Astron. Astrophys. 363, 767–778 (2000)

ASTRONOMY AND ASTROPHYSICS

Abundance in the planetary nebulae NGC 6537 and He2-111

S.R. Pottasch[1], **D.A. Beintema**[2], **and W.A. Feibelman**[3]

[1] Kapteyn Astronomical Institute, P.O. Box 800, 9700 AV Groningen, The Netherlands
[2] SRON Laboratory for Space Research, P.O. Box 800, 9700 AV Groningen, The Netherlands
[3] Laboratory for Astronomy and Solar Physics, Code 681, Goddard Space Flight Center, MD, USA

Received 11 July 2000 / Accepted 26 September 2000

Abstract. The ISO and IUE spectra of the bipolar planetary nebulae NGC 6537 and He2-111 are presented. These spectra are combined with the spectrum in the visual wavelength region from the nebulae to obtain a complete spectrum that is corrected for extinction. The chemical abundance of the nebulae is then determined and compared to previous determinations. The abundance of the two nebulae is quite similar. A comparison is then made with the abundance of two other bipolar planetary nebulae whose abundance is also determined with the help of ISO observations. It is shown that not all bipolar nebulae have similar abundance. NGC 6445 has a much lower nitrogen to oxygen ratio, similar to NGC 7027, but still not as low as the Orion nebula.

Key words: stars: abundances – stars: emission-line, Be – ISM: planetary nebulae: general – ISM: planetary nebulae: individual: NGC 6537 – ISM: planetary nebulae: individual: He2-111 – infrared: ISM: lines and bands

1. Introduction

About 5-10% of the known planetary nebulae are classified as bipolar. These are axially symmetric nebulae with a waist from which two faint, extended lobes emanate. Practically all of the light emitted is concentrated in the central regions, yet long exposure photographs clearly show the lobes. In a recent paper, Corradi & Schwarz (1995) have shown photographs of 43 of these nebulae. These authors confirm that the scale height of these nebulae is smaller than for the general sample of PN. In addition, the radial velocities of the bipolar nebulae show smaller deviations from pure circular galactic rotation than the other morphological types. These two facts indicate that the bipolar nebulae are formed from young, higher mass, stars. Furthermore there is a general feeling in the literature, stated also in the paper cited above, that helium, nitrogen and perhaps other elements, are substantially overabundant in these nebulae.

It is this last point that we wish to consider further in this paper. Pottasch & Beintema (1999, hereafter PB) have already discussed the difficulties involved in abundance determinations, and the advantage obtained by using ISO SWS spectra. The advantages are threefold. First, the infrared transitions have such small energy that the abundance obtained from them is not temperature dependent. Thus if temperature fluctuations are important they will not influence the abundance. Second, extinction in the infrared is either small or negligible. Lastly, quite a few additional ions are available in the infrared. ISO spectra are available for NGC 6537 and He2-111 and they will be used here to derive the chemical composition for these nebulae.

The procedure followed is the same as that of Beintema & Pottasch (1999, hereafter BP) in the case of NGC 6302. In Sect. 2 the ISO spectrum will be given for NGC 6537 along with the IUE spectrum and the spectrum in the visual region. Sect. 3 will contain the same information for He2-111. The composition will be derived in Sects. 4 and 5, for NGC 6537 and He2-111, respectively. In Sect. 6 these abundances will be compared to those of NGC 6302 and NGC 6445, both bipolar nebulae with ISO spectra. They will also be compared with the abundance of NGC 7027, which probably has an elliptical morphology. The luminosity of the central stars of these nebulae will be discussed in the last section.

Send offprint requests to: pottasch@astro.rug.nl

2. The spectrum of NGC 6537

2.1. ISO observations

The ISO SWS observations were made with the SWS01 observing template, which provided complete spectral coverage. The measurements were made on 29 December 1997. The position of the measurement was centered at RA (2000) $18^{\rm H}05^{\rm M}13.^{\rm S}14$ and Dec (2000) $-19^{\circ}\ 50'\ 34''$. The position was chosen to coincide with the VLA radio center (Phillips & Mampaso 1988). The diaphragm used was 15×20 arcsec below 12μm and was larger above this wavelength. The nebula itself is substantially larger than the diaphragm, but in spite of this practically all of the emission was measured. This is because the outer regions of the nebula are very faint. This can be seen in several ways. First, the radio image (Phillips & Mampaso 1988) at both 2cm and 6cm show that 95% of the emission measured is within a diameter of $8''$. These authors measure a flux density of 644 ± 35 mJy at 6cm, while Milne & Aller (1975) measure 671 ± 65 mJy at the same frequency with a half power beam of 4.5 minutes with the

Table 1. Hβ line fluxes for NGC 6537

log flux	Diaphr.	Ref.
−11.633	40″	(1)
−11.66 ± 0.02	45″	(2)
−11.71 ± 0.03	40″	(3)
−11.78	25″	(4)
−11.40 ±0.03	240″	(3)

(1) Shaw & Kaler (1985); (2) Webster (1983); (3) Kaler (1983); (4) Collins et al. (1961).

Table 2. ISO observations of NGC 6537: in units of 10^{-12} erg cm^{-2} s^{-1}

Ident.	λ	Intens.
Si VII	2.48	< 0.4
HI 6-4	2.6255	4.1
HeII 9-7	2.8266	2.3
HeII 7-6	3.0917	2.0
HI 9-5	3.2976	0.86
??	3.4110	1.3
HI 8-5	3.7399	0.83
??	3.8364	1.4
HI 5-4	4.0514	8.0
Mg IV	4.4860	4.6
Ar VI	4.5290	43
Mg V	5.6094	25
Ar II	6.9845	9.9
Na III	7.3197	3.2
HI 6-5	7.4599	2.0
Ne VI	7.6520	134
Ar V	7.9010	9.4
Na VI	8.6101	1.9
Ar III	8.9907	15.6
Na IV	9.0404	1.65
S IV	10.510	103
Ne II	12.812	16.2
Ar V	13.100	9.85
Mg V	13.520	2.46
Ne V	14.320	234
Ne III	15.554	129
S III	18.711	30.6
Ne V	24.314	170
O IV	25.888	149
S III	33.480	12.2
Si II	34.814	8.0
Ne III	36.010	9.2

Parkes telescope. Since the first measurement integrates over a region of 10″, this indicates very little emission outside this region. Furthermore Ashley (1989) measures a FWHM diameter of 4.0″ in Hβ, while the 10% level lies at 10″ × 11″. Corradi (private communication) finds that the O III line at λ5007 has a diameter of 12″ × 14″ at the 3% level. Before concluding that the SWS is measuring essentially the entire flux we shall discuss the Hβ flux of the nebula.

Table 3. NGC 6537: Comparison ISO observations, (10^{-12} erg cm^{-2} s^{-1})

λ	Ident.	ISO	IRAS (2)	IRAS (2)	KAO	(3)
9.0	[Ar III]	15.5	50			23
10.5	[S IV]	103.0	130			133
12.8	[Ne II]	16.2				21
14.3	[Ne V]	234.0	145	163		
15.5	[Ne III]	129.0	100			
18.7	[S III]	30.6	70	40	44	
24.3	[Ne V]	170.0			95	

(1) Pottasch et al. (1986); (2) Rowlands et al. (1994), 28″ beam; (3) Beck et al. (1981), 7″ beam.

The Hβ measurements are shown in Table 1. It may be seen that most of the measurements are made with a diaphragm of about 40″ and cluster about the value of −11.66. A single value exists made with a much larger diaphragm: 240″. A larger Hβ flux is measured with this diaphragm. Since the nebula extends faintly to this size, this measurement must be taken seriously. However, Ashley (1989) has already expressed his doubt: 'NGC 6537 lies in a rich area of the Milky Way with a high density of field stars, which would cause contamination of measurements made with large apertures'. The fact that the 6cm radio measurements made with the small beam by the VLA and the single dish measurement cited above, agree with each other indicates that the larger diaphragm Hβ measurement is spurious. This is confirmed by the 21cm VLA measurements of Condon & Kaplan (1998), which in addition to agreeing with the measurements of Phillips & Mampaso, show that there is no detectable larger scale emission surrounding the central regions of NGC 6537. We shall come back to the Hβ flux presently.

In Table 2 the lines measured with the ISO SWS are listed, together with their fluxes and identifications. More than 30 lines are seen, due to hydrogen, helium, sodium, oxygen, magnesium, sulfur, silicon, argon and neon. Several stages of ionization are seen in some elements; in neon four ionization stages are present.

2.2. Comparison with other infrared observations

A comparison is made in Table 3. The first two columns give the wavelength and line identification while the third column gives the ISO intensity. The following two columns give the IRAS intensity taken from two different sources. The IRAS intensity of the 18.7μm S III line is especially difficult to measure because the resolution is low in this part of the spectrum. The IRAS measured as it swept across the sky so that it has an effective aperture of at least 2-arc min. The KAO measurement had a 28″ beam while Beck et al. used a 7″ beam. Considering the uncertainties especially in the IRAS measurements, we conclude that most of the radiation originates in a small region, and that there is satisfactory agreement among the various measurements.

Table 4. Hydrogen line intensities, 10^{-12} erg cm^{-2} s^{-1}

λ	Transit.	Ident.	Obs.	Corr.	Theory
4.052	5-4	Brα	8.0	8.71	8.8
2.626	6-4	Brβ	4.1	4.91	5.2
2.166	7-4	Brγ	1.8*	2.4	3.2
7.457	6-5	Pfα	1.99	2.1	2.7
3.741	8-5	Pfγ	0.83	0.94	1.19
3.297	9-5	Pfδ	0.855	1.02	0.84
4861Å	4-2	Hβ			130.

* Ashley & Hyland (1988): 27″ diaphragm.

Table 5. Ionized helium line intensities, 10^{-12} erg cm^{-2} s^{-1}

λ	Transit.	Obs.	Corr.	Theory
3.092	7–6	2.9	3.47	3.85
2.826	9–7	2.3	2.66	1.21
2.188	10–7	0.52*	0.69	0.86
4686Å	–	–	–	110.
1640Å	–	–	–	772.

*Ashley (1989): this is from the ratio of line to Brγ in the central 3″ of the nebula.

2.3. Extinction

Ashley (1989) reports that there is no significant difference between the Brγ and Hβ images. Since the extinction coefficient varies greatly between these two lines, it is concluded that the extinction is uniform. It probably takes place outside the main body of the nebula.

The extinction can be found by the usual methods. The Balmer decrement has been used by Aller et al. (1999) and they have found a value of C = 1.80 or E_{B-V} = 1.23. The extinction can also be found by comparing the radio frequency flux density with the Hβ flux. Because the radio emission is due to helium as well as hydrogen, the helium abundance must be specified. Using He^{+} = 0.062 H and He^{++} = 0.087 H, T_e = 16500 K, and the 6cm flux density of 650 mJy, we obtain an unreddened Hβ flux of 1.28×10^{-10} erg cm^{-2}s^{-1} and an extinction of C = 1.77 or E_{B-V} = 1.21. Thus the two methods yield the same result to within the error of measurement. In the rest of this paper we shall use E_{B-V} = 1.22.

2.4. Comparison of hydrogen and ionized helium with theory

This comparison is made for several reasons. First, it is interesting to see how well the line ratios agree with the theory. Second, the ratios can then be extended to lines in the visual and ultraviolet spectrum (especially Hβ, and He II λ4686 and λ1640) to predict the intensity of these lines in an aperture of ISO size. This will make it possible to use the visual and ultraviolet spectrum in conjunction with the ISO spectrum. Third, the absolute Hβ flux can be obtained through the ISO aperture.

The hydrogen line intensities are listed in Table 4. For completeness the ground based Brγ line is included (Ashley & Hyland 1988). The first three columns give the wavelength (in microns) and the identification. The observed intensity of each line is given in Column 4, and the intensity corrected for extinction in Column 5. This correction is quite small, of the order of 10%. The predicted intensity is given in the last column, for T_e = 15 000 K and n_e = 10^4 cm^{-3}. The predicted value is normalized to best agree with the measured intensity. In addition the predicted Hβ intensity is given, based on the same normalization. It can be seen that the infrared hydrogen lines predict the same Hβ flux as the radio emission. This confirms that the infrared aperture is measuring the entire nebula.

The same can be done for the ionized helium lines and is shown in Table 5. Unfortunately the number of lines observed is limited: 2 ISO lines and one measured by Ashley (1989). As can be seen from the table, the 2.826 μm line is too strong compared to the other two lines. While the line could be a blend there is no obvious candidate for a blending line. Furthermore this higher intensity is not seen in other ISO spectra that have been analyzed. Therefore we have decided to give more weight to the other two lines when normalizing the spectrum, which is shown in the last column of the table. The predicted values of the visible and ultraviolet helium lines are also given. There is somewhat more uncertainty in these values than for hydrogen, although the ratio of λ4686 to Hβ from Tables 4 and 5 is in reasonably good agreement with the observed value. The predicted value of the λ1640 line will be used when discussing the IUE observations.

2.5. The visual spectrum

The two most comprehensive spectra of NGC 6537 are those of Aller et al. (1999) and Perinotto & Corradi (1998). Neither has measured the entire nebula. Aller et al., using the Lick Observatory spectrograph measure with a 1.2″ × 4″ slit which rotates through a small position angle. Furthermore guiding and seeing cause a blurring amounting to 2″ −3″. Thus the actual area on the sky amounted to about 3″ × 5″, presumably centered on the nebula. The measurements of Perinotto & Corradi (1998) are made in three positions: one at the center of the nebula and the other two displaced by about 9.8″ on either side. Because the latter two positions record only 2% of the flux measured at the center, and because the long slit used makes it difficult to define the measured position, we use only the central spectrum. Its size, after allowing for seeing and guiding problems, is 3″ × 10″, somewhat large than used by Aller et al. The spectral resolution of Aller et al. was 0.2 A, while that of Perinotto & Corradi was much worse, about 3 A.

The most important lines in the spectra are listed in Table 6. The first two columns in the table give the measured wavelength and the identification of the line. The third column gives the intensity measured by Aller et al., while the fourth column is the intensity measured by Perinotto & Corradi. In both columns the measurements are given with respect to Hβ = 100, and are not corrected for extinction. An average measurement is given in the last column. This column is corrected for extinction, using the extinction law tabulated by Fluks et al. (1994) and E_{B-V}

Table 6. Observed visual spectrum: unreddened intensity in units of 10^{-12} erg cm^{-2} s^{-1}

λ	Ident.	Aller et al. (1999)	Perinotto & Corradi (1998)	Norm.un-red. Intensity
3727	[O II]		10	37
3868.7	[Ne III]	41.7	49.4	143
4068.6	[S II]	3.87	5.7	10.7
4076.3	[S II]	0.95		2.6
4363.2	[O III]	14.7	15.9	33
4686	He II	94.2	83.2	133
4711.3	[Ar IV]	10.1	14.5	15.6
4714.2	[Ne IV]	1.66		2.5
4724.1	[Ne IV]	2.32	)	3.5
4725.5	[Ne IV]	1.90	)5	2.8
4740.2	[Ar IV]	19.2	21.6	28.6
4861.3	Hβ	100	100	130
5006.8	[O III]	1122	1229	1390
5191.7	[Ar III]	0.53		0.51
5309.3	[Ca V]	0.40		0.35
5754.7	[N II]	47.2	44.9	27
5875.7	HeI	31.8	36.2	18
6101.8	[K IV]	2.51	2.5	1.1
6228.3	[K VI]	0.81		0.34
6312.1	[S III]	27.4	23.4	10.3
6435.1	[Ar IV]	30.6	22.8	9.8
6583.5	[N II]	1352	1430	470
6716.5	[S II]	16.9	24.5	26
6730.8	[S II]	36.1	46.6	52
6795	[K IV]	12	0.8	0.3
7005.7	[Ar V]	88.7	71.3	21.8
7135.8	[Ar III]	151	177	39.8
7170.6	[Ar IV]	6.84	9.7	2
7237.5	[Ar IV]	7.46	6.2	1.7
7262.9	[Ar IV]	5.98	7	1.5
7319.8	[O II]	44.9	47.9	11
7330.2	[O II]	37.9	39.4	13.2
7529.9	Cl II	75	6.8	1.5
7751.1	[Ar III]	56	52.9	10.9
8045.6	[Cl IV]	18.5	19.6	3.4
8434.3	[Cl III]	1.62		0.25
8578.9	[Cl II]	2.75	5.3	0.57
9068.8	[S III]	260.6	833	42.0:
9531	[S III]	1282	1847	130.0:

= 1.22. The flux in this column is also normalized so that Hβ = 1.30 $\times$ 10^{-10} erg cm^{-2} s^{-1}. These values can be used in conjunction with the ISO measurements in Table 2. It is possible that the higher ionization lines are somewhat too high in Table 6 because the visible spectrum is more representative of the central regions than the ISO spectrum.

2.6. The IUE spectrum

Four IUE spectra have been taken of NGC 6537. The ST archive lists the position of SWP35961 as 70″ from the center of the nebula, and indeed the spectrum is so noisy that it is unusable. The three other spectra, two short-wave and one long-wave spectra,

Table 7. IUE spectrum of NGC 6537

λ	Ion	Meas.[1] Intens.	Intens.[2]	Intens.[3] & norm.	Intens. Hβ=100
1238.5	N V	2.55	153	297	2260
1402.5	O IV]	0.16	2.2	4.3	32.4
1484.8	N IV]	3.95	39.4	76.4	583
1548.8	C IV	9.23	88.9	173	1320
1577.9	[Ne V]?	1.19	10.6	20.7	158
1641.1	He II	54	43.4	84.2	643
1663.6	O III]	3.91	31.1	60.3	460
1734.1	N III?	1.57	10.2	19.6	150
1749.5	N III]	42	26.1	50.6	386
1835.1		1.50			
1889.7	Si III]	1.49	12.4	24.1	184
1908.2	C III]	3.22	26.8	52	377
2248.9		2.9			
2295.1	C III	1.2			
2307.5		0.9			
2326.9	C II]	2.6			
2336.9		3.8			
2423.3	[Ne IV]	7.2	47.8	71.7	647
2782.7	[Mg V]	1	0.965	1.45	11.1
3046.8	O III	2.5			
3131.8	O III	21.2			
3200.1	He II	9.5	3.59	5.43	41.4

[1] (10^{-14} erg cm^{-2} s^{-1})
[2] Intensity corrected for extinction E_{B-V}=1.23, (10^{-11} erg cm^{-2} s^{-1})
[3] Intensity corrected and normalized, (10^{-11} erg cm^{-2} s^{-1})

are quite good. The short-wave spectrum SWP35967 is positioned at the center of the nebula. SWP24281 is given a position 20″ from the center, but in spite of this has intensities roughly equal to the previous spectrum. This is probably because that after slewing to the listed coordinates the object was bright enough for the acquisition camera to detect so that the nebula was recentered. The average intensity of these two spectra is given in Column 3 of Table 7, and has been taken from Aller et al. (1999). The long-wavelength spectrum, LWP15324, was listed as 6″ from the center of the nebula. It has been remeasured to obtain the intensities of the weaker lines and these intensities are given in the same column of the table. These intensities were then corrected for extinction in the same manner as the visible spectra, using E_{B-V} = 1.22 and the standard extinction curve of Fluks et al. The results are shown in Column 4 of Table 7.

We have then proceeded in the same manner as has been done by BP and many other authors. It is assumed that the ratio of the He II lines is fixed by the atomic cascade processes. For example the ratio λ1640/λ4686 has a value of 6.81 at T_e = 16500 K and has a very small temperature dependence (Kingsburgh & Barlow 1994 give a temperature dependence of 0.17). To obtain the correct ratio of λ1640/λ4686, the intensities in the SWP spectrum must be increased by a factor 1.95, while the ratio of λ3204/λ4686 leads to an increase of the LWP intensities by a factor of 1.5. The use of these ratios has two advantages. First, uncertainties in the total extinction, or in the extinction law, can

Table 8. ISO observations of He 2–111: Intensities in units of 10^{-13} erg cm^{-2} s^{-1}

λ	Ident.	Intens.
4.05	HI5-4 Brα	4.3
7.653	[Ne VI]	75.4
12.81	[Ne II]	45
14.321	[Ne V]	191
15.554	[Ne III]	177
24.316	[Ne V]	278
25.889	[O IV]	434
36.10	[Ne III]	23.7

be compensated in this way. The total extinction in the ultraviolet is very large: a factor of about 10 000. Thus a relatively small uncertainty in the extinction or in the extinction law could cause a possible change of a factor 1.5-2. Second, the IUE has an oval aperture of $10'' \times 23''$. Since the positioning may be uncertain, it is possible that a part of the nebula has been missed. The fact that the intensity must be increased agrees with this suggestion. It is not necessary to know which of the possibilities is correct. The normalized intensity corrected for extinction is listed in Column 5 of Table 7. In Column 6 the intensity relative to Hβ is given, using Hβ = 1.3×10^{-10} erg cm^{-2}s^{-1}.

Note that the ratios listed in Column 6 are substantially different than those given by Aller et al. (1999). For example Aller et al. give λ1640/Hβ = 140, which is a factor of 5 lower. This has two causes. First, a factor of about 2 is due to the normalization just discussed. A somewhat larger factor is due to the use of an Hβ flux of -11.40 as measured with a24$'$ diaphragm by Kaler (1983) as shown in Table 1. As has been discussed this flux is likely to be wrong, but even if it were not wrong it would be an inappropriate flux to use. This is because the IUE fluxes, the ISO fluxes and the radio flux density all refer to the bright central region with a diameter of less than 15$''$. Furthermore the ratio λ1640/Hβ = 1.40 implies that the He II line ratio λ1640/λ4686 = 1.40, since both the visible and the ISO spectra show that λ4686/Hβ is about unity. Since this He II line ratio must be increased, we have chosen to fix the ratio at its expected value.

3. The spectrum of He2-111

This nebula is similar to NGC 6537: it is also bipolar and most of the emission is concentrated in the central region. A good photograph of it is given in Corradi & Schwarz (1993). The length of the bipolar structure is about 730$''$ compared with 240$''$ for NGC 6537. Its radio flux density is an order of magnitude lower than NGC 6537, which is one of the reasons it is less well known. Milne & Aller (1975) find a 6cm flux density of 73$\pm$4 mJy with the Parkes telescope, which has a half power beam of 4.5 minutes. The nebula has also been detected at 2cm (Milne & Aller 1982) where its emission is 56 mJy, and 11cm where the flux density is listed as 110$\pm$20 mJy (Milne & Webster 1979). Calabretta (1982) finds a flux density of 80 mJy at 75cm. We shall use a total flux density S(6cm) = 70 mJy.

He2-111 lies close (0.3°) to the galactic plane. This is similar to NGC 6537 that is 0.7° from the plane. It has an expansion velocity of 12 km/s compared to 18 km/s for NGC 6537 (Weinberger 1989). High velocities, of the order of 300-400 km/s, are observed in the central regions of both nebulae.

Like NGC 6537, the emission is concentrated in the very center. As the photographs of Gorny et al. (1999) and Webster (1978) show, the main emitting region has a size of about $9'' \times 21''$ and then falls off rather steeply.

3.1. ISO observations

The intensity of the lines measured is given in Table 8. The only hydrogen line measured is the Brα line at 4.051μm. With a small extinction correction its intensity is 4.55×10^{-13} erg cm^{-2} s^{-1}. This implies an Hβ intensity of 7.36×10^{-12} in the same units. The measured log Hβ is -12.01 (same units) for the entire nebula (Shaw & Kaler 1989). These same authors give a measurement using a 34$''$ diaphragm: -11.96 (!). While it must be an error that more emission exists in the small area than in the large area, it indicates that the outer nebular regions contribute only negligibly to the total flux. Using an extinction of E_{B-V} = 0.77 (see below) the corrected Hβ is 12.9×10^{-12}. This means that the ISO is seeing only 57% of the nebula. Considering that the Brα intensity has an uncertainty of about 30%, it is still possible that much of the nebula was seen. We will assume that all the intensities of all the lines in Table 8 should be increased by 1.75 to take into the smaller ISO diaphragm into account. An exception to this is the Ne III line at 36.010 μm that was measured with a somewhat larger diaphragm. Here no correction factor was applied.

No other far infrared measurements of this nebula have been made.

3.2. Extinction

Several authors have determined the extinction from the Balmer decrement. Perinotto & Corradi (PC, 1998) find a value of E_{B-V} = 0.82, which is roughly constant at 3 different positions in the nebula. Costa et al. (1996) give a value of 0.68, while Kingsburgh & Barlow (KB, 1994) find a value of 0.77. The extinction can also be found from a comparison of the radio emission with the Hβ flux, which we have done using S(6cm) = 70 mJy and log Hβ = -12.0, a temperature of 16 000 K and helium ionic abundances as given later in the paper. A value of E_{B-V} = 0.77 is found. Since the agreement with the extinction found from the Balmer decrement is good, it is this value which will be used in the remainder of this paper.

3.3. The visual spectrum

In the past six years three authors have observed the visual spectrum of He2-111: PC, KB and Costa et al. PC observed with a slit oriented along the major axis of the nebula. They observed in 3 positions: at the center of the nebula and 12.7$''$ on either side. The slit at the center was 5.7$''$ long, while that displaced

Table 9. Visual spectrum of He 2-111

λ	Ident.	Perinotto Corradi (1998)	Costa et al. (1996)	KB (1994)	Intens*
3727	[O II]	150		130	36.1
3868.7	[Ne III]	120	27	129	30
4070	[S II]	11.4		12.4	2.8
4363.2	[O III]	18.4	20.8	24.7	4
4685.7	He II	85.5	91	122	13
4711.3	[Ar IV]	14.1	18.6	23	2.8
4724.1	[Ne IV]	2.4			0.36
4740.2	[Ar IV]	10.8	20.1	15.8	2.3
	Hβ	100	100	100	13.4
4958.9	[O III]	420	400	404	51
5006.8	[O III]	1303	1248		159
5517.7	[Cl III]	3.3		2.6	0.24
5537.9	[Cl III]	3.1		6.2	0.38
5754.6	[N II]	63.8	50.2	45.3	4.26
5875.7	HeI	35.8	26.9	23.8	2.2
6312.1	[S III]	20.4	20.7	26.4	1.47
6435.1	[Ar V]	3.9	7.2		0.36
6548	[N II]	1670	1204	1036	80
	Hα	692	598	623	39.1
6583.4	[N II]	4825	3781	2711	229
6716.5	[S II]	265	198	173	12.2
6730.8	[S II]	280	220	189	13.3
7005.7	[Ar V]	11.9	15.7	16.5	0.74
7135.8	[Ar III]	150	129	118	6.64
7325	[O II]	39.3	33.1	28.1	1.58
7529.5	[Cl IV]	1.8			063
7751.1	[Ar III]	39			1.36
8045.6	[Cl IV]	4.2			0.14

* Normalized unreddened intensity in units of 10^{-13} erg cm^{-2} s-1

Table 10. IUE spectrum of He 2-111

λ	Ident.	Meas.[1] Flux	Unred.[2] Flux	Norm.[3] corr. Flux	Intens. Hβ=100
1240	N V	2.4:	20	45	338
1402	O IV]	0.9:	3.60	8.1	60.5
1482	N IV]	7	22.8	51.7	386
1549	C IV	4.8	15.3	34.7	259
1574	[Ne V]?	3.8	12.2	27.7	206
1641	He II	13.5	40.2	91.2	681
1664	O III]	4.8	13.6	30.8	230
1702		2.6	6.9	15.6	116
1751	N III]	5.4	13.4	30.4	227
1888	Si III]	1.1:	3.1:	7	52
1909	C III]	4.9	14.6	33.1	247
2303	C III	2.8	14.7	24.3	181
2326	C II]	1.3:	6	9.9	74
2425	[Ne IV]	4	10	16.5	123
2462	[O II]?	3.2	6.67	11	82
2540		2.9	5	8.2	61
2733	He II	2.1	1.72	2.8	21
2786	[Mg V]	2	1.5	2.5	18
2864	[Ar IV]	3.3	2.26	3.7	27
3103		5.2	2.45	4	30
3132	O III	6.4	2.9	4.8	36
3205	He II	9.6	4	6.6	49

[1] 10^{-14} erg cm^{-2} s^{-1}
[2] 10^{-12} erg cm^{-2} s^{-1}
[3] 10^{-14} erg cm^{-2} s^{-1}

from the center was 19.7″ long. In all cases the slit width was effectively 3″. Approximately equal fluxes were encompassed by each slit. The average of the 3 measurements was used to represent the nebula spectrum and is shown in the third column of Table 9. KB used a single slit about 18″ long at a position angle about 50″ away from that used by PC, thus giving more weight to the central region. Costa et al. do not specify where the slit was placed, nor how long it was. These results are shown in the fourth and fifth columns of the table. In the last column of Table 9 the average spectrum is given, with the measurements of PC having more weight. At the same time the spectrum has been corrected for extinction using E_{B-V} = 0.77, and it has been normalized so that Hβ has the intensity given above.

3.4. *The IUE spectrum*

Four low-resolution spectra were taken: LWP15326 and SWP35964 were said to be centered on the star (classification 70, visually the star has never been seen) and LWP15489 and SWP36236 were classified 71 (off star). The intensities of the helium lines in both the 'on star' and 'off star' spectra are very similar so that the position of the aperture could not have been very different. This is not surprising since the distinction between the classification 70 and 71 is not reliable. The position angle for the 'on star' spectra 'is listed as 228°, while that for the 'off star' spectra is 266°. The latter is almost along the minor axis of the nebula, so that it is not surprising that the 23″× 10″ oval aperture missed some of the emission. Because of the similarity in the helium emission line intensity we have averaged the intensity of the two LWP and SWP spectra. The resultant spectrum is shown in the first three columns of Table 10. In the fourth column the flux has been corrected for extinction using E_{B-V} = 0.77 and the extinction curve of Fluks et al. (1994). The fifth column gives the corrected flux, normalized as was done for NGC 6537 to obtain the correct ionized helium line ratios. The SWP spectrum was increased by a factor 2.27 to obtain the theoretical ratio λ1640/λ4686 = 7.04, while the LWP spectra were increased by 1.65 to obtain the correct theoretical ratios for λ3204/λ4686 and λ2733/λ4686. Recall that a similar increase, 1.75, is necessary for the ISO spectrum in order to have the Brα agree with the total Hβ flux. This agreement is probably due to the fact that the size of the ISO aperture is practically the same: 15″ × 20″.

In the final column of Table 10 the ratio of the total line intensity (Column 5) to the total Hβ is given. The only other values in the literature are given by KB, who only measure six IUE lines. They do not show the measurements they made, but only give the ratio of the line intensity to Hβ after correcting for

Table 11. Electron density indicators

			NGC 6537		He2–111	
Ion	Ioniz. Pot.	Lines Used	Observed Ratio	Elect. Density	Observed Ratio	Elect. Density
S II	10.4	6731/6716	2.0±0.1	10000±3000	1.09±0.14	1000±300
O II	13.6	3726/3729			1.12±0.3	800±500
S III	23	33.5/18.7	0.40±0.1	4000±1500		
Cl III	24	5538/5518	2.38±0.4	20000±7000	1.58±0.1	7000±3000
Ar IV	40.7	4740/4711	1.83±0.3	15000±5000	0.82±0.1	300±300
Ne III	41	155/36.0	14.0±3	10000±10000		
Ar V	60	13.1/7.9	1.05±0.2	10000±3500		
Ne V	97	24.3/14.3	0.73±015	4000±2000	1.46	LOW DENSITY

extinction using almost the same E_{B-V} as we have used. They give a value of λ1640 about 40% higher than we find, but this is entirely due to their using an intensity of λ4686 about 40% higher. Their other intensity ratios are a factor 2 to 3 higher than we find. We do not know the reason for this, except to say that the reductions have been redone recently.

The lines at λ1240 and λ1402 are weak and somewhat uncertain. The intensities given are at least upper limits. The line at λ1574 is certainly present. It is uncertain if it should be attributed to NeV, since this would require a high temperature. Furthermore it would require the presence of a line at λ2974, which originates from the same upper level. This line should have an intensity of 10 in its normalized corrected flux (Column 5 of Table 10). No such line has been seen. Note that this line was also seen in the spectrum of NGC 6537.

3.5. Errors in combining spectra

As already indicated the IUE spectra are taken with a similar size diaphram as the ISO spectra, but they are not exactly the same. The visual spectra are taken with smaller slits and are usually weighted to the brighter parts of the nebulae. To minimize errors when combining these different spectra we have always normalized them so that the H lines and the He II lines in the different spectra have their theoretical values. This will completely correct for any errors due to the different diaphragm sizes if the spectra of these two ions is the same over the nebulae.

4. Chemical composition of the nebulae

The method of analysis is the same as used by PB for NGC 6302. First the electron density and temperature as function of the ionization potential is determined. Then the ionic abundances are determined, using density and temperature appropriate for the ion under consideration, together with Eq. (1). Then the element abundances are obtained.

4.1. Electron density

The ions used to determine N_e are listed in the first column of Table 11. The ionization potential required to reach that ionization stage, and the wavelengths of the lines used, are given in Columns 2 and 3. Note that the wavelength units are A when 4 ciphers are given and microns when 3 ciphers are shown. The observed ratio of the lines is given in the fourth and sixth column for NGC 6537 and He2-111 respectively, while the corresponding electron density is given in the fifth and seventh columns. The errors given are roughly 1.5σ values. The temperature used is that discussed in the following section, but is unimportant since these line ratios are essentially determined by the density.

There is no indication that the electron density varies with ionization potential in a systematic way. It appears that the Cl III lines give a higher density than the rest in both nebulae, but this may be due to uncertainties in the collision cross-sections. It is clear that the density in NGC 6537, for which we shall use a value of 10^4 cm^{-3}, is an order of magnitude higher than the value of 10^3 cm^{-3}, obtained for He2-111.

It is interesting to compare this value of the density with the rms density found from the Hβ line. This depends on the distance and the size of each nebula, and for this calculation we use a distance of 1.5 kpc and 2 kpc for NGC 6537 and He2-111 respectively. These are averages of the values given in Acker et al. (1992). The volume of each nebula is represented by a sphere of radius 4$''$ and 8$''$ respectively. We use an Hβ flux as given above and an electron temperature as given below. We obtain $N_{rms} = 1.3 \times 10^4$ for NGC6537 and $N_{rms} = 1.3 \times 10^3$ for He2-111. These values are very close to the forbidden line densities, especially considering the uncertainties in both the distance and the emitting volume of both nebulae. In the remainder of this paper a value of density of 10 000 cm^{-3} is used for NGC 6537 and 1000 cm^{-3} for He2-111, constant over the emitting volume.

4.2. Electron temperature

A number of ions have lines originating from energy level far enough apart that their ratio is sensitive to the temperature. These are listed in Table 12, which is arranged in a similar way as the previous table. A number of things are apparent. First, the temperature derived from the Ne III lines is lower than the rest. This is true for both nebulae. It is also the case for the other nebulae analyzed with ISO data: NGC 6302 (PB), NGC 6445 (Van Hoof et al. 2000) and NGC 7027 (Bernard Salas et al. 2000). The origin of this deviation is unknown; we suspect that the atomic parameters may be wrong. We shall ignore the Ne III

Table 12. Electron temperature indicators

Ion	Ioniz. Pot.	Lines Used	NGC 6537 Observed Ratio	NGC 6537 T_e	He2–111 Observed Ratio	He2–111 T_e
N II	14.5	5755/6584	0.057±0.1	17000±1200	0.019±.004	10800±1000
S II	23.3	6312/18.7	0.34±.06	17800±1000		
Ar III	27.6	7136/8.99	2.55±.5	18100±1000		
O III	35	4363/5007	0.024±.003	16500±1000	0.025±.004	16700±1000
Ne III	41	3868/15.5	1.11±0.25	11800±1000	1.7±0.4	13800±1000
O IV	55	1400/25.9	0.33±0.06	17700±700	0.19±0.04	19000±1000
Ne IV	63	2425/4725	114±30	15000±4000	45.8±10	25000±4000
Mg V	109	2783/5.61	0.58±0.15	21500±2000		

temperature here. Second, The electron temperature appears to be constant for NGC 6537, except possibly for the very highest ionization potential. Since for the latter ions abundance determinations will be done using ISO data, it is only necessary to know the temperature for ions that require less than 70ev to reach them. Thus it is sufficient to use a constant value of temperature; we use T_e = 17 200 K.

For He2-111 the situation is different. The temperature appears to continuously rise from the lowest ionization stages to the higher ones, i.e. the temperature continuously decreases from close to the central star to further out in the nebula. This is similar to that in NGC 6302. We shall ignore the Ne III temperature and use the other values to define a temperature vs. ionization potential curve, which is then used to give the temperature for individual ions.

The NeV lines at λ3426 and λ1575 have not been used in the temperature determination. There are two reasons for this. First, the intensities are poorly determined, and in the case of λ1575 even the identification of the line is in doubt. Second, the theoretical line strengths are strongly dependent on density as well as temperature. It is clear, however, that there is substantial excitation of these lines, indicating high temperatures and/or motions in the central regions of the nebulae.

4.3. *Ionic and element abundances*

The ionic abundances have been determined using the following equation:

$$\frac{N_{ion}}{N_p} = \frac{I_{ion}}{I_{H\beta}} N_e \frac{\lambda_{ul}}{\lambda_{H\beta}} \frac{\alpha_{H\beta}}{A_{ul}} \left(\frac{N_u}{N_{ion}}\right)^{-1} \quad (1)$$

Where $I_{\rm ion}/I_{\rm H\beta}$ is the measured intensity of the ionic line compared to Hβ, $N_{\rm p}$ is the density of (ionized) hydrogen; $\lambda_{\rm ul}$ is the wavelength of this line; $\lambda_{H\beta}$ is the wavelength of Hβ; $\alpha_{H\beta}$ is the effective recombination coefficient for Hβ; $A_{\rm ul}$ is the Einstein spontaneous transition rate for the line; while $N_{\rm u}/N_{\rm ion}$ is the ratio of the population of the level from which the line originates to the total population of the ion. This ratio has been determined using the 5 level atom (see PB).

4.3.1. NGC 6537

The results are given in Table 13, where the first column lists the ion concerned, and the second column the line used from which the determination was made. The third column gives the ionic abundance. An electron temperature of 17 200 K was used for ions that require less than 70ev to reach them. For the rest a temperature of 25 000 K was used. But the latter ions are formed so close to the ground level that the precise value of the temperature is unimportant. The only exception to this is the NV line. The resultant ionic abundance of N^{+4} therefore remains uncertain. But it is known from the study of other elements that the abundance of higher ionization stages is decreasing above 70ev, so that the total abundance of nitrogen cannot be influenced by more than 20% by this uncertain temperature.

The fourth column gives the sum of the observed ionic abundances of each element. The fifth column gives the Ionization Correction Factor (ICF) for each element. This has been determined both empirically (see PB) and with the help of model nebulae (see the model results of Aller et al. 1999 and the ICF given in that paper). For most of the elements all the important ionization stages have been measured, so that only a small ICF is necessary and the total element abundances are considered to be quite accurate. As the ICF increases to a value of 2 and above, the uncertainty increases.

4.3.2. He2-111

The ion and element abundances in He2-111 can be found in a similar manner. In this case a constant electron density of 10^3 cm^{-3} was used (see Table 11). An electron temperature as function of ionization potential was found from the values given in Table 12. The resultant ionic abundances are in the third column of Table 14. Fewer ions are listed than in NGC 6537 because the ISO measurements covered only a limited part of the infrared spectrum. In the case both of Si and Mg only a single ion was observed; as a result the ionization correction factor may be rather large. It is possible to compute an abundance for Si^+, but because of the low ionization potential of neutral silicon, coupled with the low temperature needed to excite the line at 34.8 μm, part of the line may be formed in a photodissociation region outside the ionized nebula, giving an abundance which

Table 13. Ionic concentrations and chemical abundances in NGC 6537. Wavelength in Angstrom for all values of λ above 1000, otherwise in μm.

Ion	λ	n(ion)/n_p	Σn(ion)/n_p	ICF	n(el.)/n_p
He^+	5875	0.062			
He^{++}	4686	0.087	0.149		0.149
C^{++}	1909	3.9(−5)			
C^{+3}	1548	6.4(−5)	1.2(−4)	1.7	1.75(−4)
N^+	6584	2.5(−5)			
N^{++}	1750	1.4(−4)			
N^{+3}	1487	1.8(−4)			
N^{+4}	1238	7.0(−5)	4.1(−4)	1.1	4.5(−4)
O^+	7325	1.0(−5)			
O^{++}	5007	8.9(−5)			
O^{+3}	25.9	4.9(−5)	1.5(−4)	1.25	1.85(−4)
Ne^+	12.8	1.2(−5)			
Ne^{++}	15.5,36.0	5.2(−5)			
Ne^{+3}	2425,4725	7.5(−5)			
Ne^{+4}	14.3,24.3	1.9(−5)			
Ne^{+5}	7.65	3.0(−6)	1.6(−4)	1.03	1.7(−4)
Na^{++}	7.31	1.2(−6)			
Na^{+3}	9.038	3.6(−7)			
Na^{+5}	8.607	1.7(−7)	1.7(−6)	1.5	2.6(−6)
Mg^{+3}	4.49	1.1(−6)			
Mg^{+4}	5.61,13.5	3.6(−6)	4.8(−6)	2	9.6(−6)
Si^{++}	1892	3.6(−6)			
Si^{+5}	1.96	5.7(−7)			
Si^{+6}	2.48	5.4(−8)	4.3(−6)	3:	1.3(−5)
S^+	6731	1.3(−6)			
S^{++}	6312	3.5(−6)			
S^{+3}	10.5	2.3(−6)	7.1(−6)	1.5	1.1(−5)
Cl^+	8577	1.7(−8)			
Cl^{++}	5538	3.3(−8)			
Cl^{+3}	8046	8.6(−8)	1.36(−7)	1.75	2.4(−7)
Ar^+	6.99	5.5(−7)			
Ar^{++}	8.99	9.4(−7)			
Ar^{+3}	4740,4711	1.3(−6)			
Ar^{+4}	13.1,7.90	2.2(−7)			
Ar^{+5}	4.54	4.2(−7)	3.44(−6)	1.2	4.1(−6)
K^{+3}	6101	2.2(−8)			
K^{+5}	6228	4.3(−9)	2.6(−8)	2:	5.3(−8)
Ca^{+4}	5310	1.6(−8)	1.6(−8)	2.5:	4.0(−8)

Table 14. Ionic concentrations and chemical abundances in He 2-111. Wavelength in Angstrom for all values of λ above 1000, otherwise in μm.

Ion	λ	n(ion)/n_p	Σn(ion)/n_p	ICF	n(el.)/n_p
He^+	5875	0.10			
He^{++}	4686	0.085	0.185	1.0	0.185
C^{++}	1909	5.4(−5)			
C^{+3}	1548	1.3(−5)	6.7(−5)	1.6	1.1(−4)
N^+	6584	1.56(−4)			
N^{++}	1750	5.1(−5)			
N^{+3}	1487	8.0(−5)			
N^{+4}	1238	7.6(−6)	2.95(−4)	1.0	3.0(−4)
O^+	3727	4.9(−5)			
O^{++}	5007	10.2(−5)			
O^{+3}	25.9	5.4(−5)	2.05(−4)	1.3	2.7(−4)
Ne^+	12.8	3.1(−5)			
Ne^{++}	15.5,36.0	8.1(−5)			
Ne^{+3}	2425	1.6(−5)			
Ne^{+4}	14.3,24.3	1.4(−5)			
Ne^{+5}	7.65	1.5(−6)	1.44(−4)	1.1	1.6(−4)
Mg^{+4}	2783	3.2(−6)			
Si^{++}	1892	5.2(−6)			
S^+	6731	2.8(−6)			
S^{++}	6312	6.4(−6)	9.2(−6)	1.7	1.5(−5)
Cl^{++}	5538	1.4(−7)			
Cl^{+3}	7530	3.6(−8)	1.8(−7)	2	3.5(−7)
Ar^{++}	7137	1.6(−6)			
Ar^{+3}	4740	1.2(−6)			
Ar^{+4}	7005	3.4(−7)	3.1(−6)	1.75	5.5(−6)

is too high. We have chosen to ignore this line. Because Si and Mg are probably mainly in the observed ionization stage, an approximate abundance can be calculated using an ICF of 2.5. The resultant abundance is more uncertain than the other abundances, but still better than a factor of 2. All values of the composition are given in Column 6.

5. Comparison with other abundance determinations

This comparison is limited to recent work on these objects.

5.1. NGC 6537

A comparison is made in Table 15 of the relative abundance of 7 elements we have determined with those determined by Aller et al. (1999) and Perinotto & Corradi (1998, hereafter PC). PC do not make use of the IUE ultraviolet observations, while Aller et al. use the same IUE measurements which are used here. It can be seen that there is good agreement for the oxygen abundance that is based primarily on optical measurements. The slightly lower oxygen abundance of Aller et al. is caused by their use of the λ1400 line to determine the O^{+3} abundance, while we have used the 25.9μm line. As discussed above, the failure of Aller et al. to normalize the IUE measurements to obtain the correct helium line ratios, and their use of too high an Hβ flux, lead to much too low carbon and nitrogen abundance compared to our results. The results of PC for nitrogen, which are based only on the N II line and an ICF lead to results more similar to what we have found. The argon abundance, which we have based on the infrared ISO lines, and the others on the visible lines, are very similar. This indicates the general consistency of the results from the ISO lines with those from the visible spectrum. The lower neon abundance found by Aller et al. results principally from the use of a quite high temperature for the temperature sensitive Ne IV line. The neon abundance we have found is based on the measurement of all the important stages of ionization of this element. In addition four of the five ions are determined from temperature insensitive infrared lines.

Table 15. Comparison of abundances: NGC 6537

Element	Present Abundance	Aller etal. (1999)	Perinotto Corradi (1998)
He	0.149	0.131	0.189
C	1.75(−4)	0.21(−4)	
N	4.5(−4)	1.0(−4)	5.6(−4)
O	1.85(−4)	1.42(−4)	2.0(−4)
S	1.1 (−5)	2.99(−5)	0.72(−5)
Ar	4.1(−6)	4.0(−6)	3.2(−6)
Ne	1.7(−4)	4.8(−5)	0.6(−4)

Table 16. Comparison of abundances: He2-111

Elem.	Pres. Abund.	KB (1994)	PC (1998)	Costa etal. (1996)
He	0.185	0.22	0.23	0.25
C	1.1(−4)	1.96(−4)		
N	3.0(−4)	7.2(−4)	7.2(−4)	10.7(−4)
O	2.7(−4)	2.8(−4)	2.9(−4)	1.5(−4)
S	1.5(−5)	1.6(−5)	1.3(−4)	1.6(−4)
Ar	5.5(−6)	4.4(−6)	5.4(−6)	3.6(−6)
Ne	1.6(−4)	1.4(−4)	1.2(−4)	0.1(−4)

5.2. He2-111

Table 16 shows the comparison for the same seven elements of our abundances with those of Kingsburgh & Barlow (1994, hereafter KB), PC and Costa et al. (1996). KB are the only ones who use the IUE measurements. They normalize their measurements in the same way that is done here, by obtaining the theoretical ratio of the He II lines. Their ratio of other IUE lines to the He II λ1640 line is often different than ours. They do not measure the C IV lines at λ1548, which we clearly see on the spectra. On the other hand, some of the intensities they find are larger than we find, although they do not give the original measurements, but only the intensities after correction for extinction. They find a very strong N V line at λ1238, while we find that if the line is actually present it is only just above the noise.

As in NGC 6537, the oxygen abundances of all observers agree. The nitrogen abundances do not agree, but for different reasons. KB measure about the same N^+ abundance as we do, but their abundances of higher nitrogen ionization stages are considerably larger. The other two observers have only the N II lines. PC use this line to find an N^+ abundance about twice our value, while Costa et al. find 50% less than we do. That Costa et al. determine a still higher nitrogen abundance than PC with less N^+ is because the two authors use considerably different ICF. This indicates the uncertainties involved in using high values of the ICF. For sulfur, argon and neon all the results are very similar. The only exception to this is the neon abundance determined by Costa et al. But this value is very uncertain for many reasons. Only the Ne III line at λ3869 was used together with a temperature from O III. But it has been shown using the infrared Ne III lines that the electron temperature found from this line is always anomalously low. In other words, if one uses a higher temperature, the abundance is too low. Use of the infrared lines to determine abundance removes this problem.

6. Comparison with the composition of other astronomical objects

In this section the composition of NGC 6537 is compared with He2-111 and with two other planetary nebulae whose abundance is determined using the ISO spectrum: NGC 6302 (PB) and NGC 6445 (Van Hoof et al. 2000). These latter two nebulae are morphologically similar to the first two. They are all clearly bipolar nebulae, all very close to the galactic plane, and all excited by a very hot star. They all show the Ne VI line. NGC 6302 is probably excited by the hottest star with an uncertain temperature of about 350 000 K, (e.g. Ashley & Hyland 1988) followed by the exciting star of NGC 6537, with a (similarly uncertain) temperature of about 250 000 K (e.g. Aller et al., 1999). The exciting star of NGC 6445 has a temperature of 185 000 K (Van Hoof et al. 2000). This nebula has the lowest density and is probably the oldest. He2-111 has a similar temperature exciting star and a somewhat higher density. In addition to the normal expansion velocity of 10 to 40 km/s, all show very high motions of several hundred km/s close to the central star. Their radial velocities are not high, indicating that all of the nebulae are rather close. Although their distances are poorly known, they are all probably within 1 to 2 kpc of us.

The abundance of the ten best-determined elements is shown in Table 17, Columns 2-5. For comparison, the solar abundance is shown in Column 6 and that of the B-stars in Column 7. The cool clouds in the direction of ζ Oph are shown in Column 8 and the abundance in the Orion nebula is in the last column. Consider the four planetary nebulae. The abundance of sulfur, chlorine and argon are very similar to one another, and at the same time very similar to the Orion nebula. Since it is unlikely that these elements change in abundance in the course of evolution, it is reasonable to suppose that they were all formed out of material with the same chemical composition. We may examine the other elements in this light. Helium is clearly overabundant in all the PN, indicating that it has been formed in the course of evolution. There is some uncertainty in the He I abundance in NGC 6445 because of the difference of the measurement of the λ4471 line between Van Hoof et al. (2000) and Perinotto et al. (1994). The nitrogen abundance of all the PN is high; considerably higher than for the Orion nebula. However the N/O ratio is very high (greater than unity) for only the first three PN; it is considerably lower for NGC 6445. In this latter nebula is the N/O ratio only slightly larger than for the Orion nebula and slightly lower than in NGC 7027 (Bernard Salas et al. 2000). Furthermore the oxygen abundance in NGC 6445 is about a factor 3 higher than in the other PN; it is about equal to the solar abundance.

It is generally accepted that the nitrogen is formed by conversion from oxygen, later brought to the surface by dredge-up. The same may happen to carbon. The sum of the abundance of the three elements does not change however. This sum is shown

Table 17. Comparison PN abundances with other objects

Element	NGC 6537	He2-111	NGC 6302	NGC 6445	Sun[1]	B Star[2]	ISM	
							ζ Oph[3]	Orion[4,5]
He	0.149	0.185	0.17	0.14:	0.10			0.098
C(−4)	1.75	1.1	0.60	6.0	3.55	1.75	1.4	2.5
N(−4)	4.5	3.0	2.9	2.4	0.93	0.65	0.79	0.63
O(−4)	1.85	2.7	2.3	7.4	7.4	4.2	3.0	3.2
Ne(−4)	1.7	1.6	2.2	2.0	1.2	1.2		0.79
Na(−6)	2.6		2.6		2.0		0.23	
Mg(−5)	0.96	0.8:	1.3	1.7:	3.8	2.4	0.11	
S(−5)	1.1	1.5	0.78	0.79	1.86	1.2	2.8	1.4
Cl(−7)	2.4	3.5	3.4		1.9	1.9	1.2	2.2
Ar(−6)	4.1	5.5	6.0	3.8	3.6		1.2	5.0
(C+N+O)/H	8.1	6.8	5.8	15.8	11.9	6.6	5.2	6.3
N/O	2.4	1.1	1.3	0.32	0.13	0.15	0.26	0.20

[1] Solar abundance from Grevesse & Noels (1993).
[2] B star abundance are the average of Gies & Lambert(1992) and Killian-Montenbruck et al. (1994).
[3] ζ Oph abundance from Savage & Semback (1996).
[4] Rubin et al. (1993);[5] Osterbrock et al. (1992).

in Table 17 for the objects considered. It can be seen that for the first three PN that this sum is quite similar to that found in Orion and in B stars. This is not true for NGC 6445 which has a much higher value of (C+N+O)/H than the other objects, higher even than the solar value.

The following conclusions can be drawn:

1. NGC 6537, He2-111 and NGC 6302 all had originally the same abundance as the Orion nebula.
2. NGC 6445 originated with similar abundance of sulfur and argon, but had higher abundance of oxygen and carbon.
3. NGC 6445 had originally an abundance of carbon and oxygen similar to the sun or possibly higher.
4. NGC 7027 originally had abundance similar to the sun, but higher than the Orion nebula or B stars.
5. The nitrogen abundance, both with respect to hydrogen as with respect to oxygen, is higher in the PN than in the sun, B stars or the Orion nebula. Nitrogen has been formed in the course of evolution in all the PN under discussion.
6. Considerably more nitrogen has been formed in NGC 6537, NGC 6302 and He2-111 than in NGC 6445 or NGC 7027. The N/O ratio is a factor of 3-4 higher in the former nebulae.
7. The helium abundance in the former three nebulae is clearly higher than in the Orion nebula, the sun and in NGC 7027. The situation is not clear with respect to NGC 6445.
8. If, following the theoretical models of Marigo et al. (1996), the overabundance of nitrogen (and to a lesser extent of helium) indicate that the original mass of the central star of NGC 7027 was 3-4 $M_\odot$, the original mass of the central stars of NGC 6537, NGC 6302 and He2-111 must have been considerably higher. That of the central star of NGC 6445 appears to have been closer to that of NGC 7027.
9. While 3 of the 4 bipolar nebulae whose abundance has been determined with the help of ISO spectra show extreme nitrogen enrichment, it is apparently not always true that bipolar structure can be equated with nitrogen enrichment.

References

Acker A., Ochsenbein F., Stenholm B., et al., 1992, Strasbourg ESO catalogue of PN
Aller L.H., Hyung S., Feibelman W., 1999, Proc. Nat. Ac. Sci. 96, 5366
Ashley M.C.B., 1989, Thesis, Australian Nat. Univ.
Ashley M.C.B., Hyland A.R., 1988, ApJ 331, 532
Beck S.C., Lacy J.H., Townes C.H., et al., 1981, ApJ 249, 592
Beintema D.A., Pottasch S.R., 1999, A&A 347, 942
Bernard Salas J., Pottasch S.R., Beintema D.A., Wesselius P.R., 2000, A&A submitted
Calabretta M.R., 1982, MNRAS 199, 141
Collins G.W., Daub C.T., O'Dell C.R., 1961, ApJ 133, 471
Condon J.J., Kaplan D.L., 1998, ApJS 117, 361
Corradi R.L.M., Schwarz H., 1993, A&A 269, 452
Corradi R.L.M., Schwarz H., 1995, A&A 293, 871
Costa R.D.D., de Freitas Pacheco J.A., De Franca J.A. Jr., 1996, A&A 313, 924
Fluks M.A., Plez B., de Winter D., et al., 1994 A&AS 105, 311
Gies D.R., Lambert D.L., 1992, ApJ 387, 673
Gorny S.K., Schwarz H.E., Corradi R.L.M., Van Winckel H., 1999, A&AS 136, 145
Grevesse N., Noels A., 1993, In: Prantos N., Vangioni-Flam E., Casse M. (eds.) Origin of the Elements. Camb. Univ. Press, p. 15
Kaler J.B., 1983, ApJ 264, 594
Killian-Montenbruck J., Gehren T., Nissen P.E., 1994, ApJ 291, 757
Kingsburgh R.L., Barlow M.J., 1994, MNRAS 271, 256
Marigo P., Bressan A., Chiosi C., 1996, A&A 347, 975
Milne D.K., Aller L.H., 1975, A&A 38, 183
Milne D.K., Aller L.H., 1982, A&AS 50, 209
Milne D.K., Webster B.L., 1979, A&AS 36, 169
Osterbrock D.E., Tran H.D., Veilleux S., 1992, ApJ 389, 196
Perinotto M., Corradi R.L.M., 1998, A&A 332, 721
Perinotto M., Purgathofer A., Pasquali A., Patriarchi P., 1994, A&AS 107, 481

Phillips J.P., Mampaso L., 1988, A&A 190, 237
Pottasch S.R., Beintema D.A., 1999, A&A 347, 974
Pottasch S.R., Preite-Martinez A., Olnon F.M., et al., 1986, A&A 161, 363
Rowlands N., Houck J.R., Herter T., 1994, ApJ 427, 867
Rubin R.H., Dufour R.J., Walter D.K., 1993, ApJ 413, 237
Savage B.D., Semback K., 1996, A&AR 34, 279
Shaw R.A., Kaler J.B., 1985, ApJ 295, 537
Shaw R.A., Kaler J.B., 1989, ApJS 69, 495
Van Hoof P.A.M., Van de Steene G.C., Beintema D.A., et al., 2000, ApJ 532, 384
Webster B.L., 1978, MNRAS 185, 45p
Webster L., 1983, PASP 95, 610
Weinberger R., 1989, A&AS 78, 310