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# FINE-STRUCTURE LINES AND THE 10 MICRON EXCESS OF NOVA CYGNI 1975

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## ABSTRACT

We propose that the 10 $\mu$m excess of V1500 Cygni, discovered by Ennis *et al.* ~1 year after outburst, is produced by fine-structure line emission, primarily by [Ne II] 12.8 $\mu$m. The amount of excess 10$\mu$m radiation at various epochs is estimated by comparing the 10 $\mu$m flux with observations of the H$\beta$ intensity. The excess first appeared on ~day 80, and by ~day 350 it contributed nearly all of the flux in the 10 $\mu$m bandpass.

The intensity of the 12.8 $\mu$m line is predicted by scaling from optical [N II] lines, since $Ne^+$ and $N^+$ have similar ionization fractions. The 12.8 $\mu$m line intensity successfully accounts for both the amplitude and development of the 10 $\mu$m excess, a strong confirmation of our previous measurement of the Ne/N abundance ratio of the ejecta.

*Subject headings:* infrared: spectra — stars: novae

## I. INTRODUCTION

This *Letter* explains the origin of the 10 $\mu$m excess of the nova V1500 Cygni (1975). Ennis *et al.* (1977) studied its infrared energy distribution and found that, with the exception of the 10 $\mu$m bandpass, the spectrum was a bremsstrahlung continuum throughout the decline. The 10 $\mu$m light curve resembled those of the other filters until ~day 350, when another source of radiation dominated the 10 $\mu$m bandpass. Ennis *et al.* proposed that this second source might be dust in the ejecta. In this *Letter* we show that the source of the "second light" is actually fine-structure (fs) line radiation, and that its appearance provides an important confirmation of the large excess of neon in the ejecta found by Ferland and Shields (1978).

## II. THE 10 MICRON EXCESS

In this section, McDonald spectrometry (Ferland, Lambert, and Woodman 1978) is combined with the Caltech infrared data (Ennis *et al.* 1977) to investigate the development of the 10 $\mu$m excess. Table 1 gives the details of this calculation. The free-free and free-bound continuum at 10 $\mu$m is predicted from the electron temperatures derived in Ferland and Shields (1978), the $He^+$, $He^{++}$ abundances of Ferland (1978), and the H$\beta$ intensities of Ferland, Lambert, and Woodman (1978). After day 120, the electron temperature was predicted from model calculations by assuming that the power-law density decline ($N_e \propto t^{-2.4}$) continued.

Column (7) lists the ratio

$$R = [F\nu(10\ \mu\mathrm{m})/F(\mathrm{H}\beta)]_{\mathrm{obs}}/[F\nu(10\ \mu\mathrm{m})/F(\mathrm{H}\beta)]_{\mathrm{pred}}\,,$$

after correcting for a color excess of $E_{B-V} = 0.53$ (Ferland 1977).

The excellent agreement between the calculated and observed ratio for days 32 to 62 confirms our previous estimate of the interstellar reddening (Ferland 1977). Figure 1 plots $R$ as a function of time. The second light clearly dominates the flux in the 10 $\mu$m bandpass on ~day 350, as Ennis *et al.* found. The excess was present as early as ~day 90, however.

The actual excess energy above the bremsstrahlung continuum is calculated in Table 2. Column (2) lists the 10 $\mu$m excess computed by assuming that the change in $R$ was due entirely to the 10 $\mu$m excess. To obtain the actual energy radiated, the excess must be multiplied by the effective bandwidth of the 10 $\mu$m filter. The filter response function has half-power points at 8.3 and 13.3 $\mu$m, and is nearly rectangular (Neugebauer 1978). A strong $O_3$ band ($\langle\lambda\rangle = 9.6\ \mu$m, $\delta\lambda = 0.4\ \mu$m) decreases the effective bandwidth to $1.2 \times 10^{13}$ Hz. Column (3) lists the excess 10 $\mu$m flux relative to H$\beta$. (The correction for interstellar reddening has been applied.)

## III. THE ORIGIN OF THE 10 MICRON EXCESS

### *a) Dust*

In their discovery paper, Ennis *et al.* suggested that the 10 $\mu$m excess may have been the result of radiation by dust. This hypothesis is inconsistent with several considerations. The dust-forming epoch usually occurs fairly early in the nova outburst ($\Delta m \lesssim 5$ mag; Gallagher 1977), and at dust temperatures near $10^3$ K (Ney and Hatfield 1978). The infrared excess of Nova Cygni did not appear until very late in the nebular phase and seems to imply a very cool temperature (< 500 K), since the excess was not present in the 1.2 or 3.5 $\mu$m bandpasses.[1] Further, there was no optical evidence that dust formed. Stratton (1945) and Hutchings and Fisher (1973) found that characteristic line profile changes occurred when dust formed in ejecta from DQ Her and FH Ser. No profile changes occurred during the late nebular phase of Nova Cygni (Ferland, Tomkin, and Woodman 1976). Another objection is that a general reddening of the continuous spectrum would be ex-

[1] The absence of a 1.2 or 3.5 $\mu$m excess also rules out the cool secondary as the source of the 10 $\mu$m excess.

TABLE 1

10 MICRON EXCESS OF NOVA CYGNI

| $T_{days}$ | $F_\nu(10\mu)\times10^{23}$† (ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$) | $F(H\beta)\times10^{10}$‡ (ergs s$^{-1}$ cm$^{-2}$) | $F(H\beta)_{corr}\times10^{10}$§ (ergs s$^{-1}$ cm$^{-2}$) | $T_e$ (K) | $F_\nu(10\ \mu m)/F(H\beta)\times10^{15}$ | $R$ |
|---|---|---|---|---|---|---|
| 32.8 | 6.00±1.00 | 5.6 | 7.6 | 9500 | 8.15 | 1.17 |
| 34.8 | 5.00±1.00 | 5.1 | 7.0 | 9500 | 8.15 | 1.06 |
| 41.5 | 3.70±0.80 | 3.7 | 4.9 | 9400 | 8.15 | 1.12 |
| 49.6 | 2.00±0.30 | 2.8 | 3.4 | 9400 | 8.00 | 0.89 |
| 61.5 | 1.10±0.50 | 1.5 | 1.8 | 9100 | 7.90 | 0.94 |
| 90.5 | 0.70±0.20 | 0.57 | 0.62 | 8800 | 8.24 | 1.61 |
| 94.7 | 0.60±0.10 | 0.50 | 0.55 | 8800 | 8.24 | 1.61 |
| 116 | 0.31±0.04 | 0.24 | 0.26 | 8700 | 8.62 | 1.67 |
| 304 | 0.26±0.08 | 0.031 | 0.031 | 7300 | 8.60 | 11.7 |
| 376 | 0.33±0.06 | 0.028 | 0.028 | 6900 | 8.43 | 17.7 |

NOTE.—Equilibrium temperatures from Ferland and Shields (1978).
* Time reckoned as in Ennis *et al.* Every other observation is presented before day 62.
† Taken from Ennis *et al.*
‡ Interpolated from Ferland, Lambert, and Woodman (1978).
§ Corrected for H$\beta$ self-absorption as in Ferland (1978).

pected, yet Ferland and Wootten (1977) found that the optical–infrared energy distribution became bluer during the nebular phase.

### *b) Fine-Structure Lines*

The 10 micron excess of Nova Cygni is most plausibly attributed to fine-structure line radiation. Table 3 lists

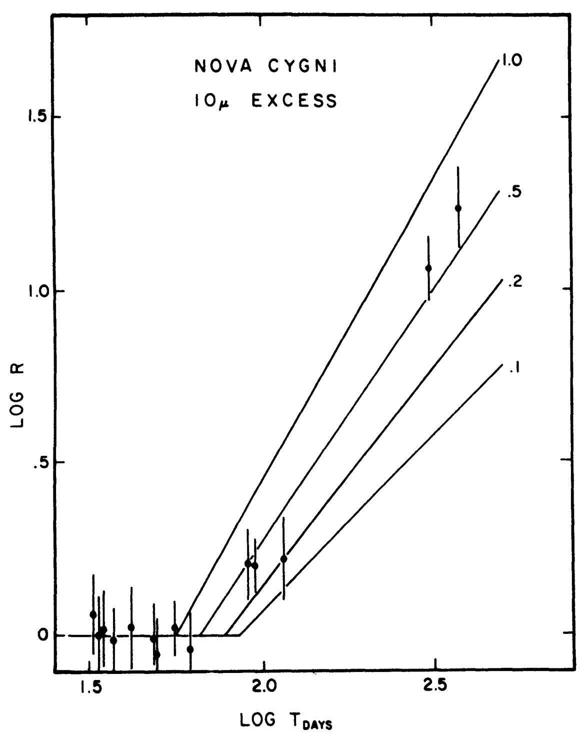


FIG. 1.—10$\mu$m excess of Nova Cygni. The ratio of observed to predicted 10 $\mu$m flux density. The theoretical 10 $\mu$m flux density was computed from the strength of H$\beta$. The lines give the intensity of [Ne II] 12.8 $\mu$m as a function of time, as predicted by scaling from optical [N II] lines. Each line corresponds to a specific Ne/N ratio, marked on the right. The range corresponds to the uncertainty in Ne/N as determined by Ferland and Shields (1978).

TABLE 2

10 MICRON EXCESS FLUX

| $T_{days}$ | *$F_\nu(10\ \mu m)_{excess}$ (ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$) | $F_\nu\delta\nu/I(H\beta)$ | [S IV]/$I(H\beta)$ | [Ne II]/H$\beta$ / Ne$^+$/N$^+$ |
|---|---|---|---|---|
| 90.5 | 3.0 (−24) | 0.08 | 0.002 | 0.155 |
| 94.7 | 2.3 (−24) | 0.07 | 0.002 | 0.155 |
| 116 | 1.3 (−24) | 0.08 | 0.005 | 0.245 |
| 305 | 2.4 (−24) | 1.1 | 0.053 | 1.68 |
| 376 | 3.0 (−24) | 1.6 | 0.062 | 2.82 |

the fs lines that lie within the 10 $\mu$m bandpass (Zeilik 1977). As a rough guide to the anticipated strength of the lines, the last column gives the product of the transition probability and abundance. The neon abundance was assumed to be 20 times solar, as derived by Ferland and Shields (1978) from the [Ne III] optical forbidden lines; the abundances of sulfur and argon were taken to be solar.

The [Ne II] 12.8 $\mu$m line should be the strongest feature. The Ar$^{++}$ line at 9.0 $\mu$m should be $\sim10^3$ times weaker, since models show that Ne$^+$ and Ar$^{++}$ have similar ionization fractions; we shall not consider it further. The [S IV] line intensity has been computed by running equilibrium photoionization models, as in Ferland and Shields (1978). Models for day 350 were computed by using the extrapolated density (§ II). The validity of this extrapolation was confirmed by the

TABLE 3

FINE-STRUCTURE LINES WITHIN 10 MICRON BANDPASS

| Ion | $\lambda(\mu m)$ | Transition | $A_{21}\times$Abundance |
|---|---|---|---|
| [Ne II] | 12.8 | $^2P_{3/2}$–$^2P_{1/2}$ | 2.1 (−4) |
| [S IV] | 10.5 | $^2P_{3/2}$–$^2P_{1/2}$ | 1.2 (−7) |
| [Ar III] | 9.0 | $^3P_2$ –$^3P_1$ | 1.2 (−7) |
| [Ne III] | 10.8 | $^3P_2$ –$^3P_0$ | 2.4 (−11) |
| [Ne V] | 9.0 | $^3P_2$ –$^3P_0$ | 2.4 (−11) |
| [S III] | 12.0 | $^3P_2$ –$^3P_0$ | 1.6 (−13) |

excellent agreement between observed and predicted [O III] λλ5007, 4363 line intensities relative to Hβ. Table 2 gives the predicted [S IV] 10.5 μm intensity relative to Hβ. This line can account for only a small fraction of the 10 μm excess.

The [Ne II] 12.8 μm line intensity cannot be predicted accurately with model calculations, since the models always underestimate the abundance of transition-zone ions (Ferland and Shields 1978). (This also typically occurs for models of planetary nebulae and Seyfert galaxies.) Models do suggest that the $O^+$, $Ne^+$, and $N^+$ emission zones coexist, however, so the strength of the [Ne II] line can be computed by scaling from the observed strength of optical [N II] or [O II] lines.

The fs $^2P$ levels are thermalized at densities greater than $N_e \sim 500$, so the strength of the [Ne II] line could be accurately predicted by comparing it with another thermalized line. The [N II] λλ5755, 6548, 6584 lines will be used, since no suitable [O II] lines are available. Because of the high electron density ($N_e \gtrsim 10^5$ K), λ3727 was not observed. The auroral λ7325 quartet was strong throughout the nebular phase of Nova Cyg, but its critical densities for de-excitation and excitation potential are both large, so its strength relative to a thermalized line will be very sensitive to the physical conditions assumed. The [N II] λλ6548, 6584 doublet is thermalized throughout our observations, and λ5755 is nearly thermalized before day 150. These lines provide the best indication of the [Ne II] 12.8 μm intensity.

Table 4 presents the details of the predictions. The predicted density is given in column (2), and the intensity of [N II] 5755 and [N II] 6548, 6584, relative to Hβ, are given in columns (3) and (5). Column (4) gives the ratio of emissivities per ion for [Ne II] 12.8/[N II] 5755, and column (6) gives ϵ([Ne II] 12.8)/ϵ([N II] 6548, 6584). Both are the result of solution of the five-level atom, using the atomic constants of Garstang (1968) and Wiese, Smith, and Glennon (1966). The 5755 auroral line will be used as the [Ne II] 12.8 indicator between days 90 and 120, since $^1S$ is more nearly thermalized at that time, and the physical conditions have been measured most reliably. The [N II] 6548, 6584 doublet is used after it appeared on ~day 300. This line is an excellent [Ne II] predictor, since its excitation potential is low, and the population of $^1D$ is very close to LTE predictions at these densities.

The ratio of emissivities per ion must be multiplied by the ion abundances to obtain the theoretical 12.8 μm intensity. Models show that $N(Ne^+)/N(N^+) = N(Ne)/N(N)$, and Ferland and Shields (1978) found $N(Ne)/N(N) = 10^{-0.6\pm0.4}$. Column (5) of Table 2 gives $I(12.8\ \mu m)/I(H\beta) \times [N(N)/N(Ne)]$. The lines of Figure 1 show the predicted intensities of [Ne II] 12.8 μm and [S IV] 10.5 μm as a function of $N(Ne)/N(N)$. Each curve is uncertain by 0.1 dex because of uncertainties in the physical conditions. The best fit is obtained with $N(Ne)/N(N) = 10^{-0.3\pm0.1}$; this confirms our previous abundance determination.

TABLE 4

[Ne II] 12.8 MICRON PREDICTIONS

| $T_{days}$ | $N_e$ | $I(5755)/I(H\beta)$ | $\epsilon(12.8)/\epsilon(5755)$ | $I(6548, 6584)/I(H\beta)$ | $\epsilon(12.8)/\epsilon(6548, 6584)$ |
|---|---|---|---|---|---|
| 90.5... | 2.4 (7) | 0.33 | 0.35 | ... | ... |
| 94.7... | 2.1 (7) | 0.31 | 0.36 | ... | ... |
| 111.... | 1.3 (7) | 0.45 | 0.58 | ... | ... |
| 305.... | 1.3 (6) | 0.69 | ... | 1.1 | 1.45 |
| 376.... | 7.7 (5) | 0.58 | ... | 1.4 | 2.00 |

## IV. DISCUSSION

The previous section demonstrated that [Ne II] 12.8 μm contributed a large fraction to the flux in the Caltech 10 μm bandpass during the late nebular phase of Nova Cygni, because of the large neon abundance and low electron temperature (a consequence of high metal abundances).

We can predict intensities of other infrared fine-structure lines with model calculations. Models (Table 5) were computed by extrapolating the density decline, and with radii and ionizing flux chosen to mimic the evolution of the nova. The [O III] λλ5007, 4959, 4363 intensities on day 360 are in excellent agreement with observations (Ferland, Tomkin, and Woodman 1976), but the [N II] lines are actually much stronger than predicted. This is a consequence of the well-known "[O II] problem" in photoionized nebulae (e.g., Shields 1978).

Figure 2 shows the electron temperature as a function of time. Since the equilibrium temperature is set by the balance between heating (photoionization) and cooling (recombination and collisional excitation), the temperature falls as the nebula becomes more tenuous and

TABLE 5

MODEL CALCULATIONS

A.

| | $T_{days}$ | | | |
|---|---|---|---|---|
| | 40 | 120 | 360 | 1200 |
| $T_*$(K) .......... | 110000 | 130000 | 170000 | 170000 |
| $N_e$(cm$^{-3}$)......... | 1.5 (8) | 1.2 (7) | 8.0 (5) | 5.0 (4) |
| $T(O^{++})$*.......... | 9300 | 8700 | 6900 | 5400 |

B. LINE INTENSITIES (relative to Hβ)

| ION | λ(μm) | $T_{days}$ 40 | 120 | 360 | 1200 |
|---|---|---|---|---|---|
| H I.... | 0.4861 | 1.00 | 1.00 | 1.00 | 1.00 |
| [N II].. | 0.6583 | ... | 0.011 | 0.217 | 0.97 |
| [N II].. | 0.5755 | ... | 0.028 | 0.029 | 0.005 |
| [O III].. | 0.5007 | 1.51 | 13.4 | 28.7 | 21.6 |
| [O III].. | 52 | ... | 0.015 | 0.158 | 2.20 |
| [O IV].. | 26 | ... | 0.028 | 0.593 | 6.00 |
| [Ne II]. | 12.8 | ... | 0.004 | 0.090 | 0.338 |
| [Ne III]. | 15.6 | ... | 0.262 | 2.21 | 9.60 |
| [Ne V].. | 24.2 | ... | 0.002 | 0.102 | 0.78 |
| [Ne VI]. | 7.6 | ... | 0.012 | 0.521 | 0.49 |

* Computed equilibrium temperature.

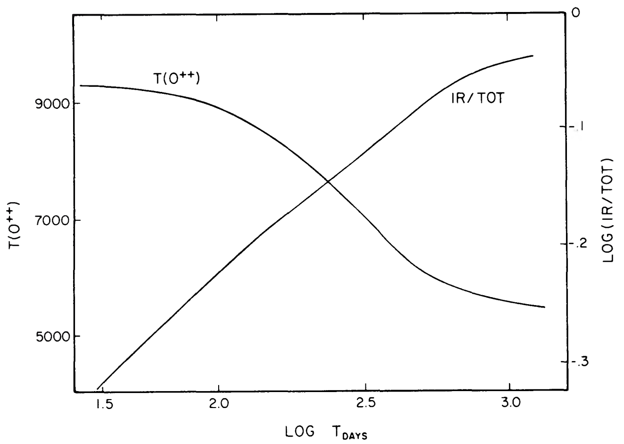


FIG. 2.—Thermal equilibrium and fine-structure cooling of Nova Cygni. The electron temperatures and fraction of collisional cooling borne by fine-structure lines are shown as a function of time. These are the result of model calculations performed by extrapolating the power-law density decline found by Ferland and Shields.

forbidden-line radiation becomes a more efficient coolant. This drop occurs because a greater fraction of excitations result in production of a line photon, rather than in collisional de-excitation.

As the temperature falls, a greater fraction of the collisional cooling is by fine-structure line radiation. Figure 2 also shows the fraction of the total collisional cooling borne by infrared fine-structure lines. Fine-structure line radiation dominates the cooling 3 years after outburst. The [Ne II] 15.6 $\mu$m and [O IV] 26 $\mu$m line should be especially strong at present (mid-1978). Observations of these lines would provide a valuable confirmation of overabundances of certain chemical elements.

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