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3–14 MICRON SPECTROSCOPY OF NOVA V445 PUPPIS

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ABSTRACT

We report 3–14 μm spectroscopy of the nova V445 Puppis on 2001 January 31.45 UT using the Broadband Array Spectrograph System on the Infrared Telescope Facility, approximately 1 month after the object was discovered. The spectrum (W cm^{-2} μm^{-1}) revealed only a smooth, featureless continuum that decreases monotonically with increasing wavelengths between 3 and 13.6 μm. Its slope is much shallower than the Rayleigh-Jeans tail of a blackbody. The spectrum is consistent with thermal emission from gray (constant) emissivity dust whose temperatures ranged from around 280 K to upward of 1300 K. IR magnitudes were $L = 2.8$, $M = 1.6$, and $N = -0.27$, all ± 0.02. The presence of such strong IR continuum emission so early after the nova's outburst may suggest that this object has undergone previous outbursts and that we observed preexisting dust, at least in part

Key words: circumstellar matter — dust, extinction — infrared radiation — novae, cataclysmic variables

1. INTRODUCTION

Novae are a surprisingly inhomogeneous group of objects. Most and perhaps all are formed by thermonuclear runaway as material accretes from a secondary onto the surface of a white dwarf, but the resulting outbursts are very diverse. The time it takes for them to fade by 2 or 3 mag from peak brightness varies from a few days to many months or years. The composition of the shell may be nearly solar or may be highly depleted in H and overabundant in C, N, O, Mg, etc. The geometries of the shells, as inferred from spectroscopy and verified on images of resolved remnants, also show a variety of shapes and spatial structures. In short, no two novae are exactly alike, and some, like the very slow nova-like object V445 Puppis, are exceedingly strange.

The nova was discovered in late 2000 December by K. Kanatsu (Kato & Takamizawa 2001) at R.A. = $7^{\mathrm{h}}37^{\mathrm{m}}56\overset{\mathrm{s}}{.}882$, decl. = $-25°56'58\overset{''}{.}88$ (equinox J2000.0; Platais et al. 2001 Galactic coordinates $l = 241\overset{\circ}{.}1241$, $b = -2\overset{\circ}{.}1909$). The early 2001 January optical and near-IR spectra (Ashok & Banerjee 2001; Wagner, Schwarz, & Starrfield 2001b; Wagner, Foltz, & Starrfield 2001a; Liller 2001a, 2001b) indicated many permitted lines of Fe II, as well as those of Ca I and Ca II, O I, and Na I. The weakness or in some cases absence of H I and He lines suggests that the observed shell was hydrogen deficient. By mid-January, there were unconfirmed reports that higher excitation permitted lines such as O IV and possibly He II began to appear (Kimeswenger et al. 2001), indicating that the shell was still fairly dense but was being illuminated by a more UV-rich source. No forbidden or coronal lines have yet been seen. At this time, we know of no estimates of the object's distance.

The dates of V445's outburst and peak brightness are not known. There is, however, substantial evidence to suggest that these events took place only days or weeks before the object was discovered. Liller (2001c) reported no outburst of the object as late as 1985 November 25, and Takamizawa advanced this date to 2000 December 3 (Kato & Takamizawa 2001). These reports are at odds with that of K. Haseda, who claimed prediscovery observations showing that the object had reached magnitude 8.8 by 2000 November 23 (Kato 2001). In view of all the evidence, it seems likely that the peak brightness occurred sometime between 2001 December 3 and 31.

Spectroscopically, the existence of P Cygni profiles (Ashok & Banerjee 2001; Wagner et al. 2001a, 2001b) means that the shell was fairly small, because P Cygni profiles usually disappear as the growing, brightening shell raises the continuum level and decreases the contrast of their absorption component (Warner 1989). The presence of Fe II lines (Liller 2001a; Wagner et al. 2001b; Kimeswenger et al. 2001; Wagner et al. 2001a) also suggests that the outburst was recent (Warner 1989). These lines usually fade in the first few days or weeks as the iron becomes multiply ionized by the white dwarf's shrinking photosphere, which grows progressively hotter, thereby hardening the spectrum.

The early light curve of V445 Pup showed a monotonically decreasing brightness, dropping about 1 visual magnitude in the 3 months since its discovery. To the extent that V445 Pup is a classical nova and that its decline rate is characteristic of the nova's behavior immediately following maximum light, the nova would be classified as *very slow* (Payne-Gaposchkin 1957).

V445 Pup appears to be an unusual nova. Wagner et al. (2001a) report, "The spectrum is not typical of 'Fe II' classical novae, recurrent novae, or symbiotic novae such as PU Vul or RR Tel." Liller (2001b) noted that "While the lack of hydrogen emission is unusual, other cataclysmic stars such as CR Boo, CP Eri, and V803 Cen are similarly hydrogen-deficient. However, unlike V445 Pup, these stars, are all hot, blue objects showing He lines in emission and never Ca I or Na I."

In this paper, we report and discuss a 3–14 μm spectrum of this interesting object and propose some simple models of the dust shell based on our IR spectra.

2. OBSERVATIONS

The nova was observed on 2001 January 31.46 UT at the NASA Infrared Telescope Facility (IRTF), on Mauna Kea.

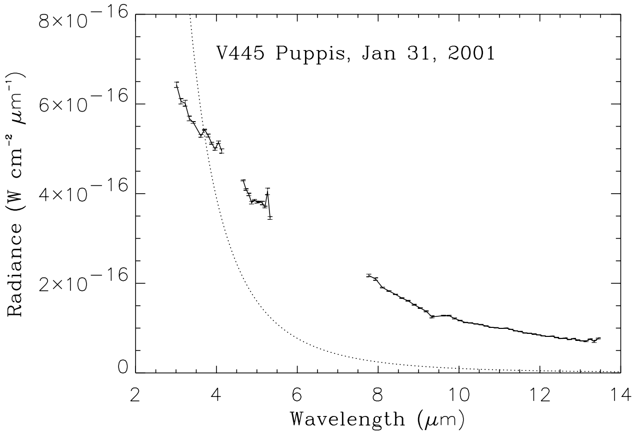

FIG. 1.—Spectrum of V445 Pup, showing a smooth, featureless continuum that cannot be matched by a single graybody spectrum. For comparison, the dotted line shows a $1/\lambda^4$ curve.

Observations were made with Aerospace's Broadband Array Spectrograph System (Hackwell et al. 1990) with a 3″.2 diameter aperture. Chopping and nodding were 20″ east-west at 7.1 Hz. Total integration time was 800 s.

The calibration star was Sirius (α CMa), whose spectrum at our wavelengths and resolutions is equivalent to an 11,200 K blackbody scaled to magnitude -1.41 at 10 μm. For zero magnitude we adopted a blackbody with a value of 1.26×10^{-16} W cm^{-2} μm^{-1} at 10 μm and $T = 9700$ K. Standard extinction corrections were derived from Sirius and applied to the nova.

3. THE SPECTRUM

Figure 1 shows the spectrum of the nova. The spectrum appears as a smooth, featureless continuum whose brightness decreases monotonically with increasing wavelength. Notably absent are any silicate, unidentified IR (UIR), or other dustborne emission features. There is no evidence of discrete atomic or molecular emission lines, a condition that has apparently existed in the IR since at least 2001 January 2 (Ashok & Banerjee 2001). The slope of the spectrum is shallow compared with $1/\lambda^4$, indicating that it was not the result of blackbody emission from a single temperature, such as one might expect from a stellar photosphere or a thin, isothermal dust shell. The IR magnitudes were $L = 2.8$, $M = 1.6$, and $N = -0.27$, all ± 0.02.

4. DISCUSSION

As with any spectrum that is featureless, little can be deduced about the dust's composition. We can say with some certainty that the lack of silicate emission rules out small silicate particles, although in principle a wide range of silicate compositions in large particles could produce a featureless spectrum. The absence of UIR features (Russell, Soifer, & Willner 1977) suggests that we are not seeing the kinds of shells found in planetary nebulae. There does not appear to be a 3.4 μm feature characteristic of C—H structures. Thus we can only speculate that perhaps the dust is in the form of carbon or graphite, both of which have emission spectra that are virtually featureless in our wavelength region.

Most novae do not produce dust for many weeks or months after outburst. Those that do form dust tend to be fast novae (Gehrz 1989), and based on its light curve, dust formation always coincides with a sharp drop in optical brightness as the dust obscures the bright central regions. Since no such drop in the light curve has been observed in V445 Pup, perhaps the dust we are seeing was preexistent and is being warmed by the latest outburst. Thus, the nova may be a recurrent nova (Webbink et al. 1987) in the sense that it may have had previous outbursts. Webbink et al. noted that as a class of objects, "recurrent novae" are very heterogeneous and that the outbursts may be powered by either thermonuclear runaways or accretion events. In view of the large variety of recurrent novae and the relatively small amount that is known about V445 Pup, we shall not force a classification on V445 Pup, and simply note the possibility that it has produced dust prior to its 2000 episode.

5. MODEL

We first tried modeling the spectrum using a single-temperature blackbody, and then a power law, but neither produced an acceptable fit. Next we modeled the emission as originating from three shells of material (Fig. 2, *top left*) on the assumption that temperature varied from warm on the inside to cool on the outside. Using three temperatures, in the ranges 1000–4000, 500–700, and 200–300 K, we summed the three corresponding graybodies (scaled Planck functions, or equivalently, constant emissivity with wavelength), i.e.,

$$F_\lambda = \sum M_i P_\lambda(T_i) ,$$

where F is the composite spectrum, M is a multiplier that is proportional to mass of the shell, and P is the Planck function at a temperature T. We adjusted the temperatures and multipliers until the fit roughly matched the spectrum. Next a χ^2 per degree of freedom was calculated for the fit using the error bars from the observations, and the temperatures and multipliers were fine-tuned. The average statistical error bars from the source data alone were under 1% for points outside the terrestrial atmospheric absorption regions. After consideration of errors in the standard-star measurements, uncertainties in their flux models, and errors in the extinction corrections, we adopted a mean uncertainty of 5% error per point. The final fits (Fig. 3) produced χ^2 values in the range 0.6–1.2 (Table 1). The fact that the χ^2 was sometimes less than unity suggests that the model fits the data to better than 5% per point. Several trials for combinations of temperatures and multipliers produced fits with values of $0.6 < \chi^2 < 0.7$, indicating that we cannot distinguish certain ranges of temperatures and multipliers in a statistically meaningful way.

We cannot say whether the hot component is on the order of 3000–4500 K, as a stellar companion's photosphere might be, or simply warm dust at 1000–1500 K, because our observations fall on the Rayleigh-Jeans tail of either Planck function. The model shows that the data are consistent with a range of temperatures, and that a stellar component could be present without making the model inconsistent with the data. Dust has been observed with temperature up to about 1500 K but no higher, so it is possible that such hot dust could have just condensed from the outflowing material and be in the process of cooling, or it could have been preexistent and been heated by the nova event.

Although both warm and cool models fit our data more or less equally, we favor the cool model for two reasons.

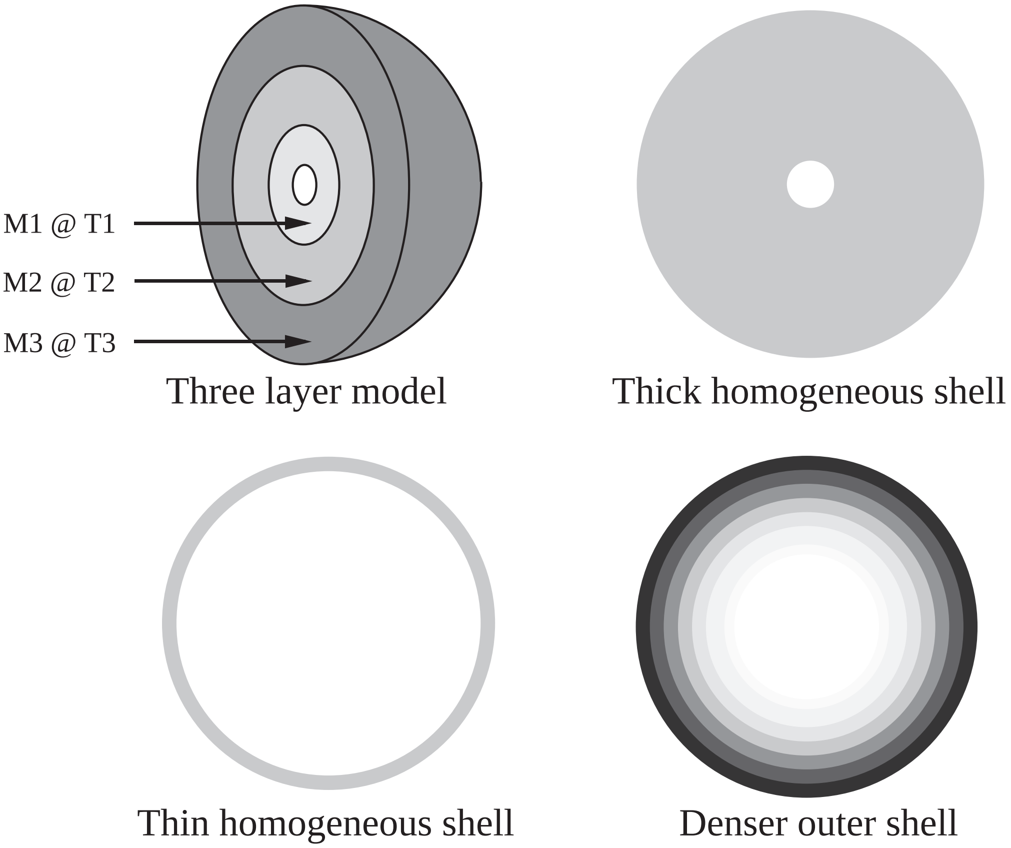

FIG. 2.—*Top left*: The model, consisting of three nested shells of homogeneous material at three discrete temperatures T_1, T_2, and T_3. A Planck function is used to model the emission, and they are scaled by multipliers M_1, M_2, and M_3 that are proportional to mass. The central region is dust-free. Assuming that the dust particles' properties (emissivity, size, composition) are not a function of distance from the central star, the thick homogeneous shell (*top right*) can be ruled out because the M-T slope is too shallow. The thin homogeneous shell (*bottom left*) can also be rejected, because it would be expected to be nearly isothermal and the spectrum cannot be fitted by a single blackbody function. A shell with more material on the outside (*bottom right*) is the simplest model that is consistent with the observations.

First, it includes a zone at a temperature where dust is thought to condense (1500 K), and dust is surely present as the major emitter in the IR. Secondly, the cold model, when extrapolated to shorter wavelengths, more closely matches the observed brightness of the source in the visible ($m_v = +9.6$, corresponding to $F = 4.2 \times 10^{-16}$ W cm^{-2} μm^{-1} at 0.55 μm).

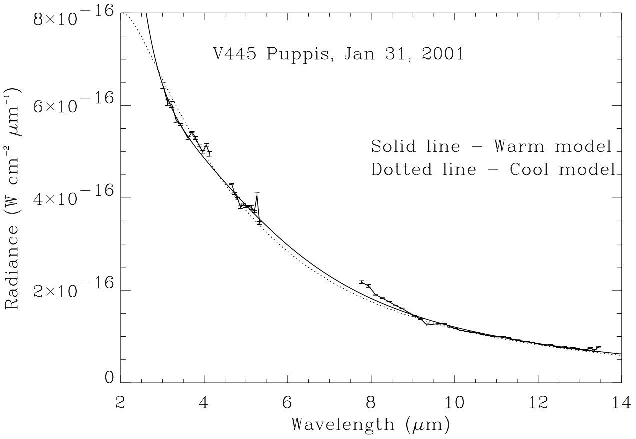

FIG. 3.—Spectrum of V445 Pup from Fig. 1, plotted with two models (1 and 4 in Table 1). The solid line shows the warm model ($T_1 = 4500$ K), and the dotted line shows the cool model ($T_1 = 1500$ K). The error bars shown (± 1 standard deviation of the mean from four 200 s integrations) are statistical errors from the measurements and do not include the uncertainties in the calibrator measurements or errors in the extinction corrections. If we adopt a total error of 5%, the χ^2 values are less than unity.

Physical realism provides further checks on the model. The temperature of a dust particle in radiative equilibrium varies as $T \sim r^{-1/2}$, where r is the distance from the central source. For a fixed thickness Δr, the mass (i.e., multiplier) of each shell varies as $M \sim r^2$, provided it is homogeneous. Eliminating r between these two relations results in $M \sim T^{-4}$.

Figure 4 shows M versus T for the models in Table 1. All the models would seem physically plausible because they fit the relation $M \sim T^{-N}$, where N is close to 4. A closer look reveals that the models have slopes $d \log M/d \log T$ in the range -2.7 to -3.5. Given the simple assumptions underlying the model, the significance of the apparent differences is uncertain. At face value, however, they could represent departures from homogeneity in the sense of there being relatively less mass in the warmer, inner regions and relatively more mass in the cooler, outer regions. Such an effect might be expected if, after the main expulsion, the stellar wind continued to flow but at an ever slackening pace. This would produce a shell that was relatively denser on the outside. We also know that nova shells are not homogeneous and almost always show a lower density inner region. Thus we feel that the models are as physically realistic as can be expected from the data.

The shell would seem to be more like a ball with a small central hole than a thin-walled shell. Assuming that the

TABLE 1

Model Parameters

Model	M_1 (at T_1)	M_2 (at T_2)	M_3 (at T_3)	χ^2 (stat.)	χ^2 (5%)
1......	1.50×10^{-17} at 4500 K	5.00×10^{-15} at 700 K	7.50×10^{-14} at 250 K	36	0.6
2......	1.74×10^{-17} at 4500 K	6.00×10^{-15} at 670 K	5.90×10^{-14} at 250 K	31	0.7
3......	1.80×10^{-17} at 4500 K	6.30×10^{-15} at 650 K	4.00×10^{-14} at 280 K	114	1.2
4......	3.80×10^{-16} at 1500 K	4.40×10^{-15} at 650 K	4.90×10^{-14} at 280 K	61	1.0

Note.—Four sets of values for the three temperatures and the multipliers of the blackbodies, along with the χ^2 values for the statistical error bars and for the 5% error bars for 66 spectral points. The obvious trend of larger multipliers with lower temperatures is consistent with a dust shell heated from within and whose individual grains are in radiative equilibrium such that lower temperatures and larger masses are found in the outer regions.

dust's temperature is determined entirely by radiative equilibrium and that it has a constant emissivity, then the $1/r^{1/2}$ temperature dependence means that the radial thickness of the shell, expressed as the ratio of outer diameter to inner diameter, is of order $(1500/280)^2$, or about 29 for the low-temperature model. For the high-temperature model, the ratio becomes $(4500/280)^2$, or about 256. In either case, the dust shell must be very extensive. An alternative interpretation might be that the shell is somewhat optically thick and therefore less extensive because the inner material could significantly attenuate the white dwarf's radiation and thereby produce large temperature ranges over a relatively smaller distance. Similarly, if the shell is optically thick, its inner, hotter regions would be shielded from us by the cooler, outer portions.

It is also possible that there is a large size distribution in the dust particles and that the smaller particles are heated to higher temperatures than the large ones, and therefore that a thin ring of material could masquerade as a thick homogeneous shell. We believe this possibility to be unlikely because in any reasonable size distribution, there are many more small (hence) hot particles than there are large (cool) ones, and our spectrum seems to have a deficit of hot particles.

The simplest interpretation is that we are seeing a non–optically thick dust shell whose temperature is varying over a fairly large range. This is probably the result of dust particles in radiative equilibrium at varying distances from the central heating source, presumably a white dwarf. Our choice of 1500 K as the hottest component was based upon the fact that little or no solid dust can exist at higher temperature. It is possible that some of this light is coming from the white dwarf or the secondary, but without accurate extinction and distance information (see below), we have no way of judging their brightnesses, so we did not extend our model to include them.

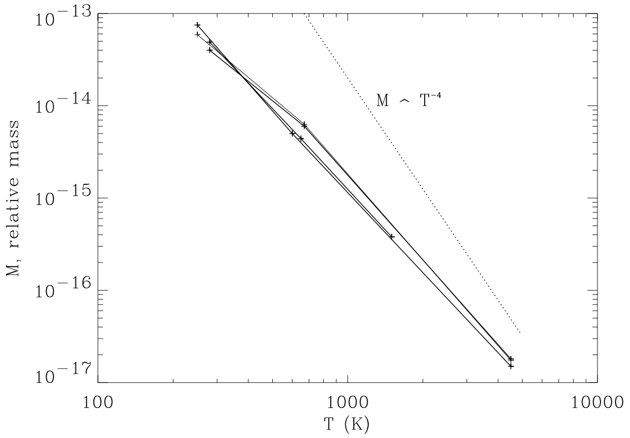

Fig. 4.—Relative mass M vs. temperature for a three-shell model. The M-T relation is consistent with a more massive, cooler outer region as compared with the inner regions. Model parameters are from Table 1.

6. SUMMARY AND CONCLUSIONS

V445 Puppis appears to be unusual nova. While its optical light curve suggests a very slow nova, the evolution of its optical spectrum suggests a fast nova. The IR continuum appears to originate in thermal emission from an extensive, possibly preexisting, dust shell. Based on visible and IR spectroscopy, V445 Pup looks to be hydrogen deficient and may be related to objects such as RR Tel, AG Per, and V1016 Cyg.

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