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Near Infrared Coronal Line Emission in Nova Herculis 1991

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Abstract. Near infrared coronal line emission at 1.98 ± 0.02μm due to [Si VI] detected in the spectrum of Nova Herculis 1991 about 17 days after optical maximum is reported. The early appearance of coronal emission is yet another unusual feature of this fast nova in which early onset of dust formation processes and X-ray detection five days after outburst have already been reported. The coronal line observations reported here are consistent with X-ray detection and support a hot shocked circumstellar envelope at the periphery of the dust formation zone in the nova.

Key words: Nova Her 91—infrared spectrophotometry—coronal line emission—shock heating—circumstellar dust

1. Introduction

Nova Herculis 1991 apart from being one of the brightest and fastest novae in recent times, has also been a very unusual nova. Optical detection of the nova was on the night of 1991 March 24 at an estimated magnitude of V = 5 (Sugano *et al.* 1991). It faded rapidly in the optical, declining by about 6 magnitudes in ~ 10 days (Woodward *et al.* 1992). Following discovery, the nova was observed extensively at other wavelengths as well. It was detected at milli Jansky level at 14.9, 8.4 and 4.9 GHz by the Very Large Array (VLA) about 11 days after optical maximum (Hjellming 1991). Near infrared photometric observations showed a brightening peaking in the K (2.2 μm) band 14 days after outburst suggesting an unusually early phase of dust formation in the nova (Chandrasekhar *et al* 1992; henceforth called Paper I). Nova Her 1991 has also been detected by Rosat satellite in the X-ray region just five days after optical maximum (Lloyd *et al.* 1992)–the first ever nova to be positively detected so early in its evolution. The high temperature zone needed for X-ray emission also constitutes a favourable environment for the production of highly ionized states of elements and for detectable coronal line emission from the excited states of these ions.

In addition to optical forbidden line emission commonly seen in novae such as [OII] 3727Å, [OIII] 4363Å, [NIII] 4640 Å, [OIII] 4959 Å, [OIII] 5007 Å some novae also exhibit optical ‘coronal’ line emission such as [FeVII] 6087 Å, [FeX] 6374 Å, [FeXI] 7892 Å (Starrfield 1988). However in the near infrared, forbidden emission lines of coronal origin were first discovered only relatively recently in Nova V1500 Cyg (Grasdalen & Joyce 1976). Subsequently infrared spectrophotometry at moderate resolving powers ($\lambda/\delta\lambda$~ 100) of novae VI500 Cyg, QU Vul, Nova Her

1987, V1819 Cyg have shown that some novae enter a coronal emission phase characterised by infrared forbidden line emission a few hundred days after eruption. (Gehrz 1988). Though the excitation temperatures for these emissions is of the order of ~ 10^3 K the temperatures required for the ions to exist are in the range $5 \times 10^5 - 10^6$ K. The presence of these lines require large energy inputs to the region to sustain the population of high lying states against adiabatic cooling. It has been pointed out by Starrfield (1988) that though the cause of coronal line emission is not exactly known, X-ray spectra can indicate whether a shock heated region exists.

In this paper we discuss the strong emission feature at 1.98 ± 0.02 μm detected by us as early as day 17 following optical maximum in Nova Herculis 1991. Subsequently Joyce (1991a, 1991b) has also detected and identified, the line in addition to other coronal emissions in the same nova on two days, 67 days and 88 days following the optical maximum.

2. Observations

The observations reported here were carried out with a liquid nitrogen cooled InSb detector based infrared photometer at the 1.2 m telescope at Gurushikhar, Mt. Abu, India. Table 1 summarises the instrument-telescope configuration used. Broad band J,H, K observations were carried out during the period 1991 April 5.97 UT – 1991 May 28.8 UT. These broad band observations and their results pertaining to early dust formation in Nova Her 1991 have been detailed in Paper I.

The IR photometer has in addition to standard J,H,K filters a circularly variable filter (CVF) operating in the spectral region 1.7–3.4 μm with a resolving power of ($\lambda/\delta\lambda$) ~ 70. The CVF is driven with a 4 phase stepper motor with a potentiometric readout of its angular position. Each fine step corresponds to a wavelength shift of 0.008 μm, while one coarse step corresponds to four fine steps and is approximately the achievable resolution with the CVF. In actual operation the stepper motor movement is hindered at certain positions of the CVF filter wheel and in those positions its movement has to be assisted manually. This exercise causes at times a jitter in the motor movement resulting in it jumping over a few fine steps but never greater than one coarse step. Spectral calibration of this potentiometer is carried out with a low pressure mercury vapour lamp with strong narrow lines in the region of

Table 1. Telescope-instrument configuration.

1. Detector	:	LN_2 cooled InSb NEP:5×10^{-15} W/$\sqrt{\text{HZ}}$ at 2.2 μm		
2. Telescope	:	1.2 m f/13 Cassegrain focus Gurushikhar, Mt. Abu, India (72° 47′ E, 24° 39′ N, 1680 m altitude)		
3. Filter	:	Band	λ_{eff}(μm)	Bandwidth (μm) (FWHM)
		J	1.25	0.30
		H	1.65	0.30
		K	2.20	0.70
		CVF	1.7–3.4	0.02–0.04

Table 2. Observations of the 1.98 μm line.

1991 April Date UT	Days since optical maximum	Observed CVF wave length range in μm	Line centre wavelength ($\pm 0.02\,\mu$m)	Peak flux $\times 10^{-10}$ erg/cm²/s/μm	Line strength $\times 10^{-10}$ erg/cm²/s
9.95	16.95	1.9–2.5	1.99	91 ± 9	2.8 ± 0.8
10.89	17.89	1.9–2.1	1.98	90 ± 9	2.5 ± 0.6
15.91	22.91	1.94–2.14	1.99	228 ± 20	7.3 ± 3
20.89	27.89	1.94–2.4	1.98	54 ± 6	1.5 ± 0.5

Table 3. IR photometry, dust temperature and angular size of dust zone derived.

1991 April Date UT	Days since optical maximum	IR magnitude J	IR magnitude H	IR magnitude K	T_{BB} (± 50 K)	Calc. angular size of dust zone (milli arcsec)
9.95	16.95	7.71 ± 0.08	6.16 ± 0.10	4.51 ± 0.03	1360	4.0
10.89	17.89	7.81 ± 0.10	5.98 ± 0.05	4.47 ± 0.03	1330	4.2
15.91	22.91	8.00 ± 0.20	6.16 ± 0.05	4.60 ± 0.03	1180	5.0
16.94	23.94	8.50 ± 0.20	6.26 ± 0.05	4.67 ± 0.03	1160	5.2
20.89	27.89	8.80 ± 0.20	6.83 ± 0.05	4.98 ± 0.05	1080	5.7

interest. Details of the spectral calibration of CVF are given in Chandrasekhar *et al* (1984).

Nova Herculis 1991 was observed in the region 1.9μm–2.1μm in the CVF mode on four days between 1991 April 9 and April 20. On some days the spectral coverage extends upto 2.4 μm. Details of the spectral line observations made are given in Table 2. Table 3 lists the infrared magnitudes measured at J, H, K on the days the spectral line was observed in the CVF mode. Also listed from our earlier paper (Paper I) are the blackbody temperature (T_{BB}) fitted to the observed spectrum and the angular extent of the dust zone ($2\theta_{BB}$) obtained from the observed flux $F_\lambda \sim \theta^2_{BB}\, B(\lambda, T_{BB})$. Visual maximum of the nova is reckoned to have been reached on 1991 March 24.0 UT. The standard stars used for photometry were α Leo, α Ser, μ Her, ε Her and α Oph. α Oph being located at almost the same declination as the nova was observationally the most convenient and hence the most frequently used calibration star. Flux density calibration is derived from Johnson's zero magnitude fluxes (Johnson 1966). The nova spectrum was ratioed with that of α Oph (A5 V) obtained with the same CVF resolution and then multiplied by a blackbody spectrum corresponding to the star's effective temperature of 8500 K in order to remove effects of atmospheric absorption.

3. Analysis

Line profiles of the 1.98 μm line obtained on the four days of observations are shown in Fig. 1 to Fig. 4. As mentioned in Table 3 on three days out of four, the spectral

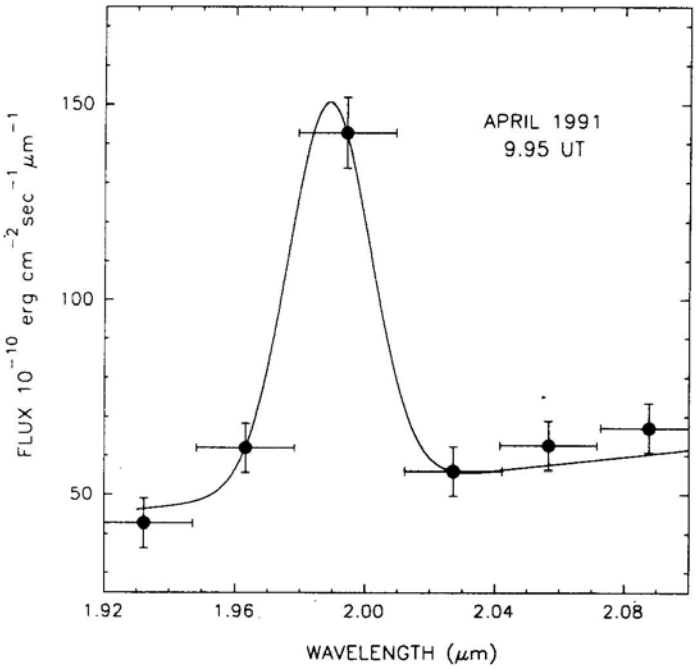

Figure 1. Observed spectral line at ~ 1.98 μm from Nova Her 1991 on day 16.95 after optical maximum.

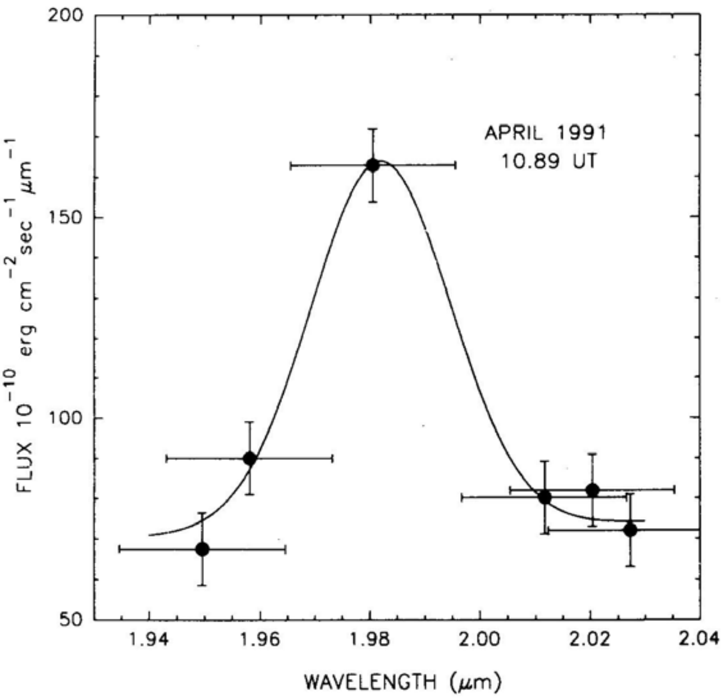

Figure 2. Observed spectral line at ~ 1.98 μm from Nova Her 1991 on day 17.89 after optical maximum.

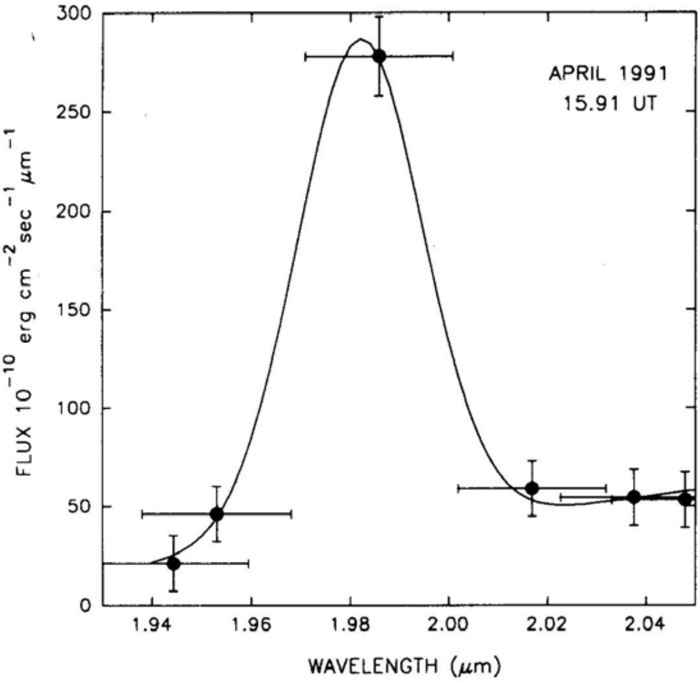

Figure 3. Observed spectral line at ~ 1.98 μm from Nova Her 1991 on day 22.91 after optical maximum.

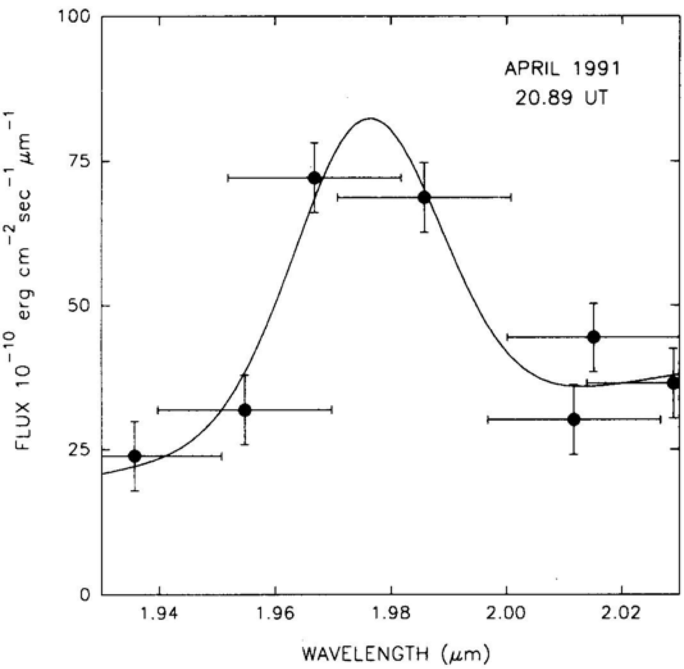

Figure 4. Observed spectral line at ~ 1.98 μm from Nova Her 1991 on day 27.89 after optical maximum.

range of observations extends beyond 2.10 μm. The full observed nova spectrum of these days is shown in Fig. 5 to Fig. 7. The region near our line of interest is also highlighted as an inset in these figures. Instrumental spectral calibration has been carried out by observing a strong laboratory spectral line at 1.97 μm in a Mercury discharge tube. The CVF instrumental width determined from the calibration is 0.03 μm. The observed line width (Fig. 1–Fig.7) does not exceed the instrumental width and hence no attempt is made to derive a line profile from the observations.

The spectral line and its adjacent continuum are represented respectively by a Gaussian of fixed width (FWHM = 0.03μm) and a line of appropriate slope. This combination is superposed on the data and is also shown in Fig. 1–7. It has a mathematical form

$$I(\lambda) = A + B\lambda + C\exp\left[-\frac{(\lambda-\lambda_0)}{2\sigma^2}\right]$$

Here σ is related to the $\Delta\lambda$, the line width (full width at half maximum, FWHM) by

$$\Delta\lambda = \sqrt{8\ln 2}\,\sigma$$

A least square fit to the expression for I (λ) results in the evaluation of the parameters A, B, C and the central wavelength of the line (λ). A value of σ corresponding to the instrumental width (0.03 μm) has been adopted in the calculations. It can be seen from Table 2 that the line centre is established with reasonable accuracy at 1.98 ± 0.02 μm.

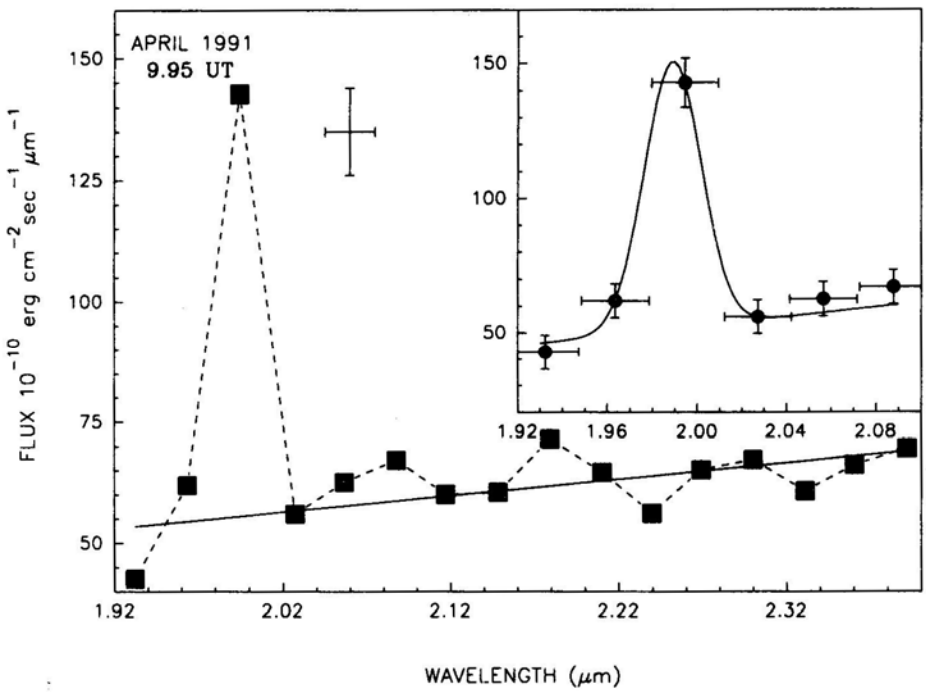

Figure 5. CVF observations of Nova Her 1991 on day 16.95 after optical maximum in the spectral region 1.922.32μm. showing the line at ~ 1.98 µm and the adjacent continuum.

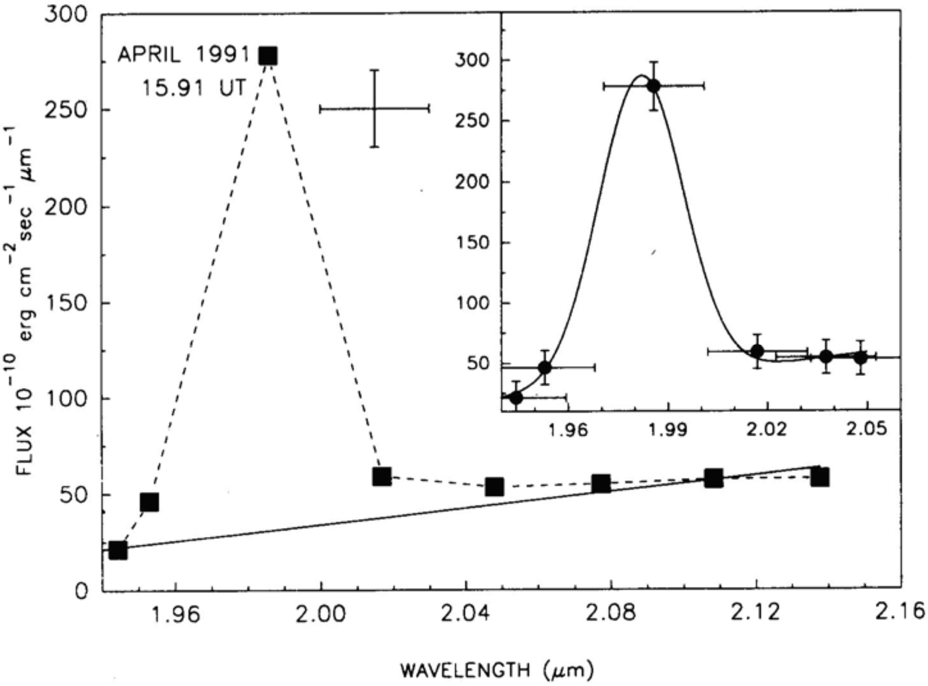

Figure 6. CVF observations of Nova Her 1991 on day 22.91 after optical maximum in the spectral region 1.94–2.16μm showing the line at ~ 1.98μm and the adjacent continuum.

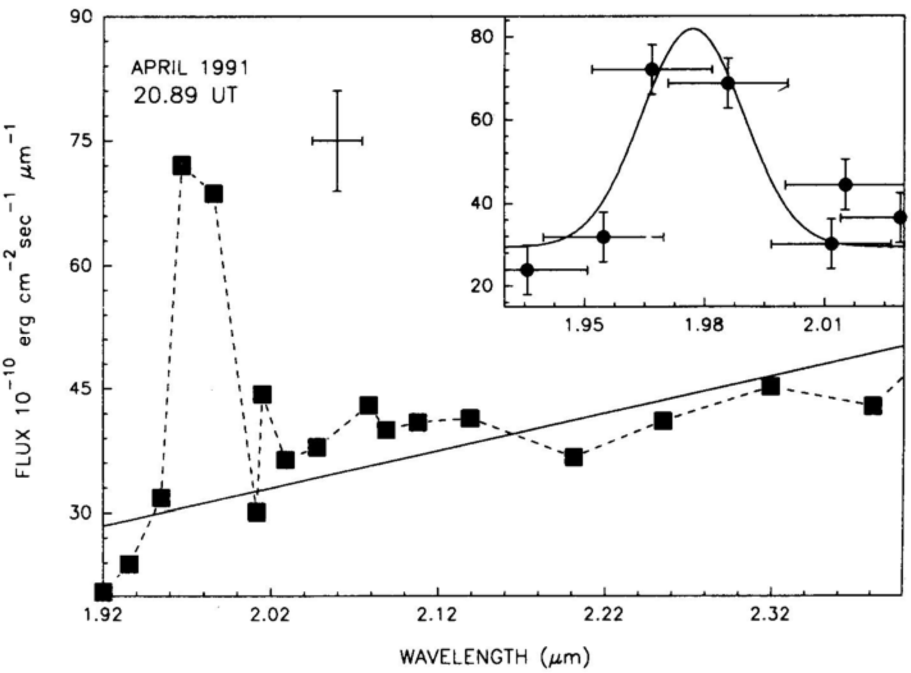

Figure 7. CVF Observations of Nova Her 1991 on day 27.89 after optical maximum in the spectral region 1.92–2.4μm showing the line at ~ 1.98 μm and the adjacent continuum.

The line strength represented as the area under observed line profile above the continuum level has been determined. It is seen that on one night (1991 April 15.9) the line appears distinctly stronger with the observed flux registering more than twice the value of the previous or subsequent observations. The average value of line strength over the period of observations of ~ (3.5 ± 1) × 10^{-10}erg/cm^2/s is adopted as a representative value for further discussions. It is to be noted from Table 3 that the K magnitude during this period has increased steadily by 0.5 magnitudes showing a decrease in intensity by a factor of ~ 1.6.

4. Line identification

The spectral lines seen at times in novae within ± 0.1μm of 1.98 μm are HI Brδ (1.95 μm), HeI (2.058 μm, [A1 IX] (2.04μm) and [Si VI] (1.96 μm,. It is not clear if HI Brδ had been seen at all in Nova Her 91. Paschen lines of neutral hydrogen Paβ, Paγ, and Brackett lines Brγ, Brl0–Brl4 with a width (FWHM) of ~ 3700 km/s were seen on 1991 March 25.7 (Day 1.7) less than 2 days after optical maximum (Harrison *et al.* 1991). On 1991 March 29.4 (Day 5.4) nova showed blue continuum with broad lines of HI, Brγ Paα, Br 10, Br 11 and also HeI (2.058μm). Line intensities measured on day 5.4 were 7.5 ×10^{-11} erg/cm^2/ for Brγ (2.17μm) and 5.1 × 10^{-11}erg/cm^2/s for HeI (2.058 μm (Moneti *et al.* 1991). Expected intensity of Brδ (1.95 μm computed from observed Bry intensity is ~ 3 × 10^{-11}erg/cm^2/s. With the rapid expansion of the nova and consequent decrease in electron density the recombination lines rapidly decrease in intensity and become unobservable. Joyce (1991a) in his observations made later did not see any hydrogen or helium emission lines. On the first and last days of our CVF observing mode, when the spectral range extended upto 2.4 μm, there is no detectable emission at 2.17μm corresponding to HI Bry which implies that HI Brδ if present would also be below our detection limits.

Since the laboratory spectral calibration of the CVF allows us to pinpoint line centre within ± 0.02μm, we can also rule out HeI (2.058μm) and [Al IX] (2.04 μm) and ascribe the observed emission to the forbidden coronal emission due to [Si VI]. Line parameters are listed in Table 4. The limited spectral range of our observations (Table 2) precludes the observation of other coronal lines like [Si VII] (2.47 μm) which could have existed at the same time. Emissions due to [Ca VII] at 2.32 μm, [Al IX] at 2.04 μm and HeI at 2.058 μm are not seen by us within detection limits.

Table 4. Spectral line parameters.

Ion Si VI
Wavelength of the coronal emission line 1.96 μm
Transition: ^{2}P (1/2, 3/2)
Coronal forbidden transition
Excitation temperature ~ 7.3 × 10^3 K
Ionisation potential (E_i)
for Si VI: 205 eV

5. Discussion

Nova Her 1991 has exhibited the coronal line emission at 1.98 μm. at an unusually early phase (day 17) in its evolution. So far medium resolution near infrared spectrophotometry has shown that novae enter into the coronal emission phase only a few hundred days after eruption. For example Nova Vul 1984 # 2 showed the IR coronal emission between 500 and 800 days after optical maximum (Greenhouse *et al.* 1988). These authors have argued that the emission is produced by photoionisation in a gas that exhibits clumpy spatial distribution. Nova Cyg 1975 (V1500 Cyg), a faster nova, exhibited the infrared coronal emission ~ 60 days after the outburst (Grasdalen & Joyce 1976).

Apart from a very early exhibition of near infrared coronal line emission Nova Her 1991 also differs markedly from other novae in its dust forming behaviour. Signature of dust formation was evident as early as day 7. Peak infrared luminosity was reached on day 14. Thereafter the IR (2.2μm) light curve declined slowly as $\sim t^{-1}$ till about day 25 and at a more rapid rate $\sim t^{-4}$ later, signifying the free expansion phase. The slow decline seen till day 25 could be due to strong forbidden line emission contributing to the K band flux (Paper I).

Another important observation which has set Nova Her 1991 apart from other novae has been the detection of X-rays from the nova as early as day 5.4 by Rosat satellite (Lloyd *et al.* 1992). Standard nova model predict X-ray emission to arise directly from nuclear burning on white dwarf surface and do not permit X-rays in the early stages following the outburst. Best fit for the Nova Her 91 X-ray observations require a flat spectrum of high temperature (KT ~ 10 KeV) thermal emission observed through a large absorbing column of neutral hydrogen with a column density $(N_H) \sim (3.4 \pm 1.6) \times 10^{21}/\mathrm{cm}^2$. The actual X-ray emission, the authors argue, arises from a hot shocked circumstellar material which is either pre-existing material or has been ejected during nova eruption. A minimum density in the range 10^{-18} – $10^{-17}\mathrm{g/cm}^3$ is required for the ejecta to be heated to X-ray temperatures.

We argue that the near infrared coronal line emission at 1.98 μm observed by us between day 17 and day 25 arises from the same high temperature region in which the X-rays were detected earlier on day 5 after eruption.

Following Greenhouse *et al* (1988) and Lang (1978) the line intensity of [Si VI] line from a spherical region of the nova of radius r, temperature T and distance d from earth is given by

$$I_{Si^{+5}} = \frac{(8.629 \times 10^{-6}) n_{Si^{+5}} n_e r^3 h\nu\,\Omega}{d^2 T^{1/2} g_u} \mathrm{cgs} \qquad (1)$$

where $n_{Si^{+5}}$: number density of Si^{+5} ions.

n_e : electron density.

h_ν: transition energy of [Si VI] line at 1.96 μm 0.63 eV.

Ω : collision strength

g_u : Statistical weight of its upper level

$$n_{Si^{+5}} = \left(\frac{n_{Si^{+5}}}{n_{Si}}\right)\left(\frac{n_{Si}}{n_H} n_H\right)$$

where n_{Si} and n_H are number densities of neutral silicon and hydrogen respectively.

From the calculations of Jordan (1969) applicable to a low density plasma where radiation field is negligible, we see that for a temperature of ~ 10^6K

$$-\log\left(\frac{n_{Si^{+5}}}{n_{Si}}\right) = 1.54$$

Further

$$-\log\left(\frac{n_{Si}}{n_H}\right) = 4.48$$

(Allen 1973) and $n_H \sim n_e$, =0.23 (Greenhouse *et al.* 1988). Following Lloyd *et al.* (1992) a distance to nova of d = 10 ± 4 kpc is adopted, Putting in the numerical values we can rewrite equation 1 in the form (for a distance d ~ 10kpc).

$$I_{Si^{+5}} = 2.86 \times 10^{-5}(r/d)^3 n_e^2$$

Taking the measured value of I_{Si+5} to be ≈ (3.5 ± 1) × 10 ^{10}erg/cm^2/s

$$(r/d)^3 n_e^2 \approx 1.2 \times 10^{-6}\text{cm}^{-6}$$

The angular extent of dust forming region for Nova Her has been estimated from broad band IR photometry to be ~ 6 milli arcsec (Paper I). Further assuming the shock heated line emitting region to be located at the outer periphery of the dust forming region we obtain $n_e \sim 2\times 10^9/\text{cm}^3$ and putting $n_e \sim n_H$ mass density $m_H n_H \approx 3.4 \times 10^{-15}\text{g/cm}^3$. Further as ne varies $(I_{Si^{+5}})^{1/2}$ it is not greatly affected by the uncertainties in the estimation of the line strength

It has been shown (Gehrz & Ney 1987) that novae developing optically thick dust shells have average dust shell densities in the range $3 \times 10^{-16} - 10^{-15}\text{g/cm}^3$ at the condensation point. The critical density for grain formation in Nova Her 1991 has been shown to be $\rho_c \sim 4 \times 10^{-16}\text{g/cm}^{-3}$ (Paper I). The mass density value derived from line strength of the coronal line is above the critical density and is consistent with the argument that dust formation had begun by the time coronal emission manifested itself.

The X-ray observations require the high velocity nova ejecta to interact with some pre-existing material surrounding the nova of density in therange ~ $10^{-18} - 10^{-17}$g/ Cm^3

It is perhaps significant that X-ray emission was detected on day 5 about 2 days before increase in IR flux indicated onset of dust formation processes in the nova ejecta. It appears that the nova ejecta added substantially to the pre-existing material of density $10^{-18} - 10^{-17}\text{g/cm}^3$ present at the time of X-ray emission (day 5) and reached a final value of ~ $3.4 \times 10^{-15}\text{g/cm}^3$ by the time dust formation processes were complete (day 25).

Is it possible that this pre-existing material has been detected in the IRAS survey indicating cold galactic dust? An elementary calculation for the angular extent of the cold dust region can be made assuming dust at ~ 30 K emitting as a blackbody at a distance of ~ 10 kpc.

The sensitivity limit of IRAS point source survey at 100μm is ~ 1.5 Jy (Beichman *et al.* 1988). Assuming that all the emitted radiation (at 30K) is received in the 100μm spectral band of IRAS which has a width of ~ 37 μm (83–120) we obtain for this sensitivity limit a minimum angular size ($2\theta_{min}$) given by

$$\theta^2_{min} T^4 \sim 1.25 \times 10^4$$

$$2\theta_{min} \sim 250 \text{ milli arc sec}$$

A quick search has been made in the IRAS catalogs – both the point source catalog and the extended source catalog. There is no detectable cold dust at the position corresponding to the nova in the IRAS surveys. The search though preliminary puts limits on the spatial extent of pre-existing dust at a temperature of 30 K or above in the prenova environment. The maximum angular extent of the cold dust at 30 K consistent with IRAS observations is 250 milli arcsec corresponding to 2500 A.U. at a distance of 10kpc. At T ~ 100 K the extent of the dust emitting predominantly in the 25 μm IRAS band would be only ~ 225 A.U. in the prenova environment. Cooler dust at ~ 10 K however would have been well below the sensitivity limits of IRAS to be detectable and could have existed prior to the nova, over a much larger extent.

6. Conclusions

Medium resolution infrared spectrophotometry ($\lambda/\delta_\lambda \sim 70$) of Nova Her 1991 has led to the positive detection of an emission line at 1.98 ± 0.02 μm with a strength of ~ (3.5 ± 1) 10^{-10} ergs/cm^2/s between 17 and 25 days of optical maximum of the nova. The line has been identified as forbidden coronal infrared emission due to [Si VI]. These observations are consistent with the X-ray emission reported earlier from the nova and could arise in the circumstellar region at the periphery of the dust forming zone. There is no detectable cold dust in the prenova environment from IRAS data, which constrains the spatial extent of dust (at 30 K) in the prenova environment to about 2500 AU at the distance to the nova of 10kpc.

Acknowledgements

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