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2D_NEB package: A new tool for calculating physical and chemical maps of planetary nebulae

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In this work we present a new tool adapted from NEBULAR, to determine, using two dimensional spatial data, the electron densities and temperatures, as well as ionic and total abundances of nebular objects. This algorithm is capable of performing the following operations: (i) to obtain the map of the $c(H\beta)$ spatial distribution, based on two dimensional maps of the Balmer lines. (ii) Once the $c(H\beta)$ map is determined, each emission-line map can be corrected by reddening. This operation allows different regions of the object to be corrected by the $c(H\beta)$ value that better represents that given region. (iii) After all the emission-line maps are corrected, the package calculates the electron density and temperature maps, based on the main diagnostic ratios in the spectral range between ~2,400 and 9,500 Å (*e.g.* N_e[OII], N_e[S II], N_e[Cl III], T_e[N II], Te[O III], T_e[S II]). (iv) Electron density and temperature maps can be used as input in the determination of the ionic abundances, using their respective emission-line maps. (v) Finally, our tool is also able of calculating maps of total chemical abundance making use of ionization correction factors from the literature.

Results obtained from our package show no significant differences when compared with those obtained from NEBULAR, the discrepancies being smaller than 1%.

We used this new tool in the analysis of the planetary nebula NGC 40, where we obtained spatially resolved maps for its physical and chemical condition.

2D_Neb Package: A new tool for calculating maps of the physical and chemical properties of nebulae

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Abstract

The well established IRAF NEBULAR package (stsdas.analysis) is a very useful tool to perform the reddening correction and to derive the physical (T_e, N_e) and chemical properties of nebular objects. On the other hand, tasks of this package work with numerical values only. Because of that, two dimensional emission-line data, as IFU data and long-slit spectroscopic maps, cannot be directly given as input of the NEBULAR tasks.

In this work we present a new tool, adapted from NEBULAR, to determine, using two dimensional spatial data, the electron densities and temperatures, as well as ionic and total abundances of nebular objects. This algorithm is also capable of determining the map of the c(Hβ) spatial distribution, and performing the reddening correction of the emission-line maps.

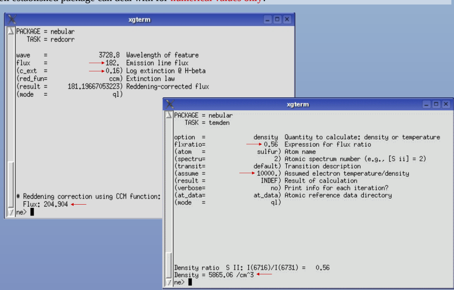
Results obtained from our package show no significant differences when compared with those obtained from NEBULAR, the discrepancies being better than 1%.

We used this new tool in the analysis of the planetary nebula NGC 40, showing very exciting results. These results will be discussed in the Gonçalves *et al.* contribution. The study of other PNe, using this tool, is also in progress.

The IRAF NEBULAR Package:

→ REDCORR: Reddening correction
→ TEMDEN: Physical propreties (N_e, T_e)
→ IONIC/ABUND: Chemical abundances (ionic and total)

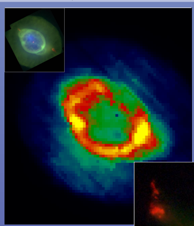
This well established package can deal with for numerical values only!



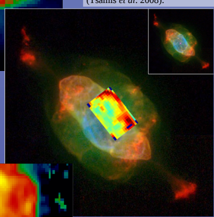
How Do Modern Data Look Like?

→ Integral Field Unit (IFU): Uses a square array of lenses remapped to a slit and then creates the image through a spectroscope to obtain spatially resolved data (Ren & Allington-Smith 2002). Tsamis *et al*. (2008) report the first work of Galactic PNe using this kind of data.
→ Spectroscopic Mapping: Interpolates the data from multiple parallel long-slit spectra of a nebula in order to generate emission-line maps (Monteiro et al. 2004).

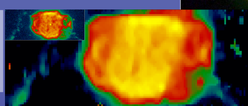
Cannot be used as input into the IRAF NEBULAR package!



NGC 7009: VLT IFU Hβ map overlaid on a HST WFPC2 image, composed of observations with F658N, F502N and F469N filters (Tsamis *et al*. 2008).



NGC 3242: VLT IFU O III map (Monteiro et al. 2010, *in prep*.) overlaid on a HST WFPC2 O III image (Ruiz *et al*. 2006).



NGC 40: Hα spectroscopic map compared with NOT Hα image (Leal-Ferreira *et al*. 2010, in prep.).

The 2D_Neb Package:

We developed a program adapted from the IRAF NEBULAR package (DeRobertis et al. 1987; Osterbrock & Ferland 2006), in IDL, in order to deal with two dimensional emission-line maps in fits format, the 2D_Neb. The atomic data used in the solution of the statistical equilibrium equation is read directly from the IRAF's atomic data directory, in order to guarantee that the atomic data of 2D_Neb will always be as updated as IRAF's.

The 2D_Neb package works as the following:

(i) It uses the Balmer lines (Hα, Hβ, Hγ and Hδ) 2D data to calculate the map of the c(Hβ) spatial distribution (Cardelli, Clayton & Mathis 1989, O'Donnell 1994, Osterbrock & Ferland 2006).

(ii) Once the c(Hβ) map is determined, each emission-line map can be corrected by reddening. This operation allows different regions of the object to be corrected by the c(Hβ) value that better represents that given region (De Robertis *et al.* 1987, O'Donnell 1994, Osterbrock & Ferland 2006).

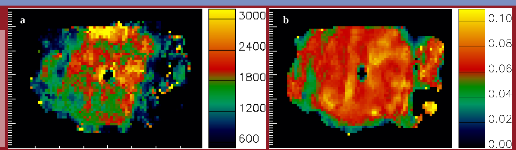
(iii) After all the emission-line maps are corrected, the package calculates the electron density (e.g. Figure 1a) and temperature maps, based on the main diagnostic ratios in the spectral range between ~2,400 and 9,500 Å. The available quantities that can be determine by the 2D_Neb package are:
Electron Densities: N_e[N I], N_e[O II], N_e[Ne IV], N_e[S II], N_e[Cl III] and N_e[Ar IV].
Electron Temperatures: T_e[N II], T_e[O I], T_e[O II], T_e[O III], T_e[Ne III], T_e[Ne V], T_e[S II], T_e[S III], T_e[Cl IV], T_e[Ar III], T_e[Ar IV] and T_e[Ar V] (De Robertis *et al.* 1987).

(iv) Electron density and temperature maps can, though, be used together with the emission-line maps (corrected by reddening) as input in the determination of the ionic abundances (e.g. Figure 1b) of the most common elements whose ionic emissions are presented in the above mentioned spectral range. They are: He I, He II, N I, N II, O I, O II, O III, Ne III, Ne IV, Ne V, S II, S III, Cl III, Cl IV, Ar III, Ar IV, Ar V, K IV, K V (Benjamin *et al.* 1999, De Robertis *et al.* 1987).

(v) Finally, our tool is also able of calculating maps of total chemical abundance making use of ionization correction factors from the literature (Kingsburgh & Barlow 1994).

Figure 1

NGC 40: N_e[S II] (left) and (He I + He II) abundance (right) maps, calculated by 2D_Neb, using spectroscopic map data (Leal-Ferreira et al. 2010, *in prep.*)



2D_Neb Benchmarks

Tables 1 and 2 present some benchmarks from the 2D_Neb program. For both tables the benchmarks were done comparing the results obtained using 2D_Neb with the results obtained using the IRAF NEBULAR package when the same input values were set.

In Table 1 we show the benchmarks of the main N_e and T_e. The first column lists the quantity that is being calculated. The second and third columns show the input values – N_e or T_e and line ratio, respectively. The fourth and fifth columns compare the results given by each program – 2D_Neb and IRAF NEBULAR (TEMDEN), respectively. The relative difference is shown in the last column.

Table 2 shows the benchmarks of the main ionic abundances. First column lists the ion and the wavelength from which the calculus in being done. The intensity of the emission-line, normalized to Hβ=100, is shown in the second column. The results obtained from 2D_Neb and IRAF NEBULAR (IONIC) are compared on columns 3 and 4, and the last column shows their relative differences.

Table 1: 2D_Neb T_e and N_e benchmarks.

Output	Input	Ratio	2D_NEB	*temden*	δ (%)
	N_e (cm^{-3})		T_e (K)	T_e (K)	
T_e[N II]	1,500	250.00	7,113.9	7,114.1	0.0
T_e[N II]	2,500	102.67	9,397.2	9,399.2	0.0
T_e[N II]	4,000	70.00	10,809.8	10,802.7	0.1
T_e[O II]	1,300	14.59	14,287.5	14,259.7	0.2
T_e[O II]	3,000	21.48	8,271.6	8,257.8	0.2
T_e[O II]	4,300	24.30	7,007.5	7,005.9	0.0
T_e[O III]	1,000	850.00	7,007.5	7,008.4	0.0
T_e[O III]	3,000	77.34	14,222.5	14,223.0	0.0
T_e[O III]	5,000	301.76	8,953.0	8,937.7	0.2
T_e[S II]	4,700	3.73	9,054.8	9,056.2	0.0
T_e[S II]	2,800	4.01	11,878.0	11,897.0	0.2
T_e[S II]	1,300	5.05	14,180.2	14,152.4	0.2
	T_e (K)		N_e (cm^{-3})	N_e (cm^{-3})	
N_e[O II]	7,000	1.90	1667.9	1,667.0	0.1
N_e[O II]	9,000	1.48	1,014.7	1,014.4	0.0
N_e[O II]	15,000	2.68	6,036.2	6,034.2	0.0
N_e[S II]	7,500	0.74	1,654.9	1,655.3	0.0
N_e[S II]	10,000	0.87	1,030.8	1,029.3	0.1
N_e[S II]	13,500	0.59	4,997.2	4,993.7	0.1
N_e[Cl III]	7,000	0.91	3,289.2	3,290.5	0.0
N_e[Cl III]	12,000	0.84	4,777.5	4,776.7	0.0
N_e[Cl III]	11,000	1.15	1,380.8	1,379.4	0.1
N_e[Ar IV]	9,000	0.94	4,952.5	4,957.8	0.1
N_e[Ar IV]	10,500	1.17	2,165.0	2,164.1	0.0
N_e[Ar IV]	12,000	1.28	1,174.4	1,173.6	0.1

Table 2: 2D_Neb ionic abundances benchmarks.

Ion / λ(Å)	I	2D_NEB ($\times 10^{-7}$)	*ionic* ($\times 10^{-7}$)	δ (%)
Input:	$N_e = 5{,}000\ cm^{-3}$		$T_e = 13{,}000\ K$	
N^+ 5755	2.36	90.96	91.03	0.1
N^+ 6548	76.01	247.7	247.8.	0.0
N^+ 6584	235.43	260.2	260.2	0.0
Input:	$N_e = 2{,}000\ cm^{-3}$		$T_e = 8{,}500\ K$	
O^0 6300	1.10	40.56	40.54	0.0
O^0 6363	0.70	81.20	81.16	0.0
Input:	$N_e = 1{,}500\ cm^{-3}$		$T_e = 13{,}000\ K$	
O^{++} 4959	60.91	273.3	273.0	0.1
O^{++} 5007	112.77	175.4	175.2	0.1
Input:	$N_e = 5{,}000\ cm^{-3}$		$T_e = 8{,}000\ K$	
S^+ 6717	2.76	6.038	6.040	0.0
S^+ 6731	9.73	12.12	12.12	0.0

The differences between the results from 2D_Neb and IRAF NEBULAR are insignificant!

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- Tables 1 and 2 show that the results obtained from the 2D_Neb are quite the same as those obtained from IRAF NEBULAR when the same input are set.
- Other benchmarks were also done for the other quantities that can be calculated by the 2D_Neb program. The discrepancies we found were never bigger than ~1%.
- Therefore, we conclude that the 2D_Neb program can be a very powerful tool to analyze 2D spatially resolved nebular data. We highlight that the use of 2D_Neb, to analyze either spectroscopic maps of IFU data, allows us to reach a very more complete, spatially resolved nebular analysis. Its robustness is evident if compared with IRAF's NEBULAR package, which better applies for single or a few slits spectra that may not represent the real nebular properties in detail.
(Gonçalves *et al.* 2010, *this meeting*, Leal-Ferreira *et al.* 2010, *in prep.*)

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