THE NEBULATOM 3 COOKBOOK

Grażyna Stasińska[1] and Christophe Morisset[2]

RESUMEN

We present a series of exercises prepared for hands-on activities on nebular and atomic physics. They make use of the following tools: Cloudy, the most widely used public photoionization code (Ferland et al. 2013), PyNeb (Luridiana et al. 2015) and pyCloudy (Morisset 2012). The solutions to the exercises, written in python in the format of ipython notebooks, can be downloaded from `https://github.com/Morisset/NEBULATOM-tools`.

ABSTRACT

We present a series of exercises prepared for hands-on activities on nebular and atomic physics. They make use of the following tools: Cloudy, the most widely used public photoionization code (Ferland et al. 2013), PyNeb (Luridiana et al. 2015) and pyCloudy (Morisset 2012). The solutions to the exercises, written in python in the format of ipython notebooks, as well as all the needed material, can be downloaded from `https://github.com/Morisset/NEBULATOM-tools`.

Key Words: H II regions — ISM: planetary nebulae

This cookbook is prepared for hands-on activities on nebular and atomic physics for NEBULATOM 3, a capacity development workshop for Latin American astronomers on emission-line objects in the Universe, held in Baia Formosa (RN, Brazil) 7–20 May 2017. Many theoretical aspects treated during this workshop can be found for example in the fundamental books by in Spitzer (1968), Osterbrock & Ferland (2006), Dopita & Sutherland (2003), Draine (2011) and in the articles by Stasińska (2004) and Stasińska (2009).

The exercises presented here are meant to familiarize the student with the various concepts involved in practical studies of emission-line nebulae. They also serve to introduce the students to Cloudy, the most widely used public photoionization code (Ferland et al. 2013) as well as to a suite of tools developed in python for an easy interpretation of nebular spectra, which are PyNeb (Luridiana et al. 2015) and pyCloudy (Morisset 2012).

The solutions to the exercises, proposed as series of codes written in python[3] in the format of ipython notebooks, can be downloaded from `https://github.com/Morisset/NEBULATOM-tools`.It is actually not expected from the students to produce similar codes by themselves, but to run the proposed codes, paying attention to the way the problems are treated, exploring alternative solutions, and keeping a critical eye on the results.

These codes are also meant to be convenient starting points for further exploration of problems dealing with emission line nebulae.

Note: The exercises should be made in the proposed order, as they may use tools developed in previous steps.

1. DEREDDENING

These exercises make use of the PyNeb software (Luridiana et al. 2015)[4].

All observations are affected by extinction due to interstellar dust. The first thing an observer must do once the spectra are calibrated and the line intensities measured is to correct the line intensities for extinction. Published data nowadays often give only reddening-corrected line fluxes and the value of the extinction in the V band, A_V. It may however be of interest to recover the observed intensities and apply a different extinction law.

1.1. The effect of different reddening laws

Consider the deep spectrum of the Galactic H II region NGC 3603 obtained by García Rojas et al. (2006) (their

[1]LUTH, Observatoire de Meudon, F-92195 Meudon Cedex, France

[2]Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 70264, Méx. D.F., 04510 México

[3]To install a version of python allowing to use the tools described in this document, see Appendix A.

[4]To install PyNeb, see Appendix C.

Table 2).

`http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=J/MNRAS/368/253&-to=3`

1.1.1.

Using the Fitzpatrick (1999) extinction law with R_V = 3.1, compute the reddening-corrected intensities for the hydrogen lines and for all the forbidden lines assuming an intrinsic value for Hα/Hβ of 2.83.

1.1.2.

Do the same, but for R_V = 5.

1.1.3.

Compute the reddening-corrected values of Hγ/Hβ, Hδ/Hβ, [O III] λ4363/[O III] λ5007, and [O II] λ3727/[O II] λ7325 for both cases of R_V.

1.1.4.

???Comment on the results.

1.1.5.

Plot the different extinction laws using the PyNeb RedCorr plot facility.

2. LINE EMISSIVITIES

These exercises make use of the PyNeb software (Luridiana et al. 2015). For any line, the word 'emissivity' is taken to be the energy per emitting ion and per electron emitted in all directions for the corresponding transition. In CGS units it is expressed in erg s^{-1} cm^3.

2.1. Emissivities of lines from O III

2.1.1.

Find all the lines emitted by the O III ion. Examine from what levels they are issued.

2.1.2.

??? For lines issued from the same level, which are the ones which will be the strongest?

2.1.3.

Compute the emissivities of all these lines between 1000 and 30000 K, at a density of n_e= 100 cm^{-3}, and plot them.

2.1.4.

??? Which are the strongest lines at T_e= 3000 K ? at T_e= 10000 K ? at T_e= 30000 K ? Why?

2.1.5.

Do the same for n_e= 10^5 cm^{-3}.

2.1.6.

??? What are the differences? How do they relate to the critical densities of the levels?

2.1.7.

Check the sources of atomic data that are used in the above computations of the line emissivities.

2.1.8.

Plot the values of the collision strengths as a function of temperature for the various available sources of atomic data.

2.1.9.

Compare the values of the Einstein coefficients A's for the various available sources of atomic data.

2.2. Energy balance in an hydrogen-oxygen nebula

Consider a nebula with constant density n_H= 100 cm^{-3} composed only of hydrogen and oxygen, and ionized by a star of temperature $T_\star$= 50000 K and radiating like a blackbody.

2.2.1.

Compute the energy gain $\Gamma/n_e/n_H$ in erg s^{-1} cm^3 due to hydrogen ionization by the stellar radiation discarding the change of the spectral energy distribution of the ionizing photons within the nebula due to absorption. Plot it as a function of T_e from 0 to 30000K.

2.2.2.

Compute the energy losses due to H recombination and to H free-free radiation as a function of T_e and plot them, together with their sum, in the same diagram.

2.2.3.

Compute the energy losses in the O^{++} region of each of the oxygen line and plot them in a diagram for an oxygen abundance O/H= 3×10^{-4}.

2.2.4.

Plot in a separate diagram the energy gains, the H losses, the O^{++} losses, and the total losses. Find the resulting electron temperature.

2.2.5.

??? By trial and error find by how much one needs to change the oxygen abundance to increase the temperature by 2000 K? To decrease it by 2000 K?

2.2.6.

???Alternatively, what change in $T_\star$ is needed to produce the same effect?

2.2.7.

??? If half of the mass of the nebula actually consisted of clumps with a density of 10^5 cm^{-3} would the [O III] λ4363/[O III] λ5007 be strongly affected?. Answer the question qualitatively and justify it.

2.3. A catalog of line emissivities

For easy reference or back-of-the envelope computations of abundances, it is useful to have a precomputed ascii catalog of line emissivities for the more important emission lines.

2.3.1.

Prepare such a catalog for T_e in the range $100 - -10^5$K and n_e in the range $100 - -10^{10}$ cm^{-3}.

2.3.2.

At the beginning of the catalog, indicate the version of PyNeb used to build it and, for each ion the atomic data used to compute the emissivities.

2.3.3.

??? What is the value of Hα/Hβ for $n = 100$ cm^{-3} and $T_\mathrm{e} = 1000, 5000, 8000, 10000, 20000$ K. Comment.

2.3.4.

Prepare a catalog of the following line ratios [O III] λ4363/[O III] λ5007, [N III] λ5755/[N III] λ6584, [S III] λ6312/[S III] λ9069 in the same T_e and n_e ranges as above.

2.3.5.

In the case of the nebula of exercise 1.1.3 , assuming that the real temperature is 10000K and that the real R_V is 5, what temperature you would find if dereddening the observed spectrum assuming $R_V = 3.1$? Comment.

3. PLASMA DIAGNOSTICS

3.1. A catalog of isoratios for plasma diagnostics

Consider the following ions: C^{++}, N^{+}, O^{+}, O^{++}, Ne^{++}, S^{+}, S^{++}, Cl^{++}, Ar^{+++}.

3.1.1.

For each of them, find line pairs that are susceptible to be easily observed (either in the UV, the optical or the IR domain) and to give temperature and/or density diagnostics. Note: some line pairs are strictly equivalent from the point of view of the plasma diagnostics. e.g. [O III] λ4363/[O III] λ5007 and [O III] λ4363/[O III] λ4959. In that case, consider only the one involving the strongest line, i.e., in this case [O III] λ4363/[O III] λ5007.

3.1.2.

For each of these pairs, construct an isoratio plot, and save the resulting plots.

3.1.3.

??? Looking at these plots, for each of them find the temperature/density domain where they are useful for plasma diagnostics.

3.2. Using PyNeb for plasma diagnostics of a planetary nebula of high excitation

Analyse the planetary nebula IC 2165.

Hyung, S. , 1994, ApJS, 90, 119 gives the intensities of optical lines, corrected for extinction and relative to Hβ= 100. The following table gives the ones that are important for diagnostics and abundance calculations:

```
NAME IC_2165
Ne5_3426A 55.88
O2_3726A 18.39
O2_3729A 9.36
Ne3_3869A 85.70
S2_4069A 0.87
S2_4076A 0.71
O3_4363A 20.75
```

```
Fe3_4659A 0.17
He2_4686A 63.48
Fe3_4703A 0.14
Ar4_4711A 5.33
Ar4_4740A 5.86
H1_4861A 100
O3_5007A  1158.31
Ar3_5192A 0.11
N1_5198A 0.16
N1_5200A 0.11
Cl4_5323A 0.07
Cl3_5518A 0.33
Cl3_5538A 0.37
O1_5577A 1.21
N2_5755A 0.47
O1_6300A  1.20
S3_6312A  1.32
Ar5_6435A  1.32
N2_6583A  17.12
S2_6716A  0.86
S2_6731A  1.34
Ar5_7006A 2.08
Ar3_7136A  7.12
Ar4_7170A 0.31
Ar4_7237A 0.26
Ar4_7262A 0.23
Cl4_7531A 0.34
O2_7319A+  1.14
O2_7330A+  0.96
Ar3_7751A 1.50
Cl4_8046A 0.73
Cl3_8501A 0.37
S3_9069A 5.96
```

3.2.1.

Construct the plasma diagnostic diagram with PyNeb. Hint: to find which line ratios provide useful diagnostics, consult Tables 1.9 to 1.14 from Stasińska (2009) available from Internet at `http://arxiv.org/abs/0704.0348`.

3.2.2.

??? What does the plasma diagnostic diagram say about the electron density in this object? Is there evidence for zones of different densities? What does it say about the electron temperature in the low excitation region? in the high excitation region? Compare with the diagnostic diagram published by Hyung.

3.2.3.

Add information from the UV spectrum (Table 1 from Hyung 1994) into the plasma diagnostic diagram. nb: the UV data have already been dereddened and put to a common scale with the optical data using the HeII 1640/HeII 4686 ratio. The corresponding line intensities are as follows:

```
N4_1487A 32.53
Ne5_1575A 16.32
O3_1666A 21.71
N3_1754A 16.95
C3_1907A 961.7
C3_1909A 943.17
```

To find out what new diagnostics are available when including UV data do the following in PyNeb, for example for N III:

```
N3 = pn.Atom('N',3)
N3.printIonic(1e4, 100, verbose=True, printA=True)
```

3.2.4.

??? Comment of the different values of the densities and temperatures from the different new diagnostics.

3.2.5.

Infrared data have been obtained by ISO for this object (Pottasch et al, 1994, A&A 423, 593, Table 2, reproduced below).

```
 ident  lambda  Intensity
He II 9-7  2.826  0.13
H I 5-4  4.053  2.81
[Mg IV]   4.487  4.18
[Ar VI]   4.530  1.82:
[Mg V]   5.610  4.76
[Ne VI]   7.655  0.52:
[Ar V]   7.903  0.75
[Ar III]   8.993  2.27
[S IV]    10.510  27.4
[Ne II]   12.816  1.50
[Ar V]   13.103  1.25
[Mg V]   13.525  0.52
[Ne V]   14.325  24.0
[Ne III]   15.558  32.2
[S III]   18.716  5.55
[Ne V]   24.320  21.3
[O IV]  25.894  84.2
[S III]   33.485  2.40
[Ne III]   36.021  3.56
[O III]   51.854  28.4
[N III]   57.385  4.53
[O III]   88.393  8.06
```

The measured intensities are in units of 10^{-12} erg cm^{-2} s^{-1}. Add information from these lines in the plasma diagnostic diagram. Caution: put the IR observations to scale with the optical ones using the H I 5-4/Hβ ratio. We will assume that all the IR observations were done using the same $14'' \times 20''$ aperture.

3.2.6.

??? Comment on the new diagnostics.

3.2.7.

??? If you have not done it yet, find an image of IC 2165 on the Internet. Comment.

4. ABUNDANCE DERIVATIONS WITH THE DIRECT METHOD

4.1. The chemical composition of IC 2165

4.1.1.

??? Using the plasma diagnostics diagram for IC 2165 estimate the following parameters: n_e([O II]), n_e([Ar IV]), T_e([N II]), T_e([O III]) *from the optical data only*.

4.1.2.

Determine the ionic abundances for N, O, and Ne ions, first 'by hand' using your emissivity table, then using PyNeb.

4.1.3.

??? Justify your choice of temperature and density to compute line emissivities.

4.1.4.

??? Comment on the abundances of the same ion as determined by different lines.

4.1.5.

??? Determine the abundances of N, O, and Ne *from the optical data only* using the ionization correction factors from Delgado-Inglada et al. (2014).

4.1.6.

Compute the error bars on the element abundances assigning reasonable uncertainties to the measured line intensities and to the effects of cross-calibrations.

4.2. The chemical composition of giant H II regions NGC 300

Bresolin et al. 2009, have observed 20 giant H II regions in the spiral galaxy NGC 300.

4.2.1.

For all these objects, compute the electron densities and temperatures from all the available ratios.

4.2.2.

Use Bresolin's et al. policy to derive the electron temperature in the low- and high-excitation zones of each object.

4.2.3.

Compute the ionic abundances for N, O, Ne for all the objects.

4.2.4.

Compute the total abundances of N, O, Ne for all the objects using the 'classical' formulas for the ionization correction factors: O/H= O^+/H + O^{++}/H, N/O = N^+/O^+, and Ne/O=Ne^{++}/O^{++}.

4.2.5.

Plot O/H, Ne/H, N/H as a function of the galactocentric distance (given in Bresolin et al 2009).

4.2.6.

Print out all the atomic data files used in this exercise.

4.2.7.

??? How should one proceed (in principle) to compute properly the error bars?

5. FIRST STEPS WITH CLOUDY

The examples are obtained running Cloudy 17.00[5].

5.1. The line list of Cloudy

5.1.1.

Produce the entire list of lines computed by Cloudy and save in a file.

5.1.2.

???If you are interested in the [O II] λ3727 line, which line(s) from the line list should you consider? Which lines of [O III] are available in the line list? In the line list, what is number of the row concerning [O III] λ4363 ? [O III] λ5007 ?

5.2. Find the atomic data used by Cloudy

5.2.1.

Create a file containing all the references for the atomic data used in the current version of Cloudy.

[5] To install Cloudy, see Appendix D.

5.2.2.

???Check whether the references for the transition probabilities and collision strengths for [O II], [O III], [N II], [Ne III],[S II], [S II], and [Ar IV] are the same as for the default version of Pyneb.

5.3. Some simple runs with Cloudy

Remember that you must always check that the models ran OK. This is especially important when running grids of models. The output file should end with 'Cloudy exited OK'.

5.3.1.

Model 1. Read the instructions in Sects. 2.1 and 2.2 in docs/QuickStart.pdf Run the simple planetary nebula model of Sect. 2.1 of Quickstart. The ionizing source is a blackbody of temperature 10^5 K and luminosity 10^{38} erg s^{-1}. The inner radius of the nebula is 10^{18} cm and its hydrogen density is 10^5 cm^{-3}. The chemical composition is the standard planetary nebula of Cloudy.

5.3.2.

??? Is the chemical composition used by Cloudy as you expected? Look at the intensity predicted for [O III] λ5007. Is it typical of planetary nebulae? Does the He II λ4686/Hβ ratio correspond to the expected one following Eq. 5 of Stasińska et al. (2015)? Why? Estimate the age of the PN assuming an expansion velocity of 20 km/sec.

5.3.3.

Model 2. Run the same model, now specifying the ionization parameter to be $10^{-2.5}$ instead of giving the inner radius and the total luminosity.

5.3.4.

??? Is the geometry assumed by Cloudy the one you wanted? How have the values of the mean ionization (over radius*electron density) changed ? Why? Does the He II λ4686/Hβ ratio now correspond to the expected one following Eq. 5 of (Stasińska et al. 2015) ? Why?

5.3.5.

Model 3. Run the same model as Model 2, now using the Solar abundances from Asplund et al. (2009) for He, C, N, O, Ne, Mg, Si, S, Ar, Fe which, in units of 12+log X/H are, respectively 10.93, 8.43, 7.83, 8.69, 7.93, 7.60, 7.12, 6.40, 7.50.

5.3.6.

??? How were chosen the abundances that you did not specify? What about grains?

5.3.7.

Model 4. Run the same model as Model 3, now adopting a blackbody temperature of 50,000 K.

5.3.8.

??? Comment on the ionization structure and the averaged electron temperature. Search for the intensities of the following lines: Halpha, [NII] 6584, [OII] 3727, [OIII] 5007, [OIII] 4363, and [OIV] 26m.

5.3.9.

Model 5.
Run the same model as Model 4, now adopting an hydrogen density of 10 cm^{-3}

5.3.10.

??? How did the intensities of the most important line change with respect to Model 4. Why ?

5.3.11.

Model 6. Run the same model as Model 5, now trying to save on execution time.

5.3.12.

??? By how much was your execution time reduced? Are the results virtually identical to the ones of Model 5? In particular, comment on the intensity of the He I λ5876 line.

5.3.13.

Model 7. Run a model ionize by a blackbody of 50,000K having a luminosity of 10^{38} erg s^{-1}, a hydrogen density of 10^2 cm^{-3} and an inner radius of 10^{17}cm. For the chemical composition, add 0.35 dex to the abundances of the heavy elements of Model 6.

5.3.14.

???Comment on the results.

5.3.15.

Model 8. Run the same model as Model 7 correcting the problem of Model 7 (if you find there was one),

5.3.16.

??? How did the intensities change with respect to Model 7? What is now the execution time?

5.3.17.

Model 9. Run the same model as Model 8 trying to reduce the execution time and checking that the results are still correct.

5.3.18.

??? General comments on this exercise: What are important things you need to check when running Cloudy?

6. RUNNING CLOUDY WITHIN THE PYCLOUDY ENVIRONMENT

The proposed exercises use the Cloudy code within the pyCloudy environment, developed by C. Morisset, in which many tools are available to easily make models and analyze them [6].

6.1. Ionization and temperature structure

6.1.1.

Compare a spherical model with n = 100 cm^{-3} and filling factor ff=1 with a model with n = 10^4 cm^{-3}and filling factor ff=0.1. Plot T_e, O^{++}/O, O^+/O as a function of fractional radius in those two models. Repeat the exercise for various values of the effective temperature.

6.1.2.

??? Comment on the results.

6.1.3.

Construct a series of constant density, spherical dust-free models of density n = 100 cm^{-3} with average ionization parameter log U = -2 ionized by a star radiating as a blackbody at a temperature of 50,000K, where the metallicity varies from 0.01 $Z_\odot$ to 3 $Z_\odot$. Plot the following parameters, as a function of metallicity: outer radius, average temperatures and ionic fractions of O^+ and O^{++} [O II] λ3727/Hβ, [O III] λ5007/Hβ, [O III] λ88μm/Hβ, and the actual mean logU from the model.

[6] To install pyCloudy, see Appendix E.

6.1.4.

??? Comment on the results.

6.1.5.

Do the same, adding dust with Orion-type grains, with a dust-to-gas ratio proportional to metallicity.

6.1.6.

??? Comment on the results.

6.1.7.

Do the same, now depleting the gas abundances according to the dust content.

6.1.8.

??? Comment on the results.

6.2. Comparing different stellar energy distributions

6.2.1.

Compute a dust-free solar abundance spherical model of density n = 250 cm^{-3} and ionization parameter log U = -2 ionized by a blackbody at 50,000 K with a total luminosity of $10^5 L_\odot$.

6.2.2.

Plot the input and output spectrum as a function of wavelength from the far IR to the EUV.

6.2.3.

??? Comment.

6.2.4.

Compute an identical model but ionized by a WMbasic model atmosphere with log g = 4.

6.2.5.

Plot the input and output spectrum as a function of wavelength from the far IR to the EUV.

6.2.6.

Plot the values of $Q(E)$, the number of stellar photons above energy E, for the two spectral energy distributions considered

6.2.7.

Compare the ionization structures of He,N,O,Ne,S,Ar for these two models, by plotting the ionic abundances as a function of fractional radius.

6.2.8.

??? Comment.

7. MODEL GRIDS WITH PYCLOUDY

7.1. Global budget

7.1.1.

Construct a series of plane-parallel models of density n = 100 cm^{-3} ionized by a blackbody at 50,000 K, varying log U between -3.5 and -1.5 by steps of 0.5 dex and the metallicity from 12+ log O/H from 7 to 9 by steps of 0.5 dex (take He/H = 0.1 for all the models and adopt the solar abundance ratios from Asplund et al. (2009) for all the heavy elements. Consider Orion-type dust grains with an abundance following that of O/H.

7.1.2.

Plot the ratio L(Hβ)/$Q_{\rm H}$ as a function of log U, coloring by the metallicity.

7.1.3.

??? Comment on the results.

7.2. The upper envelope of HII regions in the BPT digram

7.2.1.

Build a grid of plane-parallel photoionization models with open geometry, density $n_{\rm H}$= 100 cm^{-3}, no dust, varying log U between -4.5 and -1.5 by steps of 0.5 dex, for the metallicities Z = 0.001, 0.002, 0.008, 0.02, 0.040 taking as ionization sources starburst99 models (using Kroupa IMF, Geneva high metallicity tracks, Pauldrach/Hillier atmospheres) at an age of 1 Myr for the corresponding metallicities.

7.2.2.

Plot the observational BPT diagram (log [O III] λ5007/Hβ, vs log [N II] λ6584/Hα) for a set of emission line galaxies from the Sloan Digital Sky Survey. The relevant line intensities are given in file BPT4Graz_f4.dat from the `https://github.com/Morisset/NEBULATOM-tools/tree/master/Data` site.

7.2.3.

Overplot the grid of photoionization models, joining models with same metallicities by dashed lines and models with same ionization parameter by continuous lines and comment on the resulting plot.

7.2.4.

??? Comment on your results with respect to the upper envelopes of Kewley et al. (2001), Stasińska et al. (2006), and Dopita et al. (2013).

7.2.5.

Find in the 3MdB data base (see `https://sites.google.com/site/mexicanmillionmodels/`) the relevant models from the 'HII CHIM' grid and plot them in a similar diagram.

7.2.6.

??? Comments.

8. DETAILED MODEL-FITTING WITH MANY OBSERVATIONAL CONSTRAINTS

8.1. A photoionization model for IC 418

Consider the planetary nebula IC 418. A detailed photoionization model of it has been published by Morisset & Georgiev (2009). The proposed exercise is not to reproduce this model exactly but rather to show the different steps to reach an acceptable solution and keep a critical eye on the results. The following observational constraints are considered:

- HST WFPC observations in Hα, [N II] λ6584 and [O III] λ5007filters (find the 3-color image on the Internet and examine it)
- Total reddening-corrected Hβ flux
- Angular diameter
- The stellar spectrum
- A high resolution, deep optical spectrum within a slit
- Ultraviolet spectra obtained with IUE
- Infrared spectra

8.1.1.

Compute the starting model abundances using the direct method.

8.1.2.

Build a model with a density distribution reproducing the observed Hα surface brightness distribution and using the stellar model presented in Morisset & Georgiev (2009), which fits the atmospheric stellar properties.

For the fitting procedure, compare the observed line intensities with those obtained by the model *in the corresponding apertures*. Try to find a model which reproduces *all* the line intensities *within their respective error bars.*

8.2. Computing line profiles

Assume that the nebula is expanding with a given velocity law.

8.2.1.

Draw the profiles of the Hβ, [O II] λ3727, and [O III] λ5007 lines as would be observed with a pencil beam passing trough the center, for a constant expanding velocity, for a velocity increasing linearly with the radius and for a velocity increasing with the squared radius.

8.2.2.

Compute the line profiles as would be observed by a long slit along the symmetry axis, with a beam shifted by 5 arcsec from the center and for the full nebula (for the ”Hubble flow” expanding nebula).

8.2.3.

??? Comments.

9. MODEL-FITTING OF EXTRAGALACTIC PLANETARY NEBULAE

This is an example of model-fitting with few observational constraints. Consider the planetary nebulae observed in the galaxy NGC 5128 by Walsh et al. (2012), for example objects F34 1, F34 2, F34 4, F34 7, and F34 11.

9.0.1.

For each object, try to fit an ionization-bounded photoionization model to the observed data assuming a spherical geometry, constant density, a blackbody radiation, and comparing the observed line intensities with those given by the model. Before starting, think of the policy you will follow to find your best model. To analyze the goodness of your fit, use first a khi-square method on the line intensities, with weights inversely proportional to the line intensities. This is a widely used method.

9.0.2.

??? Write the results of your ’best’ model and analyze its problems.

9.0.3.

Try to obtain a better model by attempting to fit each line within its error bar.

9.0.4.

??? Write the results of the model and comment.

9.0.5.

Produce a new model, now relaxing the assumptions of constant density and ionization boundedness.

9.0.6.

??? Write the results of this model and comment.

9.0.7.

??? Estimate the error bars on the O/N and N/O ratios.

APPENDICES

Most of the softwares that you will have to install are described on this page: `https://github.com/Morisset/NEBULATOM-tools/tree/master/What2install`

A. ABOUT PYTHON AND ITS LIBRARIES

A decent version of python and ipython must be present on your computer to allow you to fully use the tools described in this document. The tools used here require python 3.

The best is certainly to have a distribution of python that includes recent versions of numpy, matplotlib, scipy, ipython and astropy. This can be done using Anaconda: http://continuum.io/downloads

The pip installer (https://pypi.python.org/pypi/pip) must also be present. It is used to install other libraries, see below. It comes with the anaconda package.

B. INSTALLING SOME PACKAGES

A few packages that do not come with anaconda need to be installed. This is achieved with the following commands from a terminal window:

```
pip install atpy
pip install pillow
```

C. INSTALLING PYNEB

To install and update PyNeb, follow the instructions on the page: https://pypi.python.org/pypi/PyNeb/. This is also where to find the PyNeb Manual, the Reference Manual, the Developer Reference Manual and more informations. We strongly recommend you to make an update of PyNeb, using for exemple

```
pip install -U [--user] pyneb
```

Do not use - -user if your python comes from Anaconda, Canopy or Ureka.

To check the version of PyNeb, enter the following in python:

```
import pyneb as pn
print(pn.__version__)
```

D. INSTALLING CLOUDY

D.1. Cloudy itself

The Cloudy photoionization code web page is http://www.nublado.org/

You can download Cloudy using the http://www.nublado.org/wiki/DownLoad page. We will use the version c17 of Cloudy.

IMPORTANT: after downloading the code and before compiling it (before typing "make"), edit the source/Makefile file to change the line number 116, by adding ".:" before "+":

```
before:  CDP = +
---
after:   CDP = .:+
```

This will indicate Cloudy that some files can be found in your current directory, and not only in the place where Cloudy store its data.

Once this is done, you can compile Cloudy by using the make command in the source directory. This will create a program file named cloudy.exe.

D.2. Testing Cloudy

From the source directory, run the following:

```
echo 'test' | cloudy.exe
```

This should run Cloudy in the smoke test mode.

D.3. Cloudy accessible from everywhere

Once you have obtained the cloudy.exe program, you must inform your operating system where to find it from everywhere. This can be done in different ways, most of them requiring editing the preferences file of the operating system. There are 2 shells that are widely used: bash and tcsh. To know which one is yours, type the following in a terminal:

```
echo $shell
```

Depending on the response your system gives, follow the instructions:

- **/bin/sh or /bin/bash:** Edit or create the file .bashrc in your home directory and add the following line (you must adapt it to the actual location of cloudy.exe on your system):

  ```
  alias cloudy.exe="/home/morisset/Cloudy/
  c17.00_rc1/source/cloudy.exe"
  ```

- **/bin/csh or /bin/tcsh:** Edit or create the file .tcshrc in your home directory and add the following line (you must adapt it to the actual location of cloudy.exe on your system):

  ```
  alias cloudy.exe "/home/morisset/Cloudy/
  c17.00_rc1/source/cloudy.exe"
  ```

From a new terminal window, you can verify that the simple command below executed from any other directory than the source directory actually runs the cloudy smoke test:

```
echo 'test' | cloudy.exe
```

D.4. A directory for the models

A lot of models will be run when doing all the exercices from this cookbook. To avoid having the results of the models invading the directory where the ipython notebooks are, the best is to create a special directory that will hold all those files. In the examples this directory is /DATA/NEBULATOM, you will have to create it (this needs root access) or to adapt the notebooks by changing some lines to reflect your choice.

D.5. Special files

For the model of IC418 (see Sect.8.1), you will need a special density distribution. Download from the page `https://github.com/Morisset/NEBULATOM-tools/tree/master/Cloudy_sources` the file dense_fabden.cpp. Put it in the Cloudy source directory, touch it by doing the following from the source directory:

```
touch dense_fabden.cpp
```

and recompile Cloudy by executing the make command (make will actually only compile this file, not all the others).

For the same model, you will need to have a special SED. Download from the page `https://github.com/Morisset/NEBULATOM-tools/tree/master/Data` the file mod103.ascii.gz, uncompress it and compile the stellar atmosphere model using Cloudy:

```
echo 'compile stars "mod103.ascii" ' | cloudy.exe
```

This will create a file mod103.mod that has to be in the directory where the models are run.

E. INSTALLING PYCLOUDY

Follow the instructions from `https://sites.google.com/site/pycloudy/`

We strongly recommend you to make an update of pyCloudy, using for example

```
pip install -U [--user] pycloudy
```

Do not use - -user if your python comes from Anaconda, Canopy or Ureka.

To check the version of PyCloudy , enter the following in python:

```
import pycloudy as pc
print(pc.__version__)
```

F. USING STARBURST99 FILES

F.1. Downloading some files

Download from `https://github.com/Morisset/NEBULATOM-tools/tree/master/Data` the 5 files named ISBxxxx.stb99.

F.2. Compile the stb99 files to be used with Cloudy

From the directory where the ISBxxx.stb99 file have been downloaded (see Sec. F.1), type:

```
echo 'compile stars "ISB_008.stb99"' | cloudy.exe
```

This makes Cloudy create the files ISB_008.ascii and ISB_008.mod, the latest one being in the right format to be used as an input spectrum for computing a model. Repeat the procedure for the 5 files.

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LUTH, Observatoire de Meudon, F-92195 Meudon Cedex, France.
Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 70264, Méx. D.F., 04510 México.