OPTICAL STUDIES OF V4332 SAGITTARI: DETECTION OF UNUSUALLY STRONG K I AND Na I LINES IN EMISSION

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Received 2003 December 17; accepted 2004 February 2; published 2004 February 26

ABSTRACT

We present optical observations of the enigmatic nova-like variable V4332 Sgr. The importance of this object should not be understated since it is considered to be the possible prototype of a new class of eruptive variables. These objects have been the subject of considerable studies at present primarily because of the spectacular eruption of V838 Mon—another member of this class—recently in 2002. The cause of the outburst in such objects is not well understood. Our recent work has shown striking changes in the near-IR spectrum of V4332 Sgr since its 1994 outburst. The optical spectrum presented here confirms that V4332 Sgr is indeed an unusual and extremely interesting object. This spectrum, the first to be taken after a hiatus of nearly 10 years after the outburst, shows several lines in emission but is dominated by exceptionally strong emission in the resonance doublet of K I at 7665 and 7699 Å and to a slightly lesser strength in the unresolved Na I doublet at 5890 and 5896 Å. The K I lines are shown to be optically thin and considerably broadened. We investigate the site of origin of the K I and Na I emission. Considering the strength of the alkali metal lines—seen at similar strength only in L- and T-type dwarfs (although in absorption)—we discuss whether the outburst of V4332 Sgr was an explosion on an L- or T-type dwarf. However, BVRI photometry does not support such a scenario but rather shows the central object of V4332 Sgr to be an M-type star with a temperature of 3250 K.

Subject headings: novae, cataclysmic variables — stars: individual (V4332 Sagittarii) — techniques: spectroscopic

1. INTRODUCTION

V4332 Sagittarii (V4332 Sgr) erupted in 1994 in a nova-like explosion that was recognized to be unusual (Martini et al. 1999). The object showed a rapid postoutburst evolution to a cool M giant/supergiant that was uncharacteristic of a classical nova outburst. The light curve of the object (Martini et al. 1999) showed a slow rise to a maximum visual magnitude of ∼2.8. This was followed by a fast decline with the decay time for 2 and 3 mag being 8 ± 1 and 12 ± 1 days, respectively. Current interest in V4332 Sgr was resurrected by the 2002 January eruption of V838 Mon, which showed the outburst characteristics of both objects to be quite similar (Munari et al. 2002). V838 Mon, iconized by its remarkable light echo (Bond et al. 2003), has been at the center of several recent and ongoing studies. There is a general consensus that V4332 Sgr, V838 Mon, and M31 RV (a red variable that erupted in M31; Rich et al. 1989) may belong to a new and select class of eruptive variables whose postoutburst behavior is different on many counts from other classes of eruptive variables (Munari et al. 2002; Banerjee & Ashok 2002). The fundamental question regarding the cause of the explosion in such eruptive variables or quasi novae is not completely understood. Plausible explanations for the outburst involve merger of stars (Soker & Yıldız 2003) and a star capturing its encircling planets (Rettler & Marom 2003). The cause of the outburst is still uncertain, and there is a definite need to study these objects further to gain a better understanding of their nature and evolution.

In a recent work (Banerjee et al. 2003, hereafter B03) we had shown that V4332 Sgr has a very interesting near-IR spectrum at present. Several new bands of ALO were detected, and it was also shown that the spectral energy distribution (SED) of the object had undergone a striking change, a new dust shell having formed recently. The present optical study shows that V4332 Sgr is rising like a phoenix from the ashes. Our results, discussed below, show that there is a variety and richness in its spectrum that is rarely encountered in astronomical sources.

2. OBSERVATIONS

The optical observations were made on 2003 September 29 using the recently commissioned 2 m Himalaya Chandra Telescope (HCT) located at Hanle, India. Spectroscopy and photometry were done using the Himalaya Faint Object Spectrograph Camera (HFOC), which uses a liquid-nitrogen cooled 2048 × 4096 pixel CCD with 15 μm pixel2 as the detector. It has a 10′ × 10′ unvignetted field in imaging mode and also has several grisms for low- and intermediate-resolution spectroscopy. The spectra presented here were obtained at R ~ 870 using a slit 1.3 wide. The spectrum of V4332 Sgr and the standard star Feige 110 were obtained with exposure times of 15 and 10 minutes, respectively. The standard star spectrum was used to ratio the V4332 Sgr spectrum to remove telluric/airglow lines. The ratioed spectrum was finally multiplied by a smooth polynomial fit to the flux-calibrated spectrum of Feige 110-232 (Landolt 1992). A cross-check for the calibration was done by observing the Landolt standard star SA 110-232 (Landolt 1992). A cross-check for the calibration was also done by calculating the magnitudes of another comparison star SA 110-230. There is a good agreement (±0.05 mag) between the derived and the listed magnitudes of the comparison star. The mean air mass at the time of observations was 1.40 and 0.0498 mag for the and Na I emissions. The ratioed spectrum was finally multiplied by a smooth polynomial fit to the flux-calibrated spectrum of Feige 110 as given in Massey et al. (1988); this gives the proper slope to the continuum of the V4332 Sgr spectrum. All spectra were wavelength calibrated using a Fe-Ar spectral lamp.

Photometry in the BVRI bands, using HFOC, was done by taking multiple exposures in the BVRI bands. Photometric calibration was done by observing the Landolt standard star SA 110-232 (Landolt 1992). A cross-check for the calibration was also done by calculating the magnitudes of another comparison star SA 110-230. There is a good agreement (±0.05 mag) between the derived and the listed magnitudes of the comparison star. The mean air mass at the time of observations was 1.40 and 2.3 for V4332 Sgr and the standard star, respectively. Extinction corrections were done using mean values of the extinction coefficient per unit air mass of 0.209, 0.121, 0.0823, and 0.0498 mag for the B, V, R, and I bands, respectively, for the HCT observatory site. The photometric and spectroscopic...
data were reduced using IRAF. The details of the photometry and the derived BVRI magnitudes for V4332 Sgr are given in Table 1.

3. RESULTS

3.1. Optical Spectroscopy

The spectrum of V4332 Sgr covering the 5000–8300 Å spectral range is shown in Figure 1. The identification of the lines and the equivalent widths of the atomic lines are given in Table 2. Some unidentified features are also listed with their observed wavelengths and equivalent widths. As can be seen, the striking feature of the spectrum is the great strength of the K i resonance doublet at 7665 and 7699 Å. The blend of the Na i doublet at 5890 and 5896 Å, although unresolved in the spectrum, is also very prominent. We have surveyed the literature, as comprehensively as possible, for reported detections of K i and Na i lines in emission. Although their occurrence is not too common (K i detection is much rarer than Na i), they have been seen in a variety of objects, viz., comets, Io, Jupiter, the Moon, R Coronae Borealis (RCB) stars at minimum, a few Be stars such as HD 45677, MWC 645, and P Cygni, around red giants such as Betelgeuse, and around some N-type stars. Among these, RCB stars in particular are seen to display strong Na i lines during their minima (Kameswara Rao et al. 1999) and K i to a much weaker extent. In general, we find that the observed strength of the K i doublet in V4332 Sgr is unusual, and it could be among the strongest to be detected in an astronomical source. The presence of the Rb i lines in emission also appears to be rare. Although the Rb i lines are blended with the neighboring TiO γ(3, 4) band, we feel that their identification is correct because of the good match between their observed and laboratory wavelengths. Several of the TiO bands identified here are also seen in emission in the peculiar red giant star U Equulei (Barnbaum, Omont, & Morris 1996).

We find that the average FWHM of the K i doublet is greater than that of the instrument profile as obtained from two spectral lamp lines in the same wavelength region. Since Gaussian fits to the K i lines and the instrument profile are found to give a good agreement, the intrinsic width of the K i lines can be obtained from

\[ \text{FWHM}_{\text{intrinsic}}^2 = \text{FWHM}_{\text{obs}}^2 - \text{FWHM}_{\text{instr}}^2, \]

where the subscripts refer to the intrinsic, observed, and instrumental widths. For the observed values of FWHM_{obs} of 10.6 Å and FWHM_{instr} equal to 8.24 Å, we find that FWHM_{intrinsic} is \( \sim 6.6 \) Å or 260 km s\(^{-1}\). The expected line width due to Doppler broadening of the K i atoms, having a mass \( m_{K_i} \), a kinetic temperature \( T \), and a turbulent velocity \( V_t \) (assumed to be Gaussian), is given by

\[ \Delta v_b = \frac{1}{\lambda} \left( \frac{2kT}{m_{K_i}} + V_t^2 \right)^{1/2}. \]

From equation (2) it is seen that thermal broadening will account for a negligible amount of the observed line width of 6.6 Å (e.g., at \( T = 1000 \) K, the thermal broadening for the K i line is only 1 km s\(^{-1}\)). Thus there is a large amount of velocity dispersion in the K i-emitting gas. A significant part of this broadening could be due to line-of-sight averaging of different velocity components in the K i shell in case it has an expansion or rotation velocity associated with it. This aspect is discussed later in § 3.3.

![Fig. 1.—Observed optical spectrum of V4332 Sgr showing the unusually strong K i resonance doublet at 7665 and 7699 Å and the unresolved Na i resonance doublet at 5890 and 5896 Å. The identification of the other prominent lines, as given in Table 1, are marked (u.i means unidentified).](image-url)

| Table 1: Log of Photometric Observations for 2003 September 29 |
|-------------------|-------------------|-------------------|-------------------|
| UT               | Band | Exposure Time | Integration Time | Magnitude (Error) |
| 12.199           | B    | 50            | 250              | 20.04 (0.15)      |
| 12.017           | V    | 10            | 90               | 17.52 (0.14)      |
| 11.955           | R    | 4             | 80               | 16.31 (0.01)      |
| 11.955           | I    | 4             | 80               | 15.01 (0.03)      |

| Table 2: List of the Observed Lines in V4332 Sgr |
|-----------------|-----------------|-----------------|-----------------|
| Serial Number   | Rest Wavelength | Species         | Equivalent Width |
| 1               | 5197            | u.i             | 40              |
| 2               | 5890, 5896      | Na i            | 210             |
| 3               | 6035            | u.i             | 15              |
| 4               | 6086.4          | VO (0, 1)?      | ...             |
| 5               | 6159            | TiO γ(0, 0)     | ...             |
| 6               | 6187            | TiO γ(0, 0)     | ...             |
| 7               | 6215            | TiO γ(0, 0)     | ...             |
| 8               | 6403            | u.i             | 16              |
| 9               | 6569            | TiO γ(0, 1)?    | ...             |
| 10              | 6651.5          | TiO γ(1, 0)     | ...             |
| 11              | 6681.1          | TiO γ(1, 0)     | ...             |
| 12              | 6714.4          | TiO γ(1, 0)     | ...             |
| 13              | 6780            | u.i             | 15              |
| 14              | 6843            | u.i             | 4               |
| 15              | 7054.5          | TiO γ(0, 0)     | ...             |
| 16              | 7087.9          | TiO γ(0, 0)     | ...             |
| 17              | 7125.6          | TiO γ(0, 0)     | ...             |
| 18              | 7197.7          | TiO γ(1, 1)     | ...             |
| 19              | 7664.9          | K i             | 193             |
| 20              | 7698.96         | K i             | 176             |
| 21              | 7800.3          | Rb i            | 9               |
| 22              | 7861           | TiO γ(3, 4)     | ...             |
| 23              | 7907.3          | TiO γ(3, 4)     | ...             |
| 24              | 7947.6          | Rb i            | 5               |
| 25              | 7987            | u.i             | 6               |

Note.—Unidentified lines are marked as u.i, and uncertain identifications are marked with a question mark.
The K I doublet lines are expected to have a strength of 2:1 in case they are optically thin. However, the observed ratio is closer to unity for the K I doublet (1.1:1) indicating that the lines are optically thick. Following Williams (1994), the optical depth \( \tau \) in the K I 7665 Å line can be calculated from

\[
\frac{I_{7665}}{I_{7699}} = \frac{1 - e^{-\tau}}{1 - e^{-\tau_i}},
\]

where \( I_{7665} \) and \( I_{7699} \) are the observed intensities. Considering the observed equivalent widths of 193 and 176 Å for the K I lines (Table 2) to represent their intensities, we get a value of \( \tau \sim 4.5 \) from equation (3).

If the K I emission arises from a column of length \( R \), the column density can then be obtained from the relation

\[
\tau = N_{K_i} \frac{\sqrt{\pi} e^2}{m_e} \frac{f}{\Delta \nu_o} R, \tag{4}
\]

where \( N_{K_i} \) is the number density of the K I atoms, \( f \) is the oscillator strength for the 7665 Å transition (\( f = 0.335 \)), and \( \Delta \nu_o \) is the local line width given by equation (2). Using values of \( \tau \sim 4.5 \) and \( \Delta \nu_o = 3.4 \times 10^{11} \) s\(^{-1} \) (corresponding to an intrinsic width of 6.6 Å), we derive a column density \( N_{K_i} R = 3 \times 10^{14} \) cm\(^{-2} \). The value of \( N_{K_i} R \) can be used to calculate the mass of the K I region (Williams 1994) in case its geometry is better established in any future study; at present we are not too sure of the geometry as discussed in § 3.3.

3.2. Photometry and SED

The SED of V4332 Sgr is shown in Figure 2. The BVRI fluxes have been computed after reddening corrections adopting \( E(B-V) = 0.32 \) from Martini et al. (1999) and using zero magnitude fluxes from Bessell, Castelli, & Plez (1998). The JHK fluxes from B03 are also plotted to show the SED over an extended wavelength range. The present BVRI data establish more definitively—as suggested in B03—that the hot component of V4332 Sgr is well fitted by a blackbody of 3250 K. The newly formed dust component (B03) is also well fitted by a 900 K blackbody. Associating the 3250 K component with the central star of V4332 Sgr shows that it has an effective temperature corresponding to M5 type. Its luminosity class is uncertain because of distance uncertainties, but as per our earlier estimate it is slightly overluminous for a main-sequence M5 object. The SED also suggests that the central star has remained at a constant temperature of 3250 K between the 1998 Two Micron All Sky Survey observations (B03) and now. If this is the quiescent state of the star, then it appears that the 1994 explosion has taken place on an M-type star. This gives a more definite classification, not available before, on the likely nature of the progenitor on which the outburst has taken place. This should be a useful input for models investigating the cause of the outburst in quasi novae. It is difficult to conclude, on the basis of the present data, whether V4332 Sgr is a binary system. The emission lines are in general found to be blueshifted by \( \sim 3 \) Å—a point already noted in the high-resolution Hα line profiles of V4332 Sgr obtained during outburst by Martini et al. (1999). The similar observed blueshift of the lines at two different epochs suggests that the blueshift of the lines could be due to systemic motion. Radial velocity monitoring at higher spectral resolution (than in the present studies) would be helpful in establishing or ruling out binarity for V4332 Sgr. It may be pointed out that a hot B3 V companion to the outbursting star has been reported in V838 Mon (Wagner et al. 2003).

Considering the large strength of the alkali metal lines in V4332 Sgr, we have investigated whether the M5 central object is some variant of a brown dwarf or a very low mass star. Brown dwarfs and very low mass stars show, like V4332 Sgr, very strong resonance lines of the alkali metals—although in absorption (e.g., Burgasser et al. 2003 and references therein). In these objects, the Na I and K I lines are the strongest, while Rb I and Cs I are progressively weaker. Rb I lines are present in our spectrum; the Cs I doublet at 8521, 8943 Å is not covered in our spectrum. Further evidence that V4332 Sgr type of objects could be related to very cool dwarfs comes from the near-IR spectra of V838 Mon, which indicate that it could be an L giant (Evans et al. 2003). We therefore compared the colors of V4332 Sgr with a large sample of L- and T-type dwarfs whose BVRIJK magnitudes are available (Dahn et al. 2002). However, our results do not show V4332 Sgr to have the colors of an L- or T-type dwarf. The BVRI colors of the suggested M5 central star are not red enough. In the near-IR, the comparison is made difficult by the contribution of the dust shell in V4332 Sgr to the JHK colors. While flaring activity on a brown dwarf—over a period of few hours—has been reported (e.g., Rutledge et al. 2000), no instance is known of a nova-like eruption in them.

3.3. Origin and Excitation of the K I Emission

Since the K I/Na I lines are seen in emission and not in absorption, they cannot be of photospheric origin but should originate from an extended envelope. It is likely that some of the emission in the K I/Na I lines could be caused by resonance scattering from the continuum of the 3250 K central source. In addition, collisional excitation could also contribute to the observed line strength. This is because the resonance lines have low-excitation energies, viz., they are at 2.1, 1.61, and 1.56 eV above the ground level for Na I, K I, and Rb I, respectively. Collisions in a low-temperature gas could excite the atoms to the upper levels. Further, the work of Tsuji (1973) on expected
molecular abundances of different species in stellar atmospheres shows that the alkali metals do not associate themselves into any molecular form at low temperatures in the range 1000–1500 K. Thus the availability of a large number of neutral atoms with low energy for their excitation could be responsible for the strong K i and Na i lines. However, we have presented here only a qualitative discussion, and an estimate of the fractional contribution of collisional excitation vis-à-vis resonance scattering to the observed line strengths needs a detailed analysis.

As the K t/Na I lines are optically thick, yet do not show P Cygni profiles, they are unlikely to originate in a stellar wind. Two possibilities for the site of the K i emission are (1) a disk around the central source or (2) the ejecta of the 1994 outburst. A point in support of the latter case is that Na I was seen in emission in the ejecta during the 1994 outburst (Martini et al. 1999). However, the 1994 ejecta is expected to have a spatially resolved diameter of 2″–3″ based on the well-estimated expansion velocity of 200–300 km s⁻¹ for the ejecta and an adopted distance estimate of 300 pc to the object (Martini et al. 1999). The present optical spectrum suggests weakly that there could be extended emission along the slit at the positions of the K i and Na i lines. A high spatial resolution image of V4332 Sgr would be invaluable to look for an extended emission zone around the object. It may be pointed out that the observed broadening of the K i lines could be accounted for by an expanding nova shell.

However, we favor the possibility of the K i gas being in an extended disk around V4332 Sgr. In a recent observation from the United Kingdom Infrared Telescope, we have detected the ¹²CO fundamental band at 4.67 μm strongly in emission (again a rare phenomenon) and also find a deep water ice absorption band at 3.1 μm (paper in preparation). The co-existence of several species, requiring successively cooler temperature conditions, in the same object, viz., neutral species such as K t/Na i, molecular species such as AlO, TiO and CO, and finally, a cold solid-phase water ice component suggests a spatial stratification of the different species. Therefore, a possible and simplistic scenario for the geometry of V4332 could be a central source at 3250 K surrounded by a dust shell. The dust shell is either clumpy or optically thin since radiation from the central source is seen in the SED. Surrounding the central source is a disk with the atomic and molecular species in the inner parts and ice in the colder outer regions. If the gas in the disk has a Keplerian velocity [which would typically be ~150 km s⁻¹ for an M5 star at a distance of (5–10)R∗], the emission lines from the disk could get broadened substantially because of rotational motion. This could account for the observed width of the K i lines in V4332 Sgr. Incidentally, the presence of a disk, if it has planetary bodies in it, creates the necessary background for the outburst mechanism of a star capturing its planets—as suggested by Retter & Marom (2003)—to become viable.

This work highlights the detection of strong emission lines of alkali metals in V4332 Sgr. The optical spectrum strengthens the idea—since nothing similar to it has been found earlier in a nova—that V4332 Sgr belongs to a new class of eruptive variables. V4332 Sgr is found to be an extremely interesting object, worthy of wider attention and studies.

The research work at the Physics Research Laboratory is funded by the Department of Space, Government of India. We thank the staff of HCT, Hanle, and CREST, Hosakote, who made these observations possible. We are grateful to the referee, M. Della Valle, for his helpful comments.

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