Astron. Astrophys. 239, 301–304 (1990)

ASTRONOMY
AND
ASTROPHYSICS

Metal-poor planetary nebulae with low-mass central stars

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Received November 24, 1989; accepted May 19, 1990

Abstract. Some type II planetary nebulae (PN) present a strong underabundance in heavy element ratios such as O/H and S/H, as compared to most objects of this type at similar galactocentric distances. In this work, both published and new data on chemical abundances are taken into account in order to determine systematic composition differences for these objects. Estimates of the temperatures and luminosities of the central stars suggest that most of them are very low mass objects.

Key words: planetary nebulae – abundances – central stars

1. Introduction

It has been recently shown that type II planetary nebulae (Peimbert 1978) present radial abundance gradients similar to those displayed by galactic and extragalactic H II regions (Faúndez-Abans & Maciel 1986, 1987a; Maciel & Faúndez-Abans 1985). This is especially true for abundance ratios such as O/H and S/H, for which no contribution from the central stars is expected. It became clear that a few objects (IC 4593, IC 4634, BD + 30°3639, Hu 2 − 1, Cn 3 − 1) presented a strong underabundance of the main heavy elements relative to H, even if the abundance variation with galactocentric distance was allowed for. For these objects, the uncertainties in the derivation of the gradients are not sufficient to account for the strong discrepancy observed, suggesting that some systematic differences exist between these and the remaining nebulae. The possibility of a subdivision of type II nebulae into types IIa and IIb (Faúndez-Abans & Maciel 1987b) does not help, as the mentioned PN are underabundant in relation to *both* subtypes, although all these PN are of type IIb, or N-poor.

In the present work, we analyze these underabundant PN, on the basis of both published and new abundance data, in order to investigate the origin of the systematic discrepancies. In Sect. 2 we discuss the chemical composition of the nebulae, and in Sect. 3 we use the available data to place their central stars on the HR diagram. Finally, in Sect. 4 we discuss the results obtained in the framework of the evolution of intermediate mass stars.

2. Metal-poor type II planetary nebulae

The planetary nebulae considered in this paper were taken from a large sample of disk nebulae studied by Maciel & Faúndez-Abans (1985) and Faúndez-Abans & Maciel (1986, 1987a). They are listed in Table 1, which includes two additional objects from de Freitas Pacheco & Veliz (1987a, b). A few more PN are known to be underabundant in some of the heavy elements (see a discussion by de Freitas Pacheco & Veliz 1987a). Here we restrict ourselves to the small group of nebulae with well determined distances that present (i) at least a 2σ deviation from the oxygen abundances estimated by Faúndez-Abans & Maciel (1986) at the nebula galactocentric position, (ii) *systematic* underabundances of the main heavy elements, and (iii) sufficiently bright central stars so that luminosities and temperatures can be estimated with reasonable accuracy. The first five columns of Table 1 give (1) the name, (2) PK number, (3) distances d(kpc) to the Sun (4) distances R(kpc) to the galactic centre projected onto the galactic plane, and (5) the height z(kpc) from that plane. The adopted distances are from Méndez et al. (1990, IC 4593, M 1 − 26), Maciel (1984, IC 4634, Cn 3 − 1), Daub (1982, BD + 30°3639, Hu 2 − 1), and de Freitas Pacheco & Veliz (1987a, SwSt-1).

The nebular abundances adopted are given in Table 2, along with the deviations from the expected abundances, in terms of the standard deviations obtained by Faúndez-Abans & Maciel (1986, 1987a). The abundances are basically from Aller & Czyzak (1983) see Faúndez-Abans & Maciel 1986), suppelemented by new data on IC 4593, SwSt-1, M 1 − 26, and BD + 30°3639 obtained from spectroscopic observations at the 1.6 m telescope of the National Astrophysical Laboratory (de Freitas Pacheco & Veliz 1987a, b; de Freitas Pacheco et al. 1989, to which the reader is referred for details on the observational and reduction procedures). As discussed by Faúndez-Abans & Maciel (1986), the abundances of the main elements have been carefully selected, and the included nebulae have at least two independent determinations with a small deviation from each other. The average accuracy of the adopted abundances of Table 2 is better than 0.1 for the more abundant elements and about twice as large for the remaining elements (Aller & Czyzak 1983; Aller & Keyes 1987). It should be stressed that, from the point of view of the present paper, it is the *abundance pattern* from Table 2 that matters, instead of the exact values of the adopted abundances.

It can be seen from Table 2 that all these objects are underabundant relative to "normal" type II PN. This effect is stronger for IC 4593, IC 4634, Hu 2 − 1, and Cn 3 − 1. BD + 30°3639 shows a marginal underabundance, which is stronger for oxygen, although recent work points to lower abundances, especially for S, C and N (Pwa et al. 1986; de Freitas Pacheco et al. 1989). The observed underabundance can also be verified by the comparison of the abundances in Table 2 with published photo-

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Table 1

Name (1)	PK (2)	d (3)	R (4)	z (5)	log T_* (6)	log $(L/L_\odot)$ (7)	Ref. (8)
IC 4593	025+40 1	3.2	7.9	2.1	4.49	3.43	1*, −8
IC 4634	000+12 1	2.5	7.6	0.5	4.62	3.04	9, 10
BD+30°3639	065+05 1	0.7	9.7	0.1	4.46	2.96	3, 5, 6, 8, 11
Hu 2−1	051+09 1	1.2	9.3	0.2	4.56	2.67	3, 5, 7, 8, 10*
SwSt-1	001−06 2	1.2	8.8	−0.1	4.44	2.61	5, 12*, 13
M 1−26	358−00 2	1.6	8.4	−0.0	4.48	3.62	7, 8, 9, 10, 14*
Cn 3−1	038+12 1	2.9	8.0	0.6	4.49	2.99	5, 10*, 11

References: 1. Cerruti-Sola & Perinotto (1989). 2. de Freitas Pacheco et al. (1986). 3. Sabbadin (1986). 4. Shaw & Kaler (1985). 5. Amnuel et al. (1985). 6. Pottasch (1984, pp. 160, 175). 7. Cahn (1984). 8. Pilyugin and Kromov (1979). 9. Shaw and Kaler (1989). 10. Martin (1981); Kohoutek & Martin (1981). 11. Preite-Martinez & Pottasch (1983). 12. de Freitas Pacheco & Veliz (1987a). 13. Flower et al. (1984). 14. de Freitas Pacheco & Veliz (1987b).

Table 2. Abundances log(X/H)+12, and deviations from the expected abundances at position R

Name	O	N	S	C	Ne	Ar	Cl
IC 4593	8.32	7.24	6.77	8.96	7.70	6.08	
	5σ	4σ	2σ	1σ	3σ	3σ	
IC 4634	8.61	7.19	6.78	8.13	8.00	6.20	4.96
	3σ	5σ	3σ	5σ	1σ	3σ	1σ
BD 30°3639	8.39	7.76	6.80	8.60			
	3σ	2σ	1σ	2σ			
Hu 2−1	8.60	7.76	6.38	8.71	7.41	6.04	4.51
	2σ	2σ	4σ	1σ	4σ	3σ	2σ
SwSt-1	8.54	7.61	6.48	8.28			5.28
	2σ	2σ	4σ	4σ			1σ
M 1−26	8.14	7.65	6.71				5.00
	6σ	2σ	2σ				1σ
Cn 3−1	8.20	7.49	6.40	8.91	7.86		5.10
	6σ	3σ	4σ	1σ	2σ		1σ

ionization models, such as those by Stasińska (1978), for stars with effective temperature around 30 000 K. The abundances estimated taking into account the gradients derived by Faúndez-Abans & Maciel (1986) are comparable to the values derived by Stasińska (1978), so that the deviations shown in Table 2 also reflect underabundances relative to the photoionization models. Correspondingly, the adopted [O III] electron temperatures are somewhat higher than the values derived from the models. although essentially normal in terms of the temperature gradient estimated by Maciel & Faúndez-Abans (1985), which is consistent with the relatively low temperatures of the central stars.

Although underabundant in most heavy elements relative to *hydrogen*, the nebulae in Table 2 have generally normal abundances relative to *oxygen*, as expected for PN of low mass progenitors. In particular, nitrogen is not enriched relative to the cosmic abundance for IC 4593 and IC 4634, which poses some doubts on the efficiency of the first dredge-up for their progenitor stars. However, carbon is enriched relative to oxygen in IC 4593, BD+30°3639, Hu 2−1 and Cn 3−1, which may be explained either by the occurrence of the third dredge-up or by the WC/WR nature of the central stars (Sect. 4).

3. Luminosities and temperatures of the central stars

In order to further investigate these metal poor objects, it is important to take into account the known properties of their central stars, such as their temperatures and luminosities, which are given in columns (6) and (7) of Table 1. The temperatures are H I Zanstra or adjusted blackbody temperatures, and the sources are listed in the table. For IC 4593 and M 1−26 temperatures derived from NLTE model atmospheres have also been considered (Méndez et al. 1990). The accuracy is very good, and all determinations are within 15% of the adopted values, corresponding to an uncertainty $\delta(\log T_*) \simeq 0.06$. This is in agreement with typical errors estimated by Gathier & Pottasch (1989) for PN with astrophysically determined distances. All planetary nebulae in this study are of medium or low excitation, and most are probably optically thick to radiation in the hydrogen Lyman continuum. Therefore, their H I Zanstra temperatures are generally similar to the colour (blackbody) temperatures, which is confirmed by the determinations referenced in Table 1.

Naturally, the luminosities are more uncertain, especially due to their dependence on the distances, which may be affected by errors of about 50%. Apart from determinations in some of the sources referenced in Table 1, new estimates have been made using: (i) Hβ fluxes (cf. Pottasch 1984, p. 217; Pottasch 1989); (ii) absolute visual magnitudes, adopting bolometric corrections from Cahn (1984) and Code et al. (1976), and (iii) central star radii and temperatures (for all objects except IC 4634 and BD+30°3639). The sources of the stellar radii are indicated by an asterisk in Table 1.

The estimated uncertainties in the adopted average luminosities are of the order of $\delta(\log)\, L/L_\odot \simeq 0.5$, which is similar to the values derived by Martin (1981), and higher than the average uncertainties given by Gathier & Pottasch (1989) for typical disk nebulae with astrophysically determined distances.

Figure 1 shows the location of the PN on the HR diagram, with the estimated error bars. Also shown in the figure are evolutionary tracks of stars in the appropriate mass range (Shaw & Kaler 1985, 1989). Although the position of a given object on this diagram is

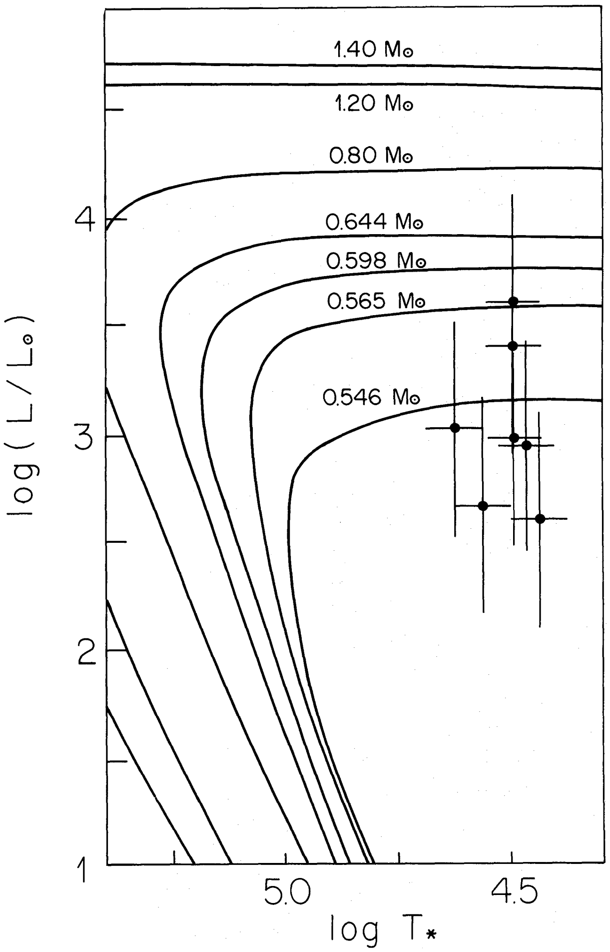

Fig. 1. Location of the PN on the HR diagram. Also shown are evolutionary tracks from Shaw & Kaler (1989)

uncertain, most of these stars seem to be located roughly to the right and below the main body of type II planetary nebulae. In other words, it is unlikely that errors in the adopted distances (and derived luminosities) would change the position of *all* the nebulae shown in Fig. 1.

4. Discussion

It can be seen from Fig. 1 that 5 of the nebulae in our sample seem to be associated with *very low* mass stars, actually stars having masses lower than predicted by most model calculations (see for example Schönberner 1981). Recalling from Sect. 2 the heavy element underabundances observed for these objects, it is tempting to explain both properties by assuming that the central stars of these PN have evolved from low mass stars formed out of metal-poor protostellar clouds. According to the accepted models of the chemical evolution of the Galaxy, there is a steady increase of the interstellar heavy element abundance since the formation of the Galaxy. Therefore, a metal-poor protostellar cloud is comparatively older, which means that the observed stars are also old. The nebulae themselves are young, according to their apparent radii and also from their estimated physical radii and densities, and from the presence of stellar winds. This is consistent with the fact that they have been ejected from low mass stars, which needed a longer time to evolve. Such stars may have gone through no more than one dredge-up, so that the heavy element contamination of the surface layers is expected to be very small.

Another piece of evidence on these objects is supplied by their space distribution and kinematics. IC 4593, IC 4634, and Cn 3 – 1 are at rather large heights z from the galactic plane. In fact, at the adopted spectroscopic distance, IC 4593 is almost a halo PN. Available data for these objects, SwSt-1, and M 1 – 26 indicate a large difference between the rotation velocity at their galactocentric radii as derived from commonly accepted rotation curves, and the velocity implied by the observed nebular radial velocities (Dutra & Maciel 1990). The evidences above suggest that these nebulae are not of type II, but instead of type III, or an intermediate type between disk and halo nebulae. This is also consistent with a smooth variation of the main sequence masses, from the massive type I progenitors to the comparatively low mass central stars of the halo PN.

The existence of central stars with masses around or lower $0.546\,M_\odot$ is an important result, since, as pointed out by Pottasch (1989, 1984, p. 218, 1983), it poses a problem to the theory of stellar evolution. Basically, the computed timescales for these objects are very large (see for example Schönberner 1981), so that the ejected nebula would have dispersed before being ionized. However, as discussed by Gathier & Pottasch (1989), the transition times could possibly be shortened due to mass loss during the transition from the AGB to observable PN, and to the uncertainty in the remnant envelope mass after the formation of the nebula. Available calculations (see for example Pottasch 1984, p. 222, 231; Osterbrock 1989, p. 268) suggest a rough correlation between the progenitor and core masses, which depends on the still largely unknown processes of mass loss. As an order of magnitude estimate, for $M(\text{core}) \lesssim 0.6\,M_\odot$, we would expect $M(\text{prog}) \lesssim 0.8\,M_\odot$. Since stars having masses $M(\text{prog}) \lesssim 0.6\,M_\odot$ are not expected to be affected by the dynamical instability that originates the planetary nebulae, it can be concluded that the progenitor masses of the underabundant PN are of the order of $0.7\,M_\odot$. This could be achieved, for example, by a $1\,M_\odot$ main sequence star with a mass loss rate of the order of $10^{-6}\,M_\odot\,\text{yr}^{-1}$ during $3\;10^5$ yr in the giant stage. It should be recalled that stars significantly less massive than $1\,M_\odot$ on the main sequence would not have had time to evolve to the PN stage in the galactic lifetime. The low mass core of the PN would then be the remnant of a strong "superwind" process: a mass loss rate of $10^{-4}\,M_\odot\,\text{yr}^{-1}$ for a period of about $2\;10^3$ yr would be sufficient to produce the low mass core.

The strong winds associated with the objects in our sample are supported by recent estimates of the *present* mass loss rates of the central stars. For SwSt-1, IC 4593 and Hu 2 – 1 (see references in Table 1), the mass loss rates are in excess of $10^{-8}\,M_\odot\,\text{yr}^{-1}$. In fact, from low-resolution IUE spectra, Cerruti-Sola & Perinotto (1985, 1989) concluded that central stars with $\log T_* < 4.80$ and $R/R_\odot > 0.31$ generally exhibit a wind. The objects in our sample satisfy these conditions, so that we would expect that all of them are actually losing mass. Moreover, 4 of the central stars in our sample display a WR spectrum, reinforcing the idea that they have a relatively dense wind. On the other hand, if the positions on the HR diagram are confirmed, another problem will be raised, as their low luminosities would make the radiation pressure mechanism of mass loss probably inefficient.

Metal-poor, low-mass planetary nebulae are probably not rare, as their large expansion time ($t > 5000$ yr, see discussion by Pottasch 1984, p. 232) could make them detectable for a long period of their lifetime. Similar positions of PN nuclei on the HR diagram have been independently obtained for a few disk and bulge nebulae. Possible candidates are He 2-131 and EGB 5 (Pottasch 1989), PHL 932 (Méndez et al. 1988), NGC 6833, M 1 − 78 and Me 2 − 2 (on the basis of abundance data from Aller & Keyes 1987), and some bulge nebulae (Zijlstra & Pottasch 1989). It would be interesting to have reliable data on the distances and the properties of their central stars, in order to check their position relative to the theoretical evolutionary tracks.

Acknowledgements. We thank Dr. J. Köppen for some helpful suggestions on an earlier version of this paper, and Dr. R. Méndez for placing some data at our disposal prior to publication. This work was partially supported by CNPq and FAPESP (Brazil).

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