On the most metal-poor PN and its binary central star

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Abstract. PN G135.9+55.9 is the most metal-poor PN known in our Galaxy. The central star resides in a short-period binary system with a compact component, probably a white dwarf. We describe new observations, which allowed us to determine the orbital period. The lower limit for the combined mass of both stars is close to the Chandrasekhar limit for white dwarfs, making this binary a possible progenitor of a supernova type Ia. The binary system must have recently emerged from a common envelope phase.

Keywords: Faint blue stars, Spectroscopic binaries, Planetary nebulae, Population II stars, Supernovae

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INTRODUCTION

PN G135.9+55.9, also known as SBS 1150+599A, is a planetary nebula (PN) discovered in the Second Byurakan Sky Survey. The spectrum of SBS 1150+599A is quite unusual for a planetary nebula, showing only lines of H I, He II and extremely weak forbidden lines of heavier elements (Tovmassian et al. 2001). A recent HST/STIS image shows PN G135.9+55.9 as a PN with axial-symmetric density enhancement (Fig. 1).

Initial analyses with photoionisation models indicated that the oxygen abundance is very low, around 1/100 of the solar value (Tovmassian et al. 2001). Carbon and nitrogen, which do not produce detectable lines in the optical spectrum of PN G135.9+55.9, have an important impact on the thermal balance of the PN and, indirectly, on the calculated oxygen abundance. New measurements of crucial line intensities in the UV by the HST-STIS spectrograph allow to put more stringent constrains on the carbon and nitrogen abundances, and thus on the nebular oxygen abundance. The oxygen abundance is now

FIGURE 1. HST Hα image of SBS 1150+599A.
constrained between 1/125 and 1/40 of the solar value (Stasińska et al. 2005), confirming PN G135.9+55.9 as the most oxygen poor PN known.

The low oxygen abundance indicates a population II nature of PN G135.9+55.9. Further evidence comes from a very large distance from the Galactic plane (15 kpc; Tovmassian et al. 2004) and a very high heliocentric radial velocity (−193 km/s; Richer et al. 2003).

In May 2003 we obtained a series of medium resolution spectra of PN G135.9+55.9 with the 3.6 m CFHT (Tovmassian et al. 2004). This produced a good S/N spectrum of the central star (CSPN). Photospheric hydrogen Balmer lines were clearly visible. Closer inspection revealed that the wavelength of the Balmer lines varied from exposure to exposure, indicating large radial velocity (RV) variations caused by orbital motion in a close binary (see Fig. 2). Since the observations were not optimised for the determination of orbital periods, it was not possible to determine an unambiguous period. However, we could show that 4 h was an upper limit with candidate values at 0.94 h, 1.5 h and 3.6 h.

The stellar temperature is constrained by the CSPN spectrum and the photoionisation models to 100,000...120,000 K. We adopt a CSPN mass of $0.55M_\odot$ (cf. discussion in Tovmassian et al. 2004).

NEW OBSERVATIONS

In April 2004 we secured a short series of photometric observations of PN G135.9+55.9 in the V band with the 2.1 m telescope at San Pedro Mártir/Mexico (SPM). The brightness of the CSPN was measured differentially to comparison stars. These observations revealed a clear photometric variability on the 0.1 mag level. However, the run was too short to determine its period and the precise nature of the variability.

Two short series covering one hour each of medium resolution spectra were obtained in May 2004 with the Hobby-Eberly telescope of McDonald observatory. These new RV measurements supported our longest candidate period.

In January 2005 we ran a campaign at three observatories to get near-simultaneous photometric and spectroscopic observations. Two half-nights of spectroscopy were scheduled at the Keck I telescope. Three nights of photometry were granted for the 2.2 m telescope of the Calar Alto observatory/Spain equipped with the BUSCA camera and one night at the SPM observatory. BUSCA is a CCD camera which is equipped with dichroic beam splitters to allow simultaneous observations in four colour bands. We used BUSCA without additional filters to be able to get a good time resolution with the best possible S/N. This resulted in four instrument specific broadband channels: UV (approximately 3500...4200 Å), blue (4200...5100 Å), red (5100...7200 Å) and IR (7200...9000 Å). SPM observations were carried out with a V filter.

While weather conditions at Calar Alto and SPM were good and both runs produced valuable results, poor weather conditions prevented us from observing at the Keck telescope. The brightness of the CSPN was measured differentially to comparison stars in the field.

The light curve and its interpretation

We combined the data from all three photometric runs (April 2004 and Jan. 2005) for the period determination. The resulting power spectrum is shown in Fig. 3. It is obvious that the period ambiguity present in the CFHT radial velocity data has now been overcome. The power spectrum shows a clear peak at 3.92 h, consistent with the
longest candidate period derived from the spectroscopic measurements. Fig. 4 shows the BUSCA four channel photometry, folded with the photometric period.

Inspection of the inset in Fig. 3 reveals that alias peaks of comparable strength are present. These are separated by 8.5 s, which corresponds to one cycle over the nine months time gap between the April 2004 and the Jan. 2005 runs. These aliases are of negligible importance for the interpretation of this system, but prevent us from computing reliable photometric phases for the spectra taken with the CFHT in May 2003. The new accurate period combined with the RV curve enables us to compute the mass function and a lower limit of the mass of the companion: $M_{\text{comp}} = 0.85 M_\odot$.

A few CSPN in close binaries with a main sequence companion are known to show photometric variability. A well investigated example is BE UMa. This system consists of a $\approx 105,000$ K hot CSPN, i.e. similar to the CSPN in PN G135.9+55.9, and a K dwarf companion (Liebert et al. 1995; Ferguson & James 1994; Wood et al. 1995), which is over-sized for its mass of $0.36 M_\odot$ (Ferguson et al. 1999). The BE UMa system is much wider than the PN G135.9+55.9 binary. Its orbital period is 2.29 days.

BE UMa shows a dramatic reflection effect causing a photometric amplitude of 1 mag (Kurochkin 1971). The strong radiation of the hot CSPN is reprocessed on the illuminated side of the main sequence companion. The luminosity of the system depends on the visible fraction of the illuminated hemisphere, which varies with the orbital phase. The EUV radiation of the very hot CSPN is responsible for a forest of recombination lines in emission (see, e.g., Fig. 1 in Ferguson & James 1994). During most of the orbit the CSPN spectrum is virtually swamped by the companion’s emission line forest and special care has to be taken to secure a relatively uncontaminated spectrum of the CSPN (Liebert et al. 1995).

Since no such forest of emission lines can be seen in our PN G135.9+55.9 spectra (Fig. 2), we concluded that the companion in this system must be a compact object, i.e. a white dwarf or a neutron star (Tovmassian et al. 2004). Péquignot & Tsamis (2005) objected that the PN G135.9+55.9 system is more extreme than BE UMa. They speculated that the intense radiation of the CSPN has the result that “the photosphere of a ‘main sequence’ companion could be so hot as to emit a spectrum totally different from the one of BE UMa” (Péquignot & Tsamis 2005).

We agree insofar as the ionisation balance is likely shifted from the predominant lines of O II, N II, C II/III towards higher ionisation stages, maybe as high as O VI, N V and C IV. However, these species have optical lines, which should be visible. Moreover, the heating of the parts of the illuminated hemisphere closer to the edge should be less extreme, which should allow for the presence of lower ionisation stages. Nevertheless, we will explore whether our new photometric light curve is compatible with a main sequence companion.

What effects can cause photometric variability in a close CSPN – main sequence star system?

**Reflection effect:** This was already described above.

**Eclipses:** For the given dimensions of the system deep eclipses would be expected, unless the system inclination is below $i = 60^\circ$.

**Ellipsoidal variation:** Both, CSPN and even more so the hypothetical main sequence star, would fill a major fraction of their Roche lobe. The gravitational pull of the companion causes deviations from spherical symmetry – an elongated ellipsoid in first approximation. The cross section and thus the brightness of the star(s) depends on their phase angle.

Note that the periodicity of the reflection effect is equal to the orbital period, while it is twice that for ellipsoidal light variation.

The multi-colour light curves were analysed with the Wilson-Devinney based solution code MORO (Drechsel et al. 1995), which is optimised for the treatment of early-type close binaries by the inclusion of radiative pressure effects. All relevant physical and geometrical parameters of the system can be simultaneously adjusted.

A rock bottom lower limit for a main sequence star of the required mass ($0.85 M_\odot$) is $R = 0.5 R_\odot$ (Baraffe et al. 1997). It turned out to be impossible to produce an acceptable fit to the observed light curve with a companion of this size. Die-hard fans of the main sequence companion could now argue that the companion might be undersized, because it has just recovered from the common envelope event. This is not too far fetched, because it is known that the main sequence star in the BE UMa sys-

![FIGURE 4. Phase folded photometry for the four broadband filters of the BUSCA camera taken during the Calar Alto run in Jan. 2005. The widths of the curve indicate the error limits.](image-url)
The system is still over-sized for its mass (Ferguson et al. 1999). Thus we treated the radius as a free parameter. In this case we were able to find a reasonable fit of the light curve. The resulting radius is \( R = 0.18R_\odot \) and the inclination angle \( i = 40^\circ \). However, the mass function derived from the RV curve requires \( 1.8M_\odot \) for this solution. This is far higher than any plausible mass for a main sequence companion. Thus the result of the light curve analysis supports our earlier conclusion (Tovmassian et al. 2004) that the companion must be a (pre-?) white dwarf or a neutron star.

Even without the main sequence companion an ellipsoidal light variation does not come unexpected, because the CSPN fills a significant fraction of its Roche lobe (cf. Table 2 and 3 in Tovmassian et al. 2004). We compare the measured light curve in Fig. 5 to the simplest possible ellipsoidal light curve, a sine-wave. As explained above the period of ellipsoidal variation is twice that of the orbital period. The first half of the observed light curve is well explained, but in the second half we see an excess over the predicted curve.

What can cause this extra light? One possible explanation could be a hot spot on the CSPN caused by irradiation from a neutron star companion. Alternatively, the extra light could stem from a tilted disk-like structure around the white dwarf/neutron star companion. This could possibly result from accretion from the CSPN wind or be a remnant from the recent common envelope phase. None of these models is without problems. Relative phasing of the binary orbit and the photometric variability will allow to distinguish between both possible models of the system.

SUMMARY AND OUTLOOK

SBS 1150+599A is the hot \( (T_{\text{eff}} \approx 120,000 \, \text{K}) \) central star of a very metal poor PN. The CSPN resides in a close binary system with a period \( P = 3.92 \, \text{h} \) as determined from the photometric light curve. The minimum companion mass is \( M_2 = 0.85M_\odot \). Since a main sequence component can be ruled out, the second star must be a compact object, most likely a white dwarf or alternatively a neutron star. Gravitational waves will cause the merging of the binary in 1 Gyr. Since the minimum mass of the system \( M \geq 0.55M_\odot + 0.85M_\odot \) is close to the Chandrasekhar limit, SBS 1150+599A is a very good SN Ia progenitor candidate within the double degenerate scenario.

Napiwotzki et al. (2003) conducted an RV survey (SPY) for DD progenitors of SN Ia as a large programme at the 8 m ESO VLT. About 100 DDs were detected, including only one good SN Ia progenitor candidate. This demonstrates the rareness of these objects. Had it not been for the PN and the extraordinary chemistry of PNe G135.9+55.9 the DD central star would have remained unnoticed. The SPY sample will provide information like period and mass distribution of DDs. However, the CSPN in PN G135.9+55.9 can be considered as DD in statu nascendi. The investigation of the PN offers unique opportunities to constrain the poorly understood common envelope phase. The kinematics of the PN constrain the dynamics and timescales of the CE event. The PN chemistry enables us to evaluate the dredge-up of processed material.

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