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Near-infrared photometry of the final helium shell flash object V4334 Sagittarii

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ABSTRACT

JHK photometry of the final helium shell flash object V4334 Sagittarii undertaken during 1996–97 is presented in this paper. The data reveal the formation of circumstellar dust of temperature ~1800 K two years after outburst. Around $5 \times 10^{-10}\,M_{\odot}$ of dust condensed at a distance of about $7R_{\star}$ from the star. The mass of V4334 Sgr is $0.8\,M_{\odot}$ and it had a radius of $\sim 70\,R_{\odot}$ in 1997 April–May.

Key words: techniques: photometric – stars: AGB and post-AGB – circumstellar matter – stars: individual: V4334 Sgr – stars: peculiar – infrared: stars.

1 INTRODUCTION

1.1 The final helium shell flash

A planetary nebula nucleus moving towards the white dwarf cooling track can experience a final thermal pulse because of an explosive helium-burning episode in its shell. The flash causes the star to expand to giant dimensions, and it becomes a 'born-again' asymptotic giant branch (AGB) star (Iben et al. 1983). Even as the star becomes luminous, expands and cools, its surface composition undergoes continual changes. Nucleosynthesis and mixing make its outer layers hydrogen-poor, helium- and carbon-rich. These physical and chemical changes are predicted to take place on time-scales of months. The consequences of the final helium flash afford us with direct experimental evidence of the late stages of stellar evolution. Observational studies of final flash stars are thus very important to formulate a good theoretical framework of the final flash scenario. This phenomenon has been invoked to explain the existence of hydrogen-deficient supergiants, R CrB stars and non-DA white dwarfs. Final flash stars are seen as a link to the formation of these objects [Iben, Tutukov & Yungelson (1996) have given extensive discussions on various competing theories regarding the formation and evolution of hydrogen-deficient supergiants]. The near-infrared (near-IR) observations presented in this paper reveal a dust condensation phase in the newly discovered final flash star V4334 Sagittarii.

1.2 V4334 Sagittarii

Sakurai's peculiar variable in Sagittarius (= V4334 Sgr; Nakano 1996) underwent a final helium shell flash and brightened in a nova-like fashion during 1995–96 to become a born-again AGB star. Takamizawa's photographic observations available at the VSNET site (http://www.kusastro.kyoto-u.jp/vsnet/) show that the object brightened by more than four magnitudes in the two years preceeding its discovery. The overall outburst amplitude is about 10 mag considering the faint precursor identified by Duerbeck & Benetti (1996, hereafter DB96) on the ESO/SERC *J* plate. Its *V* magnitude hovered at around 11.0 (±0.2) since outburst till mid-1997. Minor oscillations were superposed on the small brightness increase during 1996–97. Spectroscopically, it was an F2 supergiant in early 1996 (DB96) and cooled to an effective temperature of 6900 K in 1996 October (Asplund et al. 1997). Arkhipova & Noskova (1997) infer that the star changed from an F1–2 supergiant in 1996 February to a G0–2 supergiant in 1996 October. The rise to maximum and early spectroscopic appearance is reminiscent of V605 Aql, a previously observed final flash star (Clayton & DeMarco 1997).

2 NEAR-INFRARED PHOTOMETRY

V605 Aql brightened up long before the advent of astronomical infrared detectors. However, *IRAS* data and the optical light curve provide evidence of circumstellar dust condensation in this object (see, for example, Harrison 1996). The outburst of V4334 Sgr has provided us with a rare opportunity to monitor a final flash star in the infrared.

We observed this unique object in the *JHK* bands on several occasions during 1996–97. The near-IR photometric data presented in Table 1 were obtained using a liquid-nitrogen-cooled InSb photometer on the 1.2-m telescope of PRL's Mt. Abu Infrared Observatory. The details of the experimental setup are given in Ashok et al. (1994). A chopping frequency of 10 Hz, a throw of 35 arcsec and a 26-arcsec aperture were used for the observations. The 1996 observations were taken with dewar 2, and dewar 1 was used in 1997. Typical errors are ±0.3 mag for the 1996 observations and ±0.05 mag for the 1997 observations in all bands. η Oph [$J = 2.328$, $H = 2.313$ and $K = 2.288$ (Bouchet, Manfroid & Schmider 1991)] was used as the standard star on all days.

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Table 1. *JHK* photometry of V4334 Sgr.

Date UT	JD 245 0000+	*J*	*H*	*K*
Feb 1996				
27.00	140.50	—	—	8.7
28.00	141.50	—	—	8.5
Mar 1996				
2.99	145.49	—	—	8.0
24.00	166.50	—	—	9.0
Apr 1997				
17.98	556.48[a]	7.69	6.86	6.07
18.94	557.44	7.73	6.87	6.12
May 1997				
11.85	580.35	7.92	7.03	6.12
12.93	581.43	7.81	6.97	6.27
13.83	582.33	7.86	7.06	6.11
14.85	583.35	7.70	6.96	6.13
15.96	584.46	7.75	6.91	6.13
16.87	585.37	7.92	6.98	6.10
17.92	586.42	7.84	6.84	6.13
22.88	591.38	7.74	6.89	6.15
24.83	593.33	7.64	6.80	6.12

[a] 13 arcsec aperture.

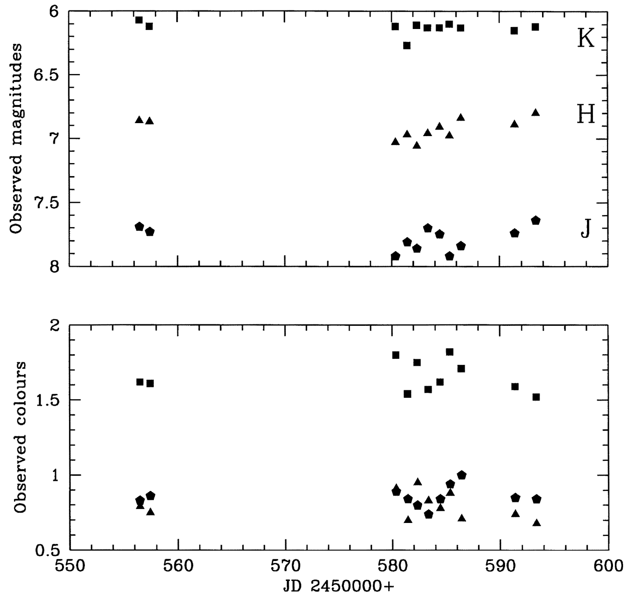

Figure 1. Observed magnitudes and colours of V4334 Sgr during the dust condensation phase in 1997 April–May. In the bottom panel, $(J-H)$ is denoted by filled pentagons, $(H-K)$ by filled triangles and $(J-K)$ by filled squares.

3 ANALYSIS AND DISCUSSION

3.1 Extinction, distance and luminosity

Extinction towards V4334 Sgr has been determined by various methods. DB96 have primarily used the Balmer decrement to arrive at $E_{B-V}=0.54$. However, a higher value of 0.7 is given by N. Kameswara Rao (private communication, hereafter NKR) from the strength of diffuse interstellar bands. D. Pollacco (private communication) has derived 0.71 ± 0.08 from the Balmer decrement. Duerbeck et al. (1997, hereafter D97) find that the value of $E_{B-V}=0.53$ gives a good match to the dereddened $U-B$ and $B-V$ colours when they are compared to synthetic colours of R CrB stars. Taking into account various arguments in favour of adopting this value (D97) we use the same number in our analysis and also explain the effects of using the larger extinction value.

DB96 have derived a statistical distance of 5.5 kpc. Kinematical distances based on observed radial velocities lead to values of 6.5 kpc (NKR) and 8 kpc (D97) depending on the assumptions regarding galactic structure and rotation. Assuming an actual radius of 0.6 pc for the nebula (typical of old planetary nebulae), the angular radius of 16 arcsec (DB96) gives a distance of 7.7 kpc. Therefore, we adopt the D97 distance estimate of 8 kpc. The expansion velocity of 25 km s^{-1} (DB96) then gives an expansion age of 23 000 years for the nebula. We note that the distance of 1.1 kpc derived by Kimeswenger & Kerber (1998) leads to an M_v of -0.8, which is too low for an object of this nature. A luminosity of $L_\star \sim 10^4\,L_\odot$ (D97) is more reasonable for an object of this type.

3.2 Dust formation in V4334 Sgr

The optical photometry of Kimeswenger et al. (1997), dereddened using $E_{B-V}=0.53$, implies a colour temperature of 5000 K for the star. This corresponds to a spectral type of G3I. We assume that this physical condition, valid in 1997 late March, did not change much during 1997 April-May. Prominent C_2 Swan bands seen in the optical spectra obtained by Kerber, Gratl & Roth (1997) in 1997 late March testify to the rapid cooling of Sakurai's object since 1996 October. The appearance of molecular features indicates that physical conditions in the circumstellar matter were conducive to dust formation.

The star had an average K magnitude of 8.5 in early 1996. By 1997 April–May it had brightened to mean magnitudes of $J=7.78 \pm 0.09$, $H=6.92 \pm 0.08$ and $K=6.13 \pm 0.05$ (Fig. 1). The K flux had thus increased by almost 1000 per cent over the 1996 observations, a fact also noticed by Kimeswenger et al. (1997). This increase is far greater than that caused by spectroscopic changes alone and calls for a newly developed IR source. The dereddened near-IR colour indices show a clear excess over a G3I star, implying dust condensation (Fig. 2). We calculate this excess to result from a dust shell of temperature 1900 K. If the reddening is $E_{B-V}=0.71$, the spectral type of the star remaining the same, a dust temperature of 1750 K is obtained. On the other hand, we can use this reddening to redetermine the spectral type of the star. The result is a colour temperature of around 5500 K, implying a spectral type of G0I. The IR excess now yields a dust temperature of 1875 K. We adopt a mean value of 1800 K in further discussions. This dust formation episode did not lead to any immediate dimming in the V band. Therefore, the dust may have formed in a portion of the spherical shell not in our line of sight or in an asymmetric or bipolar outflow.

Assuming that the condensed dust is composed of carbon grains $\leq 1\,\mu$m in size and having a density of ~ 2.25 g cm^{-3}, the mass of the dust can be estimated using (Woodward et al. 1993 and references therein)

$$M_{\rm d} = 1.1 \times 10^6 (\lambda F_\lambda)_{\rm max} D^2 / T_{\rm d}^6,$$

with $(\lambda F_\lambda)_{\rm max}$ in W cm^{-2}, D, the distance to the star, in kpc and $T_{\rm d}$, the dust temperature, in units of 10^3 K. Using the K-band flux contribution of the dust shell we find the mass of dust to be $\sim 5 \times 10^{-10}\,M_\odot$ for a dust temperature ($T_{\rm d}$) of 1800 K. The mass of dust in V605 Aql is not known. A weak near-IR excess over an F2 supergiant in early 1996 was interpreted by DB96 as evidence of hot ($T \approx 3000-4000$ K) dust. However, they found no evidence of mass loss by a thick wind. This means that the dust was very close to the star at that time. The distance at which the dust is present, $R_{\rm d}$,

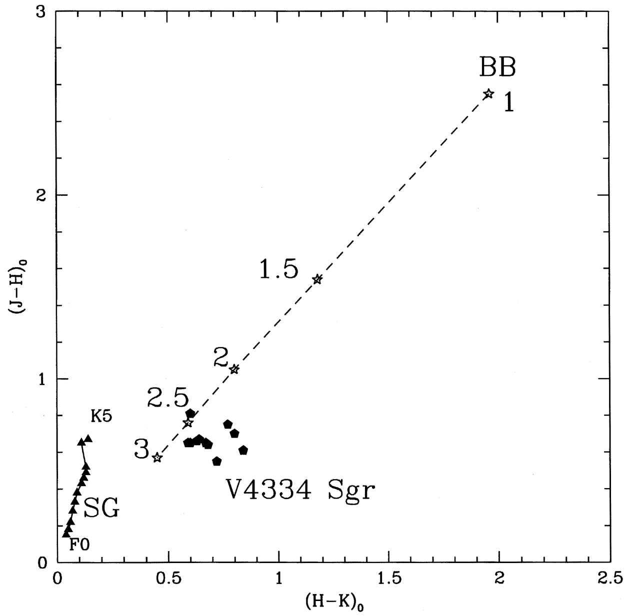

Figure 2. Two-colour diagram for V4334 Sgr. Observed magnitudes have been dereddened using $E_{B-V} = 0.53$ and are represented by filled pentagons. Supergiant (SG) and blackbody (BB) lines are shown for comparison. Numbers along the BB line give temperature in units of 1000 K.

can be calculated using

$$R_{\rm d} = (L_\star/16\pi\sigma T_{\rm d}^4 Q_{\rm d})^{1/2}.$$

$R_{\rm d}$ turns out to be $\sim$500 $R_\odot$ for $Q_{\rm d} = 1$ and other values as assumed above. Assuming the idealized case that all the stellar radiation is absorbed and re-emitted by black dust particles, the radius of the star, $R_\star$, is

$$R_\star = R_{\rm d}/(T_{\rm d}/T_\star)^2.$$

Thus, the radius of the star was 70 $R_\odot$ during 1997 April–May. The dust lies at $7R_\star$ from the star and it would have formed in a slow ($\sim$4 km s^{-1}) wind.

3.3 Mass of V4334 Sgr

Asplund et al. (1997) have compared the observed abundance ratios of V4334 Sgr with the Iben & MacDonald (1995) model of a 0.6 $M_\odot$ star and find them to be quite similar. However, the evolution of V4334 Sgr has been faster than that predicted by the same model. Since larger-mass stars evolve faster through the final flash (Iben et al. 1983), the mass should be higher than 0.6 $M_\odot$. D97 arrived at a value of 0.7 $M_\odot$ for the star based on the core–mass luminosity relation. Blöcker & Schönberner (1997) have constructed a grid of thermally pulsating post-AGB models to determine the mass of FG Sge. Comparing the VSNET *V* light curve of V4334 Sgr to their fig. 4 one can see that the mass of V4334 Sgr must lie closer to 0.8 $M_\odot$. If the similarity between V4334 Sgr and V605 Aql is because of similar masses, then a mass of $\sim$1 $M_\odot$ is appropriate. This is the value given by Bond et al. (1993) for V605 Aql. Considering these factors, a mass of 0.8 $\pm$ 0.2 $M_\odot$ seems a good estimate in the case of V4334 Sgr.

4 CONCLUSIONS

The conclusions may be summarized as follows:

1 A large increase in the near-IR flux because of a dust condensation episode was seen about two years after the outburst of the final helium shell flash object V4334 Sgr.

2 About 5×10^{-10} $M_\odot$ of dust condensed around the star. The dust temperature was around 1800 K.

3 The mass of V4334 Sgr is estimated to be about 0.8 $M_\odot$.

4 Observations of V605 Aql and V4334 Sgr have revealed dust formation episodes in their evolutionary process. Thus, dust formation may be a natural phenomenon in final flash objects.

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