Astron. Astrophys. 300, L25–L28 (1995)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

Fading and variations in the spectrum of the central star of the very young planetary nebula SAO 244567 (Hen 1357)*

M. Parthasarathy[1], P. Garcia-Lario[2], D. de Martino[2], S.R. Pottasch[3], D. Kilkenny[4], P. Martinez[5], K.C. Sahu[6], B.E. Reddy[1], and B.T. Sewell[5]

[1] Indian Institute of Astrophysics, Koramangala, Bangalore–560034, India
[2] IUE Observatory, Villafranca Satellite Tracking Station, P.O. Box 50727, E-28080 Madrid, Spain
[3] Kapteyn Astronomical Institute, Postbus 800, 9700 AV Groningen, The Netherlands
[4] South African Astronomical Observatory, P.O. Box 9, Observatory 7935, South Africa
[5] Electron Microscopy Unit, University of Cape Town, Rondebosch 7700, South Africa
[6] European Southern Observatory, Karl-Schwarzschildstr. 2, D-85748 Garching bei München, Germany

Received 28 March 1995 / Accepted 15 June 1995

Abstract. The optical spectrum of SAO 244567 obtained in 1971 shows that it was a post-AGB B1 or B2 supergiant at that time. It has turned into a planetary nebula (PN) within the last 20 years.

The IUE ultraviolet spectra obtained during the last seven years show that the central star is rapidly evolving. It is found that the central star of this young PN has faded by a factor of 2.83 within the last seven years. The terminal velocity of the stellar wind has decreased from -3500 km s^{-1} in 1988 to almost zero in 1994. In 1988 the CIV (1550Å) line which was a P-Cygni profile with strong absorption component has almost vanished by 1994. The UV absorption and nebular features show variations in strength. This may be due to the fading of the central star and also possibly to expansion of the nebula.

These results suggest that in the central star the nuclear fuel is almost extinct as a result of post-AGB mass loss. The main stellar energy may be gravothermal energy. Typical for hydrogen-burning AGB remnants is a very fast drop in luminosity by an order of magnitude when the burning cannot be sustained any longer. These results suggest that the central star of this young PN is rapidly evolving to become a DA white dwarf.

An alternative interpretation is that the present fading could be due to an episode of high mass loss, which is now just completed. If the ultraviolet fading was a factor of 2.83 from 1988 to 1995, the luminosity would remain the same if the temperature increased from 37500K to 47500K in the same period. It may be that these changes occur in steps which are triggered by episodic mass loss periods during the post-AGB evolution, and that the hydrogen burning has not stopped or stopped temporarily.

Key words: Planetary nebulae: individual: SAO 244567 (Hen 1357) - stars: post-AGB - stars: mass-loss- stars: evolution - ultraviolet: stars

1. Introduction

The post-Asymptotic Giant Branch (AGB) stars are understood to evolve from the tip of the AGB towards the left in the H-R diagram at constant luminosity. However, the increasing temperature, combined with a steadily decreasing radius, results in a temporal change of the spectral distribution of the emergent flux. When the surface temperature of the remnant becomes high enough, photons from the remnant cause a portion of the nebula to fluoresce in the optical. Also, a fast wind from the remnant forms a hot bubble which helps shape the nebula. Eventually, nuclear burning dies out and the remnant fades and cools as a white dwarf. SAO 244567 appears to be evolving along the above mentioned evolutionary scheme. However the time scales are extremely rapid compared to those predicted from the models (Vassiliadis and Wood 1994).

SAO 244567 (CPD -59 6926 = Hen 1357 = IRAS 17119-5926) is a high galactic latitude early type star (l = 331°, b = -12°), originally classified as a B or A type Hα emission line star by Henize (1976). Parthasarathy and Pottasch (1989) found it to be an IRAS source with far infrared (IRAS) colours similar to planetary nebulae (PN). Based on the IRAS colours, far infrared flux distribution and dust shell characteristics, Parthasarathy and Pottasch (1989) suggested that it is a post-AGB star. They also suggested that it is rapidly evolving into early stages of planetary nebula. Recently Parthasarathy et al. (1993) analysed the IUE ultraviolet and optical spectra of SAO 244567 and discovered it to be a rapidly evolving young planetary nebula (PN). Based on all the available data since 1950 Parthasarathy et al. (1993) concluded that SAO 244567 has turned into a PN within the last 40 years. Parthasarathy et al. (1993) found nebular features in the ultraviolet and optical spectra. They found evidence for variations in the spectrum

*Based on observations made with the IUE Satellite, VILSPA, Madrid, Spain, South African Astronomical Observatory, South Africa, and European Southern Observatory, La Silla, Chile.
Send offprint requests to: M.Parthasarathy

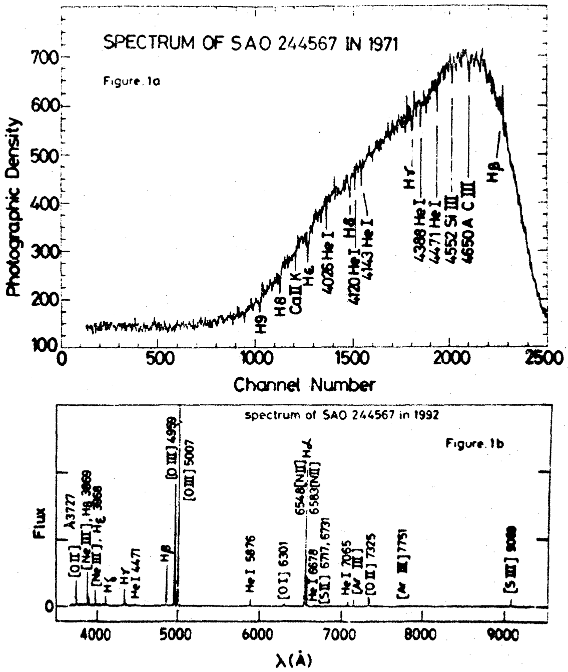

Fig. 1. Optical spectrum of SAO 244567 in 1971 and 1992

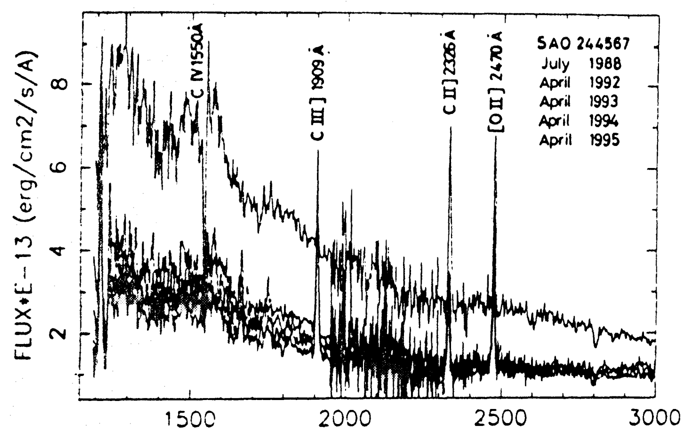

Fig. 2. IUE low resolution spectra of SAO 244567 from 1988 to 1995

and for fading of the star. The radio observations at 6 cm revealed the extent of the nebula to be 1.″5 to 2 ″. Recently Bobrowsky (1994) obtained narrowband optically resolved images of SAO 244567 with the HST Planetary Camera. The HST images in both Hβ and [OIII] 5007Åshow a well resolved nebula surrounding the central star.

The IUE ultraviolet absolute fluxes (1200Åto 3200Å) obtained in July 1988 and April 1992 show that within 4 years the central star has faded by a factor of 2. The CIII] 1909Å emission strength has increased very markedly within 4 years (Parthasarathy et al 1993). We continued to monitor this star in the ultraviolet region with the IUE satellite. In this paper we present an analysis of the recent ultraviolet spectra of SAO 244567. We also show the optical spectrum of this star obtained in 1971, which gives support to the idea that SAO 244567 has turned into a PN within the last 20 years.

2. Observations

The ultraviolet spectra (1150Å to 3200Å) were obtained in July 1988, April 1992, April 1993, April 1994 and April 1995 using the IUE satellite from the Villafranca Satellite Tracking Station, Madrid. The low resolution (6Å) spectra were obtained through the large aperture which includes all the flux of the object. All these spectra are well exposed and have relatively high signal to noise ratio.

3. Analysis

3.1. The optical spectrum in 1971

The moderate-dispersion (86Å mm^{-1} at Hγ) optical spectrum of SAO 244567 obtained in 1971 is shown in Figure 1a. It was obtained with two-prism spectrograph at the Cassegrain focus of the Radcliffe 1.88-m telescope in 1971 (Hill, Kilkenny and van Breda 1974., Kilkenny and Hill 1975). Hill et al. (1974) give the HD spectral type to be B0 and the MK spectral type to be B3e. We made a careful spectral classification of the spectrum of SAO 244567 (Figure 1a) obtained in 1971 and found the spectral type to be B1 or B2 and luminosity class I or II. The UBV colours obtained at about the same time are consistent with this classification. The UBV colours and B1 or B2 supergiant spectrum indicate that the Teff of SAO 244567 in 1971 was 21000 K. Only the Hβ is found to be relatively strongly in emission. It is likely that the higher order Balmer lines would be affected by emission, especially Hγ and perhaps Hδ. The Hγ looks quite shallow and might even have a central emission (although the low resolution makes this more uncertain) (Figure 1a). The strengths of the rest of the hydrogen lines , helium lines and nitrogen lines appear to be normal. The optical spectrum of SAO 244567 obtained in 1992 using the 1.5-m ESO telescope at La Silla (Chile) is shown in Figure 1b. The optical spectrum in 1990 (Parthasarathy et al.(1993)) and 1992 (Fig 1b), the IUE ultraviolet spectra and the HST Hβ and [OIII] 5007Å images (Bobrowsky 1994) show that SAO 244567 has turned into a PN within the last 20 years.

3.2. Stellar UV continuum

The IUE ultraviolet spectra are reduced using the standard IUE data reduction programmes. The spectra are shown in Figure 2. The degradation in the sensitivity of the SWP and LWP cameras from 1988 to 1995 has been corrected for; it is only 3 and 5 percent respectively (Garhart and Eby 1994). The integrated ultraviolet fluxes (1250Å to 3000Å) of SAO 244567 during the period July 1988 to April 1995 are given in Table 1. From the data given in Table 1 it is clear that the central star has gradually faded by a factor of 2.83 in seven years (i.e. since July 1988). Hill et al. (1974) made UBV photometry of SAO 244567 in 1968-1970. They derived V = 10.75, B-V = -0.02 and U-B = -0.89. Kozok (1985) made UBV photometry in 1980 and derived V = 10.95, B-V = -0.043 and U-B = -0.884. The V magnitudes and B-V colours suggests that the star has become fainter and hotter since 1970. The UBV colours in 1970 and 1980, after correcting for reddening (E(B-V) = 0.2), correspond to that of a B1 supergiant of effective temperature Teff = 21000K. The ultraviolet flux distribution

Table 1.

UV Flux (ergs cm^{-2}s^{-1})$\times$ 10^{-10}

July 1988	April 92	April 93	April 94	April 95
8.06	4.06	3.69	3.28	2.85

Fluxes of UV nebular emission lines ergs cm^{-2}s^{-1}$\times$ (10^{-12})

	OIII]	NIII]	CIII]	CII]	[OII]
July 1988	-	0.33	0.23	4.86	3.64
April 1992	1.05	0.35	4.74	2.49	2.71
April 1993	0.68	0.49	4.06	2.19	3.49
April 1994	0.61	0.61	3.66	1.49	3.50
April 1995	0.61	0.61	3.15	2.36	2.91

Stellar wind velocities(km s^{-1}) derived from the CIV line

July 1988	April 92	April 93	April 94	April 95
-3540	-3390	-700	≈0	≈0

obtained in 1988 yields Teff = 37500 K (Parthasarathy et al. 1993). In the optical spectrum the [OIII] 5007Å line is substantially stronger than Hβ and is consistent with a temperature of 35000 K to 40000K for the central star. The UV flux distributions obtained since 1988 (Figure 2) indicates that the central star is gradually becoming hotter and at the same time fainter. In addition to fading in the UV, the strength of UV absorption lines has also decreased by 1995. The strengths of 1255Å, 1300Å (SiIII), 1371Å (OV), 1394Å + 1403Å (SiIV), 1550Å (CIV) features suggest that the spectral type of the star has changed from O8V to earlier than O7V. The decrease in the strength of SiIV (1394Å + 1403Å) and CIV (1550Å) resonance doublets with time suggests that the surface gravity of the star has increased since 1988. These lines have a positive luminosity effect in early-type stars.That is in early-type stars these lines show a decrease in strength as the surface gravity increases. These results suggest an increase in surface gravity and effective temperature during this period.

3.3. Stellar wind

In the UV spectrum of SAO 244567 obtained in 1988 (Figure 2) the NV (1239-1243Å) and CIV (1548-1551Å) resonance doublets are found to be blue-shifted and show P-Cygni profiles (Parthasarathy et al. 1993),indicating the presence of strong stellar wind and mass loss. The absorption strength of CIV (1550Å) has decreased significantly in 1992 (Figure 2), however the terminal velocity of the stellar wind is the same as that observed in 1988 (Parthasarathy et al 1993). By 1994 the CIV line has almost vanished and the stellar wind velocity decreased to almost zero (Figure 2, Table 1). The absorption strength of NV increased in 1992 and by 1995 it has decreased and the P-Cygni emission has vanished. These variations indicate the cessation of the rapid mass loss episode. The relation between the terminal velocity of the stellar wind and the Teff found for central stars of PNe (Heap 1986) suggests Teff=80000K during the period 1988 to 1992 . Comparision with the wind models for central stars of PNe developed by Pauldrach et al. (1988) suggests Teff=80000K, mass loss rate of 4.9$\times$ 10^{-9}M$_\odot$ per year and the central star mass to be 0.565M$_\odot$

3.4. The UV nebular lines

The strengths of nebular emission lines of OIII]1660Å, NIII]1750Å, CIII]1909Å, CII]2326Å and [OII] 2470Å since July 1988 to April 1995 are given in Table 1. In 1988 the OIII], NIII], and CIII] lines were very weak (Fig 2). In 1992 the CIII] line strength has increased very substantially, and OIII] and NIII] also show slight increase in strength, and the CII] and [OII] lines show a significant decrease in strength indicating an increase in the ionization in the nebula. During the period 1993 to 1995 CIII] line shows a gradual decrease in strength and the CII] and [OII] lines show significant variations in strength (Table 1).

4. Discussion

The HST imaging of SAO 244567 (Bobrowsky 1994) reveals that the nebular gas appears more strongly concentrated in an ellipse with its major axis subtending 1.″6 from NW to SE. Above and below this ring of gas there are two bubbles containing lower density gas and the full extent of the nebula including the low density bubbles is 2.″3. Using a distance of 5.6 kpc and an expansion velocity of 8 km s^{-1} derived from the high resolution [OIII] 5007Å line profile (Parthasarathy et al 1993), the 1.″6 bright elliptical ring revealed in the HST imaging corresponds to an expansion age of 2700 years and a size of 0.0434 parsec. This ring is formed by the previous mass loss experienced by the star on the tip of the AGB. Thus the AGB phase of evolution of SAO 244567 was terminated about 2700 years ago. The low density gas bubbles seen in the HST images may be the result of fast wind from the remnant during the post-AGB stage. The IUE ultraviolet spectra show evidence for fast stellar wind with a velocity of -3000 km s^{-1} (Figure 2, Table 1). The total size of the nebula including these bubbles is 2.″3 and corresponds to 0.0624 parsec. If we use the -3000 km s^{-1} stellar wind velocity this size corresponds to a wind blown bubble of age 20 years. The optical spectrum in 1971 and the present (Fig 1) also suggest that the post-AGB remnant became hot enough within the last 20 years to cause the nebula to fluoresce and the fast stellar wind helped to shape the nebula.

Using a distance of 5.6 kpc we estimated the luminosity of the central star to be 3000 L$_\odot$ and the core mass luminosity relation (Wood and Zarro 1981) suggested the core mass to be 0.55 M$_\odot$ (Parthasarathy et al 1993). Bobrowsky (1994) using the Hβ flux, estimated the luminosity of the central star to be 5012 L$_\odot$, and the core mass to be 0.59 M$_\odot$. A 0.6 M$_\odot$ post-AGB star takes 10,000 years to evolve from the tip of the AGB to the white-dwarf cooling track (Iben 1984). The luminosity, the core mass, observed rapid evolution and fading of SAO 244567 are not in agreement with the time scales of evolution of low mass or high mass post-AGB models.

The post-AGB evolution is mainly controlled by the (hydrogen) burning rate at the base of the envelope and available nuclear fuel (envelope mass). The fading in luminosity towards the cooling path when shell sources are practically extinct, is, however, dependent on the thermo-mechanical structure of the core, which in turn is determined by its mass and age counted from the end of central helium burning. Typical for hydrogen-burning AGB remnants is a very fast drop in luminosity by an order of magnitude when the burning cannot be sustained any longer (Schonberner 1981). In SAO 244567 the nuclear fuel may be almost extinct as a result of post-AGB mass loss. The fading, mass loss via stellar wind , cessation of stellar wind, and the decrease in strength of UV absorption lines, and also the rapid evolution towards higher temperatures of SAO 244567 suggests that the nuclear burning has become unimportant. The main stellar energy source should be gravothermal energy. SAO 244567 is the only known central star of a PN which has faded as fast as a factor of 2.83 within a period of 7 years. Blocker and Schonberner's (1990) post-AGB evolutionary calculations pointed out that not only the remnant mass, but also the initial mass, and thus the mass loss history of the models determines the fading timescales. They find that their massive remnant of 0.84 $M_\odot$ fades slower than a less massive one of 0.61 $M_\odot$.

Schonberner's (1986) study shows that only post-AGB models which burned hydrogen quiescently when the they left the AGB, and which continue to do so, depict such a rapid luminosity drop. The hydrogen-burning post-AGB model evolves about three times faster through the region occupied by the central stars than a helium -burning model of the same mass. These results suggest that the central star of SAO 244567 is on its way to become a DA white dwarf.

Our previous mention of the post-AGB models of Schonberner and Vassiliadis and Wood does not mean that the observations of SAO 244567 are following the expectations as given by the models. First of all, the fading is occurring much more rapidly than predicted, considering that it has taken 2700 years to go from the tip of the AGB to Teff = 21000 K (Teff in 1971 as determined from the UBV colours and spectrum),and about 20 years to turn into a PN. Secondly, if the nuclear burning has stopped, it has stopped at a much lower surface temperature than any of the post-AGB evolutionary models suggest.

An alternative interpretation is that the present fading could be due to an episode of high mass loss, which is now just completed. In this case the total luminosity is not decreasing, but is remaining constant. If the ultraviolet fading was a factor of 2.83 from 1988 to 1995, the luminosity would remain the same if the temperature increased from 37500 K to 47500 K in the same period. It may be that these changes occur in steps which are triggered by episodic mass loss periods during the post-AGB evolution, and that hydrogen burning has not stopped (or only temporarily has stopped) and will continue in the future.

In the number - luminosity distribution of homogeneous samples of observed PN nuclei there are clear and pronounced minima., these minima are highly likely to be associated with large but temporary increases in the rate of dimming experienced by a post-AGB hydrogen burner when CN cycle burning ceases abruptly, may be as a result of an episode of high mass loss.

5. Conclusions

An analysis of the IUE ultraviolet spectra of the central star of the young PN SAO 244567 (Hen 1357) reveals that the central star has faded by a factor of 2.83 within the last seven years. The stellar wind velocity which was -3500 km s^{-1} from 1988 to 1992 has decreased and it became almost zero by 1994. The UV nebular emission lines show significant variations in strength. The CIV (1550Å) line decreased in strength from 1988 and almost vanished by 1994. The NV strength has decreased and the P-Cygni emission has vanished by 1995. These results indicate the cessation of the rapid mass loss episode.

The 1971 optical spectrum of SAO 244567 shows that in 1971 it was a B1 or B2 supergiant like star in post-AGB stage of evolution. It evolved rapidly and turned into a PN within the last 20 years. The nebular size from the HST images, the expansion velocity of 8 km s^{-1} and an uncertain distance of 5.6 kpc suggest that the AGB phase of SAO 244567 was terminated about 2700 years ago. The -3500 km s^{-1} fast stellar wind has helped to shape the nebula.

The B1 supergiant like spectrum of SAO 244567 in 1971 shows that the post-AGB stars before they turn into PN have extended atmospheres and may mimic the spectra of supergiants. Recently, Parthasarathy (1993,1994) found LS II +34 26 (B1.5 Ia-Iabe) to be a post-AGB star with far-infrared colours and nebular lines similar to PN. The B1 supergiant like spectrum of SAO 244567 before it turned into a PN confirms the evolutionary sequence of post-AGB supergiants.

Note added in proof

Recently Feibelman (ApJ 443,245, 1995) found numerous Fe V and Fe VI photospheric absorption lines in the high resolution ultraviolet (IUE) spectrum of SAO 244567. The presence of Fe V and Fe VI absorption lines indicate that the Teff of the central star to be of the order of 55000K.

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