Draft version June 9, 2007
Preprint typeset using LaTeX style emulateapj v. 12/14/05

DETECTION OF ALUMINA DUST IN V4332 SAGITARRII FROM SPITZER OBSERVATIONS

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ABSTRACT

We present broad-band 24, 70 and 160 μm photometry and the 5-35 μm and 55-90 μm spectra of the eruptive variable V4332 Sgr from *Spitzer* observations. The distinguishing feature of the 5-35 μm spectrum is an unusually broad absorption feature near 10 μm at the position generally associated with silicate-rich dust. Through radiative transfer modeling, we show that this broad feature cannot arise from silicates alone but requires the inclusion of alumina (Al_2O_3) as a dust condensate. The present detection indicates that porous alumina manifests itself through a broadening of the 9.7 μm silicate feature and additionally displays, on the shoulder of the silicate feature, a component at $\sim$ 11.5 μm. We also conclude that the 13 μm feature sometimes seen in the spectra of cool stars - the origin of which is debated and sometimes attributed to alumina - does not arise from porous alumina. We discuss how further observations of V4332 Sgr may have the potential of verifying a few general predictions of the dust condensation process.

Subject headings: infrared: stars-novae, cataclysmic variables - stars: individual (V4332 Sagitarrii)

1. INTRODUCTION

Alumina (Al_2O_3) is considered to play a significant role in dust formation around oxygen-rich cool stars. Thermodynamic equilibrium calculations indicate that it, along with titanium oxides, is one of the earliest condensates in the mineralogical condensation sequence (Tielens 1990). Observationally, there is some debate and uncertainty regarding the spectral signatures that can be ascribed to alumina that permit a firm conclusion to be drawn for its presence. In particular, two features, one at 11.3 μm and the other at 13 μm, seen in the spectra of O-rich AGB and supergiant stars have often been attributed to alumina (e.g. Speck et al. 2000 and references therein). Additionally, various authors have shown that the inclusion of alumina grains in dust models yields better fits to the observed profile of the silicate feature at 9.7 μm (especially when the feature is broad) and also reproduces better the overall infrared spectral energy distribution (SED) in selected AGB and OH/IR stars (Speck et al. 2000; Maldoni et al. 2005). In the this paper, we present evidence for alumina dust detection from *Spitzer Space Telescope* observations of the nova-like variable V4332 Sgr. The distinguishing feature of its mid/far IR spectrum is a deep, unusually broad absorption feature at 10 μm. We show that this feature cannot be reproduced by silicate dust alone and that it is necessary to invoke the presence of amorphous alumina grains to explain it.

V4332 Sgr is an intriguing object which erupted in 1994 in a nova-like outburst (Martini et al. 1999) but showed considerable difference from a classical nova in its post outburst properties by evolving to a cool spectral type. Enhanced interest in this object arises because it is thought that V4332 Sgr, along with V838 Mon and M31 RV (a red-variable which exploded in M31 in 1988), could form a new class of eruptive objects (e.g. Munari et al. 2002; Bond et al. 2003). Since the nature and cause of the outbursts in these objects is not well resolved they are currently the subject of considerable interest. V4332 Sgr shows an interesting emission-line spectra in the optical and in the near-infrared with several rare spectral features. Prominent molecular bands of TiO, ScO, VO and AlO are also seen in the optical (Kimeswenger 2006, Tylenda et al. 2005) implying an oxygen rich environment. The fundamental band of ^{12}CO at 4.67μm has also been detected in the source along with water ice at 3.05μm (Banerjee, Varricatt & Ashok 2004). The IR excess detected in the source, along with the molecular and ice features, suggest a cool dusty environment around the central star whose effective temperature is estimated to be $\sim$ 3250-3280K (Banerjee et al. 2003; Tylenda et al. 2005).

2. OBSERVATIONS AND DATA REDUCTION

V4332 Sgr was imaged with the Multiband Imaging Photometer for *Spitzer* (MIPS; Rieke et al. 2004) at 24 and 70 μm on 15 Oct 2005 and at 2 Nov 2006 (70 μm Fine and Default modes, respectively). Due to scheduling errors, 160 μm data were only obtained on 15 Oct 2005. Spectra were obtained using the Infrared Spectrograph on *Spitzer* (IRS, Houck et al. 2004) on 18 April 2005 and 19 April 2006. In 2005, low resolution ($\sim$ 60-100) data from $\sim 5-38$ μm and high resolution data (R = 600) from $\sim 18-38$ μm were obtained. In 2006, high resolution data from $\sim 19-38$ μm and low resolution data from $\sim 5-14$ μm were obtained. In addition, MIPS SED mode data covering the wavelength range from $\sim 55-90$ μm were obtained on 27 Sept 2005. For the following discussion, data obtained in 2005 and 2006 will be referred to as Epoch 1 and Epoch 2, respectively.

The MIPS data were reduced using the Data Analysis Tool v3.06 (Gordon et al. 2005). V4332 Sgr was detected as a point source by MIPS at 24, 70, and 160 μm, and the flux densities were extracted using both PSF fitting and aperture photometry. The measured MIPS flux densities were 2.34$\pm$0.07, 1.07$\pm$0.11, and 0.12$\pm$0.02 Jy at 24, 70, and 160 μm respectively. At 24 and 70 μm the flux densities measured in Epochs 1 and 2 were identical within the errors and we report the weighted mean of those measurements. The basic instrumental calibra-

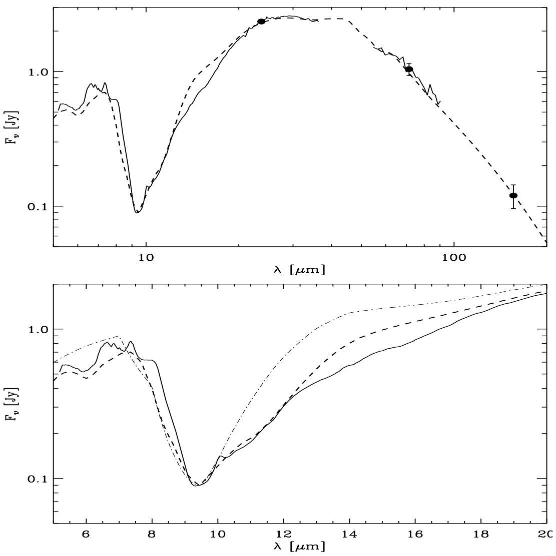

FIG. 1.— Top: Epoch 1 along with best model fit; see Table 1. Bottome: Expanded view around the 10 μm complex. In addition to the best fit model, the best fit silicate only model is overplotted. It is clearly seen that a pure silicate model yeilds a poor fit to the data.

tion of the MIPS SED mode is similar to that of the 70 μm imaging mode (Gordon et al. 2007) but with a wavelength-dependent illumination correction. The final spectrum of the source is obtained by extracting a 5-column (49.″25) aperture on the sky subtracted 2-D spectrum after correcting for slit loss. The MIPS SED data were scaled down by a factor of 0.88 to match the flux density in the 70 μm bandpass. Details of the SED reduction can be found in Lu et al. (2007, in prep.). The IRS data were processed and extracted using the SSC (*Spitzer* Science Center) Pipeline S15.3 product. Since V4332 Sgr is a bright point source, the final spectrum of the low resolution modules were combined using the SSC post-BCD coadded, nod-subtracted spectra. No background observation was obtained for the high resolution modules and the background level on the 2005 observations was $\sim$ 0.06 Jy (a factor of 20 fainter than the source) around 20 μm and fairly uniform in the coadded 2-D low resolution spectra. The SSC post-BCD extraction of the high-resolution spectrum agrees with the low-resolution spectrum within errors. There is no obvious emission/absorption lines seen in the high-resolution spectrum; therefore, the final spectra of V4332 Sgr in epochs 1 and 2 are computed by averagin both low- and high-resolution modules. In Figure 1, we present the observed IRS and MIPS SED spectra of V4332 Sgr overlaid with the combined broad band MIPS fluxes at 24, 70 and 160 μm. As there is little apparent evolution in the broad band fluxes from 2005 to 2006, we show only the 2005 data in Figure 1; evidence for changes in the detailed shape of the SED between 2005 and 2006 will be examined below.

3. RESULTS

The spectrum of V4332 Sgr is dominated by a deep, broad feature at $\sim$ 10 μm, normally associated with the presence of amorphous Mg-Fe silicate grains. However, this observed 10 μm feature is relatively broad, with an additional feature at $\sim 11\mu$m and a flattened wing beyond $\sim$ 13 μm. Additionally, signatures of ices and organic materials are evident from $\sim 5-8$ μm (water ice at 6 μm, "organics" at 6.8 μm and possibly methane ice at 7.7 μm; see eg. Bowey & Hoffmeister 2005). We have modeled the V4332 Sgr spectrum using the radiation transfer code DUSTY (Ivezic, Nenkova &Elitzur 1999). The limitations of DUSTY include the assumption of a spherically symmetric shell of material which may not be completely appropriate for the V4332 Sgr system (the system may have a disk; Banerjee et al. 2004); however since we are interested in exploring the overall shape of the observed SED rather than providing a detailed physical model of the complete system with this preliminary modeling, we have restricted ourselves to the simplest and most generalized assumption in our calculations. As the luminosity of V4332 Sgr is poorly known, we have fixed the stellar luminosity for V4332 Sgr at 10^4 $L_\odot$, the default input value assumed by DUSTY. This assumption does not affect the shape of the computed spectrum, only the physical scale of the system when taken with the dust temperature at the inner radius of the shell. We have fit the observed SED with two models viz. model 1 containing silicate dust only and model 2 a mixture of silicate and alumina dust. Prompted by the presence of ice absorption at $\sim$ 6 μm, in both models, the grains are coated with a mantle ice (20% by volume). The silicate dust optical constants are from Draine & Lee (1984) while the alumina optical data used are those of the 'porous' sample in Begemann et al. (1997) and the ice constants are those of Wiscombe (ftp://climate1.gsfc.nasa.gov/wiscombe/). The range of parameters explored is given in Table 1. The output spectra computed using both dust models are shown in Figure 1. It is clearly seen that a pure silicate composition matches the observed 10 μm feature poorly. On the other hand, the inclusion of alumina in model 2 improves the fit significantly. While there is considerable degeneracy in the fits, especially between the optical depth and the dust temperature (low temperature, low optical depth models are somewhat degenerate with high temperature, high optical depth models, though they consitently yeild formally worse fits), it is notable that no model consisting of only silicate grains provided a satisfactory fit to the 10 μm absorption feature.

The plots in Figure 1 permit a few conclusions to be drawn: (i) the substantial improvement in the fits with the inclusion of alumina indicates that alumina is be-

TABLE 1
DUSTY MODELING

Parameter	Value	Best Fit
Stellar Luminosity	$10^4 L_\odot$	fixed
Stellar Temperature	3250 K[1]	fixed
R_{out}/R_{in}	1000[2]	fixed
Shell ρ Distribution	r^{-2}	fixed
Composition	silicates/alumina	65%/35%
$\tau_{9.8}$ μm	2 – 55	45
$T_{dust}(R_{in})$	300 – 1750 K	1750 K
Grain Size Distribution	MRN[3]	fixed

[1] Banerjee et al. 2003; Tylenda et al. 2005.
[2] see eg. Maldoni et al. 2005.
[3] Mathis et al. 1977; $n(a) \sim a^{-3.5}$ with $a_{min,max} = 0.005, 0.25$ μm.

ing detected in the source; (ii) the presence of alumina broadens out the 9.7 μm silicate feature considerably and this should be taken as an indication of its presence. A similar conclusion has been reached by Speck et al. (2000, Figure 19) but unfortunately their data extend up to 13.5 μm and the full extent of broadening is better seen in the present data; (iii) a small, yet clearly discernible, feature is seen at 11 μm. This feature is definitely attributable to porous alumina since our model calculations show that increasing the percentage of alumina in the alumina-silicate mixture of model 2 enhances the strength of this feature. We note that this 11μm feature is seen in a significant number of stars studied by Speck et al. (2000) implying that alumina grains are fairly prevalent; (iv) since no discernible feature is seen at 13 μm, we do not believe that porous alumina is responsible for this feature in other instances when it has been observed - a similar conclusion is drawn by Begemann et al. (1997) in their study. None or our models can reproduce the flattening of the feature beyond $\sim$ 13 μm.

4. DISCUSSION

4.1. *The Case for Alumina Condensation*

It is perhaps not surprising to see evidence for alumina in the dust surrounding V4332 Sgr given the presence of the AlO radical in the optical and NIR specra of the object (Banerjee et al. 2003, Tylenda et al. 2005, Kimeswenger 2006) since AlO can play a critical role in the production of alumina. Laboratory experiments by Demyk et al. (2004) show that aluminum oxide clusters with stoichiometry AlO-$(Al_2O_3)_n$ are readily formed in laser vaporized metallic Al when quenched in oxygen and argon. These clusters are found to be very stable and thus very good nucleation sites for dust growth. Additionally, Belyun & Fontijn (1995) studied the kinetics of AlO + O_2 reactions at temperatures in the range 300-1700K with a view to studying the fate of aluminum in combustion. The higher end of this temperature range, it may be noted, is very close to the predicted condensation temperature (1760K; Tielens 1990) of alumina dust around stars. The Belyung & Fontijn (1995) experiment shows that AlO gets oxidized to AlO_2 by O_2. An additional reaction involving AlO is AlO + O +M = AlO_2 + M, where the "chaperon", M, is any atom or molecule present that can remove some energy from the newly-formed, activated AlO_2 (A. Fontijn, private communication). Newly formed AlO_2 can further interact with AlO to generate alumina: AlO + AlO_2 + M = Al_2O_3 + M.

These results indicate that AlO is likely to play a significant role in the route to Al_2O_3 formation. Such a conclusion has theoretical support in the work of Gail and Sedlmayr (1998, 1999) wherein it is shown that any possible nucleation species that can go on to form dust formation around stars, should begin with a monomer with exceptionally high bond energy. AlO, the monomer, satisfies this criterion and is thus a favored candidate to lead to the formation of larger Al_mO_n clusters that serve as nucleation sites for the formation of other grains or to alumina grains themselves by homogeneous nucleation. While the Gail and Sedlmayr (1990) analysis is based on thermal equilibrium considerations, an alternative model is the non-equilibrium formation of chaotic silicates proposed by Stencel et al. (1990) and Nuth & Hecht (1990). Chaotic silicates form rapidly from a supersaturated vapour of metal atoms, SiO, AlO and OH in a hydrogen atmosphere (Stencel et al., 1990; the role of AlO in this scenario too may be noted). In the initial stages, the higher reduction of Al with respect to Si will lead to the preferential formation of Al-O bonds at the expense of Si-O bonds. This implies that the IR bands of alumina associated with Al-O stretching mode should be prominent early in the formation of the "chaotic silicate". However, as the Al atoms become fully oxidized, the higher abundance of Si will make the 9.7μm band associated with Si-O bonds dominate.

Titanium oxides are considered to also be an early dust condensate along with alumina - given the "freshness" of the condensate in V4332 Sgr, we might expect some signature of them in the our spectra, though Ti is nearly 30 times less abundant than Al (Speck et al. 2000). Bulk titanium oxides can have different forms: TiO, TiO_2, Ti_2O_3 and Ti_3O_5 (Demyk et al. 2004). The most common, TiO_2 can exist as brookite and anatase which convert at high temperature into rutile which is the third and most common form. The rutile spectrum is expected to show a broad and strong band at 13-17 μm; the spectrum of anatase shows two strong and broad bands around 17 and 29 μm. The titanium oxide clusters, studied by Demyk et al. (2004) as possible nucleation sites, have a vibrational transition at $\sim$13.5 μm. It is possible that the flattening of the absorption long ward of 13 μm in our spectra is indicating the presence of titanium oxides.

4.2. *Evolution of the Dust Condensates*

There is potential in the present data to address certain aspects of the dust condensation process in astrophysical environments. We first note, that the dust that has formed around V4332 Sgr is of fairly recent origin as evidence from the abrupt infrared brightening that developed in the source between 2MASS observations in 1998 and subsequent observations in 2003 (Banerjee et al. 2003, Figure 2). Since the dust forming process has begun recently - certainly less than 10 years ago - and is possibly still ongoing, there are a few spectral features that could change with time. As an example, in the "chaotic silicates" hypothesis, it is predicted that with time a strengthening of the silicate component of the 9.7 μm feature should take place relative to that of the alumina component that blends with this feature. There is some observational support for such evolution comparing our data between 2005 and 2006 (see Fig 2). There is a hint that the broad red wing of 9.7 μm feature has weakened in 2006 relative to 2005 and there has been an overall narrowing of the 10 μm absorption complex. Though the evidence is only tentative given the small change ($\sim 1\sigma$) and only two epochs of data, such a behavior is just what might be expected as Al atoms become oxidized and Si-O begins to dominate the composition. Further, it is also predicted that the ratio of the 10 μm/18 μm silicate features could be expected to change monotonically as silicate dust nucleates and anneals in a circumstellar environment (Nuth & Hecht 1990). Freshly nucleated silicates, as laboratory experiments show, are expected to have a large 10 μm/18 μm ratio i.e. the 18 μm feature is expected to be weak (consistent with what is seen in the V4332 Sgr spectrum). Thermal processing with time, should increase the strength of the 18 μm feature. Though the time

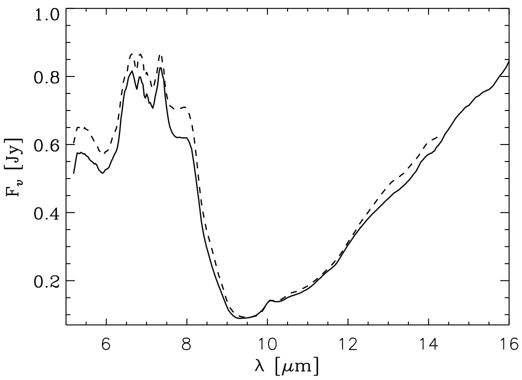

FIG. 2.— Enlargment of the 10 μm absorption complex comparing epoch 1 (solid) and 2 (dashed) data. There is weak evidence for a narrowing of the absorption complex between the two epochs.

scales involved in the above processes are not clear, it would be worthwhile to follow V4332 Sgr in the future to monitor the evolution of the spectrum of V4332 Sgr as a test of the evolution of dust condensates.

The detection of alumina condensate in V4332 Sgr may have implications for the origin of this object. It has been postulated that, along with V838 Mon and M31 RV, V4332 Sgr forms a new class of eruptive variables. The nature of these objects and the source of their eruptive behavior has not been established and models ranging from an outburst from a compact object in a red giant envelope, various thermonuclear events in a single high-mass evolved star, a late He-shell flash (born again AGB), stellar mergers and even the swallowing of multiple planets by a massive star have been proposed (e.g. Tylenda & Soker 2006 and references therein). It also appears that the cool M type star detected here may have had a hot B type companion that was destroyed in the eruption (Goranskii & Barsukova 2007). Within the scope of this work, it is not possible to discuss in depth the complexities of the origin and nature of the V4332 Sgr system - this will be attempted elsewhere in a separate study. But it may be tempting to speculate that the detection of alumina condensate in V4332 Sgr supports the involvement of an evolved object since, to date, alumina dust has been almost exclusively detected in AGB and other cool evolved stars. However, as discussed above, alumina is likely a very early condensate in any oxygen rich environment, so the detection of alumina in the early condensate of V4332 Sgr only indicates that conditions in the ejecta are similar to those found around cool evolved stars. More detailed modeling of the aftermath of some of the proposed eruption mechanisms may rule out conditions conducive to the formation of alumina grains. In addition, the detection of alumina around V4332 Sgr motivates long term monitoring of the ejecta formed around V838 Mon (Banerjee et al. 2006). If indeed these objects are related at a more fundamental level than simply having roughly similar outburst characteristics, we might expect the conditions in the post outburst ejecta of V838 Mon to be similar to those in V4332 Sgr. Given that V838 Mon erupted ∼8 years after V4332 Sgr, we might expect to detect similar signatures of alumina formation around V838 Mon in the coming years - AlO is detected in this object too - if both objects do indeed share a common origin.

Research at the Physical Research Laboratory is funded by the Department of Space, Government of India. This work is based on observations made with the *Spitzer* Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. Support for this work was provided by NASA through Contract Number 1277253 issued by JPL/Caltech.

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