Near-infrared observations of Nova Herculis 1991

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Accepted 1991 October 28. Received 1991 October 23; in original form 1991 August 23

SUMMARY
Observations of Nova Herculis 1991 made in the near infrared are reported, mainly in the $J$, $H$, and $K$ filter bands, commencing from day 13 after the nova explosion and spread over a period of over 50 days. The temporal variations of the IR flux indicate an early onset of dust formation processes in this fast nova. The light curve shows a slow decline $\propto t^{-1}$ until day 25 and then a sharper decline $\propto t^{-4}$. Blackbody angular-size calculations exhibit a steady increase until about the same time and a sharp change thereafter, suggesting cessation of dust formation following onset of the free expansion phase. Blackbody temperatures show a steady decline $T_{BB} \propto t^{-1/2}$, from a value of 1400 K observed on day 14.

1 INTRODUCTION
Infrared (IR) observations are important in studies of novae because they provide a direct means of detecting formation of dust in nova ejecta and for studying its subsequent evolution. In particular, temporal studies of novae in the infrared are crucial for delineating the different phases of nova evolution - pseudoo-photospheric expansion, optically thin gas-emission phase and dust formation. The rapid changes that occur in nova environments necessitate infrared observations as early as possible after the outburst, followed by frequent subsequent observations.

The infrared observations of novae observed so far, particularly the temporal behaviour, are well documented (Gehrz 1988). A general summary of classical nova outbursts can be found in a recent work (Starrfield 1988). Infrared temporal development of less than 10 novae has been properly followed through, while isolated infrared observations exist for a few more novae. Coordinated temporal infrared studies of novae are yet to be carried out on a regular basis.

An interesting aspect that has emerged from the infrared observations of novae made so far is the wide variety exhibited by these objects in their dust-forming behaviour (Gehrz 1988). Earlier it was thought that all dust-forming novae formed shells without spectral features and composed of graphite grains only. Nova Aql 1982 was a deviant from this general picture which exhibited a 10-$\mu$m emission feature attributable to SiC. Nova QU Vul exhibited dust composed entirely of oxygen-rich silicates with characteristic 10- and 20-$\mu$m spectral signatures in emission, superposed on a complex gas-shell spectrum composed of thermal bremsstrahlung continuum with strong forbidden-line emission (Gehrz et al. 1988). In faster novae like V1668 Cyg (Gallagher et al. 1980; Piirona & Korhonen 1979) and V1500 Cyg (Ennis et al. 1977) there is only limited evidence for dust formation. V1688 Cyg condensed an optically thin dust shell with a maximum optical depth of 0.1 in about 60 d while V1500 Cyg exhibited only a weak 10-$\mu$m excess after 100 d, attributable to a dust shell. The diversity of infrared behaviour exhibited by novae makes it very important to study the temporal behaviour of every nova in the infrared. Whether fast novae can form substantial dust shells remains to be established.

The eruption of Nova Herculis in 1991 March provided a good opportunity for studying its dust-forming behaviour from observations made in the near infrared at the recently established 1.2-m telescope at Gurushikhar, India.

2 THE OBSERVATIONS
First reports of the Nova Herculis 1991 outburst (Sugano et al. 1991) were received only on 1991 April 3. Following this a programme of infrared observations of the nova was quickly formulated and first observations were made on 1991 April 5. The observations were continued at intervals of a few days, weather permitting, until the end of 1991 May when cloudiness associated with pre-monsoon conditions set in.

The coordinates of Nova Herculis 1991 are
(a) Equatorial: RA= 18h 44m 11.83
    Dec. = +12° 10' 45.0''

(b) Galactic:  $\ell^\prime = 43^\circ 18' 9''$
    $b^\prime = +6^\circ 37' 2''$.

The infrared photometric observations were carried out at the 1.2-m telescope at Gurushikhar (72°47'E, 24°39'N) with
a liquid-nitrogen cooled InSb IR photometer. Observations were made mainly in the J, H, and K near-infrared filter bands and occasionally at a longer wavelength near 3.3 μm with a narrower circular variable filter (CVF). Sky chopping with an amplitude of ~26 arcsec at a frequency of ~10 Hz was accomplished with a tertiary vibrating plane mirror in the light path. A focal-plane aperture of 26 arcsec was generally used. The sky near the nova was also sampled regularly in all the filters to correct for sky gradients. Nearby standard stars were also frequently monitored during the observations. The standard stars used were α Leo, α Ser, μ Her, ε Her and α Oph. α Oph, being observationally conveniently located at about the same declination as the nova, was the most frequently used calibration star with its infrared magnitudes taken as J = 1.78, H = 1.64, K = 1.66 and m (3.3μm) = 1.61 (Gezari, Schmitz & Mead 1987). The flux-density calibration is derived from Johnson's zero-magnitude fluxes (Johnson 1966).

Table 1 summarizes the instrument–telescope configuration used. Table 2 gives the journal of observations. K-band data could be taken on all the observation days while J- and H-band observations were discontinued once the nova became fainter than 9 mag in these filter bands. Only a few observations could be taken in the longer wavelength at ~3.3 μm. As a narrower bandwidth was used in this case and as this wavelength falls in a region of relatively poor atmospheric transmission, the errors of measurement are correspondingly higher.

The nova discovery observations, according to reports (Sugano et al. 1991), were made on March 24.781 at a visual magnitude of 5.4. A pre-maximum photographic sighting at mag 10 has been reported (Yamamoto 1991) on March 23.77. From the limited reports available it is assumed, for the purpose of this paper, that the nova reached maximum light on March 24.0 at a visual magnitude of m_v = 5.0. All our temporal variations in the infrared light curve of the nova are with reference to this date.

## 3 DISCUSSION

The observations reported in this paper cover a span of about 50 days starting from about day 13. Earlier infrared observations of this nova have been reported (Hekkert &

<table>
<thead>
<tr>
<th>Table 1. Telescope - instrument configuration.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Detector: LN_{2} cooled InSb</td>
</tr>
<tr>
<td>NEP: 5 x 10^{-14} W/√Hz at 2.2 μm</td>
</tr>
<tr>
<td>2. Telescope: 1.2m f/13 Cassegrain focus</td>
</tr>
<tr>
<td>Gurushikar, Mt Abu, India</td>
</tr>
<tr>
<td>(72^47′ E, 24^39′ N, 1680 m)</td>
</tr>
<tr>
<td>3. Filter: Band λ_{eff}(μm) Bandwidth(μm)</td>
</tr>
<tr>
<td>(FWHM)</td>
</tr>
<tr>
<td>J     1.25  0.30</td>
</tr>
<tr>
<td>H     1.65  0.30</td>
</tr>
<tr>
<td>K     2.20  0.70</td>
</tr>
<tr>
<td>3.30  0.06</td>
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</table>

<table>
<thead>
<tr>
<th>Table 2. IR observations of Nova Her 1991.</th>
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<tbody>
<tr>
<td>UT DATE</td>
</tr>
<tr>
<td></td>
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<tr>
<td>APRIL 5.97</td>
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<td>MAY 19.70</td>
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<tr>
<td>MAY 23.70</td>
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<td>MAY 28.80</td>
</tr>
</tbody>
</table>

*Date of visual maximum: March 24.0 UT.
**Zero-magnitude fluxes from Johnson (1966).

Harrison 1991; Doyon & Aycock 1991; Moneti & Bouchet 1991; Feast & Carter 1991; Gehrz, Jones & Lawrence 1991). There is no IR observation of the nova in the psuedo-photospheric expansion phase. The early IR observations show a decline in IR flux until about day 6, consistent with a free–free emission phase. Thereafter there is an increasing brightness in the K and L filter bands, suggesting dust formation. This development has been commented upon as early and unusual in a fast nova (Feast & Carter 1991).

### 3.1 IR light curve

In Fig. 1 we have plotted these early IR observations together with visual observations available in the literature (Mattei 1991; McNaught 1991; Schmeer & Royer 1991). It is seen clearly that as the optical light sharply declines on about day 6,5, the IR light curve shows a corresponding increase. This type of behaviour was exhibited earlier by Novae NQ Vul (1976) and LW Ser (1978) which formed optically thick dust shells (Gehrz 1988). However, what is peculiar is that while these novae exhibited this phenomenon on about day 80, in the present case of Nova Her 1991 it has happened as early as day 7.

Fig. 2 presents an overview of near-infrared (JHK) observations of the nova. The increase in flux signifying dust formation is clearly seen in the K and H filter bands and, to a lesser extent, in the J filter band.

In Fig. 3 we have plotted our observations (J, H, K fluxes) as a function of time (t) since visual maximum. The light curve exhibits a slow decline in the flux ∝ t^{-1} until about day 23 and then a faster decline ∝ t^{-4}. It has been remarked (Gehrz et al. 1988) that a t^2 law arises from an expanding optically thick pseudo-photosphere during the initial stages.
of a nova outburst. $t^{-2}$ and $t^{-3}$ laws are characteristic of optically thin gas shells in constant-thickness expansion and free expansion, respectively. The slow initial $t^{-1}$ decline in the IR could have been caused by the presence of strong emission lines. Strong IR emission lines in the nova have been reported (Joyce 1991). This type of temporal behaviour has been shown by PW Vul (Gehrz et al. 1988). The subsequent temporal behaviour of the IR light of Nova Her 1991, however, is distinctly different from that of PW Vul. Again, the remarkable characteristic of Nova Her 1991 is the extreme rapidity of events. While in the case of PW Vul the transition to free-expansion phase occurred about 100 d after the event, in the case of Nova Her 1991 it occurred in less than 25 d. This early transition is consistent with the steep decline in optical output and subsequent rapid development in the nova.

3.2 Blackbody temperature

Blackbody distributions fitted to the data yield equilibrium dust temperatures. The dust temperature shows a steady decline from a peak value of $\sim 1400$ K. In Fig. 4 is plotted the cooling curve, wherein the last two values are from observations by others (Russell & Chatelain 1991; Joyce 1991; Harrison & Stringfellow 1991). The dust temperature exhibits a slow decline $\propto t^{-1/2}$. For a constant expansion velocity $V$, this behaviour indicates a constant-luminosity phase, since $L \propto R^2 T_{BB}^4 \propto V^2 \propto$ constant. Such behaviour has been seen before (Gehrz 1988) in novae that have formed optically thick dust shells.

3.3 Blackbody angular size

Assuming the newly formed dust around the nova to be a blackbody at temperature $T_{BB}$ distributed in a shell of radius $R$, the observed flux $F_\lambda$ is given by

$$F_\lambda = \theta_{BB}^2 B(\lambda, T_{BB}),$$

where $\theta_{BB}$ is the angular size of the blackbody.

Figure 3. Light curve of Nova Her 1991 in $I, H, K$ filter bands. Observations in $K$(2.2 $\mu$m) cover the period 13 to 66 d since visual maximum. In $H$(1.65 $\mu$m) the coverage is from day 13 to 47 while in $J$(1.25 $\mu$m) it is from day 13 to 35. The data show a sharp change at $\sim$ day 25. Power laws of $t^{-1}$ before day 25 and $t^{-4}$ afterwards are superposed on the observation points.
where $B(\lambda, T_{\text{BB}})$ is the Planck function at wavelength $\lambda$ and temperature $T_{\text{BB}}$. Using deduced dust temperature (Section 3.2) we can estimate $\theta_{\text{BB}}$, the angular radius, from the above expression.

Fig. 5 shows the temporal behaviour of angular size ($2\theta_{\text{BB}}$). After a smooth increase, the angular size shows an abrupt change around day 30. This behaviour suggests that dust formation has nearly ceased by this time, with the onset of optical thinness and free expansion. It is consistent with the temporal behaviour of the IR light curve, which steepens at about the same time. Similar behaviour has been exhibited by novae which formed dust shells – NQ Vul, LW Ser and V1668 Cyg (Gehrz 1988). The transition in these novae however occurred at a much later time, 60–80 d after the eruption.

### 3.4 Distance to the nova

Considering Fig. 5 again, we see a linear increase in the angular size with time until about day 30, implying uniform expansion velocity. A least-square fit to the linear portion yields an angular expansion rate ($\omega$) of $\sim 0.15$ milliarcsec (mas) per day. Spectroscopic reports (Della Valle & Zelinger 1991; Sivaraman et al. 1991) imply a large expansion velocity ($V$) of $\sim 3000$ km s$^{-1}$. From the expression $D = V/\omega$:

$$D(\text{kpc}) = \frac{5.8 \times 10^{-4} V(\text{km s}^{-1})}{\omega(\text{mas d}^{-1})}.$$ 

Putting $V = 3000$ km s$^{-1}$ and $\omega = 0.15$ mas d$^{-1}$, we get $D \sim 11.5$ kpc. This result appears rather large but it could be due to the uncertainty in the actual value of the angular expansion rate ($\omega$) which is correct only to within a factor of about 2.

One can also estimate the distance to the nova using the relationship between absolute visual magnitude $M_V$ and time $t_3$ (in days) for the nova to decrease by 3 mag from visual maximum (Payne-Gaposchkin 1957; Gehrz, Grasdalen & Hackwell 1980):

$$M_V = -11.5 + 2.5 \log_{10} t_3.$$ 

From reports of visual sightings of the nova (Schmeer & Royer 1991; McNaught 1991) one can infer that the nova faded from $M_V \sim 5$ to $\sim 8$ in about 6 d. Then $M_V = -9.6$. We obtain a distance modulus (without assuming any extinction) of $m_V - M_V = 14.6$ and hence distance ($D$) to the nova of $\sim 8.3$ kpc. In the absence of any information on the line-of-sight extinction to the nova, the distance estimates remain somewhat uncertain. We adopted the distance of 8.3 kpc derived from maximum visual magnitude considerations (without extinction) as the upper limit.

Using the value of $\lambda F_\lambda)_{\text{max}} = 1.7 \times 10^{-15}$ W cm$^{-2}$ ($\lambda = 2.2$ $\mu$m) measured by us on day 14, a distance of 8.3 kpc would imply that the IR luminosity of Nova Her 1991 was $4 \pi D^2 [1.34 (\lambda F_\lambda)_{\text{max}}] = 5.2 \times 10^4 L_\odot$. From initial visual observations a magnitude $m_V \sim 5$ without extinction would yield an outburst luminosity $L_{\text{max}} = 6.7 \times 10^7 L_\odot$. This is clearly above the Eddington limit. It has been argued that only a fraction of this luminosity would have been transferred to the infrared, while the rest could have resulted in a high-speed stellar wind (Bath & Shaviv 1976). If we assume that an Eddington Luminosity for a $1-M_\odot$ star of $2.5 \times 10^4 L_\odot$ appeared as the IR luminosity, then the observed flux implies a distance to the nova of only 5.8 kpc.

A characteristic feature of novae that form optically thick dust shells has been the appearance in the infrared of an appreciable fraction of the outburst luminosity. In case of Nova Her 1991 only a small fraction ($< 10$ per cent) of the
outburst luminosity appears in the infrared. Considering
the peak visual magnitude of $\sim 5$ and a peak $K$ mag-
nitude of 4.26, we get an inferred visual optical depth $\tau_v =
(\lambda F_\lambda)_{2.2}/(\lambda F_\lambda)_{0.55} \sim 0.07$.

3.5 Mass of gas expelled in the outburst

If we presume that the expanding nova shell went optically
thin at a time $t$ after the outburst and the Thomson scattering
dominated shell opacity at this time, we can estimate the gas
expelled from the expression (Gehrz et al. 1988):

$$M_{\text{gas}} \sim \pi R^2(t) k_T^{-1},$$

where $R(t)$ is the shell radius at the time of onset of optical
thinness and $k_T$ is the Thomson opacity for hydrogen ($0.36$
$\text{cm}^2 \text{g}^{-1}$). Early spectroscopic observations of the nova
(Della Valle & Zelingier 1991) report hydrogen lines in
emission as early as day 2.6. If we assume a time $t = 2$ d
for the onset of optical thinness and an expansion velocity
of 3000 km s$^{-1}$ then

$$M_{\text{gas}} \sim 1.3 \times 10^{-5} M_\odot.$$  

3.6 Mass of grains expelled in the outburst

The total grain mass in the dust shell is given by

$$M_{\text{dust}} = N \frac{4}{3} \pi \rho a^3,$$

where $\rho$ is the density of condensed material and $a$ is
the grain size. Assuming the grains formed are of carbon with
$a = 1 \mu$m, taking $\rho = 2.25 \text{ g cm}^{-3}$ we can estimate $M_{\text{dust}}$ from
the expression given in Gehrz et al. (1980):

$$M_{\text{dust}} = \frac{1.1 \times 10^6 (\lambda F_\lambda)_{\text{max}} D^2}{T_{\text{bb}}^6} M_\odot,$$

with $(\lambda F_\lambda)_{\text{max}}$ in W cm$^{-2}$, $D$ in kpc, and $T_{\text{bb}}$ in units of $10^3$ K.
Taking $(\lambda F_\lambda)_{\text{max}} = 1.7 \times 10^{-15}$ W cm$^{-2}$, $T_{\text{bb}} = 1420$ K and
$D = 8.3$ kpc, we get

$$M_{\text{dust}} = 1.6 \times 10^{-4} M_\odot.$$  

3.7 Early grain formation in Nova Her 1991

The most interesting aspect of Nova Her 1991 has been the
rise in IR luminosity as early as day 7 after maximum light,
signifying dust formation (Feast & Carter 1991). A typical
1$M_\odot$ nova has an Eddington Luminosity $L_{\text{Ed}} = 2.5 \times 10^4 L_\odot$. It has been argued that the radiative luminosity in fast
novae is limited to $L = L_{\text{Ed}}$. Assuming that this is the case for
the present nova we can write an expression for the dust
formation time ($t_d$) as

$$t_d = \frac{2}{T_d^6(0)} \left(\frac{L}{4\pi \rho a}ight)^{1/2} \frac{1}{V},$$

where $T_d(0)$ is the temperature of the grain at the time of its
formation. $V$ is the velocity of expansion such that $R = V t_d$
gives the inner radius of the dust formation zone. It has been
argued (Clayton & Wickramasinghe 1976) that grains could
condense at temperatures ($T_d$) as high as 2000 K. Taking
$T_d(0) \sim 2000$ K we find:

$$t_d = \frac{138}{V} \left(\frac{L}{L_\odot}\right)^{1/2} \text{d}.$$  

Taking $L = L_{\text{Ed}} \approx 2.5 \times 10^4 L_\odot$ and an expansion velocity
$V = 3000$ km s$^{-1}$ we get

$$t_d = 7.3 \text{ d}.$$  

The time $t$ when the grain temperature ($T_d$) reaches a value
$\sim 1420$ K is then

$$t = t_d \left[\frac{T_d(0)}{T_d}\right]^2 \sim 14.5 \text{ d}.$$  

This value matches well with the peak $K$-band flux reached on day 14
and an inferred blackbody temperature of $\sim 1400$ K. Thus
early dust formation in Nova Her 1991 can be explained by
the presence of refractory grains which form at temperatures
close to $\sim 2000$ K, close to the theoretical predictions
(Cernuschi, Marsico & Codina 1967; Clayton & Wick-
ramasinghe 1976).

Gehrz (1988) has discussed the question of why some
novae produce much more dust than others. Ionization of
ecta before reaching the condensation zone, elemental
underabundance of grain constituents so that nuclei are
unable to accrete mantles despite high local gas densities,
and failure of ejecta to reach a critical density $\rho_c$ for grain
formation at the condensation point are some mechanisms
which inhibit dust formation. The condition of critical density
$\rho_c$ for grain formation seems independently capable of
explaining dust-forming scenarios in most novae. It has been
shown (Gehrz & Ney 1987) that novae developing opti-

cally thick dust shells have average shell densities of
$3 \times 10^{-18}$ to $10^{-15}$ g cm$^{-3}$ at the condensation point. Calculat-
ing this quantity for Nova Her 1991 we find:

$$\rho_c = 1.2 \times 10^{-4} \left(\frac{M}{M_\odot}\right) \left(\frac{L}{L_\odot}\right)^{-3/2},$$

where $M = \text{total mass ejected}$, $L = \text{outburst luminosity}$. We
earlier found $M_{\text{gas}} \sim 1.3 \times 10^{-5} M_\odot$ and $L \approx L_{\text{Ed}} \approx 2.5 \times 10^4 L_\odot$

Therefore for Nova Her 1991 we obtain

$$\rho_c = 4 \times 10^{-16} \text{ g cm}^{-3}.$$  

In Fig. 6 we have plotted the position of Nova Her 1991 in
relation to other novae and find it located on the borderline
dust-poor and dust-rich novae.

In order that dust formation is not suppressed, the shell
ionization time $t_i$ must be $> t_d$. Gallagher (1977) has
determined the shell ionization time as

$$t_i = \frac{2.2 \times 10^6}{VL^{1/3}} \text{ d}.$$  

Taking $V = 3000$ km s$^{-1}$, $L = L_{\text{Ed}} = 2.5 \times 10^4 L_\odot$, we find

$$t_i \approx 25 \text{ d}.$$  

Since in our case $t_d \sim 7 \text{ d}$ this condition ($t_d < t_i$) for dust
formation is satisfied.

Chemical abundances also play an important role in deter-
mining dust formation. Williams et al. (1987) have shown,
from spectra of evolved ejecta, that DQ Her was enhanced in
CNO by a factor of $\sim 100$ compared to the solar abundance.

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Figure 6. A comparison of the outburst luminosity $L_0$ and mass of gas ejected $M_{gas}$ in different novae (after Gehrz 1988). Nova Her 1991 is seen to lie in a region between dust-poor novae like PW Vul and novae which form optically thick dust shells like LW Ser and NQ Vul.


<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>NOVA HER 1991</th>
<th>NOVA SER 1978</th>
<th>NOVA PW VUL 1984</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day zero</td>
<td>JD 2448339.5±1.0</td>
<td>JD 2443569</td>
<td>JD 2445910±1.0</td>
</tr>
<tr>
<td>Expansion velocity $V(km/s)$</td>
<td>3000</td>
<td>1250</td>
<td>285</td>
</tr>
<tr>
<td>$(mV)_{max}$</td>
<td>~5</td>
<td>7.86</td>
<td>6.4</td>
</tr>
<tr>
<td>$A_V$</td>
<td>0</td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td>$t_2$(for $m_V$) (days)</td>
<td>~6</td>
<td>55</td>
<td>100</td>
</tr>
<tr>
<td>$M_V$</td>
<td>-9.6</td>
<td>-7.15</td>
<td>-7.5±1</td>
</tr>
<tr>
<td>D(kpc) (from $M_V$)</td>
<td>&lt; 8.3</td>
<td>6.3</td>
<td>6.35±0.35</td>
</tr>
<tr>
<td>D(kpc) (from $\theta_{BB,V}$)</td>
<td>~ 11.5</td>
<td>5</td>
<td>6.7</td>
</tr>
<tr>
<td>Time for dust to condense $t_d(\text{days})$</td>
<td>7</td>
<td>60</td>
<td>158</td>
</tr>
</tbody>
</table>

$M_{gas} = 10^{-4}M_\odot$, $M_{dust} = (1.6-2.7) \times 10^{-4}M_\odot$, $L = (3-5) \times 10^4 L_\odot$.
PW Vul, in which dust formation was severely suppressed, did not exhibit this chemical enhancement (Gehrz et al. 1988). Nova Her 1991 is a member of the O/Ne class of objects (Dopita, Ryder & Vassiliadis 1991), with large neon enhancements. It would possibly also have large light-element abundances, which help dust formation.

Finally, in Table 3 we compare the deduced physical properties of Nova Her 1991 with two other novae – Nova Ser 1978, which showed a thick dust shell, and PW Vul 1984, wherein dust formation processes were severely suppressed. Nova Her 1991 emerges as a distant, luminous nova wherein the general nova evolution took place at a more rapid pace compared to other novae. The mass of gas released appears comparable to other novae, while the mass of dust condensed falls between the values for a thick dust-shell-forming nova (LW Ser) and a dust-poor nova (PW Vul). The early dust formation requires highly refractory material which can condense at a temperature of 2000 K.

4 CONCLUSIONS

Near-infrared photometric observations of Nova Herculis 1991 have led to the following conclusions.

(i) Nova Herculis 1991 was an unusually fast nova in which grain formation processes began as early as day 7 after the eruption, at a dust temperature of ~ 2000 K. Maximum near-infrared luminosity was reached on day 14 with $L_{\text{IR}} \sim 5 \times 10^4 L_\odot$ at a blackbody temperature of ~ 1400 K. Thereafter the dust cooled at a slow rate $T_{\text{BB}} \propto t^{-1/2}$. The mass of dust condensed was ~ $2 \times 10^{-8} M_\odot$.

(ii) The blackbody angular diameter of the dust shell increased linearly with time, reaching a peak value of 6 mas about 30 d after the eruption. The infrared light curve sharply steepened from a slope of ~ 1 to ~ 4 at about the same time, indicating the onset of optical thinness and the completion of the dust formation phase.

ACKNOWLEDGMENTS

This work was supported by the Department of Space, Government of India. The authors would also like to thank the unknown referee for his valuable comments.

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