significant fraction of the scatter in $L-\sigma$ relation ($\sim 25\%$) with a minimum degree of collinearity. $W_{H\beta}$ has the advantage of being a simpler parameter to be obtained from the spectra, though it depends on continuum detection. Alternatively, if the intense [OIII] $\lambda\lambda 4959, 5007$ and [OII] $\lambda 3727$ lines are detected one can use, with the same precision, the $L-\sigma$ -[OIII]/[OII] regression model. On the other hand, the $L-\sigma$ -O/H empirical model as distance indicator would be more difficult

to apply at great distances, since it requires the detection of [OIII] $\lambda 4363$ auroral line to precisely calculate oxygen abundances by T_e -method.

Figure 10 presents all five regression models, including those with two (a, b and c panels) and three (d and e panels) independent parameters plotted against the observed $L_{\text{H}\alpha}$. The outliers identified in Appendix A are plotted as open red circles in all panels. Their predicted luminosity values were computed from the respective regression models for 45 objects presented in Table 10. Figure 11 presents the histograms of all five parameters used in regression models, $L_{\text{H}\alpha}$ (a), σ_{H} (b), O/H (c), $W_{\text{H}\beta}$ (d) and [OIII]/[OII] (e), with their mean values and standard deviation in logarithmic units. These histograms characterize our calibration sample. Note that we have included some galaxies with $W_{\text{H}\beta} < 30\text{\AA}$ in our sample, which were not included by MTM in their calibration sample. Nevertheless, one might show, based on our data set, that similar regression coefficients can be obtained excluding these galaxies from the calibration sample. Our calibration sample with 45 local objects is a good representative sample of HIIGs in general. The mean, standard deviation and median (8.03) of the distribution of metallicity (Figure 11 panel c) are consistent with studies that characterize the population of HIIGs from much larger samples (Kniazev et al. 2004).

5. Discussion

The $L-\sigma$ relation for local HIIGs have been confirmed in this work for the largest sample ever studied in the literature. Our high spectra resolution allowed us to derive with high precision the gas velocity dispersion in these systems. In addition, we were able to examine the effect of non-Gaussianity of the emission line profiles in the $L-\sigma$ plane. We have found that HIIGs showing nearly Gaussian line profiles produce the tighter $L-\sigma$ relation. A further investigation has shown that a significant part of the observational scatter can be accounted for by age and metallicity systematic effects. We were able to produce empirical relationships that account for one or both effects.

5.1. Internal Dynamics

The existence of $L-\sigma$ relation for GHIIRs and HIIGs poses an intriguing question about the origin of the supersonic velocity widths of the emission line profiles. Several works have tried to answer this question through different approaches, but the hypothesis that these systems are gravitationally bound at least in early stage of their evolution persists

as a paradigm (Terlevich & Melnick 1981). Figure 12 presents the σ - Z relation for the whole sample presented in PCA (Section 4.3, 95 objects) and for those galaxies presented in calibration sample (Section 4.4, 45 objects). If σ correlates with metallicity in a similar manner as in gravitational bound systems, the underlying relation could be the one between mass and metallicity. We present the bisector regression fits for different samples in the caption of Figure 12. In a recent work considering a large sample of HIIGs, Salzer et al. (2005) have shown the existence of the L - Z relation for these systems. The NIR $L^{0.20} \propto Z$ relation found by the authors, which more directly reflect the underlying relationship between mass and metallicity, could be compared with our results in order to check whether the gravitational interpretation of the L - σ relation of HIIGs is acceptable. However, the Near-infrared luminosity comes mostly from the old stellar population, which may not be directly associated with the current mass of the starburst. Another option would be to compare the B band L - Z with our Z - σ relation. In fact, if we use the scaling relation $L^{0.28} \propto Z$ derived for B band by Salzer et al. (2005) and consider the $Z \propto \sigma^{1.6}$ found here, we get closer to the $L \propto \sigma^4$. It still can not constrain much about the gravitational interpretation, since we have to explain how σ of gas from the current starburst correlates with metallicity. A simple explanation would be that metal rich galaxies produce more massive starbursts, and this should be verified by observations. These interesting questions are above the scope of this work and should be further investigated.

Another hint about the origin of velocity widths found in HIIGs is provided by the systematic difference found between the width of HII and [OIII] lines. This difference was firstly found in GHIIRs by Hippelein (1986). Figure 13 shows the differences found for our sample of HIIGs. In the left panel of Figure 13 we plot all galaxies with two lines observed, H β and [OIII] 4959Å, whereas in right panel we only plot the lines with the highest S/N with the smallest σ errors ($\delta\sigma < 1.2 \text{ km s}^{-1}$). We do not see any systematic difference between these measurements above $\sim 50 \text{ km s}^{-1}$. In fact, we note high discrepancies (5-20 km s^{-1}) between σ_{H} and $\sigma_{[\text{OIII}]}$ with no trend. On the other hand, we see that HIIGs showing σ values in the regime $15 < \sigma < 50 \text{ km s}^{-1}$ present the intrinsic kinematic property also found in GHIIRs. There is a small systematic difference between σ derived from both ions, $\langle \sigma_{\text{H}} - \sigma_{[\text{OIII}]} \rangle = 1 - 2 \text{ km s}^{-1}$. It seems to be a special consequence of coupled kinematic and physical conditions in these systems. A possible explanation would be the existence of a well behaved ionization structure, in which more excited ions are concentrated closer to the ionizing sources and densest regions. However a gradient of velocity dispersion is not observed at scales of tens to hundreds of parsecs in giant HII regions. Other kinematic mechanisms that can be invoked to account for the observed systematic difference can be associated with turbulence. (Hippelein 1986).

We note that many HIIGs presented in Figure 13 (right panel) are in fact those classified

as Gaussian line profiles (open circles). It is another indication that these systems define a homogeneous sample in terms of their internal kinematics. Although our sample presents few galaxies with both measurements in high σ regime, Figure 13 (left panel) suggests that HIIGs with $\sigma > 60 \text{ km s}^{-1}$ do not seem to share the same kinematic properties as the ones with $\sigma < 60 \text{ km s}^{-1}$.

5.2. Age Effects: Short- and Long-Term Evolution

We have been shown that the age effect (short-term evolution) is the first order effect over $L-\sigma$ relation and should not be neglected explicitly in a empirical relation in order to derive a distance indicator. Here we have tested $W_{\text{H}\beta}$ and [OIII]/[OII] as fiducial chronometers of the starburst. Both are virtually equally efficient in order to explain the scatter in $L-\sigma$ plane. In order to reduce the scatter due to an age effect, one does not need a parameter that measure the burst age, but that measures efficiently the luminosity variation of the starburst as it ages. Photoionized models have shown that the most robust parameter to measure the luminosity evolution of the starburst is in fact the $W_{\text{H}\beta}$ (Stasińska & Leitherer 1996; Martín-Manjón et al. 2008). Its advantage is due to its weak dependence on the metallicity. [OIII]/[OII] and $W_{[\text{OIII}]\text{5007}}$ are more sensitive to metallicity. Figure 14 shows the predictions from photoionized models by Stasińska & Leitherer (1996) for $\text{H}\beta$ luminosity evolution of the starburst as a function of $W_{\text{H}\beta}$ (panels b and d) and [OIII]/[OII] (panels a and c), for a given starburst mass of $10^6 M_\odot$ and two metallicities $12+\log(\text{O/H})=7.93$ (panels a and b) and 8.33 (c and d). It is possible to see that $L(W_{\text{H}\beta})$ presents nearly constant curve shape in both abundance sets, whereas $L([\text{OIII}]/[\text{OII}])$ does not present a monotonic curve in $12+\log(\text{O/H})=8.33$ set, especially in the first 5 Myrs of the starburst. Note that $L(W_{\text{H}\beta})$ still presents a more stable curve for $\log W_{\text{H}\beta} > 1.5$ or $\sim 30\text{\AA}$. Models considering the continuous burst scenario have shown that $W_{\text{H}\beta}$ is in fact a robust age indicator of the starburst even for a significant presence of an underlying stellar population (Martín-Manjón et al. 2008).

Metallicity itself is also a tracer of the evolution, though it is more closely linked to the long-term history of the star formation of the galaxy. The metallicity given by O/H ratio, as proposed by MTM, may represent a second parameter in $L-\sigma$ relation, since successive chemical enrichment promoted by generations of stars may affect globally the luminosity evolution (short-term) of each starburst.

One last point we would like to mention is about the possible application of the empirical relationships found here for the local sample of HIIGs as distance indicators of galaxies at high redshifts. If the star formation mechanism has been preserved from early HIIGs to the local ones, and if we were able find distant counterpart of the local HIIGs, both systematic

effects identified here over $L-\sigma$ relation, i.e. age and metallicity, would lose relevance with look-back time. Distant HIIGs may be more metal poor in average and should present a simpler star formation history. Not many older stellar populations would be present and they would affect more similarly the stellar continuum. They should represent a population of galaxies with a narrower range in metallicity, and the Malmquist Bias would allow us only detect the youngest starbursts within a narrow range of ages. In idealized conditions, one should only be able to select galaxies in the upper envelope of the $L-\sigma$ relation with a minimum scatter. Assuming that the $L-\sigma$ relation is valid for primordial HIIGs, we can see that the look-back time has a positive role with regard to the applicability of this relation as a distance indicator, since the systematic effects should be reduced with the cosmic time. This is remarkably different from what occurs with the Tully-Fisher and $D_n-\sigma$ relations, or even SNe Ia distance modulus method.

6. Summary

- (i) The family of HIIGs does not represent a homogeneous sample in terms of their internal kinematics. Gaussianity of their emission line profiles is closely related to the physical origin of the $L-\sigma$ relation, since galaxies showing the most Gaussian line profiles seem to produce a steeper $L \propto \sigma^4$ relation with the least scatter ($\delta \log L_{\text{H}\alpha} = 0.30$). These objects represent a more homogeneous class in terms of kinematics and define the key property of the HII galaxies targets of the $L-\sigma$ relation. These objects also seem to suffer less from the aperture effect.
- (ii) The $L-\sigma$ relation is simultaneously affected by the short- and the long-term evolution of the starburst. Both effects can be simultaneously accounted to predict Balmer luminosity in a functional form in order to obtain a more accurate distance indicator. Here we have quantified the contribution of $\text{H}\beta$ equivalent width and the ionization parameter $[\text{OIII}]\lambda\lambda 5007, 4959/[\text{OII}]\lambda 3727$ as measures of short-term evolution and O/H as measures the long-term evolution.
- (iii) We calibrated the $L-\sigma$ -O/H empirical relation, previously presented by MTM as the distance indicator of the HIIGs and provided an alternative set of new empirical relations that can be used alternatively, with greater accuracy ($\delta \log L_{\text{H}\alpha} = 0.20$) and simplicity, to determine distances of HII galaxies at high redshifts with interests cosmological.
- (iv) HII galaxies reveal to be ideal objects to be used as extragalactic distance estimators based on $L-\sigma$ relation. All systematic effects that hinder the use of classical Tully-Fisher and $D_n-\sigma$ estimators seem to have decreasing importance for HIIGs with the look-back time.

This is mainly because HIIGs seem to be relics that most resemble the primordial galaxies abundant in the early Universe (Phillips et al. 1997; Guzman et al. 1997; Pettini et al. 2001; Erb et al. 2003).

REFERENCES

- Arsenault, R. & Roy, J.-R. 1988, A&A, 201, 199
- Bordalo, V., Plana, H., & Telles, E. 2009, ApJ, 696, 1668
- Bosch, G., Terlevich, E., & Terlevich, R. 2002, MNRAS, 329, 481
- Brosche, P. 1973, A&A, 23, 259
- Bujarrabal, V., Guibert, J., & Balkowski, C. 1981, A&A, 104, 1
- Campbell, A., Terlevich, R., & Melnick, J. 1986, MNRAS, 223, 811
- Chu, Y.-H. & Kennicutt, Jr., R. C. 1994, ApJ, 425, 720
- Cohen, J., Cohen, P., West, S. G., & S., A. L. 2003, Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences (Third Edition), ed. LEA
- Coziol, R., Demers, S., Pena, M., Torres-Peimbert, S., Fontaine, G., Wesemael, F., & Lamontagne, R. 1993, AJ, 105, 35
- Denicoló, G., Terlevich, R., & Terlevich, E. 2002, MNRAS, 330, 69
- Drosg, M. 2007, Dealing with Uncertainties, ed. Springer
- Erb, D. K., Shapley, A. E., Steidel, C. C., Pettini, M., Adelberger, K. L., Hunt, M. P., Moorwood, A. F. M., & Cuby, J.-G. 2003, ApJ, 591, 101
- Fairall, A. P. 1980, MNRAS, 191, 391
- François, P. 1999, Fiber Extended Range Optical Spectrograph User's Manual
- Fuentes-Masip, O., Muñoz-Tuñón, C., Castañeda, H. O., & Tenorio-Tagle, G. 2000, AJ, 120, 752
- García-Díaz, M. T., Henney, W. J., López, J. A., & Doi, T. 2008, Revista Mexicana de Astronomía y Astrofísica, 44, 181

- Guzman, R., Gallego, J., Koo, D. C., Phillips, A. C., Lowenthal, J. D., Faber, S. M., Illingworth, G. D., & Vogt, N. P. 1997, *ApJ*, 489, 559
- Hippelein, H. H. 1986, *A&A*, 160, 374
- Hoyos, C. & Díaz, A. I. 2006, *MNRAS*, 365, 454
- Isobe, T., Feigelson, E. D., Akritas, M. G., & Babu, G. J. 1990, *ApJ*, 364, 104
- Izotov, Y. I., Chaffee, F. H., & Green, R. F. 2001, *ApJ*, 562, 727
- Izotov, Y. I. & Thuan, T. X. 1998, *ApJ*, 500, 188
- Jolliffe, I. T. 2002, *Principle Component Analysis* (Second Edition), ed. Springer
- Kehrig, C., Telles, E., & Cuisinier, F. 2004, *AJ*, 128, 1141
- Kehrig, C., Vílchez, J. M., Sánchez, S. F., Telles, E., Pérez-Montero, E., & Martín-Gordón, D. 2008, *A&A*, 477, 813
- Kewley, L. J., Jansen, R. A., & Geller, M. J. 2005, *PASP*, 117, 227
- Kniazev, A. Y., Pustilnik, S. A., Grebel, E. K., Lee, H., & Pramskij, A. G. 2004, *ApJS*, 153, 429
- Kniazev, A. Y., Pustilnik, S. A., Ugryumov, A. V., & Pramsky, A. G. 2001, *A&A*, 371, 404
- Kunth, D., Sargent, W. L. W., & Kowal, C. 1981, *A&AS*, 44, 229
- Lequeux, J., Peimbert, M., Rayo, J. F., Serrano, A., & Torres-Peimbert, S. 1979, *A&A*, 80, 155
- Lowenthal, J. D., Koo, D. C., Simard, L., & van Kampen, E. 2009, ArXiv e-prints
- MacAlpine, G. M., Smith, S. B., & Lewis, D. W. 1977, *ApJS*, 34, 95
- Markarian, B. E. 1967, *Astrofizika*, 3, 55
- Martín-Manjón, M. L., Mollá, M., Díaz, A. I., & Terlevich, R. 2008, *MNRAS*, 385, 854
- Mas-Hesse, J. M. & Kunth, D. 1999, *A&A*, 349, 765
- Masegosa, J., Moles, M., & Campos-Aguilar, A. 1994, *ApJ*, 420, 576
- Maza, J., Ruiz, M. T., Gonzalez, L. E., Wischnjewsky, M., & Pena, M. 1991, *A&AS*, 89, 389

- Melnick, J. 1977, ApJ, 213, 15
- . 1978, A&A, 70, 157
- . 1979, ApJ, 228, 112
- Melnick, J. 2003, in Astronomical Society of the Pacific Conference Series, Vol. 297, Star Formation Through Time, ed. E. Perez, R. M. Gonzalez Delgado, & G. Tenorio-Tagle, 3–+
- Melnick, J., Moles, M., Terlevich, R., & Garcia-Pelayo, J.-M. 1987, MNRAS, 226, 849
- Melnick, J., Tenorio-Tagle, G., & Terlevich, R. 1999, MNRAS, 302, 677
- Melnick, J., Terlevich, R., & Moles, M. 1988, MNRAS, 235, 297
- Melnick, J., Terlevich, R., & Terlevich, E. 2000, MNRAS, 311, 629
- Miesch, M. S., Scalo, J., & Bally, J. 1999, ApJ, 524, 895
- Pagel, B. E. J., Simonson, E. A., Terlevich, R. J., & Edmunds, M. G. 1992, MNRAS, 255, 325
- Papaderos, P., Guseva, N. G., Izotov, Y. I., Noeske, K. G., Thuan, T. X., & Fricke, K. J. 2006, A&A, 457, 45
- Pena, M., Ruiz, M. T., & Maza, J. 1991, A&A, 251, 417
- Pettini, M., Shapley, A. E., Steidel, C. C., Cuby, J.-G., Dickinson, M., Moorwood, A. F. M., Adelberger, K. L., & Giavalisco, M. 2001, ApJ, 554, 981
- Phillips, A. C., Guzmán, R., Gallego, J., Koo, D. C., Lowenthal, J. D., Vogt, N. P., Faber, S. M., & Illingworth, G. D. 1997, ApJ, 489, 543
- Pilyugin, L. S. 2000, A&A, 362, 325
- Plionis, M., Terlevich, R., Basilakos, S., Bresolin, F., Terlevich, E., Melnick, J., & Georganopoulos, I. 2009, ArXiv e-prints
- Pustilnik, S. A., Kniazev, A. Y., Masegosa, J., Márquez, I. M., Pramskij, A. G., & Uglyumov, A. V. 2002, A&A, 389, 779
- Rozas, M., Richer, M. G., López, J. A., Relaño, M., & Beckman, J. E. 2006, A&A, 455, 539
- Sage, L. J., Welch, G. A., & Young, L. M. 2007, ApJ, 657, 232

- Salzer, J. J., Lee, J. C., Melbourne, J., Hinz, J. L., Alonso-Herrero, A., & Jangren, A. 2005, ApJ, 624, 661
- Scalo, J. & Chappell, D. 1999, MNRAS, 310, 1
- Shaw, R. A. & Dufour, R. J. 1995, PASP, 107, 896
- Shi, F., Kong, X., Li, C., & Cheng, F. Z. 2005, A&A, 437, 849
- Siegel, E. R., Guzmán, R., Gallego, J. P., Orduña López, M., & Rodríguez Hidalgo, P. 2005, MNRAS, 356, 1117
- Smith, M. G., Aguirre, C., & Zemelman, M. 1976, ApJS, 32, 217
- Stasińska, G. & Izotov, Y. 2003, A&A, 397, 71
- Stasińska, G. & Leitherer, C. 1996, ApJS, 107, 661
- Surace, C. & Comte, G. 1998, A&AS, 133, 171
- Telles, E., Muñoz-Tuñón, C., & Tenorio-Tagle, G. 2001, ApJ, 548, 671
- Telles, E. & Terlevich, R. 1993, Ap&SS, 205, 49
- Tenorio-Tagle, G., Muñoz-Tuñón, C., Pérez, E., Silich, S., & Telles, E. 2006, ApJ, 643, 186
- Tenorio-Tagle, G., Munoz-Tunon, C., & Cox, D. P. 1993, ApJ, 418, 767
- Terlevich, R. & Melnick, J. 1981, MNRAS, 195, 839
- Terlevich, R., Melnick, J., Masegosa, J., Moles, M., & Copetti, M. V. F. 1991, A&AS, 91, 285
- Terlevich, R., Silich, S., Rosa-González, D., & Terlevich, E. 2004, MNRAS, 348, 1191
- van Zee, L., Salzer, J. J., Haynes, M. P., O'Donoghue, A. A., & Balonek, T. J. 1998, AJ, 116, 2805
- Vílchez, J. M. & Iglesias-Páramo, J. 2003, ApJS, 145, 225
- White, R. L., Becker, R. H., Helfand, D. J., & Gregg, M. D. 1997, ApJ, 475, 479
- Whitford, A. E. 1958, AJ, 63, 201
- Zwicky, F., Herzog, E., & Wild, P. 1966, Catalogue of galaxies and of clusters of galaxies, Vol. 3, ed. F. Zwicky, E. Herzog, & P. Wild

A. Detecting Outliers and Measuring Multicollinearity

In Section 4.4 we derived a new set of empirical relations for a homogeneous sample of HIIGs by multiple linear regressions that can be used as distance estimators. Here we show the procedure used to detect 8 outliers that were deleted from the initial sample with 53 G objects in order to find a robust set of regression coefficients. The use of good statistics presumes that any cause of discrepancy eliminated from the data set should be documented and investigated, taking into account the history of the data point. That is what we do below. In what follows we evaluate the degree of multicollinearity of all regression models based on appropriate statistical measurements.

Outliers are those data points in a set that do not fall within the rest of the data, that agree with the model in use (Drosg 2007). If there is an outlier there are four possibilities in our context: (i) the model is wrong, after all the theory is the basis on which we decide whether a data point is an outlier or not; (ii) the value of the data point is wrong because of a failure of the apparatus or human mistake, which means here photometric errors in general propagated to derived parameters including assumptions to derive O/H; (iii) the data point refers to an object that does not share the same physical properties as the whole sample; (iv) the data point might not be an actual outlier, but part of a legitimate statistical fluctuation. All these possibilities should be considered.

A specialized statistics used to detect outliers in the context of multiple regressions is through the computation of leverage, discrepancy (studentized residual)⁹ and influence indexes (Cook's D)¹⁰. Conceptually, influence represents the product of leverage and discrepancy. These are known as the three characteristics of potentially errant data points (see Cohen et al. 2003, for a didactic presentation and concepts).

Figure 15 shows a set of index plots that will be described in sequence. Each of these indexes can help us identify different aspects of errant data points. Left plots (a, c and f) present the leverage, studentized residuals and Cook's D indexes obtained from regression $L_{H\alpha}-\sigma_H-O/H-W_{H\beta}$ (R1), whereas right plots (b, d and f) present the same index plots from regression $L_{H\alpha}-\sigma_H-O/H-[OIII]/[OIII]$ (R2). Thus all values for 53 objects are analyzed as potential source of “error” that can lead us to identify a galaxy as an outlier.

Leverage measures how unusual is the case (given galaxy) in terms of its values on the

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⁹Also called “Externally Studentized Residual” our “Studentized Deleted Residual”.

¹⁰DFFITS is another global measure of influence very closely related to Cook's D .

independent variables, i.e. σ_H , O/H and $W_{H\beta}$ for R1 and σ_H , O/H and [OIII]/[OII] for R2. It measures how far case i 's score, on each of the independent variables, is from the centroid of the independent variables. MRK 1201 (N°19) is first detected as a possible outlier (Figure 15a and b). This galaxy is very peculiar. Their [OIII] $\lambda\lambda 4959,5007$ lines are very weak (T91, KTC) and were not detected in FEROS spectrum. The derived abundance is an extreme one, $12 + \log(O/H) = 9.36$ based on p-method. This value is higher than the most metal rich HII regions used by Plyugin in his empirical calibration for high-abundance branch $12+\log(O/H)_{P2} > 8.15$ (see Section 3.2) and may be uncertain. It is classified in NED as a galaxy pair and was also detected as a radio source (White et al. 1997). Certainly this galaxy represents an outlier in our regression models. Note that high leverage values are not necessarily associated to an outlier. In fact, extreme cases can also stabilize the regression line and decrease the standard deviations of both the slope and intercept. But a close look at the global properties of MRK 1201 has shown that it does not represent a normal HIIG and can not be considered in a homogeneous calibration sample.

Figure 15c and d show the studentized residuals t_i for both R1 and R2, respectively. This index measures the discrepancy, i.e. the distance between the predicted $\hat{L}_{H\alpha}$ and observed values on $L_{H\alpha}$. It is very similar to the raw residuals ($e_i = Y_i - \hat{Y}_i$) but it computes the difference between the original L observation for case i and the predicted value for case i based on the data set with case i deleted. Thus it is used to identify cases whose observed values are highly discrepant from their predicted values. Objects for which there are large gaps in the value of this index (ignoring sign) from the reminder of the cases merit particular attention. We found eight discrepant objects if we choose a cutoff value of $t_c \pm 1.5$, including early mentioned MRK 1201. Tol 2138-397 (N°52) was also considered discrepant in R1 because of its t value of -1.49 is very close to t_c and it met the cutoff value in R2. The nature of MRK 1318 (N°37) is uncertain since it is also classified as an elliptical peculiar (Sage et al. 2007). In addition, oxygen abundance derived here by T_e -method based on KTC data is greater (8.27) than the one found by Shi et al. (2005) (8.12). We derived an unusual low T_e value 1.01×10^4 K which may be responsible for the high O/H ratio found here. UM 559 by its turn presents an unusual high value of $W_{H\beta} = 535\text{\AA}$. T91 and Papaderos et al. (2006) found 323\AA and 293\AA , respectively. These values are in agreement with the aperture namely UM559(giant E-RHII) by KTC with $W_{H\beta} = 262\text{\AA}$, but data from this aperture were not used here.

Tol 1008-286 (N°22) and UM 463 (N°36) were also detected as possible outliers in Figure 15c and d. They had their physical conditions gathered from different sources and thus they do not present a homogeneous set of data (see Table 3). At last, UM 417 (N°10), Tol 0505-387 (N°13) and Tol 2138-397 (N°52) present very low continuum and line S/N in KTC's spectra. Since linear regressions without weighting were obtained, very large photometric

errors due to low S/N spectra can introduce an additional scatter not well accounted to derive here the best fits.

Figure 15e and f show the Cook’s D influence index plots from R1 and R2. The galaxies discussed as potential outliers are labeled in these plots near their respective Cook’s D values as red color dots. Cook’s D is a global measures of influence, i.e. it combines information from leverage and discrepancy to inform us about the amount that the regression coefficients would change if the outlier were removed from the data set. It is always ≥ 0 . The greater the value the more influential is the data point. Note that almost all galaxies detected as outliers using studentized residuals index are also the ones that present the highest Cook’s D values. Thus Cook’s D values confirm these galaxies as being potentially influential. UM 461 (N°35) presents also a relative high Cook’s D value in both regressions but in this case the high values are expected since this galaxy present an extreme low σ value (12.5 km s^{-1}) and has a significant influence to stabilize the regressions and it should not be considered an outlier.

Given the necessity to suppress the uncertainties in the calibration of the $L-\sigma$ relation and evaluate precisely its sensitivity to systematic effects, such as age and metallicity found here, one should obtain “true” homogeneous sample and “real” good data. Raw data set without a careful previous statistical analysis can result in regression models that may not reduce significantly the scatter or show the real sensitivity of $L-\sigma$ relation to other independent parameters. The regression diagnostics presented here should be used in the future to filter larger raw data sets. We argue that a careful program to observe HIIGs aimed to minimize observational errors and select a complete and homogeneous sample should result in a data set that can provide a powerful extragalactic distance estimator based on regression models presented in Table 10.

Table 11 presents the PCA applied to the calibration sample with 45 objects. We show that the global result does not change and the interpretations presented in Section 4.4 are valid, but the residual variances in PCIII were greatly reduced from 4.2-4.5% to 1.6-1.7%. This is in fact due to the homogeneity of the calibration sample (only galaxies with Gaussian profiles) and the absence of outliers. It shows how robust is the PCA technique applied to our data.

Another statistical problem that we should worry about in order to evaluate the precision of an empirical regression model is multicollinearity. In multiple regression, its assumed that each independent variable can potentially add to the prediction of the dependent variable Y . However, as one of the independent variables, X_i , becomes increasingly correlated with the set of other independent variables in the regression equation, X_i will have less and less unique information that it can potentially contribute to the prediction of Y . The indi-

vidual regression coefficients can change appreciably in magnitude and even in sign, making such coefficient difficult to interpret. As the predictors become increasingly correlated, the estimate of the individual regression coefficient also becomes more and more unreliable, a problem that reflects in large standard errors.

There are some indexes which can be used to measure the degree of multicollinearity in a set of independent variables. Here we used the condition number¹¹, cn , based on PCA technique. A correlation matrix containing only the set of independent variables is decomposed into a set of orthogonal dimensions. Condition number is defined as $cn = \sqrt{l_{\max}/l_{\min}}$, where l_{\max} and l_{\min} are the maximum and minimum eigenvalues of a correlation matrix, respectively. If all independent variables are uncorrelated, each eigenvalue will equal 1.0, so that each independent dimension will account for $1/p$ of the total variance, where p is the number of independent variables. As independent variables become increasingly correlated, more and more of the variance in the independent variables is associated with the first dimension, so that the value of the first eigenvalue (l_{\max}) will become larger and the value of the last (l_{\min}) will become smaller. Table 12 presents l_{\max} , l_{\min} and cn for each regression model for the calibration sample (45 objects). Firstly, we should mention that even the highest values for cn are considered small in magnitude, posing no very high degree of multicollinearity in any regression models. However, the results for regressions with two independent parameters show that the lowest degree of collinearity occurs in regression $L-\sigma-W_{H\beta}$, $cn = 1.02$, and the highest, $cn = 1.66$, in regression $L-\sigma-O/H$. R1 and R2 present similar cn values, 2.91 and 2.74, respectively. It is expected that both R1 and R2 present relatively higher cn than the other regression models with two independent parameters, since O/H and [OIII]/[OII] ($r = -0.70$) and O/H and $W_{H\beta}$ ($r = -0.65$) are the independent variable pairs more strongly correlated. However, both represent viable regression models to derive the distance indicators if one can measure all parameters.

¹¹The letter κ is more frequently used to denote the condition number but here we used cn in order not to be confused with the kurtosis denoted by κ and presented in Section 4.2.

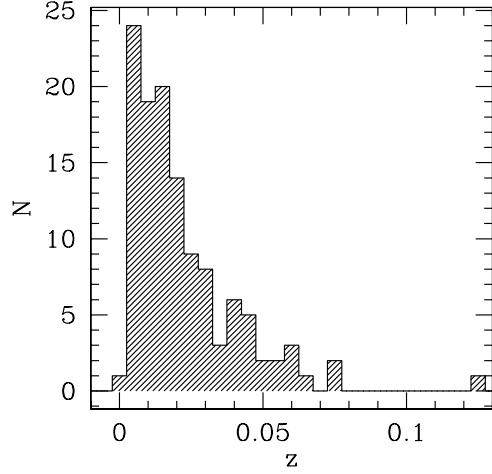


Fig. 1.— The redshift distribution of our sample containing 120 objects. The mean of the distribution is 0.0222, whereas the median is 0.0167.

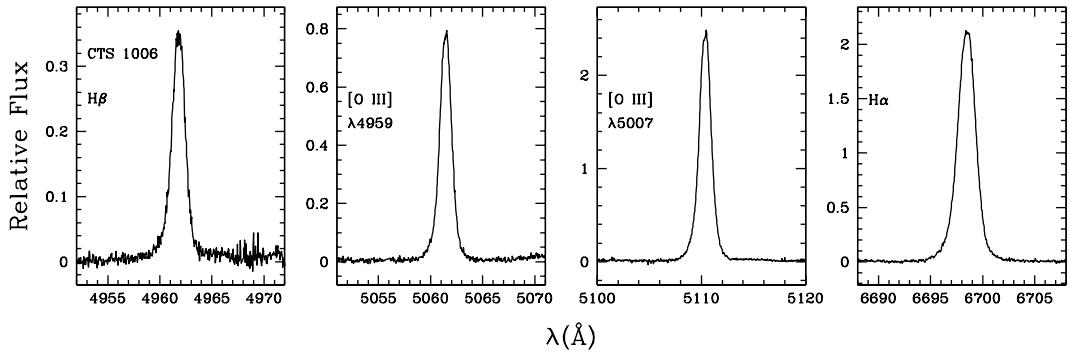


Fig. 2.— Optical wavelength calibrated spectrum of CTS 1006 obtained with FEROS spectrograph. FEROS is an optical echelle spectrograph covering a wide range in wavelength, thus the most intense lines are shown in separated boxes.

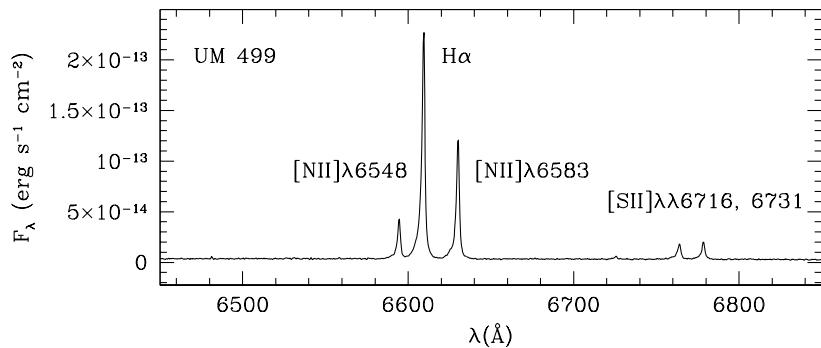


Fig. 3.— Optical calibrated spectrum of UM 499 obtained with Coudé spectrograph.

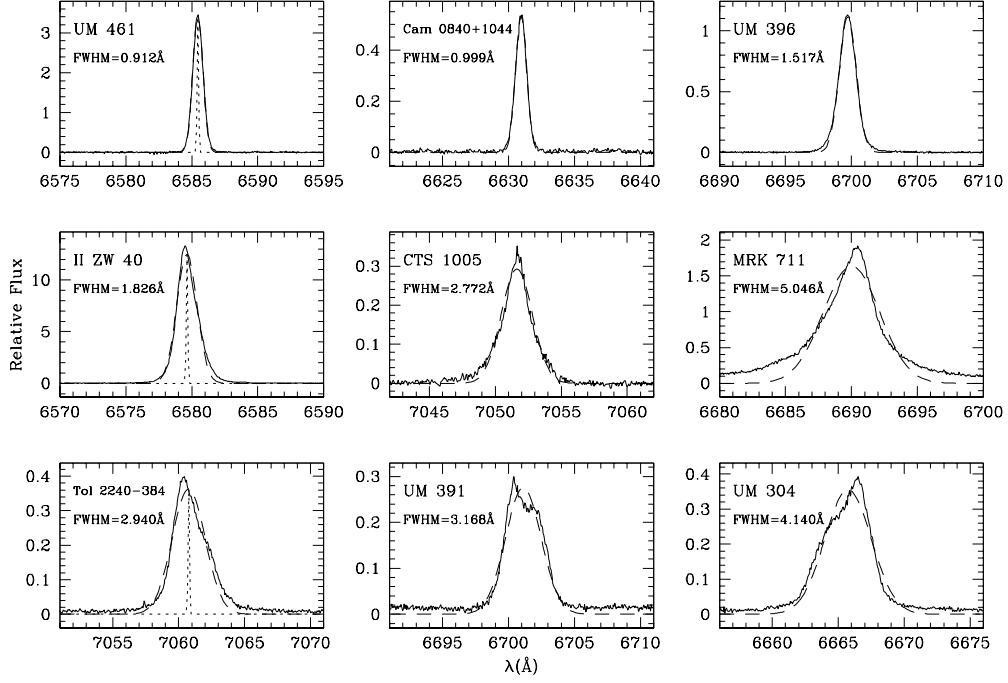


Fig. 4.— Examples of the three classes of line profiles visually identified. (*first row*) Galaxies with nearly Gaussian profiles; (*second row*) galaxies with irregular profiles; (*third row*) galaxies with lines profiles clearly showing components. The dotted narrow lines in all left boxes represent the FEROS instrumental profile, $\sigma_{\text{inst}} = 2.50 \text{ km s}^{-1}$. The dashed lines represent single Gaussian fits to the observed profiles.

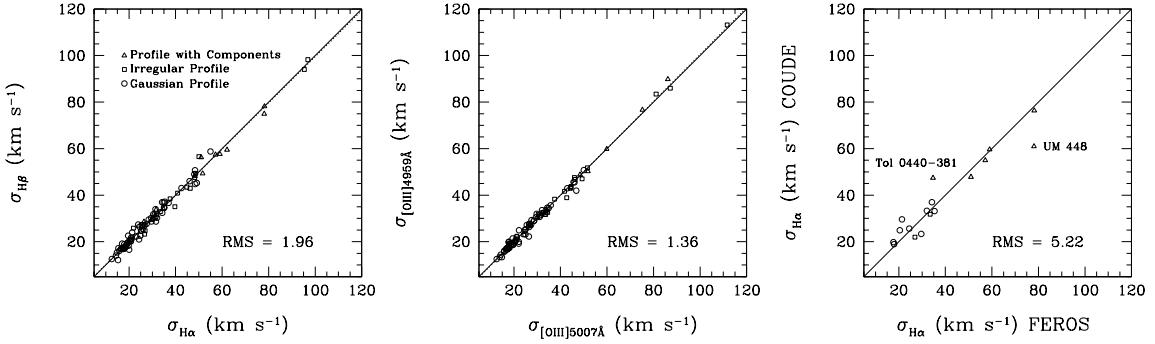


Fig. 5.— (*left*) Testing the consistency of measurements between σ derived from $\text{H}\alpha$ and $\text{H}\beta$ (FEROS); (*center*) $\sigma_{[\text{OIII}]5007\text{\AA}}$ and $\sigma_{[\text{OIII}]4959\text{\AA}}$; (*right*) $\text{H}\alpha$ from FEROS (x) and Coudé (y). Tol 0440-381 and UM 448 noted in the right plot present the most discrepant measurements possibly due to different position covered by observations.

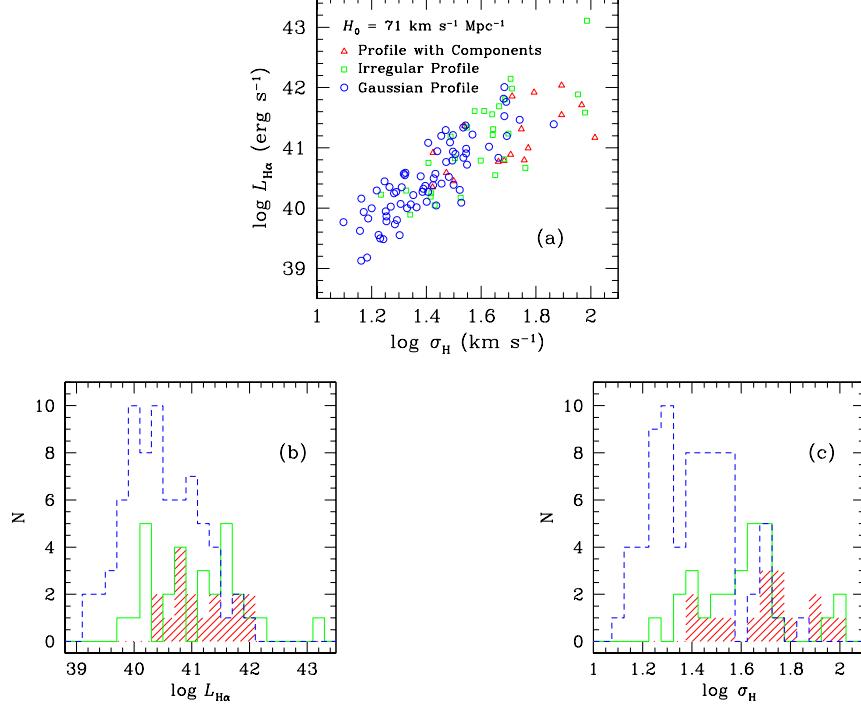


Fig. 6.— (a) The $L_{\text{H}\alpha}$ - σ_{H} for 118 galaxies with spectrophotometry obtained; (b) the luminosity distribution; and (c) the velocity dispersion distribution. The color codded for each class o galaxy, (G,I and C) respect the label presented in plot (a). The Hubble Constant was $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

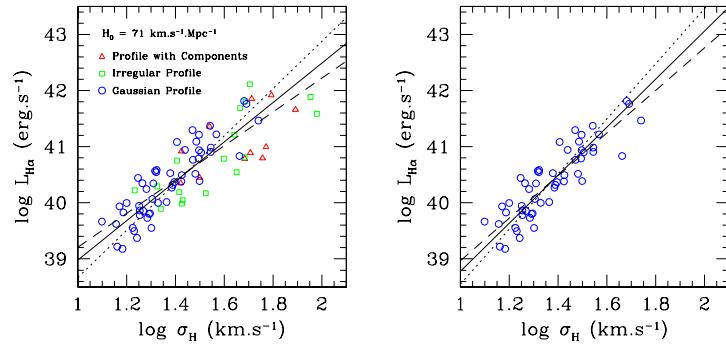


Fig. 7.— The $L_{\text{H}\alpha}$ - σ_{H} relation for all galaxies with homogeneous spectrophotometry (81 objects G, I and C, *left*) and only for those showing regular Gaussian profiles (53 objects G, *right*). The dashed line represents OLS(Y|X), the dotted line represents OLS(X|Y) and the solid line represents the bisector fit. All regression coefficients are presented in Table 6. The Hubble Constant was $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

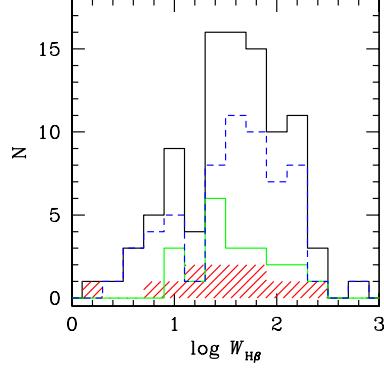


Fig. 8.— The $\text{H}\beta$ equivalent width distributions (in log) for each class of galaxies namely G (53), I (17) and C (11) presented in Figure 7.

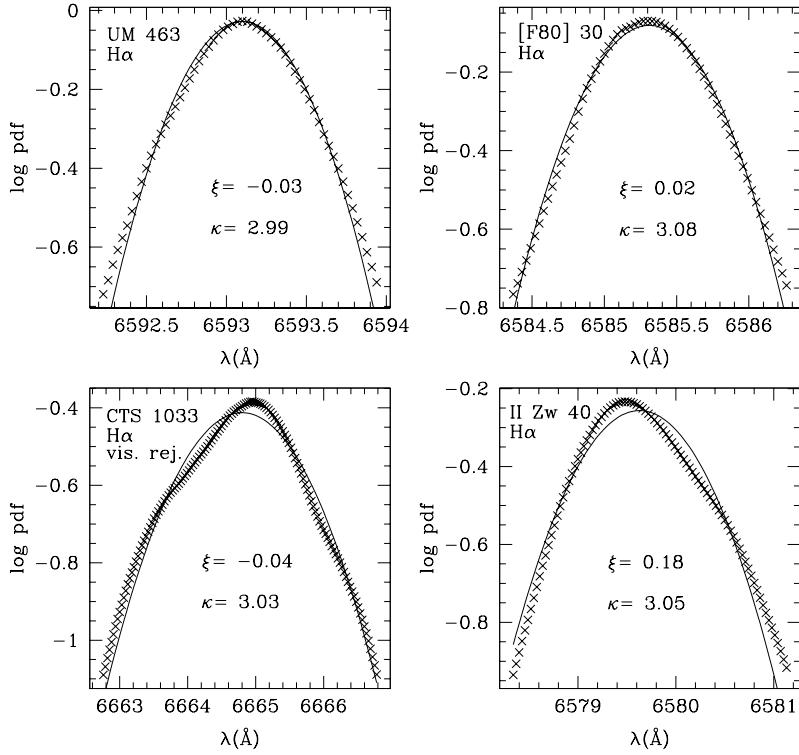


Fig. 9.— Examples of emission line profiles in linear-logarithmic axes. UM 463 (upper left) and [F80] 30 (upper right) met the criterium of symmetry described in the text (G'), (bottom left) CTS 1033 was qualitatively visually rejected by presenting multiple components and (bottom right) II Zw 40 does not met the symmetry criterium. Measurements of ξ and κ estimators shown in each panel. Solid lines represent single Gaussian fits to the observed profiles (crosses).

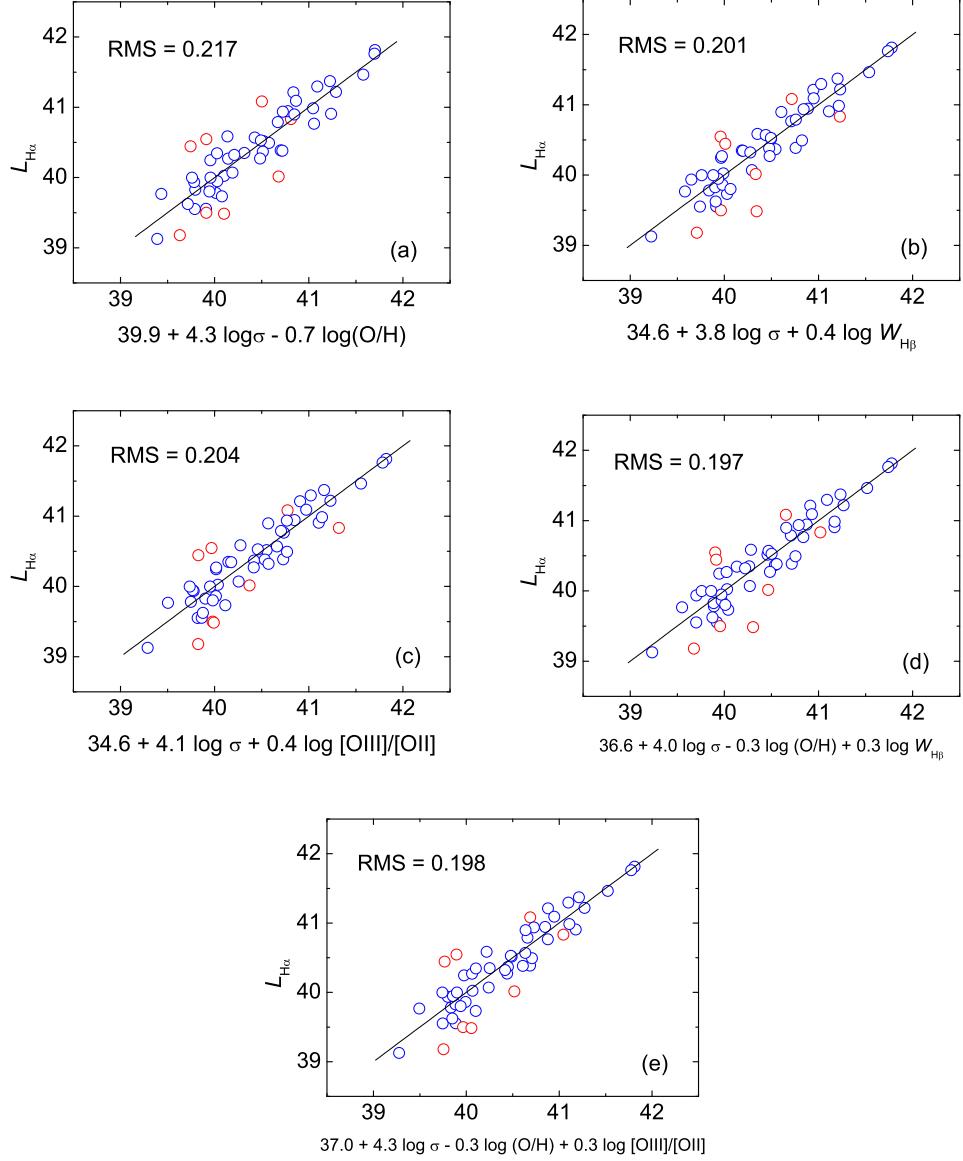


Fig. 10.— Regression models plotted against observed $\text{H}\alpha$ luminosities for 53 objects. The functional forms are presented in x axis of each graph. The solid lines represent the 1 to 1 lines fitted to the data. The calibration galaxies are plotted as open blue circles, whereas the outliers are plotted as open red circles.

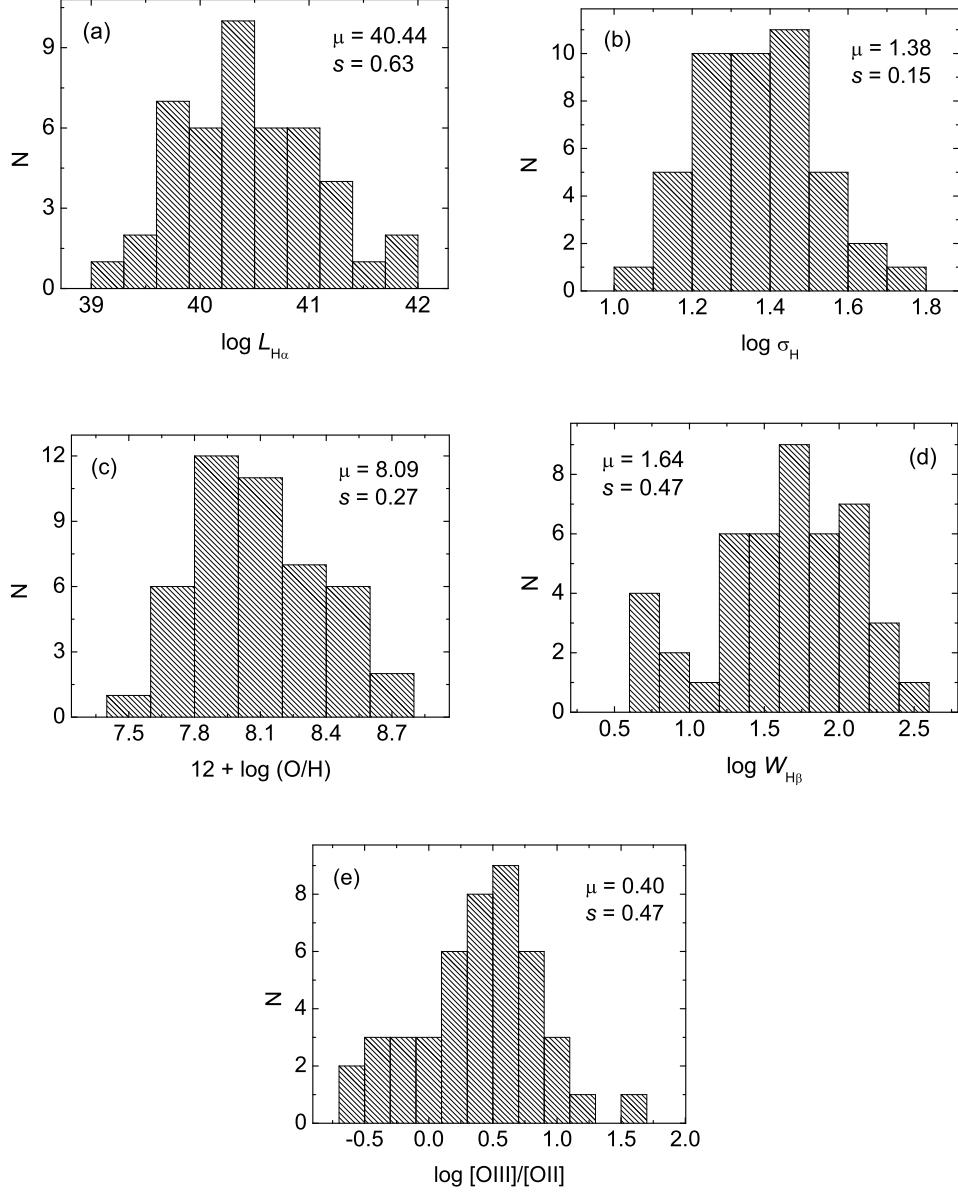


Fig. 11.— Histograms for all parameters in calibration sample (45 objects) in logarithmic units. Mean (μ) and standard deviations (s) of the distributions are shown in each plot.

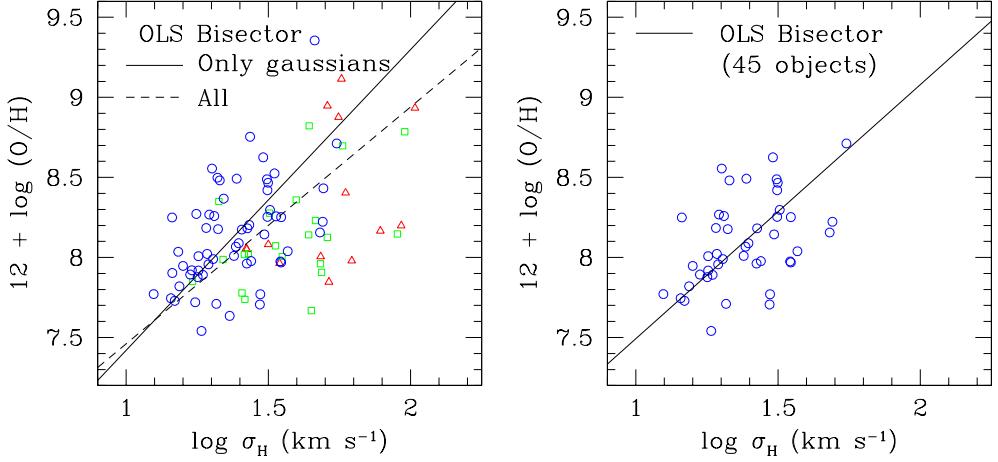


Fig. 12.— (*left panel*) The σ - Z relation presented by 95 objects included in PCA. The solid and dashed lines represent the OLS bisector fits to the entire sample, $12 + \log(O/H) = (5.98 \pm 0.19) + (1.48 \pm 0.14) \log \sigma_H$, and to the G sample, $12 + \log(O/H) = (5.54 \pm 0.34) + (1.88 \pm 0.26) \log \sigma_H$, 60 objects), respectively. (*right panel*) The σ - Z relation for the 45 objects used in calibration sample without outliers (Table 10). The solid line represents the OLS bisector fit, $12 + \log(O/H) = (5.91 \pm 0.23) + (1.59 \pm 0.17) \log \sigma_H$.

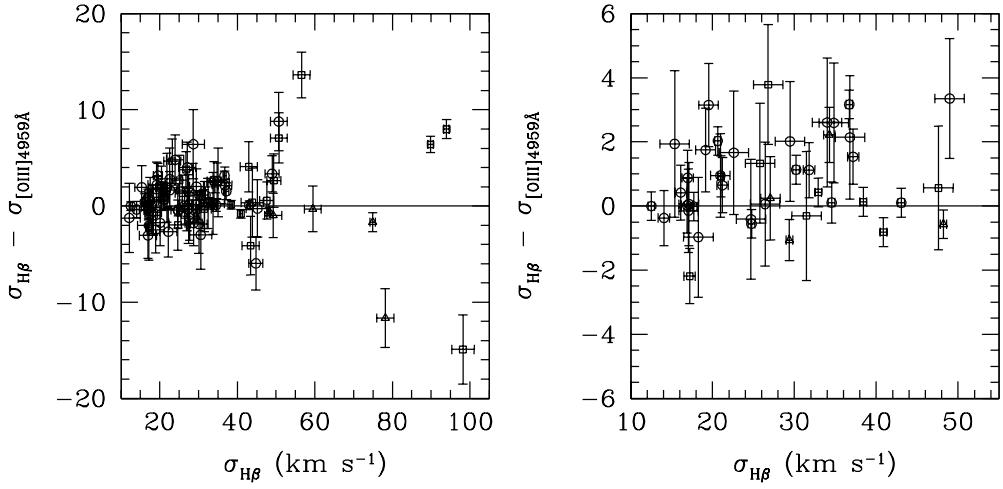


Fig. 13.— Comparison between σ derived from $H\beta$ and $[\text{OIII}]\lambda 4959$. (*left panel*) All galaxies included. (*right panel*) Only galaxies presenting $\delta\sigma < 2 \text{ km s}^{-1}$. A small systematic difference $\sigma_H - \sigma_{[\text{OIII}]} = 1 - 2 \text{ km s}^{-1}$ is verified for galaxies with $\sigma \lesssim 60 \text{ km s}^{-1}$.

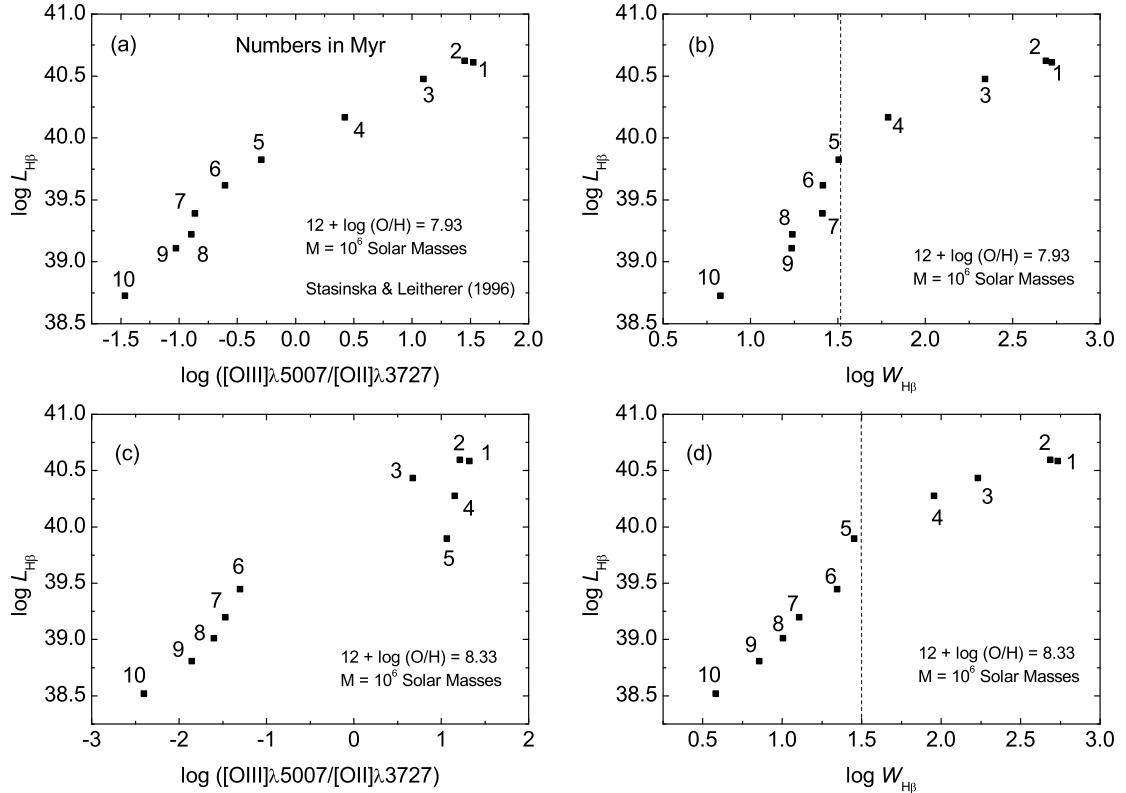


Fig. 14.— $\text{H}\beta$ luminosity as a function of the $[\text{OIII}]\lambda 5007/\text{[OII}]\lambda 3727$ (a and c panels) and $\text{H}\beta$ equivalent width (b and d) in logarithmic units as predicted by single stellar population models by Stasińska & Leitherer (1996) with $M = 10^6 M_\odot$ and two metallicities, $12 + \log (\text{O/H}) = 7.93$ (a and b panels) and 8.33 (c and d panels). Numbers indicate the age of the starburst in Myr. Vertical dotted lines in panels b and d indicate the cutoff value $W_{\text{H}\beta} \sim 30 \text{\AA}$ which coincides with age ~ 5 Myr of the starburst in both models.

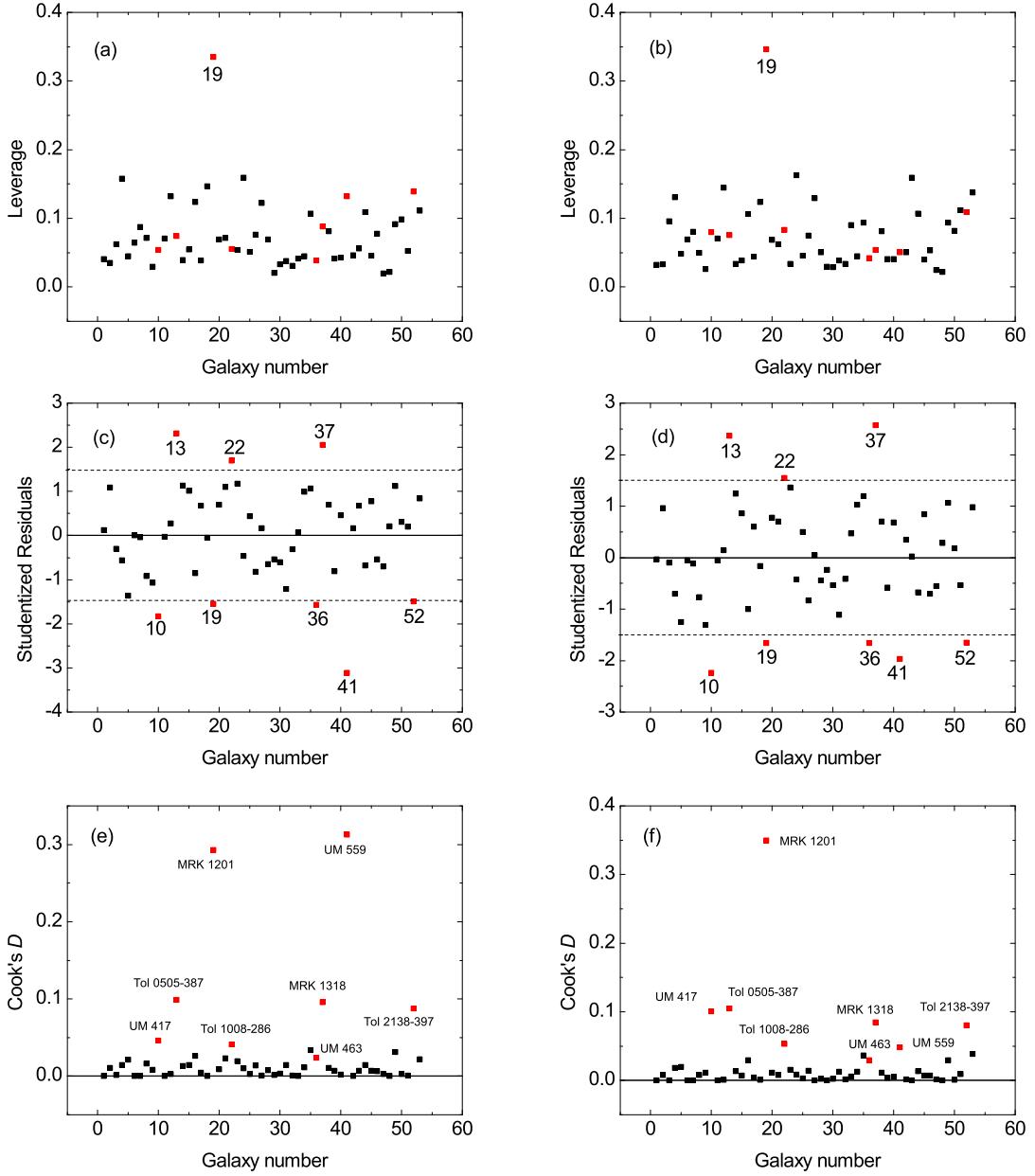


Fig. 15.— Indexes plots for regression diagnostics: (a), (c) and (e) show leverage, studentized residuals and Cook's D indexes plots for R1; (b), (d) and (f) show the same plots for R2. The name of objects considered as outliers in both regressions are shown in (e) and (f). The objects are numbered in RA order from 1 to 53.

Table 1: Journal of observations.

Galaxy	α (2000)	δ (2000)	Total Exp. Time (s)	Number of Exp.	Coudé Detector (CCD)	Obs. Date	Total Exp. Time (s)	FEROS Number of Exp.	Obs. Date	Other Name
UM 238	00h24m42.3s	+01d44m02s					3600	1	21/07/2001	MRK 557
MBG 00463-0239	00h48m53.2s	-02d22m55s	3600	3	106	13/09/1998	5400	2	23/11/2000	
UM 304	01h06m54.0s	+01d56m44s	5400	3	48	28/07/1997	5400	1	10/01/2002	CTS 1001
Tol 0104-388	01h07m02.1s	-38d31m52s					5400	2	23/11/2000	
UM 306	01h10m35.0s	+02d06m51s					5400			
UM 307	01h11m30.7s	+01d19m16s	1800	1	48	29/07/1997	5400	2	21/11/2000	
UM 323	01h26m46.6s	-00d38m46s					5400	1	20/11/2000	
Tol 0127-397	01h29m15.8s	-39d30m38s	1200	1	106	17/09/1998	5400	2	24/11/2000	
Tol 0140-420	01h43m03.1s	-41d49m41s					5400	1	21/07/2001	
UM 137	01h46m23.9s	+04d16m11s					5400	1	21/07/2001	MRK 1169
UM 151	01h57m38.8s	+02d25m24s					3600	1	21/07/2001	
UM 382	01h58m09.3s	-00d06m38s					3600	1	22/07/2001	
MBG 01578-6806	01h59m06.0s	-67d52m13s	1200	1	106	12/09/1998				NGC 802
UM 391	02h03m30.4s	+02d33m59s	6000	5	106	14/09/1998	5400	2	22/11/2000	MRK 585
			2400	2	106	15/09/1998				
UM 395	02h06m56.8s	+01d41m52s					5400	2	24/11/2000	
UM 396	02h07m26.5s	+02d56m55s					5400	2	22/11/2000	
UM 408	02h11m23.4s	+02d20m30s					5400	2	22/11/2000	
UM 417	02h19m30.2s	-00d45m91s					4200	1	22/07/2001	
Tol 0226-390	02h28m12.3s	-38d49m20s	2400	2	106	14/09/1998	7200	2	20/11/2000	
CTS 1003	02h32m43.7s	-39d34m27s					5400	1	09/01/2002	Tol 0230-397
MBG 02411-1457	02h43m29.2s	-14d45m16s	4800	4	106	12/09/1998	6300	1	23/07/2001	NGC 1076
Tol 0242-387	02h44m37.9s	-38d34m54s					5400	1	09/01/2002	Tol 0306-405
CTS 1004	03h08m43.3s	-40d24m28s					4800	2	23/11/2000	
CTS 1005	03h59m08.9s	-39d06m25s					3600	1	07/01/2002	Cam 0357-3915
Tol 0440-381	04h42m08.1s	-38d01m11s	2400	2	106	17/09/1998	3600	2	20/11/2000	
CTS 1006	04h42m09.5s	-45d25m12s					3600	1	10/01/2002	
CTS 1007	04h46m49.4s	-30d08m58s					6000	2	22/11/2000	
CTS 1008	04h51m39.6s	-31d53m06s					7200	2	21/11/2000	
Tol 0505-387	05h07m00.8s	-38d38m58s					4800	2	23/11/2000	
Tol 0510-400	05h11m56.3s	-39d59m47s					5400	1	09/01/2002	
Tol 0528-383	05h29m57.4s	-38d18m07s					3600	2	20/11/2000	
II ZW 40	05h55m42.6s	+03d23m32s	3600	3	101	05/02/1997	4200	1	21/11/2000	
Tol 0559-393	06h00m43.9s	-39d19m07s					900	1	28/03/2001	
Tol 0610-387	06h12m14.2s	-38d46m23s					3600	1	23/11/2000	
Tol 0614-375	06h16m13.8s	-37d36m37s					4800	2	22/11/2000	
Tol 0633-415	06h35m10.2s	-41d33m42s					3600	1	14/04/2007	
Tol 0645-376	06h46m50.1s	-37d43m22s	1800	1	101	04/02/1997	2700	1	20/11/2000	
MRK 1201	07h25m45.7s	+29d57m10s					3600	1	31/03/2001	
Cam 0840+1201	08h42m20.9s	+11d50m00s					6000	2	24/11/2000	
Cam 0840+1044	08h42m36.6s	+10d33m14s					2700	1	29/03/2001	

Table 1: Continue.

Table 1: Continue.

Galaxy	α (2000)	δ (2000)	Total Exp. Time (s)	Number of Exp.	Condé Detector (CCD)	Obs. Date	Total Exp. Time (s)	FEROS Number of Exp.	Obs. Date	Other Name
UM 559 [SC98] 68	13h17m42.8s 13h21m50.0s	-01d00m01s -22d28m31s					3600	1	28/03/2001	
UM 570 [SC98] 88	13h23m47.4s 13h25m33.0s	-01d32m52s -26d02m50s					3600	1	31/03/2001	
CTS 1030	13h25m33.3s	-25d55m33s					4500	1	22/07/2001	
POX 186	13h25m48.6s	-11d36m38s					4500	1	29/03/2001	[SC98] 84
CTS 1031 Tol 1345-420	13h25m58.5s 13h48m22.2s	-23d38m09s -42d21m15s	600	1	106	14/03/1999	3600	1	14/04/2007	[SC98] 91
CTS 1033 Tol 1400-397	13h49m44.8s 14h03m05.7s	-18d11m28s -40d02m28s					3600	1	30/03/2001	Tol 111
UM 649	14h14m27.7s	-00d28m08s					7200	1	13/04/2007	
CTS 1034 II ZW 70	14h19m32.4s 14h50m56.5s	-27d35m08s +35d34m18s					5400	1	23/07/2001	Tol 115
CTS 1035	14h57m19.7s	-22d23m35s					5400	2	21/07/2001	
CTS 1037 Cam 1543+0907	15h15m44.0s 15h45m38.6s	-18d18m52s +09d03m28s					1400	1	28/03/2001	MRK 829
Tol 1924-416	19h27m58.2s	-41d34m32s	3600	2	48	28/07/1997	3600	1	30/03/2001	
Tol 1939-419	19h33m32.0s	-41d50m56s					4500	1	13/04/2007	
Tol 1937-423	19h40m58.6s	-42d15m45s	2400	2	106	16/09/1998	3100	1	16/04/2007	
CTS 1038	19h54m52.6s	-32d56m40s					5400	1	21/07/2001	
CTS 1039	20h05m51.3s	-45d28m42s					4500	1	01/04/2001	
Tol 2010-382	20h14m06.4s	-38d07m41s	5400	3	48	29/07/1997	3600	1	16/04/2007	
Tol 2019-405	20h23m06.2s	-40d20m33s					5400	1	14/04/2007	
Tol 2041-394	20h44m50.8s	-39d13m17s					5400	1	21/07/2001	
NGC 6970	20h53m09.4s	-48d46m40s	2400	2	48	28/07/1997				22/07/2001
MBG 20533-4410	20h56m43.4s	-43d59m10s	4800	4	48	28/07/1997	3600	1	21/11/2000	
Tol 2122-408	21h25m46.9s	-40d39m12s	4800	4	106	16/09/1998	5400	1	23/07/2001	
Tol 2138-405	21h41m21.8s	-40d19m06s					1800	1	16/04/2007	
Tol 2138-397	21h41m38.4s	-39d31m30s					5400	1	21/07/2001	NGC 7165
Tol 2146-391	21h49m48.2s	-38d54m09s								
MBG 21567-1645	21h59m26.1s	-16d30m44s	5400	3	48	29/07/1997	3600	1	22/07/2001	
MBG 22012-1550	22h03m56.3s	-15d36m00s	5400	3	48	29/07/1997				
IC 5154	22h04m30.3s	-66d06m45s	2400	2	106	12/09/1998				
ESO 533-G 014	22h19m50.6s	-26d20m30s	3600	3	106	12/09/1998				
MCG -01-57-017	22h38m13.5s	-07d02m05s	2400	2	106	14/09/1998				
Tol 2240-384	22h43m32.4s	-38d11m24s					5400	1	23/07/2001	
MBG 23121-3807	23h14m52.3s	-37d51m20s	8700	8	106	11/09/1998	3600	1	23/07/2001	
Tol 2326-405	23h28m49.4s	-40d15m26s					4500	1	23/07/2001	
UM 167	23h36m14.1s	+02d09m19s	3600	2	48	29/07/1997	7200	2	21/11/2000	MRK 538, NGC 7714
UM 191	23h56m59.6s	-02d05m02s	5400	3	48	29/07/1997				MRK 542
			2400	2	106	13/09/1998				
			4800	4	106	14/09/1998				

Table 2: Measurements of redshifts, distances and line widths from FEROS and Coudé spectra. The last column indicates the class of the galaxies discussed in the text.

Galaxy	z_{hel}	D Mpc	FWHM $H\beta$	FWHM [OIII] 4959Å	FWHM [OIII] 5007Å	FWHM $H\alpha$	FWHM $H\alpha$ (Coudé)	Class
UM 238	0.01427	55.3	0.844	0.775	0.785	1.158	–	G
MBG 00463-0239	0.01328	51.4	–	–	–	–	3.200	I
UM 304	0.01570	61.7	3.063	3.556	3.444	4.140	4.107	C
Tol 0104-388	0.02263	92.4	1.914	1.880	1.988	2.618	–	I
UM 306	0.01649	65.1	0.846	0.703	0.736	1.147	–	G
UM 307	0.02249	90.4	–	–	–	–	2.772	G
UM 323	0.00648	23.0	0.873	0.853	0.786	1.143	–	G
Tol 0127-397	0.01735	70.3	1.510	1.420	1.440	1.950	2.045	G
Tol 0140-420	0.02205	89.9	1.193	1.092	1.104	1.510	–	C
UM 137	0.00591	20.8	–	–	0.676	0.962	–	G
UM 151	0.01607	63.9	1.196	0.892	1.066	1.760	–	G
UM 382	0.01206	47.0	0.812	0.772	0.742	1.028	–	G
MBG 01578-6806	0.00490	19.8	–	–	–	–	1.669	G
UM 391	0.02101	84.9	2.291	–	3.188	3.168	3.320	C
UM 395	0.02234	90.6	1.255	1.281	1.206	1.711	–	G
UM 396	0.02078	84.0	1.134	1.099	1.110	1.517	–	G
UM 408	0.01153	45.0	0.867	0.661	0.681	1.165	–	G
UM 417	0.00872	33.3	0.639	0.544	0.606	0.994	–	G
Tol 0226-390	0.04771	199.2	3.620	3.410	3.346	–	4.219	I
CTS 1003	0.01684	68.9	1.055	1.005	1.000	1.452	–	G
MBG 02411-1457	0.00686	26.1	–	–	–	–	2.047	G
Tol 0242-387	0.12635	531.5	4.252	4.966	4.949	5.664	–	I
CTS 1004	0.04734	198.3	1.804	1.780	1.831	–	–	I
CTS 1005	0.07441	313.3	2.082	1.963	1.964	2.772	–	I
Tol 0440-381	0.04082	172.2	1.440	1.308	1.310	1.967	2.776	C
CTS 1006	0.02072	87.5	1.492	1.341	1.360	2.032	–	G
CTS 1007	0.04130	174.2	1.255	1.123	1.108	1.648	–	G
CTS 1008	0.06106	257.7	2.030	1.891	1.910	2.693	–	G
Tol 0505-387	0.02897	122.6	0.967	0.812	0.906	1.269	–	G
Tol 0510-400	0.04132	174.9	1.425	1.282	1.281	1.795	–	G
Tol 0528-383	0.01163	49.8	0.826	0.760	0.794	1.188	–	G
II Zw 40	0.00258	11.8	1.329	1.277	1.300	1.826	1.951	I
Tol 0559-393	0.04478	190.3	2.073	1.713	1.929	2.677	–	G
Tol 0610-387	0.00575	25.7	0.771	–	0.929	1.199	–	G
Tol 0614-375	0.03157	134.8	1.820	2.045	2.036	2.646	–	G
Tol 0633-415	0.01640	71.1	1.310	1.223	1.251	1.705	–	G
Tol 0645-376	0.02579	110.9	1.229	1.228	1.198	1.708	1.670	G
MRK 1201	0.01857	80.6	1.843	–	–	2.491	–	G
Cam 0840+1201	0.02938	128.2	1.510	1.397	1.400	1.945	–	G
Cam 0840+1044	0.01044	48.0	0.752	0.549	0.573	0.999	–	G

Table 2: Continue.

Galaxy	z_{hel}	D Mpc	FWHM $H\beta$	FWHM [OIII] 4959Å	FWHM [OIII] 5007Å	FWHM $H\alpha$	FWHM $H\alpha$ (Coudé)	Class
Can 08-28A	0.05304	227.8	2.090	1.797	1.856	–	–	I
MRK 710	0.00502	25.9	2.201	–	2.127	2.708	2.697	C
MRK 711	0.01944	86.7	3.685	3.418	3.499	5.046	–	I
Tol 0957-278	0.00334	18.8	1.031	1.051	1.044	1.503	1.543	I
Tol 1004-296NW	0.00370	20.2	–	–	–	1.943	1	G'
Tol 1004-296SE	0.00359	19.8	–	–	–	1.738	G	G'
Tol 1008-286	0.01384	63.1	1.054	1.010	1.008	1.455	–	G'
CTS 1011	0.01207	55.9	0.921	0.823	0.837	1.241	–	G'
CTS 1012	0.01089	50.9	0.787	0.650	0.646	1.051	–	G'
CTS 1013	0.02688	118.5	1.390	1.346	1.380	1.774	–	C
Tol 1025-285	0.03073	134.5	2.356	–	2.438	2.986	–	G
Haro 24	0.04327	187.3	1.770	1.587	1.759	2.565	–	I
CTS 1014	0.05895	253.8	2.333	1.778	1.849	2.803	–	I
CTS 1016	0.03450	150.6	1.456	1.323	1.410	2.203	–	I
CTS 1017	0.03544	154.5	1.186	1.176	1.176	1.598	–	G'
CTS 1018	0.03925	170.6	1.453	1.313	1.316	1.977	–	G
CTS 1019	0.06651	285.8	1.888	1.895	1.936	2.761	–	G'
CTS 1020	0.01248	57.7	1.393	1.365	1.399	1.911	–	G'
CTS 1022	0.01369	62.9	0.974	0.839	0.854	1.427	–	G
[F80] 30	0.00335	18.2	0.903	0.741	0.749	1.205	–	G'
MRK 36	0.00212	13.2	0.782	0.687	0.717	1.051	–	G'
UM 439	0.00382	21.3	0.805	0.708	0.711	1.103	1.444	G'
UM 448	0.01834	82.6	2.947	3.043	3.017	4.143	3.376	C
Tol 1147-283	0.00626	31.2	0.793	0.799	0.724	1.113	–	G'
UM 455	0.01306	60.3	0.998	0.746	0.740	1.518	–	I
UM 456	0.00572	29.3	0.757	0.631	0.643	1.017	–	G'
UM 461	0.00352	20.0	0.669	0.512	0.519	0.912	–	G'
UM 463	0.00468	24.9	0.849	0.680	0.676	1.057	–	G'
CTS 1026	0.00577	29.2	1.710	1.689	1.705	2.284	–	G
UM 477	0.00422	22.8	2.243	–	2.860	3.019	3.038	C
UM 483	0.00792	38.4	0.816	0.776	0.744	1.105	–	I
CTS 1027	0.00674	33.4	0.892	0.799	0.821	1.217	–	I
MRK 1318	0.00504	26.2	0.756	0.680	0.695	1.052	1.448	G'
CTS 1028	0.01776	79.9	1.141	1.074	1.098	1.520	–	C
UM 499	0.00707	34.8	–	–	–	–	2.520	I
Tol 1223-359	0.00930	44.2	0.828	0.681	0.707	1.163	–	G'
Haro 30	0.01552	69.5	1.746	1.887	1.845	2.428	–	I
[SC98] 01	0.01041	48.4	0.975	0.791	0.720	1.185	–	G'
CTS 1029	0.03633	157.8	–	–	–	1.787	–	G
[SC98] 11	0.03104	135.5	1.317	1.285	1.244	1.801	–	I

Table 2: Continue.

Galaxy	z_{hel}	D Mpc	FWHM $H\beta$	FWHM [OIII] 4959Å	FWHM [OIII] 5007Å	FWHM $H\alpha$	FWHM $H\alpha$ (Coudé)	Class
UM 559	0.00429	22.5	0.794	0.676	0.687	1.103	–	G
[SC98] 68	0.02377	104.7	1.274	1.346	1.300	1.758	–	G
UM 570	0.02249	99.3	0.930	0.884	0.867	1.291	–	G
[SC98] 88	0.01454	65.6	1.066	0.896	0.860	1.491	–	I
CTS 1030	0.01505	67.7	1.221	1.213	1.212	1.668	–	C
POX 186	0.00415	21.9	0.715	0.584	0.586	0.984	–	G
CTS 1031	0.04525	195.3	1.338	1.296	1.386	1.770	–	I
Tol 1345+420	0.00807	37.5	0.877	0.743	0.791	1.188	1.655	G
CTS 1033	0.01549	69.4	1.921	1.935	1.939	2.602	–	C
Tol 1400-397	0.03101	134.3	1.352	1.299	1.368	1.922	–	G
UM 649	0.02611	113.9	1.152	0.935	1.018	1.480	–	G
CTS 1034	0.02292	100.2	–	1.091	1.037	1.533	–	G
II Zw 70	0.00406	19.2	0.901	0.794	0.823	1.377	–	G
CTS 1035	0.02848	123.2	1.164	1.120	1.086	1.409	–	G
CTS 1037	0.02130	92.5	1.562	1.530	1.513	2.074	–	I
Cam 1543+0907	0.03766	160.8	1.293	1.186	1.179	1.716	–	G
Tol 1924+416	0.00952	38.4	–	–	–	2.065	–	I
Tol 1939+419	0.02525	104.8	–	–	0.962	1.336	–	G
Tol 1937+423	0.00932	37.4	1.022	0.768	0.888	1.262	1.874	G
CTS 1038	0.04984	208.0	–	2.123	2.136	–	–	I
CTS 1039	0.04486	187.4	1.693	1.704	1.722	2.287	–	I
Tol 2010-382	0.02026	83.0	1.506	–	1.480	1.899	2.166	G
Tol 2019+405	0.01495	60.6	1.095	0.978	0.996	1.300	–	I
Tol 2041+394	0.02576	106.0	–	1.178	1.121	1.627	–	G
NGC 6970	0.01751	71.6	–	–	–	–	2.594	C
MBG 20533-4410	0.01714	69.7	–	–	–	–	3.075	C
Tol 2122+408	0.01480	59.4	1.114	1.052	1.071	1.416	1.717	G
Tol 2138+405	0.05802	241.7	2.445	2.468	2.496	3.444	–	C
Tol 2138+397	0.01570	63.0	0.996	0.998	0.900	1.391	–	G
Tol 2146+391	0.02953	121.3	1.154	0.935	0.991	1.503	–	I
MBG 21567+1645	0.01738	68.8	–	–	–	–	5.513	C
MBG 22012-1550	0.04227	173.9	–	–	–	–	5.074	C
IC 5154	0.01068	43.7	–	–	–	–	2.035	G
ESO 533-G 014	0.00873	32.6	–	–	–	–	1.317	G
MCG -01-57-017	0.00962	35.6	–	–	–	–	1.567	G
Tol 2240+384	0.07584	316.6	2.082	2.112	2.196	2.940	–	C
MBG 23121-3807	0.00945	36.2	–	–	–	–	1.777	G
Tol 2326+405	0.05515	229.3	–	–	1.556	2.456	–	I
UM 167	0.00928	34.0	–	–	–	–	3.925	G
UM 191	0.02427	97.4	1.265	–	1.584	1.798	2.000	G

Table 3: H α and [OIII] λ 5007 integrated fluxes of line emissions, H α extinction coefficient, H β equivalent width, O/H ratio and electronic temperature.

Galaxy	$F_{\text{H}\alpha}$ (erg s ⁻¹ cm ⁻²)	$C_{\text{H}\beta}$	$W_{\text{H}\beta}$ Å	[OIII]/[OII]	N_e cm ⁻³	T_e 10 ⁴ K	12+ $\log(\text{O}/\text{H})$	Ref.
UM 238	2.0e-14	0.23	36	3.31	867	1.53	7.89	1,1,1,1,1,1,18
MBG 00463-0239	8.2e-14	0.38	10	0.19	374	1.40	8.70	1,1,1,1,1,22,16
UM 304	1.5e-13	1.09	-	-	204	1.40	-	14.2,-,7,22,22,-
Tol 0104-388	4.7e-14	0.19	60	1.14	846	1.49	7.96	1,1,1,1,1,1,18
UM 306	3.1e-14	0.08	24	2.21	27	1.16	8.18	1,1,1,1,1,1,18
UM 307	1.1e-13	0.25	23	0.67	983	1.40	8.43	1,1,1,1,1,22,16
UM 323	2.6e-14	0.85	21	0.90	27	1.76	7.92	1,1,1,1,1,1,18
Tol 0127-397	4.1e-14	0.51	-	-	204	1.40	-	14.2,-,7,22,22,-
Tol 0140-420	2.3e-14	0.00	56	1.98	27	1.28	8.06	1,1,1,1,1,1,18
UM 137	1.5e-14	0.37	4	0.55	27	1.40	8.25	1,1,1,1,1,22,17
UM 151	2.6e-14	0.41	20	0.79	94	1.40	8.47	1,1,15,1,22,17
UM 382	1.9e-14	0.18	135	10.90	45	1.62	7.82	6,6,6,6,6,6
MBG 01578-6806	-	-	-	-	204	1.40	-	7,-,7,22,22,-
UM 391	5.1e-14	0.54	14	0.35	27	1.40	8.40	1,1,1,1,1,22,16
UM 395	1.6e-14	0.49	6	0.42	579	1.40	8.63	1,1,1,1,1,22,17
UM 396	3.7e-14	0.00	153	5.85	27	1.22	8.18	1,1,1,1,1,1,18
UM 408	2.0e-14	0.06	33	3.66	207	1.33	8.02	1,1,1,1,1,1,18
UM 417	5.8e-15	0.45	46	7.65	27	1.40	8.04	1,1,1,1,1,22,17
Tol 0226-390	1.0e-13	0.31	115	3.03	193	1.16	8.15	1,1,1,1,1,1,18
CTS 1003	2.2e-14	0.24	-	-	204	1.40	7.90	3,3,-,22,22,3
MBG 02411-1457	4.7e-14	0.76	2	0.15	132	1.40	8.26	1,1,1,1,1,22,16
Tol 0242-387	1.1e-13	0.78	-	-	204	1.40	8.23	2,2,-,22,22,19
CTS 1004	3.5e-14	0.00	77	3.83	101	1.21	8.14	1,1,1,1,1,1,18
CTS 1005	4.3e-14	0.16	134	11.14	204	1.46	7.91	1,1,1,1,22,1,18
Tol 0440-381	5.5e-14	0.11	29	1.77	27	1.53	7.96	1,1,1,1,1,1,18
CTS 1006	1.4e-13	0.15	70	2.88	27	1.28	8.04	1,1,1,1,1,1,18
CTS 1007	4.3e-14	0.01	-	-	204	1.40	7.83	3,3,-,22,22,3
CTS 1008	5.7e-14	0.24	140	6.04	278	1.21	8.16	1,1,1,1,1,1,18
Tol 0505-387	1.1e-14	0.35	10	0.66	27	1.40	8.50	1,1,1,1,1,22,17
Tol 0510-400	3.3e-14	0.19	64	2.39	227	1.40	8.25	1,1,1,1,1,22,16
Tol 0528-383	3.7e-14	0.35	21	1.86	133	1.48	7.96	1,1,1,1,1,1,18
II ZW 40	3.5e-13	0.61	184	10.98	217	1.31	8.07	1,1,1,1,1,1,18
Tol 0559-393	4.5e-14	0.35	-	-	204	1.40	-	2,2,-,22,22,-
Tol 0610-387	1.1e-14	0.93	4	0.44	27	1.40	8.56	1,1,1,2,1,22,17
Tol 0614-375	6.9e-14	1.25	-	-	204	1.40	7.86	2,2,-,22,22,20
Tol 0633-415	1.1e-13	0.40	83	4.59	67	1.25	8.14	1,1,1,21,1,21,4
Tol 0645-376	2.9e-14	0.19	28	1.58	27	1.78	7.77	1,1,1,1,1,1,18
MRK 1201	3.9e-14	0.52	8	0.50	1467	1.40	9.36	1,1,1,1,22,16
Cam 0840+1201	1.1e-13	0.03	105	3.53	27	1.32	7.98	1,1,1,1,1,1,18
Cam 0840+1044	2.1e-14	0.25	44	7.85	27	1.58	7.73	1,1,1,1,1,1,18

References- (1) Kehrig et al. (2004); (2) T91; (3) Pena et al. (1991); (4) Denicoló et al. (2002); (5) Telles et al. (2001); (6) Kniazev et al. (2001); (7) Izotov & Thuan (1998); (8) Vílchez & Iglesias-Páramo (2003); (9) Papaderos et al. (2006); (10) Mas-Hesse & Kunth (1999); (11) Kniazev et al. (2004); (12) Izotov et al. (2001); (13) Kehrig et al. (2008); (14) Coudé spectrophotometry; (15) Pustilnik et al. (2002); (16) O/H derived from p-method (Pilyugin 2000); (17) O/H derived from N2 calibrator (Denicoló et al. 2002); (18) O/H derived from T_e -method; (19) Melnick et al. (1988); (20) Masegosa et al. (1994); (21) Campbell et al. (1986); (22) mean values for T_e and N_e .

Table 3: Continue.

Galaxy	$F_{\text{H}\alpha}$ (erg s $^{-1}$ cm $^{-2}$)	$C_{\text{H}\beta}$	$W_{\text{H}\beta}$ Å	[OIII]/[OII]	N_e cm $^{-3}$	T_e 10 4 K	12+ log(O/H)	Ref.
Cam 08-28A	1.5e-13	0.28	37	1.60	97	1.11	8.13	1,1,1,1,1,1,1,8
MRK 710	4.5e-13	0.50	29	0.23	184	1.40	8.95	1,1,1,1,1,22,16
MRK 711	1.9e-13	0.54	28	1.61	460	1.40	8.79	1,1,1,2,1,22,17
Tol 0957-278	2.0e-13	0.17	36	1.92	74	1.24	8.02	1,1,1,1,1,1,18
Tol 1004-296NW	7.4e-13	0.40	62	3.50	122	1.04	8.28	1,1,1,1,1,1,18
Tol 1004-296SE	5.0e-13	0.30	52	2.69	69	1.08	8.20	1,1,1,1,1,1,18
Tol 1008-286	5.1e-14	1.05	123	9.55	395	1.30	8.17	1,1,1,21,1,21,4
CTS 1011	6.2e-14	0.34	93	3.80	233	1.28	8.18	1,1,1,1,1,1,18
CTS 1012	6.3e-14	0.01	–	–	204	1.40	8.41	3,3,-,-,22,22,3
CTS 1013	1.7e-14	0.00	38	3.40	185	1.29	8.08	1,1,1,1,1,1,18
Tol 1025-285	4.0e-14	0.79	9	0.31	27	1.40	8.71	1,1,1,2,1,22,17
Haro 24	4.8e-14	0.57	11	0.88	27	1.40	8.23	1,1,1,1,1,22,17
CTS 1014	2.2e-14	0.01	–	–	204	1.40	7.98	3,3,-,-,22,22,3
CTS 1016	1.7e-14	0.19	26	1.24	27	1.40	8.36	1,1,1,1,1,22,3
CTS 1017	2.2e-14	0.22	161	6.68	247	1.46	7.98	1,1,1,1,1,1,18
CTS 1018	1.8e-14	0.16	58	2.43	140	1.40	7.97	1,1,1,1,1,1,18
CTS 1019	4.2e-14	0.22	90	3.87	27	1.11	8.22	1,1,1,1,1,1,18
CTS 1020	1.5e-13	0.33	109	2.94	101	1.12	8.25	1,1,1,1,1,1,18
CTS 1022	2.6e-14	0.43	57	1.53	147	1.33	8.09	1,1,1,1,1,1,18
[F80] 30	2.9e-13	0.00	97	5.07	215	1.41	7.99	1,1,1,7,1,7,7
MRK 36	1.5e-13	0.08	62	3.48	96	1.38	7.89	1,1,1,1,1,1,18
UM 439	1.2e-13	0.05	49	4.30	27	1.39	8.01	1,1,1,1,1,1,18
UM 448	7.3e-13	0.40	48	1.16	151	1.08	8.17	1,1,1,1,1,1,18
Tol 1147-283	5.6e-14	0.20	40	1.08	79	1.51	7.88	1,1,1,1,1,1,18
UM 455	2.0e-14	0.48	29	4.32	27	1.73	7.74	1,1,1,1,1,1,18
UM 456	8.9e-14	0.06	44	3.09	27	1.41	7.95	1,1,1,1,1,1,18
UM 461	1.1e-13	0.05	155	9.43	115	1.66	7.77	1,1,1,1,1,1,18
UM 463	3.3e-14	0.17	74	6.08	102	1.32	7.92	1,1,1,20,1,11,11
CTS 1026	1.0e-12	0.33	–	–	204	1.40	8.30	3,3,-,-,22,22,3
UM 477	2.6e-13	0.88	17	0.34	979	1.40	9.12	1,1,1,1,22,16
UM 483	4.7e-14	0.45	19	0.84	133	1.71	7.85	1,1,1,1,11,11,11
CTS 1027	1.5e-13	0.08	50	1.88	63	1.01	8.35	8,8,8,8,8,8,8
MRK 1318	2.2e-13	0.27	68	1.70	78	1.01	8.27	1,1,1,1,1,1,18
CTS 1028	4.5e-14	0.57	82	3.90	344	1.40	8.05	1,1,1,1,1,1,18
UM 499	6.1e-13	0.55	24	0.45	611	1.40	8.82	1,1,1,1,22,16
Tol 1223-359	7.5e-14	0.16	129	7.18	27	1.73	7.54	1,1,1,12,1,12,12
Haro 30	6.1e-14	0.00	28	0.93	103	1.54	7.67	1,1,1,1,1,1,18
[SC98] 01	1.8e-14	0.14	34	1.39	45	1.40	8.27	1,1,1,1,22,17
CTS 1029	1.9e-14	0.29	35	1.05	489	1.40	8.42	1,1,1,1,22,3
[SC98] 11	–	–	–	–	204	1.40	–	–,-,-,-,22,22,-

Table 3: Continue.

Galaxy	$F_{\text{H}\alpha}$ (erg s $^{-1}$ cm $^{-2}$)	$C_{\text{H}\beta}$	$W_{\text{H}\beta}$ Å	[OIII]/[OI]	N_e cm $^{-3}$	T_e 10 4 K	12+ log(O/H)	Ref.
UM 559	5.0e-14	0.00	535	4.92	204	1.58	7.72	1,1,1,1,22,9,9
[SC98] 68	2.1e-14	0.52	22	0.76	343	1.40	8.49	1,1,1,1,22,17
UM 570	3.1e-14	0.00	180	43.00	204	1.83	7.71	1,1,1,9,22,9,9
[SC98] 88	1.9e-14	0.29	20	1.24	339	1.41	8.02	1,1,1,1,1,18
CTS 1030	7.0e-14	0.01	–	–	204	1.40	8.25	3,3,*,*,22,22,3
POX 186	7.2e-14	0.01	274	19.26	342	1.66	7.74	1,1,1,1,1,18
CTS 1031	3.4e-14	0.22	–	–	204	1.40	8.23	3,3,*,*,22,22,3
Tol 1345-420	8.7e-14	0.27	51	2.89	71	1.07	8.26	1,1,1,1,1,18
CTS 1033	7.4e-14	0.24	59	8.69	155	1.42	8.01	1,1,1,1,1,18
Tol 1400-397	2.3e-14	0.20	–	–	204	1.40	–	2,2,*,*,22,22,*
UM 649	1.2e-14	0.00	–	–	204	1.40	–	2,2,*,*,22,22,*
CTS 1034	1.3e-14	0.28	20	1.53	1288	1.47	7.96	1,1,1,1,1,18
H II ZW 70	2.7e-13	0.30	49	1.90	96	1.21	8.07	5,13,10,10,13,13,4
CTS 1035	1.5e-14	0.12	62	2.91	510	1.40	8.01	1,1,1,1,1,22,3
CTS 1037	4.0e-13	0.29	–	–	204	1.40	8.21	3,3,*,*,22,22,3
Cam 1543+0907	5.9e-14	0.05	192	8.96	74	1.68	7.71	1,1,1,1,1,18
Tol 1924-416	1.0e-12	0.11	100	4.86	131	1.35	8.01	1,1,1,1,1,18
Tol 1939-419	1.3e-14	0.00	–	–	204	1.40	–	2,2,*,*,22,22,*
Tol 1937-423	2.0e-14	0.70	5	0.49	39	1.40	8.48	1,1,1,1,1,22,17
CTS 1038	1.9e-13	0.53	–	–	204	1.40	7.82	3,3,*,*,22,22,3
CTS 1039	9.7e-14	0.01	–	–	204	1.40	7.70	3,3,*,*,22,22,3
Tol 2010-382	8.2e-14	0.76	–	–	204	1.40	–	14,2,*,*,22,22,
Tol 2019-405	1.5e-14	0.10	11	1.90	76	1.45	7.99	1,1,1,1,1,18
Tol 2041-394	1.9e-14	0.00	–	–	204	1.40	–	2,2,*,*,22,22,*
NGC 6970	9.7e-14	0.00	–	–	204	1.40	–	14,2,*,*,22,22,
MBG 20533-4410	1.0e-13	0.81	8	0.20	90	1.40	8.88	1,1,1,1,1,22,16
Tol 2122-408	2.6e-14	0.41	14	4.47	97	1.40	8.49	1,1,1,1,1,22,16
Tol 2138-405	8.9e-14	0.19	208	7.08	204	1.38	7.98	9,9,9,9,22,9,9
Tol 2138-397	1.8e-14	0.12	33	2.49	27	1.86	7.64	1,1,1,1,1,18
Tol 2146-391	2.8e-14	0.09	246	7.70	47	1.59	7.78	1,1,1,1,1,18
MBG 21567-1645	3.2e-14	1.36	2	0.08	281	1.40	8.93	1,1,1,1,1,22,17
MBG 22012-1550	3.9e-14	0.84	7	0.70	27	1.40	8.20	1,1,1,1,1,22,16
IC 5154	4.9e-14	0.38	10	0.79	250	1.40	8.52	1,1,1,1,1,22,17
ESO 533-G 014	5.7e-14	0.45	6	0.41	27	1.51	7.90	1,1,1,1,1,18
MCG -01-57-017	6.5e-14	0.10	11	0.23	27	1.40	8.37	1,1,1,1,1,22,16
Tol 2240-384	3.4e-14	0.37	165	8.72	204	1.53	7.85	1,1,1,1,22,18
MBG 23121-3807	2.4e-14	0.71	4	0.11	27	1.40	8.75	1,1,1,1,1,22,17
Tol 2326-405	4.1e-14	0.22	–	–	204	1.40	8.03	2,2,*,*,22,22,19
UM 167	1.2e-12	0.26	–	–	204	1.40	–	14,2,*,*,22,22,
UM 191	3.6e-14	0.43	7	0.26	108	1.40	8.30	1,1,1,1,1,22,16

Table 4: Errors in σ as a function of signal-to-noise ratio of the line-emission.

S/N H lines	$\delta\sigma_H$ km s $^{-1}$	S/N O lines	$\delta\sigma_O$ km s $^{-1}$
FEROS			
S/N < 10	2.9	S/N < 10	2.1
10 < S/N < 20	2.2	10 < S/N < 20	1.4
20 < S/N < 30	1.8	20 < S/N < 30	0.9
30 < S/N < 40	1.2	30 < S/N < 50	0.7
40 < S/N < 75	0.7	50 < S/N < 150	0.5
S/N > 75	0.4	S/N > 150	0.2
Coudé			
S/N < 110	4.6		
S/N > 110	3.5		

Table 5: Velocity dispersion and H α luminosities.

Galaxy		σ (km s $^{-1}$)			Coudé H α	$\log L$ (erg s $^{-1}$) H α
		H β	$\lambda 4959$	FEROS $\lambda 5007$	H α	
UM 238	18.3±1.8	19.2±0.5	19.3±0.5	18.6±0.4	–	40.02
MBG 00463-0239	–	–	–	–	57.7±3.5	40.67
UM 304	78.2±2.2	89.8±2.1	86.1±1.4	78.2±0.4	76.3±4.6	41.55
Tol 0104-388	47.6±1.8	47.0±0.7	49.3±0.5	48.2±0.4	–	40.81
UM 306	19.1±1.2	17.4±0.5	18.1±0.5	19.1±0.4	–	40.25
UM 307	–	–	–	–	49.4±3.5	41.20
UM 323	18.9±2.2	21.4±0.9	19.5±0.5	18.0±0.4	33.2±3.5	39.78
Tol 0127-397	37.2±0.7	35.6±0.5	35.8±0.5	35.4±0.4	–	40.72
Tol 0140-420	28.6±2.2	27.2±2.1	27.2±2.1	26.4±0.4	–	40.35
UM 137	–	–	–	16.7±2.1	14.5±2.2	–
UM 151	28.7±2.9	22.2±2.1	26.4±2.1	31.6±1.8	–	39.13
UM 382	17.2±2.9	19.2±2.1	18.2±1.4	15.4±2.2	–	40.39
MBG 01578-6806	–	–	–	–	24.8±4.6	–
UM 391	57.7±2.2	–	79.3±1.4	59.1±0.4	59.6±4.6	41.00
UM 395	30.1±2.2	32.0±2.1	29.8±1.4	30.3±0.4	–	40.52
UM 396	27.1±2.2	27.4±0.2	27.4±0.5	26.7±0.4	–	40.49
UM 408	19.5±1.2	16.4±0.5	16.7±0.5	19.3±0.4	–	39.73
UM 417	12.1±2.9	13.4±2.1	14.8±0.7	15.3±1.2	–	39.18
Tol 0226-390	89.9±0.7	83.5±0.5	81.1±0.2	–	75.5±3.5	41.89
CTS 1003	24.7±1.8	25.1±0.5	24.7±0.7	25.2±0.4	–	40.10
MBG 02411-1457	–	–	–	–	33.7±4.6	40.09
Tol 0242-387	98.2±2.9	113.1±2.1	111.7±0.9	96.9±2.9	–	43.11
CTS 1004	43.8±2.9	43.5±2.1	44.3±0.2	–	–	41.21
CTS 1005	49.4±1.8	46.8±2.1	46.3±0.5	48.6±0.4	–	41.81
Tol 0440-381	34.3±0.7	32.0±0.5	31.8±0.2	34.7±0.4	47.4±4.6	41.36
CTS 1006	36.7±0.4	33.5±0.2	33.7±0.2	37.0±0.4	–	41.22
CTS 1007	29.5±1.8	27.4±0.5	26.8±0.5	28.5±0.4	–	41.20
CTS 1008	49.0±1.8	45.6±0.5	45.6±0.7	48.0±1.2	–	41.81
Tol 0505-387	21.8±2.9	19.9±2.1	22.1±0.7	21.0±1.8	–	40.55
Tol 0510-400	34.0±1.8	31.4±0.9	31.1±0.9	31.4±0.7	–	41.21
Tol 0528-383	18.0±2.2	18.9±0.9	19.6±1.4	19.5±0.7	–	40.27
II ZW 40	32.9±0.4	32.5±0.2	32.8±0.2	33.5±0.4	31.8±3.5	40.17
Tol 0559-393	50.7±2.2	41.9±2.1	46.8±0.7	48.3±1.2	–	41.53
Tol 0610-387	16.6±2.9	–	23.2±0.7	20.1±0.7	–	39.55
Tol 0614-375	44.8±1.8	50.8±2.1	50.0±0.9	48.4±0.4	–	42.01
Tol 0633-415	32.0±0.7	30.7±0.5	31.1±0.2	30.6±0.4	–	41.09
Tol 0645-376	28.7±2.2	30.5±0.9	29.4±0.5	29.6±0.7	23.3±3.5	40.76
MRK 1201	46.0±2.2	–	–	46.0±0.7	–	40.83
Cam 0840+1201	36.8±1.8	34.6±0.7	34.4±0.2	34.9±0.4	–	41.37
Cam 0840+1044	15.4±1.8	13.4±1.4	13.9±0.2	14.8±0.4	–	39.94

Table 5: Continue.

Galaxy	σ (km s $^{-1}$)			Coudé H α	log L (erg s $^{-1}$) H α
	H β	FEROS $\lambda 4959$	FEROS $\lambda 5007$	H α	
Cam 08-28A	51.0 \pm 2.2	43.7 \pm 1.4	44.7 \pm 0.5	–	42.14
MRK 710	56.2 \pm 1.8	–	53.7 \pm 1.4	51.0 \pm 0.4	40.89
MRK 711	94.0 \pm 0.7	86.0 \pm 0.7	87.2 \pm 0.5	95.3 \pm 0.4	41.59
Tol 0957-278	24.7 \pm 2.2	26.7 \pm 1.4	26.2 \pm 0.5	26.9 \pm 0.4	40.05
Tol 1004-296NW	–	–	–	–	31.9 \pm 3.5
Tol 1004-296SE	–	–	–	–	27.1 \pm 3.5
Tol 1008-286	24.9 \pm 0.4	25.3 \pm 0.2	25.0 \pm 0.2	25.5 \pm 0.4	41.08
CTS 1011	21.2 \pm 0.7	20.6 \pm 0.5	20.7 \pm 0.5	21.1 \pm 0.4	–
CTS 1012	17.0 \pm 0.7	16.1 \pm 0.5	15.8 \pm 0.2	16.6 \pm 0.4	40.29
CTS 1013	33.7 \pm 2.9	33.5 \pm 1.4	34.0 \pm 0.5	31.6 \pm 1.8	40.45
Tol 1025-285	58.8 \pm 2.9	–	60.0 \pm 1.4	55.0 \pm 1.2	41.47
Haro 24	43.0 \pm 2.2	38.9 \pm 1.4	42.7 \pm 0.7	46.3 \pm 0.7	41.69
CTS 1014	56.6 \pm 2.2	42.9 \pm 0.9	44.2 \pm 0.7	50.0 \pm 1.8	41.23
CTS 1016	35.1 \pm 2.9	32.6 \pm 2.1	34.5 \pm 1.4	39.7 \pm 1.8	–
CTS 1017	27.7 \pm 2.2	28.9 \pm 0.7	28.6 \pm 1.4	27.5 \pm 0.7	–
CTS 1018	34.8 \pm 1.8	32.2 \pm 0.5	32.0 \pm 0.5	35.1 \pm 0.7	40.91
CTS 1019	45.2 \pm 2.9	45.5 \pm 0.7	46.0 \pm 0.5	49.1 \pm 0.7	41.76
CTS 1020	34.5 \pm 0.4	34.4 \pm 0.5	35.0 \pm 0.2	35.1 \pm 0.4	40.98
CTS 1022	22.6 \pm 1.8	20.9 \pm 0.7	21.1 \pm 0.7	24.9 \pm 0.4	40.37
[F80] 30	20.6 \pm 0.4	18.6 \pm 0.2	18.6 \pm 0.2	20.2 \pm 0.4	40.07
MRK 36	17.1 \pm 1.2	17.2 \pm 0.5	17.8 \pm 0.2	16.8 \pm 0.4	39.55
UM 439	17.7 \pm 0.4	17.7 \pm 0.2	17.6 \pm 0.2	18.0 \pm 0.4	18.9 \pm 4.6
UM 448	75.1 \pm 0.7	76.6 \pm 0.7	75.3 \pm 0.5	78.3 \pm 0.4	61.2 \pm 3.5
Tol 1147-283	17.0 \pm 2.2	20.0 \pm 0.9	17.9 \pm 0.5	17.8 \pm 0.4	–
UM 455	22.6 \pm 2.2	18.5 \pm 0.7	18.2 \pm 0.9	26.2 \pm 1.2	40.25
UM 456	16.1 \pm 0.7	15.7 \pm 0.5	15.8 \pm 0.2	15.9 \pm 0.4	–
UM 461	12.5 \pm 0.4	12.5 \pm 0.2	12.6 \pm 0.2	12.5 \pm 0.4	–
UM 463	19.2 \pm 2.2	17.0 \pm 0.9	16.7 \pm 0.2	17.0 \pm 0.7	39.50
CTS 1026	43.1 \pm 0.4	43.0 \pm 0.2	42.9 \pm 0.2	42.5 \pm 0.4	41.02
UM 477	57.4 \pm 1.2	–	72.3 \pm 1.4	57.2 \pm 0.4	55.0 \pm 3.5
UM 483	17.2 \pm 0.7	19.4 \pm 0.5	18.4 \pm 0.2	17.1 \pm 0.4	–
CTS 1027	21.0 \pm 0.4	20.1 \pm 0.5	20.5 \pm 0.2	21.2 \pm 0.4	40.29
MRK 1318	17.1 \pm 1.2	17.0 \pm 0.5	17.2 \pm 0.2	17.7 \pm 0.4	19.8 \pm 4.6
CTS 1028	27.1 \pm 1.2	26.8 \pm 0.5	27.2 \pm 0.5	26.6 \pm 0.4	40.44
UM 499	–	–	–	–	44.0 \pm 3.5
Tol 1223-359	17.5 \pm 2.2	16.9 \pm 0.9	17.4 \pm 0.2	18.4 \pm 0.4	41.31
Haro 30	43.4 \pm 2.2	47.6 \pm 2.1	46.0 \pm 0.9	44.8 \pm 0.7	–
[SC98] 01	22.6 \pm 2.9	19.8 \pm 1.4	17.7 \pm 0.7	19.6 \pm 0.7	39.80
CTS 1029	–	–	–	31.4 \pm 1.8	–
[SC98] 11	31.5 \pm 1.8	31.8 \pm 0.9	30.5 \pm 0.5	31.9 \pm 0.4	–

Table 5: Continue.

Galaxy		σ (km s $^{-1}$)		FEROS	$\lambda 4959$	$\lambda 5007$	$H\alpha$	Coudé	$\log L$ (erg s $^{-1}$)
		H β					H α		H α
UM 559		16.9 \pm 0.7	16.9 \pm 0.5	17.0 \pm 0.2	17.5 \pm 0.4	—	—	39.48	
[SC98] 68		30.6 \pm 2.9	33.6 \pm 2.1	32.1 \pm 0.9	31.3 \pm 0.7	—	—	40.79	
UM 570		20.1 \pm 2.2	21.8 \pm 0.9	21.2 \pm 0.5	20.8 \pm 0.4	—	—	40.57	
[SC98] 88		25.1 \pm 2.2	22.4 \pm 1.4	21.2 \pm 1.4	26.1 \pm 1.2	—	—	40.19	
CTS 1030		29.4 \pm 0.4	30.5 \pm 0.5	30.1 \pm 0.2	29.7 \pm 0.4	—	—	40.59	
POX 186		14.1 \pm 0.7	14.4 \pm 0.5	14.3 \pm 0.2	14.4 \pm 0.4	—	—	39.62	
CTS 1031		31.6 \pm 2.2	31.6 \pm 1.4	33.5 \pm 0.7	30.8 \pm 0.4	—	—	41.19	
Tol 1345-420		20.4 \pm 2.2	18.6 \pm 0.7	19.6 \pm 0.2	20.4 \pm 0.4	24.9 \pm 4.6	—	40.35	
CTS 1033		48.2 \pm 0.4	48.8 \pm 0.2	48.4 \pm 0.2	48.3 \pm 0.4	—	—	40.79	
Tol 1400-397		32.4 \pm 2.2	32.1 \pm 1.4	33.5 \pm 0.5	34.3 \pm 0.7	—	—	40.84	
UM 649		27.1 \pm 2.2	23.1 \pm 1.4	25.0 \pm 0.5	25.5 \pm 1.8	—	—	40.27	
CTS 1034		—	27.1 \pm 2.1	25.5 \pm 1.4	26.6 \pm 1.8	—	—	40.38	
II Zw 70		21.0 \pm 1.2	20.0 \pm 0.5	20.5 \pm 0.2	24.3 \pm 0.4	—	—	40.27	
CTS 1035		27.4 \pm 2.9	27.7 \pm 2.1	26.6 \pm 0.5	23.9 \pm 2.2	—	—	40.53	
CTS 1037		38.4 \pm 0.4	38.3 \pm 0.2	37.5 \pm 0.2	37.7 \pm 0.4	—	—	41.61	
Cam 1543+0907		30.2 \pm 0.4	29.1 \pm 0.2	28.6 \pm 0.2	29.5 \pm 0.4	—	—	41.29	
Tol 1924-416		—	—	—	—	35.4 \pm 3.5	—	41.34	
Tol 1939-419		—	—	23.6 \pm 0.9	22.5 \pm 1.2	—	—	40.22	
Tol 1937-423		24.0 \pm 2.2	19.2 \pm 1.4	22.1 \pm 0.7	21.3 \pm 0.7	29.6 \pm 4.6	—	40.00	
CTS 1038		51.8 \pm 2.1	51.6 \pm 0.7	—	—	—	—	41.98	
CTS 1039		40.9 \pm 0.4	41.7 \pm 0.2	41.7 \pm 0.2	40.9 \pm 0.4	—	—	41.61	
Tol 2010-382		37.0 \pm 1.8	—	36.7 \pm 1.4	34.2 \pm 0.4	37.0 \pm 3.5	—	41.34	
Tol 2019-405		25.8 \pm 1.8	24.5 \pm 0.5	24.7 \pm 0.7	21.9 \pm 0.4	—	—	39.89	
Tol 2041-394		—	29.3 \pm 2.1	27.5 \pm 0.7	28.5 \pm 1.8	—	—	40.41	
NGC 6970		—	—	—	—	46.0 \pm 4.6	—	40.77	
MBG 20533-4410		—	—	—	—	55.8 \pm 4.6	—	41.31	
Tol 2122-408		26.4 \pm 1.8	26.4 \pm 0.7	26.6 \pm 0.5	24.5 \pm 0.4	25.6 \pm 4.6	—	40.32	
Tol 2138-405		59.5 \pm 2.2	59.8 \pm 0.9	59.9 \pm 0.5	62.1 \pm 1.8	—	—	41.92	
Tol 2138-397		22.2 \pm 2.2	24.9 \pm 1.4	22.2 \pm 0.7	23.1 \pm 0.7	—	—	40.01	
Tol 2146-391		26.8 \pm 1.8	23.0 \pm 0.5	24.2 \pm 0.2	25.6 \pm 0.4	—	—	40.75	
MBG 21567-1645		—	—	—	—	103.5 \pm 4.6	—	41.17	
MBG 22012-1550		—	—	—	—	92.7 \pm 4.6	—	41.71	
IC 5154		—	—	—	—	33.2 \pm 3.5	—	40.30	
ESO 533-G 014		—	—	—	—	14.5 \pm 3.5	—	40.16	
MCG -01-57-017		—	—	—	—	22.0 \pm 3.5	—	40.06	
Tol 2240-384		49.3 \pm 2.2	50.3 \pm 0.7	51.8 \pm 0.2	51.6 \pm 0.4	—	—	41.85	
MBG 23121-3807		—	—	—	—	27.3 \pm 4.6	—	40.04	
Tol 2326-405		—	—	37.3 \pm 0.7	43.7 \pm 2.2	—	—	41.56	
UM 167		—	—	—	—	73.2 \pm 3.5	—	41.39	
UM 191		30.3 \pm 2.2	—	39.2 \pm 0.9	32.0 \pm 0.4	33.3 \pm 3.5	—	40.90	

Table 6: Regressions for $\log L_{\text{H}\alpha}$ versus $\log \sigma_{\text{H}}$.

Linear Regression	Intercept (A)	Slope (B)	RMS
All galaxies (81 objects)			
Pearson correlation coefficient (r) = 0.85			
$\log L = A + B \times \log \sigma$			
OLS(Y X)	36.21 ± 0.32	3.01 ± 0.23	0.37
OLS(X Y)	34.52 ± 0.38	4.18 ± 0.27	
OLS Bisector	35.49 ± 0.32	3.51 ± 0.23	
Galaxies with Gaussian profiles (53 objects)			
$r = 0.88$			
OLS(Y X)	35.29 ± 0.42	3.72 ± 0.31	0.31
OLS(X Y)	33.73 ± 0.47	4.85 ± 0.34	
OLS Bisector	34.61 ± 0.41	4.22 ± 0.30	
More restrictive subsample (37 objects)			
$r = 0.90$			
OLS(Y X)	34.80 ± 0.41	4.14 ± 0.29	0.29
OLS(X Y)	33.45 ± 0.53	5.13 ± 0.38	
OLS Bisector	34.19 ± 0.43	4.58 ± 0.30	

Table 7: Correlation Matrix.

PCA $L_{\text{H}\alpha}$, σ_{H} , O/H, $W_{\text{H}\beta}$ and [OIII]/[OII] (95 objects)					
	$\log L_{\text{H}\alpha}$	$\log \sigma_{\text{H}}$	$\log (\text{O}/\text{H})$	$\log W_{\text{H}\beta}$	$\log [\text{OIII}]/[\text{OII}]$
	1	0.82	0.22	0.13	-0.03
	$\log L_{\text{H}\alpha}$	$\log \sigma_{\text{H}}$	$\log (\text{O}/\text{H})$	$\log W_{\text{H}\beta}$	$\log [\text{OIII}]/[\text{OII}]$

Table 8: Eigenvectors and eigenvalues.

	Principal component		
	I	II	III
$\log L_{\text{H}\alpha}$	0.39	-0.88	-0.11
$\log \sigma_{\text{H}}$	0.66	-0.70	-0.08
$\log (\text{O}/\text{H})$	0.86	0.07	0.51
$\log W_{\text{H}\beta}$	-0.77	-0.54	0.25
$\log [\text{OIII}]/[\text{OII}]$	-0.88	-0.38	0.16
Eigenvalues	2.69	1.70	0.37
% variance	53.9%	34.0%	7.3%

Table 9: Testing the second parameter through individual principal component analysis - 95 objects undistinguished by their emission line profiles.

Parameter	Principal Component		
	I	II	III
$\log L_{\text{H}\alpha}$	0.88	-0.42	0.23
$\log \sigma_{\text{H}}$	0.96	-0.12	-0.27
$\log (\text{O}/\text{H})$	0.61	0.79	0.09
Eigenvalues	68.5%	27.0%	4.5%
$\log L_{\text{H}\alpha}$	0.95	0.18	-0.25
$\log \sigma_{\text{H}}$	0.96	-0.15	0.25
$\log W_{\text{H}\beta}$	-0.03	0.99	0.08
Eigenvalues	60.8%	34.9%	4.3%
$\log L_{\text{H}\alpha}$	-0.90	-0.36	0.24
$\log \sigma_{\text{H}}$	-0.97	-0.03	-0.25
$\log [\text{OIII}]/[\text{OII}]$	0.38	-0.92	-0.08
Eigenvalues	63.2%	32.6%	4.2%

Table 10: Multiple regressions for $L_{\text{H}\alpha}$, σ_{H} , O/H, $W_{\text{H}\beta}$ and $[\text{OIII}]/[\text{OII}]$.

Parameters	Regressions for $\log L_{\text{H}\alpha}$	RMS
Galaxies with Gaussian profiles (53 objects) ¹		
$L-\sigma$	$(35.29 \pm 0.42) + (3.72 \pm 0.31)\log \sigma$	0.312
$L-\sigma\text{-O/H}$	$(38.22 \pm 1.02) + (4.19 \pm 0.31)\log \sigma - (0.44 \pm 0.14)\log(\text{O}/\text{H})$	0.289
$L-\sigma\text{-}W_{\text{H}\beta}$	$(34.60 \pm 0.39) + (3.84 \pm 0.25)\log \sigma + (0.32 \pm 0.08)\log W_{\text{H}\beta}$	0.274
$L-\sigma\text{-}[\text{OIII}]/[\text{OII}]$	$(34.69 \pm 0.38) + (4.06 \pm 0.27)\log \sigma + (0.34 \pm 0.09)\log [\text{OIII}]/[\text{OII}]$	0.275
$L-\sigma\text{-O/H-}W_{\text{H}\beta}$	$(35.63 \pm 1.43) + (3.96 \pm 0.31)\log \sigma - (0.14 \pm 0.18)\log(\text{O}/\text{H}) + (0.27 \pm 0.11)\log W_{\text{H}\beta}$	0.275
$L-\sigma\text{-O/H-}[\text{OIII}]/[\text{OII}]$	$(35.95 \pm 1.01) + (4.17 \pm 0.22)\log \sigma - (0.17 \pm 0.17)\log(\text{O}/\text{H}) + (0.27 \pm 0.11)\log [\text{OIII}]/[\text{OII}]$	0.275
Galaxies with Gaussian profiles (45 objects) without outliers.		
$L-\sigma$	$(35.26 \pm 0.38) + (3.76 \pm 0.27)\log \sigma$	0.270
$L-\sigma\text{-O/H}$	$(39.94 \pm 0.99) + (4.33 \pm 0.25)\log \sigma - (0.68 \pm 0.14)\log(\text{O}/\text{H})$	0.217
$L-\sigma\text{-}W_{\text{H}\beta}$	$(34.58 \pm 0.30) + (3.78 \pm 0.20)\log \sigma + (0.39 \pm 0.06)\log W_{\text{H}\beta}$	0.201
$L-\sigma\text{-}[\text{OIII}]/[\text{OII}]$	$(34.64 \pm 0.30) + (4.09 \pm 0.21)\log \sigma + (0.39 \pm 0.07)\log [\text{OIII}]/[\text{OII}]$	0.204
$L-\sigma\text{-O/H-}W_{\text{H}\beta}$	$(36.64 \pm 1.38) + (4.01 \pm 0.25)\log \sigma - (0.27 \pm 0.18)\log(\text{O}/\text{H}) + (0.29 \pm 0.09)\log W_{\text{H}\beta}$	0.197
$L-\sigma\text{-O/H-}[\text{OIII}]/[\text{OII}]$	$(37.04 \pm 1.29) + (4.26 \pm 0.22)\log \sigma - (0.32 \pm 0.17)\log(\text{O}/\text{H}) + (0.28 \pm 0.09)\log [\text{OIII}]/[\text{OII}]$	0.198

1.- The same subsample with 53 G objects used in Table 6.

Table 11: PCA for calibration sample (45 objects) without outliers.

Parameter	Principal Component		
	I	II	III
$\log L_{\text{H}\alpha}$	0.90	-0.40	0.15
$\log \sigma_{\text{H}}$	0.98	-0.11	-0.16
$\log (\text{O}/\text{H})$	0.57	0.82	0.05
Eigenvalues	70.2%	28.1%	1.7%
$\log L_{\text{H}\alpha}$	0.99	0.02	-0.16
$\log \sigma_{\text{H}}$	0.95	-0.29	0.15
$\log W_{\text{H}\beta}$	0.26	0.96	0.05
Eigenvalues	64.6%	33.7%	1.7%
$\log L_{\text{H}\alpha}$	0.95	0.29	-0.15
$\log \sigma_{\text{H}}$	0.99	-0.02	0.15
$\log [\text{OIII}]/[\text{OII}]$	-0.26	0.96	0.05
Eigenvalues	64.6%	33.8%	1.6%

Table 12: Measuring multicollinearity by condition number.

Regressions	l_{\max}	l_{\max}	cn
$L-\sigma-\text{O}/\text{H}$	1.47	0.53	1.66
$L-\sigma-W_{\text{H}\beta}$	1.02	0.98	1.02
$L-\sigma-[\text{OIII}]/[\text{OII}]$	1.27	0.73	1.32
$L-\sigma-\text{O}/\text{H}-W_{\text{H}\beta}$	1.81	0.21	2.91
$L-\sigma-\text{O}/\text{H}-[\text{OIII}]/[\text{OII}]$	1.98	0.26	2.74

Capítulo 5

Conclusões

Neste trabalho, fomos capazes de identificar aspectos fundamentais da cinemática da região HII gigante em II Zw 40 através da espectroscopia bidimensional. A região estudada apresenta diversas propriedades em comum com aquelas de regiões do Grupo Local, como 30 Doradus e NGC 604, ainda que represente uma versão distante de maiores proporções e escalas galácticas típicas de galáxias HII. Buscamos compreender a origem da dispersão de velocidades (σ) encontrada nesses sistemas. Verificamos que bolhas em expansão, possíveis produtos da evolução estelar massiva, estão presentes e ocupam um volume significativo da região HII gigante, entretanto contribuem pouco para o fluxo total H α . A presença de ventos de estrelas massivas no núcleo dessas regiões não foi verificada diretamente, pois não é resolvida em escalas de dezenas de parsecs. Entretanto, a componente larga fraca subjacente, detectada no perfil de linha da região nuclear, pode estar associada ao efeito desses ventos agindo em escalas de subparsec. O que predomina, portanto, é uma componente turbulenta suave que permeia praticamente

toda a região e está presente em todo intervalo de intensidade. Regiões aparentemente pouco perturbadas pela formação estelar foram detectadas e podem indicar a presença de um campo turbulento de dispersão de velocidades mínimas, e que interpretamos como sendo imposto pelo potencial gravitacional. Este campo de velocidades mínimas por sua vez não é muito diferente daquele encontrado na região nuclear brilhante e característico de toda a região HII. Assim, concluímos que a gravitação é o mecanismo dominante que impõe a dispersão de velocidades característica da região de formação estelar. Verificamos que a assimetria observada no perfil global de II Zw 40 pode estar associada a presença de múltiplos sítios de formação estelar, possivelmente associados a super aglomerados estelares. Este pode ser considerado como sendo o efeito multiplicidade agindo sobre a medida de σ resultante, ainda que este efeito seja pequeno em II Zw 40.

Se a gravitação é o principal mecanismo físico de agitação do gás nebuloso em galáxias HII, pelo menos nos primeiros milhões de anos da evolução do *starburst*, as larguras dos seus perfis de linha integrados podem de fato conter a informação sobre a massa total do sistema a partir da hipótese de equilíbrio do virial. Isso pode explicar a existência da relação $L-\sigma$ encontrada primeiramente por Melnick et al. (1988) e verificada aqui para uma amostra significativamente maior e com dados de alta qualidade. Verificamos que as galáxias que mais estreitamente seguem a relação $L-\sigma$ são aquelas que apresentam também os perfis de linha mais regulares, isto é, Gaussianos. Este critério, portanto, seleciona as galáxias HII alvos da relação $L-\sigma$ e representam assim uma amostra homogênea do ponto de vista cinemático. Além disso este critério pode ser eficiente em selecionar aquelas galáxias que menos sofrem

de efeitos sistemáticos observacionais, como o efeito de abertura e multiplicidade. Identificamos que os efeitos sistemáticos sobre a relação $L-\sigma$, e que afetam mais diretamente o parâmetro dependente L (Balmer), são devidos à evolução do *starburst* e à metalicidade. Testamos os parâmetros independentes adicionais largura equivalente $H\beta$ ($W_{H\beta}$) e $[OIII]/[OII]$, como medidas da evolução do *starburst*, e a razão O/H como medida da metalicidade. Ambos efeitos contribuem separadamente para a redução do espalhamento observacional da relação $L-\sigma$, com preferência para os parâmetros que medem a evolução do *starburst*, representando portanto o efeito de primeira ordem ou de curto-prazo, pois age diretamente sobre L no decorrer da evolução de cada *starburst* (poucos Mega-anos). A metalicidade dada pela razão O/H, como proposta por Melnick et al. (1988), pode de fato representar um segundo parâmetro na relação $L-\sigma$, entretanto, representa um efeito de segunda ordem, ou de evolução de longo-prazo, pois afeta globalmente L de cada *starburst*, devido ao enriquecimento químico promovido por gerações de estrelas oriundas de sucessivos *starbursts* ocorridos durante toda a história de formação estelar da galáxia (Giga-anos). Ambos os efeitos sobre a luminosidade do *starburst* são tópicos de intenso debate na literatura no contexto de condições físicas em galáxias HII e investigados a luz de modelos de fotoionização (Stasińska & Leitherer 1996; Stasińska & Izotov 2003; Martín-Manjón et al. 2008). Estes modelos podem alimentar as investigações sobre a relação $L-\sigma$ das galáxias HII fornecendo parâmetros independentes alternativos aos testados aqui como preditores de L . Recalibrarmos a relação $L-\sigma$ -O/H considerada como o indicador de distâncias das galáxias HII (Melnick et al. 1988) e fornecemos um conjunto novo de relações empíricas que podem servir como

indicadores de distâncias alternativos de galáxias HII com interesses cosmológicos.

Bibliografia

- Aaronson, M. & Mould, J. 1983, ApJ, 265, 1
- Bordalo, V., Plana, H., & Telles, E. 2009, ApJ, 696, 1668
- Brosche, P. 1973, A&A, 23, 259
- Castor, J., McCray, R., & Weaver, R. 1975, ApJ, 200, L107
- Chu, Y.-H. & Kennicutt, Jr., R. C. 1994, ApJ, 425, 720
- Copetti, M. V. F., Pastoriza, M. G., & Dottori, H. A. 1986, A&A, 156, 111
- Denicoló, G., Terlevich, R., & Terlevich, E. 2002, MNRAS, 330, 69
- Djorgovski, S. & Davis, M. 1987, ApJ, 313, 59
- Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R. L., Faber, S. M., Terlevich, R., & Wegner, G. 1987, ApJ, 313, 42
- Dyson, J. E. 1979, A&A, 73, 132
- Eisenstein, D. J. & Loeb, A. 1996, ApJ, 459, 432
- Erb, D. K., Shapley, A. E., Steidel, C. C., Pettini, M., Adelberger, K. L., Hunt, M. P., Moorwood, A. F. M., & Cuby, J.-G. 2003, ApJ, 591, 101

- Faber, S. M. & Jackson, R. E. 1976, ApJ, 204, 668
- Fish, R. A. 1964, ApJ, 139, 284
- García-Díaz, M. T., Henney, W. J., López, J. A., & Doi, T. 2008, Revista Mexicana de Astronomia y Astrofisica, 44, 181
- Guzmán, R., Gallego, J., Koo, D. C., Phillips, A. C., Lowenthal, J. D., Faber, S. M., Illingworth, G. D., & Vogt, N. P. 1997, ApJ, 489, 559
- Haro, G. 1951, PASP, 63, 144
- . 1956a, Boletin de los Observatorios Tonantzintla y Tacubaya, 2, 8
- . 1956b, Mitteilungen der Astronomischen Gesellschaft Hamburg, 7, 60
- Hippelein, H. H. 1986, A&A, 160, 374
- Humason, M. L. & Zwicky, F. 1947, ApJ, 105, 85
- Izotov, Y. I., Stasińska, G., Meynet, G., Guseva, N. G., & Thuan, T. X. 2006, A&A, 448, 955
- Izotov, Y. I. & Thuan, T. X. 1998, ApJ, 500, 188
- Izotov, Y. I., Thuan, T. X., & Lipovetsky, V. A. 1994, ApJ, 435, 647
- . 1997, ApJS, 108, 1
- Jorgensen, I., Franx, M., & Kjaergaard, P. 1995a, MNRAS, 273, 1097
- . 1995b, MNRAS, 276, 1341
- . 1996, MNRAS, 280, 167

- Kehrig, C., Telles, E., & Cuisinier, F. 2004, AJ, 128, 1141
- Kelson, D. D., Illingworth, G. D., Tonry, J. L., Freedman, W. L., Kennicutt, Jr., R. C., Mould, J. R., Graham, J. A., Huchra, J. P., Macri, L. M., Madore, B. F., Ferrarese, L., Gibson, B. K., Sakai, S., Stetson, P. B., Ajhar, E. A., Blakeslee, J. P., Dressler, A., Ford, H. C., Hughes, S. M. G., Sebo, K. M., & Silbermann, N. A. 2000, ApJ, 529, 768
- Kniazev, A. Y., Pustilnik, S. A., Grebel, E. K., Lee, H., & Pramskij, A. G. 2004, ApJS, 153, 429
- Lagos, P. 2008, PhD thesis, Observatório Nacional-MCT, (2008)
- Lagos, P., Telles, E., & Melnick, J. 2007, A&A, 476, 89
- Lequeux, J., Peimbert, M., Rayo, J. F., Serrano, A., & Torres-Peimbert, S. 1979, A&A, 80, 155
- MacAlpine, G. M. & Williams, G. A. 1981, ApJS, 45, 113
- Maíz-Apellániz, J., Muñoz-Tuñón, C., Tenorio-Tagle, G., & Mas-Hesse, J. M. 1999, A&A, 343, 64
- Markarian, B. E. 1967, Astrofizika, 3, 55
- Martín-Manjón, M. L., Mollá, M., Díaz, A. I., & Terlevich, R. 2008, MNRAS, 385, 854
- Mayall, N. U. 1951, PASP, 63, 294
- McCray, R. & Kafatos, M. 1987, ApJ, 317, 190

- Melbourne, J. & Salzer, J. J. 2002, AJ, 123, 2302
- Melnick, J. 1979, ApJ, 228, 112
- Melnick, J., Moles, M., Terlevich, R., & Garcia-Pelayo, J.-M. 1987, MNRAS, 226, 849
- Melnick, J., Tenorio-Tagle, G., & Terlevich, R. 1999, MNRAS, 302, 677
- Melnick, J., Terlevich, R., & Moles, M. 1988, MNRAS, 235, 297
- Melnick, J., Terlevich, R., & Terlevich, E. 2000, MNRAS, 311, 629
- Mo, H. J., Mao, S., & White, S. D. M. 1998, MNRAS, 295, 319
- Muñoz-Tuñón, C., Gavryusev, V., & Castoneda, H. O. 1995, AJ, 110, 1630
- Muñoz-Tuñón, C., Tenorio-Tagle, G., Castaneda, H. O., & Terlevich, R. 1996, AJ, 112, 1636
- Öpik, E. 1922, ApJ, 55, 406
- Osterbrock, D. E. 1989, Astrophysics of gaseous nebulae and active galactic nuclei, ed. D. E. Osterbrock
- Pagel, B. E. J., Simonson, E. A., Terlevich, R. J., & Edmunds, M. G. 1992, MNRAS, 255, 325
- Papaderos, P., Guseva, N. G., Izotov, Y. I., Noeske, K. G., Thuan, T. X., & Fricke, K. J. 2006, A&A, 457, 45
- Pettini, M., Shapley, A. E., Steidel, C. C., Cuby, J.-G., Dickinson, M., Moorwood, A. F. M., Adelberger, K. L., & Giavalisco, M. 2001, ApJ, 554, 981

- Phillips, A. C., Guzmán, R., Gallego, J., Koo, D. C., Lowenthal, J. D., Vogt, N. P., Faber, S. M., & Illingworth, G. D. 1997, *ApJ*, 489, 543
- Pilyugin, L. S. 2000, *A&A*, 362, 325
- Roberts, M. S. 1969, *AJ*, 74, 859
- Roy, J.-R., Arsenault, R., & Joncas, G. 1986, *ApJ*, 300, 624
- Sakai, S., Mould, J. R., Hughes, S. M. G., Huchra, J. P., Macri, L. M., Kennicutt, Jr., R. C., Gibson, B. K., Ferrarese, L., Freedman, W. L., Han, M., Ford, H. C., Graham, J. A., Illingworth, G. D., Kelson, D. D., Madore, B. F., Sebo, K., Silbermann, N. A., & Stetson, P. B. 2000, *ApJ*, 529, 698
- Sargent, W. L. W. & Searle, L. 1970, *ApJ*, 162, L155+
- Scalo, J. & Chappell, D. 1999, *MNRAS*, 310, 1
- Scott, P., Asplund, M., Grevesse, N., & Sauval, A. J. 2009, *ApJ*, 691, L119
- Searle, L. & Sargent, W. L. W. 1972, *ApJ*, 173, 25
- Seyfert, C. K. 1943, *ApJ*, 97, 28
- Shaw, R. A. & Dufour, R. J. 1995, *PASP*, 107, 896
- Shklovskii, I. S. 1962, *AZh*, 39, 209
- Siegel, E. R., Guzmán, R., Gallego, J. P., Orduña López, M., & Rodríguez Hidalgo, P. 2005, *MNRAS*, 356, 1117
- Skillman, E. D. & Kennicutt, Jr., R. C. 1993, *ApJ*, 411, 655

Smith, M. G., Aguirre, C., & Zemelman, M. 1976, ApJS, 32, 217

Smith, M. G. & Weedman, D. W. 1970, ApJ, 161, 33

—. 1972, ApJ, 172, 307

Stasińska, G. 1990, A&AS, 83, 501

Stasińska, G. & Izotov, Y. 2003, A&A, 397, 71

Stasińska, G. & Leitherer, C. 1996, ApJS, 107, 661

Steinmetz, M. & Navarro, J. F. 1999, ApJ, 513, 555

Telles, E. & Terlevich, R. 1993, Ap&SS, 205, 49

—. 1997, MNRAS, 286, 183

Telles, J. E. 1995, PhD thesis, Univ. Cambridge, (1995)

Tenorio-Tagle, G., Muñoz-Tuñón, C., & Cid-Fernandes, R. 1996, ApJ, 456, 264

Tenorio-Tagle, G., Muñoz-Tuñón, C., & Cox, D. P. 1993, ApJ, 418, 767

Terlevich, R. & Melnick, J. 1981, MNRAS, 195, 839

Tully, R. B. & Fisher, J. R. 1977, A&A, 54, 661

Weaver, R., McCray, R., Castor, J., Shapiro, P., & Moore, R. 1977, ApJ, 218, 377

Westera, P., Cuisinier, F., Telles, E., & Kehrig, C. 2004, A&A, 423, 133

- Whitford, A. E. 1958, AJ, 63, 201
- Williams, R. E., Blacker, B., Dickinson, M., Dixon, W. V. D., Ferguson, H. C., Fruchter, A. S., Giavalisco, M., Gilliland, R. L., Heyer, I., Katsanis, R., Levay, Z., Lucas, R. A., McElroy, D. B., Petro, L., Postman, M., Adorf, H.-M., & Hook, R. 1996, AJ, 112, 1335
- Woltjer, L. 1970, in IAU Symposium, Vol. 39, Interstellar Gas Dynamics, ed. H. J. Habing, 229–+
- Yang, H., Chu, Y.-H., Skillman, E. D., & Terlevich, R. 1996, AJ, 112, 146
- Yao, L., Bell, T. A., Viti, S., Yates, J. A., & Seaquist, E. R. 2006, ApJ, 636, 881
- Zwicky, F., Herzog, E., & Wild, P. 1966, Catalogue of galaxies and of clusters of galaxies, Vol. 3, ed. F. Zwicky, E. Herzog, & P. Wild
- Zwicky, I. F. 1964, ApJ, 140, 1467

Apêndice A

Catálogo de Perfis de Linha

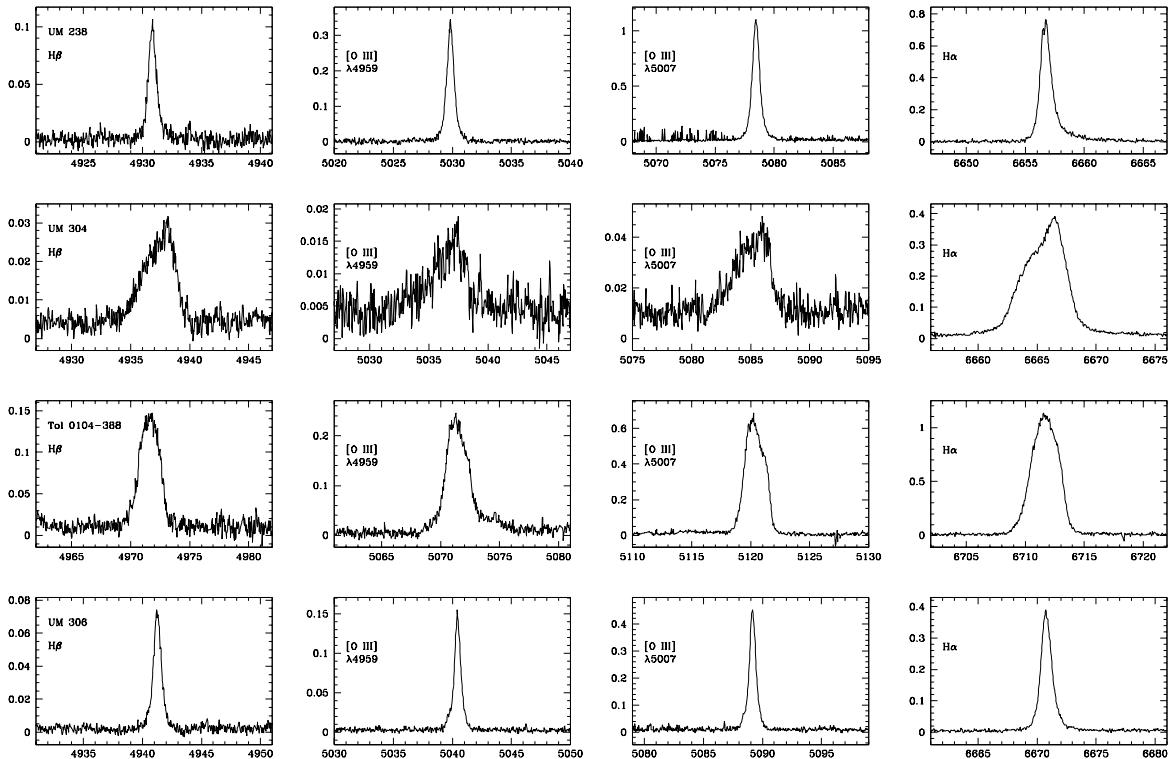
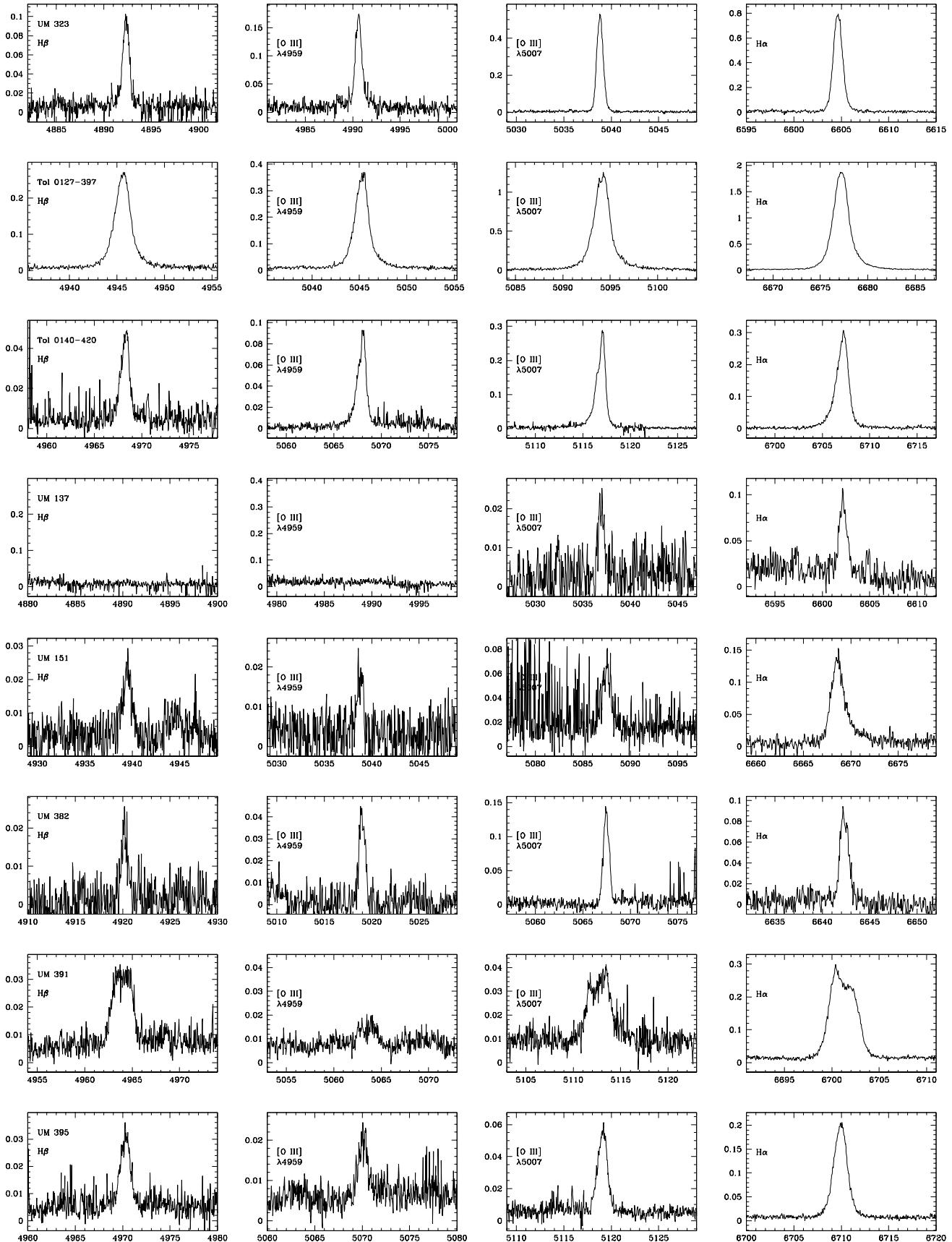
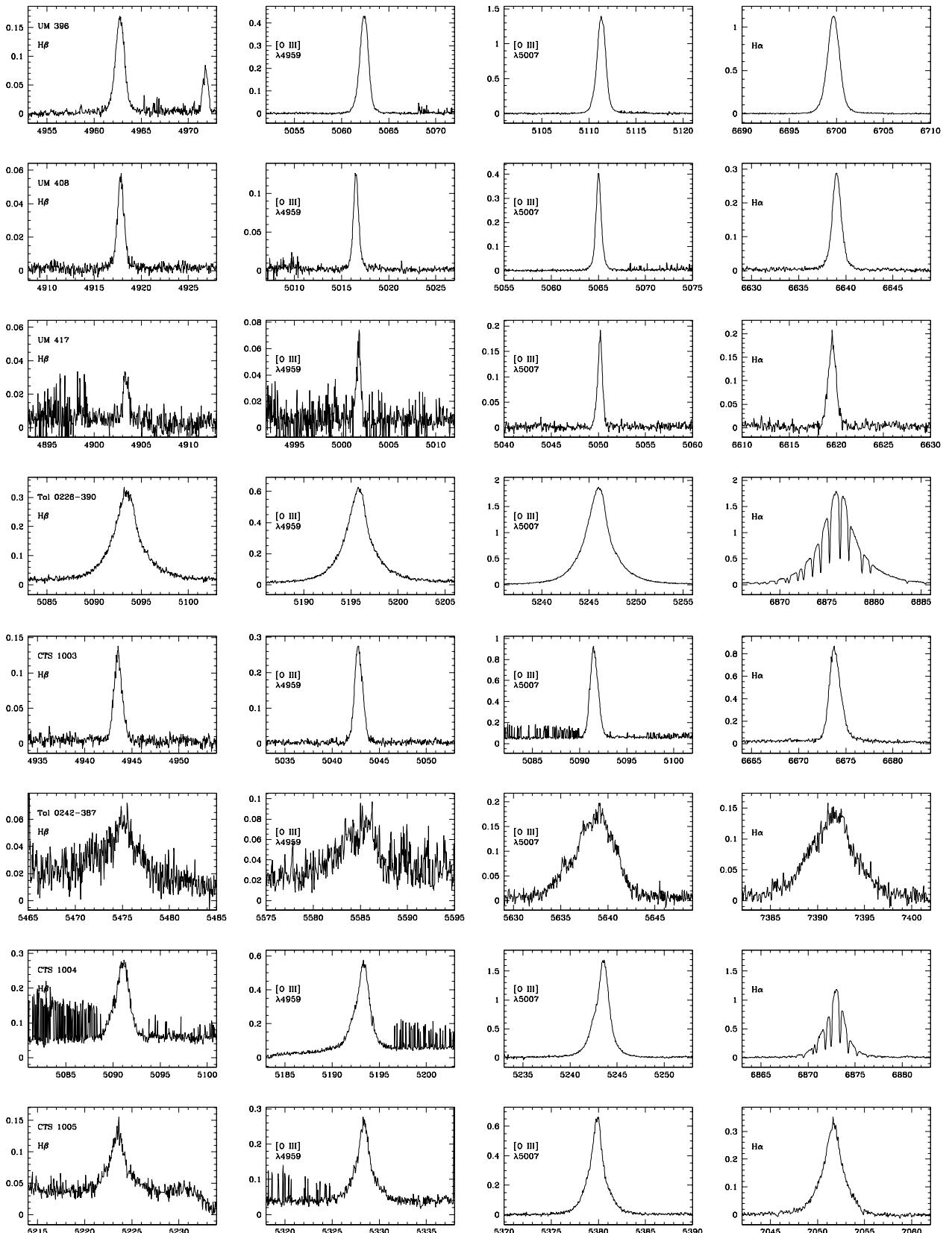


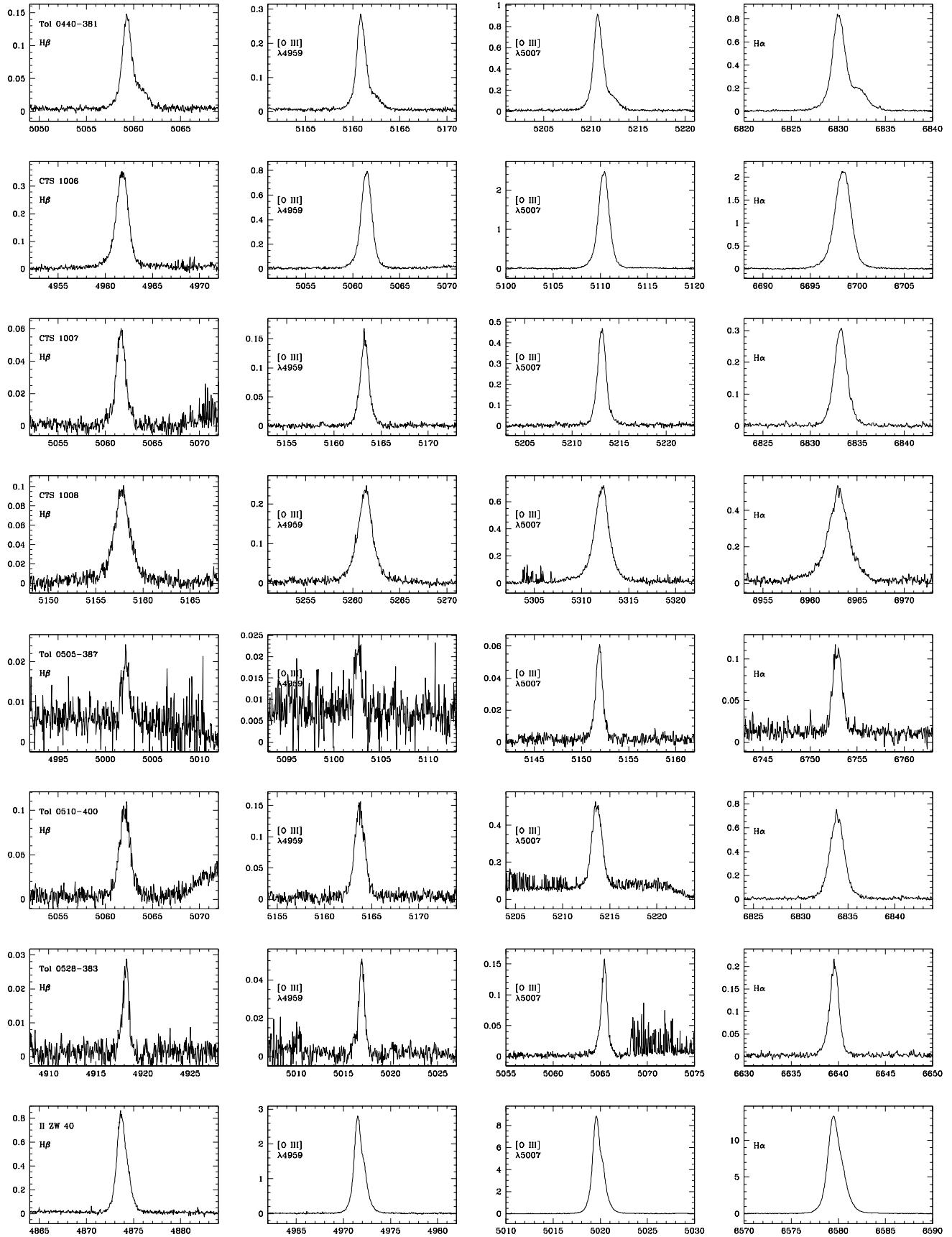
Figura A.1: Perfis $H\beta$, $[O III]\lambda\lambda 4959, 5007$ e $H\alpha$ obtidos dos espectros FEROS. O eixo y corresponde ao fluxo relativo (não calibrado) e o eixo x ao comprimento de onda em ångström (\AA).

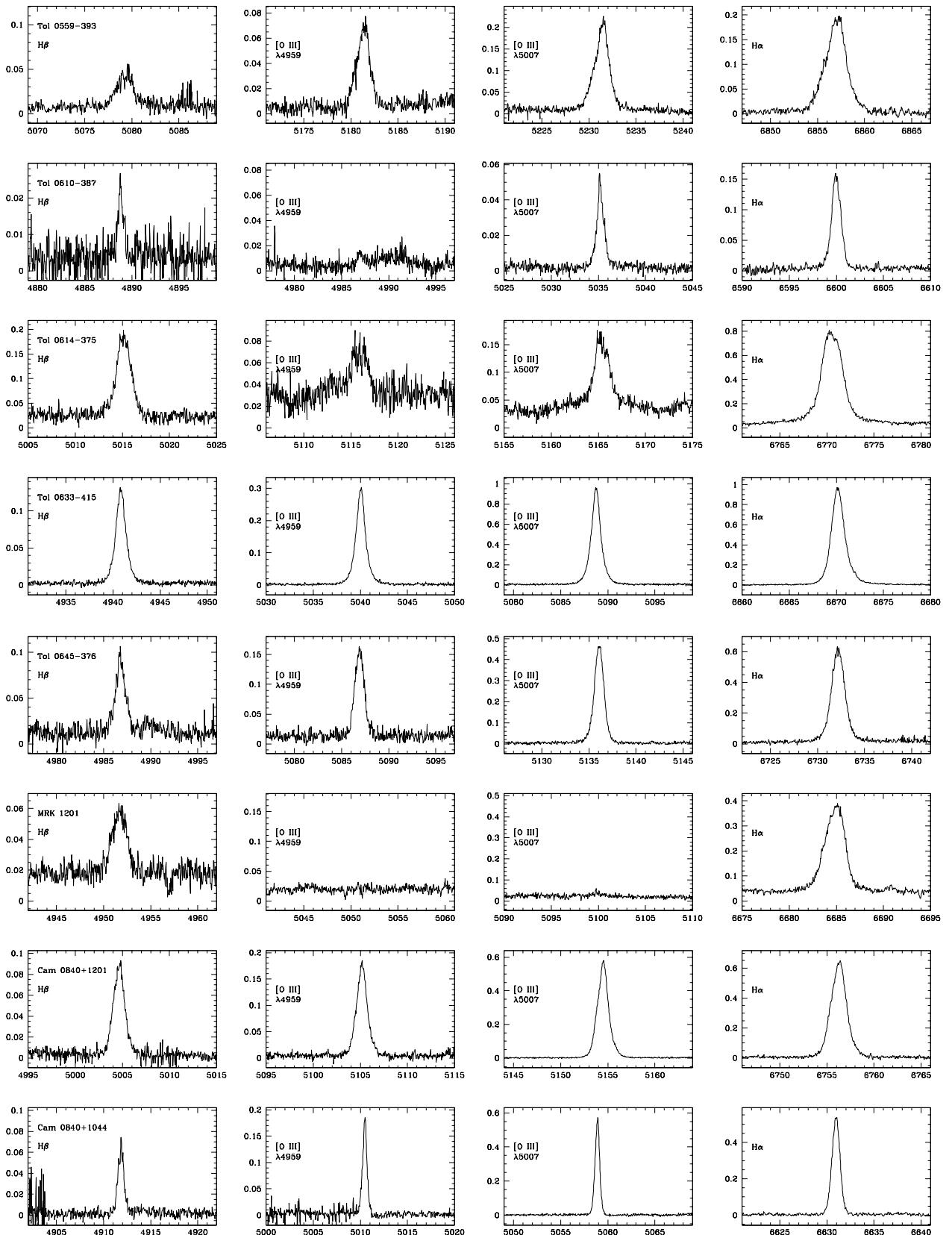
APÊNDICE A. CATÁLOGO DE PERFIS DE LINHA



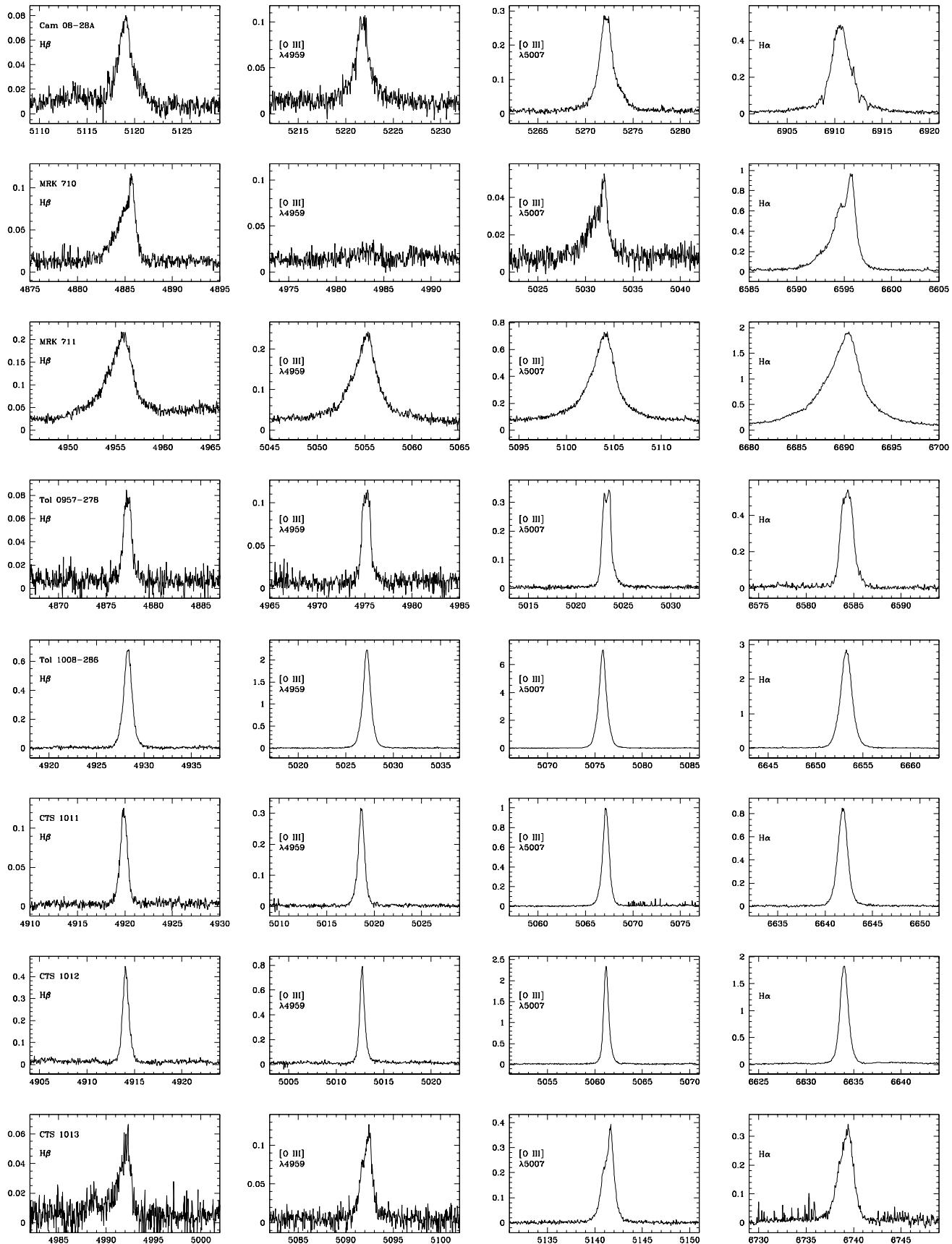


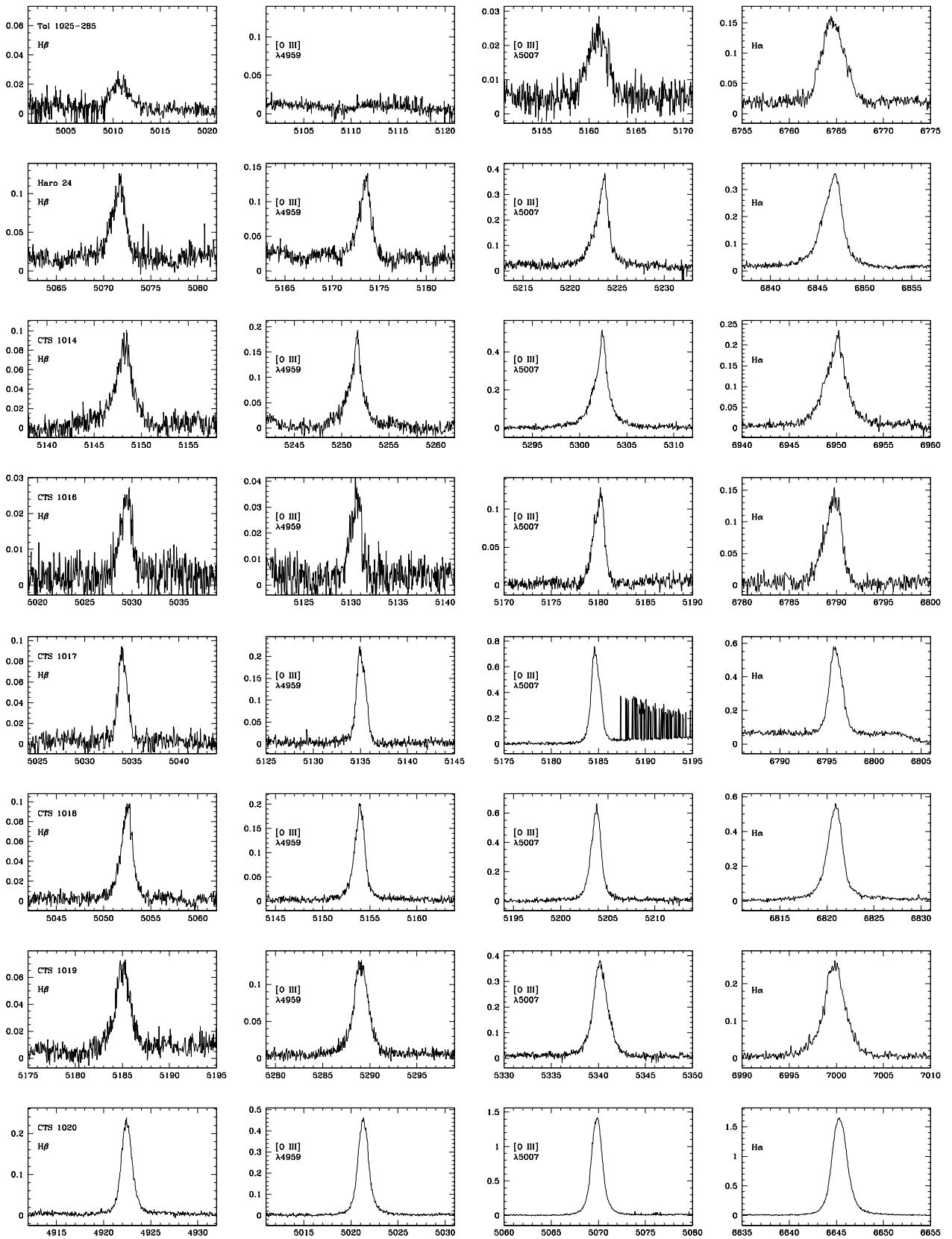
APÊNDICE A. CATÁLOGO DE PERFIS DE LINHA



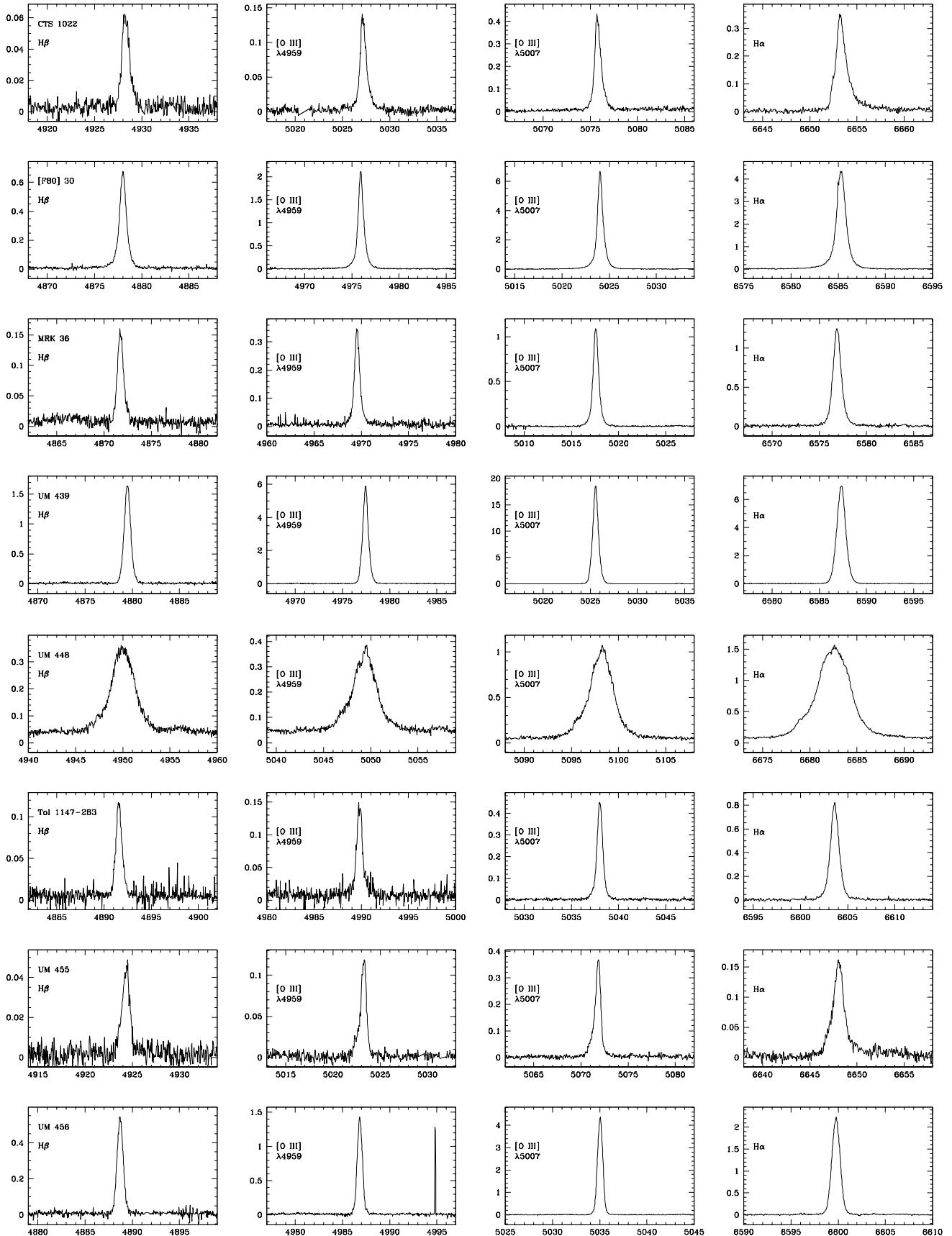


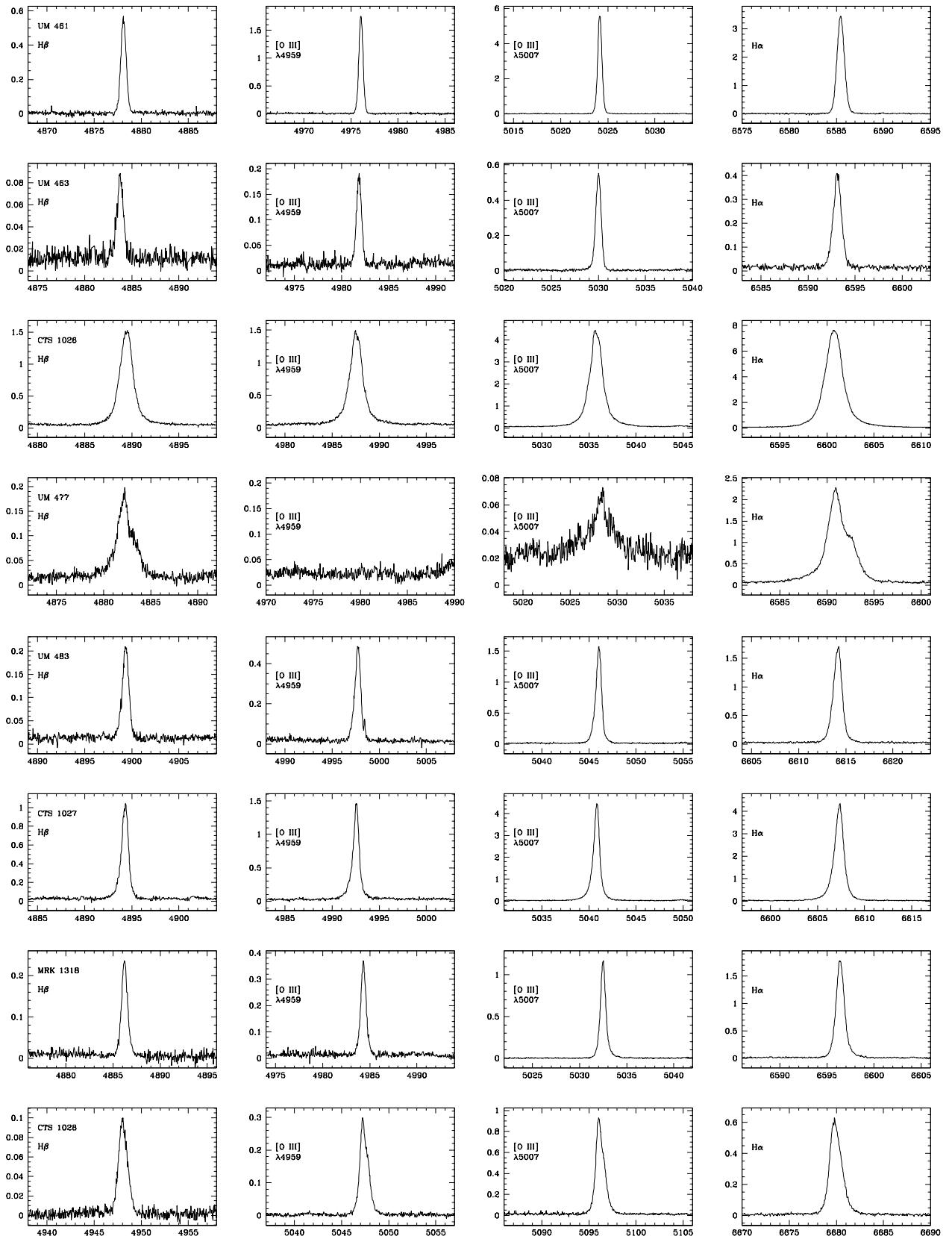
APÊNDICE A. CATÁLOGO DE PERFIS DE LINHA



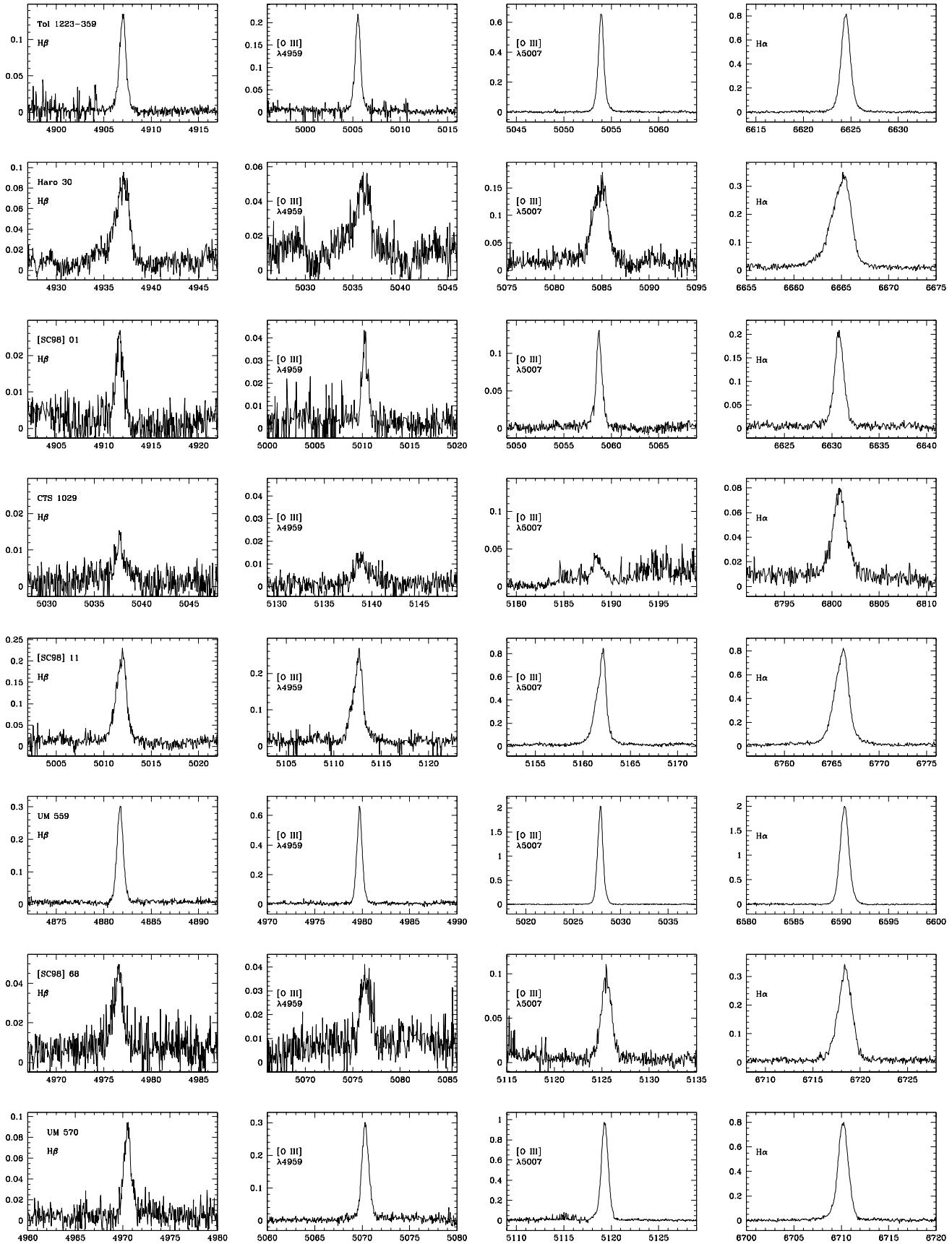


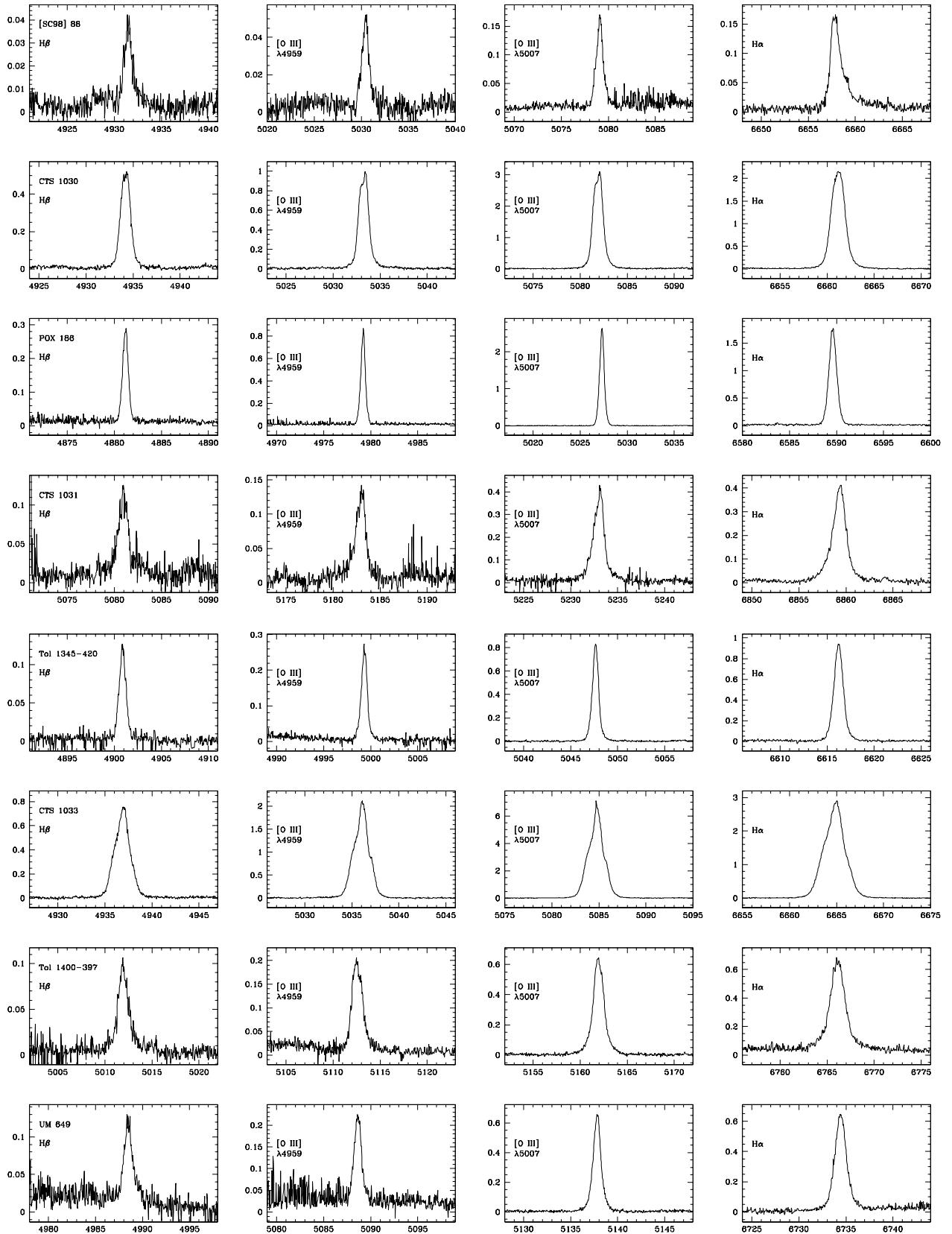
APÊNDICE A. CATÁLOGO DE PERFIS DE LINHA



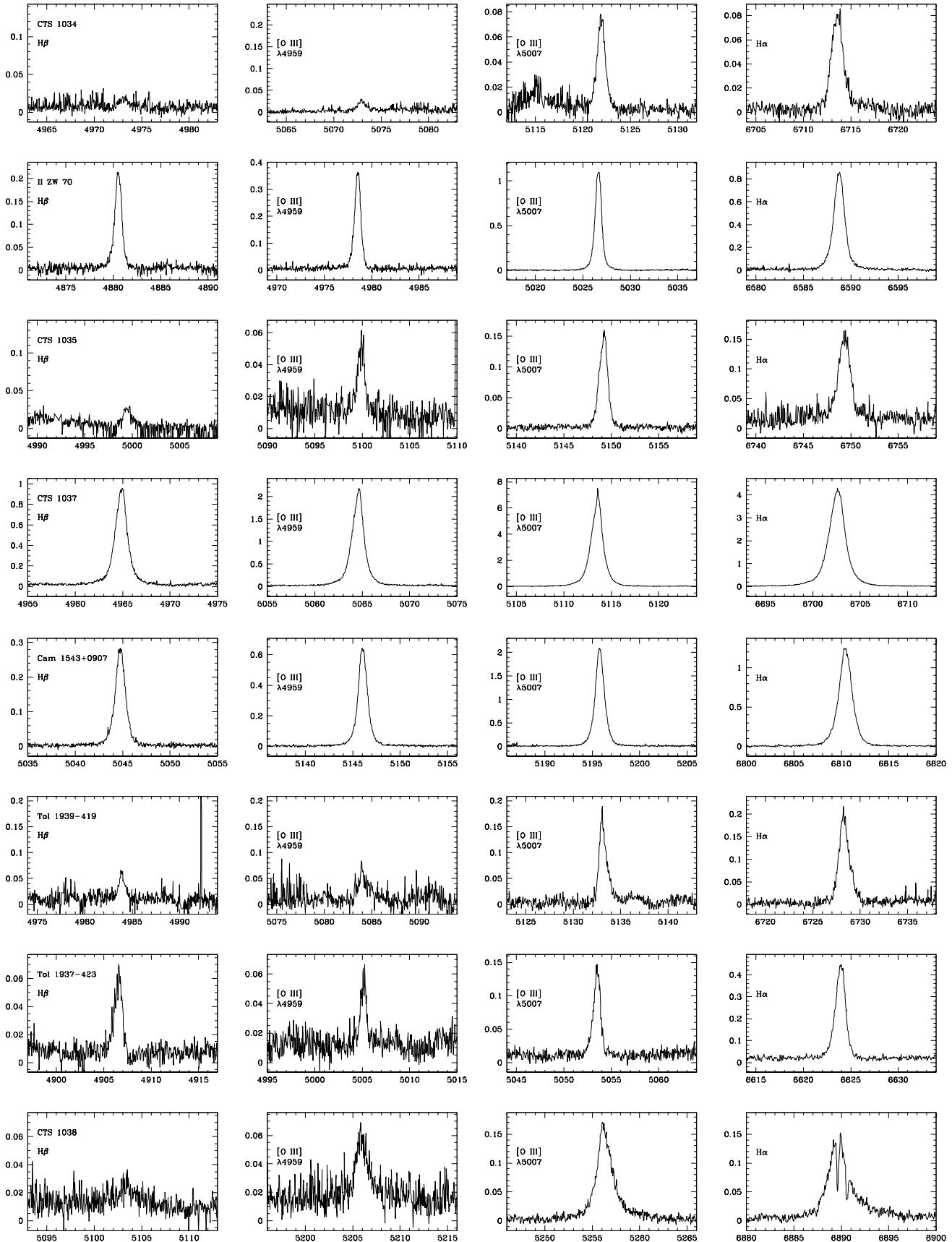


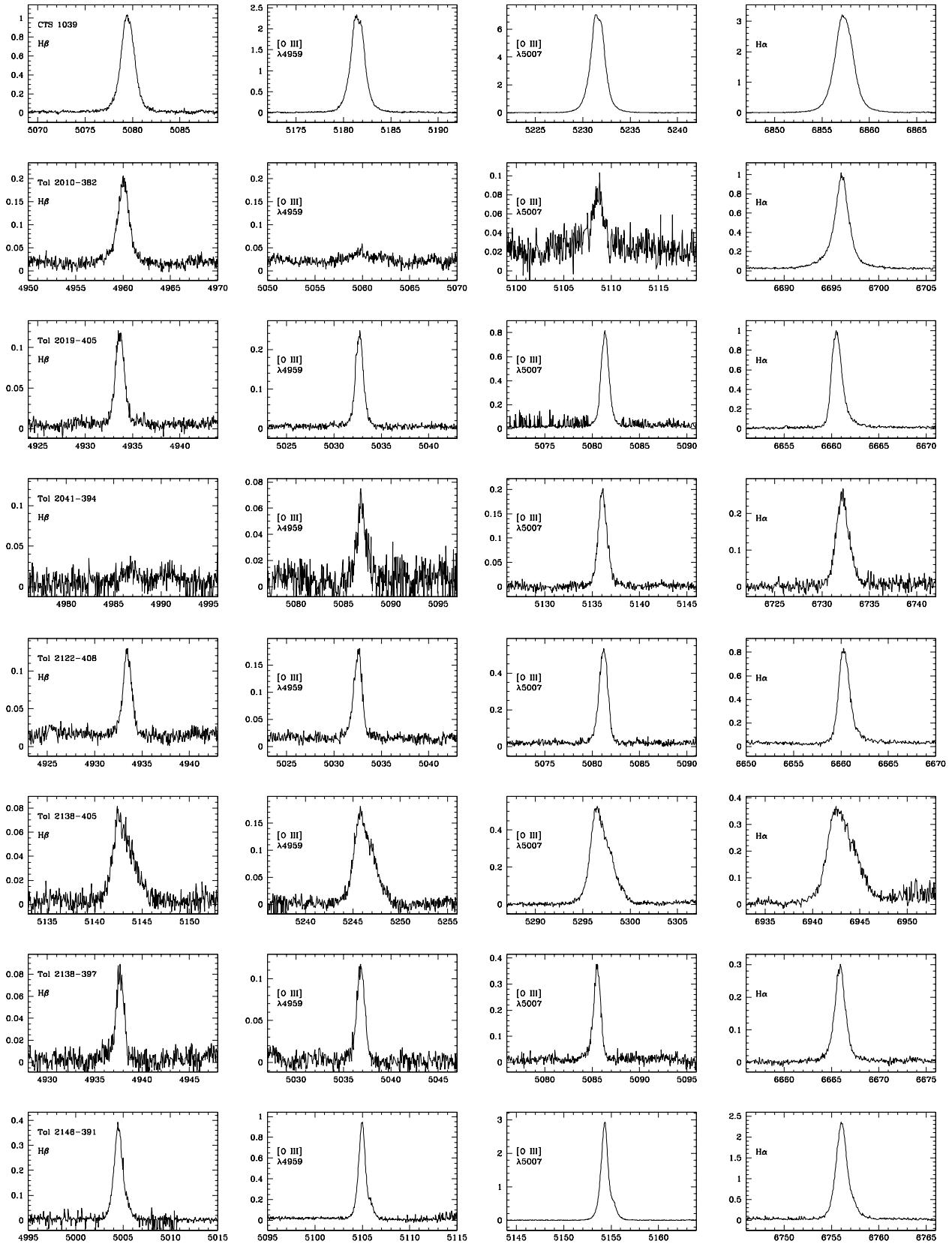
APÊNDICE A. CATÁLOGO DE PERFIS DE LINHA



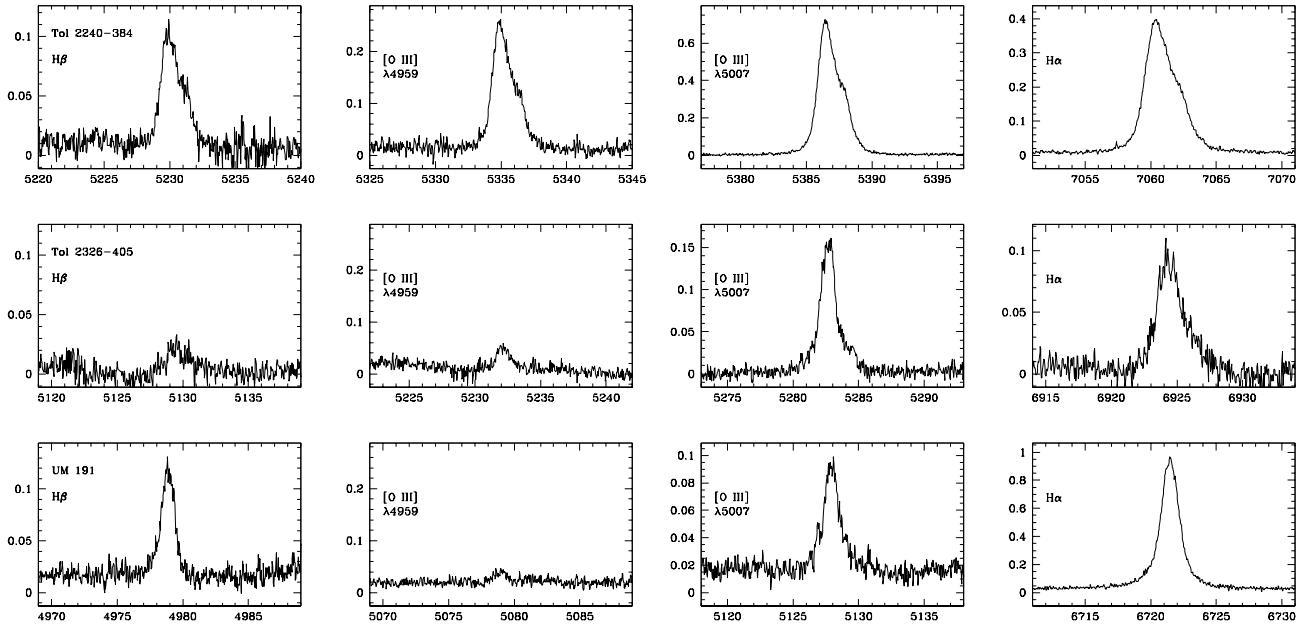


APÊNDICE A. CATÁLOGO DE PERFIS DE LINHA





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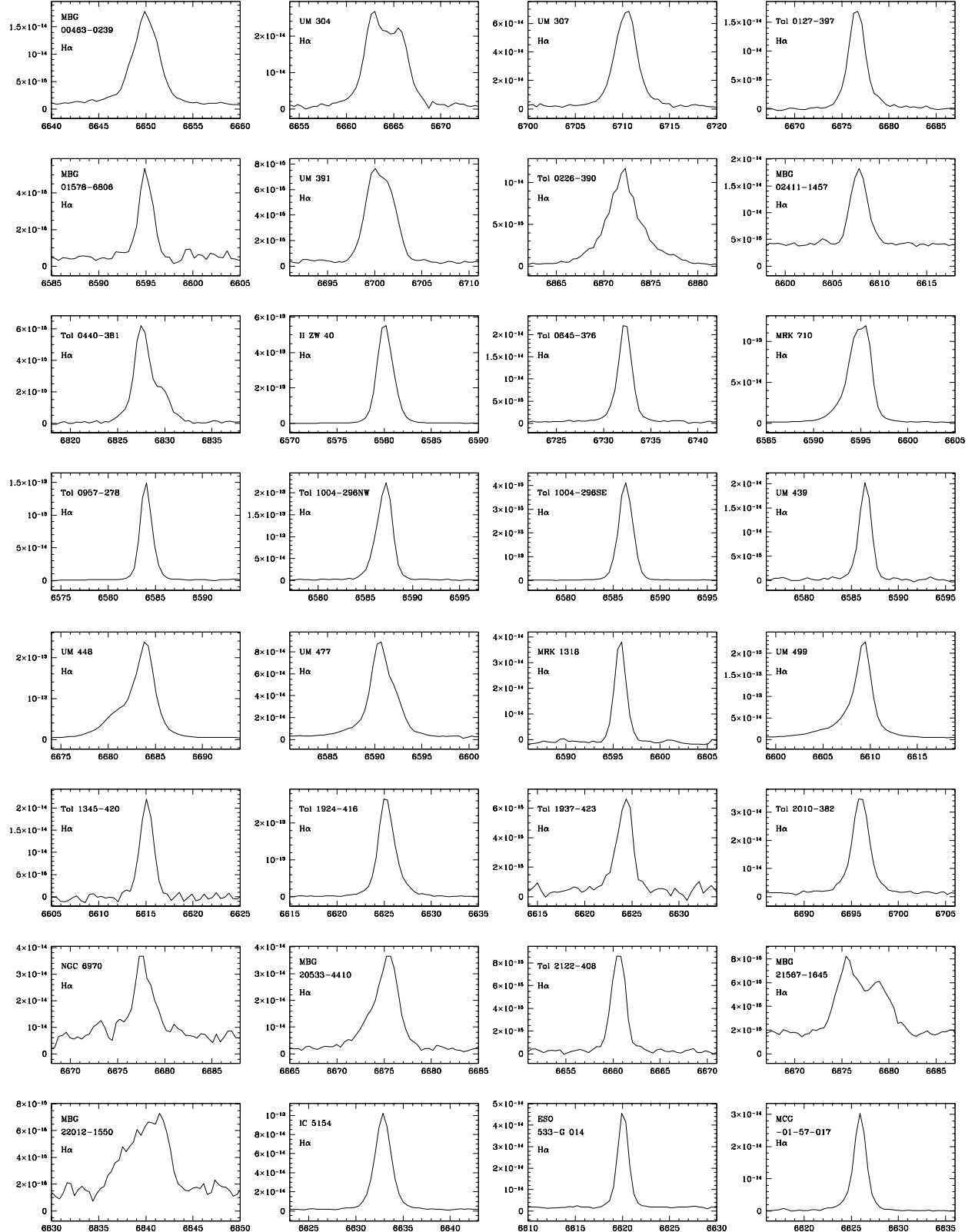
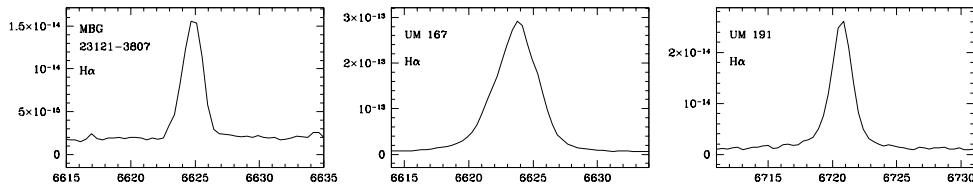


Figura A.2: Perfis H α dos espectros Coudé. O eixo y corresponde ao fluxo calibrado em erg s $^{-1}$ cm $^{-2}$ e o eixo x ao comprimento de onda em Å.



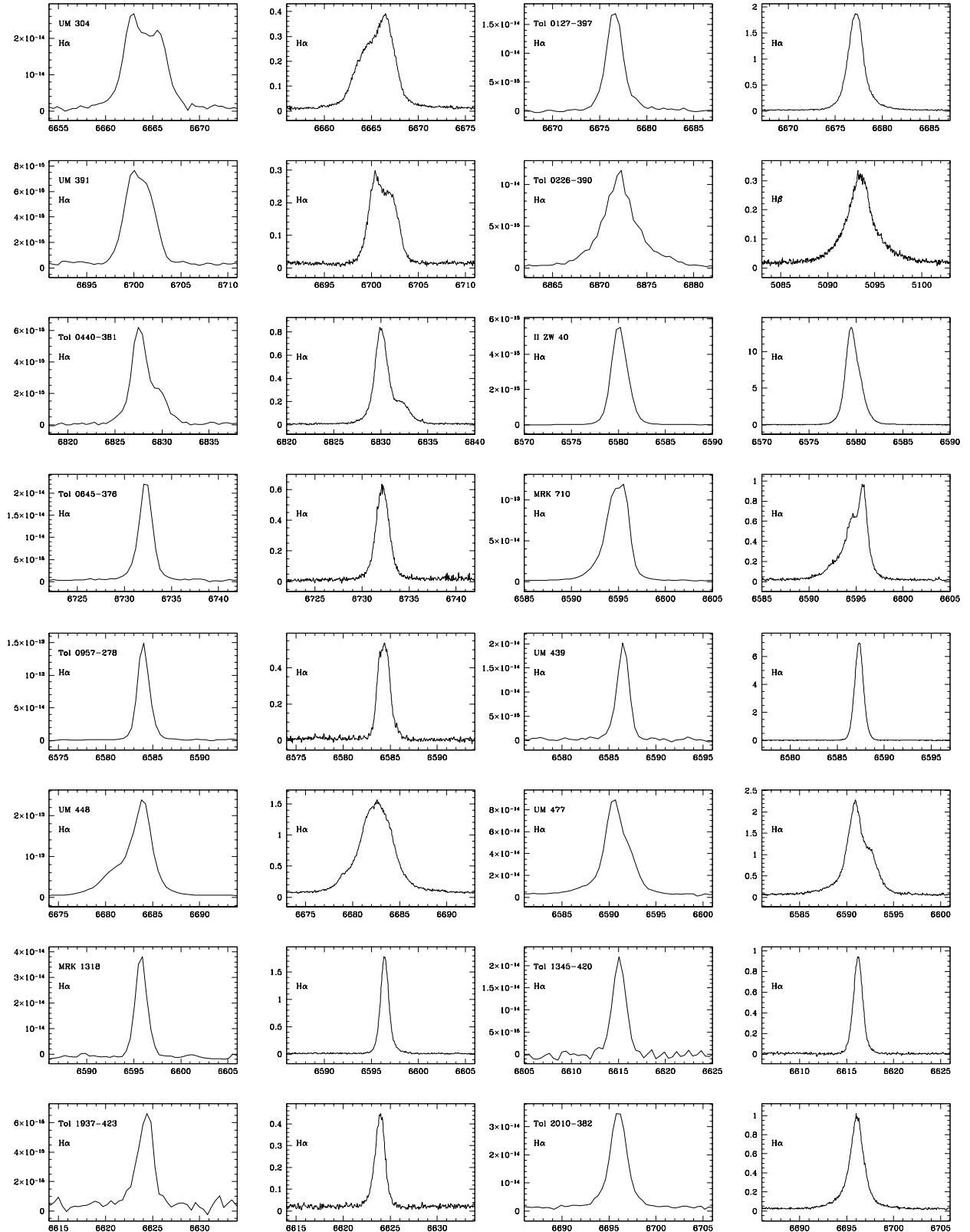


Figura A.3: Comparaç $\tilde{\text{a}}$ o lado a lado entre perfis de linha obtidos com o Coudé e FEROS para mesmos objetos.

