THE EVOLUTIONS OF CLOUDY

Christophe Morisset
Instituto de Astronomía, UNAM, México

PLASMA SIMULATION CODE

Description of the object

- (ionizing) SED
  - Shape (Teff, age, Z, …)
  - Luminosity (L, Q0, U, …)
- (Ionized) gas
  - Inner R
  - nH(R)
  - X/H
  - Outer R (e.g. recomb)
  - filling and covering factors
- PDR
- Dust

Atomic data

- (photo)ionization
- recombination [di-electronic]
- collisional (de)excitation
- transition probabilities
- energy levels
- charge exchange
- fluorescence

Dust properties

Molecular properties

CODE

PLASMA SIMULATION CODE

Description of the object

Data

CODE

computes at each radial step:

- radiative transfert
- ionization equilibrium
- thermal equilibrium
- molecular equilibrium

PLASMA SIMULATION CODE

Description of the object

Atomic data

CODE

Outputs

- Ne, Te, X^i/X, Molecules versus radius (or depth //)
- Line emissivities (intensities), dust emission
- Continuum absorption and emission
- Heating and Cooling balance

PLASMA SIMULATION CODE

~~Description of the object~~

Atomic data

e.g. fixed Te

CODE

Outputs

- Ne, Te, X^i/X, Molecules versus radius (or depth //)
- Line emissivities (intensities), dust emission
- Continuum absorption and emission
- Heating and Cooling balance

PHOTOIONIZATION MODELS

P-space

- ionizing SED
  - Shape (Teff, age, Z, …)
  - Luminosity (L, Q0, U, …)
- Ionized gas
  - Inner R
  - nH(r)
  - X/H
  - Outer R (e.g. recomb)
  - filling and covering factors
- PDR characteristics
- Dust (amount, composition)
- Distance

Model →

O-space

- Absolute line intensity
- line ratios
  - [OIII]/Hb
  - [OIII]5007/4363
  - [SII]6716/31
  - …
- images (if 3D)
- IR Dust continuum
- (ionic fractions)
- (electron temperature)

PHOTOIONIZATION MODELS

P-space

- ionizing SED
  - Shape (Teff, age, Z, …)
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  - filling and covering factors
- PDR characteristics
- Dust (amount, composition)
- Distance

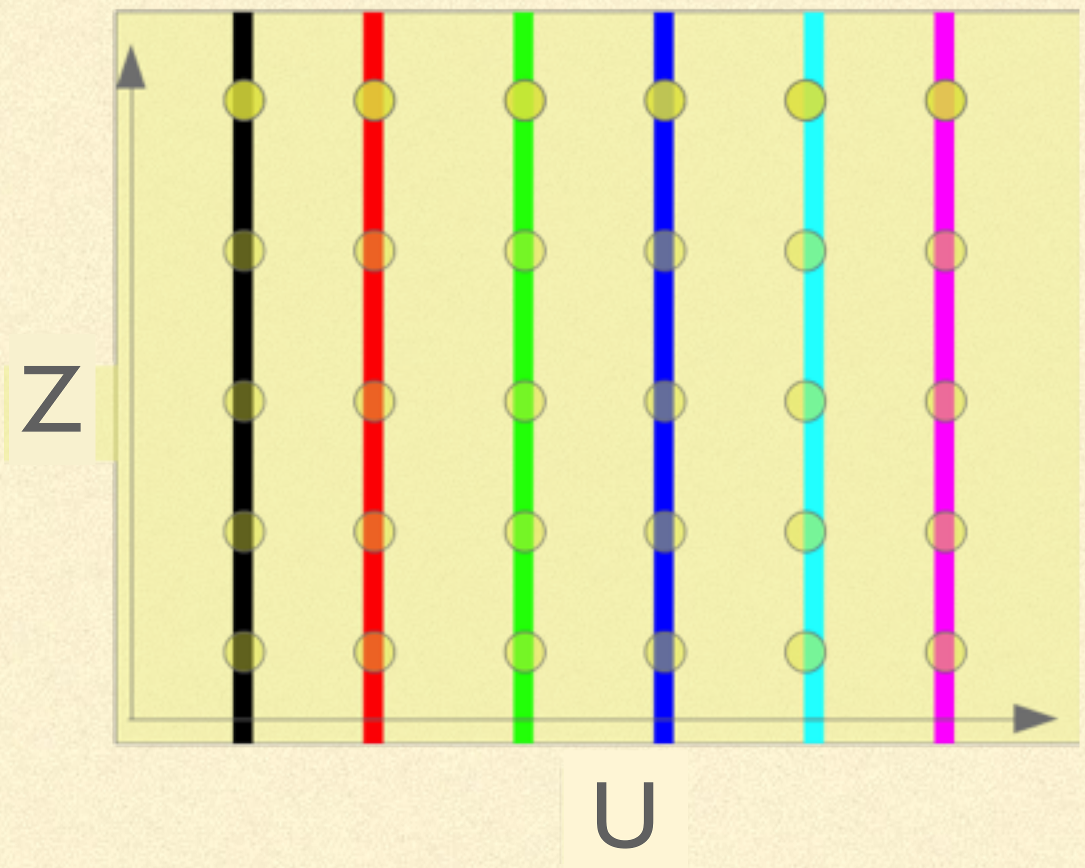
What we want!

O-space

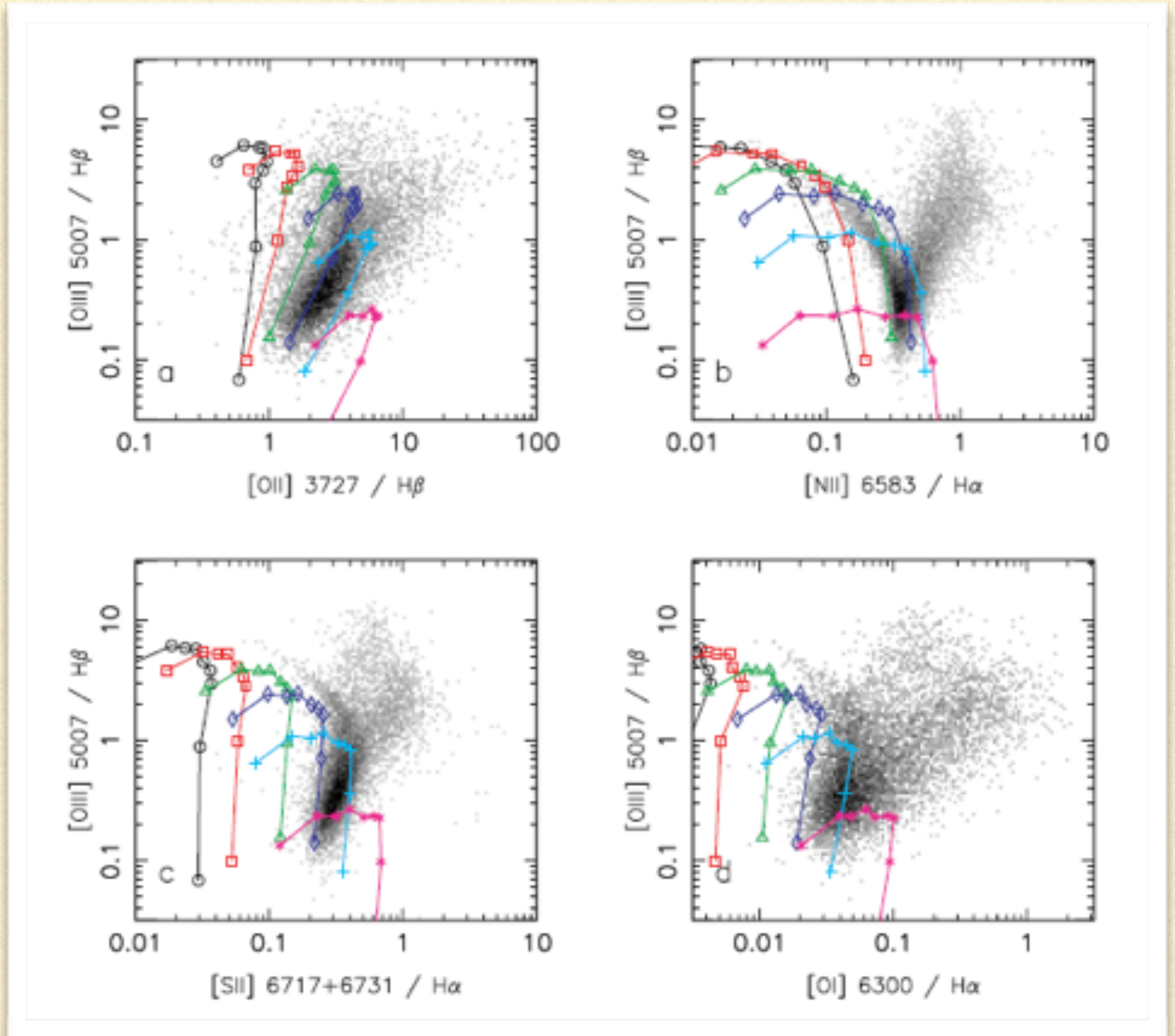
- Absolute line intensity
- line ratios
  - [OIII]/Hb
  - [OIII]5007/4363
  - [SII]6716/31
  - …
- images (if 3D)
- IR Dust continuum
- (ionic fractions)
- (electron temperature)

NO LINEARITY

P-space



O-space



THE FIRST CODES (50 YEARS AGO!)

- Hjellming 1966, Rubin 1968 **for HII regions**
- Goodson 1967, Flower 1968, Harrington 1968 **for Planetary Nebulae**
- Williams 1967 **for Supernova (Crab Nebula)**
- Bahcall 1969, Tarter 1969, Davidson 1972, Mac Alpine 1972, Shields 1974, Netzer 1976 **for QSO, Seyfert**
- Kirkpatrick 1970 **first 3D PN model (yes!)**
- Tylenda 1977, Shields & Ferland 1978, Ferland & Shields **for Nova**
- Péquignot & Stasinska 1978 **compute Charge exchange rates for NGC 7027**
- Ferland & Truran 1981 Nova DQ Herculis, X-rays

THE ASTROPHYSICAL JOURNAL, **244**:1022–1032, 1981 March 15

AN X-RAY MODEL FOR THE NEBULA OF NOVA DQ HERCULIS 1934

G. J. FERLAND AND J. W. TRURAN [1,2]
Institute of Astronomy, Madingley Road, Cambridge, CB3 OHA, England
Received 1980 June 2; accepted 1980 October 2

a) Model Calculations

A model photoionization program is used to study the thermal and ionization structure of a nebula surrounding the X-ray source discussed in § II. Calculations are performed with a newly developed computer program similar to those described by Williams (1967), Davidson (1972), MacAlpine (1972), Shields (1976), Netzer (1976), and Péquignot, Aldrovandi, and Stasinska (1976). The nebula is divided into a set of thin concentric zones, and the equations of statistical and thermal equilibrium are solved in the standard manner. The ionizing continuum is then extinguished by the photoelectric optical depth of that zone, and the conditions in the next zone are determined.

First publication using Cloudy

PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, **110**:761–778, 1998 July

Invited Review

CLOUDY 90: Numerical Simulation of Plasmas and Their Spectra

G. J. FERLAND,[1] K. T. KORISTA,[1,2] D. A. VERNER,[1] J. W. FERGUSON,[1,3] J. B. KINGDON,[1,4] AND E. M. VERNER[1]
Received 1998 January 19; accepted 1998 March 3

ABSTRACT. CLOUDY is a large-scale spectral synthesis code designed to simulate fully physical conditions within an astronomical plasma and then predict the emitted spectrum. Here we describe version 90 (C90) of the code, paying particular attention to changes in the atomic database and numerical methods that have affected predictions since the last publicly available version, C84. The computational methods and uncertainties are outlined together with the direction future development will take. The code is freely available and is widely used in the analysis and interpretation of emission-line spectra. Web access to the Fortran source for CLOUDY, its documentation Hazy, and an independent electronic form of the atomic database is also described.

Revista Mexicana de Astronomía y Astrofísica, **49**, 137–163 (2013)

Review

THE 2013 RELEASE OF CLOUDY

G. J. Ferland,[1] R. L. Porter,[2] P. A. M. van Hoof,[3] R. J. R. Williams,[4] N. P. Abel,[5] M. L. Lykins,[1] Gargi Shaw,[6] W. J. Henney,[7] and P. C. Stancil[2]

ABSTRACT

This is a summary of the 2013 release of the plasma simulation code CLOUDY. CLOUDY models the ionization, chemical, and thermal state of material that may be exposed to an external radiation field or other source of heating, and predicts observables such as emission and absorption spectra. It works in terms of elementary processes, so is not limited to any particular temperature or density regime. This paper summarizes advances made since the last major review in 1998. Much of the recent development has emphasized dusty molecular environments, improvements to the ionization/chemistry solvers, and how atomic and molecular data are used. We present two types of simulations to demonstrate the capability of the code. We consider a molecular cloud irradiated by an X-ray source such as an active nucleus and show how treating EUV recombination lines and the full SED affects the observed spectrum. A second example illustrates the very wide range of particle and radiation density that can be considered.

- *0 or 1* (C or Fortran)? 1978, when Gary became Martin Rees' postdoc at Cambridge University

A model photoionization program

- *33* 1983
- *67* 1987-1988 **1986: Meudon workshop**
- *72* 1988-1989
- *74* 1989-1991
- *80* 1991-1993
- *84* 1993-1996 **1994: Lexington 1rst workshop**
- ***90* 1996-1999 Ferland, Korista, Verner, Ferguson, Kingdon and Verner 1998,**

A large scale spectral synthesis code

- ***switch Fortan to C***
- *94* 2000-2004 Gold version of C code **2001: Lexington 2nd workshop**
- *96* 2004 Oct 16 to 2005 July 08
- *C05.07* 2005 Jul to 2006 Jan
- *C06.02* 2006 Feb to 2007 Feb
- *C07.02* 2007 Feb to 2008 Aug
- *C08* 2008 Aug
- *C10* 2011 July
- ***C13* 2012 Nov 16 Ferland, Porter, van Hoof, Williams, Abel, Lykins, Shaw, Henney and Stancil 2013**

A plasma simulation code

- *C16* sooon

CLOUDY AT 10

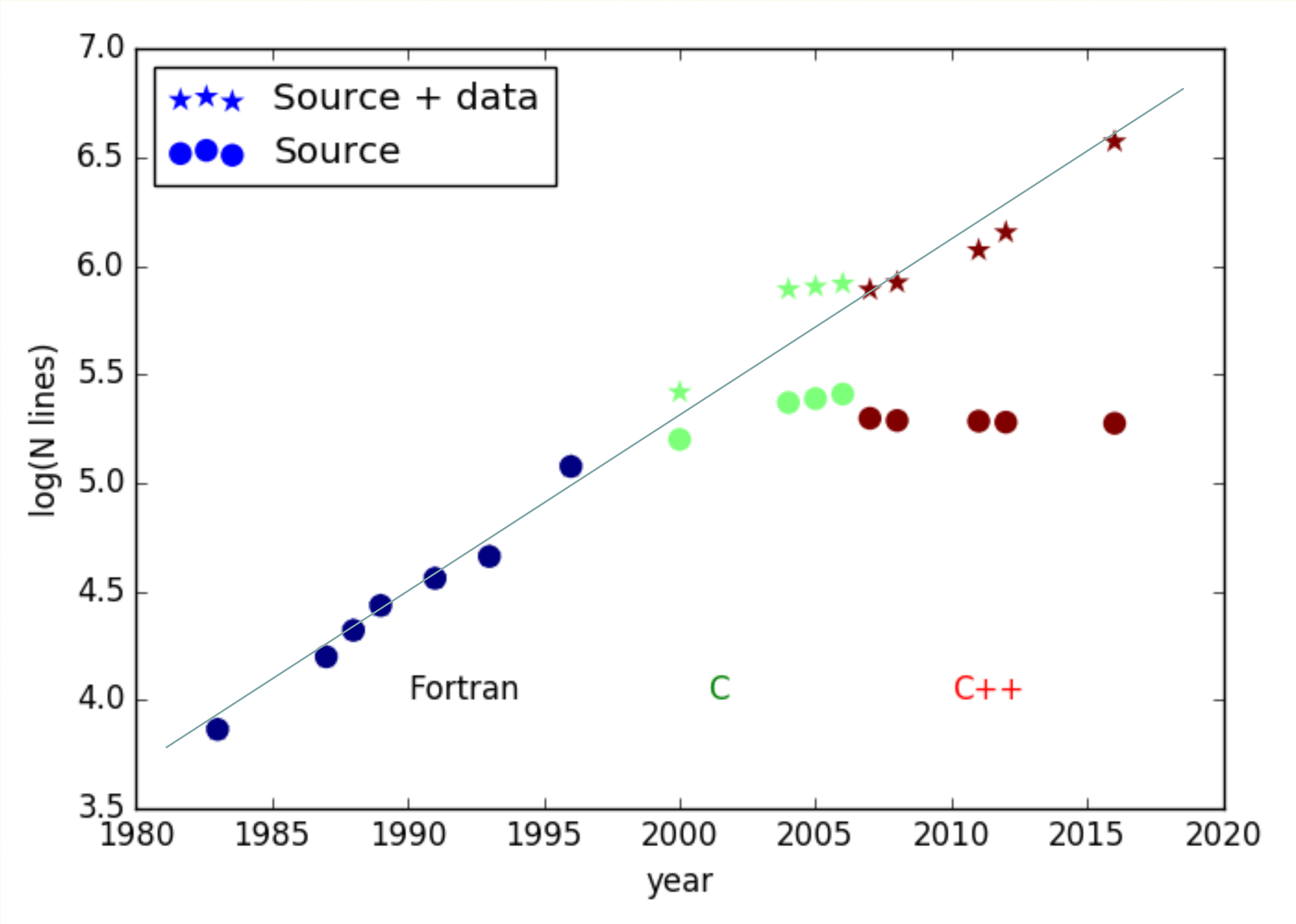
From left to right, Jack Baldwin, Peter Martin, and Gary Ferland, the occupants of room 5 in the Institute of Astronomy's Hoyle Building in mid 1978.

In late summer of 1988. From left to right, Hagai Netzer (the father of Cloudy's old friend ION), Gary Ferland, Cloudy, and Jack Baldwin.

CLOUDY AT 21

Tom Troland, Gary Ferland, and Jack Baldwin in front of a simulation of Cloudy.

SIZE EVOLUTION



NOW CLOUDY IS 38

- 200,000 lines of code
- 3,500,000 lines of data
- Would be 1850 boxes of 2,000 punched cards each!

MEUDON WORKSHOP 1986

369

TABLE 1. LISTE OF CODES

CODES	AUTHORS	A	B	C	D	Mg	Si	S	Cl	Ar	Fe	OTHERS
	a) PHOTOIONIZATION											
1	P. Harrington	2	1	1		x	x	x				
2	R. Rubin	1	1	1				x		x		
3	H. Netzer	3	2	1	1	x	x	x			x	
4	D. Péquignot G. Stasińska	3	2	1		x	x	x	x	x	x	
5	G. Ferland	3	2	1	1	x	x	x		x	x	
6	L. Binette	3	2	2-1	2	x	x	x	x	x		
7	S. Kraemer (fm1)	3	3	1		x	x	x				
8	S. Aldrovandi (fm4)	3	2	2		x		x				
9	J. Köppen	2	3	3		x	x	x	x	x		
10	M. Perinotto	2	3	3-1		x	x	x	x	x	x	x
11	R. Tylenda	2	2	2	2			x				
12	S. Torres-Peimbert	2	3	2		x	x	x				
13	W. Deuel	2	2	2		x	x					
14	M. Baessgen G. Maluck	2	1	2		x	x	x		x		
15	J. Raymond	2	2	1		x	x	x	x	x	x	x
16	S . Collin et al	3	1		1	x					x	
	b) STEADY SHOCKS											
17	J. Raymond		2	1		x	x	x	x	x	x	x
18	L. Binette		2	1		x	x	x	x	x		
19	S. Aldrovandi M. Contini		2	2		x		x				
20	S. Falle J. Giddings D. Innes		2	2	3							
21	D. Péquignot G. Stasińska		2	1		x	x	x	x	x	x	

16 codes

LEXINGTON WORKSHOP 1994

"The Analysis of Emission Lines", Proc. STScI Symposium May 16--18, 1994, Eds. R.E. Williams & M. Livio, Cambridge University Press.

THE LEXINGTON BENCHMARKS FOR NUMERICAL SIMULATIONS OF NEBULAE

G. Ferland[1], L. Binette[2], M. Contini[3], J. Harrington[4], T. Kallman[5], H. Netzer[3], D. Péquignot[6], J. Raymond[7], R. Rubin[8], G. Shields[9], R. Sutherland[10], S. Viegas[11]

Abstract

We present the results of a meeting on numerical simulations of ionized nebulae held at the University of Kentucky in conjunction with the celebration of the 70th birthdays of Profs. Donald Osterbrock and Michael Seaton.

11 codes

LEXINGTON WORKSHOP 2001

Spectroscopic Challenges of Photoionized Plasmas
ASP Conference Series, Vol. 247, 2001
Gary Ferland and Daniel Wolf Savin, eds.

Photoionization Model Nebulae

Daniel Péquignot *Observatoire de Meudon, 92195 Meudon, France*

Gary Ferland *Physics & Astronomy, University of Kentucky, Lexington, KY 40506, USA*

Hagai Netzer *Tel Aviv University, Physics & Astronomy, Tel Aviv 69978, Israel*

Timothy Kallman *Laboratory for High Energy Astrophysics, code 662, GSFC, Greenbelt, MD 20874, USA*

David R. Ballantyne *Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*

Anne-Marie Dumont *Observatoire de Meudon, 92195 Meudon, France*

Barbara Ercolano *University College London, Gower Street, London WC1E 6BT, UK*

Patrick Harrington *Astronomy Department, University of Maryland, College Park, MD 20742, USA*

Steve Kraemer *Catholic University of America, Department of Physics, 200 Hannan Hall Washington DC 20064, USA*

Christophe Morisset *Laboratoire d'Astrophysique de Marseille, Traverse du Siphon, BP 8, 13376 Marseille Cedex 12, France*

Sergei Nayakshin *Laboratory for High Energy Astrophysics, code 662, GSFC, Greenbelt, MD 20874, USA*

Robert H. Rubin *NASA/Ames Research Center, Astrophysics Branch, MS 245-6, Moffett Field, CA 94035-1000, USA*

Ralph Sutherland *Mount Stromlo & Siding Spring Observatories, Institute of Advanced Studies, The Australian National University, Private Bag, Weston Creek, P.O., ACT 2611, Australia*

Abstract. Outputs of photoionization model nebulae, obtained from independent photoionization codes, are compared. Case studies encompass conditions relevant to classical nebulae (H II regions; planetary nebulae) and active galactic nuclei (narrow line regions; dilute and dense X-ray emitting clouds).

8 codes

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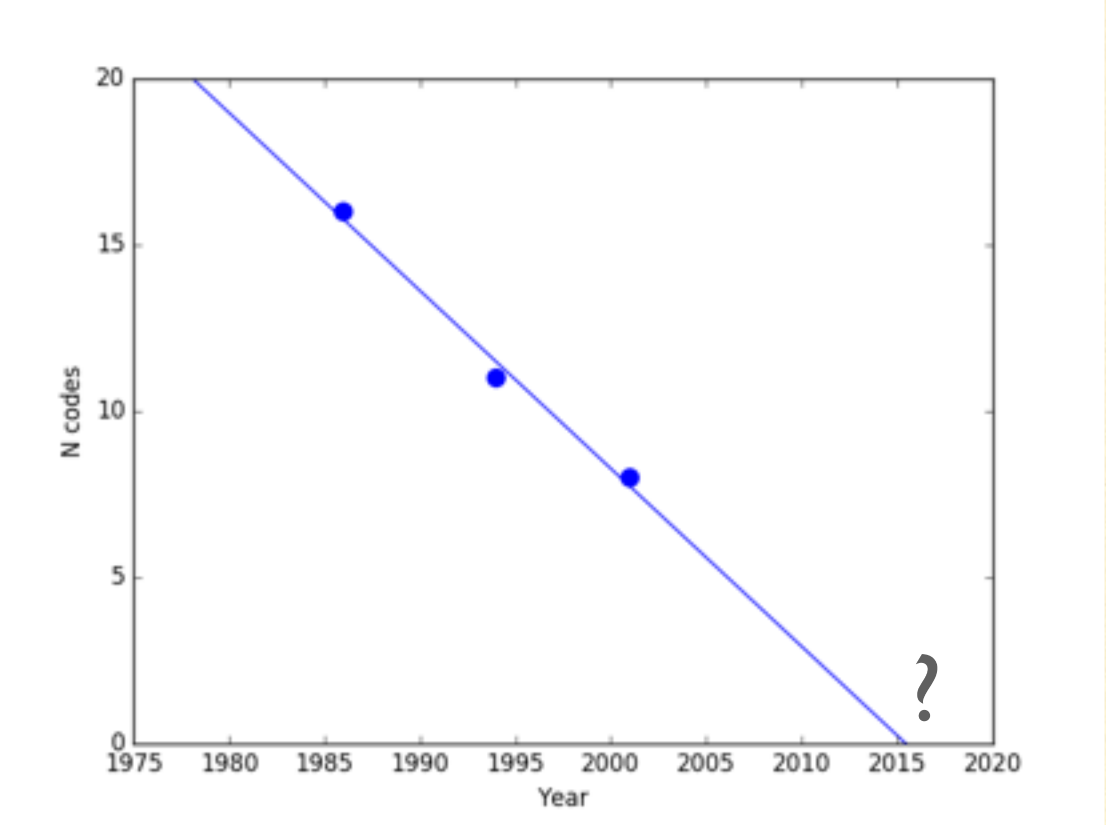
8 codes

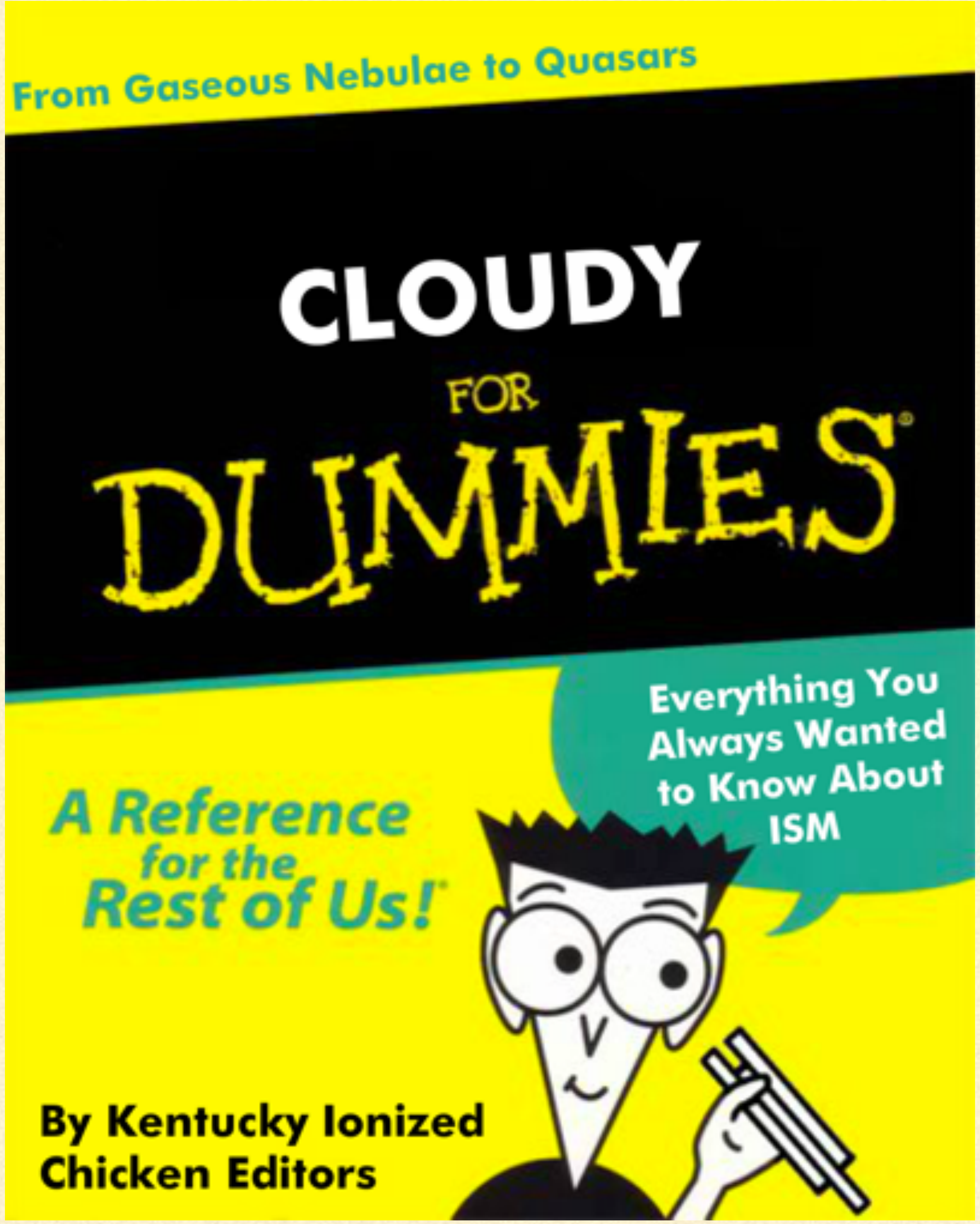


CLOUDY EVOLUTIONS

CLOUDY REVOLUTIONS

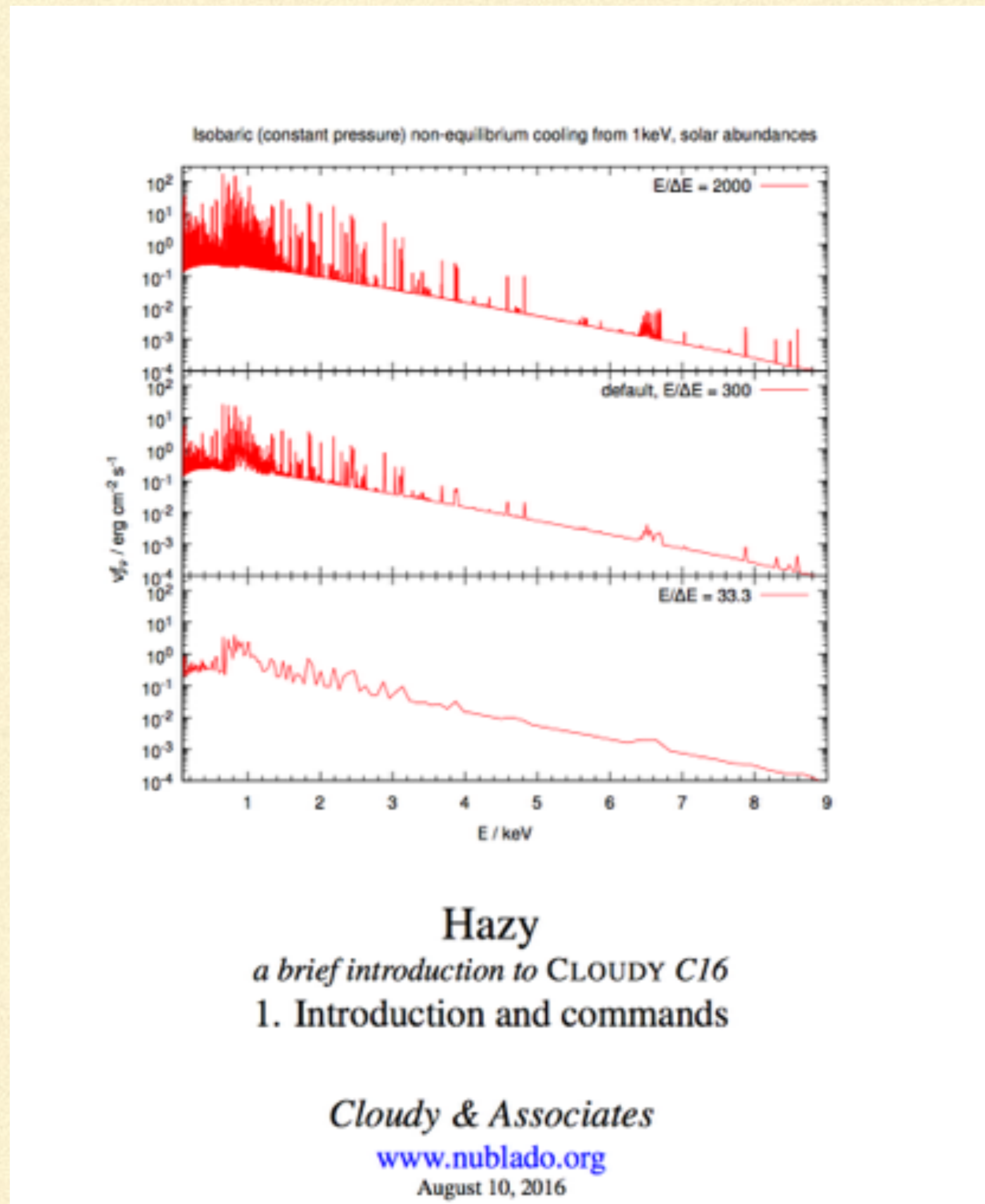
REVOLUTION: Transferring the *Modeling* Power to the People

CLOUDY REVOLUTIONS



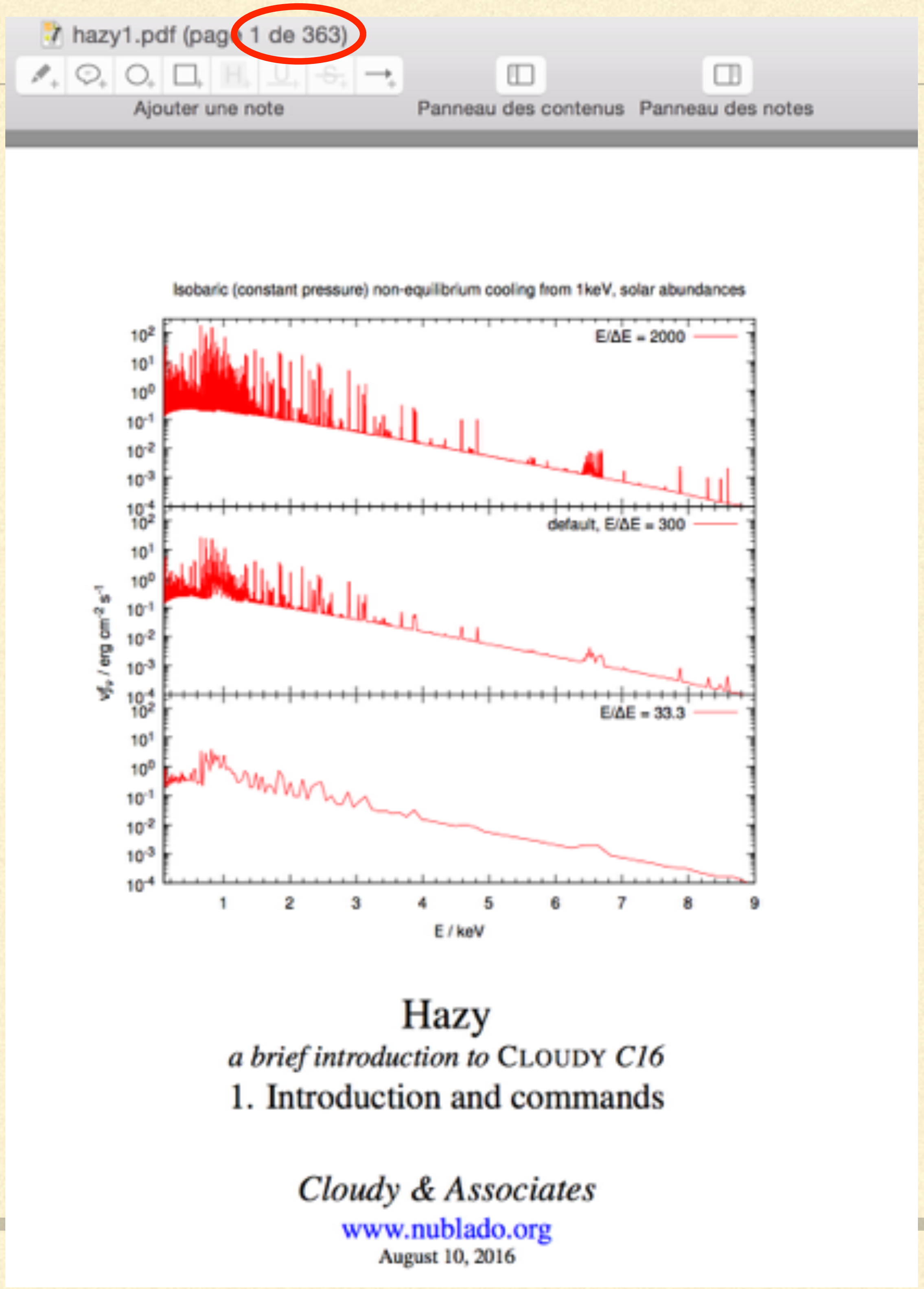
WHAT MAKES CLOUDY UNIQUE?

AMAZING HAZY!



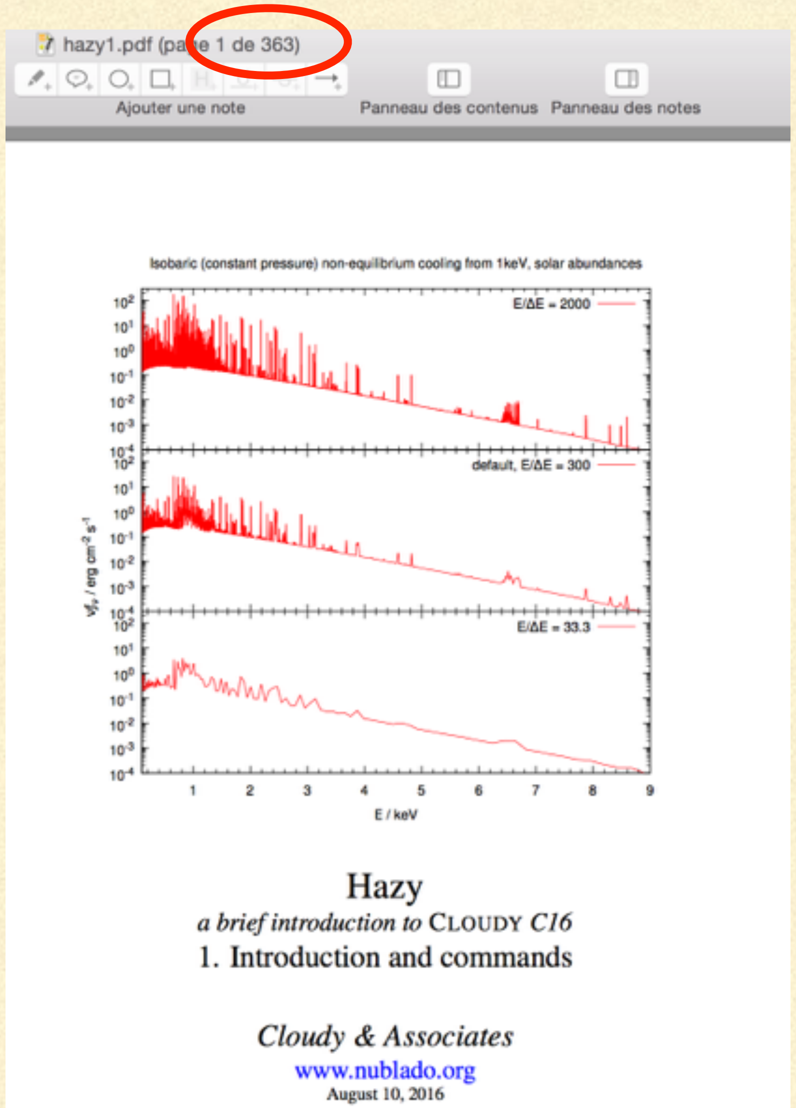
WHAT MAKES CLOUDY UNIQUE?

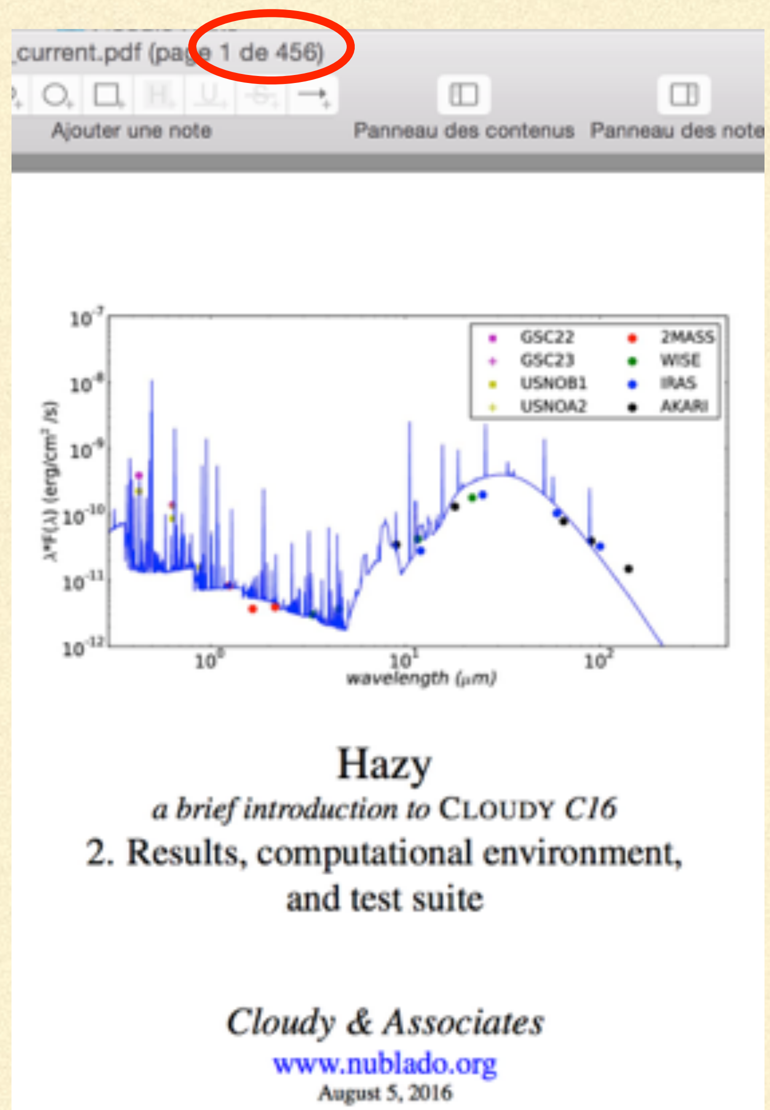
AMAZING HAZY!

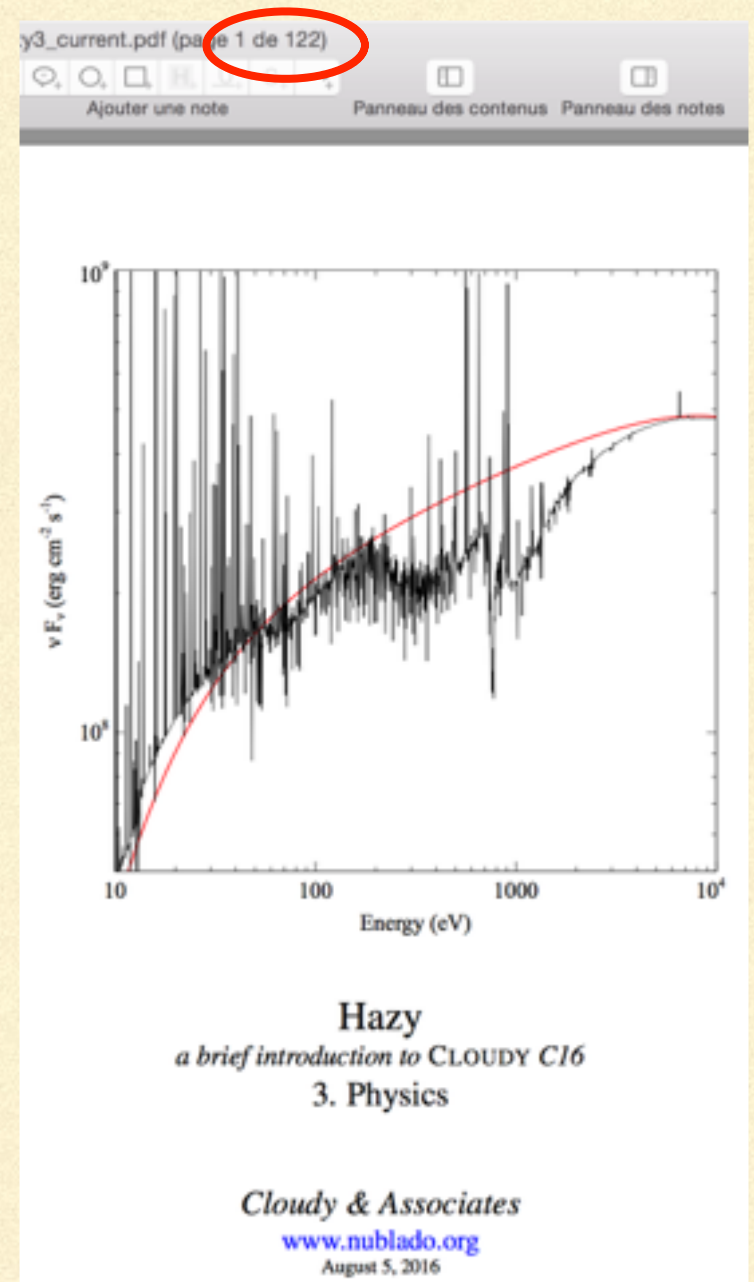


WHAT MAKES CLOUDY UNIQUE?

AMAZING HAZIES!

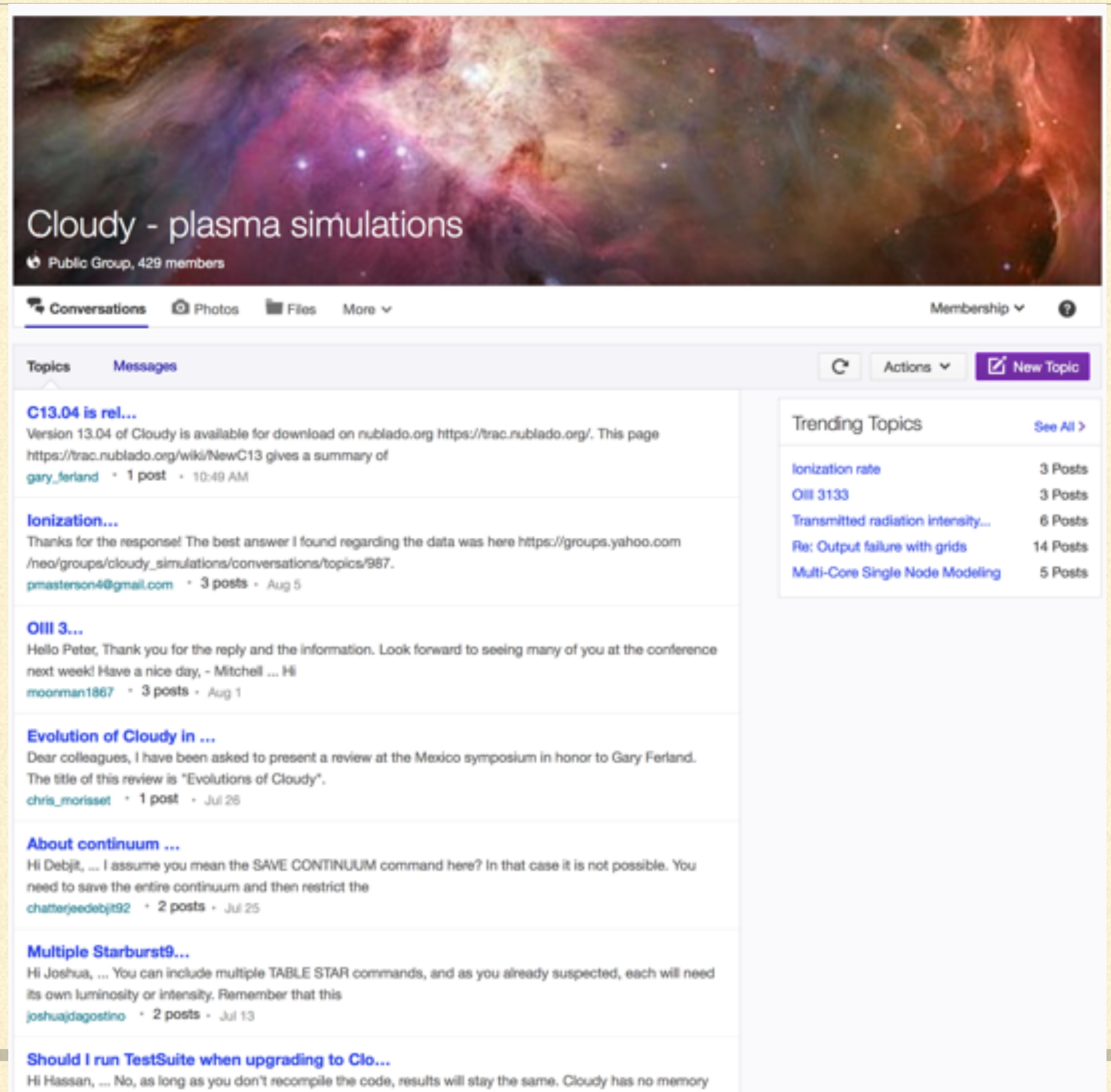






WHAT MAKES CLOUDY UNIQUE?

- When HAZY is not enough (!): Yahoo discussion group

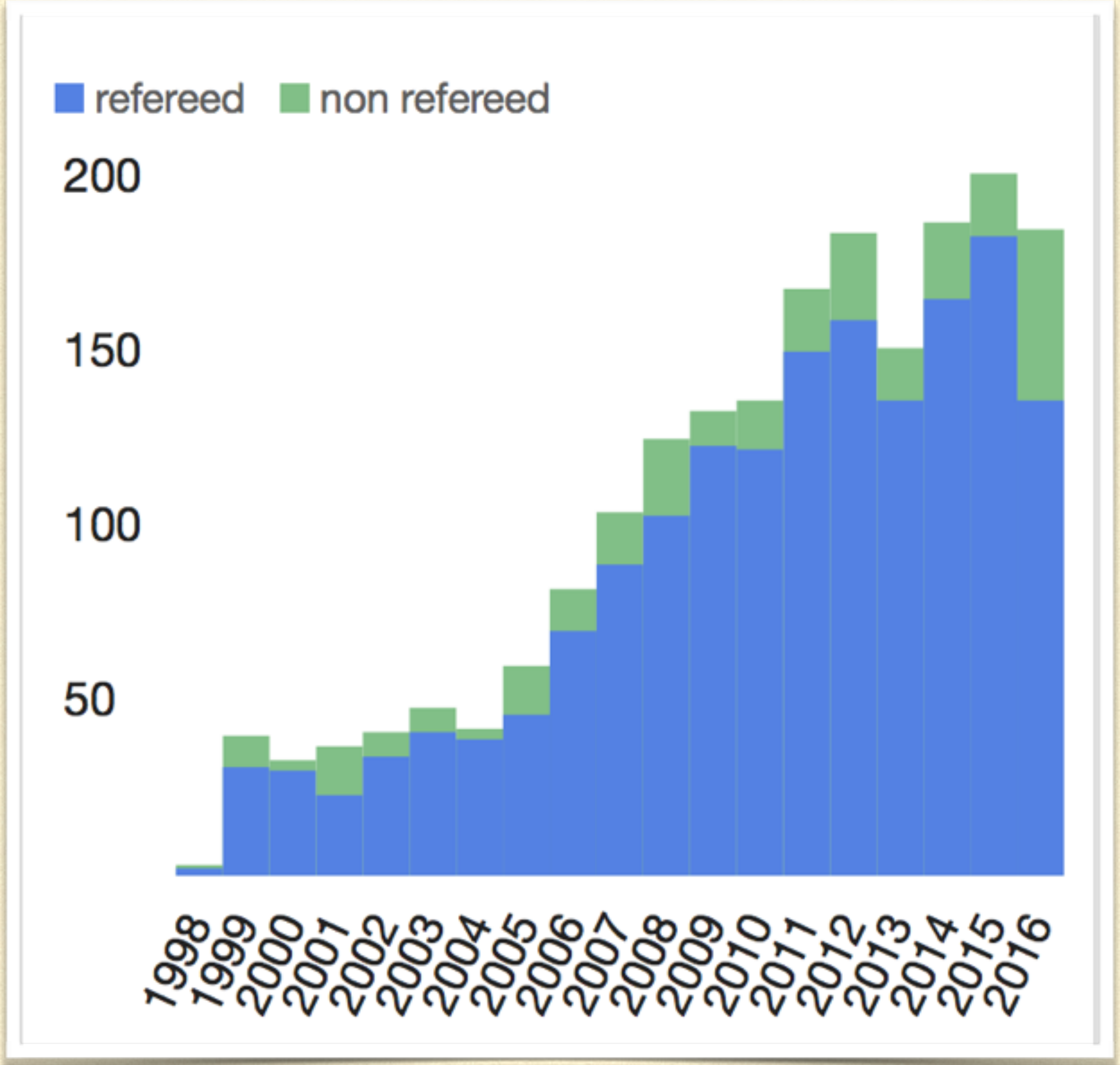


PLASMA SIMULATION CODE

WARNING

- CLOUDY is a « physical » code, it does not know about astrophysics.
- That's why it can model an HII region and a PN changing a few numbers in the input file, while those objects are *astrophysicaly* totally different.
- A « stupid » set of input parameters will gives you… a model.

citations(2013RMxAA..49..137F) OR citations(1998PASP..110..761F)
1960 citations (2016, July 27)



MOST CITED PAPERS CITING CLOUDY

1 2001ApJ...556..121K 2001/07 cited: 936
Theoretical Modeling of Starburst Galaxies
Kewley, L. J.; Dopita, M. A.; Sutherland, R. S. *and 2 more*

2 2003ApJ...588...65S 2003/05 cited: 847
Rest-Frame Ultraviolet Spectra of z~3 Lyman Break Galaxies
Shapley, Alice E.; Steidel, Charles C.; Pettini, Max *and 1 more*

3 2002ApJS..142...35K 2002/09 cited: 594
Using Strong Lines to Estimate Abundances in Extragalactic H II Regions and Starburst Galaxies
Kewley, L. J.; Dopita, M. A.

4 2008ApJ...681.1183K 2008/07 cited: 593
Metallicity Calibrations and the Mass-Metallicity Relation for Star-forming Galaxies
Kewley, Lisa J.; Ellison, Sara L.

5 2006MNRAS.373.1265O 2006/12 cited: 350
Cosmological simulations of intergalactic medium enrichment from galactic outflows
Oppenheimer, Benjamin D.; Davé, Romeel

6 2010MNRAS.402.1536S 2010/03 cited: 348
The physics driving the cosmic star formation history
Schaye, Joop; Dalla Vecchia, Claudio; Booth, C. M. *and 7 more*

7 2009MNRAS.398...53B 2009/09 cited: 341
Cosmological simulations of the growth of supermassive black holes and feedback from active galactic nuclei: method and tests
Booth, C. M.; Schaye, Joop

8 2004ApJ...609..667S 2004/07 cited: 340
Star Formation Thresholds and Galaxy Edges: Why and Where
Schaye, Joop

9 2013RMxAA..49..137F 2013/04 cited: 323
The 2013 Release of Cloudy
Ferland, G. J.; Porter, R. L.; van Hoof, P. A. M. *and 6 more*

10 2007ApJ...655...98N 2007/01 cited: 323
Testing X-Ray Measurements of Galaxy Clusters with Cosmological Simulations
Nagai, Daisuke; Vikhlinin, Alexey; Kravtsov, Andrey V.

11 2006RvMP...78..755R 2006/07 cited: 321
Experimental astrophysics with high power lasers and Z pinches
Remington, Bruce A.; Drake, R. Paul; Ryutov, Dmitri D.

12 2007ApJ...668....1N 2007/10 cited: 320
Effects of Galaxy Formation on Thermodynamics of the Intracluster Medium
Nagai, Daisuke; Kravtsov, Andrey V.; Vikhlinin, Alexey

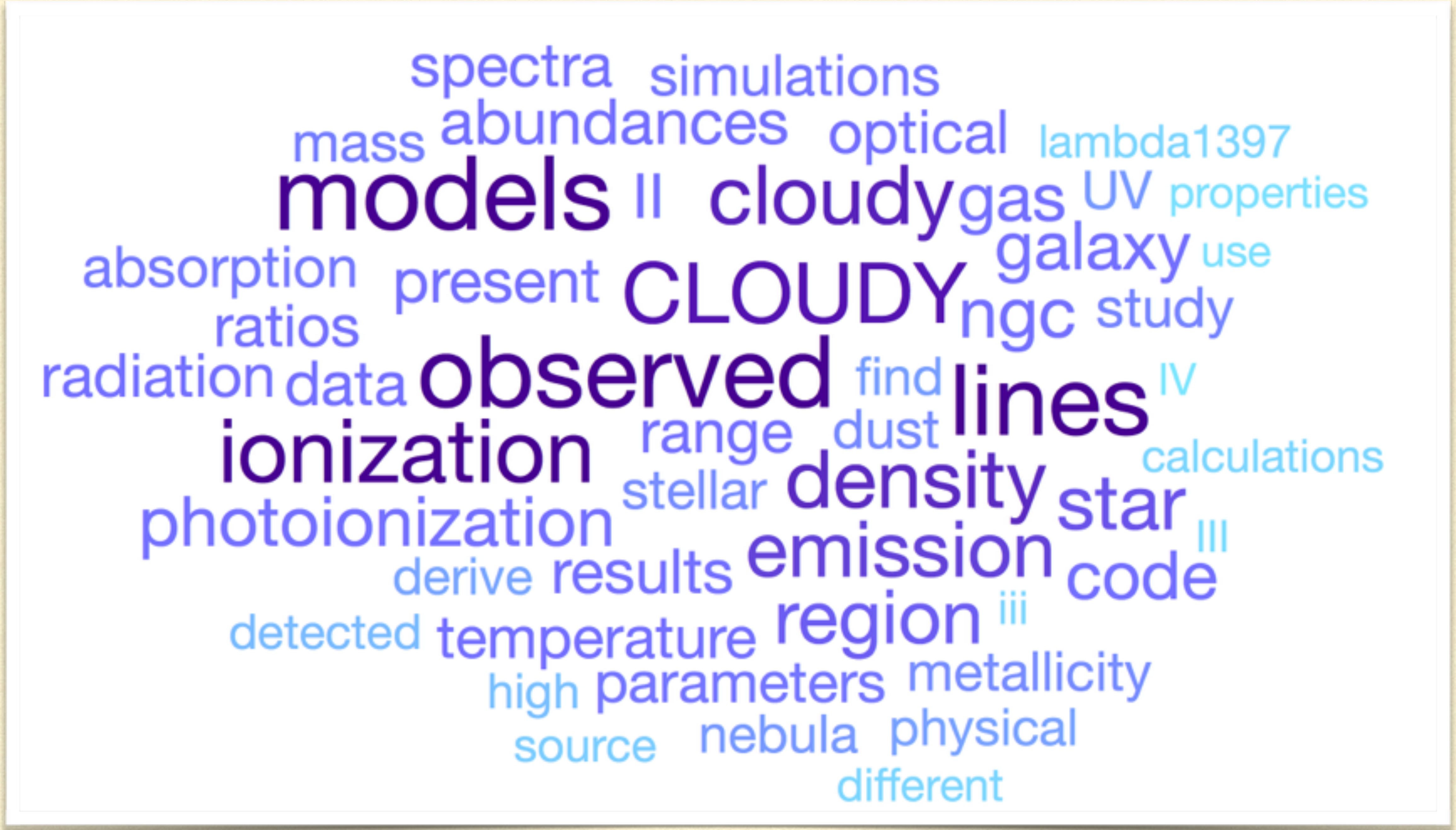
13 1999ARA&A..37..487H 1999 cited: 316
Elemental Abundances in Quasistellar Objects: Star Formation and Galactic Nuclear Evolution at High Redshifts
Hamann, Fred; Ferland, Gary

14 2015MNRAS.446..521S 2015/01 cited: 315
The EAGLE project: simulating the evolution and assembly of galaxies and their environments
Schaye, Joop; Crain, Robert A.; Bower, Richard G. *and 19 more*

15 2009MNRAS.393...99W 2009/02 cited: 315
The effect of photoionization on the cooling rates of enriched, astrophysical plasmas
Wiersma, Robert P. C.; Schaye, Joop; Smith, Britton D.

ABSTRACT: « CLOUDY »

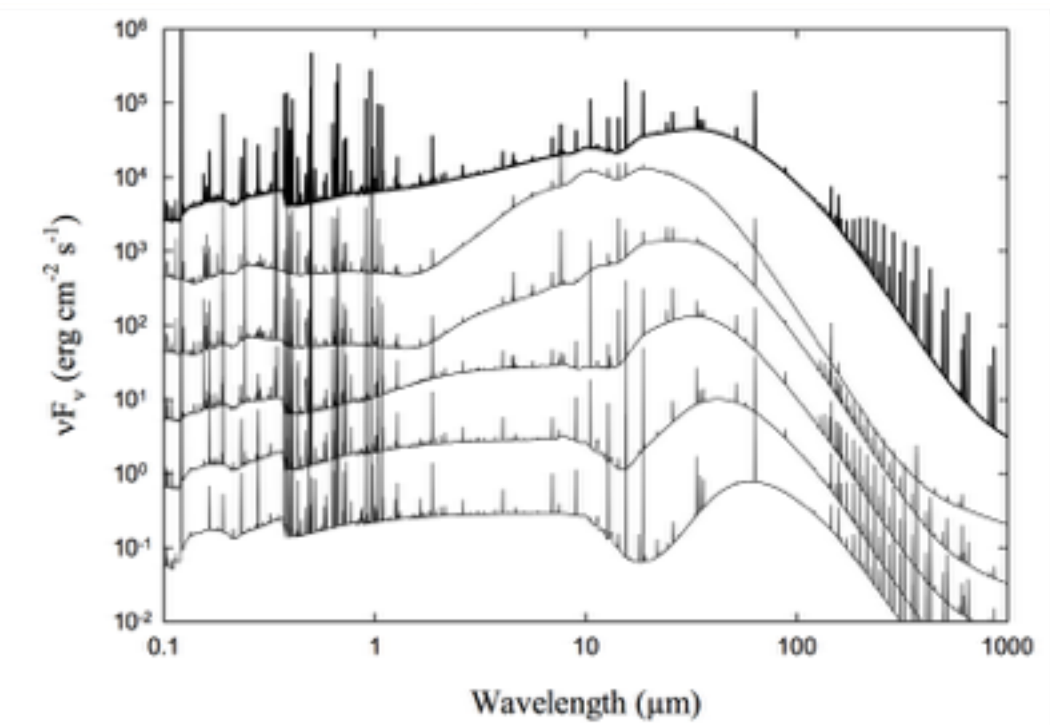
Concept Cloud: terms frequently found in the abstract of papers



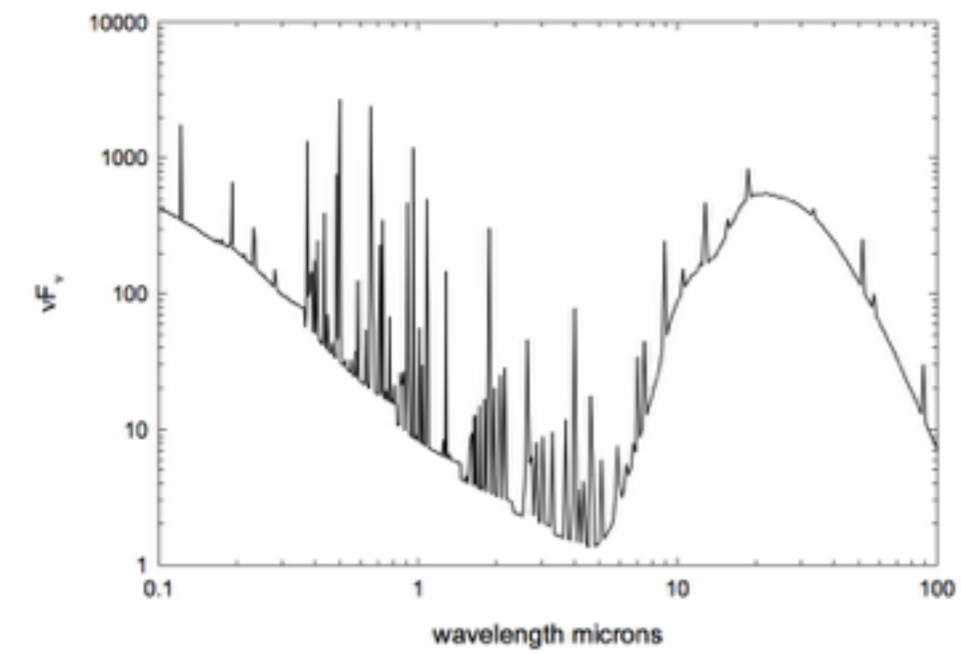
USES OF CLOUDY

- Detailed photoionization models of a given object, e.g. for abundance determination.
- Theoretical studies of physical effects (origin of heating), line transfer, …
- (Large) grid of models(3MdB)
- Cooling rates/functions
- Atomic data (HeI, FeII, …)

HAZY ILLUSTRATIVE PLOTS

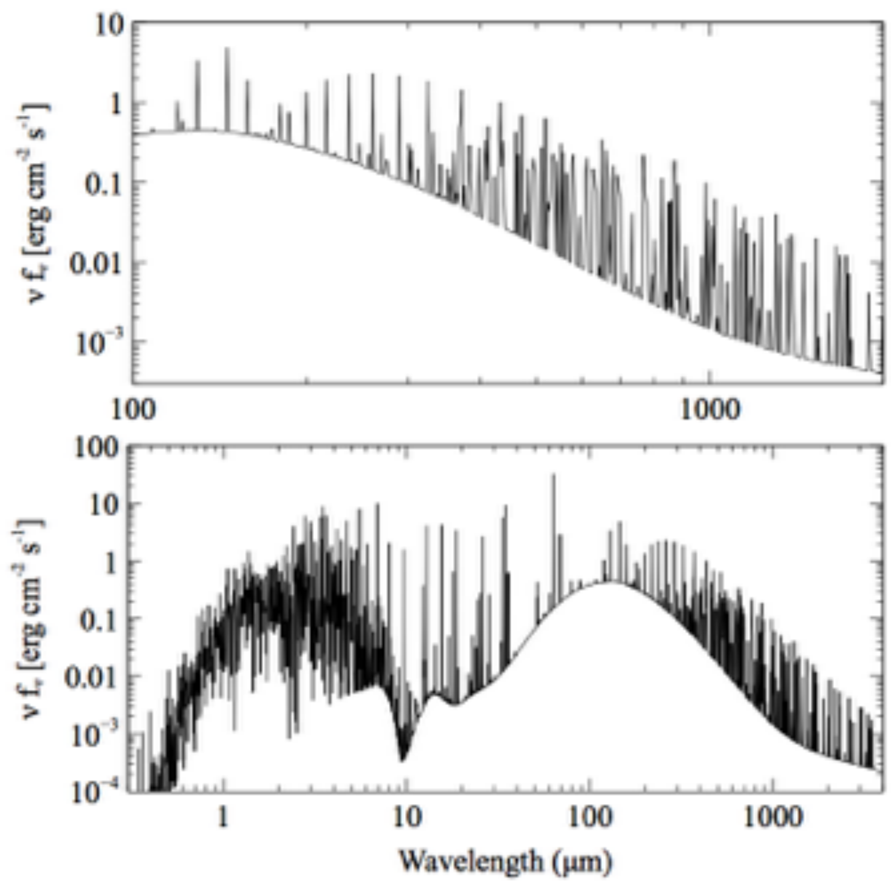


Emission from molecular clouds irradiated by an intense non-thermal continuum. Each continuum corresponds to a cloud located at a different distance from the central object with brighter emission corresponding to a smaller separation.



IR dust emission

Cover image: The spectrum emitted by a dusty filament exposed to ionizing radiation and particles. Moderate to low ionization species emit in the optical and ultraviolet, the left part of the lower panel. Strong H_2 emission is present in the near infrared (1 – 10 μm). Lines from other molecules dominate in the infrared and sub-mm, as shown in the upper panel. Thermal dust emission peaks at roughly 150 μm. The entire spectrum is computed self consistently by specifying only the composition, density, and column density of the gas, and the SED and flux of ionizing photons and particles.

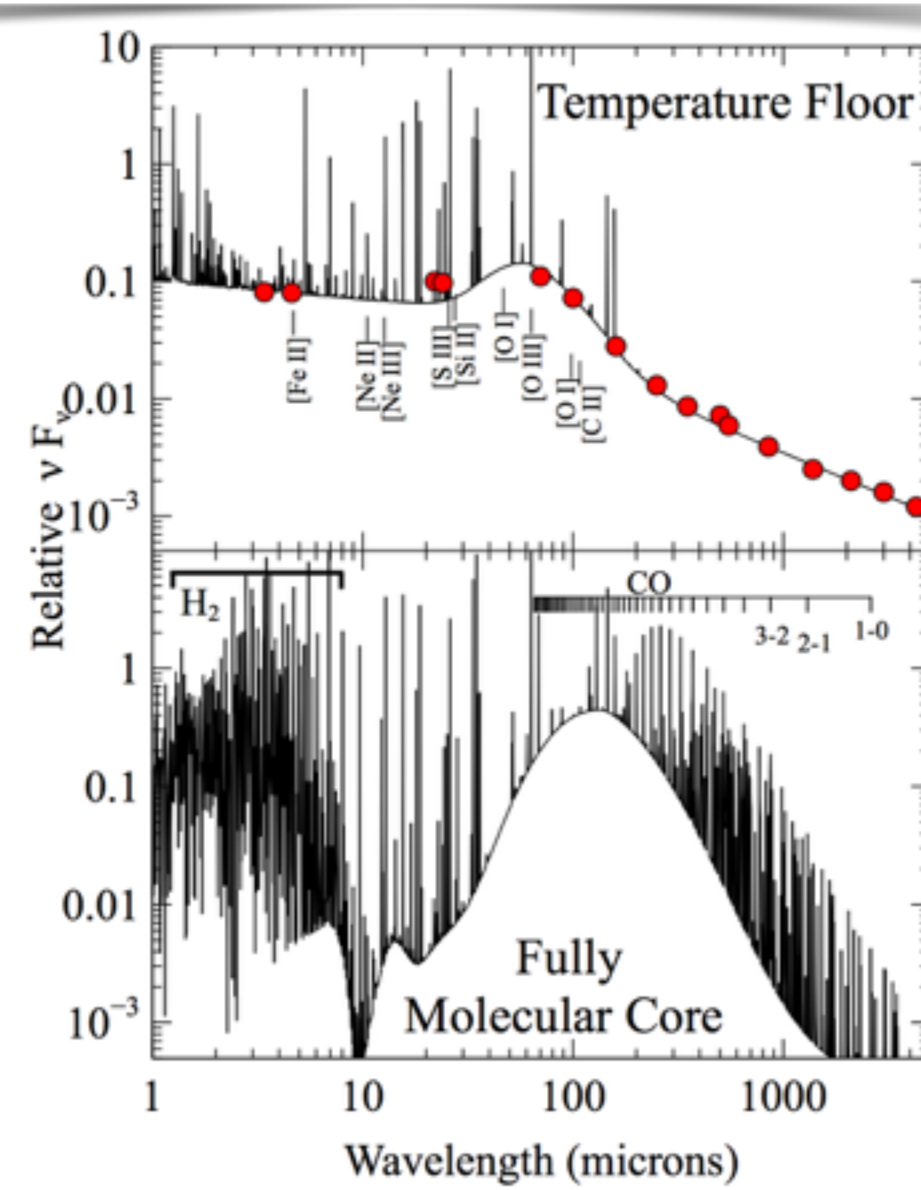


Hazy

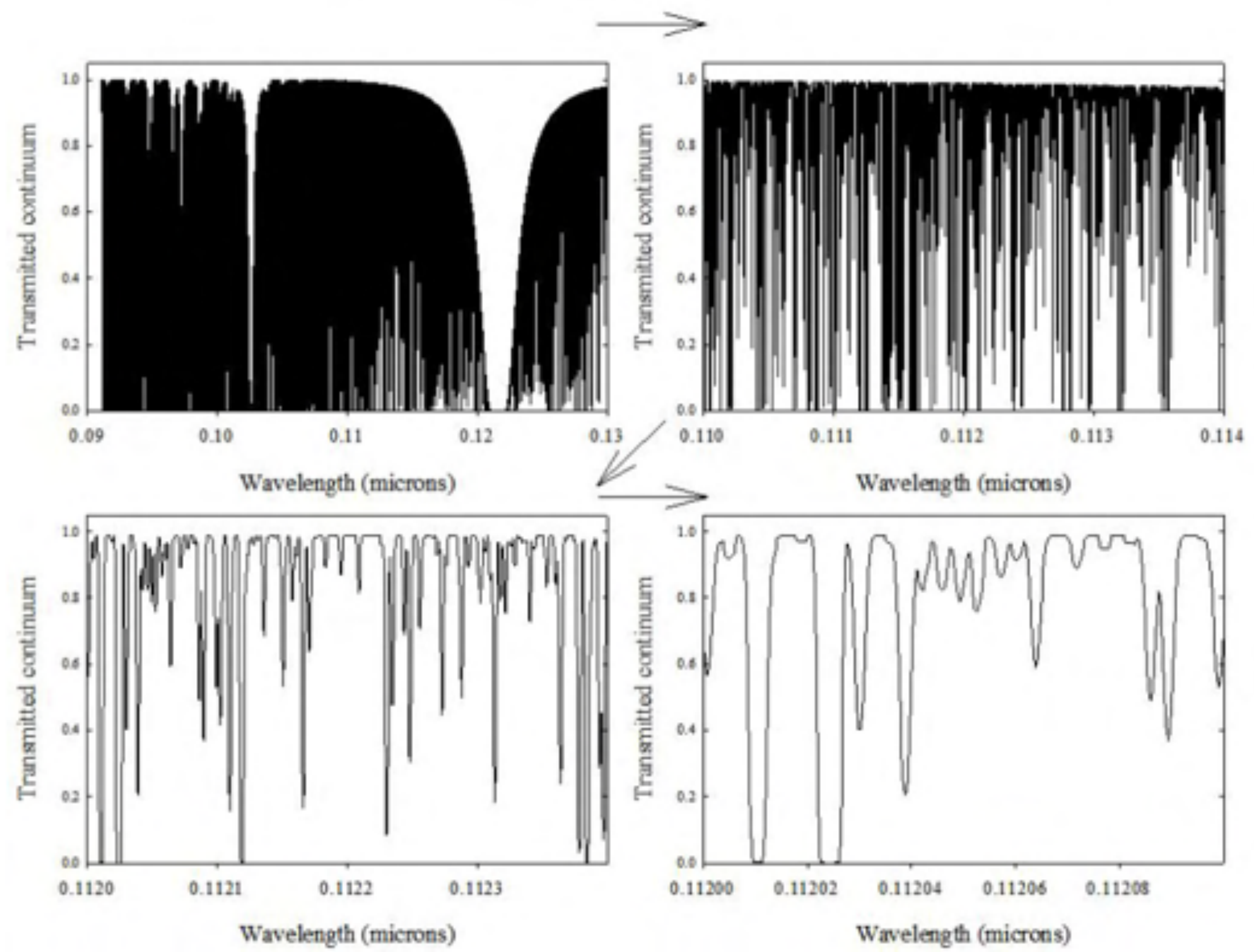
a brief introduction to CLOUDY *C10*

2. Results, computational environment, and test suite

Cover image: Two models of the molecular cores in Crab Nebula filaments are shown. The upper panel is a scenario where shocks or other energy sources maintain the temperature of the filament while the lower panel shows the case where the synchrotron continuum energizes the filaments. H_2 *and CO emission lines are labeled in the lower panel. The red circles in the upper panel compares the predicted shape of the dust thermal emission peak at 70 microns with the shape found from the Herschel observations by Gomez et al. The entire spectrum, including* H_2*, CO, and dust emission, is computed self consistently by specifying only the composition, density, and column density of the gas, and the SED and flux of ionizing photons and particles. Figure prepared by Jack Baldwin and is from Richardson et al. (2012).*



Molecular lines



The radiation field at the position in the Orion PDR where half of hydrogen is in H_2. Most of the light originated in the Trapezium stars and has been filtered throught the H^+, H^0 and H_2 regions of the Orion Nebula. Strongly damped Lα and Lβ absorption lines are present along with a host of much sharper electronic transitions of H_2. Each panel is a zoom of a small region of the previous panel. This information is contained in the fine continuum within Cloudy. From Shaw et al. 2005, ApJ, 624, 794

A forest of molecular lines

(PDR)

THE H II REGION/PDR CONNECTION: SELF-CONSISTENT CALCULATIONS OF PHYSICAL CONDITIONS IN STAR-FORMING REGIONS

N. P. Abel,[1] G. J. Ferland,[1] G. Shaw,[1] and P. A. M. van Hoof[2]

Received 2005 March 22; accepted 2005 June 9

Research in Astron. Astrophys. **2009** Vol. **9** No. **4**, 457–469
http://www.raa-journal.org *http://www.iop.org/journals/raa*

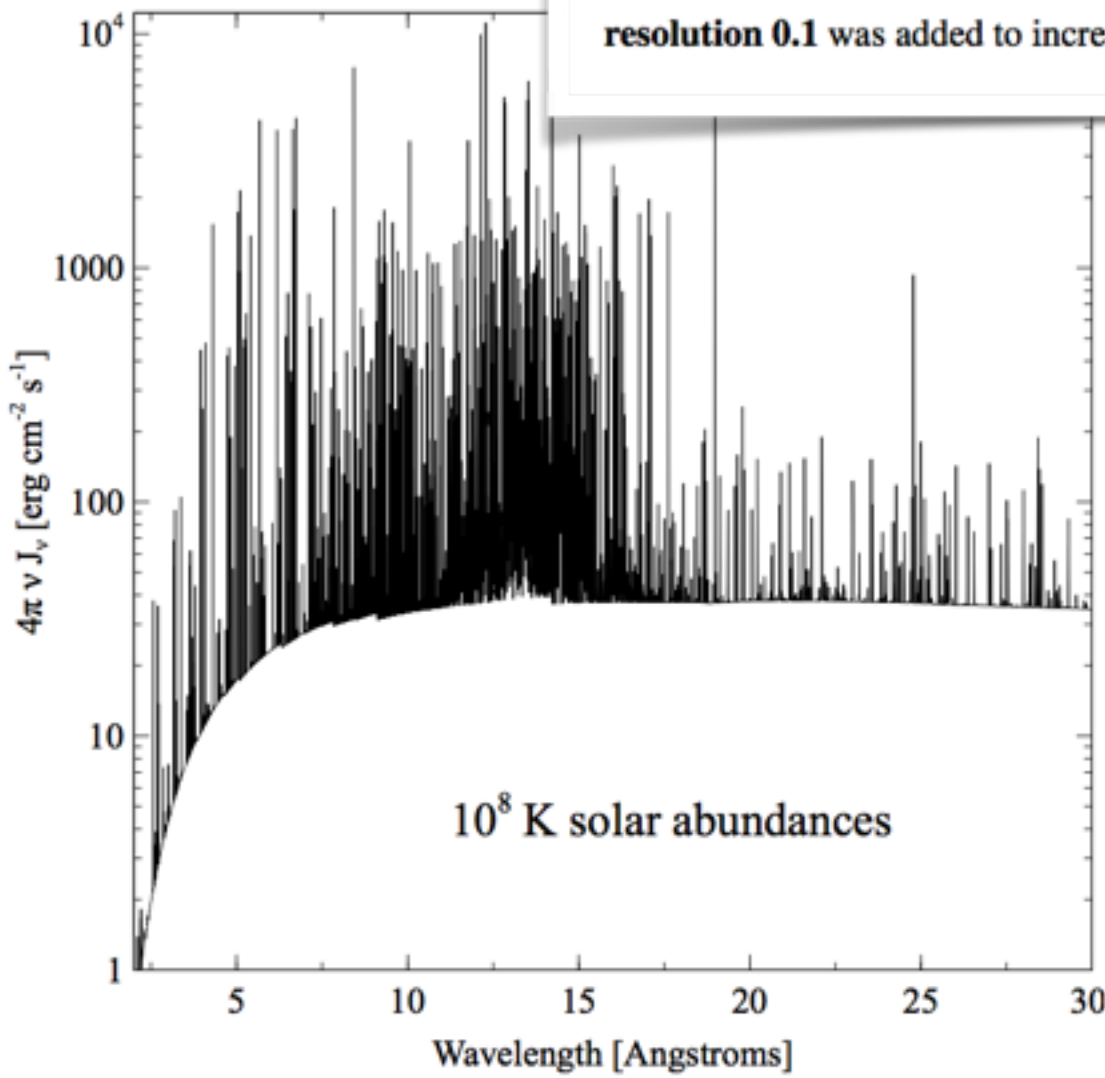
Research in Astronomy and Astrophysics

PDR diagnostics study with CLOUDY

Rui Xue and Maohai Huang

National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China;

Cover image: The spectrum emitted by a cloud with solar abundances, a temperature of 10^7 K, a density of 10^{10} cm^{-3}, and a column density of 10^{15} cm^{-2}. This shows recent improvements in the X-ray spectrum and was done with the test case `coll_t7.in` located in `tsuite/auto`. The command **set continuum resolution 0.1** was added to increase the continuum resolution by a factor of ten.

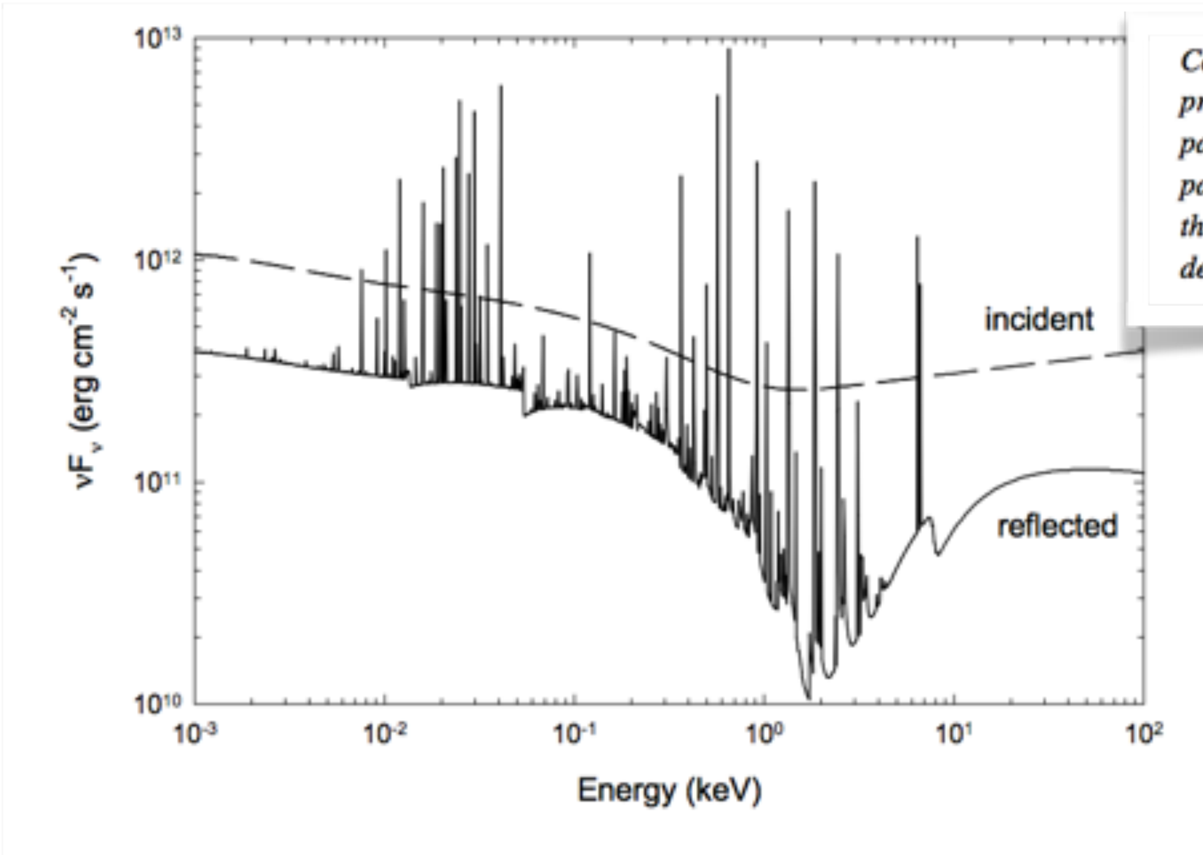


Hazy

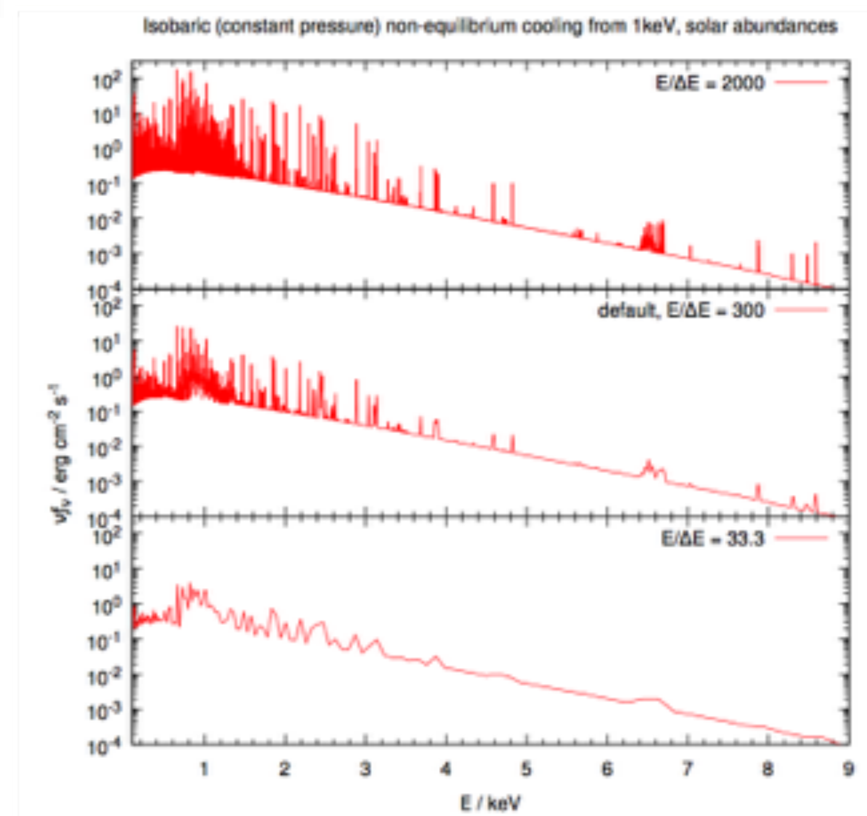
a brief introduction to CLOUDY *C13.1*

2. Results, computational environment, and test suite

X ray spectrum



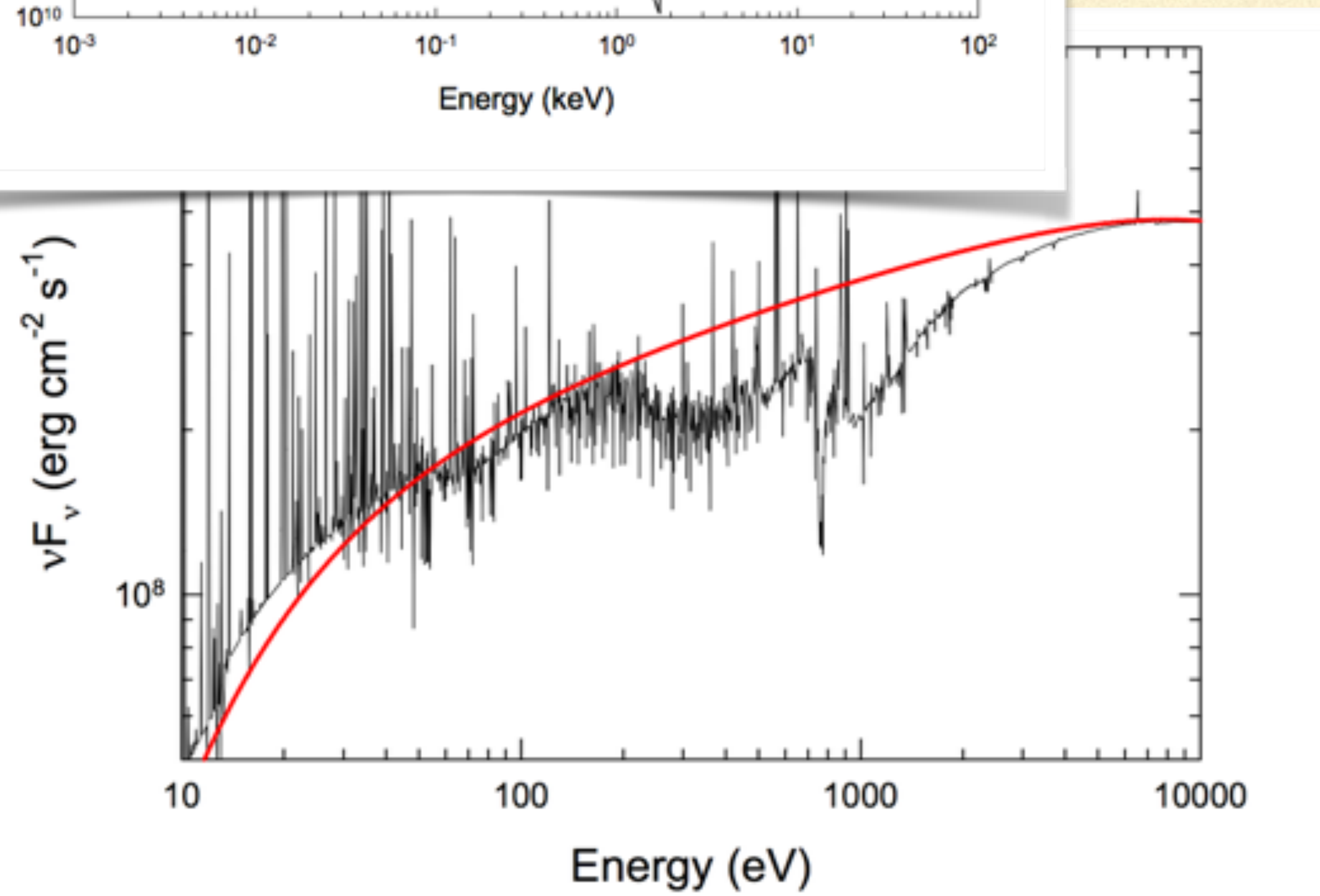
Cover image: The X-ray spectrum of a unit-volume parcel of gas cooling under conditions of constant pressure (isobarically) from X-ray temperatures (1 keV), computed at three resolving powers. In the top panel, the resolving power is comparable the proposed Athena resolving power around 6 keV. In the bottom panel, the resolving power is comparable to the Chandra non-dispersive resolving power around 1 keV. In the middle panel, the resolving power is at the code default. This functionality is new to CLOUDY, *and it is described in Chatzikos et al. (2015), and Section 14.3 below.*



Hazy

a brief introduction to CLOUDY *C16*

1. Introduction and commands



The predicted X-ray spectrum of a warm absorber in an Active Galactic Nucleus. Prominent emission and absorption lines are present along with broad UTA absorption features. The parameters are from Reynolds & Fabian (1995, MNRAS, 273, 1167)..

ATOMIC DATA

THEORETICAL He I EMISSIVITIES IN THE CASE B APPROXIMATION

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Received 2004 October 22; accepted 2005 February 3; published 2005 February 28

ABSTRACT

We calculate the He I case B recombination cascade spectrum using improved radiative and collisional data. We present new emissivities over a range of electron temperatures and densities. The differences between our results and the current standard are large enough to have a significant effect not only on the interpretation of observed spectra of a wide variety of objects, but also on determinations of the primordial helium abundance.

Subject headings: atomic data — atomic processes — ISM: atoms — ISM: clouds — plasmas

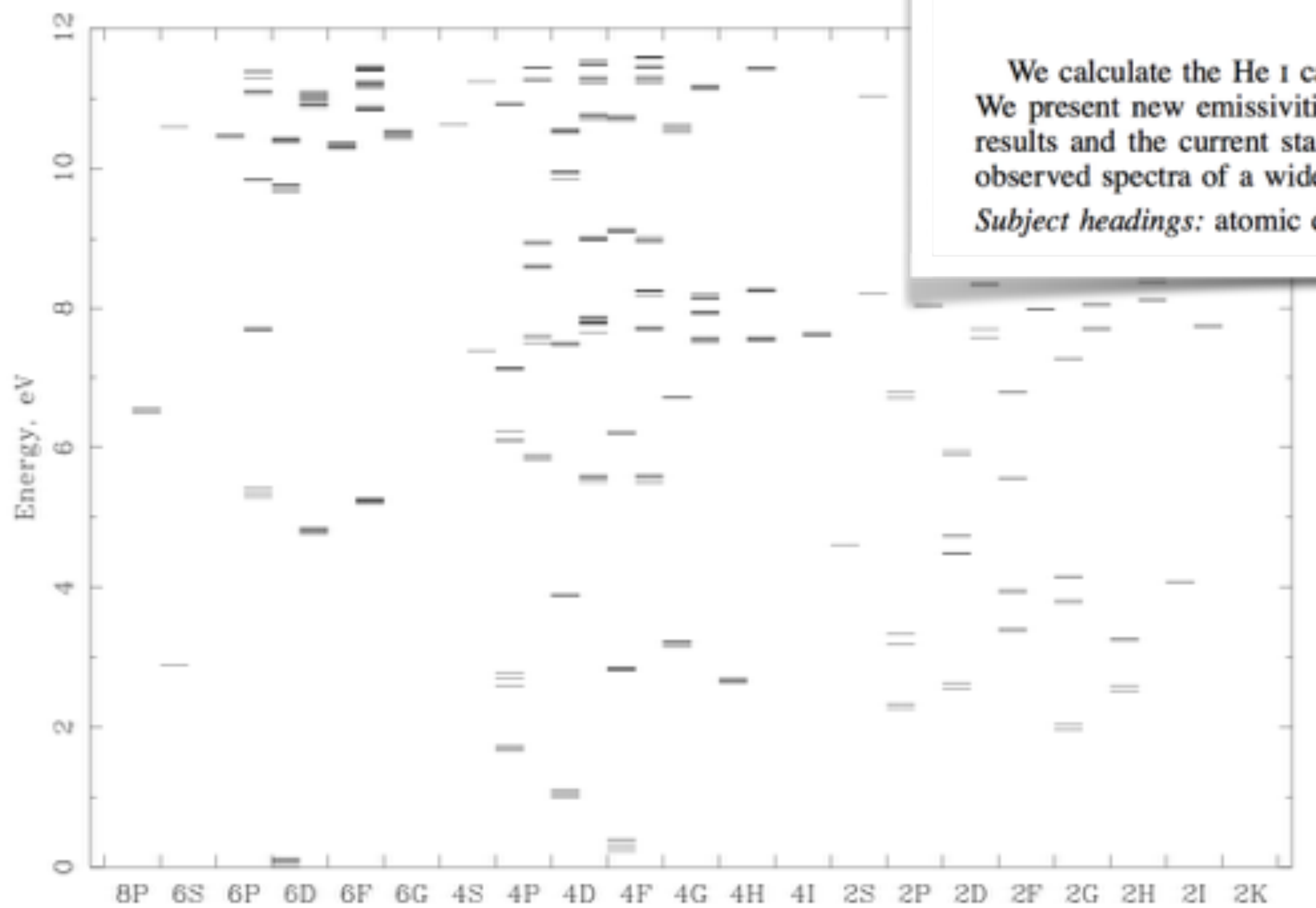

FIG. 1.—Energy distribution of the 371 lowest levels of Fe II that are included in our calculations. The horizontal axis shows terms ranged from octets to doubl...

NUMERICAL SIMULATIONS OF Fe II EMISSION SPECTRA

E. M. Verner,[1] D. A. Verner,[1] K. T. Korista,[1,2] J. W. Ferguson,[1,3] F. Hamann,[4] and G. J. Ferland[1]
Received 1998 April 23; accepted 1998 August 10

ATOMIC DATA: NEW FORMAT

STOUT: CLOUDY'S ATOMIC AND MOLECULAR DATABASE

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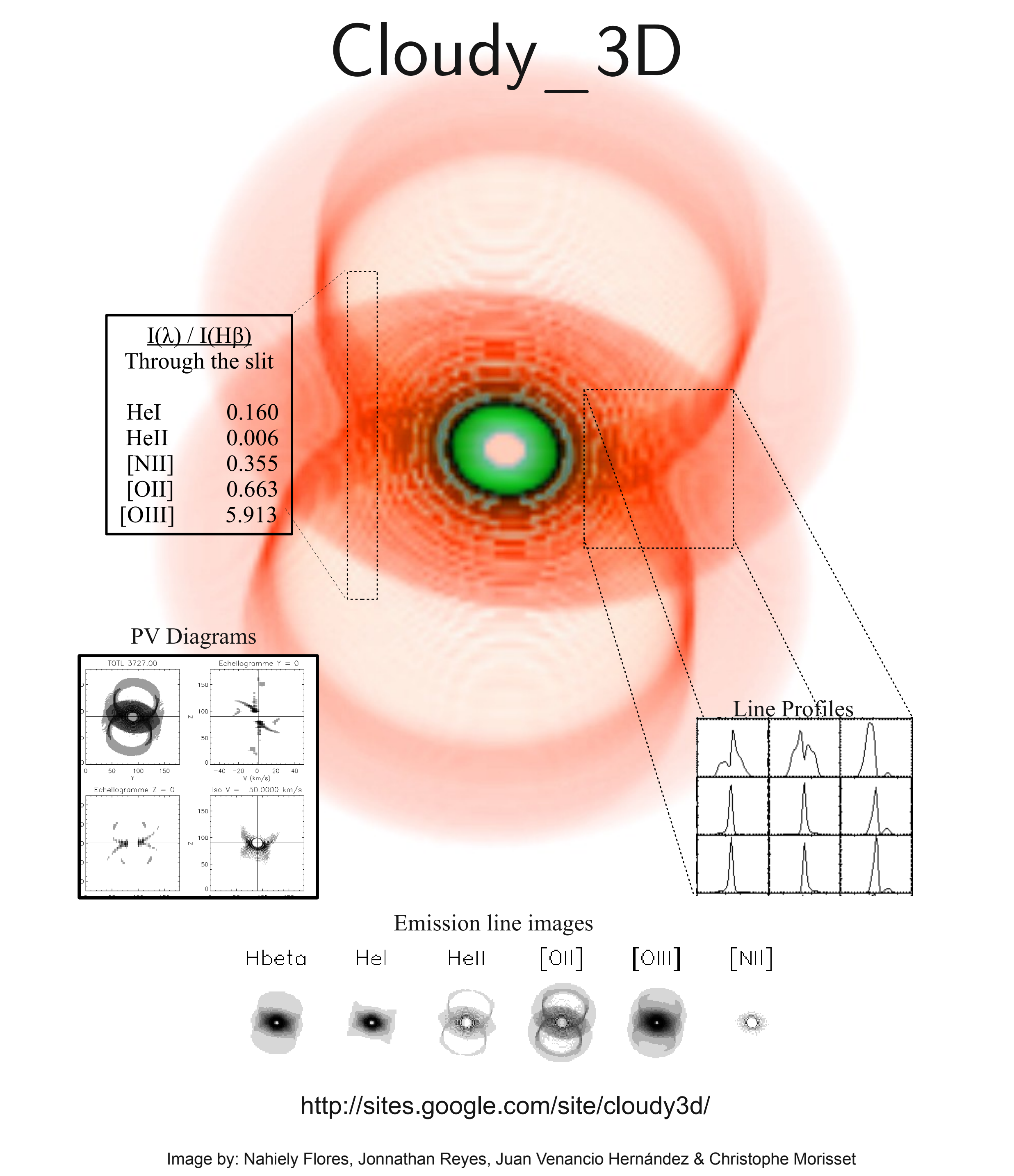
ABSTRACT

We describe a new atomic and molecular database we developed for use in the spectral synthesis code Cloudy. The design of Stout is driven by the data needs of Cloudy, which simulates molecular, atomic, and ionized gas with kinetic temperatures $2.8\ \mathrm{K} < T < 10^{10}\ \mathrm{K}$ and densities spanning the low-to high-density limits. The radiation field between photon energies 10^{-8} Ry and 100 MeV is considered, along with all atoms and ions of the lightest 30 elements, and $\sim 10^2$ molecules. For ease of maintenance, the data are stored in a format as close as possible to the original data sources. Few data sources include the full range of data we need. We describe how we fill in the gaps in the data or extrapolate rates beyond their tabulated range. We tabulate data sources both for the atomic spectroscopic parameters and for collision data for the next release of Cloudy. This is not intended as a review of the current status of atomic data, but rather a description of the features of the database which we will build upon.

Key words: atomic data – atomic processes – molecular data

PSEUDO-3D MODELS



LARGE SCALE EVOLUTION

- Pure photoionization
- Dust
- PDR
- X-rays
- High/low Te
- High Ne

FOLLOWING HARDWARE EVOLUTION

- Many issues in CLOUDY development are due to compiler updates, related to processors upgrades.
- As computers became more powerful and multi-CPU, CLOUDY provided tools like *grid* and *optimizer* to run multiple models.
- Next improvements may be achieved using GPUs.

C16

- Mainly developed by Gary Ferland, Robin Williams, Peter van Hoof, Marios Chatzikos and Fran Guzman.
- Atomic data in a more versatile format, *a la* Chianti (stout format).
- Much more emission lines.
- Faster.

C19… C22…

- Parallel processing (CPU and GPU)
- Ray tracing, 3D geometry
- ALI radiative transfer (Accelerated Lambda Iteration method, like for stellar atmospheres)
- shocks? MAPPINGS, M. Dopita, L. Binette
- hydro? W. Henney