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Turbulence in giant extragalactic HII regions

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ABSTRACT

Key words: HII regions – ISM: individual object: NGC 604 – ISM: kinematics and dynamics – techniques: spectroscopic – turbulence

1 INTRODUCTION

It is possible to consider that the large lengths of astrophysical objects, ranging in scales from 10^6 to 10^{17} m (Chepurnov & Lazarian 2010), is closely related to the existence of turbulent flows, as is suggested by the high Reynolds numbers (Re) (in the order of10^4 and 10^9 Chandrasekhar (1949); Lagrois & Joncas (2011)) that characterized these objects. There is much evidence (Franco & Carramiñana 1999; Elmegreen & Scalo 2004; Scalo & Elmegreen 2004) that the velocity field of different phases of the interstellar medium exhibits a chaotic behavior, with the motions showing complex velocity fields in the plane-of-sky (POS) and a non-thermal broadening on their spectral lines, suggesting disordered motion along the line-of-sight (LOS). Within the class of objects know as gaseous nebula, active centers of star formation named Giant extragalactic HII regions (GEHRs) are ideal objects for the study of turbulence in the interstellar medium (Castañeda et al. 1992).

These objects have large dimensions (≥100 pc) and high luminosity (10^{38} < $L_{H\alpha}$ < 10^{40} erg s^{-1}). There is a strong interaction between the stars clusters (≥100 stars with $T_{eff} \geq 30,000$ K) and the surrounding medium (n_e=1-10^4 cm^{-3} and T_e=10,000 K) via the injection of mechanical energy and the momentum given to the ionized gas (Weaver et al. 1977; Dyson 1979). This energy and momentum comes in the form of stellar winds ($v_w \sim 1000$ km s^{-1}) of the O ($\dot{M}$=$10^{-5} M_\odot\ yr^{-1}$) and B ($\dot{M}$=$10^{-6.5} M_\odot\ yr^{-1}$) stars.

As supersonic motions dissipate energy by shocks in time scales relatively short compared with the age of the region, it is necessary an energy source to replenish continuously the energy lost. From the observed velocity dispersion σ, and assuming that we have an isotropic distribution of velocities, we can estimate the 3D velocity dispersion by $\sigma_{3D} = \sqrt{3}\sigma$. The mass of the ionized gas together with the velocity dispersion σ_{3D} are used to estimate the kinetic energy in the GEHRs. As these objects have typically masses of the ionized gas of $\sim 10^5\ M_\odot$ and velocity dispersion values of ~ 20 km s^{-1} (**?**), typical kinetic energy of the ionized gas is $\sim 10^{51}$ erg.

In the standard Kolmogorov model, the energy spectrum of turbulence becomes dependent only on ϵ, the mean dissipation of energy per unit time per unit mass of fluid, with the inertial forces transferring without losses kinetic energy from larger to smaller turbulent elements within the inertial range. Let L be the characteristic length of the largest eddies, and δv the typical velocity.

We have then that $\epsilon = (\delta v)^3/L$ (**?**). In steady-state turbulence, equilibrium exists between the energy input and the energy dissipation rates. Although the present observations indicate that turbulence in GEHRs may not follow the Kolmogorov model, with energy input occurring at different scales, so that a truly inertial range may not exist at all, lets us make a crude estimation of the amount of energy transferred between scales using this simple model. Assuming the above figures for the mass of the gas and velocity dispersion, $\delta v = \sigma_{3D}$, and $L = 100$ pc, we obtain that the energy transfer rate is $\sim 10^{37}$ erg s^{-1}, and the time scale for energy transfer, $L/\delta v$, would be of few million years. Assuming this time is longer than the dissipation of a shockwave a continuous energy injection is required to match the observed values. There are several energy sources that could provide or contribute to the energy required: supernova explosions, champagne flows, stellar winds from massive stars, and cometary shocks produced by the winds of low mass stars.

The strong stellar winds of OB clusters provide a mechanical luminosity of $L_W = \frac{1}{2}\dot{M}v_\infty^2$, where $\dot{M}$ is the total stellar mass loss rate and v_∞ is the mean terminal velocity of the ejected material. The relative contribution to the total mechanical luminosity of stars of different types depends on the history of star formation of the ionizing cluster and its age. Assuming a single burst of star formation, the ages of GEHRs are estimated to be between 1 and 6 Myr (Copetti et al. 1985). These values should more properly be considered as the age of the current ionizing stars, since in GEHRs many episodes of star formation may be occurred and lower mass stars of previous generations may be presented. In the first 3 Myr since the ionizing cluster formation, the strong winds of O type stars are the dominant source of stellar winds. All massive stars go over the Wolf-Rayet phase, about 3 Myrs after the formation. During this phase the star presents much higher mass-loss than normal O stars.

Leitherer et al. (1992) have calculated the total output of mass, momentum, and energy from stellar winds and supernovae to the interstellar medium from a stellar population, assuming different

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histories of star formation (instantaneous burst or continuous), initial mass function (IMF), age, and chemical abundances. They concluded that in the case of a burst of star formation with an age of less than 10 Myr, which is the case of GEHRs, the contribution of stellar winds to the total power may be larger than that of supernovae. They also found that the total power from stellar wind of a population of massive stars scales linearly with the metallicity Z, and that the Wolf-Rayet stars are the main source of energy after 3 Myr. For an instantaneous burst of total mass of 10^5 $M_\odot$, with typical parameters for the IMF (slope of 2.35, upper and lower stellar mass limits of 120 and 1 $M_\odot$, respectively), the total power from stellar winds (excluding supernovae contribution) would be $\sim 10^{39}$ erg s^{-1} for $Z \approx Z_\odot$.

Therefore, the stellar wind from a young and massive cluster could provide in 1 Myr the energy of more than 10 supernova explosions. Even if the efficiency of transferring the kinetic energy from the winds to the interstellar medium is only a few percent, the stellar wind can power the turbulence in GEHRs. A more detailed energetic balance was presented by Chu & Kennicutt (1994) in their kinematical study of the inner zone of 30 Doradus.

Besides the complex gas motions observed in GEHRs and their galactic counterparts, the excess of non-thermal width in the emission lines is interpreted as a turbulent component of the ionized gas. Smith & Weedman (1970) discovered that the line width of GEHRs was supersonic, of the order of $\sigma \sim$ 17-26 km s^{-1}. Melnick (1977); Terlevich & Melnick (1981) have shown an empirical relationship between the line width and the integrated properties of the HII regions as the diameter or the luminosity ($R \sim \sigma^{\sim 2}$; $L \sim \sigma^{\sim 4}$). They conclude that GEHR follow this relations as self-gravity systems like globular clusters or elliptical galaxies. The idea of a virial system has been developed by Tenorio-Tagle et al. (1993); Muñoz-Tuñon et al. (1996) into the *Cometary Stirring Model* (CSM) with the aim to separate the mechanism that contribute to the line broadening.

It is also possible to consider the position of the GEHR in relation to its associated molecular cloud to explain part of the high-velocity dispersion values. Since the physical properties of the ionized gas and molecular cloud are different, the interaction between these two phases would develop complex motions and complex emission-line profiles. The champagne model (Tenorio-Tagle 1979) has been used as an explanation of this observed velocity dispersion values (Skillman & Balick 1984). Also, the expanding bubbles and shells formed in these regions consequence of the stellar winds of massive stars have been studied by Rosa & D'Odorico (1982); Chu & Kennicutt (1994); Yang et al. (1996) as a contributor to the line broadening.

The mathematical techniques initially developed by Taylor (1935); Kolmogorov (1941); Heisenberg (1951) were first applied to astronomical observations by Von Hoerner (1951) and Münch (1958). They investigated the projection of a three-dimensional correlation function onto the plane of the sky allowing to determine a distinction between homogeneous turbulence and pure random velocity fluctuations in the galactic HII region, the Orion Nebula. The analysis using structure functions of the velocity centroids for galactic HII regions and GEHRs has been carried out since by Kaplan & Klimishin (1964); Scalo (1984); O'Dell & Castañeda (1987); Castañeda (1987); Miville-Deschenes et al. (1995); Medina-Tanco et al. (1997); Joncas (1999); Lagrois & Joncas (2011); Medina et al. (2014); Arthur et al. (2016); Melnick et al. (2019).

Previous attempts at characterizing turbulence...Others techniques...Limitations....

Our objective is to determine the existence and characterization of a turbulence regime for different ions in different GEHRs, as we are interested in increasing the understanding of this random motions. Also we compare our results in the context of previous investigations with the aim to establish if a relation hold for this objects...

2 METHODS

2.1 Observations

The archival data used in this work were retrieved from the La Palma archive[1] and reduced again by Pérez-Oregón (2013) using the IRAF (National Optical Astronomy Observatories 1999) astronomical software.

The data used in this work was obtained with the ISIS spectrograph and the TAURUS-II Fabry perot in the 4.2-m William Herschel Telescope of del Roque de los Muchachos Observatory (ORM) in La Palma, Spain. The ISIS observations were used by Maíz-Apellániz et al. (2004) and Tenorio-Tagle et al. (2000). Maíz-Apellániz et al. (2004) provides the details of the observational setup. The TAURUS observations were used by...

For the ISIS instrument, the spectra were obtained using a position angle of 90° and the slit width was 1". Two different spectra were taken simultaneously for each position: one for the red arm, between 6390 and 6849 Å and another on the blue arm between 4665 and 5065 Å. The slit had a length of 200" and for NGC 604 we observed ten positions with an exposure time of 1000 s for every slit.

3 TURBULENCE

The classic turbulence theory (Kolmogorov 1941) assumes a three-dimensional isotropic, incompressible and subsonic flow, where an energy cascade, with different l sizes in an auto-similar configuration, is taking place. The energy cascades goes downward, from the large vortices until it reaches dissipation with the smallest vortices. In this energy cascade three scales can be defined: the energy injection scale (Re $\rightarrow \infty$), L_{EI}, the dissipation scale (Re $\rightarrow$ 1), L_D and the inertial scale (L_I) between the previous two. The energy cascade concept is described with an energy spectrum, $E(k) \propto k^{-\beta}$ where k is the wave number for a scale l ($k \equiv l^{-1}$).Following the mathematical description of the Kolmogorov theory the mean specific energy transfer, $\langle\epsilon\rangle$, in the inertial range can be denoted as $\epsilon \sim \frac{v_l^2}{\tau_l}$, where v_l^2 is the kinetic energy per mass unit and τ_l the time related with velocity fluctuations. Since the total specific energy of a determined l scale is of the order $\langle v_l^2\rangle$ and is the energy integral above the associated k, defined as:

$$\langle v_l^2\rangle = \int_k^\infty E(k)dk \tag{1}$$

Considering that this energy is of the order of $(\epsilon l)^{\frac{2}{3}} \sim (\frac{\epsilon}{k})^{\frac{2}{3}}$ we can substitute in equation 1 and obtain the Kolmogorov law:

$$E(k) \propto \epsilon^{\frac{2}{3}} k^{-\frac{5}{3}} \tag{2}$$

Considering the quadratic velocities differences:

$$(\Delta v)^2 \sim (\epsilon l)^{\frac{2}{3}} \tag{3}$$

[1] http://casu.ast.cam.ac.uk/casuadc/ingarch

the term $(\Delta v)^2$ can be defined as the structure function. The left term with index that we define as $\alpha = 2/3$ in equation 3 is directly related to the energy, the left term in equation 1. This index α serves as a reference for the Kolmogorov theory and it is used for direct comparison with observations.

The techniques we used to study the radial velocity sample, $V_r(\boldsymbol{x})$, where $V_r(\boldsymbol{x}) = V_{obs}(\boldsymbol{x}) - \langle V_{obs}(\boldsymbol{x})\rangle$ of a two dimensional field were the second order structure function, $S_2(l)$, and the auto correlation function, $R(l)$, defined as:

$$S_2(\boldsymbol{l}) = \frac{\sum[V_r(\boldsymbol{x}+\boldsymbol{l}) - V_r(\boldsymbol{x})]^2}{N(\boldsymbol{l})} \qquad (4)$$

where σ^2 is the variance of the sample and N($\boldsymbol{l}$) the number of points at each separation.

4 ASTRONOMICAL OBJECTS

4.1 NGC 604

NGC 604 is the brightest HII region of M33, at a distance of 840 kpc (1 arcsec ~ 4 pc) (Kam et al. 2017). Bosch et al. (2002) measured a luminosity of $L_{H_\alpha} = 10^{39.42}$ erg s^{-1}, while the stellar population has been identified and classified by several authors (Conti & Massey 1981; D'Odorico & Rosa 1981; Rosa & D'Odorico 1982; Drissen et al. 1993; Hunter et al. 1996). Works by Eldridge & Relaño (2011) have focused on the Wolf-Rayet and the red super giants (RSGs) stars population, while Fariña et al. (2012) focused on the massive young stellar objects (MYSOs). The region presents in its center a star cluster with a mass range between 15 and 60 $M_\odot$, mainly composed by O-type stars (~ 200), 14 WR and 4 RSG (~ 4) stars (see Figure **??**).

The average age of the massive stars was determined to be from 3 to 5 Myr (Hunter et al. 1996), while the older populations of RSGs have an age of 12.4 ± 2.1 Myr was calculated (Eldridge & Relaño 2011). This suggests that at least two episodes of star formation have taken place in the region (Martínez-Galarza et al. 2012). Relaño & Kennicutt Jr (2009) present a multiwavelength study of the region with the pinpointing the star formation zones.

The molecular gas in NGC 604 has been studied by Israel et al. (1990) obtaining a mass of 3×10^6 $M_\odot$ and a FWHM of 30 km s^{-1}for an atomic gas cloud extending over 700 pc. Two components has been observed by (Tachihara et al. 2018), one blue-shifted of 6×10^6 $M_\odot$ and one red-shifted of 9×10^6 $M_\odot$. Their velocity components with systemic correction are, respectively, -185 < V < -158 km s^{-1}and -197 < V < -170 km s^{-1}. One supernova remnant (SNR) was detected by Benvenuti et al. (1979) in the south portion of the region, outside the zone studied in this paper.

5 RESULTS

We use Equation 4 to calculate the second order structure function of the velocity fields of different emission lines.

6 DISCUSSION

7 CONCLUSIONS

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