Hydrogen-poor planetary nebulae

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Abstract. Five planetary nebulae are known to show hydrogen-poor material near the central star. In the case of A58, this gas was ejected following a late thermal pulse similar to Sakurai. In this paper I will review these five objects. One of them, IRAS 18333−2357, may not be a true PN. I will show that there is a strong case for a relation to the [WC] stars and their relatives, the weak emission-line stars. The surface abundances of the [WC] stars are explained via diffuse overshoot into the helium layer. The hydrogen-poor PNe do not support this: their abundances indicate a change of abundance with depth in the helium layer. A short-lived phase of very high mass loss, the r-AGB, is indicated. Sakurai may be at the start of such a phase, and may evolve to very low stellar temperatures.

1. Introduction

Planetary nebulae (PNe) are the evidence for a phase of stellar evolution where the stellar wind reaches $10^{-6} - 10^{-4} M_\odot yr^{-1}$ at a velocity of $10 - 20 \text{ km s}^{-1}$. Such winds occur on the Asymptotic Giant Branch (AGB). Abundances in AGB winds can be affected by carbon dredge-up and s-process enrichment, but otherwise reflect normal ISM values.

Five PNe are known to have hydrogen-poor inner regions. This material cannot have been ejected on the AGB but must trace post-AGB or pre-White Dwarf evolution. The central stars have therefore experienced a second phase of high mass-loss rates at low outflow velocity. Normal post-AGB evolution predicts that the surface of the star retains a H-rich layer with mass of $\sim 0.01 M_\odot$ which shields the underlying H-poor layers. The favoured model for removing these layers involves a late thermal pulse (Herwig, these proceedings), as now shown by Sakurai’s object. Therefore, it seems likely that Sakurai’s object will become the 6th member of the class.

There are in fact H-poor post-AGB stars known, in particular the R Cor Bor stars, the extreme helium stars, and the [WC] central stars of PNe. The central stars of the H-poor PNe, and by implication Sakurai as well, may be evolutionary related to one (or more) of these classes.

In this review paper I will first discuss the 5 PNe with hydrogen-poor inner shells. I will discuss the morphologies and kinematics. Abundances and dust will be discussed. The possible relation to the [WC] stars will be discussed. Finally the relation to Sakurai’s object will be discussed. An earlier review can be found in Harrington (1996).
2. Numbers and birth rates

H-poor material in PNe is identified through long-slit spectroscopy and/or narrow-band imaging, searching for regions which have very large ratios of [OIII]/Hα or [NII]/Hα. The H-poor regions are expected to be embedded in the outer H-rich regions. Detection requires sufficient spatial resolution to separate the regions. High contrast is also a plus, since the H-rich and H-poor regions are seen superimposed. This favours old, low surface-brightness nebulae where the recent ejecta stand out clearly against the faint outer nebulosity.

It is therefore no surprise that three of the five H-poor PNe are Abell-type nebulae: old, extended and faint. Similar regions in young, bright PNe could easily have gone unnoticed. In total there are 72 Abell-type PNe known, of which three (4%) contain H-poor material. If we assume that the sample of H-poor Abell-type nebulae is complete, the fraction of PNe which may at some time form a H-poor object, would be between 5 and 10 per cent. However, if the H-poor phase has a much shorter observability than a ordinary PN (as may be expected if less material is ejected, and at higher velocity, than in the AGB ejection phase), the final fraction may be higher. Blöcker (2000) finds that about 25% of all central stars of PNe may experience a late thermal pulse. This is consistent with the assumption that all H-poor PNe originate from such an event. However, it is not necessary to assume that all late thermal pulses give rise to H-poor PNe.

If the timing of the late thermal pulse is random, a smaller fraction of young PNe will show H-poor material. The observational difficulties do not allow us to confirm this prediction based on the presently available data.

The birth rate of PNe in the Galaxy is 0.5–1 yr$^{-1}$. Within our Galaxy, a H-poor PN would form on the order of once per decade.

3. Members of the class

3.1. IRAS 15154–5258

This PN was discovered by Manchado et al. (1989). The nebular diameter is reported as 35 arcsec and the electron density $N_e = 10^2$ cm$^{-3}$; the H-poor region has a diameter of 9 arcsec with undetectable Hα (Harrington 1996). The central star is classified as [WC4]. There is considerable foreground extinction. The images from which the diameters have been measured are unpublished. The distance is unknown; given the properties, 5 kpc may be a reasonable assumption.
Figure 1. The HST Hα and [OIII] images of IRAS 15154-5258

The HST images (taken with the Planetary Camera) are shown in Fig. 1. The outer shell is not seen due to its faintness. The Hα image shows a limb-brightened shell surrounding the H-poor bubble. The [OIII] image traces a slightly larger region but has much stronger
emission near the centre than seen in Hα. Note the elongated, jet-like feature visible in Hα. The [OIII] image shows strong fragmentation of the shell, with elongated features pointing away from the star, reminiscent of the cometary knots in the Helix nebula.

Manchado et al. comment on the strong IR emission and argue that the nebula is young. This is unlikely, given the very low density. The IR emission is likely associated with the H-poor region instead.

3.2. IRAS 18333−2357: the exception

This PN is located in the Galactic globular cluster M22 (Gillet et al. 1986, 1989). It is one of only 3 PNe known in globular clusters, and one of 8–10 PNe known in the Galactic halo. To have such a rare class represented in the halo population is remarkable but worrisome. The distance of 3.2 kpc (Harris 1999, 1996) is accurately known, as is the extinction ($E_{B-V} = 0.34$) and the metallicity ([Fe/H] = −1.64), all derived from the parent cluster. The nebular diameter is 12 by 6 arcsec in [O III]; the density is $N_e = 10 \text{ cm}^{-3}$. No hydrogen or helium lines have been detected in the nebula. The gas mass is $m_g \leq 0.01 \text{ M}_\odot$ and the dust mass $m_d \approx 8.4 \times 10^{-4} \text{ M}_\odot$.

The object is remarkable for several reasons. First, the morphology is bow shaped (Borkowski et al. 1993), indicating the nebula is moving through and interacting with the ISM. This is explained by the velocity of the globular cluster: a similar effect is visible in K648, the PN in the cluster M15 (Alves et al. 2000). Second, photo-ionization heating is relatively ineffective at these low densities: Borkowski & Harrington (1991) show that instead the electron gas is heated by photoelectric grain heating. This is an inefficient process which gives a very large ratio between the IR (dust) luminosity and the emission-line luminosity.

Third, a spectrum of the central star (Harrington & Paltoglou 1993) shows substantial hydrogen and helium, as well as N-enrichment. The presence of hydrogen in the star is not easily reconciled with its absence in the nebula. The luminosity of the star is also very high for a PN central star with a low progenitor mass (the turn-off mass of the cluster).

The peculiar location of the object, the presence of hydrogen in the star and the high luminosity all suggest that this object is not a true member of the class. Its origin may be sought in a binary merger (as globular clusters are very dense star systems) rather than in a late thermal pulse.
3.3. A58: THE YOUTH

A58 is a large, old PNe, with a bright edge on the southern side indicating interaction with the ISM through which the star is moving. The star underwent a nova outburst in 1919, and became a cool, R Cor Bor-type star after which it ejected a dusty shell. After 1923, the star became invisible due to circumstellar extinction from its newly ejected dust shell. Pottasch et al. (1986) and Seitter (1987) showed that these new ejecta were hydrogen-poor. A58 therefore is the living evidence that a late thermal pulse can lead to the ejection of a hydrogen-poor nebula. Pollacco et al. (1992) show velocities for the ejecta of $\sim 200$ km/s; the red-shifted side is not seen due to high extinction. NIR images (Zijlstra, unpublished) show that the diameter of the dusty ejecta is 0.45 arcsec. Mid-infrared ISO images are presented by Kimeswenger et al. (1998). Interestingly, the star shows a strong CIV line, seen in scattered light (Seitter 1987, Pollacco, these proc.). It should be classified as a [WC4] star because of this.

Following its eruption, the star very quickly evolved first from the WD cooling branch to the cool post-AGB branch, followed by reverse evolution to a present temperature of $\sim 7 \times 10^4$ K. The minimum increase during the latter period was $10^3$ K/yr.

From the diameter of the shell, one can estimate a mass $\sim 5 \times 10^{-4}$ M$_\odot$ if the density is $10^4$ cm$^{-3}$. Seitter (1987) estimates $10^{-2}$ M$_\odot$. The mass-loss episode, during and following the 1923 disappearance act, must have reached at least $10^{-5}$ M$_\odot$ yr$^{-1}$ but may have been much higher. The fact that the star is becoming visible again (in reflected light) suggests that the mass loss rate has declined since.

3.4. A30 AND A78: THE ELDERLY TWINS

These are the easiest H-poor PNe to study: the ejections occurred probably $\sim 10^3$ yr ago and the ejecta have expanded out to 10 arcsec from the stars. HST images (Borkowski et al. 1995, 1993) show numerous cometary knots, embedded in a faster stellar wind. The knots are believed to have cold, neutral cores, and are dominated by helium. The total amount of H-poor gas is $\sim 10^{-2}$ M$_\odot$.

Both A30 and A78 show evidence that the knots are located in a disk or torus structure, with two additional knots located in the polar direction, symmetric with respect to star. The precise structures are not identical (see the description in Harrington 1996) but the similarities are striking. The polar knots are extraordinary well aligned (to 5 arcmin), which may indicate that their origin is very near the stellar surface. Dust emission in A30 is seen in the torus but not in the polar knots (Dinerstein & Lester 1984).
The outer nebulae have ages of order $10^4$ yr. There is no question that the stars evolved on normal post-AGB evolution before, at a late stage, the H-poor material was ejected. This is consistent with a late thermal pulse. However, Harrington (1996) argues that the disk/pole structure is more akin to binary interaction and suggests the evolution may have been more complicated. The outer nebulae are spherical or mildly elliptical, often assumed to indicate mass loss from a single AGB star.

The stars are hot, with temperatures of $1.1\times10^5$ K for both A30 and A78. Borkowski et al. (1993) adopt a luminosity of $4000\ L_\odot$. If correct, this would indicate declining luminosities compared to those expected shortly after a late thermal pulse. Both stars are classified as weak-emission-line stars (Tylenda et al. 1993). These may be related to the [WC] stars, but with weaker winds. (The class is not well defined and probably contains H-rich objects unrelated to the [WC] stars as well. The H-poor nature of the ejecta makes a relation to the [WC] stars more likely.) The weaker wind could be a consequence of a declining luminosity.

3.5. Indicated evolution: A58→IRAS1514–5258→A30/A78

Comparing the different objects shows that a late thermal pulse may very quickly lead to hydrogen-poor eject in the centre of an old PN, which may remain observable for at least $10^3$ yr. During this time, the star makes a fast excursion to cool (7000 K) temperatures but than heats up quickly. The sequence of A58 to A30/A78 (if this is a correct interpretation) would indicate that after a rapid early increase in temperature, subsequently the star evolves fairly slowly back to the cooling branch with a slowly declining luminosity.

4. Kinematics

The outer nebulae show normal expansion velocities for old PNe, with 40 km/s for A78 (Meaburn et al. 1998) and A30 (Meaburn & Lopez 1996) and 31 km/s for A58 (Pollacco et al. 1992). The morphologies show only small deviations from spherical symmetry, and the outer velocity fields are probably also spherically symmetric, or mildly elliptical (Meaburn & Lopez 1996).

The inner edge of the outer nebulae shows clumpy, strongly enhanced emission. For A30 and A78 this is located at a little over half of the outer radius of the nebula (e.g. Harrington et al. 1995, par. 3), while for IRAS 15154–5258 its radius is about 1/4 of the outer radius.
These features are interpreted as a wind-swept shell, where the present, fast and H-poor, wind from the star collides with the H-rich gas in the older nebula. The stellar winds of A30 and A78 have terminal velocities of 3600 km/s; the expansion velocity of the swept-up shell is 73 km/s for A78 (Manchado et al. 1989, Harrington et al. 1995), although highly variable with location (Meaburn et al. 1998). The H-poor bubble inside this shell is therefore still growing with respect to the outer nebula.

The knots described above are located inside this bubble. They are moving much slower than the stellar wind, as shown by their morphology (Borkowski et al. 1995). Meaburn et al. (1998) show that the knots in the equatorial plane of A78 may be distributed throughout an elongated disk, expanding at 25 km/s. The polar knots have much higher velocities, of 380 km/s. The kinematic age of the equatorial knots may be similar to that of the swept-up shell, but the polar knots appear to have much younger kinematic ages.

In A30 the central knots may show a similar disk/pole structure, but due to the viewing angle these components are not as easy to separate. Within the central regions, velocities of up to 200 km/s are seen, which Meaburn & Lopez (1996) attribute to material evaporating of slow knots and mixing with the fast stellar wind. Such a mass-loaded wind is also proposed for A78 (Harrington et al. 1995).

A58 has a very small hydrogen-poor region which is only barely resolvable from the ground. Pollacco et al. (1992) show emission over a velocity width of 360 km/s (assuming symmetry, since the red-shifted emission is not seen due to dust absorption). They suggest that the flow may be collimated.

5. Dust and abundances

The hydrogen-poor regions are found to have a high fraction of dust. In A58, the central star is almost completely obscured by dust in the innermost region, which must have formed soon after the 1919 outburst and caused the optical disappearance in 1923. IRAS 15154−5258 and IRAS 18333−2357 also have strong IRAS emission. The dust colours indicate that the dust is not very hot. Kimeswenger et al. (1998) find $T_d = 90$ K for the dust in A58. The same authors show that in the older nebula A78 the dusty region is located near the star, possibly coincident with the knots.

The H-poor nebulae show a very large ratio of IR flux over optical line flux. This suggests (Harrington 1996) that the heating of the nebula is dominated by electrons ejected from the dust following photon
Table I. Abundances by mass, as measured in the hydrogen-poor regions

|                  | O/He | N/He | Ne/He | C/He   | Reference            |
|------------------|------|------|-------|--------|----------------------|
| A30 polar knot   | 0.0034 | 0.0020 | 0.0015 | 0.960: | Jacoby & Ford 1983   |
| equatorial knot  | 0.024 | 0.0070 | 0.014  |        | Jacoby & Ford 1983   |
| equatorial plane | 0.021 | 0.018 | 0.029  |        | Kingsburgh & Barlow 1994 |
| A78              | 0.021 | 0.0036 | 0.012  |        | Jacoby & Ford 1983   |
| A78              | 0.740: | 0.640: | 0.210  |        | Manchado et al. 1988 |
| 18333−2357       | 0.240 | 0.275 |        |        | Borkowski & Harrington 1991 |

absorption. Without this unusual heating source, the gas would be too cool to be easily detectable.

Dust-to-gas ratios of the order of 0.2 (Borkowski & Harrington 1991) require both a large carbon overabundance and very efficient dust formation. Dust formation in carbon-rich regions is thought to be initiated by C$_2$H$_2$. In H-poor regions, instead carbon chains need to grow to provide the building blocks. LeToeff (2000) finds that around hot stars, dust formation in such regions does not take place unless extreme, unlikely densities are reached. Instead a cooler star (∼10$^4$ K or less) is required. The condensation cores may be formed by fullerenes (C$_{30}$) which could form in a C-rich, H-poor environment.

Table 1 lists published nebular abundances. There is no detectable hydrogen and the abundances are therefore quoted with respect to helium. The numbers show substantial enrichment of all elements with respect to helium. The polar knot shows lower abundances. Elements in the dust (which will not include helium) are not included in the listed values.

6. Evolution

6.1. Relation to the [WC] stars

It is natural to postulate a relation between the five H-poor PNe and the H-poor [WC] central stars. The fact that two of the five have [WC] central stars and two have weak-emission line stars indeed suggests a direct link between the present objects and the [WC] stars.

The precise origin of the [WC] stars is under discussion. The fact that the late-thermal-pulse object A58 has a [WC] star shows that at least some (probably most) of the [WC] stars originate from such an
Figure 2. Atmospheric and sub-atmospheric abundances of a post-AGB star (Blöcker 2001). The panels show the mass fraction versus the mass coordinate below the surface. The top panel shows the abundances assuming no overshoot on the AGB. The middle panel shows the abundances immediately after the late thermal pulse, under the assumption of enhanced overshoot. The bottom panel shows the same model after the dredge up which follows the pulse.

event. However, this is probably not true for all [WC] stars. A group of cool [WC] stars with extreme IR emission appears to have evolved directly from the AGB (Zijlstra 2001). A search for H-poor material around [WC] stars would be of interest (e.g. Pena et al. 2000).

If re-ignition of the helium occurs on the cooling track, the star will first return to the horizontal part of the Schönberner track. Later the luminosity will again decline slowly while the helium burning tapers off (in contrast to the hydrogen-burning stars where the luminosity drops very fast in the knee of the Schönberner track). It is tempting the associate the [WC] star characteristics with the 'horizontal' part of the evolution and the subsequent luminosity decline with the weak-emission-line stars.
6.2. The helium layer

The nebular abundances in Table 1 must arise from the upper layers of the star. These layers are both nuclear processed and expelled following the thermal pulse. The surface abundances of [WC] stars should also approximate the abundances in the ejected, hydrogen-poor material.

Typical surface abundances of [WC] stars (Dreizler & Heber 1998) are \([\text{He}:\text{C}:\text{O}] = [0.33:0.50:0.17]\) by mass. Fig. 2 (upper panel) shows that such abundance ratios do not occur anywhere in the upper layers of a post-AGB star. Herwig et al. (1999) therefore propose that there is diffusive overshoot into the helium layer, following thermal pulses. This yields the modified abundance profiles shown in the middle panel. During a late thermal pulse, the remaining hydrogen will now be ingested into the helium layer and burned (bottom panel). Prior to the late thermal pulse, the hydrogen-rich layer of the star comprises about \(10^{-4} \, \text{M}_\odot\). The He layer contains a few times \(10^{-2} \, \text{M}_\odot\).

The resulting abundances in the helium layer correspond well to the [WC] stars: the large observed oxygen abundance requires efficient diffusion. (But oxygen dredge-up in PNe does not support efficient diffusion, Pequignot et al. 2000.) Comparing the abundances in Table 1 shows that the H-poor PN also have an enhanced oxygen abundance. However, the helium abundance appears to be much higher than in the [WC] stars. Note that the carbon abundance is not well known but could be high, especially if a large fraction is contained in dust. The amount of H-poor gas in A30 and A78, \(\sim 10^{-2} \, \text{M}_\odot\), agrees with the mass of the helium layer.

The abundance ratios in the inner knots of A30 are in better agreement with the non-diffusive overshoot model of the top panel, with the exception of the uncertain carbon abundance. Better observed abundances are needed: it appears that the H-poor PNe do not well support the diffuse overshoot scenario. Instead it appears that the surface abundances seen in [WC] stars are only reached after a significant fraction of the helium layer has been ejected. However, the disappearance of hydrogen in Sakurai following its nova outburst confirms the ingestion of hydrogen shortly after the thermal pulse.

The neon abundance in the intershell following a late thermal pulse is of the order of 3.5%. The extreme neon abundance in 18333–2357 cannot easily be explained and may confirm its origin in a separate event.

6.3. Mass loss history

H-poor nebulae indicate substantial mass loss. A30 and A78 have ejected \(\sim 10^{-2} \, \text{M}_\odot\) over \(10^4 \, \text{yr}\), or an average mass loss of \(10^{-6} \, \text{M}_\odot \, \text{yr}^{-1}\), sub-
stancially larger than their present winds of $\sim 10^{-9} \text{M}_{\odot} \text{yr}^{-1}$. The dense nebula in A58 shows that within a decade after the pulse, mass loss rates of $10^{-5} \text{M}_{\odot} \text{yr}^{-1}$ or (much) higher can be reached.

The models predict a short-lived luminosity spike coinciding with the lowest temperature reached ($10^4 \text{K}$). This could trigger high mass loss, which is not taken into account in the models. The mass loss may cause the star to evolve to much lower temperatures than shown by the models. The equatorial systems of knots in A30 and A78 have expansion velocities of $\sim 25 \text{km/s}$: this is consistent with the escape velocity of an AGB star ($\sim 3000 \text{K}$).

A58 underwent a R Cor Bor-like phase within years after its late thermal pulse. At this time its temperature was around 7000 K, and episodic dust formation commenced. Shortly after the star disappeared. The evolution of A58 may not have been identical to A30/A78, but it is possible that the star of A58 resembled an AGB star while hiding behind its dust shell, and experienced an unobserved superwind phase.

The disk-like structure of the knot system in A30 and A78 would also have formed during this r-AGB phase (‘r’ for resemble). The reason for their morphology is not clear: one can speculate about magnetic fields or back-fall of the nova ejecta. After an equatorial system formed, it could have collimated subsequent ejection events to give the polar knots. It would be of interest to see whether similar evolution is also occurring in A58. Pollacco et al. (1992) find some indication for collimated flows, but the evidence is not conclusive.

The present temperature of the star of A58 is $\sim 7 \times 10^4 \text{K}$ (based on its [WC4] class). The excursion to low temperatures lasted for no more than a few decade, possibly less. The bulk of the helium layer may have been lost during a very short phase.

6.4. Sakurai’s Object

Thanks to A58, the association between Sakurai and the hydrogen-poor PNe is not in doubt. We have a good idea how it will evolve over the next $10^3 \text{yr}$, thanks to its older relatives.

The immediate prediction from the evidence above is that Sakurai may undergo a phase of very high mass loss. It is important to monitor its evolution in the infrared, so that its mass-loss evolution can be followed. The present wind velocity, from the He I line, is 600 km/s indicative of a still hot star. If the path of A30 and A78 is followed, it is possible that the ejection velocity will drastically reduce while the star becomes cooler. The morphology may change to form an equatorial disk. It would be important to test these predictions, but the high extinction makes such studies very difficult.
As more of the helium layer is removed, the abundance ratios in the ejected material may change over time. As the expansion velocities will vary over time, this tracer of the helium layer will become more confused. Early studies of wind abundances are therefore important.

The dust-formation process can itself be studied for the first time. But while shedding light on the dust formation in the absence of hydrogen, the dust formation obscures our view of the evolution of the underlying star. The study of Sakurai will be a challenging opportunity for some time to come.

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