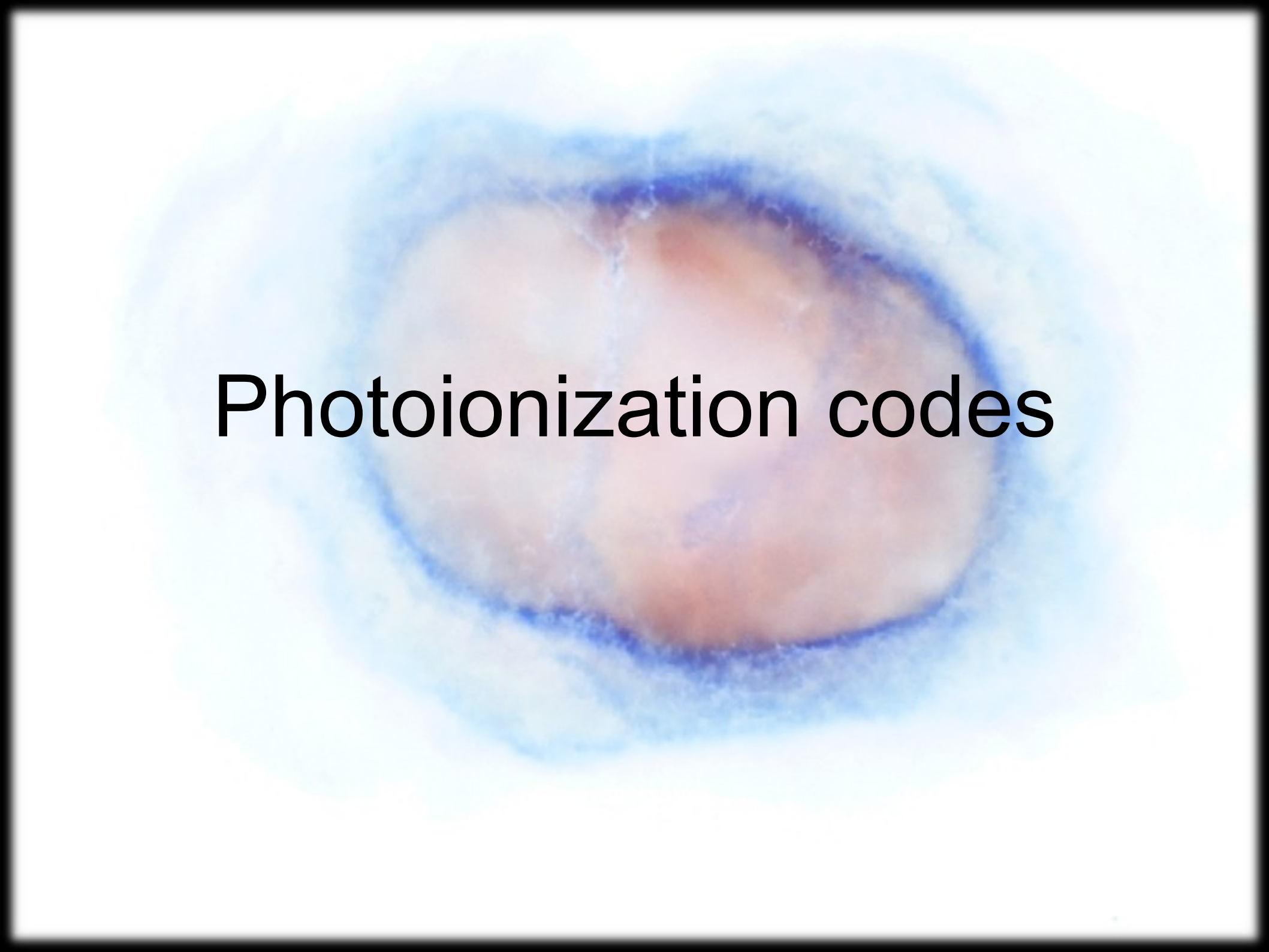
Photoionization codes

Photoionization codes – first ones

- First models in late 60's by D. Flower, P. Harrington, B. Rubin among others.
- Photoionization codes can be seen as a complete summary of all the physics we know about the interaction between energetic radiation and interstellar gas.

COMPUTER MODELS OF THE PLANETARY NEBULAE NGC 7662 AND IC 418

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Discrepancies between the observed and calculated spectra of the nebulae are discussed. There is evidence for the importance of dynamical effects and filamentary structure and possibly for deviations of the flux of the central star of NGC 7662 from black-body values in the far ultra-violet.

Photoionization codes - today

- Today the more used photoionization code is certainly **Cloudy** (G. Ferland, P. van Hoof, R. Porter, R. Williams, W. Henney). It's a 200,000 lines C++ code (with 500,000 lines of data files).
- Some other 1D codes are also used (**PHOTO** by Stasinska, **NEBU** by Péquignot, **MAPPINGS** by Dopita and Binette)
- **MOCASSIN** (Ercolano) is a Monte-Carlo full 3D code
- Cloudy_3D/**pyCloudy** (IDL and Python versions, by Morisset) is a pseudo-3D code.

Photoionization codes – inputs and outputs

Description of the model (inputs)

- Ionizing SED (BB, stel. model, synth. Spectrum.) T*, L*, Z*
- Gas distribution : nH(r – x,y,z)
- Chemical composition (spatial var?)
- Dust (spatial var?)

Atomic database

- Cross sections
- Recomb. coeffs.
- Collision strengths
- Einstein coeffs.
- Dust properties

PHOTOIONISATION CODE

- Te, ne
- X^i / X (r – x,y,z)
- Line emissivities

The temperature is an **output**

- Contrary to the H density, which is an input.
- Results of the thermal equilibrium.
- Obtained by GAINS = LOSS.
- GAINS: depend on ionizing photons mean energy (T*).

$$G(H^0) = n_e n_p \alpha_A(H^0, T) \frac{\int_{\nu_0}^{\infty} \frac{J_\nu}{h\nu} h(\nu - \nu_0) a_\nu(H^0) d\nu}{\int_{\nu_0}^{\infty} \frac{J_\nu}{h\nu} a_\nu(H^0) d\nu}$$

The temperature is an **output**

- Contrary to the H density, which is an input.
- Results of the thermal equilibrium.
- Obtained by GAINS = LOSS.
- GAINS: depend on ionizing photons mean energy (T*).
- LOSS: depend on line emission, especially on forbidden lines from metals, thus depend on Z.

$$4\pi j_{ul} = n_u A_{ul} h\nu_{ul} = n_l \frac{g_u}{g_l} e^{-h\nu_{ul}/kT} \left[1 + \left(\frac{A_{ul}}{n_e q_{ul}} \right) \right]^{-1} A_{ul} h\nu_{ul}$$

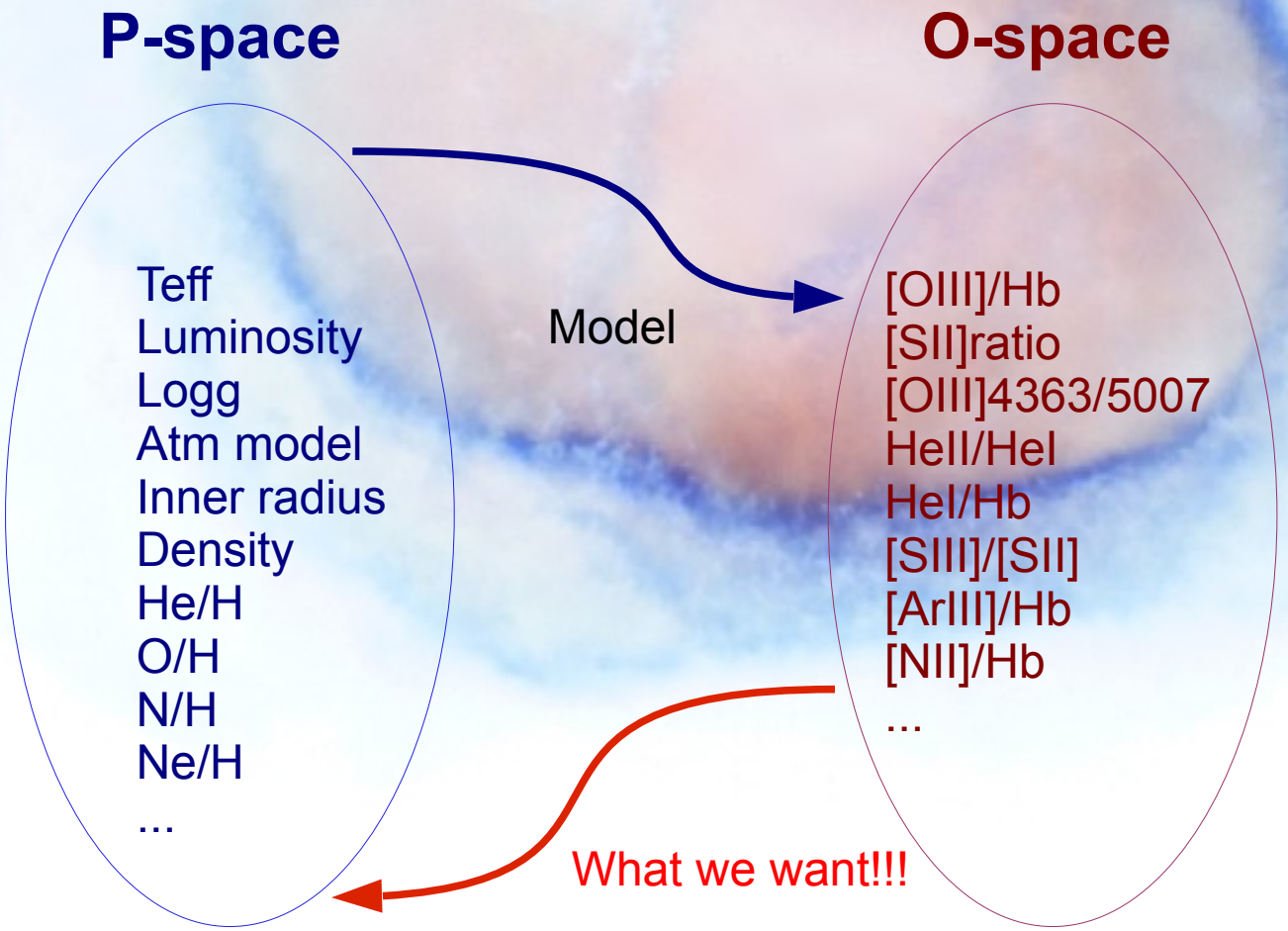
How to make a model ? - basics

Making a model of an given object is **finding** a (unique?) set of **input** parameters that are able to **reproduce all the observables:**

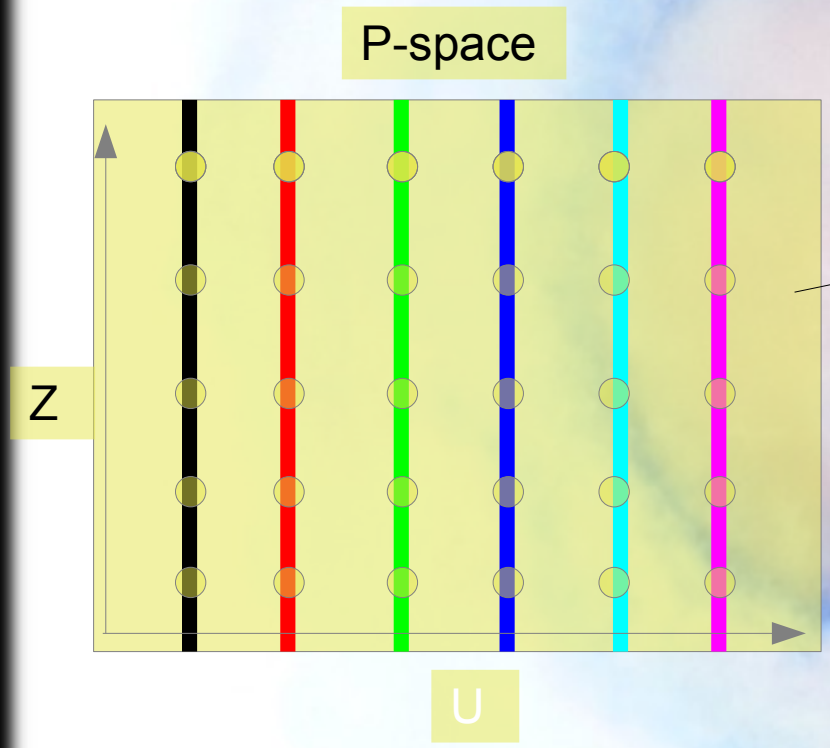
- Emission line ratios (Te- and ne-diagnostics, and also I/Ibeta).
- Absolute value of one emission line intensity.
- Images (shape and angular size – Distance).
- Continuum flux (radio – IR – Opt – UV – X)
- Line profiles, PV-diagrams (velocity field).

How to make a model ? P- and O-spaces

The modeling process can be seen as solving an inverse problem :



No linearity



Mon. Not. R. Astron. Soc. 371, 972–982 (2006) doi:10.1111/

Semi-empirical analysis of Sloan Digital Sky Survey galaxies - How to distinguish AGN hosts

Grażyna Stasińska,[1]★ Roberto Cid Fernandes,[2] Abílio Mateus,[3] Laerte S
and Natalia V. Asari[2]

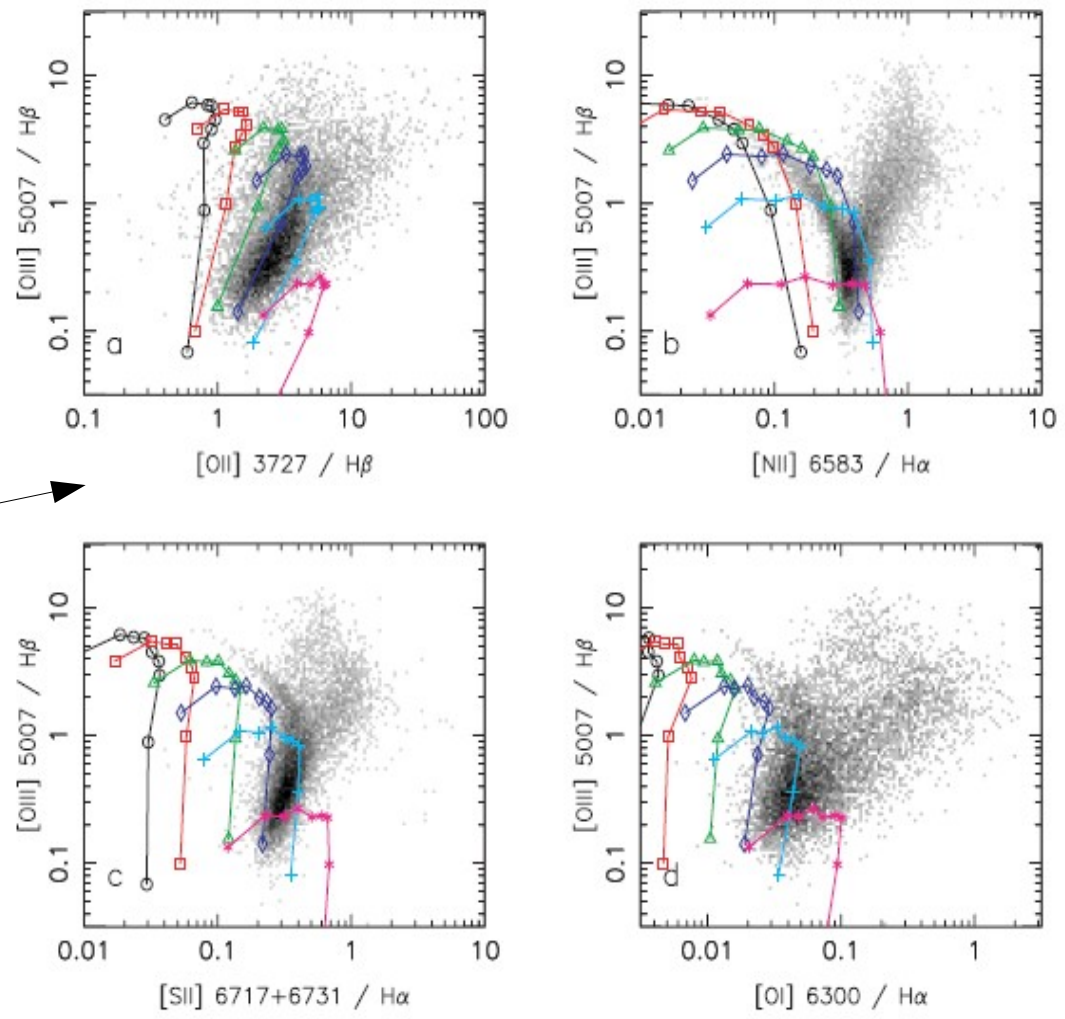


Figure 2. Sequences of photoionization models with varying metallicities Z and constant ionization parameter U. The symbols on the curves correspond to the location of models with metallicities $Z = 0.1$, 0.2, 0.3, 0.4, 0.6, 0.8, 1.0, 1.5 and 2.5 $Z_{\odot}$, going from the upper left to the lower right (in panels b, c and d, the lowest metallicity models are actually outside the range of the plots). The values of the ionization parameter U are 10^{-2} (black circles), 5×10^{-3} (red squares), 2×10^{-3} (green triangles), 10^{-3} (blue diamonds), 5×10^{-4} (cyan + signs) and 2×10^{-4} (purple ∗ signs).

Go to Nublado

- https://www.nublado.org/
- Contains downloads for the code (current and previous versions), hotfixes, help.
- https://cloudyastrophysics.groups.io/g/Main is the forum : report problems, ask for help.
- C17 version of Cloudy is described here : https://ui.adsabs.harvard.edu/abs/2017RMxAA..53..385F/abstract


Short comments
on Cloudy/pyCloudy

Cloudy, short how-to

- Cloudy:
  - C++ code (200,000 lines!)
  - freeware
  - easy to install
  - very well supported by an active group of developers/users.
  - New version every 2-3 years (c17.02 just released)
  - Very detailed documentation (Quickstart and Hazy)

Cloudy, short how-to

- Cloudy.exe < model.in > model.out
- New form : cloudy.exe -p model
- Other test.*** files (radius, physics, ionic abundances, emissivities, etc)

Cloudy input file

- Ionizing source:
  - Shape (T[BB], T, Z, logg[Atm Mod], stellar cluster, power law, AGN)
  - Intensity (Luminosity, logU, Q0)
- Gas properties
  - Distribution (R_in, R_out, nH(r), ff)
  - Metallicity
  - Dust

Cloudy standart output

- The standart output from Cloudy is a collection of information about the model without a simple format, described in the Hazy manual.

Look at the output

- Control that everything is OK : check warnings, number of steps, and why it stops (this can be defined in the input file).
- Look at the mean ionization stages of the principal ions, mean temperature, heating and cooling sources.
- Some line intensities.
- More informations are available in other files.

Cloudy short how-NOT-to

- Use Cloudy to automatically find a solution, but not giving it the way to... by for example giving a small weight to weak lines like... [OIII]4363 !

The rms relative difference between the observed and modeled spectra was determined with

$$\mathrm{rms}^2 = \frac{1}{N}\sum W_i \frac{(O_i - M_i)^2}{O_i^2}, \qquad (2)$$

where N is the number of lines included in the analysis, W_i is a line weight factor, and O_i and M_i are the observed and modeled line intensities. The line weight factor is equal to 1 when $O_i/\mathrm{H}\beta > 0.5$, 0.5 if $O_i/\mathrm{H}\beta \in [0.1, 0.5)$ and 0.25 if $O_i/\mathrm{H}\beta \in [0.01, 0.1)$. Obviously, all hydrogen recombination lines are ex-

Parameter	A 79		BV 5-1		JnEr 1		M 1-41		NGC 2818		Sh 1-89		Sh 2-71E	
	Obs.	Model	Obs.	Model	Obs.	Model	Obs.	Model	Obs.	Model	Obs.	Model	Obs.	Model
[O II] λ3727	511	491	352	367	782	734	290	274	509	498	408	385	179	232
[Ne III] λ3869	155	155	163	163	115	112	102	101	155	155	108	112	133	133
Hδ λ4101	30.5	25.8	25.7	25.1	24.5	25.9	25.1	25.4	26.4	25.9	24.5	25.8	23.5	24.7
Hγ λ4340	48.8	46.8	48.3	46.5	57.0	46.9	46.0	46.7	48.0	46.9	45.2	46.8	43.4	46.3
[O III] λ4363	9.19	5.21	25.1	18.2	5.42	4.87	17.2	10.2	14.6	8.06	4.07	3.49	21.4	18.8
He I λ4471	7.19	10.2	6.12	5.99	5.15	7.36	...	4.83	4.40	6.15	4.75	7.16	...	5.96
He II λ4686	48.6	49.8	66.9	68.5	22.9	22.9	53.2	53.0	32.9	32.7	25.7	23.6	90.8	91.3
[Ar IV] λ4740	...	0.35	3.89	3.89	...	0.48	6.92	3.00	...	1.92	...	0.29	8.14	8.54
[O III] λ5007	444	443	951	923	721	820	653	654	808	747	668	691	833	838
[N I] λ5200	34.9	37.0	19.2	19.6	4.84	5.59	22.5	22.6	22.0	23.2	13.3	13.3	24.3	24.8
[Cl III] λ5518	...	1.34	2.59	2.36	...	0.87	...	1.65	...	1.21	...	0.72	...	2.13
[Cl III] λ5538	...	0.99	1.64	1.87	...	0.62	...	1.60	...	0.87	...	0.53	...	1.69
[N II] λ5755	36.1	34.7	26.4	25.0	7.96	6.94	26.1	22.6	19.3	17.3	7.38	8.19	33.8	34.8
He I λ5876	26.9	26.8	16.1	16.1	19.4	19.4	13.7	13.8	16.0	16.1	19.2	19.2	16.1	16.1
[O I] λ6300	98.8	12.5	43.6	10.0	27.3	11.4	43.8	13.7	47.0	16.7	46.3	13.6	25.4	6.58
[S III] λ6312	...	4.86	7.37	9.51	...	0.52	7.75	5.22	2.83	4.46	...	1.43	9.64	15.4
Hα λ6563	291	291	299	299	290	290	296	296	289	289	292	292	302	302
[N II] λ6584	2155	2050	1135	1101	633	584	1010	1011	1175	1191	793	813	1614	1615
He I λ6678	10.4	7.51	4.73	4.35	...	5.49	3.58	3.54	4.86	4.55	5.56	5.42	6.83	4.35
[S II] λ6717	145	144	99.0	98.1	16.4	16.8	48.7	48.7	114	115	47.7	48.5	106	107
[S II] λ6731	117	116	94.9	94.2	11.4	11.8	66.1	66.2	82.5	83.3	40.2	40.8	101	102
[Ar V] λ7006	...	...	2.10	0.36	...	...	5.80	0.17	...	0.51	...	...	...	1.82
[Ar III] λ7136	33.5	33.2	44.6	44.6	28.0	27.2	62.1	62.2	31.6	31.4	15.1	15.3	59.1	59.1
$C(H\beta)$	0.37	...	0.80	...	0.21	...	1.99	...	0.20	...	1.00	...	0.67	...
$T(N II)$	10937	10983	12702	12535	10996	10726	12997	12070	10884	10326	8625	8915	12046	12229
$T(O III)$	15529	12272	17528	15183	10524	9791	17461	13638	14599	11891	9862	9338	17284	16117
N_e	194	195	549	552	20	20	2059	2010	31	36	251	250	524	535
rms	...	0.10	...	0.07	...	0.08	...	0.12	...	0.13	...	0.08	...	0.12
log [$L(H\alpha)$]	...	34.8	...	35.1	...	33.8	...	34.9	...	34.6	...	34.6	...	35.1
$D(L)$	...	6.5	...	7.1	...	0.9	...	1.3	...	3.2	...	1.9	...	5.4
$D(R)$	...	1.8	...	2.7	...	1.3	...	0.4	...	4.9	...	0.8	...	1.0
[C I] λ9850	...	6.95	...	1.08	...	14.6	...	11.3	...	4.65	...	87.8	...	1.81
[C II] λ2326	...	56.6	...	30.3	...	71.7	...	281	...	30.7	...	447	...	41.1
[C III] λ1909	...	106	...	166	...	119	...	1066	...	96.2	...	711	...	406
[C IV] λ1549	...	4.20	...	45.1	...	8.97	...	133	...	45.1	...	31.4	...	252
[N III] λ1750	...	72.2	...	264	...	7.53	...	120	...	9.68	...	9.68	...	707
[N III] 57.21 μm	...	295	...	207	...	216	...	67.4	...	361	...	275	...	405
[N IV] λ1486	...	3.80	...	70.7	...	1.00	...	20.3	...	41.4	...	0.93	...	488
[O IV] 25.88 μm	...	15.9	...	109	...	67.6	...	48.1	...	152	...	66.0	...	177
[Ne IV] λ2424	...	2.84	...	30.2	...	1.20	...	8.92	...	22.4	...	1.44	...	61.3
[Ne V] 14.32 μm	...	0.17	...	7.59	...	...	...	1.82	...	12.2	...	0.41	...	20.7
[S III] λ9532	...	131	...	175	...	21.7	...	111	...	134	...	67.5	...	262
[S IV] 10.51 μm	...	12.1	...	63.4	...	5.06	...	28.3	...	58.9	...	19.6	...	150
[Cl IV] λ8047	...	1.27	...	2.17	...	1.29	...	1.81	...	1.15	...	0.75	...	1.94

Wrong conclusion from wrong assumptions

4. Models underestimate the observed T(O III) temperature in all cases but three (class 1 regions K 3-72, M 3-5, and Wray 16). This has not been observed in other works involving Cloudy modeling of PNs (i.e., van Hoof & Van de Steene 1999; Gonçalves et al. 2007; SDK07). Discrepancies are smaller among most class 1 objects, and in 10 out of 12 cases these differences are within the observational error range reported in B01 and B03. Temperature discrepancies are much larger and beyond the observational error range among class 2 objects. This suggests that this inconsistency may be connected to aperture effects; real slits do not usually contain the entire in-depth extent of the ionized region, but these models cannot account for this and assume full coverage.

pyStuffs

- pyCloudy
  - Python package to manage Cloudy inputs and outputs,
  - Easy grids,
  - Pseudo-3D facility,
  - Related to PyNeb and 3MdB