L. AND M BAND INFRARED STUDIES OF V4332 SAGITTARII: DETECTION OF THE WATER ICE ABSORPTION BAND AT 3.05 \( \mu \text{m} \) AND THE CO FUNDAMENTAL BAND IN EMISSION

DIPANKAR P. K. BANERJEE
Physical Research Laboratory, Navrangpura, Ahmedabad Gujarat 380009, India; orion@prl.ernet.in

WATSON P. VARRICATT
Joint Astronomy Center, 660 North A’ohoku Place, Hilo, HI 96720; w.varricatt@jach.hawaii.edu

AND

NAGARHALI M. ASHOK
Physical Research Laboratory, Navrangpura, Ahmedabad Gujarat 380009, India; ashok@prl.ernet.in

Received 2004 July 29; accepted 2004 September 15; published 2004 September 21

ABSTRACT

L and M band observations of the nova-like variable V4332 Sgr are presented. Two significant results are obtained, viz., the unusual detection of water ice at 3.05 \( \mu \text{m} \) and the fundamental band of \(^{12}\)CO at 4.67 \( \mu \text{m} \) in emission. The ice feature is a first detection in a nova-like variable, while the CO emission is rarely seen in novae. These results, when considered together with other existing data, imply that V4332 Sgr could be a young object surrounded by a circumstellar disk containing gas, dust, and ice. The reason for a nova-like outburst to occur in such a system is unclear. But since planets are believed to form in such disks, it appears plausible that the enigmatic outburst of V4332 Sgr could be due to a planetary infall. We also give a more reliable estimate for an epoch of dust formation around V4332 Sgr that appears to have taken place rather late in 1999—nearly 5 years after its outburst.

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

1. INTRODUCTION

We present here L and M band results on V4332 Sgr. Recent studies of V4332 Sgr have shown that it is an interesting object, and the present results further support this view. V4332 Sgr erupted in 1994 in a nova-like outburst with an outburst amplitude of 9.5 mag in the visible region. There was only one detailed study of the object during its outburst (Martini et al. 1999), which showed that its eruption was different from that of a classical nova or other classes of eruptive variables. Interest in the object has been rekindled because of the recent outburst of V838 Mon, which drew considerable attention because of its light echo (Munari et al. 2002; Bond et al. 2003). It is believed that V838 Mon, V4332 Sgr, and M31 RV (a red variable that exploded in M31 in 1988; Rich et al. 1989) could be members of a new class of eruptive objects (Munari et al. 2002; Bond et al. 2003; Kimswenger et al. 2002). The cause of the outburst in these objects does not appear to be satisfactorily explained by conventional mechanisms. Thus, new theories have been proposed, viz., a scenario involving the merger of main-sequence stars (Soker & Tylenda 2003) and a hypothesis invoking planetary capture by an expanding star to explain the eruption (Retter & Marom 2003). The present data indicate that the second mechanism could be viable in V4332 Sgr.

Recent infrared studies of V4332 Sgr have detected several bands of AlO at a low rotational temperature of 200–300 K (Banerjee et al. 2003). A considerable change in the spectral energy distribution (SED) of the object was seen between Two Micron All Sky Survey (2MASS) data of 1998 and observations in 2003 indicating the formation of a dust shell between these two epochs (Banerjee et al. 2003). A better estimate of the epoch when the dust actually formed is discussed here. Optical spectroscopy of V4332 Sgr in 2003 showed an interesting spectrum dominated by very strong emission in the resonance lines of K i and Na i (Banerjee & Ashok 2004). The SED of the star, derived from optical and IR data, indicated a central star with a blackbody temperature of 3250 K and an IR excess attributed to a dust component at \( \sim 900 \text{ K} \) (Banerjee & Ashok 2004).

2. OBSERVATIONS

Observations were done using the 3.8 m UK Infrared Telescope (UKIRT). Spectroscopy was done using the UKIRT 1–5 \( \mu \text{m} \) Imager Spectrometer (UIST), which uses different grisms to cover the 1.4–5 \( \mu \text{m} \) range. \( L' \) (3.77 \( \mu \text{m} \)) and \( M' \) (4.68 \( \mu \text{m} \)) band photometry—not available earlier for V4332 Sgr—was also done using UIST. Flat-fielding, spectral calibration, and other reduction procedures were done on the same lines as our earlier JHK study of V4332 Sgr (Banerjee et al. 2003). The log of the observations and the observed \( L' \) and \( M' \) magnitudes of V4332 Sgr are given in Table 1.

3. RESULTS

3.1. The Water Ice Feature at 3.05 \( \mu \text{m} \) and the CO Fundamental Band Emission

Figure 1 shows the spectrum; the A–X bands of AlO in the HK band, reported earlier (Banerjee et al. 2003), are seen prominently in the present spectrum also but are not discussed here. A remarkable feature—never seen before in a nova-like object—is the deep, solid-state 3.05 \( \mu \text{m} \) water ice band formed as a result of the O–H stretching mode. At very low temperatures, atoms and molecules can collide and adhere to a dust grain to produce an ice mantle on the surface. Atoms can migrate from one site to another on the mantle to form a molecule—water ice is believed to form this way with H atoms combining with an O atom. The presence of cold water ice around V4332 Sgr is extremely unexpected since the ejecta of classical novae generally evolve to high temperatures of \( \sim 10^6 \) K (the coronal phase). Following a standard procedure, we have obtained the optical depth plot of the ice feature by fitting a polynomial to the continuum around it (Gibb et al. 2004). The depth of the ice feature below this continuum was found and converted to an optical depth. The
TABLE 1

Log of Observations for V4332 Sgr

| Date (UT)   | Band | Resolution | Integration Time (s) | Standard Star | Magnitude |
|-------------|------|------------|----------------------|---------------|-----------|
| 2003 Sep 5.294       | M    | 1000       | 312                  | BS 6998       |           |
| 2003 Sep 5.359       | KL   | 700        | 360                  | BS 6998       |           |
| 2003 Sep 5.328       | Short L | 650      | 720                  | BS 6969       |           |
| 2004 Apr 15.606      | HK   | 500        | 720                  | BS 7038       |           |
| 2004 Apr 29.642      | Long L | 1150    | 320                  | BS 6998       |           |

Photometry

| Date (UT)   | L'   | Integration Time (s) | Standard Star | Magnitude |
|-------------|------|----------------------|---------------|-----------|
| 2003 Sep 5.262 |      | 252                  | HD 161743     | 7.23 ± 0.025 |
| 2003 Sep 5.276 |      | 322                  | HD 161743     | 6.10 ± 0.03 |

optical depth plot is shown in Figure 2. The 3.05 μm feature was compared with laboratory data for the optical depth of water ice at different temperatures (10, 30, 50, 120, and 160 K) taken from the Leiden database for ice analogs. From a χ²-test to the observed and model data, we find that the 50 K data give the smallest value of χ². The 30 K data also give a comparable value of χ², thus suggesting a low temperature of ~30–50 K for the water ice. An extended red wing between 3.3 and 3.8 μm, which is not well fitted by the models, is seen in the observed data. This extended ice wing is also seen in several other ice detections, but the species responsible for it is unidentified (Gibb et al. 2004). From Figure 2, the column density of the water ice was calculated using $N = \int \tau dv/A$, where $A$ is the band strength for water ice with a laboratory measured value of $A = 20 \times 10^{-17}$ cm molecule$^{-1}$. While carrying out the integration, we have assumed that the missing data points around 2.65 μm (due to atmospheric cutoff), are represented by the data points of the 50 K laboratory model in that region. We obtain a value of $\int \tau dv = 362 \pm 27$ cm$^{-1}$ leading to $N = (1.81 \pm 0.13) \times 10^{18}$ cm$^{-2}$—this value may be used in case of future detection of other ices (CO, CH$_3$OH, CH$_4$, etc.) in V4332 Sgr to get a better understanding of the ice composition.

Another rare feature seen in V4332 Sgr is the fundamental band ($v = 1–0$) of $^{13}$CO at 4.67 μm in emission. There appear to be only a few other detections of the CO fundamental in emission—mostly toward young stellar objects (YSOs) and Herbig AeBe stars (e.g., Blake & Boogert 2004; Pontoppidan et al. 2002). In a few novae, emission in the CO first overtone bands has been seen (Rudy et al. 2003, Table 3; Evans et al. 1996), but the detection of the fundamental band appears rare (Lynch et al. 1997). The expanded CO rovibrational spectrum in V4332 Sgr is shown in Figure 3. Individual branch lines from $P_1$ to $P_{12}$ and $R_0$ to $R_{12}$ are clearly seen. The lines are not resolved at their intrinsic width at the observed resolution of 1000. A simple

---

1 See http://www.strw.leidenuniv.nl/~lab.
model for the $^{12}$CO emission was computed assuming LTE conditions with the level populations proportional to $(2J + 1)e^{-\frac{E_J}{kT}}$, where $B$ and $J$ are the rotational constant for CO and the rotational quantum number, respectively; $T$ is the temperature. The strength of each $P$- or $R$-branch line was then obtained using the transition probabilities for the lines given by Goorvitch (1994). The line positions were also taken from Goorvitch (1994). The model spectrum thus obtained was convolved with a Gaussian instrument function of FWHM 0.046 μm (i.e., a resolution of 1000). From the model fits, it is difficult to constrain the temperature of the gas too accurately, but a relatively low temperature of $\sim 300–400$ K is suggested. This could possibly be the reason for the absence in V4332 Sgr of the first overtone CO bands at 2.3–2.45 μm. These bands have been modeled to have a temperature in the range 2500–4500 K in novae (Rudy et al. 2003; Evans et al. 1996). Furthermore, the strong presence of AlO bands in V4332 Sgr in the same spectral region as the CO first overtone bands makes it difficult to draw definite conclusions on the absence/presence of the latter. A better estimate for the CO temperature than that derived here would require modeling based on higher resolution spectra (e.g., Blake & Boogert 2004; Pontoppidan et al. 2002).

3.2. The Case for V4332 Sgr Being a Young Object with a Surrounding Circumstellar Disk

The detection of water ice at 30–50 K in V4332 Sgr is very intriguing since such a low-temperature component is not expected in novae ejecta. Based on the recent comprehensive survey (Gibb et al. 2004 and references therein), most water ice detections are seen toward embedded YSOs/protopstars. Such objects are known to have circumstellar disks (CSDs) around them. In addition, water ice has also been seen in Herbig AeBe stars and a few T Tauri stars (Creech Eakman et al. 2002; Meeus et al. 2001; Gibb et al. 2004). These are all young objects observationally known to possess CSDs. Furthermore, all the gaseous components of V4332 Sgr are seen in emission, i.e., the K i/Na i, CO, AlO, and TiO lines (Banerjee & Ashok 2004; Banerjee et al. 2003). These species are at a low temperature (200 K for AlO; a low excitation temperature is also implied for the K i/Na i lines, which need only $\sim 1.5–2$ eV for excitation). If the region in which these species exist were to be a shell surrounding the central 3250 K star of V4332 Sgr (Banerjee & Ashok 2004), the relatively cold gas of these species should lead to lines in absorption. Such is not the case. Instead, if the various species are in a disk, their lines can be expected in emission. Furthermore, in the case of a disk, the central star would also be observable since it will be unobscured (some obscuration could occur depending on the orientation and thickness of the disk). Such is the case in V4332 Sgr, where the continuum from the central star is clearly seen. Additional support for a CSD is the infrared excess seen in V4332 Sgr (Banerjee & Ashok 2004). This IR excess can be attributed to dust in the disk and not in a shell around the star since the dust shell would obscure the visible radiation of the star. A similar reasoning is used to explain the IR excess in T Tauri stars. It is also relevant to note that many of the known CO fundamental detections are in disk-dominated Herbig Ae stars (Blake & Boogert 2004). The considerable width of the K i lines in V4332 Sgr was also shown to be consistent with line broadening arising from rotational motion of gas in a disk (Banerjee & Ashok 2004). An additional signature that V4332 Sgr has preexisting matter around it at the time of the 1994 outburst comes from the high-resolution Hα profiles of the object taken shortly after its outburst. These profiles (Fig. 8 of Martini et al. 1999) show a deep absorption trough at the center, which could be caused by absorption by preexisting matter. Therefore, many of the observed characteristics of V4332 Sgr support the existence of a CSD around the object. However, it is difficult to rule out the possibility of the matter being in clumps instead of a disk. It may be pointed out that the maximum value of $\tau \sim 1$ of the ice feature (Fig. 2) would imply a large extinction of $A_p \sim 14$ mag toward the central star, had the 3.05 μm absorption arisen because of cold, intervening matter in the line of sight (as in embedded YSOs in dark clouds; Whittet 1992). As the central star appears unobscured ($V = 17.52$; Banerjee & Ashok 2004), the 3.05 μm feature could instead be caused by ice in the CSD viewed against the IR flux from dust in the disk leading to the absorption feature.

3.3. The Formation of Dust around V4332 Sgr

It was earlier shown that the $JHK$ fluxes of V4332 Sgr changed considerably between 2MASS observations of 1998 May ($J = 12.1, H = 11.6, K = 10.992$) and observations of 2003 June ($J = 13.25, H = 11.986, K = 10.023$; Banerjee et al. 2003). While the 2MASS data showed no IR excess and was well modeled by a 3250 K blackbody, the 2003 data showed a composite SED of a blackbody component at 900 K (due to newly formed dust) and a weakening of the 3250 K component due to obscuration by dust. However, it was not possible to establish with accuracy at which stage between 1998 and 2003 the dust formed. Data from the Deep Near Infrared Survey (DENIS) is now available, and this shows that in 1999 September V4332 Sgr had IR magnitudes of $J = 12.46$ and $K = 10.65$ (DENIS did not observe in the $H$ band). A comparison between 2MASS and DENIS JK magnitudes clearly shows the IR flux increasing toward longer wavelengths, indicating that dust formation had begun by the DENIS epoch. The formation of dust therefore took place at $t_{\text{dust}} \sim 5.5$ yr after the outburst of 1994.
February. This is much larger than the typical timescale of 50–100 days for dust formation in classical novae. The difficulty in having a large dust-condensation time in novae is that the density in the ejecta decreases to a low level—owing to expansion—that does not favor dust formation. The density $\rho$ in the ejecta of novae that form dust is in the range $10^{-15}$ to $10^{-16}$ g cm$^{-3}$ (Gehrz 1988). In V4332 Sgr, the electron density $n_e$ after $\sim$2–3 months from the outburst was estimated to be $10^5–10^6$ cm$^{-3}$ (Martini et al. 1999). A geometric dilution for the expanding ejecta may be a reasonable assumption, i.e., $n_e \propto 1/r^2$ provided the ejecta expands freely, unhindered by preexisting matter. Assuming $n_e \propto 1/r^2$, after a time of 5.5 yr, $n_e$ should have evolved to $\sim 10^{-16}$ g cm$^{-3}$, giving a value of $\rho = 10^{-17}$ to $10^{-18}$ g cm$^{-3}$. Such a low value of $\rho$ appears unfavorable for dust formation. It therefore appears that dust formation may not have occurred per se in the ejecta of the 1994 outburst. It is likely the ejecta, after a stage of free expansion, could have impinged on preexisting matter around V4332 Sgr—sufficiently far from the star—thereby heating it and giving rise to the observed emission at present from different species. This could be one possible scenario to explain the large observed time for the formation of dust. In a connected aspect, we note that the present $L^*$ and $M^*$ data of Figure 1 show the continuum peaking at $\sim$4.4 $\mu$m, indicating a lower dust temperature than the 900 K that was inferred earlier. However, mid-/far-IR observations planned on the Spitzer Space Telescope should give more definite information on the dust temperature.

4. DISCUSSION: IS A PLANETARY INFALL RESPONSIBLE FOR THE OUTBURST IN V4332 SGR?

More than a hundred stars with planets (SWPs) are known today, and in $\sim$15% of these the planetary companion is unexpectedly close to the host star (e.g., 0.05 AU). The orbits of such short-period planets around Sun-like stars can be unstable because of tidal dissipation, and they can be subsequently consumed by the host stars (Sandquist et al. 2002; Rasio et al. 1996). More evolved stars are also capable of swallowing their planets as they expand (Siess & Livio 1999). The viability of planetary ingestion is observationally supported by the enhanced metallicity seen in many SWPs—and the presence of Li isotopes in one of them—suggesting that planetary material has been accreted by the host star in the past (Santos et al. 2000; Gonzalez et al. 2001; Israeli et al. 2003). In the particular context of V4332 Sgr–type objects, Retter & Marom (2003) have explained the multiperiod outburst of V838 Mon due to an expanding star ingesting its planets.

We have shown that there is considerable evidence that V4332 Sgr is surrounded by a cold, dusty disk. It is precisely in such an environment that planets are believed to be born from the coagulation and accretion of solid ice and dust particles (Lissauer 1993). Therefore, while it may appear speculative, it is not entirely unlikely that a planet existed around V4332 Sgr and its infall led to the outburst. The plausibility of this scenario is strengthened since other conventional mechanisms—such as a thermonuclear runaway on a white dwarf surface (invoked for classical, recurrent, symbiotic novae) or a final helium shell flash (invoked for a born-again asymptotic giant branch star)—fail to explain the pre- and postoutburst properties of V4332 Sgr or similar objects. It was shown (Retter & Marom 2003) in the analysis for V838 Mon that the gravitational energy released by a $1 M_\odot$ planet falling into a solar-mass star is $4 \times 10^8 L_\odot$. The outburst luminosity of V4332 Sgr is difficult to estimate, as the distance $d$ to the object is very uncertain. Using an estimate of $d = 300$ pc (Martini et al. 1999), we have shown that the star has a quiescent luminosity of $0.3 L_\odot$ (Banerjee et al. 2003). A 9.5 mag brightening at outburst would yield an outburst luminosity of $\sim 2 \times 10^3 L_\odot$. This is lower than the predicted energy release for the capture of a $1 M_\odot$ planet but could be made consistent by revising the distance (the current distance estimate to V838 Mon has been revised upward by a factor of nearly 10 from its first estimate), invoking a smaller mass for the captured planet or assuming that a large part of the released gravitational energy has gone into expansion of the stellar envelope (Retter & Marom 2003) rather than visible radiation. However, we feel there are many aspects about the nature of V4332 Sgr that are still unclear and there is scope for alternative models, apart from that proposed here, to explain its outburst.

Research at the Physical Research Laboratory is funded by the Department of Space, Government of India. We thank the UKIRT service program for observation time covering a part of these observations. UKIRT is operated by the Joint Astronomy Center, Hawaii, on behalf of the UK PPARC. We are grateful to the referee for several helpful comments.

REFERENCES

Banerjee, D. P. K., & Ashok, N. M. 2004, ApJ, 604, L57
Banerjee, D. P. K., Varricatt, W. P., Ashok, N. M., & Launila, O. 2003, ApJ, 598, L13
Blake, G. A., & Boogert, A. C. A. 2004, ApJ, 606, L73
Bond, H. E., et al. 2003, Nature, 422, 405
Creech Eakman, M. J., Chiang, E. I., Joung, R. M. K., Blake, G. A., & van Dishoeck, E. F. 2002, A&A, 385, 546
Evans, A., Geballe, T. R., Rawlings, J. M. C., & Scott, A. D. 1996, MNRAS, 282, 1049
Gehrz, R. D. 1988, ARA&A, 26, 377
Glidden, T. L., Whittet, D. C. B., Boogert, A. C. A., & Tielens, A. G. G. N. 2004, ApJS, 151, 351
Gonzalez, G., Laws, C., Tyagi, S., & Reddy, B. E. 2001, AJ, 121, 432
Goorvitch, D. 1994, ApJS, 95, 353
Israelian, G., Santos, N. C., Mayor, M., & Rebolo, R. 2003, A&A, 405, 753
Kimeswenger, S., Lederle, C., Schmeja, S., & Armstron, B. 2002, MNRAS, 336, L43
Lissauer, J. J. 1993, A&A, 31, 129
Lynch, D. K., Russell, R. W., Kellogg, R. C., Mazuk, A. L., & Hanner, M. S. 1997, AJ, 113, 1391
Martini, P., Wagner, R. M., Tomany, A., Rich, R. M., Della Valle, M., & Hauschildt, P. H. 1999, AJ, 118, 1034
Meeus, G., et al. 2001, A&A, 365, 476
Munari, U., et al. 2002, A&A, 389, L51
Pontoppidan, K. M., Schier F. L., van Dishoeck, E. F., & Dartois, E. 2002, A&A, 393, 585
Rasio, F. A., Tout, C.A., Lubow, S. H., & Livio, M. 1996, ApJ, 470, 1187
Retter, A., & Marom, A. 2003, MNRAS, 345, L25
Rich, R. M., Mould, J., Picard, A., Frogel, J. A., & Davies, R. 1989, ApJ, 341, L51
Rudy, R. J., Dimpf, W. L., Lynch, D. K., Mazuk, S., Venturini, C. C., Wilson, J. C., Pietier, R. C., & Brady Perry, R. 2003, ApJ, 596, 1229
Sandquist, E. L., Dokter, J. J., Lin, D. N. C., & Mardling, R. A. 2002, ApJ, 572, 1012
Santos, N. C., Israeli, G., & Mayor, M. 2000, A&A, 363, 228
Siess, L., & Livio, M. 1999, MNRAS, 308, 1133
Soker, N., & Tylenda, R. 2003, ApJ, 582, L105
Whittet, D. C. B. 1992, Dust in the Galactic Environment (Bristol: IOP)