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Abell 58 – a Planetary Nebula with an ONe–rich knot: a signature of binary interaction?

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Abstract. We have investigated the possibility that binary evolution is involved in the formation of the planetary nebula Abell 58. In particular, we assume a neon nova is responsible for the observed high oxygen and neon abundances of the central hydrogen-deficient knot of the H-deficient planetary nebula Abell 58 and the ejecta from the explosion are mixed with the planetary nebula. We have investigated different scenarios involving mergers and wind accretion and found that the most promising formation scenario involves a primary SAGB star that ends its evolution as an ONe white dwarf with an AGB companion at a moderately close separation. Mass is deposited on the white dwarf through wind accretion. So neon novae could occur just after the secondary AGB companion undergoes its final flash. However, the initial separation has to be fine-tuned. To estimate the frequency of such systems we evolve a population of binary systems and find that that Abell 58-like objects should indeed be rare and the fraction of Abell-58 planetary nebula is on the order of 10^{-4}, or lower, among all planetary nebulae.

Key words. binaries:general, planetary nebula-individual: Abell 58, evolution:star

1. Introduction

Abell 58 (V605 Aql) consists of a large faint shell with a bright hydrogen-deficient knot at its geometric centre. The dynamical age of the old faint planetary nebula is about 20,000 yr (Pollacco et al. 1992). In 1919 V605 Aql was undergoing a nova-like outburst and brightened over a period of 2 yr to a peak of $m_{\rm pg}$ = 10.2 in 1919. The surface temperature of the star was 5,000 K and its spectrum in 1921 was very similar to an R Coronae Borealis (R CrB) star (Clayton 1996; Clayton & De Marco 1997). Clayton et al. (2006) estimated the current surface temperature of the central star to be 95,000 K and considered Abell 58 as an older twin of Sakurai's object.

The classical explanation for the origin of the hydrogen-deficient knot in Abell 58 is that the central star, after the formation of its surrounding nebula, underwent a very late thermal

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pulse (VLTP) which ejected freshly processed stellar material into the centre of the nebula (Iben et al. 1983; Herwig 2001). The observed nova-like outburst resulted from the central star undergoing the final flash.

However, Wesson et al. (2008) compared the known properties of Abell 58 to those of Abell 30, Sakurai's object and several nova remnants and argued that the abundances observed in the ejecta of Abell 58 have more in common with novae, particularly neon novae, than with Sakurai's Object. Wesson et al. (2008) found the knot to be very oxygen-rich. The observed C/O ratio is not only less than unity but on the order of 1/10. This is not predicted by the single born-again scenario. For example, Werner & Herwig (2006) found carbon is more abundant than oxygen and Karakas et al. (2008) found that the lowest C/O ratio predicted is 0.38.

Moreover, while the occurrence of very late thermal pulses can explain the hydrogen deficiency, it cannot explain the presence of substantial quantities of neon in the ejecta. In particular, the high neon abundances in the hydrogen-deficient knot seem to suggest the possibility that Abell 58 has previously undergone a nova explosion. High neon abundances could be the signature of neon novae, with observed neon abundances as high as 0.52 by mass fraction in V1370 Aql (Snijders et al. 1987). 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 and high neon abundances are found because the runaway occurs on the surfaces of a high-mass ($1 - 1.35\,M_{\odot}$) ONeMg white dwarf.

Also, while the spectra show that V605 Aql has stellar abundances similar to those seen in Wolf-Rayet [WC] central stars of PNe, with 55% helium and 40% carbon (Clayton et al. 2006), the knots consist of 32.3% oxygen, 34.5%neon with only 2.1% carbon (Wesson et al. 2008). If the knot is ejected from the central star, it seems rather odd that the knot has higher oxygen and neon abundances, as well as much lower carbon abundances. The abundances of the knot seem to suggest that it should be ejected from a star that has undergone some degree of carbon burning, but the central star is still carbon rich. This suggests the need for binary interaction to explain this discrepancy.

2. Possible scenarios

The driving observation that needs to be explained by all possible scenarios is the presence of Ne- and O-rich ejecta inside a H-rich PN. This suggests the scenario involves a super-asymptotic giant branch (SAGB) star, a star that is hot enough to ignite carbon in the early AGB phase and end up with an ONeMg core. The first scenario that comes to mind is that of a nova that went off in 1917 and that we later misinterpreted as a final flash. The immediate problem with this scenario is that a nova alone is unlikely to produce H deficiency and it also produces a long-lived giant star. This is the reason why we have searched for alternative scenarios.

As it turns out, this has proved to be a challenge and there is no scenario that can explain all the observations in a satisfactory way. There are two classes of possible scenarios, one that involves a nova explosion following a traditional final flash and the other in which the H deficiency is achieved in a merger, a scenario already used to explain R CrB stars (Iben et al. 1996; Clayton et al. 2007). The four scenarios are described below and summarised in Table 1.

2.1. The first common envelope scenario

Because a classical nova scenario fails and we know that R CrB stars are likely to result from a merger type scenario, we have constructed a merger scenario for V605 Aql. The immediate objection to such a scenario is that the abundances of the post-merger object, though they be H-deficient, should actually be dominated by helium rather than *carbon* and helium (Clayton et al. 2007). This said, mergers remain quite complex phenomena, so we relax this constraint and assume that there is a way to make a [WC] star with a merger (e.g.

De Marco 2002). In this scenario a massive AGB star ($M \lesssim 6 - 8$ $M_\odot$) suffers common-envelope evolution with a lower-mass main-sequence star when the primary evolves to the SAGB branch. This common envelope (CE) results in a merger which strips the primary of hydrogen (by ejection and ingestion) revealing the intershell region. If the primary is massive enough to have an ONeMg core then the ejecta could be rich in Ne and have a C/O ratio lower than unity, as observed. The main problem in this scenario is that the ejecta would derive from the CE and it is unclear how and which stars produced the first, older H-rich PN. If the old PN came from the envelope of the SAGB star during CE, the merger event, corresponding to the 1919 outburst, had to occur around 20,000 yr after the CE phase. This could be possible if the binary survived through the CE phase, to leave a very close binary with the ONeMg core with the MS secondary. Then the merger occurred afterwards because gravitational radiation caused the two stars to spiral in.

2.2. The second common envelope scenario

To alleviate the problem with the common envelope scenario of sect. 2.1 we designed a second scenario where a first CE takes place between an AGB giant and a MS star. In this case, both stars need to have considerable mass ($6 - 8$ $M_\odot$) and to have similar masses. During the first CE the old PN is produced. This first CE is survived by the binary but it results in a very close binary which eventually suffers a second CE when the primary is a WD star. This second CE results in a merger which makes the secondary H-deficient, in a similar way to the scenario above. This scenario does produce a first PN and ejecta but it is unlikely to produce a close-to-spherical PN, as was instead observed. In addition, the stars need to have very similar masses to ensure that the second CE takes place within 10,000 – 20,000 yr of the first CE. Finally, the first CE has to result in a WD secondary close enough to the primary so that it merges upon the second CE.

2.3. Primary responsible for both the planetary nebula and nova explosion

In a third scenario we have an AGB giant secondary at an intermediate separation from an ONeMg WD primary that already has a PN around it. At some point the WD goes through a final flash, producing the right kind of nebula. The WD then becomes a H-deficient giant with an AGB companion. Following this the H-deficient giant becomes a WD of the DB spectral type. Mass is accreting on to the DB WD from the wind of the AGB companion until the WD experiences a nova outburst. In this case the [WC] features, that are observed from 1987 onwards, are produced by the outburst in a similar way to the N66 nova in the LMC. If the witnessed outburst in 1917 is the FF then it is hard to explain how we could have missed the nova flash. On the other hand if the FF happened some time in the past and what we witnessed was the nova, then it would be hard to explain why we did not see a star in the middle of the PN prior to 1917. Finally, in this scenario, our post-nova WD (with its [WC] spectral type) would be orbited by an AGB giant which is not seen. The secondary should be either a massive AGB star or a SAGB star, so it is hard to explain why it is not observed. If a nova explosion did occur the core of the primary has to be ONe core but that does not fit with the observed helium- and carbon-rich nature of the central star. Also, the observed N/O ratio of the old planetary nebula is 0.72 (Guerrero & Manchado 1996). This suggests the star responsible for the old PN is less massive than a SAGB star which should have a much higher nitrogen abundance owing to hot bottom burning.

Also, in order for a nova explosion to occur immediately after the formation of the planetary nebula, the initial masses of the two stars have to be almost equal. Otherwise, the evolution of the secondary would not catch up to that of the primary and, when mass is transferred from secondary on to the primary resulting in a nova, the old planetary nebula would have already disappeared. In order for scenario 3 to occur, the binary systems must have a mass ratio $q > 0.99$. This scenario can explain the abundances of the hydrogen-deficient knot, as well as the presence of the old planetary nebula. However, the system has to be very fine-tuned, and even so, it cannot fit all the observations.

2.4. Primary responsible for nova explosion and secondary responsible for the planetary nebula

In the final scenario we have an ONeMg WD primary and an AGB secondary (which can have any mass). The separation is once again intermediate. This mass transfer is from wind accretion, not Roche Lobe overflow. The AGB secondary makes a PN and becomes a WD, during which time mass transfer is reduced greatly as the WD primary does not have enough mass accumulation on its surface to produce a nova. Eventually the WD secondary goes through a FF that produces C-rich ejecta. During the FF the new H-deficient giant expands and starts transferring mass to the WD primary again. This pushes it over the limit for a nova detonation. Depending on the accretion rate, the nova can occur relatively quickly. The nova ejecta is O and Ne rich and is then mixed with the recently produced FF ejecta. The primary WD eventually fades as a typical post-nova WD, while the secondary WD follows the canonical post-FF evolution developing a [WC] spectral type which is observed from 1987 onward. The main drawback of this scenario is that the nova explosion has to follow very shortly after the FF creating a possible fine tuning problem. Also, it is not clear whether the nova should have been observed as an outburst at some time after the FF or whether the FF lightcurve, including dust production, could have hidden the nova lightcurve behaviour.

This is the most promising scenario of all four. If the observed central star is the secondary, final flashes can explain the surface temperature change from 5,000 K in 1919 to 95,000 K now. Ejecta from the novae explosion are responsible for the observed high oxygen and neon abundances of the hydrogen-deficient knot, while the secondary is responsible for the observed central star abundances. Also, if the accretion rate is high enough, the luminosity of neon novae is only around $4.8 - 6 \times 10^4\,L_\odot$ and the decline time could be as short as 12 d. This could explain the non-detection (Prialnik & Kovetz 1995). The only coincidence is that the secondary, when undergoing final flashes, had an ONe WD as a companion star with a suitable separation.

3. Method: the BSE code

Scenario 4 is the most promising of the four possible scenarios but requires fine-tuning of the initial conditions of the binary systems for novae explosions to occur at the right moment. Therefore, we use a rapid binary-evolution algorithm (BSE) to investigate the frequency of these two scenarios. Using this rapid binary code, we can generate a sample of large binary populations and check which systems can lead to the formation of systems like Abell 58. The code uses the detailed single-star evolution (SSE) formulae of Hurley et al. (2000) to calculate the stellar luminosity, radius, core mass, core radius and spin frequency for each of the component stars as they evolve. Details of the binary-evolution algorithm are thoroughly described in Hurley et al. (2002).

4. Frequency of scenario 4 objects

For the case of scenario 4, the primary had already become an ONe white dwarf a long time ago and mass was deposited on to the white dwarf by wind accretion. However, the accretion stopped when the secondary evolved to a white dwarf. When the final flash caused the secondary to expand and then evolve back on to the post-AGB track wind accretion could then restart. This is only a brief period in which mass transfer could take place and hence this is a fine tuning problem regarding whether enough mass could be deposited on to the ONe white dwarf. Based on nova evolution models by Prialnik & Kovetz (1995), a massive white dwarf at $1.25 - 1.4\,M_\odot$ with an accretion rate of $10^{-7}\,M_\odot\,yr^{-1}$ would have a short recurrent

Table 1. Initial conditions and comparison with observations for four different binary scenarios

Parameter	CE Merger 1	CE Merger 2	Wide binary 1	Wide binary 2
M_1	massive AGB	AGB	WD	WD
M_2	MS	WD	AGB	AGB
Separation	less than a few au	a few $R_\odot$	intermediate	intermediate
Observations				
Old PN (non-TypeI)	No PN	Type I, wrong shape	Type I, from primary	non-Type I, from secondary
FF 1917	is the merger event	second CE leading to merger	from primary	from secondary
Hdef giant 1921	produced by the merger	produced by the merger	from primary	from secondary
O and Ne-rich ejecta	from the ONeMg primary	from the ONeMg primary	from nova after FF	from nova right after FF
[WC] 1987-today	regular post-FF evolution	regular post-FF evolution	from nova?	from secondary
Other drawbacks	Lack of old PN	Short time between CEs	unobserved AGB companion?	unobserved nova outburst?

period of 0.771 – 19.6 yr. Therefore, if the system is close enough to maintain a high accretion rate through wind accretion, enough mass could be deposited on to the white dwarf for a nova explosion to occur shortly after the final flash. However, the system has to be wide enough to avoid common envelope evolution when the secondary evolved to an AGB star. The mass accretion rate in a common envelope is likely to be too high for novae to occur and observations do not seem to support the idea that Abell 58 is a post-common envelope object.

Typical initial separations range from 2,000 – 10,000 $R_\odot$. A typical example of the evolutionary path is shown in Fig. 1. We set the lower initial mass limit for the secondary to be 0.8 $M_\odot$, because it is still impossible for any secondary with lower mass to evolve through the entire AGB phase within the age of the Universe. It is worth pointing out the nitrogen-rich nature of the old PN favours the secondary having a high initial mass because hot-bottom burning can convert dredged-up carbon into nitrogen. The actual distribution of initial periods of binary stars is not well known. A common practice is to assume the separation is uniform in logarithmic space (Eggleton et al. 1989, based on observed frequency of doubly bright visual binaries).

The models used to construct the formula used by Hurley et al. (2002) include overshooting and hence give SAGB stars from initial masses 6.4 – 8.1 $M_\odot$. Like Hurley et al. (2002) we assume one binary is born with mass greater than 0.8 $M_\odot$ in the Galaxy per year. This is in agreement with the white dwarf birth rate in the Galaxy given by Phillips (1989). Then, based on the IMF of Kroupa et al.

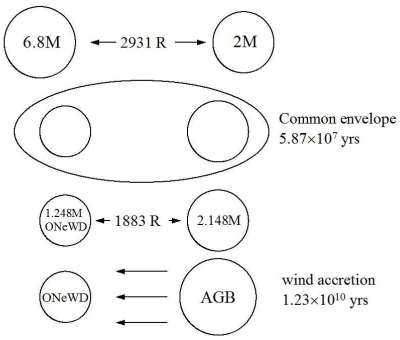

Fig. 1. The primary star evolved to a SAGB star at the age of 5.8734×10^7 yr and common envelope occurred at 5.94678×10^7 yr. After the common envelope, the primary lost all its envelope and became an ONe white dwarf and the system became closer. Eventually the secondary evolved to an early AGB star at the age of 1.2310×10^{10} yr. Mass was then accreted on to white dwarf at a slow rate of $10^{-11}\, M_\odot\, yr^{-1}$ at first. Then the accretion rate slowly increased as the AGB star grew in size and reached a rate of $10^{-7}\, M_\odot\, yr^{-1}$. Such a high accretion rate leads to recurrent novae.

(1993), only about 0.01 binary systems with a SAGB star primary is formed in the Galaxy per year. At the moment the distribution of the mass ratio of primary to secondary is uncertain. If we assume a flat distribution of mass ratio around 8.8×10^{-4} of binary systems that satisfy scenario 4 are born per year in the Galaxy.

However, this rate should be seen as an upper limit because not all AGB stars undergo very late thermal pulses. In our population synthesis, we assume every AGB stars undergoes final flashes. A more realistic rate would be the fraction of AGB stars that undergo final flashes multiplied by 8×10^{-4}. Assuming 20 –

25% of AGB stars become hydrogen-deficient (Blöcker 2001), we can estimate another upper limit of around 2×10^{-4} per year in the Galaxy.

5. Conclusion

Our result shows that Abell 58 can be formed as a result of some relatively rare binary interaction. The observed high oxygen and neon abundances could come from ejecta from a neon nova explosion. We have not ruled out that the final flash is responsible for the hydrogen-deficiency nature of the knot. The observed hydrogen-deficient knot could well be a mixture of the neon nova ejecta and final flash ejecta. We have considered four different scenarios, but none of the scenarios fit perfectly with the observations. The best scenario involves a pair of binary stars at a moderate separation. The primary went through super-AGB evolution and then became an ONe white dwarf. Then the secondary became an AGB star and mass was accreted on to the white dwarf, causing a neon nova explosion. If the neon nova occurred just after the final flash occurred near the end of the secondary AGB evolution, the ejecta from the nova could then mix with the planetary nebula, resulting in the observed abundances. However, there is no observation of the nova explosion or the primary white dwarf.

The frequency of such a system has to be very low because of the fine-tuning of the initial conditions. Therefore, we do not expect to see significant numbers of planetary nebula with low hydrogen but high oxygen and neon abundances. Otherwise, other formation channels are needed to explain the frequency.

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