# The hydrogen-deficient knot of the ‘born again’ planetary nebula Abell 58 (V605 Aql)

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**Summary.** We have analyzed deep optical spectra of the ‘born-again’ planetary nebula Abell 58 and its hydrogen-deficient knot. We derive very high temperatures (15–20 kK) from temperature-sensitive ratios of collisionally excited lines, and very low temperatures (<1 kK) from temperature-sensitive recombination line ratios. We find that abundances derived from recombination lines exceed those from collisionally excited lines by a factor of almost 200. These finding suggest that the knot contains some very cold ionized material.

Although the central star is carbon-rich (C/O>1), the knot is found to be oxygen-rich, a situation not predicted by the single-star ‘born again’ theory its formation. We compare the known properties of Abell 58 to those of Abell 30, Sakurai’s Object and several novae and nova remnants. We argue that abundances in the ejecta observed in A 30 and A 58 have more in common with neon novae than with Sakurai’s Object, which is believed to have undergone a final helium flash. In particular, the C/O ratio of less than unity and presence of substantial quantities of neon in the ejecta of both Abell 30 and Abell 58 are not predicted by very late thermal pulse models.

**Key words:** ISM: abundances – planetary nebulae: individual: Abell 58

## 1 Introduction

Abell 58 (V605 Aql) consists of a large (44 × 36 arcsec) faint shell, with a brighter knot at its geometric center. The knot is assumed to have formed in a nova-like outburst which peaked in 1919, by which time the central star had increased in brightness by five magnitudes. The central knot is extremely hydrogen-deficient (Seitter 1985, Guerrero & Manchado 1996), and is thought to be one side of a bipolar collimated flow, the other side being obscured by dust (Pollacco et al. 1992). The central star is not seen directly due to heavy dust obscuration, but stellar emission lines can be seen via scattered light. The star's surface temperature is estimated to be 95 000 K (Clayton et al. 2006).

The generally accepted explanation of the origin of the knots in A 58 and similar objects such as Abell 30 is that the central star, after the formation of its surrounding planetary nebula, underwent a very late thermal pulse (VLTP), which ejected freshly processed stellar material into the center of the nebula (Iben et al. 1983, Herwig 2001). However, analysis of Abell 30's polar knots has shown that they are oxygen-rich (Wesson et al. 2003), the opposite of the situation predicted by the born-again theory. The observed C/O ratios are similar to those seen in PNe with large abundance discrepancies, such as NGC 6153 (Liu et al. 2000).

This paper presents an analysis of long-slit spectra of A 58's central knot. We find that its properties are very similar to those found for A 30's knots and consistent with the Ercolano et al. (2003) model whereby a cold, extremely hydrogen-deficient core contributes essentially all the strong ORL emission, and a hot outer shell emits CELs. As with A 30, the knots are found to be oxygen-rich. We discuss the implications of these findings for the born-again theory, and for planetary nebulae in general.

## 2 Observations

A 58 was observed using the double-armed ISIS spectrograph on the 4.2-m William Herschel Telescope (WHT) at the Observatorio del Roque de los Muchachos, on La Palma, Spain, on the night of 2003 August 01. The seeing was sub-arcsecond throughout the observations. The spectrograph slit was placed along the major axis of the outer nebula. Spectra covering wavelengths from 3500 to 5100 Å and 5100 to 7600 Å were taken, with R600B and R300R gratings giving spectral resolutions of 1.5Å and 2.8Å on the blue and red arms respectively. The total exposure time in each arm was 2.5 hours. We extracted a spectrum of the central knot, subtracting the contribution of the outer nebula using a spectrum extracted from a region outside the knot covering the same number of rows on the CCD chip. Lines in the spectra of the knot and outer nebula were identified and measured by fitting Gaussian profiles in MIDAS. Overall we detect 42 lines from the knot, due to H, He, C, N, O, Ne, Ar, S, Cl and Fe.

## 3 Central knot

### 3.1 Excitation mechanism

The central knot has previously been studied by Guerrero & Manchado (1996), who suggested that abundances derived from CELs might be unreliable due to shock excitation. We calculate the ratio of energy input from shocks and from photoionization as follows: the luminosity of the central star is $10^4 L_\odot$, and its effective temperature is 95 000 K (Clayton et al 2006). Based on model atmospheres of hydrogen-deficient stars by Rauch et al. (2003), we estimate that 89% of the energy from the star is emitted shortward of 912Å, giving a total ionizing luminosity of $8.9\times10^3 L_\odot$. Adopting $\dot{M} = -1.3\times10^{-7}\,M_\odot yr^{-1}$ and $v_\infty = 2500\,km\,s^{-1}$ from Clayton et al (2006), we calculate that the wind luminosity is only $67L_\odot$, or 0.7% of the ionizing luminosity. Therefore photoionization dominates over shock excitation in producing the observed spectrum.

### 3.2 Extinction

From the observed $H\alpha/H\beta$ ratio, correcting for the contribution of He II Pickering series lines to the observed fluxes, we derive $c(H\beta)=2.38$. However, the extreme weakness of the observed $H\alpha$ and $H\beta$ lines means that this value is very uncertain.

We also measure the extinction using the relative intensities of He I recombination lines. The observed line ratios $\lambda5876/\lambda4471$ and $\lambda6678/\lambda4471$ depend both on the temperature of the gas and the extinction, and so the two line ratios can be used to derive the temperature and extinction simultaneously. We find that the observed line ratios in A 58 are consistent with either a temperature of ~500 K and $c(H\beta)=2.00$, or with a temperature of 14 000 K and $c(H\beta)=2.44$. Given the very high abundance of CNO coolants that we derive (Section 3.4), and the fact that Ercolano et al. (2003) found that in the knots of A 30, helium emission come predominantly from the cold core, we believe that the cold solution is physically more realistic for the knot of Abell 58, and adopt $c(H\beta)=2.0$ for our subsequent analysis.

### 3.3 Temperature and density

The electron density of the central knot was measured from the [O II] $\lambda\lambda3726,2729$, [S II] $\lambda\lambda6717,6731$ and [Ar IV] $\lambda\lambda4711,4740$ line ratios, which give 1520, 2730 and 2050 $cm^{-3}$ respectively. We adopt a density of 2100 $cm^{-3}$. This value is expected to be representative of the hotter regions of the knot, from which essentially all of the CEL emission will arise.

The temperatures derived from the [O III] and [N II] nebular-to-auroral line ratios in the knot are 20,800 K and 15,200 K respectively. In our subsequent abundance analysis we use a temperature of 15 200 K to derive CEL abundances from singly ionized species, and 20 800 K for more highly ionized species. These very high electron temperatures suggest that grain photoelectron heating is the dominant heating mechanism in the hot regions of the knot, by analogy with IRAS 18333-2357 (Borkowski & Harrington 1991) and Abell 30 (Ercolano et al. 2003).

We also determined temperatures from the ratios of helium recombination lines. These vary weakly with temperature (Smits 1996). We find that the ratio of He I $\lambda5876$ to $\lambda4471$ implies a temperature of 350 K, while the ratio of He I $\lambda6678$ to $\lambda4471$ implies a temperature of 550 K. We adopt T(He I) = 500 K. These values are much lower than the values of 8 850 K and 4 450 K found for the knots of A 30.

Finally, we estimate the temperature in the knot based on the weak temperature dependence of the O II recombination line ratio $\lambda4649/\lambda4089$, using recent atomic data from Bastin & Storey (2006). We find a ratio in A 58 of 1.23, which is lower than the value derived for any density at 600 K by Storey (2007), providing strong evidence that the knot of A 58 contains ionized material at very low temperatures. This indicates that the situation in the knot of Abell 58 is similar to that seen in Abell 30, with cold, metal-rich ionized plasma existing within the knot. We adopt an electron temperature of 500 K for our derivation of abundances from ORLs.

### 3.4 Elemental abundances and abundance discrepancy factors

To derive chemical abundances in Abell 58's central knot, we follow the same general approach as described in detail by Wesson et al. (2003), using the same atomic data. To calculate total elements abundances, we adopt the ionization correction scheme of Kingsburgh & Barlow (1994). The abundances derived are presented in Table 1. We also list the abundances derived in Abell 30 (Wesson et al. 2003).

Given the exponential temperature dependence of CEL emissivities, and the inverse power-law temperature dependence of ORL emissivities, strongly enhanced ORL emission provides evidence in favor of a cold, extremely hydrogen-deficient core in A 58's knot. Observations and modelling supported this interpretation in the case of the polar knots of Abell 30 (Wesson et al. 2003, Ercolano et al. 2003). For an element or ion X, the abundance discrepancy factor, adf(X), is defined as $adf(X) = \frac{X(ORL)/H}{X(CEL)/H}$. With the current data it is only possible to derive an adf for oxygen. We find that adf($O^{2+}$) and adf(O) are both 174. These values are among the largest found in any ionized nebulae, considerably larger than the values of 32 and 70 found for oxygen in the 'normal' PNe NGC 1501 (Ercolano et al. 2004) and Hf 2–2 (Liu et al. 2006), but still lower than the adfs of ~700 seen in the polar knots of Abell 30 (Wesson et al. 2003).

**Table 1.** Total elemental abundances in the knot of A 58 by number, on a logarithmic scale where N(H)=12.0, compared with those found in the knots of A 30.

| Object | | He | C | N | O | Ne |
|---|---|---|---|---|---|---|
| A58 | ORLs | 12.51 | 10.95 | - | 12.27 | - |
| | CELs | - | - | 9.21 | 10.03 | 9.92 |
| A30 J1 | ORLs | 13.03 | 11.65 | 11.49 | 12.15 | 11.51 |
| | CELs | - | - | 8.88 | 9.26 | 9.70 |
| A30 J3 | ORLs | 13.07 | 11.66 | 11.43 | 12.10 | 11.99 |
| | CELs | - | 9.22 | 8.90 | 9.32 | 9.78 |

### 3.5 Evolution of the knot

Abundances for A 58's knot were previously derived by Guerrero & Manchado (1996). They adopted a temperature of 12 450 K and $c(H\beta)$=0.29, and found $O^{2+}/O^{+} = 0.05$, while we obtain a value of ~1. This difference is partly accounted for by the lower extinction and temperature adopted by GM96: we derived abundances from their observed fluxes but using $c(H\beta)$=2.0 and $T_e$=20 800 K, and obtained $O^{2+}/O^{+} = \sim 0.4$. The remaining factor of 2.5 may be due to the temperature of the central star, and thus the ionization degree of the nebula, increasing during the nine years between GM96's observations and our own.

## 4 Abundance patterns in the knot of A 58 and other objects

Table 2 presents a comparison between the mass fractions of H, He, C, N, O and Ne that we have derived for the ejecta of A 58 and A 30, and those derived by other authors for the central stars of these two objects, as well as for a number of other objects, including PG 1159-035, which may be a descendant of a star similar to the nucleus of A 30; V4334 Sgr, which has been proposed to be a younger counterpart to A 58/V605 Aql; the shells of two old novae, DQ Her and RR Pic; and the ejecta of three neon novae. The nitrogen and neon abundances listed for the A 58 central knot are given in parentheses, since they are based on its measured CEL N:O:Ne ratios, normalized to its ORL oxygen abundance.

### 4.1 Abell 30

Our analysis of A 58's knot reveals many similarities with the older knots of A 30. In both cases, extreme abundance discrepancies are observed, C/O ratios are less then unity, neon is present in significant quantities, and ORL temperature diagnostics indicate the presence of very cold ionized plasma. A model of A 30's knots consisting of a core with a very high abundance of CNO coolants, and an outer region in which heating is dominated by dust photoelectric heating, successfully reproduces their observed spectra (Ercolano et al. 2003). VLTP models predict that C/O should be greater than unity, and that neon mass fractions should be $\leq$0.02 in born-again objects, and therefore the abundances derived for the knots of both A 30 and A 58 are inconsistent with the predictions of the born-again theory.

The A 58 knot is presumed to have a red-shifted counterpart, on the opposite side of the star and completely obscured by dust. The collimation of A 30's knots argues against a single star being their source, and if A 58 also has collimated outflows, as suggested by Pollacco et al. (1992), this could argue for some mechanism involving an accretion disc and polar jets in a double star system. In contrast to A 30, though, the knot of A 58 is expanding quite rapidly. While the knots of A 30 are broadened by $<20\,\mathrm{km\,s^{-1}}$ (Meaburn & López 1996), our data indicate that the knot of A 58 is expanding at $\sim95\,\mathrm{km\,s^{-1}}$, from the FWHM of the observed lines, after correcting in quadrature for the instrumental resolution of $110\,\mathrm{km\,s^{-1}}$.

### 4.2 Sakurai's Object

Sakurai's Object (V4334 Sgr) was discovered in February 1996, and was initially thought to be a slow nova (Nakano et al. 1996). However, its spectrum showed a rapid cooling, hydrogen abundance decline and an enhancement of s-process elements, over just a few months after its discovery, and it is thought to have undergone a final helium flash (Duerbeck & Benetti 1996). The spectrum of Sakurai's object at its maximum brightness was very similar to the spectrum of V605 Aql obtained at its maximum in 1919, with the appearance of a cool RCB star (Lundmark 1921). Because of this, A 58 is often described as an older twin of Sakurai's Object. The He:C:O mass ratios at the surface of Sakurai's object were found to be 85:5:3 in July 1996, compared to 54:40:5 for the central star of A 58 (Clayton et al. 2006). Our derived nebular abundances for A 58's knot correspond to He:C:O mass ratios of 18:2:41. Freshly ionized material has been detected around Sakurai's Object, indicating that a knot or knots similar to those seen in A 58 may be forming. The freshly ionized material is found to be expanding at 1500 $\mathrm{km\,s^{-1}}$ (Kerber et al. 2002). At this expansion rate, its density will decline rapidly and it seems unlikely that any knot formed could survive to be seen as long after the event as the knots of A 58 and A 30. The physical conditions and chemical abundances in the freshly ionized ejecta have yet to be determined.

### 4.3 Classical novae

Possible links between planetary nebulae showing high adfs and classical novae have been discussed by Wesson et al. (2003) and Liu et al. (2006). In several cases, nova shells have been found to show very strong recombination line emission and evidence for very low temperatures. One good example is the shell surrounding DQ Her, which was found by Williams et al. (1978) to have a Balmer jump temperature of ∼500K. The C/O number ratio in the ejecta of DQ Her is 0.36 – quite similar to that seen in the knots of Abell 30.

We have included in Table 8 a summary of the elemental mass fractions measured for two old nova shells and for three 'neon novae'. All five show C/O ratios of less than unity but the neon novae also show neon mass fractions that are comparable to the large values (0.1–0.4) that we have measured for the knots of A 58 and A 30. Models for neon novae (e.g. Starrfield et al. 1986; Politano et al. 1995) invoke the usual thermonuclear runaway on the surface of a white dwarf following mass transfer from a low mass companion, with the high neon abundances resulting from the fact that the runaway occurs on the surface of a high-mass (1.0-1.35 $M_{\odot}$) O-Ne-Mg white dwarf, some of whose subsurface material is mixed to the surface and ejected during the nova event. This suggests that the central stars of A 58 and A 30 might have high mass O-Ne-Mg cores, some of whose material may been brought to localized parts of the surface by the event that led to the ejection of the observed knots. If entropy barriers prevent such a scenario during a VLTP event then an alternative scenario could involve the transfer of mass from a companion on to localized parts of a massive white dwarf surface, leading to a thermonuclear runaway and the excavation and ejection of material from the O-Ne-Mg region of the white dwarf, whose thin surface layer still has $C/O > 1$.

## 5 Discussion

We have now carried out detailed ORL/CEL abundance studies of two of the five known hydrogen-deficient planetary nebulae. In both cases, we find that the VLTP born-again scenario commonly invoked to account for the production of H-deficient material within an old planetary nebula cannot account for the abundance ratios observed, while the collimated outflows seen in both objects seem inconsistent with a single star at the center.

The presence of knots of cold hydrogen-deficient material has commonly been invoked to account for the observed discrepancy in planetary nebulae whereby ORLs give much higher chemical abundances than CELs for heavy elements (e.g. Liu et al. 2000, Tsamis et al. 2004, Wesson et al. 2005). The origin of this H-deficient material

**Table 2.** Comparison between the properties of Abell 58 and those of related objects

| Name | Type | Mass fractions | | | | | | Reference |
|---|---|---|---|---|---|---|---|---|
| | | H | He | C | N | O | Ne | |
| A 58 | knot | 0.014 | 0.178 | 0.015 | (0.029) | 0.410 | (0.354) | 1 |
| A 58 | WCE star | | 0.54 | 0.40 | | 0.05 | | 2 |
| A 30 | J1 knot | 0.012 | 0.519 | 0.065 | 0.052 | 0.273 | 0.078 | 3 |
| A 30 | J3 knot | 0.010 | 0.485 | 0.057 | 0.039 | 0.208 | 0.202 | 3 |
| A 30 | WCE-PG1159 | | 0.41 | 0.40 | 0.04 | 0.15 | | 4 |
| PG1159-035 | PG1159 | <0.02 | 0.33 | 0.48 | 0.001 | 0.17 | 0.02 | 5 |
| V4334 Sgr | (RCrB) | 0.003 | 0.845: | 0.051 | 0.019 | 0.027 | 0.059 | 6 |
| DQ Her | old nova | 0.34 | 0.095 | 0.045 | 0.23 | 0.29 | | 7 |
| DQ Her | old nova | 0.254 | 0.123 | 0.046 | 0.302 | 0.276 | | 8 |
| RR Pic | old nova | 0.53 | 0.43 | 0.004 | 0.022 | 0.006 | 0.011 | 9 |
| V693 CrA | neon nova | 0.408 | 0.212 | 0.004 | 0.070 | 0.069 | 0.237 | 10 |
| V4160 Sgr | neon nova | 0.470 | 0.338 | 0.006 | 0.058 | 0.062 | 0.065 | 11 |
| V1370 Aql | neon nova | 0.053 | 0.088 | 0.035 | 0.14 | 0.051 | 0.52 | 12 |

References: 1) This paper; 2) Clayton et al. (2006); 3) Wesson et al. (2003); 4) Leunenhagen et al. (1993); 5) Jahn et al. 2007; 6) Asplund et al. 1999 (July 1996 spectrum); 7) Williams et al. (1978); 8) from our re-analysis of the relative line intensities presented by Ferland et al. (1984); 9) Williams & Gallagher (1979); 10) Vanlandingham et al. (1997); 11) Schwarz et al. 2007; 12) Snijders et al. 1987

in normal nebulae is as yet unknown. Given the uncertainty at the moment about how the knots in A 30 and A 58 have been produced, it is difficult to say if the proposed knots present in 'normal' nebulae could have a similar origin. However, we note that it is difficult for the evolution of a single star to explain the morphology and abundances in A 30 and A 58, and that recent work has suggested that most or all central stars of planetary nebulae could be binary systems (Moe and De Marco 2006).

However, spatially resolved spectroscopy and high resolution imaging of nebulae with high abundance discrepancy factors, such as NGC 6153, seem to suggest that knots in 'normal' nebulae must be very small, <60 AU across, numerous, and have a smooth distribution, as no clumps are seen in HST images, nor spikes in long slit spectra, but rather a smooth decline of adf from center to edge, for example in NGC 6153 (Liu et al. 2000). This is in contrast to the highly clumpy distribution of H-deficient material seen in Abell 30, Abell 58 and Abell 78.

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