THE ASTROPHYSICAL JOURNAL, 308:L63–L66, 1986 September 15

THE NEON NOVA. II. CONDENSATION OF SILICATE GRAINS IN THE EJECTA OF NOVA VULPECULAE 1984 NUMBER 2

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Received 1986 May 23; accepted 1986 June 17

ABSTRACT

Infrared photometry of Nova Vulpeculae 1984 number 2 (NV2) from 2.3 to 19.5 μm during 1985 May 14 to 1986 March 31 shows that silicate grains had condensed and grown in the nova ejecta by 1985 August 23, 240 days after the eruption. A relative overabundance of oxygen in the nova shell seems indicated. Forbidden 12.8 μm [Ne II] emission was a factor of ≈ 41 above the continuum at a spectral resolution of $\lambda/\Delta\lambda = 67$ on day 240; the line persisted through day 461. The anomalous chemical composition of NV2's ejecta supports recent suggestions that ONeMg white dwarfs evolved from 8–12 $M_{\odot}$ progenitor stars are accreting matter in binary systems.

Subject headings: infrared: sources — stars: individual — stars: novae

I. INTRODUCTION

We report the discovery of the 10 and 20 μm silicate emission features in Nova Vulpeculae 1984 number 2 (NV2) and suggest that silicate grains have formed in the ejecta. The observations provide an estimate of the total mass of silicate grains condensed in the shell.

The observations reported here, together with our earlier discovery in NV2 of strong [Ne II] emission at 12.8 μm (Gehrz, Grasdalen, and Hackwell 1985; hereafter Paper I), confirm the presence of oxygen-neon-magnesium (ONeMg) white dwarfs accreting matter in binary systems. Such novae may be capable of contributing significant quantities of the interesting radioactive isotopes ^{22}Na and ^{26}Al to the interstellar medium (see, for example, Hillebrandt and Thielemann 1982 and Truran 1984). Meteoritic abundance anomalies suggest that these extinct isotopes, the by-products of a transient nucleosynthetic event such as a nova eruption, were injected into the primitive solar system during the early stages of its formation (Truran 1984).

II. OBSERVATIONS

Photometric and spectrophotometric observations (Table 1 and Figs. 1–3) were obtained with the Wyoming bolometer (Gehrz, Hackwell, and Jones 1974) and the $\lambda/\Delta\lambda = 67$ As:Si spectrophotometer (Gehrz *et al.* 1984) on the 234 cm Wyoming Infrared Telescope. Several apertures (5″ or 6″.8) and beam separations (10″–18″) were used; the measurements are independent of these parameters because NV2's shell is spatially unresolved. Most observations reported here were made with remote telephone links enabling observers to control the Wyoming telescope and its instrumentation from laboratories in Laramie, Wyoming, and Minneapolis, Minnesota.

III. INFRARED SILICATE EMISSION

Broad-band photometry and narrow-band spectrophotometry for 1985 August 23.4 show the presence of the 10 μm silicate emission feature (Fig. 2). The 20 μm silicate emission feature was present on August 23.4, but the 19.5 μm flux level on May 15.4 was consistent with the free-free continuum extrapolated from data at shorter wavelengths (Fig. 1).

Both silicate features should have been detectable over the free-free continuum on May 15.4 had they been present at the level measured in August (see Figs. 1–3). The data imply that the silicate emission features had increased in intensity by at least a factor of 2 between May 15.4 and August 23.4 due to grain condensation and growth.

An alternative source of the silicate emission could be the illumination after day 140 of a dust shell remnant of the mass-loss phase of the nova progenitor (see Bode and Evans 1983). This seems unlikely. First, the material would have to lie $\geq 3.6 \times 10^{17}$ cm from the binary system and would subtend an angular diameter $\geq 16''$. NV2 is unresolved by a 5″ beam at 10 μm. Second, the temperature for grains directly illuminated by starlight at this distance from a source with NV2's outburst luminosity of $\approx 10^5$ $L_{\odot}$ (Paper I, erratum) will be ≤ 40 K. The observed grain temperature is 200–400 K on day 240 assuming that the 20 μm/10 μm opacity ratio for silicate grains lies between 0.3 and 1. We cannot entirely rule out the possibility that the progenitor's ejecta are anisotropically distributed and that very small dust grains lying along the line of sight of our beam are impulsively heated by hard photons (Desert, Boulanger, and Shore 1985).

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TABLE 1

PHOTOMETRY OF NOVA VULPECULAE 1984 NUMBER 2

λ (μm)	MAGNITUDE Day 140 (05/14/85)	Day 171 (06/13/85)	Day 230 (08/13/85)	Day 240 (08/23/85)	Day 294 (10/16/85)	Day 335 (11/26/85)	Day 382 (01/12/86)	Day 461 (03/31/86)
2.3	$+7.29 \pm 0.04$	$+7.42 \pm 0.03$	$+7.86 \pm 0.08$	$+8.11 \pm 0.03$	$+8.30 \pm 0.05$	...	$+8.62 \pm 0.12$	$+8.90 \pm 0.21$
3.6	$+6.09 \pm 0.02$	$+6.22 \pm 0.01$	$+7.04 \pm 0.14$	$+6.87 \pm 0.03$	$+6.63 \pm 0.05$	...	$+6.93 \pm 0.10$	$+6.59 \pm 0.06$
4.9	$+5.71 \pm 0.08$	$+5.61 \pm 0.07$	$+6.00 \pm 0.24$	$+6.34 \pm 0.09$	...	$+6.91 \pm 0.28$	$+7.03 \pm 0.15$	
8.7	$+4.43 \pm 0.20$	$+4.03 \pm 0.09$	$+4.49 \pm 0.33$	$+4.70 \pm 0.16$	$+4.44 \pm 0.27$	...	$+4.61 \pm 0.23$	$+4.34 \pm 0.14$
10.0[a]	...	$+3.07 \pm 0.09$	...	$+2.99 \pm 0.05$	$+3.15 \pm 0.16$	$+3.28 \pm 0.02$	$+3.38 \pm 0.14$	$+3.28 \pm 0.08$
N[b]	$+2.70 \pm 0.07$	$+3.04 \pm 0.05$	$+3.10 \pm 0.08$	$+3.20 \pm 0.06$	$+3.30 \pm 0.04$	$+2.67 \pm 0.08$	$+3.39 \pm 0.08$	$+3.30 \pm 0.12$
11.4	$+3.20 \pm 0.23$	$+3.04 \pm 0.10$	$+2.76 \pm 0.28$	$+2.81 \pm 0.03$	$+2.91 \pm 0.08$	$+2.02 \pm 0.32$	$+3.44 \pm 0.20$	$+3.19 \pm 0.16$
12.6	$+1.69 \pm 0.07$	$+2.05 \pm 0.04$	$+2.25 \pm 0.14$	$+2.33 \pm 0.08$	$+2.38 \pm 0.06$	$+1.95 \pm 0.11$	$+2.20 \pm 0.10$	$+2.95 \pm 0.18$
Q[b]	$+2.55 \pm 0.29$	$+1.97 \pm 0.25$	$+1.97 \pm 0.25$	$\geq +1.75(3\ \sigma)$	$+1.83 \pm 0.33$	...	$+2.03 \pm 0.20$	$+2.42 \pm 0.14$

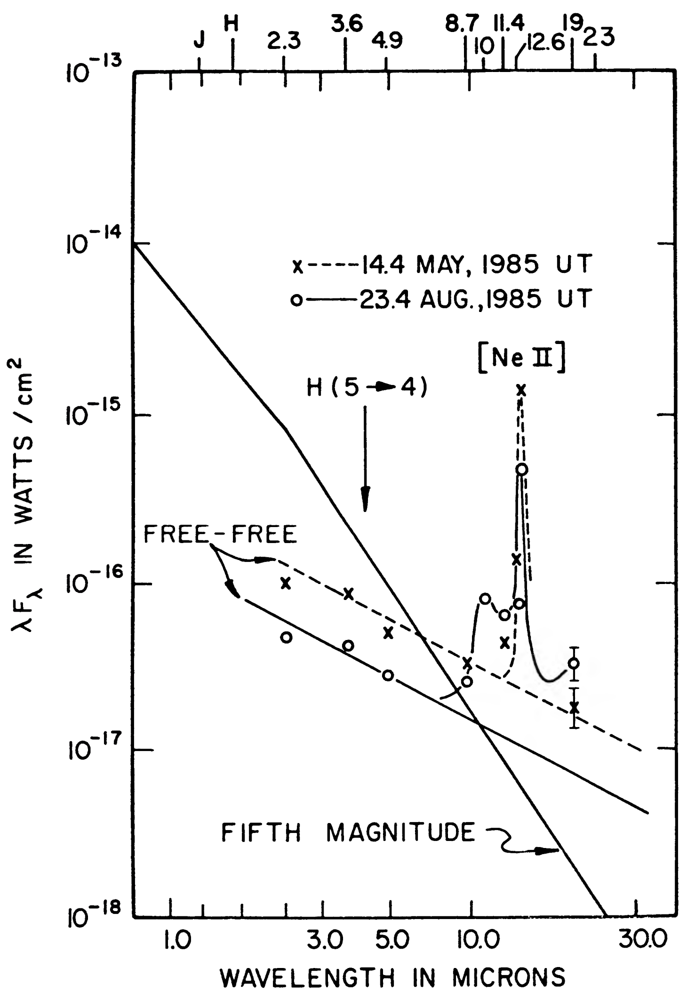

FIG. 1

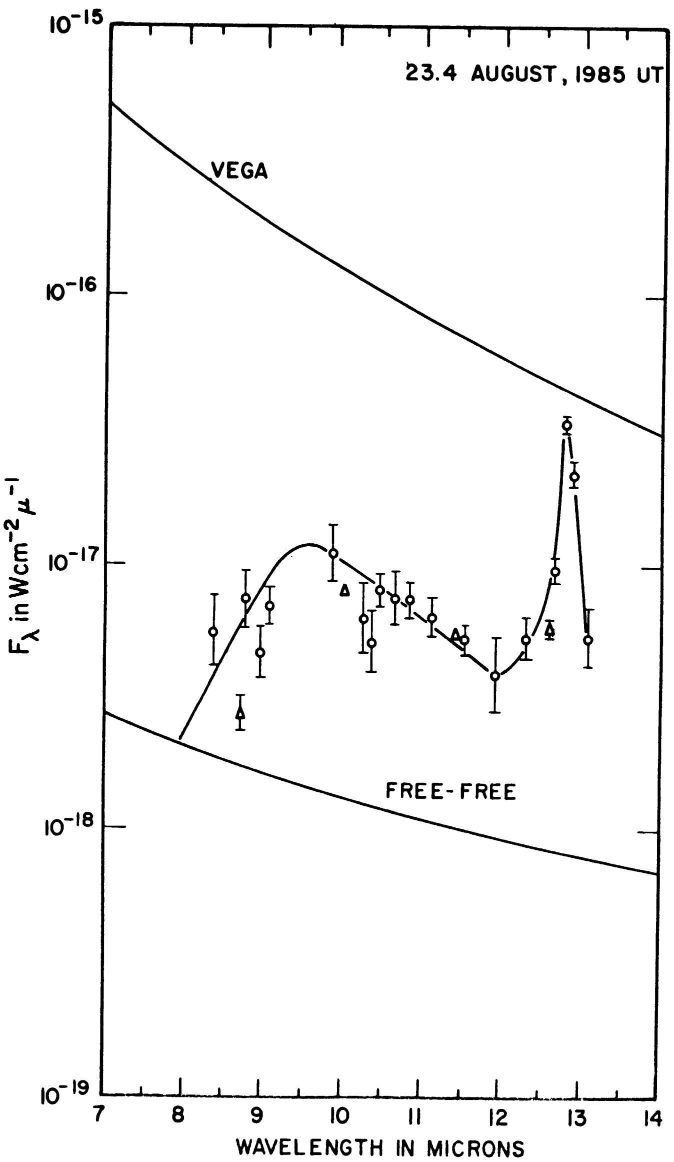

FIG. 2

FIG. 1.—Broad-band infrared energy distributions of NV2 before (*dashed line*) and after (*solid line*) the formation of circumstellar silicate grains. Narrow-band data are plotted for the 12.8 μm [Ne II] emission peak. Free-free lines indicate νF_ν = constant and have been normalized to photometry at $\lambda \geq 5$ μm. Hydrogen (5 → 4) was present in the 3 μm band in 1985 May (Gehrz, Grasadalen, and Hackwell 1985). Error bars are smaller than the plotting symbols unless indicated. The neon line contaminates the 11.4 μm passband. Both the 10 and 20 μm silicate features are present in 1985 August.

FIG. 2.—Infrared spectrum of NV2 from 8 to 13.2 μm showing the 12.8 μm [Ne II] emission line and the 10 μm silicate emission feature. Triangles denote broad-band photometry. Vega denotes the zero magnitude calibration. Errors as indicated in legend for Fig. 1.

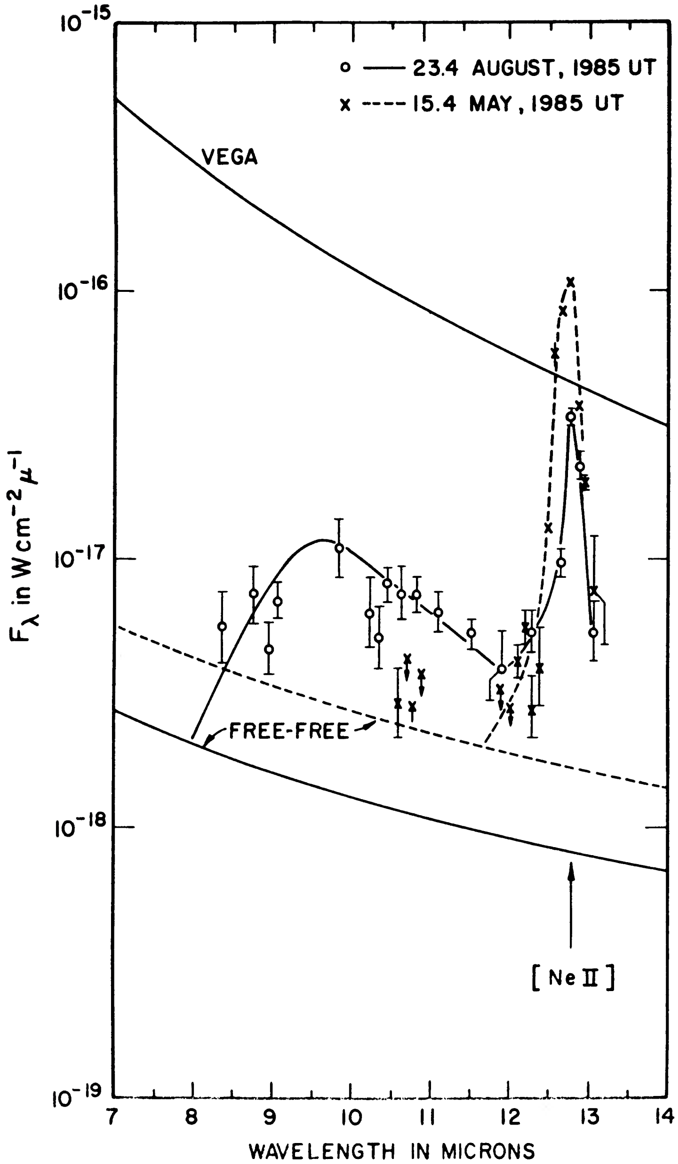

FIG. 3.—Comparison of the 10 μm spectra in 1985 May (*dashed line*) and August (*solid line*) showing that the silicate emission feature should have been detected well above the free-free continuum in May if it had been present at the level measured in August. Error bars are as indicated in the legend to Fig. 1.

IV. ABUNDANCES OF OXYGEN, NEON, AND GRAIN CONSTITUENTS

The formation of silicate grains suggests that the ejecta of NV2 are oxygen rich. It is believed (Hackwell 1971, 1972) that amorphous carbon and silicon carbide (SiC) grains form when C/O > 1, and that silicate grains condense when C/O < 1. Thus, the formation of carbon-rich (Gehrz *et al.* 1980*a*; Gehrz *et al.* 1980*b*) and SiC-rich (Gehrz *et al.* 1984) shells in novae presumably results from eruptions on carbon-oxygen (CO) white dwarfs evolved from low-mass stars.

In Paper I, we reported the discovery of forbidden 12.8 μm [Ne II] emission from NV2 with a peak intensity of ≈ 60 Jy in a 0.2 μm bandpass on 1985 May 15.4. We argued that neon was overabundant in the ejecta of NV2. C. H. Townes (private communication) confirmed the presence of the [Ne II] emission feature in 1985 June. The 12.8 μm [Ne II] emission feature had a peak intensity on August 23.4 of 18.5 Jy in a 0.2 μm bandpass. The decline in the line strength over the past year, considering the effects of shell expansion, suggests that excitation conditions have not changed appreciably. Our conclusion (Paper I) that the amount of neon in the form of [Ne II] alone must be at least solar abundance still obtains. Recent optical and ultraviolet spectroscopy of NV2 by the *IUE* nova team (S. G. Starrfield, private communication) reveals strong lines of Ne III and Ne IV ions as well. The infrared and *IUE* data demonstrate that neon is enhanced in the ejecta of NV2. Starrfield, Sparks, and Truran (1986) also report strong UV and optical emission from Mg II. Magnesium, predicted to be enhanced in the ejecta of ONeMg white dwarfs, is a primary constituent of the minerals which produce the 10 and 20 μm emission features.

We can estimate a lower limit to the total mass of the silicate material in the ejecta of NV2. The ratio of the flux observed from the 10 μm emission peak to the flux that would be emitted by an optically thick dust shell reradiating the outburst luminosity of $\approx 10^5 L_\odot$ (Paper I, erratum) gives the mean shell silicate optical depth $\langle \tau_{10} \rangle$. The total mass M_{si} of silicates in the shell is

$$M_{si} \approx \pi R_s^2 \langle \tau_{10} \rangle / \kappa_{si},$$

where R_s is the shell radius and $\kappa \approx 3 \times 10^3$ cm^2 g^{-1} is the 10 μm silicate opacity. Assuming an expansion velocity of $V_0 \approx 1000$ km s^{-1} for the dust-forming component of the ejecta (Paper I), the shell should have attained a radius of 2.1×10^{15} cm by day 240, and an optically thick shell reradiating $10^5 L_\odot$ on that day would have had a temperature of ≈ 600 K. The 10 μm flux predicted for such a shell compared to the intensity of the 10 μm silicate feature on day 240 gives $\langle \tau_{10} \rangle \approx 4 \times 10^{-3}$ and $M_{si} \approx 10^{-8} M_\odot$. We note that the hydrogen mass associated with the silicate dust alone is $\approx 250 M_{si} \approx 3 \times 10^{-6} M_\odot$ if the Si abundance is normal. This is a fair fraction of the mass loss predicted for an explosion on the surface of an ONeMg white dwarf (Starrfield, Sparks, and Truran 1986) and, of course, excludes the mass associated with the high-velocity ejecta (see Paper I). Our calculations underestimate the value of $\langle \tau_{10} \rangle$ if the nova remnant subsided to the Eddington limit shortly after outburst (see Starrfield, Sparks, and Truran 1986) and if the nova remnant luminosity declined from the Eddington value thereafter. Thus, our estimate for M_{si} represents a lower limit.

V. DISCUSSION

We have argued that the silicate emission in NV2 indicates that grains nucleated and grew in the slow ejecta of NV2. Models of runaway nuclear explosions on the surface of an ONeMg white dwarf show that about half the ejected mass travels outward at velocities as low as 500–1000 km s^{-1}, which is consistent with the rather long time scale on which NV2 was observed to condense dust grains. Because silicates have a very low emissivity in the near-infrared, the late appearance of the shell is not unexpected and is generally consistent with the proposition that the grains nucleated and grew after the ejecta in which the grains condensed passed the 1000 K radiation field point in the expanding shell (Gallagher 1977; Gehrz *et al.* 1980*a*; Gehrz *et al.* 1980*b*). Starrfield, Sparks, and Truran (1986) have suggested that the anomalous emission from the ejecta of NV2 can be explained by a runaway nuclear explosion on the surface of an ONeMg white dwarf. Law and Ritter (1983) suggested that some nova systems might contain ONeMg white dwarfs, and Nomoto (1983) has shown theoretically that these white dwarfs could be the remnants of 8–12 $M_\odot$ main-sequence progenitors.

The data presented in Paper I and by Starrfield, Sparks, and Truran (1986) establish that two of the crucial ingredients, neon and magnesium, are enhanced in the ejecta of NV2. Our discovery of the existence of silicate grains in the ejecta of NV2 shows that there is an enhancement of the third crucial ingredient of an ONeMg white dwarf, oxygen, in this nova.

We thank J. G. Cohen, J. S. Gallagher, F. C. Gillett, E. P. Ney, G. W. Preston, S. G. Starrfield, and J. W. Truran for stimulating discussions. C. H. Townes communicated his spectra of NV2 prior to publication. L. D. Chisholm, L. R. Shaw, C. Jaworowski, and T. Williams assisted with the observations and maintained the Wyoming systems. R. D. G. is supported by the Institute of Technology at Minnesota. Astronomy at Wyoming is funded by the National Science Foundation, the USAF, and the Department of Physics and Astronomy.

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