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Research Note

On the discovery of an enormous ionized halo around the hot DO white dwarf PG 1034+001

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Abstract. The discovery of the largest known planetary nebula on the sky surrounding the DO white dwarf PG 1034+001 with an apparent diameter of about $2°$, corresponding to a linear diameter of 3.5–7.0 pc at the likely distance of 100–200 pc, has been reported by Hewett et al. (2003). A careful inspection of available sky survey data has now shown that this planetary nebula, Hewett 1, is surrounded by an elliptical emission shell with an apparent diameter of $6° \times 9°$ ($16.2^{+6.1}_{-4.5} \times 24.3^{+9.1}_{-6.8}$ pc at $d = 155^{+58}_{-43}$ pc). A further emission structure, detected northeast of the central star, may indicate another shell with a size of $10° \times 16°$. From presently available observational data we do not have indications revealing whether the emission arises from material ejected from PG 1034+001 or from ionized ambient ISM.

Improved proper motion data combined with radial velocity and distance data from the literature have enabled us to derive a Galactic orbit for the central star PG 1034+001. Its thin disk orbit and the morphology of the first halo suggest that the nebula is in an advanced stage of interaction with the interstellar medium.

Key words. ISM: planetary nebulae: individual: PN G080.3-10.4 – ISM: planetary nebulae: general – stars: AGB and post-AGB – stars: individual: PG 1034+001

1. Introduction

PG 1034+001 ($\alpha_{2000} = 10^h37^m04\overset{s}{.}0$, $\delta_{2000} = -0°8'20''$) is a very hot, hydrogen-deficient DO white dwarf. Werner et al. (1995) determined $T_{eff} = 100^{+15}_{-10}$ kK, $\log g = 7.5 \pm 0.3$ (cgs) by means of NLTE model atmosphere techniques. From its position in the $\log g$–$\log T_{eff}$ plane (Fig. 2), they concluded that PG 1034+001 is a successor of the hydrogen-deficient PG 1159 stars.

Very recently, Hewett et al. (2003) found by investigation of spectra from the Sloan Digital Sky Survey (SDSS, York et al. 2000) that, at a distance of 155^{+58}_{-43} pc (Werner et al. 1995), a planetary nebula (PN) with a linear diameter of about 3.5–7.0 pc surrounds PG 1034+001. This is larger than the PN Sh 2-216 with a size of 3.5 pc at distance of 130^{+9}_{-8} pc (Harris et al. 1997). Only one PN, namely PN G080.3–10.4 (MWP 1) surrounding the PG 1159 star RX J2117.1+3412 (Appleton et al. 1993), may be physically larger. At a distance

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of $1.4^{+0.7}_{-0.5}$ kpc (Motch et al. 1993), its apparent diameter of $14'45''$ (Rauch 1997) corresponds to a physical size of 6^{+3}_{-2} pc.

However, whatever an improvement of the distance determination for the PN around PG 1034+001 or RX J2117.1+3412 may yield, our inspection of the Southern H-Alpha Sky Survey Atlas (SHASSA, Gaustad et al. 2001) has shown two much more extended emission structures surrounding PG 1034+001 which might make this object the largest PN known to date. In the following, we will describe our discovery in more detail.
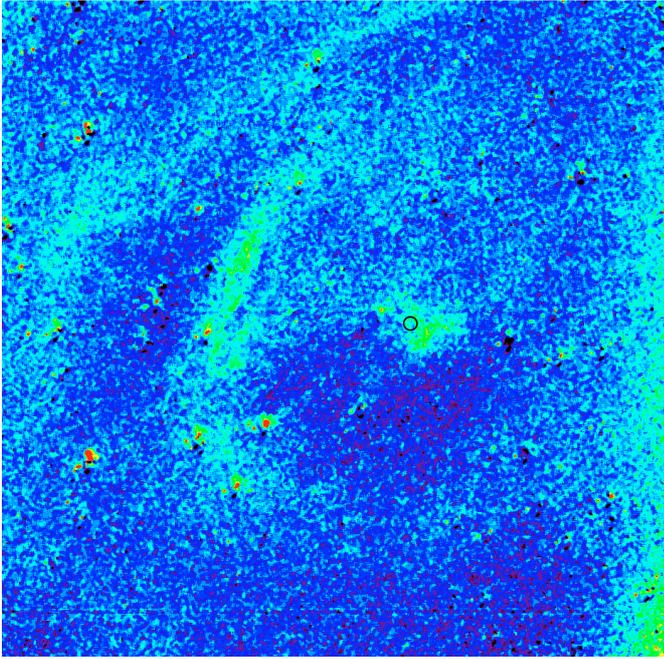
2. Examination of the SHASSA images

A close inspection of SHASSA field #214 (Fig. 1), centered on $\alpha_{2000} = 01^h43^m$ and $\delta_{2000} = -0°14'$), shows in addition to the planetary nebula discovered by Hewett et al. (2003) two larger, elliptic structures which are apparently surrounding PG 1034+001. The inner has a diameter of $6° \times 9°$ corresponding to linear diameter of $16.2^{+6.1}_{-4.5} \times 24.3^{+9.1}_{-6.8}$ pc at $d = 155^{+58}_{-43}$ pc. The wider shell (only a fragment is visible in the NE, see Fig. 1) has an estimated diameter of $10° \times 16°$. At a galactic latitude of $+47°$ filaments forming an elliptical shell are rare in

Fig. 1. SHASSA field #214. PG 1034+001 is marked by a circle. East is left and North is up. The field size is about $13° \times 13°$ with a pixel size of $0\rlap{.}'8$. Note the elliptic emission structure lying from SSE to NW, most prominent on the NE side. The diameter is about $6° \times 9°$. A second emission structure further outside can be seen to the NE.

the SHASSA survey. Therefore the likelihood of a chance su-perposition with PG 1034+001 is very small.

These structures are even larger than the ionized halo of ambient interstellar matter ($4° \times 5°$, 17×21 pc at a distance of 240 pc) around the PN A 36 which was recently discovered by McCullough et al. (2001) also using SHASSA.

3. PG 1034+001 – the exciting star?

Since the newly found emission structures are located at a sig-nificant distance (up to about 12 pc) from PG 1034+001 the question arises whether this object can actually excite them. Werner et al. (1995) proposed that PG 1034+001 is a de-scendant of the PG 1159 stars. By comparing the position of PG 1034+001 with theoretical evolutionary tracks of born-again post-AGB stars we can determine a stellar mass of $M = 0.62 \pm 0.06$ $M_\odot$ (Fig. 2) which is slightly higher than the one found by Werner et al. (1995, $M = 0.59^{+0.14}_{-0.03}$ $M_\odot$) who com-pared their data with evolutionary tracks of Wood & Faulkner (1986) for He burning post-AGB stars that had not experienced a final helium-shell flash.

From $M = 0.62 \pm 0.06$ $M_\odot$, we can calculate a stellar ra-dius $R = 0.0232^{+0.0112}_{-0.0076}$ $R_\odot$ for PG 1034+001. The number of emergent photons with energies higher than 13.6 eV and the corresponding Strömgren radii $R_{H\,II}$ are summarized in Table 1. Werner et al. (1995) determined a current $T_{eff} = 100^{+15}_{-10}$ kK, but of course PG 1034+001 has passed through a much hotter stage ($T_{eff} = 150$ kK) during its evolution (Fig. 2), only about 30 000 years ago (Blöcker 1995). Since the recombination time scale in such a low-density nebula is longer than 30 000 years,

Table 1. Strömgren radii for PG 1034+001. The pure He models are calculated with $\log g = 7.5$, $R_{H\,II}$ is calculated with an electron temper-ature $T_e = 10\,000$ K, an electron density $n_e = 3/cm^3$, and a volume filling factor of $\epsilon = 0.25$, and $R = 0.0232$ $R_\odot$.

$T_{eff}/$ kK	$N_{13.6}$ / cm^2 / s	$R_{H\,II}$ / pc
90	1.529×10^{26}	6.5
100	2.076×10^{26}	7.2
120	3.384×10^{26}	8.5
140	5.088×10^{26}	9.8
160	7.217×10^{26}	11.0
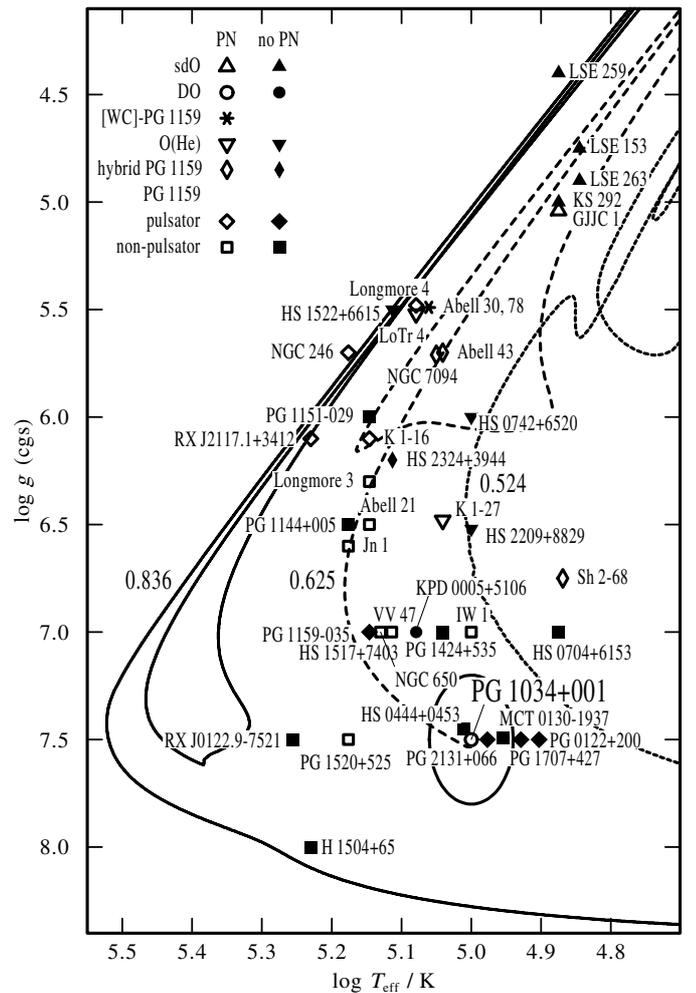
Fig. 2. Position of PG 1034+001 and related objects in the $\log T_{eff} - \log g$ plane compared with evolutionary tracks (labeled with the respective stellar masses in $M_\odot$) of born-again post-AGB stars (Blöcker 1995). The ellipse shows the error range in the spectral anal-ysis of Werner et al. (1995).

PG 1034+001 is most likely the exciting star of the nebula and the halo.

4. Galactic orbit of PG 1034+001

Proper motion (PM) of PG 1034+001 had already been re-ported by Hewett et al. (2003). We have found two addi-tional independent measurements in the UCAC2 and USNO-B

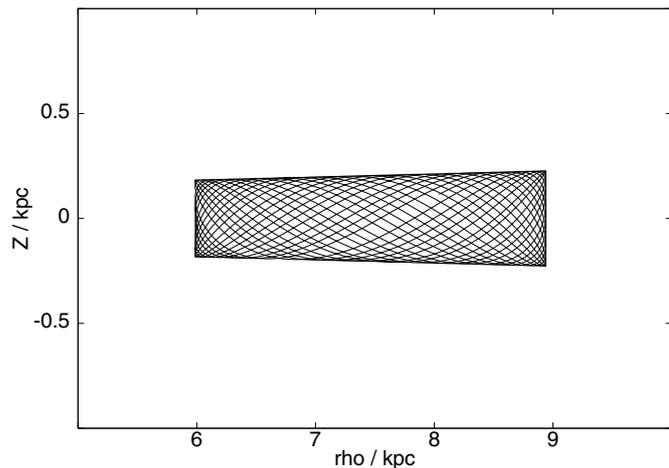**Table 2.** Proper motion (in mas yr^{-1}) for PG 1034+001 from different sources.

	Hewett et al. (2003)	UCAC2	USNO-B
$\mu(\alpha)\cos(\delta)$	-86 ± 5	-83.7 ± 3.3	-80 ± 4
$\mu(\delta)$	$+31 \pm 5$	$+28.9 \pm 1.5$	$+32 \pm 4$

Fig. 3. Galactic orbit of PG 1034+001. ρ ist the distance from the Galactic Center, z is the distance perpendicular to the disk.

catalogues, which confirm and improve upon the previous value (Table 2). For the USNO-B entry, errors smaller than 4 mas yr^{-1} are considered too optimistic (Gould 2003), and have been set to 4 mas yr^{-1}. This puts us in a position to calculate a Galactic orbit for the star, adopting a distance of 155^{+58}_{-43} pc as derived by Werner et al. (1995). In terms of radial velocity one can improve upon the previously reported value by using the velocity of the photospheric absorption lines found in the IUE spectra (Holberg et al. 1998) which result in a value of 50.83 ± 1.33 km s^{-1}. An orbit representative of the actual motion of the star is then derived by integrating back in time, with a code from Odenkirchen & Brosche (1992), using a Galactic potential from Allen & Santillan (1991). It should be noted that this orbit is an idealized one as the Galactic potential used is simplified and scattering processes between individual stars are neglected. Nevertheless orbital parameters (such as the eccentricity) can be computed and combined with velocities to gain information on population membership. We use the classification scheme presented in Pauli et al. (2003), where additionally to the position in the classical U–V-diagram, the position in the angular-momentum-eccentricity diagram and the Galactic orbit are considered. We find that all three criteria favor a thin disk membership of PG 1034+001. The orbit found (Fig. 3) is typical for a thin disk star showing both low inclination and eccentricity. We use the Galactic velocity reference system in which the local standard of rest has $(U, V, W) = (0, 220, 0)$ km s^{-1}. U is in radial direction towards the galactic center, V in the direction of the galactic rotation and W in the direction perpendicular to the Galactic disk. Details of the procedure can be found in Pauli et al. (2003).

It is interesting to note that a number of stars with rather similar PM values are present in the vicinity. Within a search radius of $2°$ we found 15 stars which have the same PM within 3σ. While small number statistics prevent us from drawing any firm conclusions, this indicates that PG 1034+001 might be part of a group of stars with a common origin. Most of these stars are faint but one object has a magnitude of about 11, which will make it easy to obtain high quality spectra and investigate its properties. Using stars within a radius of $1°$, we have also investigated the reddening as a function of distance towards PG 1034+001. We find the distance compatible with the range of 100 to 200 pc reported before, with a possible preference for the lower end of the range.

5. Interaction with the ISM

For highly evolved PNe the density in the shell can become so low that the ram pressure of the moving PN becomes comparable to the thermal pressure of the surrounding interstellar medium (ISM). At this point it will start to interact with the ISM, a process described in detail by Borkowski et al. (1990) and Soker et al. (1991). The examples for interaction with the ISM range from mild cases like Sh 2–216 (Tweedy et al. 1995) to the extreme case of the PN abandoned by its CS, Sh 2–174 (Tweedy & Napiwotzki 1994). Many more examples of PNe interacting with the ISM have been reported recently, (Tweedy & Kwitter 1996; Xilouris et al. 1996; Kerber et al. 2000; Rauch et al. 2000).

Kerber et al. (2004) have most recently demonstrated that the orbital motion of the PN is indeed the cause of this interaction with the ISM. Moreover, they showed that the parameters of the orbit, most notably eccentricity and inclination, both of which can have a pronounced effect on the velocity relative to the ISM, strongly influence the kind and degree of interaction. Figure 1 shows the $7°$ halo as an incomplete ellipse that is well defined in the E and fades in the N and SW. Unfortunately the W edge of the halo is located close to the border of the frame in the SHASSA survey and flat fielding is critical for analysis of such a low surface brightness structure. The adjacent field 213 shows diffuse emission which lacks any arclike structure and which is about a factor 1.5 fainter than the arc in the E. This diffuse emission could be part of a varying background. It seems, therefore that no well-defined halo exists in the W. The major axis of the halo has a position angle (PA) of about $310 \pm 15°$, roughly consistent with the PA of the proper motion of $289 \pm 2°$. This structure can be understood in terms of an advanced interaction with the ISM. In this scenario the leading edge of the halo has already been destroyed and its matter has mixed with the ISM, forming the faint diffuse emission in the W, while the trailing eastern edge is still rather well defined. Since PG 1034+001 is located close to the Galactic plane it is likely to reside in relatively dense ISM and interaction is possible even at modest relative velocities. The thin disk orbit found for PG 1034+001 also suggests a mild form of interaction, which because of the long time scales involved can be expected to be in an advanced stage.

For the outer halo a similar line of reasoning is possible but remains highly speculative because of the limited information we have on this structure. The inner nebula, Hewett 1, is highly filamentary and the CS is not in the geometric center of the nebula. As already pointed out by Hewett et al. (2003) the spatially varying ratios of [O III], Hα and [N II] can also be explained by an interaction with the ISM. Since the leading edge of the halo is missing it is also likely that the ISM can interact with the inner nebula. In the case of PG 1034+001 particular caution is needed with regard to this interpretation, since it is a DO white dwarf, and it probably has experienced a final helium-shell flash in its past, which produces a second PN with a very different, hydrogen-deficient chemical composition. Also, this second PN can be ejected in a highly non-spherically symmetric manner, as seen in A 30 (Borkowski et al. 1995) and V4334 Sgr (Kerber et al. 2002a).

6. Conclusions

We have discovered a huge elliptical halo with a linear diameter of $16.2^{+6.1}_{-4.5} \times 24.3^{+9.1}_{-6.8}$ pc at $d = 155^{+58}_{-43}$ pc surrounding the PN Hewett 1 and its exciting star PG 1034+001 on SHASSA images. An even larger emission structure is also visible but much fainter. From presently available observational data we do not have indications whether the emission arises from material which was ejected from PG 1034+001 or from ionized ambient ISM. Clearly better spectra and images as well as a better distance determination are needed to understand the nature of the PN surrounding PG 1034+001.

The largest PNe known so far, Sh 2–68 (Kerber et al. 2002b), Hewett 1, and MWP 1, have been found around so-called born-again post-AGB type central stars (Iben et al. 1983). Since their exciting stars have quite different masses ($0.50 M_\odot$, $0.62 M_\odot$, and $0.83 M_\odot$, respectively, see Fig. 2), the size of the PN does not appear to be related to the final mass of the ejecting star.

We have derived the Galactic orbit of PG 1034+001 and determined that it belongs to the thin disk population. The kinematical parameters and the morphology of the halo indicate that the nebula is in an advanced stage of interaction with the ISM. Since this is one of the closest and most evolved PNe, it is ideally suited for detailed study of this process which governs the return of processed matter to the ISM.

Note added in proof. The discovery of a H II region with a diameter of 1°.5, close to the position of PG 1034+001, has already been reported by Haffner (2001) using WHAM (Wisconsin H-Alpha Mapper, http://www.astro.wisc.edu/wham/) data. As a candidate for the ionizing source of this nebula he considered PG 1034+001.

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