RevMexAA (Serie de Conferencias), **12**, 100–105 (2002)

CHEMICAL COMPOSITION OF PLANETARY NEBULAE: INCLUDING *ISO* RESULTS

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RESUMEN

Se discute el método para determinar abundancias usando espectros del *Infrared Space Observatory*. Se presentan los resultados para siete nebulosas planetarias. Con estos resultados, se presenta una discusión preliminar de su evolución.

ABSTRACT

The method of determining abundances using *Infrared Space Observatory* spectra is discussed. The results for seven planetary nebula are given. Using these data, a preliminary discussion of their evolution is given.

Key Words: **ISM: ABUNDANCES — ISM: LINES AND BANDS — PLANETARY NEBULAE: GENERAL — SPACE VEHICLES: INSTRUMENTS — STARS: EVOLUTION**

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
Editors: William Henney, José Franco, Marco Martos, & Miriam Peña

1. INTRODUCTION

The determination of the chemical composition of planetary nebulae has a long history. But it has always been difficult to determine the errors involved. This is because of the many uncertainties in the analysis. The measurements of the spectra are probably the least uncertain. The optical spectra usually only refers to a small region in the nebula, as well as a limited spectral region. To get a more complete picture they should be combined with ultraviolet measurements, almost always taken with the *International Ultraviolet Explorer* (*IUE*). These measurements refer to a region about $10 \times 23''$. When combining the measurements it must be assumed that the optical spectra are constant over the *IUE* area (or over the entire nebula, if its size is smaller).

But even the above combination of measurements leave something to be desired. Firstly, for many elements only a part of the total number of expected ions are measurable. Thus the abundance of the missing ions must be 'estimated', leading to uncertainties in the total abundance. Secondly, it is expected that the higher stages of ionization will occur near the ionizing star while the lower stages of ionization will occur near the edge of the nebula. If a temperature gradient occurs in the nebula, it will probably be such that the higher ionization stages show higher temperatures. This is because they absorb the highest energy photons. This is probably the origin of fact that the N II lines give a lower electron temperature than the O III lines in many nebulae.

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In the following section, it is shown that observations using the *Infrared Space Observatory* (*ISO*) greatly increase the number of ions for which an electron temperature ($T_{\rm e}$) can be found. This makes it possible to specify $T_{\rm e}$ as a function of ionization potential (IP) of the ion concerned. This can be used for all observed ions, increasing the accuracy of the ionic abundances found. This has been done for 8 nebulae and the results are given in § 3.

A comparison of the new abundances with earlier work of the past decade is given in § 4. For many elements substantial changes, i.e., a factor of 2 or more, are found. Oxygen is an exception to this, probably because O III is usually the dominant ion and its temperature was quite well determined.

In § 5 a discussion of the abundances found is given. In particular an attempt is made to find evolutionary effects in the abundance changes which are seen.

2. *ISO* OBSERVATIONS

The spectral data taken by *ISO* were made by two different spectrographs: The Short Wavelength Spectrometer (SWS) and the Long Wavelength Spectrometer (LWS). The more sensitive SWS measured between 2.48 and 45 μm with a spectral resolution of between 1000 and 3000. It observed with a diaphragm of $14 \times 20''$ for the shorter wavelengths and slightly larger for the higher wavelengths. A description can be found in De Graauw et al. (1996). The LWS measured from 45 to 200 μm with a spectral resolution of about 200 and a much larger diaphragm, about $80''$ in diameter. Details are given by Clegg et al. (1996). Sometimes the diaphragms contain the entire nebula, sometimes only part of

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
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Abundances of individual ions:

Oxygen	Nitrogen	Carbon	Neon	Sulfur	Argon	Chlorine
O^{+} $\times$	N^{+} $\times\bigcirc$	C^{+} $\times$	Ne^{+} $\bigcirc$	S^{+} $\times$	Ar^{+} $\bigcirc$	Cl^{+} $\times\bigcirc$
O^{2+} $\times\bigcirc$	N^{2+} $\times\bigcirc$	C^{2+} $\times$	Ne^{2+} $\times\bigcirc$	S^{2+} $\times\bigcirc$	Ar^{2+} $\times\bigcirc$	Cl^{2+} $\times\bigcirc$
O^{3+} $\times\bigcirc$	N^{3+} $\times$	C^{3+} $\times$	Ne^{3+} $\times$	S^{3+} $\bigcirc$	Ar^{3+} $\times$	Cl^{3+} $\times\bigcirc$
	N^{4+} $\times$		Ne^{4+} $\times\bigcirc$		Ar^{4+} $\times\bigcirc$	Cl^{4+} $\times\bigcirc$
			Ne^{5+} $\bigcirc$		Ar^{5+} $\bigcirc$	

Magnesium	Silicon	Potassium	Aluminum	Calcium	Iron
Mg^{+} $\times$	Si^{+} $\bigcirc$				Fe^{+} $\bigcirc$
	Si^{2+} $\times$	K^{2+} $\bigcirc$			Fe^{2+} $\bigcirc$
Mg^{3+} $\bigcirc$		K^{3+} $\times\bigcirc$		Ca^{3+} $\bigcirc$	Fe^{3+} $\times$
Mg^{4+} $\bigcirc$			Al^{4+} $\bigcirc$	Ca^{4+} $\times\bigcirc$	Fe^{4+} $\bigcirc$
	Si^{5+} $\bigcirc$	K^{5+} $\times\bigcirc$	Al^{5+} $\bigcirc$		Fe^{5+} $\bigcirc$
Mg^{6+} $\bigcirc$	Si^{6+} $\bigcirc$	K^{6+} $\bigcirc$	Al^{6+} $\bigcirc$	Ca^{6+} $\bigcirc$	Fe^{6+} $\bigcirc$
Mg^{7+} $\bigcirc$				Ca^{7+} $\bigcirc$	
	Si^{8+} $\bigcirc$				

$\times$: Optical or ultraviolet lines.

$\bigcirc$: *ISO* far-infrared lines.

Fig. 1. Ions of 13 elements with measurable lines in NGC 6302 are listed. A cross near the ion indicates that the line is in the optical or ultraviolet part of the spectrum; an open circle indicates that it is measured by *ISO*.

the nebula is seen. There may be minor problems in bringing the optical measurements, the *IUE* measurements and the *ISO* measurements onto the same scale. The method of doing this may differ from nebula to nebula and papers on the individual nebula should be consulted. At present results on the following nebulae have been published: NGC 6302 (Beintema & Pottasch 1999; Pottasch & Beintema 1999), NGC 7027 (Bernard Salas et al. 2001), NGC 6445 (Van Hoof et al. 2000), NGC 6537 and He 2-111 (Pottasch et al. 2000). In addition results on NGC 7662, BD+30 3639 and NGC 6741 are available in preliminary form and will be discussed here. LWS results have been published for many nebulae by Liu (1997).

In Figure 1, the various ions whose abundances can be determined in NGC 6302 are shown. After each ion a cross and/or a circle is shown: a cross indicates that the abundance can be determined from an optical or ultraviolet line and a circle indicates that an *ISO* far infrared line can be used. It can be seen that the *ISO* measurements contribute to determination of ion abundances for all elements except carbon. They are very important for the determination of total element abundance in Ne, S, Ar, and Cl, and they are indispensable for a good abundance determination of Mg, Si, K, Al, Ca, and Fe. They are thus important in increasing the quality of the abundance determination and the number of elements which can be observed.

3. ELECTRON TEMPERATURES AND DENSITIES

The second important point to note is that all of those ions for which lines exist in the *ISO* far infrared form these lines close to the ground state. Therefore the collisional excitation rate is essentially not dependent on T_e, or only in small way. Thus for these ions there is no need to speak of temperature fluctuations because such hypothetical fluctuations will not affect the ionic abundances.

How can this help in determining abundances for ions which are only represented by optical or ultraviolet lines? Notice that in 14 cases in Figure 1 an ion is represented by both infrared and optical or ultraviolet lines. The infrared line gives the ionic abundance. The other line can then be used to determine the electron temperature which will give the same abundance for that particular ion. This temperature cannot initially be determined for all 14 cases because a few have an important density dependence as well. Table 1 shows 11 cases in which T_e can be determined in NGC 6302, seven of them involving *ISO* lines. These temperatures are plotted in Figure 2 as a function of IP or the energy required to bring them

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
Editors: William Henney, José Franco, Marco Martos, & Miriam Peña

TABLE 1

ELECTRON TEMPERATURE INDICATORS

Ion	IP	Observed Ratio	T_e
N II	14.5	0.040 ± 0.0008	$13\,600 \pm 1500$
S III	23.3	0.19 ± 0.02	$16\,000 \pm 1500$
Ar III	27.6	0.40 ± 0.1[a]	$13\,500 \pm 2500$
Ar III	27.6	0.195 ± 0.03[b]	$15\,500 \pm 2000$
O III	35	0.0306 ± 0.003	$18\,500 \pm 1500$
Ne III	41	0.61 ± 0.1	$11\,000 \pm 2000$
O IV	55	1.25 ± 0.3	$23\,000 \pm 2000$
Ne IV	63	61.5 ± 6.2	$21\,500 \pm 3000$
Na IV	72	2.9 ± 0.6	$25\,000 \pm 5000$
Ne V	97	1.11 ± 0.2	$24\,500 \pm 2500$
Mg V	109	0.89 ± 0.1	$20\,000 \pm 1500$

[a]5192 Å/21.8 μm [b]5192 Å/7136 Å

TABLE 2

ELECTRON DENSITY INDICATORS

Ion	IP	Observed Ratio	N_e
S II[b]	10.4	2.00 ± 0.04	$10\,800 \pm 1500$
O II[b]	13.6	2.17 ± 0.01	$8\,100 \pm 300$
S III[a]	23	0.35 ± 0.04	$5\,000 \pm 600$
Cl III[c]	24	2.4 ± 0.2	$23\,000 \pm 5000$
C III[b]	24	1.1 ± 0.1	$17\,000 \pm 1000$
Ar III[a]	28	> 0.059	$< 18\,000$
Ar IV[b]	40.7	1.79 ± 0.03	$14\,500 \pm 500$
Ne III[a]	41	16.2 ± 1.7	$20\,000 \pm 15\,000$
Ar V[a]	60	1.5 ± 0.15	$3\,000 \pm 2500$
Ne V[a]	97	0.49 ± 0.05	$10\,000 \pm 1500$

[a]Paper I [b]Barral et al. 1982 [c]Oliva et al. 1996

into this state. A clear temperature increase can be seen as the IP of the ion increases. Another example is shown in Figure 3 where the result for NGC 6741 is shown.

In Figure 3 the IP of a few ions which do not have *ISO* lines is shown as well. The temperature found from the curve is used to determine the ionic abundance from the line intensity. This is mainly used for carbon and nitrogen abundances, and leads to an increase in the accuracy of these ionic abundances.

The electron density (N_e) can be determined from line pairs which are insensitive to the electron temperature. Usually these are lines close together in wavelength so that they both have the same temperature dependence. But *ISO* lines can be used as well since they have little temperature dependence.

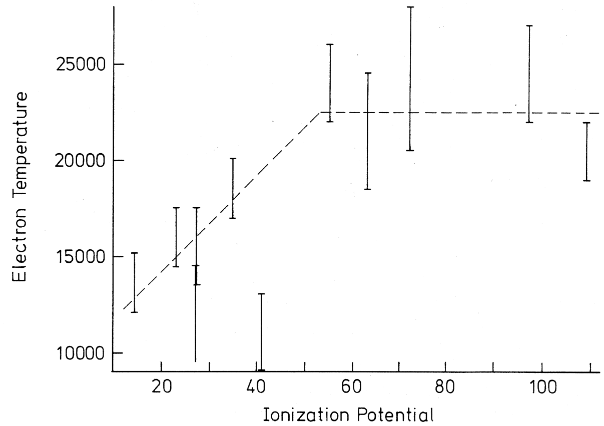

Fig. 2. The electron temperature in NGC 6302 as determined from different ions is plotted as a function of the ionization potential of the ion. The ions are specified in Table 1.

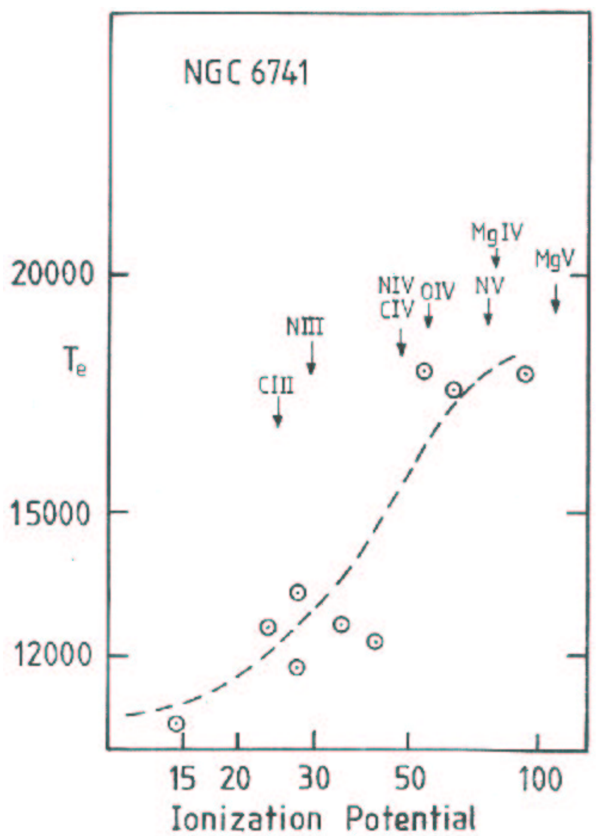

Fig. 3. Same as Fig. 2, but for NGC 6741. The ions are listed only to indicate their ionization potential.

An example is shown in Table 2. There seems to be no change of density with ionization potential. This is true of all cases studies up to now. Consequently abundance determinations were made using a constant density for each nebula.

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
Editors: William Henney, José Franco, Marco Martos, & Miriam Peña

TABLE 3

COMPARISON OF PN ABUNDANCES WITH OTHER OBJECTS

Element	NGC 6537	He 2-111	NGC 6302	NGC 6445	NGC 6741	NGC 7027	Sun	B Star	ISM ζ Oph	ISM Orion
He	0.149	0.185	0.17	0.14:	0.11	0.106	0.10	···	···	0.098
$C \times 10^4$	1.75	1.1	0.60	6.0	3.6	6.0	3.55	1.75	1.4	2.5
$N \times 10^4$	4.5	3.0	2.9	2.4	1.8	1.6	0.93	0.65	0.79	0.63
$O \times 10^4$	1.85	2.7	2.3	7.4	4.5	4.1	7.4	4.2	3.0	3.2
$Ne \times 10^4$	1.7	1.6	2.2	2.0	1.5	1.0	1.2	1.2	···	0.79
$Na \times 10^6$	2.6	···	2.6	···	···	1.2	2.0	···	0.23	···
$Mg \times 10^5$	0.96	0.8:	1.3	1.7:	0.15	2.2	3.8	2.4	0.11	···
$S \times 10^5$	1.1	1.5	0.78	0.79	0.80	0.94	1.86	1.2	2.8	1.4
$Cl \times 10^7$	2.4	3.5	3.4	···	1.8	1.1	1.9	1.9	1.2	2.2
$Ar \times 10^6$	4.1	5.5	6.0	3.8	3.2	2.3	3.6	···	1.2	5.0
$(C+N+O)/H$	8.1	6.8	5.8	15.8	9.9	11.7	11.9	6.6	5.2	6.3
N/O	2.4	1.1	1.3	0.32	0.53	0.39	0.13	0.15	0.26	0.20

4. ABUNDANCES

4.1. *Comparison with Previous Work*

As mentioned above, abundance determinations have been made for 8 nebulae, and several others are in progress. The results are given in Table 3, and are compared to abundances in the sun, B stars, an interstellar cloud and the Orion nebula (references are given in Pottasch & Beintema 1999). The accuracy of the values is difficult to estimate. Errors based on uncertainties in the measurements are less than 30% and uncertainties due to corrections for missing ionization stages are even less for the main elements.

It is interesting to compare these results with the abundances determined by others for these nebulae, mainly over the last decade. The comparison with NGC 7027 is quite good (Table 4). Further NGC 6537, He 2-111 and NGC 6741 are shown as Tables 5, 6, and 7 respectively. The good agreement of the oxygen, sulfur and argon abundance by all authors for all nebulae (usually better than 50%) is in contrast to that of some other elements. Carbon and nitrogen are the worst offenders, with differences sometimes as high as a factor of 5. We believe that the present results are more accurate than that since it is possible to give reasons why the other results are discordant. But a good value of the error is difficult to give.

4.2. *Evolutionary Trends in Individual Elements*

It is supposed that the He/H ratio is a measure of the conversion of hydrogen to heavier elements, and in a qualitative way a measure of the mass of the central star. In Figure 4 (top left) the sulfur abundance has been plotted for 7 of the planetary nebulae discussed (BD+30 3639 is not used, because it appears that the helium is exhausted close to the central star). The abundance of sulfur in the sun and the Orion nebula are also plotted. There does not appear to be a discernible trend; in fact it looks as if no sulfur was produced in the course of evolution. In addition the initial sulfur abundance was very similar for all these PNe, and within 50% for the sun and the Orion nebula as well.

TABLE 4

COMPARISON OF ABUNDANCES: NGC 7027

Element	BS00	B96	KH96	K90	M90
$C \times 10^4$	6.0	7.41	9.6	6.5	11.2
$N \times 10^4$	1.6	1.32	1.63	1.4	1.86
$O \times 10^4$	4.1	4.47	5.08	3.1	4.90
$Ne \times 10^4$	1.0	0.62	1.37	1.0	1.20
$Mg \times 10^5$	2.2	0.66	···	0.38	2.14
N/O	0.39	0.30	0.32	0.45	0.38
C/O	1.46	1.66	1.88	2.10	2.29

REFERENCES—BS00: Bernard Salas et al. (2000); B96: Beintema et al. (1996); KH96: Kwitter & Henry (1996); K90: Keyes et al. (1990); M90: Middlemass (1990)

The nitrogen abundance is shown in the second left part of Figure 4. It is clear that nitrogen has increased by an order of magnitude during evolution. This has been known for some time, but the fluctuations are quite low in the plot. In addition this is the first time that the solar and Orion nebula abundance have been shown to fit on this type of plot.

The top right part of Figure 4 shows the plot for carbon. There seems to be somewhat more scatter

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
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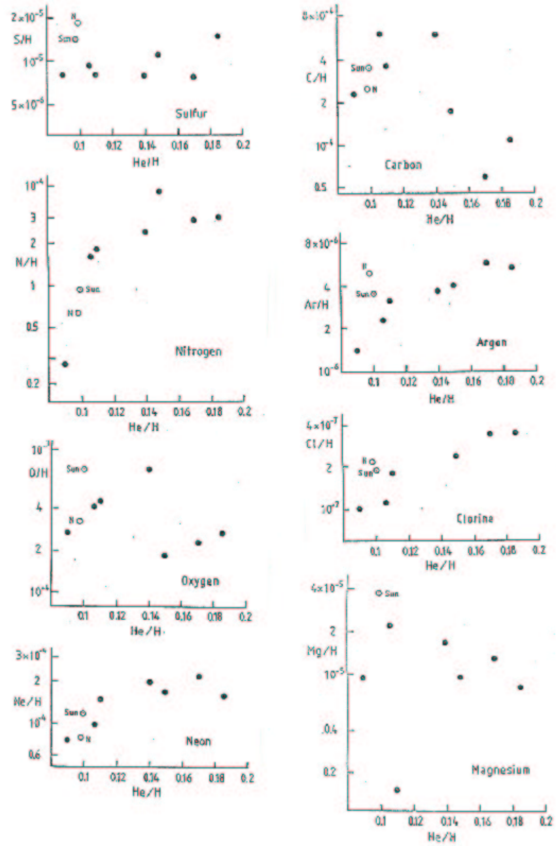

Fig. 4. Element abundance of the various nebulae as a function of the helium abundance. The solar abundance is also indicated, as well as the Orion nebula (N).

TABLE 5

COMPARISON OF ABUNDANCES: NGC 6537

Element	This Work	A99	PC98
He	0.149	0.131	0.189
C × 10^4	1.75	0.21	...
N × 10^4	4.5	1.0	5.6
O × 10^4	1.85	1.42	2.0
S × 10^5	1.1	2.99	0.72
Ar × 10^6	4.1	4.0	3.2
Ne × 10^4Ne	1.7	0.48	0.6

References—A99: Aller et al. (1999); PC98: Perinotto & Corradi (1998)

in this plot, possibly indicating that the error in the carbon abundance is greater. But there is an unmistakable decrease of the carbon abundance as the helium increases, indicating that carbon burning is occurring in higher mass stars.

The oxygen abundance is shown in the third left-hand part of Figure 4. Since the oxygen abundance appears to be accurately determined, the last 3 points cannot be considered as errors. Possibly oxygen burning occurs for higher mass stars.

Figure 4 also shows the abundances of neon, argon and chlorine. Taken at face value these plots indicate a production of these elements in the course of evolution, by a factor of 2 to 3. More PNe should be measured to corroborate this.

Finally the magnesium abundance is also plotted in Figure 4. For 6 of the PNe the abundance is a factor of 2 to 3 lower than the solar abundance. This could be due to this element being tied up in dust grains, which has been discussed earlier in the literature. The reason why NGC 6741 shows an order of magnitude lower abundance is not clear.

TABLE 6

COMPARISON OF ABUNDANCES: HE 2-111

Element	This Work	KB94	PC98	C96
He	0.185	0.22	0.23	0.25
C × 10^4	1.1	1.96	...	...
N × 10^4	3.0	7.2	7.2	10.7
O × 10^4	2.7	2.8	2.9	1.5
S × 10^5	1.5	1.6	13.0	16.0
Ar × 10^6	5.5	4.4	5.4	3.6
Ne × 10^4	1.6	1.4	1.2	0.1

References—KB94: Kingsburgh & Barlow (1994); PC98: Perinotto & Corradi (1998) C96: Costa et al. (1996)

TABLE 7

COMPARISON OF ABUNDANCES: NGC 6741

Element	This Work	HA97	KB94	A85
He	...	0.11	0.11	0.11
C × 10^4	3.6	8.0	6.5	12.0
N × 10^4	1.8	2.4	1.4	5.2
O × 10^4	4.5	5.4	4.9	5.4
S × 10^6	8.0	6.8	8.1	3.1
Ar × 10^6	3.2	3.5	2.4	3.6
Ne × 10^4	1.5	1.3	1.3	1.6

References—HA97: Hyung & Aller (1997); KB94: Kingsburgh & Barlow (1994); A85: Aller et al. (1985)

5. CONCLUSIONS

1. Including the *ISO* results produces abundances that are much less sensitive to electron temperature and possible temperature fluctuations.

2. It is now possible to specify the electron temperature structure within the nebula as function of IP.

3. Many more ions can be measured, reducing the need for substantial correction factors for unseen ions.

4. Substantial abundance changes from earlier work are sometimes found.

5. As more helium is produced: (a) much more nitrogen is produced, (b) more carbon may initially be produced, but then it is burned, (c) the same may be true of oxygen, but this requires verification, (d) there is an indication that neon, argon and chlorine are being produced in small amounts, but this remains to be verified.

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Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
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