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Abundances in Planetary Nebulae: Including ISO Results

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Abstract. The far infrared nebular spectrum provides a valuable complement to the observed lines in other spectral regions. There are several reasons for this, the most important being the large increase in the number of ions observed, and the fact that the abundances found from these lines are relatively insensitive to the electron temperature. This leads to a more accurate determination of the abundances. To date, twelve PN have had abundances determined in this way. These results are summarized. The evolution of the central star is discussed in the light of these results.

1. Introduction

There are several limitations on obtaining spectra of PN in the far infrared. One of these is that the atmosphere is opaque in much of this region. A second limitation is that suitable instrumentation in this spectral range has only been developed in very recent years.

A small part of this spectral range, from 9 μm to 13 μm is visible from the ground, and this consequently this region has been the first observed (see e.g. Roche et al (1983) and Beck et al (1981)). The difficulty of observing from the ground is the high infrared background due to the surroundings of the observatory. This has the consequence that only a small diaphragm is used (to keep the background to a minimum). Furthermore only the strongest lines can be measured: Ar III at 8.99 μm, S IV at 10.5 μm and Ne II at 12.8 μm.

At about the same time measurements above the atmosphere were made. The Kuiper Airborne Observatory flew at a height of about 12.5 km, which is sufficiently high to observe between 16 μm and 27 μm, but not high enough

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to measure the Ne V line at 14.2 μm or the Ne III line at 15.5 μm. Because the instrumental background radiation is reduced in the airplane, a larger diaphragm can be used. For example, Shure et al. (1983) use a 30″ diaphragm, between 2 and 4 times larger than ground based instruments could use. Their spectral resolution was about 100, and only the strongest lines could be measured.

The first far infrared satellite, IRAS, which flew in 1983-84 and was entirely above the atmosphere, contained a spectrograph which worked between 7.7 μm and 22 μm. It had a much larger effective diaphram, about 2′, so that in most cases the entire nebula was measured, In addition, it was a survey instrument so that very many nebulae were measured. For example, Pottasch et al. (1986) report measurements of about 60 PN. The resolution was low, however, between 30 and 50, so that at best 7 lines could be measured (3 or 4 was more usual).

The ISO satellite was launched in November 1995 and was active for about 2 years. It contained two spectrographs: the Short-Wavelength Spectrometer (SWS)(de Graauw et al. 1996) and the Long-Wavelength Spectrometer (LWS)(Clegg et al. 1996). The SWS covered the spectral range from 2.4μm to 45μm with a resolution of about 2000, which could be increased considerably for special measurements. It had a rectangular diaphragm of 14″x 20″ for the lower wavelengths and somewhat larger at the higher wavelengths. The LWS measured from 43 μm to 197 μm with a resolution of about 200, which also could be increased for special measurements. Its diaphragm was larger, about 70″, so that usually the entire flux of the nebula was measured. Most of the LWS measurements of PN have been reduced and published (Liu et al. 2001).

In section 2 of this paper we will discuss the many advantages of combining the ISO measurements with existing ground-based and IUE ultraviolet measurements to obtain nebular abundances. In section 3 the results for 12 PN will be shown, while in section 4 these results will be discussed in terms of the evolution of the central star.

2. Advantages of the ISO measurements

There are four important advantages gained by including the far infrared lines in the abundance analysis. These are: (1) the abundances derived from these lines are not sensitive to the electron temperature, (2) the number of ions observed may double, often reducing the uncertainty in the 'ionization correction factor' (ICF) substantially, (3) a new insight is given in the electron temperature structure of the nebula, and (4) the extinction corrections may be determined in an independent way. We discuss these advantages in more detail below:

2.1. Insensitivity to electron temperature

The infrared lines are all formed by transitions in or close to the ground state. Because the electron collision to the upper level entails only a relatively small energy jump, the temperature dependance is substantially reduced in the range of expected nebular temperatures.

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Table 1. The ions for which at least one line has been measured in NGC 6302. If the line is found in the optical or ultraviolet part of the spectrum it is marked with a cross; if it is found in the ISO spectrum it is marked with a filled circle.

Oxygen	Nitrogen	Carbon	Neon	Sulfur	Argon	Chlorine
O^{+} ×	N^{+} ×•	C^{+} ×	Ne^{+} •	S^{+} ×	Ar^{+} •	Cl^{+} ×•
O^{2+} ×•	N^{2+} ×•	C^{2+} ×	Ne^{2+} ×•	S^{2+} ×•	Ar^{2+} ×•	Cl^{2+} ×
O^{3+} ×•	N^{3+} ×	C^{3+} ×	Ne^{3+} ×	S^{3+} •	Ar^{3+} ×	Cl^{3+} ×•
	N^{4+} ×		Ne^{4+} ×•		Ar^{4+} ×•	Cl^{4+} •
			Ne^{5+} •		Ar^{5+} •	
				S^{7+} •		
Magnesium	**Silicon**	**Potassium**	**Aluminum**	**Calcium**	**Iron**	
Mg^{+} ×	Si^{+} •				Fe^{+} •	
	Si^{2+} ×	K^{2+} •			Fe^{2+} •	
Mg^{3+} •		K^{3+} ×•		Ca^{3+} •	Fe^{3+} ×	
Mg^{4+} •			Al^{4+} •	Ca^{4+} ×•	Fe^{4+} •	
	Si^{5+} •	K^{5+} ×•	Al^{5+} •		Fe^{5+} •	
Mg^{6+} •	Si^{6+} •	K^{6+} •		Ca^{6+} •	Fe^{6+} •	
Mg^{7+} •			Al^{7+} •	Ca^{7+} •		
	Si^{8+} •					

2.2. Increased number of ions observed

For the bright planetary nebula NGC 6302 IRAS measure seven lines of the same number of ions. The intensity range spanned a factor of 10. ISO has measured more than 100 lines of 40 different stages of ionization, thanks to its ability to measure lines as faint as 0.001 times the brightest line. In the visual and ultraviolet spectral range 'only' 27 different stages of ionization have been measured. The various ions involved are shown in Table 1, where it can be seen that in 14 cases the same ion has been measured in the two wavelength ranges. The additional ionization stages translate into a lower uncertainty in the ICF, which increases the accuracy of the abundance in the case of neon, sulfur, argon, chlorine and potassium, while the infrared measurements are indispensible in the case of magnesium, silicon, aluminum, calcium and iron. In addition, the oxygen and nitrogen abundances are less dependent on the electron temperature.

2.3. New insights into nebular temperature structure

As mentioned above, a substantial number of ions have lines originating both from both an infrared line, which is insensitive to electron temperature, and an optical or ultraviolet line whose strength is dependent both on the temperature and the abundance of the ion. The infrared line can therefore be used to determine the ionic abundance, while the optical (ultraviolet) line can be used to determine the temperature. It is found that electron temperatures determined in this way have a dependence on the ionization potential of the next lower stage

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of ionization, in the sense that ions with low ionization potential are formed at lower temperature (presumably further out in the nebula). An example of the temperatures determined for NGC 6741 is shown in Fig. 1.

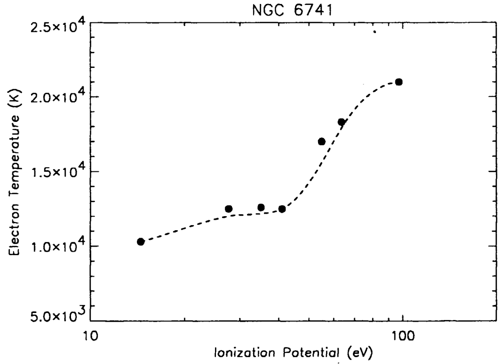

Figure 1. The effective electron temperature is plotted against the ionization potential for the seven ions having both a temperature sensitive and a temperature insensitive line in NGC 6741.

These kinds of plots have been made for 12 PN at present. In 10 of these cases a similar temperature dependence is found. The change is always in the same sense: higher temperatures are found for ions with a higher ionization potential. There are two cases where the temperature is more or less constant with ionization potential (e.g. NGC 6537).

The effective temperature can now be easily determined from the figure for other temperature sensitive lines. The increased accuracy in the temperature leads to an increased accuracy in the determination of the ionic abundance. This can have especially important consequences in nitrogen and carbon abundances, where most of the lines are very temperature sensitive.

2.4. New insights into extinction correction

For nebulae whose total hydrogen en helium line emission has been measured, it is possible to determine the extinction directly. This makes use of the fact that the ratio of all hydrogen (and ionized helium) lines is known theoretically. The ratio is only slightly dependent on the electron temperature, but this is known well enough so that it plays only a small role. The principal is illustrated using measurements of NGC 6537, shown in Table 2. In the left table, the first 4 columns show the observed intensites of 6 infrared lines. The fifth column,gives the intensities of these lines corrected for extinction. The correction is seen to be small even though the extinction is more than 3 mag. The last column gives the theoretical predictions (Hummer & Storey 1987) normalized to the infrared lines. The predicted value of Hβ is also shown. This value can be used in conjunction with the observed flux of the line to obtain the extinction at this wavelength. The right hand Table 2 shows that the same thing can be done with the ionized helium lines to obtain the extinction at 4686 Å and 1640 Å. While the values of extinction obtained are not substantially different than what is found from either the Balmer decrement or the "radio continuum-H beta" determination, this method leads to a more accurate extinction.

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Table 2. The infrared lines of Hydrogen and Ionized Helium can be used to find the extinction in the optical and ultraviolet.

Hydrogen line intensities†						Ionized helium line intensities†				
$\lambda(\mu m)$	Trans.	Ident.	Obs.	Corr.	Theory	$\lambda(\mu m)$	Trans.	Obs.	Corr.	Theory
4.052	5-4	Brα	8.0	8.71	8.8	3.092	7-6	2.9	3.47	3.85
2.626	6-4	Brβ	4.1	4.91	5.2	2.826	9-7	2.3	2.66	1.21
2.166	7-4	Brγ	1.8*	2.4	3.2	2.188	10-7	0.52*	0.69	0.86
7.457	6-5	Pfα	1.99	2.1	2.7	4686Å	-	-	-	110.
3.741	8-5	Pfγ	0.83	0.94	1.19	1640Å	-	-	-	772.
3.297	9-5	Pfδ	0.855	1.02	0.84					
4861Å	4-2	Hβ			130.					

† $10^{-12} erg\, cm^{-2}\, s^{-1}$
* Ashley (1989)

2.5. Electron density

The infrared lines also contribute to this subject by adding 5 (and sometimes more) pairs of lines which can be used to determine the electron density. With the optical and ultraviolet pairs, a wide range of ionization potential is covered. Although the accuracy leaves something to be desired, there is no indication that the density changes as a function of ionization potential. Furthermore the density found is similar to the root-mean-square density found from the hydrogen line brightness. This indicates that none of these lines come from small regions of high density; rather a constant density seems to be a good approximation.

3. Results

To date 9 nebulae have been analysed using this method: NGC 6302 (Beintema & Pottasch 1999; Pottasch & Beintema 1999), NGC 6445 (van Hoof et al. 2000), NGC 7027 (Bernard Salas et al. 2001), NGC 6537 and He2-111 (Pottasch, Beintema, & Feibelman 2000), NGC 7662 and NGC 6741 (Pottasch et al. 2001), NGC 2440 (Bernard Salas et al. 2002) and NGC 5315 (Pottasch et al. 2002). In addition NGC 6543, Hu1-2, NGC 6153 and NGC 2346 have been (partially) analysed but not yet published.

The results for two nebulae, NGC 6537 and NGC 7662, are shown in Table 3, and are compared there with other results in the recent literature. The results are usually, but not always, within a factor of 2 of each other. Several things may be noted. In NGC 6537, the large difference between our results and those of Aller, Hyung, & Feibelman 1999) for carbon and nitrogen have a different origin than simply the inclusion of the infrared lines. In NGC 7662, the two different methods used by Hyung & Aller (1997a) show larger differences than between their results using a model nebula and our results. This may however just be chance, because for NGC 6741 our results are closer to theirs (Hyung & Aller 1997b) for their method of ion summation, rather than using a model nebula (see Pottasch et al. 2001 for a comparison).

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Table 3. A comparison of the ISO abundances with other recent determinations is shown for two nebula.

Elem.	NGC 6741 Present Abund.	HA(1) Model	HA(1) Σ_{ion}	KB(2)	A(3)	NGC 6537 Present Abund.	A2(4)	PC(5)
He	0.11	0.11	0.11	0.11	0.11	0.149	0.131	0.189
C	6.4(-4)	8.0(-4)	7.3(-4)	6.5(-4)	12.0(-4)	1.75 (-4)	0.21 (-4)	
N	2.8(-4)	1.4(-4)	2.4(-4)	1.4(-4)	5.2(-4)	4.5(-4)	1.0 (-4)	5.6 (-4)
O	6.6(-4)	4.5(-4)	5.4(-4)	4.9(-4)	5.4(-4)	1.85(-4)	1.42(-4)	2.0(-4)
S	1.1(-5)	5.7(-6)	8.0(-6)	8.1(-6)	3.1(-6)	1.1(-5)	2.99 (-5)	0.72(-5)
Ar	4.9(-6)	3.5(-6)	3.1(-6)	2.4(-6)	3.6(-6)	4.1(-6)	4.0(-6)	3.2(-6)
Ne	1.8(-4)	1.0(-4)	1.3(-4)	1.3(-4)	1.6(-4)	1.7(-4)	4.8(-5)	0.6(-4)

(1) Hyung & Aller (1997b); (2) Kingsburgh & Barlow (1994); (3) Aller et al. (1985); (4) Aller et al. (1999); (5) Perinotto & Corradi (1998)

The complete results are given in the references cited above and are summarized by Pottasch et al. (2001). The accuracy is thought to be considerably better than previous analyses, but it is expected that a 20% to 30% error still remains, much of which is due to observational errors. Above this there are errors due to uncertainties in the collisional cross-sections, which are difficult for us to estimate. One might think that the relative abundances from nebula to nebula are not affected by errors in the cross-sections, and this is partially true, but only for individual ions. When comparing nebulae of considerably different excitation errors in the cross-section may play a role. But the consistent change of the different stages of ionization of a given element in each nebula implies that possible errors are not large.

4. Evolutionary considerations

The similarity of the abundances of some of the elements in the nebulae considered is interesting. This might be expected since only 'local' PN have been measured (within 2 kpc). The sulfur abundance (relative to hydrogen) seems to be approximately constant for all the nebulae, and very similar to the solar and Orion nebula sulfur abundance. This is consistant with the expectation that no nuclear reactions have taken place in the earlier stages of these low mass stars to produce this element.

On the other hand the helium abundance changes significantly from nebula to nebula, consistent with the expectation that it has been produced and brought to the surface in the course of the previous evolution. In this light the abundances of the other elements may be investigated to better define which processes take place and when they occur, what the conditions are where they take place, and if possible to find the initial mass of the star which produced them.

Fig. 2 is a plot of the nitrogen abundance of these nebulae as a function of the helium abundance. The solar and Orion nebula nitrogen abundances are also shown. From the figure it appears that the nitrogen abundance increases by about an order of magnitude as the He/H ratio increases from 0.095 to 0.12.

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Presumably the nitrogen is being produced by the same process that produces the helium, and is being brought to the surface at the same time.

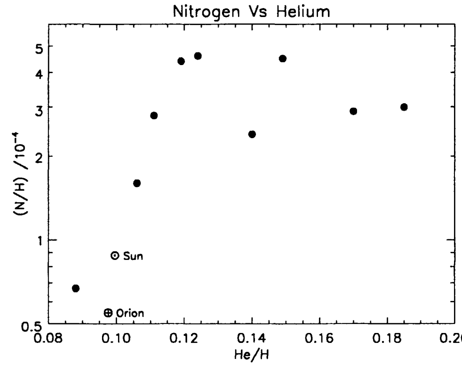

Figure 2. The nitrogen abundance of the PN is plotted against their helium abundance. The solar abundance and the Orion nebula abundance are also plotted.

On the left hand side of Fig. 3 the carbon abundance C/H is plotted as a function of the helium abundance. The carbon abundance has a reasonably high value for low values of the helium abundance. This is similar to the solar carbon abundance. For the three nebulae with the highest helium abundance, the carbon abundance has fallen by a factor 3 to 5, indicating that carbon is being converted to another element when these high helium abundances are produced. Presumably this occurs only in stars with initially high mass. It may be that the scatter is somewhat higher for the carbon than for the nitrogen.

On the right hand side of Fig. 3 the neon abundance Ne/H is plotted against the helium abundance. While the range is small, not more than a factor of three, there is a very good correlation with very little scatter. The neon abundance is probably better determined than other elements since all ionization stages are observed. From the increase of the neon with hydrogen, it can be concluded that neon is being produced in higher mass stars. This has been concluded earlier on the basis of somewhat weaker evidence (Corradi & Schwarz 1995).

5. Conclusions

1. Including ISO measurements increases the accuracy of abundance determinations because: (A) the abundances are much less sensitive to the electron temperature and possible temperature fluctuations; (B) the ionization correction is substantially reduced. 2. Most PN have a gradient in effective nebular electron temperature, such that it is highest where high ionization stages are formed, and lowest for the outer low ionization stages. 3. The 'local' nebulae were formed from material of similar chemical composition. 4. As the helium abundances increases as a result of evolution: (A) the nitrogen abundance first increases (by a factor of 10) until He/H=0.13 and then remains constant; (B) the carbon abundance first increases by a small factor, and then decreases rather strongly; (C) there is evidence that the oxygen is somewhat lower for high He/H

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nebulae; (D) there is evidence that the abundance of neon (and argon) increases when nitrogen increases.

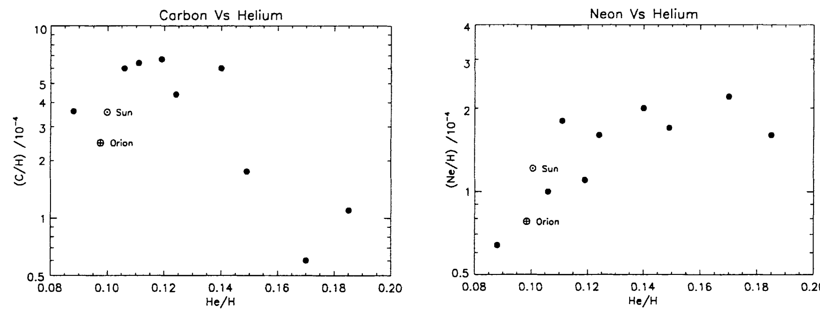

Figure 3. On the left hand diagram the carbon abundance is abundance is plotted as function of the helium. On the right hand diagram the neon abundance is plotted as a function of helium. The solar and Orion nebula values are also shown.

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