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Planetary nebulae abundances and stellar evolution[*]

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ABSTRACT

A summary is given of planetary nebulae abundances from ISO measurements. It is shown that these nebulae show abundance gradients (with galactocentric distance), which in the case of neon, argon, sulfur and oxygen (with four exceptions) are the same as HII regions and early type star abundance gradients. The abundance of these elements predicted from these gradients at the distance of the Sun from the center are exactly the solar abundance. Sulfur is the exception to this; the reason for this is discussed. The higher solar neon abundance is confirmed; this is discussed in terms of the results of helioseismology. Evidence is presented for oxygen destruction via ON cycling having occurred in the progenitors of four planetary nebulae with bilobal structure. These progenitor stars had a high mass, probably greater than 5 $M_\odot$. This is deduced from the high values of He/H and N/H found in these nebulae. Formation of nitrogen, helium and carbon are discussed. The high mass progenitors which showed oxygen destruction are shown to have probably destroyed carbon as well. This is probably the result of hot bottom burning.

Key words. ISM: abundances – planetary nebulae: general – evolution – HII regions – Sun: abundances – stars: abundances

1. Introduction

Planetary nebulae (hereafter PNe) are an advanced stage of stellar evolution of low and intermediate mass stars. Their abundances have been changed by various processes which have occurred in these objects since their formation. Not all elements have been affected in the same way or to the same extent; some elements have not been affected in the course of evolution. Our present purpose is to determine which elements have been processed in the course of evolution, and which are the affected nebulae. This is done using the abundances determined with the help of the Infrared Space Observatory observations (ISO, Kessler et al. 1996). In particular the result of the Short and Long Wavelength Spectrometers have been used (hereafter SWS and LWS respectively).

In order to determine which abundances have changed in the course of evolution it is necessary to find the initial abundances before evolution began. These values are taken from three sources: HII regions, young (B and O type) stars, and the Sun. For the first two groups it is known that they show a gradient in abundance as a function of their distance from the Galactic Center (see for example Shaver et al. 1983; and Rolleston et al. 2000). Thus in comparing planetary nebulae abundances with that in HII regions and young stars this gradient must be taken into account. This is done by plotting the abundances as function of the distance from the galactic center and then comparing these plots.

Two potential problems arise. Firstly, the distance to individual objects from the Sun is often uncertain. This is especially a problem for PNe whose distances are sometimes uncertain by more than 50%. But because the distance to the Galactic Center depends in an important way on the direction of the nebula from us, the distance to the Galactic Center is actually considerably less uncertain than the distance to the Sun.

The second problem is the following. It is assumed that the galactic abundance gradient arises because the material out of which the object is formed has a different (initial) abundance at different distances from the galactic center. The abundance in the objects measured reflects the initial abundance at the position in which they are measured. This is easy to defend in the case of HII regions and O and B stars because it is unlikely that these young objects have moved far (radially) from the position in which they have been formed. This is not obvious for planetary nebulae since they are older objects; they may have orbited the galaxy one or several times since they were formed. Only if they are on nearly circular orbits will their present position reflect the position of formation. We will assume that this is true for the nebulae to be considered, as is usually done (e.g. Maciel & Costa 2003). We demonstrate in this paper that this leads to consistent results.

The subject of nebular abundances has been discussed often in the past 25 years, especially from the theoretical point of view. A recent summary has been given by Lattanzio (2003) at the 2001 IAU PNe Symposium. In ending this summary Lattanzio remarks the following: "what is really needed is a complete test of the model predictions against observations, which has so far been rather limited...". This limitation lies in a general feeling that the theory qualitatively explains the observations, while quantitatively little has been done. The reason for this is, on the one hand, the uncertainty of the theoretical results, and on the other hand the inaccuracy of the observational abundances.

That the abundances derived from observations are often not very accurate can be seen by a comparison of abundances derived for well studied nebulae. Abundances derived by different authors for the same nebula often show disagreements of a factor of 2; sometimes considerably larger differences are found. These differences are usually not due to differences in the observations used, and they occur in spite of the fact that often the different authors used the same or similar observations. The differences occur for two reasons. The first is that the electron temperature (T_e) is usually assumed to be constant in the nebula. This assumption is made because using the optical spectrum only two ions have a sufficient number of lines to determine T_e: these are [O III] and [N II]. These two ions usually give somewhat different temperatures. The reason that one still chooses to use a single temperature is probably that one is not certain enough of the reality of this difference. Only after the ISO infrared spectra became available could these temperature variations be verified, because enough lines are now measured in many nebulae so that electron temperatures from five to ten ions may be obtained for a given nebula. In addition, these temperatures are correlated with the ionization potential required to reach the observed ionization stage. Thus a temperature gradient is often found; the higher temperature regions occuring for the ions with the higher ionization potentials; these probably lie closer to the center of the nebula. From this it is now possible to measure (or predict) more accurately the electron temperature to be assigned to each measured ion. This in turn leads to an important improvement in the abundance of the ion considered. Actually when the infrared lines are used, the derived abundances are relatively insensitive to the electron temperature since the lines are formed from very low lying energy levels.

There is a second reason why the inclusion of the infrared observations leads to increased accuracy. This is because many more ions are now measured, and therefore there are many less unobserved stages of ionization. This improvement in abundance accuracy is especially important for neon, argon, nitrogen and sulfur.

One of the difficulties which are encountered in the analysis of the SWS data (see de Graauw et al. 1996) occurs when the nebula is larger than the aperature of the instrument and a correction must be made. This is usually done by relating the hydrogen and helium lines in the SWS spectrum to lines of the same elements in other spectral regions. The theoretical line ratios then relate the lines in the various spectral regions. The errors introduced in this correction are rather limited. The LWS ISO observations (see Clegg et al. 1996) are made with a larger diaphragm so that no diaphragm correction is necessary. A more important difficulty involve the density dependence of a few of the infrared lines with very low transition probabilities. In practice this involves the [N II] line at 121 μm, the [O III] lines at 51 and 88 μm and to a lesser extent the [N III] line at 57 μm and the [S III] line at 33 μm. Errors can occur in low density nebulae if the density is not well determined or if large density gradients are present. For three of these ions other lines are available to check this effect.

In this paper the abundances of 26 nebulae are considered. They are listed in the Appendix, together with the references from which they were taken. Their abundances have all been determined including ISO SWS and LWS spectra and we believe are the most accurate available. They were all determined in a similar manner, and all contain information about electron temperature gradients in the nebulae. These nebulae have been selected primarily because they are strong infrared emitters. They are therefore mostly nearby PNe. They are not very much larger than the ISO diaphragm of about 20″. Because the constraints are mostly observational, this can be seen in a first approximation as a random selection of nearby nebulae. For 23 of these nebulae ultraviolet observations (IUE) are also available, without which carbon abundances cannot be determined.

This is the second time that abundance results including ISO data have been used in discussing element evolution in planetary nebulae. It was done several years ago by Marigo et al. (2003) who used the results of 10 PNe. In that discussion new evolution models were made in discussing the results. We now have results from many more ISO PNe. In addition we approach the problem of the initial abundances of the stars which form PN in a different way. On the other hand we do not include any self-made evolutionary models.

This paper is structured as follows. First the references are given for the comparison objects (HII regions, early type stars and the Sun). These are presented in Sect. 2. In the next four sections oxygen, neon, sulfur and argon are discussed. These are the elements for which evolutionary abundance changes are relatively small. In Sect. 7 nitrogen and helium are discussed and in Sect. 8 carbon is discussed. In each of the individual sections a comparison is made with the abundances found in the theoretical evolutionary models made earlier by Marigo et al. (2003), and especially by Karakas (2003), which were chosen because of the large amount of detail available in these calculations. Section 9 gives a summary and conclusions.

2. Comparison abundances

As discussed above, abundances from the Sun, HII regions and early type stars will be used for comparison. In this section the references to the sources of the data are given. The actual comparisons will be made when discussing the individual elements. In this work it has been assumed that the galactocentric distance of the Sun is 8 kpc. Where necessary the distances given by individual authors have been made compatible with this distance.

2.1. Solar abundances

The solar photospheric abundances are taken from the recent compilation by Asplund et al. (2005) and are shown in Table 1. All elements listed are taken from this source except for neon and argon which have no lines in the solar photosphere. The abundance of these two elements is taken from the measurement of coronal lines by Feldman & Widing (2003). Because the coronal lines of neon, argon and magnesium have about the same ionization potential and strength, the Ne/Mg(=3.6) and Ar/Mg(=0.15) ratio's are taken from this source. The photospheric value of magnesium (taken from Apslund et al. 2005) is then used to find the values of neon and argon given in Table 1. Because the solar value of neon is controvertial this will be further discussed in the section about neon. It should further be noted that the present solar abundances are somewhat different than were found a decade ago. Especially oxygen, nitrogen and carbon are now almost a factor of two lower.

2.2. HII region abundances

Three sources have been used for the abundances of HII regions. The first is the work of Martín-Hernández et al. (2002) who have analysed far infrared (ISO) measurements of 34 compact HII regions at galactocentric distances between 0 and 15 kpc. They have measured abundances of neon, sulfur, argon and nitrogen.

Table 1. Solar abundances. Numbers in brackets indicate: $A(-b) = A \times 10^{-b}$.
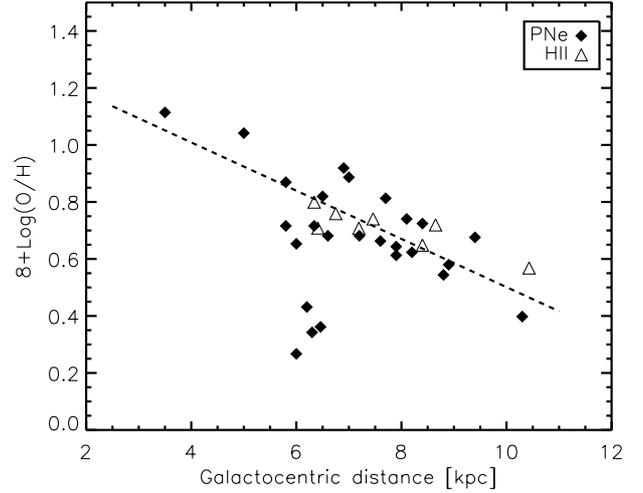
Element	Solar abundance
He	0.085
C	2.5(–4)
N	0.60(–4)
O	4.6(–4)
Ne	1.2(–4)
Mg	3.4(–5)
S	1.4(–5)
Cl	3.2(–7)
Ar	4.2(–6)

Fig. 1. Oxygen abundance versus the galactocentric distance. The dashed line is a fit to the PNe points (see Sect. 3). This line reproduces the solar oxygen abundance at $R = 8$ kpc.

Even though some of the HII regions have appreciable extinction in the visible, this problem is greatly reduced in the mid-and far-infrared. For Ne, S and Ar lines representing all important stages of ionization are found, so that no correction for unseen ionization stages need to be made. To obtain abundances relative to hydrogen, the hydrogen Brackett alpha line was used. This has the advantage over Hβ both because the extinction correction is much smaller and the diaphragm size is well defined. Nitrogen is more difficult because the aperture size used to measure the infrared nitrogen lines is not the same as the hydrogen Brackett alpha line used for comparison, as it was for neon, sulfur and argon. In the case of nitrogen, radio continuum measurements with a similar diaphragm size were used to obtain the abundance relative to hydrogen. In addition only doubly ionized nitrogen is measured by ISO so that singly ionized nitrogen must be found from optical measurements. This increases the uncertainty of the nitrogen abundances. We have made use of their results for HII regions with galactocentric distances from 3 to 11 pc, which is the range for which PNe abundances are available.

The other sources of HII abundances are the work of Esteban et al. (2005) and Carigi et al. (2005). Esteban et al. (2005) have measured the oxygen and carbon abundances for 8 HII regions between a galactocentric distance of 6 and 11 kpc. They have used optical spectra and have corrected for extinction using the Balmer decrement. Oxygen abundances have been determined using both collisional and recombination lines. Carbon abundances are only from the recombination line at $\lambda4267$ Å and an ionization correction factor (ICF) to correct for the presence of singly ionized carbon. Carigi et al. (2005) have measured nitrogen abundances, but these authors consider them to be less robust than the carbon and oxygen. This is because only singly ionized nitrogen is measured and a correction must be made for the more abundant doubly ionized nitrogen.

2.3. Stellar abundances

Abundances of main-sequence B-type stars in open clusters have been calculated by Rolleston et al. (2000). They have measured these abundances in clusters with galactocentric distances between 5.5 and 17 kpc (reducing the galactocentric distance of the Sun to 8 kpc). We consider only the results below 11 kpc. The abundances of the elements oxygen, nitrogen, carbon, magnesium, aluminum and silicon have been derived, but we use only the first three elements for comparison.

3. Abundance of oxygen

A plot of the PNe abundances is given in Fig. 1. The planetary nebulae are shown as solid squares in the figure and the HII regions as open triangles. The dashed line is a linear fit to the PNe data (except for the 4 PNe with low O/H at 6 kpc), reproducing the PN points as well as possible. Interestingly this line also goes through the solar abundance at $R = 8$ kpc, 4.7×10^{-4}, indicating that the solar oxygen abundance is the same as what is expected from PNe at this galactocentric distance. The best fit to the data points has a slope of -0.085 dex/kpc.

The dashed line reproduces most of the PN abundances quite well, considering that there could be a 30% uncertainty in the abundance determination and an additional uncertainty in the galactocentric distance. In addition the agreement with the HII abundances is very good. The agreement with the B-star abundances is also good, although on the average they seem to have a 30% higher oxygen abundance. The B-star abundances are not shown in Fig. 1 because it makes the figure less clear. The abundances of four PN are clearly lower than the rest by a factor of between 2 and 3. It is suggested that the oxygen in these nebulae has been depleted in the course of their evolution. The evidence for this is the following.

First of all it is unlikely that an error of this magnitude in the abundance determination could be made. The nebulae involved (NGC 6302, NGC 6537, Mz 3 and He2-111) are bright and rather easy to measure. Secondly, these nebulae have much in common. Morphologically the first three have a classic bilobal structure; He2-111 looks older and is irregular in shape. Another common property is the high helium content of these nebulae, which have higher values than any of the other nebulae whose helium has been measured. Three of the four PNe are very high excitation objects so that although O^{+3} was always measured (and always found to be at least a factor of two less than O^{+2}), the correction for higher ionization stages is always necessary. This was done by comparing the distribution of the ionization stages of neon, for which every ion from Ne^+ to Ne^{+5} has been measured. In addition a photo-ionization model of NGC 6537 was made (Surendiranath, private communication) which reproduces the distribution of the neon ions quite well and confirms the lower oxygen abundance.
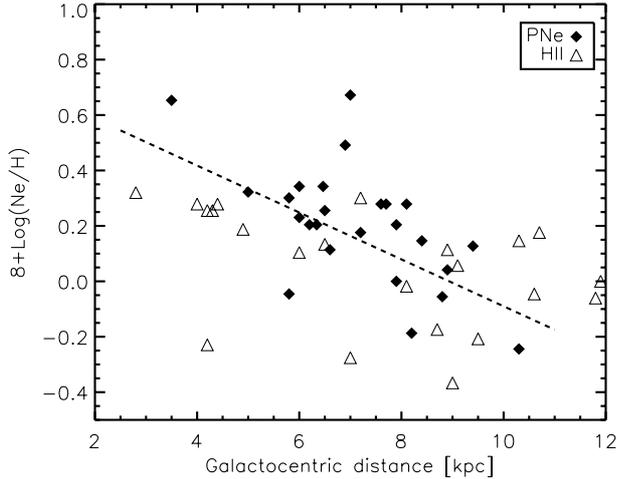
Fig. 2. Neon abundance as a function of the galactocentric distance. The dashed line is not related to the points on the diagram, but is a line of the same slope as the line in Fig. 1 that passes through the solar neon abundance at $R = 8$ kpc.

Thus it seems likely that for these four nebulae about half the oxygen has been destroyed via ON cycling in the course of the evolution of the central stars of these four nebulae. Marigo et al. (2003) have already noticed the lower oxygen abundance of several of these nebulae but because these authors found it difficult to make a model which burned sufficient oxygen and did not produce too much nitrogen, they suggested that these stars may be descendents of stars with lower (sub-solar) abundances. The models made by Karakas (2003) also show some oxygen destruction in higher mass stars. In her models with masses greater than 5 $M_\odot$ and with $Z = 0.008$ and $Z = 0.004$ Karakas also finds that too much nitrogen is produced. But in her $Z = 0.02$ models (solar metallicity) with 6 $M_\odot$ and 6.5 $M_\odot$ a lower N/O ratio is found (1.2), agreeing with observations. Because of this agreement we tentatively conclude that oxygen destruction via hot bottom burning has taken place in these four stars and that they have masses of the order of 6 $M_\odot$.

4. Neon abundance

A plot of the neon abundances is given in Fig. 2, The dashed line in the figure has a different meaning than the dashed line in Fig. 1. In this case it is not directly related to the points in the figure. The dashed line is a line with the same slope as in Fig. 1 and which has (as fixed point) the solar abundance at the galactocentric distance $R = 8$ kpc. The fact that the points cluster about the line means that planetary nebulae have the same neon abundance as the Sun. That appears true of the HII regions as well. Because of the controversy about the solar neon abundance (e.g. Bahcall et al. 2005) we stress the point that had the solar neon abundance of Asplund et al. (2005) been used, the dashed line would lie quite far from the observed points.

The scatter of the individual points is somewhat larger for neon than for oxygen, both for the PNe and for the HII regions. There is no strong evidence, however, that neon was either created or depleted in the course of central star evolution, to within 50%, as there was for oxygen. The high point at $R = 6.9$ kpc is from NGC 6153, which shows high abundances for other elements as well, and is probably not an indication of neon formation in the object. There are sometimes suggestions in the literature that neon has been created in certain PNe. We have ourselves suggested that in the case of NGC 6302 neon has
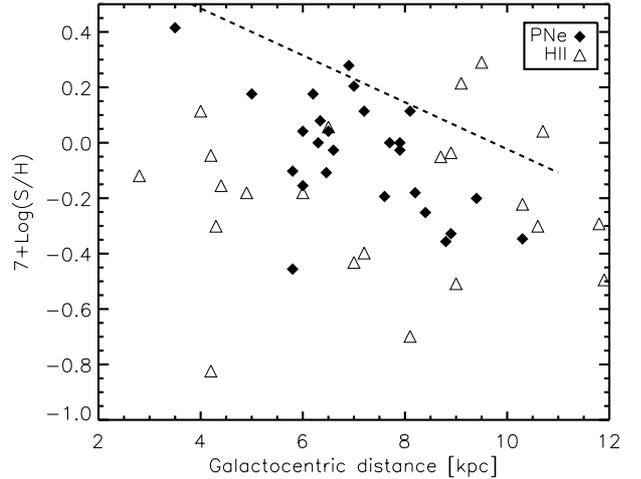

Fig. 3. Sulfur abundance as a function of galactocentric distance. The dashed line has the same slope as the line in Fig. 1 while it passes through the solar abundance at $R = 8$ kpc. Thus unlike oxygen and neon for which the PN and HII abundances agree with that of the Sun, it appears that the solar sulfur abundance is almost twice as high as in PN and HII regions.

been created (Pottasch & Beintema 1999). We were probably misled by the rather high neon to oxygen ratio, which is caused by the depletion of oxygen as discussed above. In their sample Marigo et al. (2003) find that the neon abundances are comparable (or slightly larger) to the solar value. To reproduce the neon abundance of three of their PNe (those with the largest helium and lower oxygen abundances) under the assumption that they evolved from sub-solar metallicity (LMC) they require a significant production of neon. Karakas & Lattanzio (2003) have suggested that some PNe may experience moderate neon enrichment. The latter authors show that there is only a small mass range, near 3 $M_\odot$, where neon is produced in sufficient quantities to affect the neon abundance by more than 20%. This happens for values of Z less than 0.008. Since the evidence for enrichment greater than 50% is lacking (as presented in Fig. 2) it is possible that none of the PNe we have observed fall within this narrow mass range or the neon enrichment has remained modest.

5. Sulfur abundance

Figure 3 is a plot of the sulfur abundances. Since the squares and the triangles more or less coincide, it may be concluded that the sulfur abundance in HII regions is the same as in the planetary nebulae. The dashed line again is a line with the same slope as in Fig. 1 and which has the solar sulfur abundance at $R = 8$ kpc. The fact that the points lie generally below the line indicates either that the PNe (and the HII regions) have an abundance lower than solar or that the solar abundance is actually higher than given by Asplund et al. (2005) and shown in Table 1. The difference is slightly less than a factor of 2 and has already been noticed before by several persons and is discussed in detail by Henry et al. (2004) for PNe and by Martín-Hernández et al. (2002) for HII regions. Henry et al. (2004) suggested that the lower sulfur abundance might be due to the incorrect ICF because they had very few observations of the infrared [SIV] line. We can eliminate this possibility because this line is always observed in the ISO spectra.

Since the PNe and solar abundances agree so well for the other elements which are not produced in the course of evolution, it is likely that the sulfur abundances are actually equal.
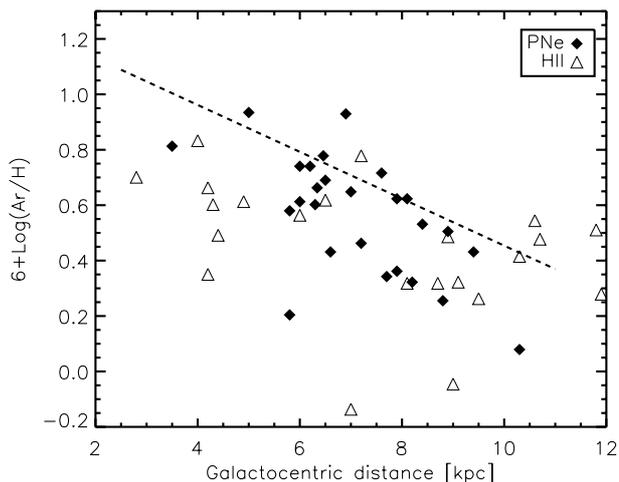
Fig. 4. Argon abundance as function of the galactocentric distance.

Fig. 5. Nitrogen to hydrogen ratio is shown as a function of galactocentric distance.

Fig. 6. Nitrogen abundance plotted against the helium abundance for the ISO sample of planetary nebulae.

One possibility is that the solar sulfur abundance has been overestimated by a factor of 2. While we consider this the most likely possibility, other possibilities exist. It is possible that the sulfur is depleted into dust, for example. This has been suggested by Henry et al. (2004) but they discard it because sulfur is not refractory. However sulfur-based dust features (e.g. MgS and FeS) have been seen and it would be interesting how much sulfur is contained in such features. Another possibility is that the atomic parameters used in the PNe and HII analyses are incorrect. This is more unlikely because transitions in both the [SIII] and [SIV] lines would have to be incorrect.

6. Argon abundance

The argon abundance is shown in Fig. 4. As can be seen from the figure, there is good agreement between the PN and HII regions, although there are several HII regions and one PN (Me 2-1) which are somewhat lower than the rest.

The dashed line is as before that line which has the same slope as that in Fig. 1 and passes through the solar argon abundance at $R = 8$ kpc. As can be seen the points would be better fit if the line were slightly (between 30% and 40%) lower, indicating that a somewhat lower solar abundance would have been preferable. Considering the present uncertainty in the solar abundance (Asplund et al. 2005) there is agreement in argon abundance in all three types of objects.

7. Nitrogen and helium abundances

The nitrogen abundance is shown in Fig. 5. The dashed line in the figure is, as before, not related to the points, but is the line with the same slope as that shown in Fig. 1 that passes through the solar nitrogen abundance at the galactocentric distance $R = 8$ kpc. The HII regions clearly adhere closely to the line, as do the early type stars (with slightly more scatter). The nitrogen abundance in planetary nebulae shows a large scatter, mostly above the line. Only 5 PNe clearly fit to the line. These are Me2-1 (the only PN under the line), NGC 7662. IC 418, NGC 6818 and BD+30 3639. This is interpreted to mean that these five PNe have formed little nitrogen in the course of their evolution. These nebulae have the common property that their helium abundance, when known, is low i.e. about equal to solar. Four additional PNe have a slightly higher nitrogen abundance: NGC 40, NGC 2022, IC 2165 and IC 4191. Of these nebulae
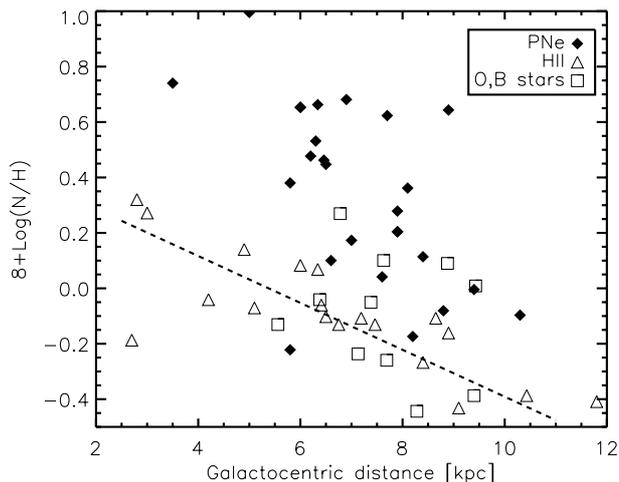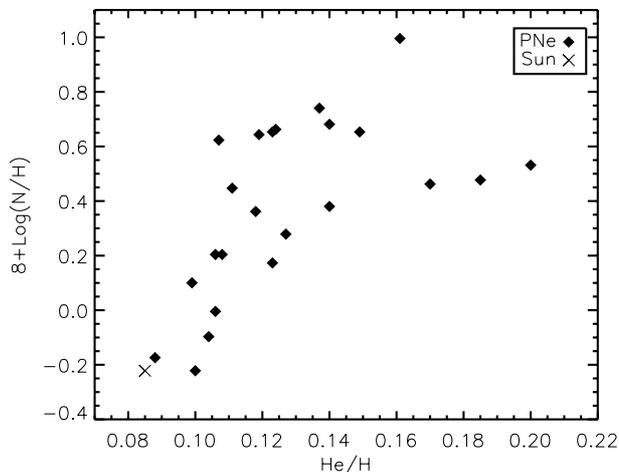
only IC 4191 has a somewhat higher helium abundance. Almost all the PNe with higher nitrogen abundance show a higher helium abundance as well. This is shown in Fig. 6, which is a plot of the nitrogen abundance against the helium abundance of the sample of ISO PNe. Some of the scatter in this diagram is because the effect of the position in the galaxy is not taken into account. However the well known relation between nitrogen and helium is clearly shown. Of the five PNe with the highest helium abundance, four are the nebulae which have shown evidence for oxygen destruction in the course of evolution, as discussed in Sect. 3.

The most likely explanation of this relation is the occurance of hot bottom burning (HBB) in higher mass stars. The models of Karakas (2003) produce helium for high mass stars but do not find a higher value than He/H = 0.16, while at least two of our nebulae have a higher value. Marigo et al. (2003) found it difficult to produce the higher helium values without at the same time producing more nitrogen than was observed. They therefore chose to start with lower initial metallicity. The $Z = 0.004$ and $Z = 0.008$ high mass models of Karakas (2003) have this problem as well, but the $Z = 0.02$ models do not overproduce nitrogen for higher helium values. For both her 6 $M_\odot$ and 6.5 $M_\odot$ models the N/O ratio is about 1.2, which is similar to the observed value. The answer may lie in this direction.
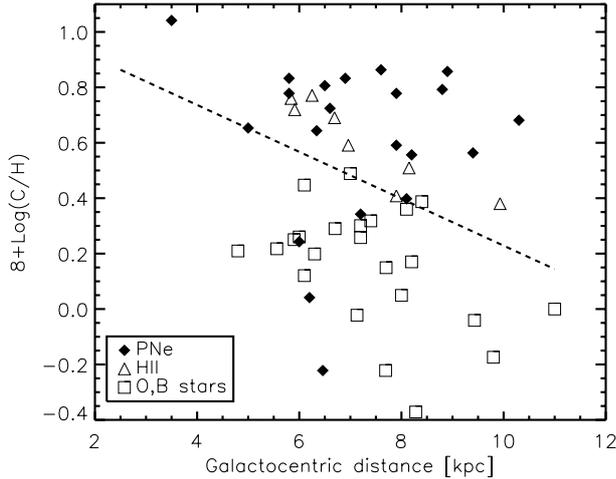
Fig. 7. The carbon abundance is shown as a function of galactocentric distance. The line has the same slope as in Fig. 1 and passes through the solar carbon abundance at $R = 8$ kpc.

Fig. 8. The carbon abundance is shown as a function of the helium abundance.

8. Carbon abundance

The carbon abundance as a function of galactocentric distance is shown in Fig. 7. The line has the same slope as the oxygen abundance and passes through the solar carbon abundance at $R = 8$ kpc. As can be seen from the figure, the line passes quite close to the carbon abundances of the HII regions, as it also has done for the other elements. Again note that the HII carbon abundance is from the recombination line. The carbon abundances of the early type stars given by Rolleston et al. (2000) are about a factor of two less than the HII regions. Carbon is the only element for which there appears to be a difference between the two classes. There is some evidence that this is caused by a systematic error in the determination of the carbon abundances by Rolleston et al. (2000). Recently Nieva & Przybilla (2006) have also determined carbon abundances in six nearby early type stars and have consistently found a higher carbon abundance. The difference is exactly a factor of two, giving the nearby early type stars exactly the solar abundance.

It will be assumed that the stellar carbon abundances agree with the line in Fig. 7. It can be seen that the planetary nebulae carbon abundances have quite a large scatter about this line. While about 40% have carbon abundances agreeing with those of HII regions, about an equal number have higher abundances, indicating that carbon has been formed in at least 10 PNe in the course of their evolution, presumably the effects of the third dredge-up. This is what is expected of stars of mass greater than about 2.5 $M_\odot$ in the $Z = 0.02$ models computed by Karakas (2003), and a slightly lower mass for the lower Z models. Marigo et al. (2003) predict that this will happen for masses of 1.5 $M_\odot$.

Three PNe show extremely low carbon abundances. These are the same nebulae which have low oxygen abundances as well as high helium abundances (there are four PNe which have these last two properties, but no measurements of carbon lines are available in the fourth nebula, Mz 3). Thus it appears that carbon, as well as oxygen is destroyed in these stars. While the higher mass models of Karakas show initial carbon destruction due to hot bottom burning this is followed by a few final pulses which are rich in carbon so that the net result does not produce a decrease in carbon. The high mass models of Marigo et al. (2003) do show some carbon burning, but these models are not the result of full evolutionary calculations. This should be resolved by
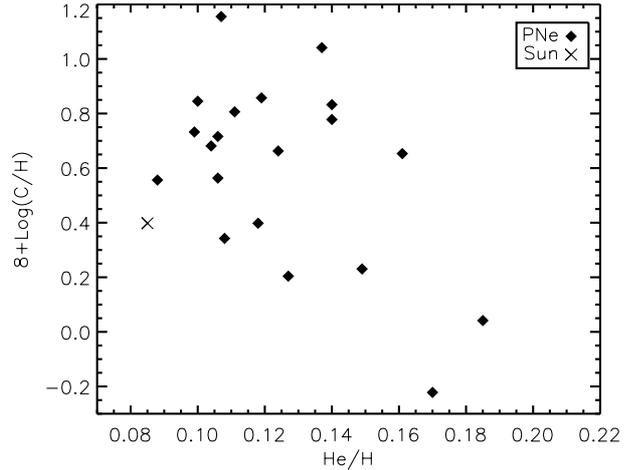
carefully reconsidering the models as well as reconsidering the obervations.

It is interesting to ask whether there is a relation between carbon abundance and helium abundance as there is between nitrogen and helium. The results are shown in Fig. 8. The scatter in this figure is larger than the scatter shown in Fig. 6 (nitrogen vs. helium). A reason for this could be that the carbon abundances are somewhat more uncertain since the carbon lines are in the ultraviolet part of the spectrum where the extinction plays more of a role. The correction for unseen ionization stages may also be more uncertain, as often only a single ionization stage is observed. Still a clear relation is seen, although it should be remarked that this relation depends strongly on the three high helium nebulae.

9. Discussion and conclusions

1) For neon, sulfur, argon and most of the oxygen abundances, the galactocentric PNe and HII values of composition are essentially identical. This is remarkable because the HII regions are young objects while PN are older objects. The conclusion is drawn that the galactocentric position of the PNe does not significantly change with time, at least for the nebulae which have been measured. This must mean that their galactic orbits are roughly circular. In addition all galactocentric gradients are consistent with a single value: −0.085 dex/kpc assuming that the Sun is at 8 kpc from the Galactic Center.

2) The solar abundances of the above elements are the same as both the PNe and HII regions at 8 kpc from the center. This is shown quite strikingly for oxygen in Fig. 1. Sulfur is an exception, being almost a factor of two higher. Because it is difficult to find a reason for this difference, the question arises as to the correctness of either the solar sulfur abundance on the one hand or the HII and PNe abundance on the other.

3) The solar abundance of neon is the same in the PNe and HII regions, using the determination of the solar neon abundance given in Table 1. This determination is very similar to that of Feldman & Widing (2003), but differs from the solar neon abundance given by Asplund et al. (2005). This has significance for the controversy concerning the consistency of solar models with helioseismological measurements (see discussions given by Antia & Basu 2005; and Bahcall et al. 2005).

Table A.1. Elemental abundance of PNe with ISO data in addition to optical and UV data.

PNe	He/H	C/H ×10⁻⁴	N/H ×10⁻⁴	O/H ×10⁻⁴	Ne/H ×10⁻⁴	S/H ×10⁻⁵	Ar/H ×10⁻⁶	Distance (kpc)	$R^\natural$ (kpc)	Ref., Comment
BD+30 3639		7.3	1.1	4.6	1.9	0.64	5.2	1.0	7.6	a
Hb 5	0.130		11.5	6.6	1.8	1.2	6.3	3.2	4.8	b
He 2-111	0.185	1.1	3.0	2.7	1.6	1.5	5.5	2.5	6.2	c
Hu 1-2	0.127	1.6	1.9	1.6	0.49	0.42	1.1	1.5	7.9	d
IC 418	>0.072	6.2	0.95	3.5	0.88	0.44	1.8	1.0	8.8	e
IC 2165	0.104	4.8	0.73	2.5	0.57	0.45	1.2	3.0	9.8	e, *
IC 4191	0.123		1.49	7.7	4.7	1.6	4.45	1.8	7.0	p
M 1-42	0.161	4.5	10.0	11.0	2.1	1.5	8.6	3.0	5.0	h
M 2-36	0.137	11.0	5.5	13.0	4.5	2.6	6.5	4.5	3.5	h
Me 2-1	0.1	7.0	0.51	5.3	0.93	0.91	1.6	2.3	5.8	r
Mz 3	>0.080	<16	3.0	2.3	1.2	1.0	5.0	2.0	6.3	q
NGC 40	>0.046	19	1.3	5.3	1.4	0.56	3.4	0.8	7.9	f
NGC 2022	0.106	3.7	9.9	4.7	1.3	0.63	2.7	1.5	9.4	p
NGC 2440	0.119	7.2	4.4	3.8	1.1	0.47	3.2	1.6	8.9	g
NGC 5315	0.124	4.4	4.6	5.2	1.6	1.2	4.6	2.6	6.3	i
NGC 5882	0.108	2.2	1.6	4.8	1.5	1.3	2.9	1.0	7.2	e, *
NGC 6153	0.140	6.8	4.8	8.3	3.1	1.9	8.5	1.2	6.9	f
NGC 6302	0.170	0.6	2.9	2.3	2.2	0.78	6.0	1.6	6.4	j
NGC 6445	0.14:	6.0	2.9	2.3	2.2	0.78	6.0	2.25	5.8	k
NGC 6537	0.149	1.7	4.5	1.8	1.7	1.1	4.1	2.0	6.0	c
NGC 6543	0.118	2.5	2.3	5.5	1.9	1.3	4.2	1.0	8.1	a
NGC 6741	0.110	6.4	2.8	6.6	1.8	1.1	4.9	1.65	6.5	l
NGC 6818	0.099	5.4	1.26	4.8	1.27	0.94	2.7	1.5	6.6	p
NGC 6886	0.107	14.3	4.2	6.5	2.0	1.0	2.1	2.0	7.7	o
NGC 7027	0.106	5.2	1.5	4.1	1.0	0.94	2.3	0.65	7.4	m
NGC 7662	0.088	3.6	0.67	4.2	0.64	0.66	2.1	0.96	8.2	l

$\natural$Galactocentric distance assuming the Sun is at 8 kpc from the center.
*Higher resolution observations.
References: a) Bernard-Salas et al. (2003, A&A 406, 165); b) Pottasch et al. (2006); c) Pottasch et al. (2000, A&A, 363, 767); d) Pottasch et al. (2003, A&A, 401, 205); e) Pottasch et al. (2004, A&A, 423, 593); f) Pottasch et al. (2003, A&A, 409, 599); g) Bernard-Salas et al. (2002, A&A, 387, 301); h) to be published, see also Liu et al. (2001, MNRAS 327, 141); i) Pottasch et al. (2002, A&A, 393, 285); j) Pottasch et al. (1999, A&A, 347, 975); k) van Hoof et al. (2000, ApJ, 532, 384); l) Pottasch et al. (2001, A&A, 380, 684); m) Bernard-Salas et al. (2001, A&A 367, 949); o) Pottasch & Surendiranath (2005, A&A, 432, 139); p) Pottasch et al. (2005, 436, 965); q) Pottasch & Surendiranath (2005, A&A, 444), 861; r) Surendiranath et al. (2004, A&A, 421, 1051).

Our results support the higher neon abundance suggested by these authors.

4) Four of the 26 PNe studied show evidence of oxygen burning in the course of evolution. Three of these PNe have large bilobal structures, but there are other bipolar nebulae which show no evidence for oxygen burning. We have considered the suggestion of Marigo et al. (2003) that these PNe originated from material with a lower oxygen abundance but find the Karakas models, which are able to reproduce the observed N/O ratio starting with solar metalicity, a more likely expanation for the lower oxygen abundance.

5) The four PNe which show evidence of oxygen destruction all have high helium abundances. Their nitrogen abundances are somewhat higher than that of the oxygen. These four nebulae have abundances which are compatible with model predictions of Karakas (2003) for progenitor stars with masses higher than 5 $M_\odot$, and a value of $Z = 0.02$.

6) The remaining PNe show helium abundances ranging from slightly below solar, He/H = 0.088 to He/H = 0.15. The nitrogen increases from about solar to a factor of 10 above solar, directly proportional to the helium.

7) The carbon abundance is the most difficult to interpret because it shows the largest scatter. This is probably caused by the fact that in some nebulae carbon is created in the course of evolution while in others it is destroyed. Carbon was only measured in three of the four high mass progenitor PNe, and in all these cases the carbon was found depleted. Of the remaining PNe about half have C/O > 1 which is almost certainly an indication that carbon has been formed in the progenitor star in the course of evolution.

Appendix A: Table

The data used is given in the table, together with the references.

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