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Dust formation in novae

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Scaling from the observed time of dust formation in Nova FH Ser 1970 and using plausible assumptions for the postmaximum luminosities of novae, the time scale for observable dust to form in novae is $t_d \approx (320/v)\ (L/L_\odot)^{1/2}$ days, where v is the expansion velocity in kilometers/sec. The predicted t_d are in reasonable agreement with observations of FH Ser- and DQ Her-type novae. Luminous novae such as V1500 Cyg 1975 do not form dust, and we suggest that ionization of the gas prevents grain condensation. A simple model for ionization of nova ejecta gives $t_i = 2.2\times10^6/v\,(L/L_\odot)^{1/3}$ days. Novae with peak luminosities $\gtrsim 5\times10^4 L_\odot$ have $t_i < t_d$ and are unlikely to produce grains. The model fails for very slow novae such as HR Del which also appear not to produce dust. For these novae it is possible that the density is below the threshold for the growth of nucleation centers.

INTRODUCTION

ALTHOUGH circumstellar dust is known to be associated with a variety of stellar classes, it is rarely possible to find a setting in which the grain formation process might be directly observable. One of the best cases for an observed grain condensation event may have been Nova FH Ser 1970. For 55 days after visual maximum the infrared spectral energy distribution was dominated by the optical photosphere, but between days 55 and 60 a hot (~1000 K) infrared blackbody source appeared (Hyland and Neugebauer 1970). By day 100 the total luminosity of FH Ser had been shifted into the infrared (Geisel, Kleinmann, and Low 1970).

These remarkable observations are most simply interpreted by assuming that FH Ser had maintained constant luminosity (Gallagher and Starrfield 1976) and that grain condensation produced an optically thick thermosphere (Geisel *et al.* 1970; Clayton and Wickramasinghe 1976) which led to a redistribution of ultraviolet luminosity into the infrared (Gallagher and Code 1974). Other interpretations are possible (e.g., Clayton and Hoyle 1976), but the above picture is most simply consistent with the observations.

However, not all novae become thermal infrared sources. For example, Nova V1229 Aquilae 1970 did (Geisel *et al.* 1970) while Nova V1500 Cygni 1975 has not (Gallagher and Ney 1976). We have therefore developed a rudimentary model for the processes which might control grain formation in nova ejecta. On the basis of this model it is possible to predict which types of nova are good candidates for dust production as well as an approximate time scale for the appearance of an observable infrared excess.

I. A CASE STUDY—FH SER 1970

FH Ser is the Rosetta stone of nova energetics. The decline in optical luminosity was first compensated by radiation in the ultraviolet spectral region (Gallagher and Code 1974) and later by the rise in infrared luminosity (Geisel *et al.* 1970). Figure 1 shows the energy budget for FH Ser; the nova maintained a luminosity plateau for at least 100 days even though the optical brightness had declined to ~1% of its peak value. Thus, the optical light curve of a nova contains little direct information about the bolometric luminosity (see Gallagher and Starrfield 1976).

However, several secondary optical characteristics in FH Ser were correlated with the onset of the infrared phase: (1) There is a slope break in the light curve coincident with the beginning of reradiation by dust. Such dips are common in the light curves of the moderate- and the slow-speed classes of novae (Payne-Gaposchkin 1957; McLaughlin 1960; hereafter PG and ML). (2) The [Fe II] spectrum becomes strong and peaks near day 100 (Grygar, Smolinski, and Hutchings 1971; Andersen, Borra, and Dubas 1971). This spectral development is sometimes known as the η Carinae stage (Aller 1954), which is an especially appropriate nomenclature as both the present η Car and the day 100 FH Ser are imbedded in dust shells of their own making and radiate virtually all of their luminosity in the infrared. Geisel (1970) has noted a more general correlation between thermal infrared excesses and the presence of optical Fe emission lines in a variety of stellar sources. (3) During the day 100 optical minimum, the redshifted components of most emission lines weakened, probably as a result of absorption in the nova shell (Hutchings and Fisher 1975). It is important to emphasize that these three related characteristics are not unique to FH Ser (PG, ML) and in particular we will later wish to use slope breaks in optical light curves as evidence for the presence of substantial amounts of dust in novae. [This point is in principle somewhat controversial. It was originally suggested that the deep minimum in DQ Her was due to the formation of an obscuring cloud

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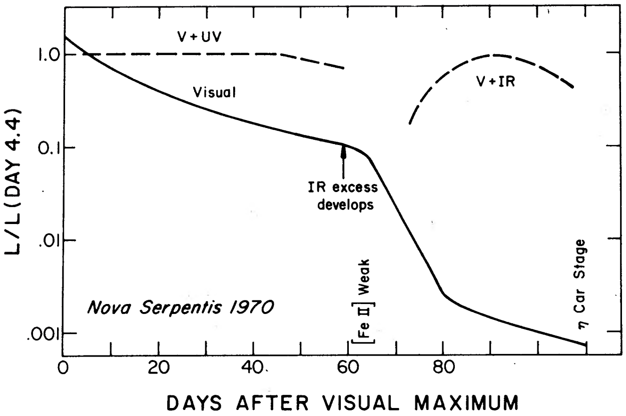

FIG. 1. Energy budget for FH Ser based on the ultraviolet and optical observations from Gallagher and Code (1974) and the infrared measurements of Geisel, Kleinmann, and Low (1970). FH Ser maintained constant luminosity despite an optical luminosity decline by a factor of 10^3. Qualitative estimates of emission line strengths are based on Grygar, Smolinski, and Hutchings (1971) and Andersen, Borra, and Dubas (1971).

(McLaughlin 1936; Stratton 1945), but this hypothesis later lost favor (ML).]

II. AN EMPIRICAL MODEL FOR GRAIN FORMATION

The formation of grains in nova ejecta is strongly dependent on the physical conditions in the nova during the first 100 days following the initial visual rise. For any individual case, these conditions are poorly known and for this preliminary study we have chosen an extremely simplistic model.

Gallagher and Starrfield (1976) have reviewed the evidence for a universal postvisual maximum constant luminosity stage in normal novae. The observations provide good support for a luminosity plateau at near peak luminosity in the moderate- and slow-speed classes of novae. The rate of decline from visual maximum which defines nova speed classes is directly related to peak luminosity (Arp 1956; Rosino 1963) in the sense that slower novae are less luminous. Thus, for novae with $M_{\rm bol} \gtrsim -7$, it is likely that the constant luminosity level is $L_{\rm CL} \approx L_{\rm peak}$.

For the faster and therefore more luminous novae, it is likely that $L_{\rm CL} < L_{\rm peak}$. The mass of a typical nova binary system is probably $\approx 1\frac{1}{2}\, M_\odot$ (Kraft 1964; Paczynski 1965; Robinson 1976) and thus the Eddington limit for the system is $L_{\rm Ed} \approx 6 \times 10^4 L_\odot$ ($M_{\rm bol} \approx -7.2$). Gallagher and Starrfield have therefore suggested that the radiative luminosity in the fast novae is limited to $L_{\rm CL} \approx L_{\rm Ed}$. The remainder of the nuclear luminosity may produce a high-velocity stellar wind (Bath and Shaviv 1976).

Since a major difference between novae which produce dust and those which do not appears to be luminosity, we will consider the possibility that the grain formation process is primarily controlled by the ambient radiation field. The time scale for grain formation, t_g, can then be found as a function only of $L_{\rm CL}$ and the expansion velocity v associated with the principal absorption spectrum. There is some confusion as to which velocity best represents the bulk of the ejecta (e.g., Clayton and Hoyle 1976), but studies of novae in the nebular stage clearly show that the densest matter is associated with the principal velocity (Sanford and Greenstein 1957; ML; Gallagher and Anderson 1976). The radius of the ejecta is then simply $R = vt$ and the temperature of a grain at radius R is

$$T_g{}^4 = \frac{1}{4\sigma}\cdot\frac{L_{\rm CL}}{4\pi R^2}\cdot\frac{\overline{Q}(T_*,a)}{\overline{Q}(T_g,a)}. \qquad (1)$$

$\overline{Q}$ is the Planck mean absorption cross section for grains of radius a and temperature T_g in a radiation field characterized by the stellar photosphere temperature T_*.

Both theoretical and observational studies show that novae become hotter during the early decline (Gallagher and Code 1974; Gallagher and Starrfield 1976). It is probably a good approximation to take the area of the constant luminosity photosphere to be that of the white dwarf's critical surface (Sparks, Starrfield, and Truran 1976). For a typical nova this area (based on a Roche model for the binary) is $A_{\rm RL} \approx 10^{23}\ {\rm cm}^2$ (Gallagher and Oinas 1974) and

$$T_* = (L_{\rm CL}/A_{\rm RL}\sigma)^{1/4} = 5100(L_{\rm CL}/L_\odot)^{1/4}\ {\rm K}. \qquad (2)$$

Since $L_{\rm CL} > 10^4 L_\odot$ in all novae, $T_* \gtrsim 50\,000$ K. In the limit of high T_* and small grains, Gilman's (1974) models give $\overline{Q}(T_*,a)/\overline{Q}(T_g,a) \approx 10^2$ for iron or graphite spheres. For more complex grain compositions, the ratio of cross sections depends in detail on grain size and temperature. Assuming that the early grains are simple, Eq. (1) becomes

$$T_g \approx 2(L_{\rm CL}/4\pi\sigma r^2)^{1/4}. \qquad (3)$$

As a check against gross inaccuracies due to the simplifications inherent in Eq. (3) we compare observed and calculated grain temperatures for FH Ser. Equation (3) can be rewritten in terms of the time t_d at which dust initially becomes observable,

$$t_d \approx \frac{2}{T_g{}^2(0)}\left(\frac{L_{\rm CL}}{4\pi\sigma}\right)^{1/2}\frac{1}{v}. \qquad (4a)$$

From Geisel, Kleinmann, and Low (1970) we estimate $t_d = 60$ days an from Gallagher and Code (1974) $L_{\rm CL} = 1.6 \times 10^4 L_\odot$. Unpublished spectra show the half-velocity width of nebular emission lines in FH Ser to be $\sim$700 km sec^{-1}. Equation (4a) then requires $T_g(0) = 2000$ K, which is in reasonable agreement with the observed $T_g(0) \approx 1300$ K (Geisel *et al.* 1970). We now assume $T_g(0)$ is the same for all novae which produce grains and, adopting $T_g(0) = 1300$ K, Eq. (4a) becomes

$$t_d = (320/v)\sqrt{L_{\rm CL}/L_\odot}\ \ {\rm days}, \qquad (4b)$$

where v is in kilometers/sec. For a more detailed model of grain formation in FH Ser, the reader should see Clayton and Wickramasinghe (1976) and the recent general theoretical model by Yamamoto and Nishida (1977).

If all novae formed dust of the same composition, then Eqs. (1) and (4a) could be used to find t_d provided that $T_g(0)$ is known. Although physical conditions may vary, on the basis of estimates for temperatures at the time of grain condensation (Gilman 1969; Salpeter 1974) we expect Eq. (4b) to be accurate to within a factor of 2. However, in some novae grains apparently never form. For example, Nova V1500 Cygni 1975 had a peak luminosity of $\sim 3 \times 10^5 L_\odot$ (Gallagher and Ney 1976) and an expansion velocity of ~ 2000 km sec^{-1}. It is unlikely that the constant level was near the peak value, and thus for Nova Cygni $3 \times 10^5 > L_{CL}/L_\odot \gtrsim 6 \times 10^4 = L_{Ed}$. [Wu and Kester (1976) find $L = 3 \times 10^4 L_\odot$ at $t = 100$ which appears to support the assumption $L_{CL} \approx L_{Ed}$ for luminous novae. At this time T_* was observed to be 65 000 K as compared to the prediction of 67 100 K from Eq. (2).] From Eq. (4b), $88 > t_d > 39$ days. Gallagher and Ney obtained infrared observations up to 51 days after maximum with no indications of a thermal infrared excess, and unpublished observations show that no dust emission developed later. There is also indirect evidence that dust never forms in fast, luminous novae. The summaries by PG and ML show that light curve dips and η Carinae phases are rarely found in *novae* with M_{bol} (max) $\lesssim -7.5$. [An obvious exception is η Carinae itself. For the present infrared luminosity of $\sim 2 \times 10^6 L_\odot$ (Gehrz *et al.* 1973) and an expansion velocity of ~ 250 km sec^{-1} (Gratton 1963), Eq. (4b) gives $t_d = 5$ yr. However, from the visual light curve reproduced by Gratton, $t_d \gtrsim 10$ yr. Evidently grain condensation occurred under different physical conditions than in the galactic novae.]

There are several characteristics of fast novae which might act to limit grain formation. (1) The ejection velocities are larger than in slower novae and it is therefore possible that the gas densities are too low to support grain formation once the critical expansion radius is reached. If all novae eject the same mass (ML), then in the approximation of a spherically expanding nebula, the mean gas density at time t_d will scale as

$$\rho_{gas}(t_d) \propto (vt_d)^3 \propto L_{CL}^{-3/2}. \quad (5)$$

Since for the fast novae L_{CL} is only at most ten times that of a nova such as FH Ser, it appears somewhat unlikely that the density effect alone would completely inhibit dust formation. (2) The fast novae are, due to their high luminosities, more likely to produce substantial stellar winds. If winds give rise to the diffuse enhanced and Orion absorptions (Friedjung 1966), then $v_{wind} \approx 2$–$3v_{principal}$. In this circumstance strong shocks could form which might disrupt the grain nucleation process. However, high-velocity material was evident in FH Ser as early as ten days after maximum (Hutchings, Smolinski, and Grygar 1972) and yet dust formed.

A third possibility is that ionization leads to a cessation of grain formation. If ionization occurs rapidly enough, then the gas in which nucleation might occur will become optically thin to high-energy photons. Such photons have sufficient energy to disrupt the multiatom structures (monomers) which appear to be required during the building of grain nuclei (Salpeter 1974). We are rather certain that at least some high-energy photons are soon present in the ejecta of luminous novae as high-excitation emission lines such as He II appear within ~ 20 days after maximum (PG). If the gas is fully ionized before monomers have formed, then Coulomb repulsion will inhibit the growth of any nucleation centers.

In order to facilitate a comparison between ionization and dust formation time scales, it is useful to develop a simple model for the ionization of the principal ejecta. We take the principal ejecta to be a uniform sphere with mass M expanding with velocity v centered on a nova remnant whose temperature is given by Eq. (2). During the early stages in which we are interested, the recombination time scale is much shorter than the time for significant changes in density. A simple on-the-spot approximation therefore suffices to give the radius r_i of the ionized region. For a source producing q_H hydrogen-ionizing photons/sec,

$$r_i = [q_H/\tfrac{4}{3}\pi n_H n_e \alpha_B(T)]^{1/3}, \quad (6)$$

where $n_H \approx n_e$ and $\alpha_B(T)$ is the case B hydrogen recombination coefficient (cf. Osterbrock 1974). The hydrogen density is approximately

$$n_H = \frac{M}{\tfrac{4}{3}\pi(vt)^3 m_H}. \quad (7)$$

The ejecta are completely ionized when $r_i = vt_i$ and the ionization time scale is therefore approximately

$$t_i = [3M^2\alpha_B(T)/4\pi v^3 m_H{}^2 q_H]^{1/3}. \quad (8)$$

The ejected mass M is unfortunately poorly known for novae as a class. Malakpur (1973) found $M = 3 \times 10^{-4} M_\odot$ for the slow nova HR Del while Mustel and Boyarchuk (1970) estimated the DQ Her nebula to have a mass in the range of $(4$–$10) \times 10^{-4} M_\odot$. From the size and temperature of the expanding photosphere, Gallagher and Ney (1976) suggested that $M \gtrsim 10^{-4} M_\odot$ for V1500 Cygni. A reasonable but uncertain choice is $M = 10^{-4} M_\odot$.

We have estimated $q_H(T)$ by using the solar abundance model atmospheres computed for nuclei of planetary nebulae by Hummer and Mihalas (1970). For $40\,000 < T_* < 90\,000$ K, the ionizing flux may be approximated to within a factor of 2 (with 25% for $T \geq 50\,000$ K) by

$$q_H = 3.6 \times 10^{24}\,(T_*/50\,000)^{3.5} A, \quad (9)$$

where A is the effective area of the photosphere which we take to be $A = A_{\rm RL} = 10^{23}$ cm^2. Equation (9) can then be expressed in terms of $L_{\rm CL}$,

$$q_{\rm H} = 1.2 \times 10^{44}\,(L_{\rm CL}/L_\odot)^{0.9}. \qquad (10)$$

For a standard nebular electron temperature of 10^4 K, $\alpha_{\rm B} = 2.5 \times 10^{-13}$ (Osterbrock 1974) and Eq. (8) becomes

$$t_{\rm i} = 2.2 \times 10^6/v(L_{\rm CL}/L_\odot)^{1/3}\ \text{days}. \qquad (11)$$

A critical luminosity L^* for dust formation in novae can be defined by setting $t_{\rm i} = t_{\rm d}$, and from Eqs. (11) and (4b), $L^* = 4 \times 10^4 L_\odot$. Novae for which $L_{\rm CL} > L^*$ are expected to be poor candidates for dust formation. As $L_{\rm CL}$ is not usually directly observed, it is necessary to attempt to define $L_{\rm CL}$ in terms of the optical peak luminosity. For FH Ser the data shown in Fig. 1 suggest $L_{\rm CL}/L_{\rm peak} \approx 0.75$, and for slow novae such as DQ Her this ratio is probably close to 1. Using Rosino's (1963) calibration of $L_{\rm peak}$ in terms of decline rate δ, we expect that novae which have $\delta \geq 0.07 - 0.1$ mag day^{-1} will not show evidence for dust formation. This conclusion appears to be basically consistent with the observations; of the 19 novae with $\delta \geq 0.1$ listed in Table 16 of PG, only EU Sct has a slope break in its visual light curve.

Table I provides a more detailed comparison between predicted and observed time scales. A few representative cases are also shown in Fig. 2. The novae in Table I were selected either as illustrative examples of various speed classes or because infrared observations are available. For novae with FH Ser- or DQ Her-type light curves, the break in the visual light curve which we associate with the onset of dust formation is predicted with reasonable accuracy. EU Sct is included with other FH Ser novae by PG, and we have also estimated $t_{\rm d}$ from the mean decline rate $\delta = 0.06$ mag day^{-1}. Note that the time of the observed break would be correctly given if EU Sct has $L_{\rm CL} = 0.9 \times 10^4 L_\odot$. Another interesting feature is the lack of dust in the slow but anomalously luminous RR Pic novae. This is expected on the basis of $t_{\rm i} < t_{\rm d}$ and is consistent with the observed absence of a thermal infrared excess from the RR Pic-type nova, V373 Sct near $t = 60$ days (Ney, private communication). V1500 Cygni also showed no dust emission for at least 300 days after maximum (Gallagher and Ney 1976; Ennis *et al.* 1977) while ultraviolet observations made on day 100 imply that little, if any, circumstellar dust had formed (Wu and Kester 1976). [In mid-December 1976 a thermal infrared excess developed in Nova Vul 1976 indicating that a dust shell had formed (Ney *et al.* 1977) on a time scale consistent with Eq. (4b). Coincident with the appearance of dust, the optical light underwent a steep decline. Nova Vul appears to be an intermediate case between the FH Ser- and DQ Her-type novae.]

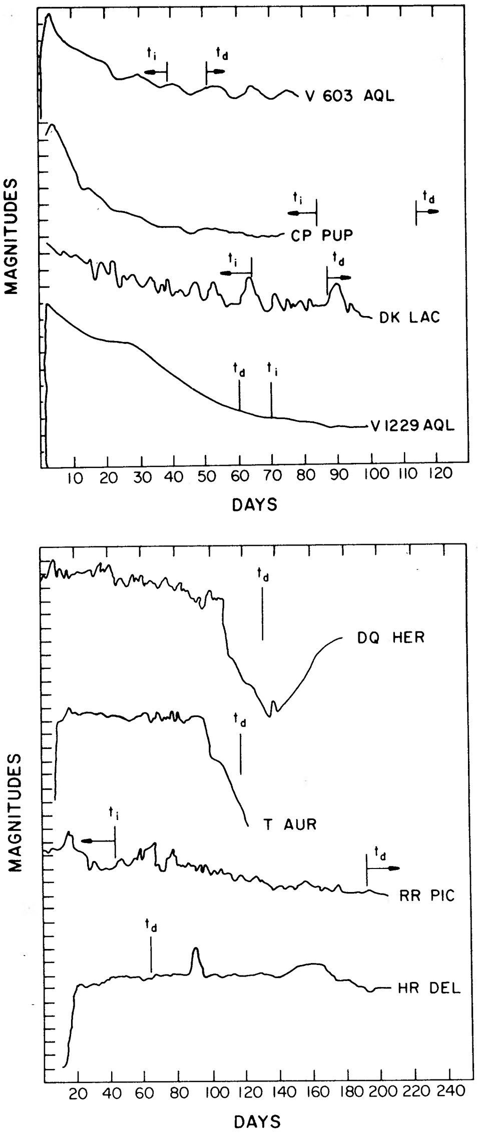

FIG. 2. The times $t_{\rm d}$ and $t_{\rm i}$ given in Table I are shown on the optical light curves of representative novae. The light curves are based on those given by Payne-Gaposchkin (1957) except for V1229 Aql and HR Del which are from Ciatti and Rosino (1974) and from Sanyal (1974).

There are also some problems in Table I. The presence of [Fe II] (an η Carinae stage) in the luminous CP Pup could be indicative of dust formation, although higher-ionization stages of forbidden iron appeared later (Sanford 1945) which suggests that a different physical mechanism might have been involved. A more serious failure is HR Del. The predicted dust time scale is only 45 days and yet the nova remained at a visual plateau for $\simeq 350$ days and thereafter underwent a smooth, slow (0.006 mag day^{-1}) decline (Sanyal 1974). Polarization measurements of HR Del during its early development have been interpreted by Zellner (1971) as being consistent with the presence of circumstellar dust. However, the asymmetric, extended atmosphere of the nova could also have produced the observed polarization (cf. Cassinelli and Haisch 1974). On the basis of the $V - N$ color, Geisel, Kleinmann, and Low (1970) reported a 300-K thermal infrared source at 1150 days after max-

TABLE I. PREDICTED AND OBSERVED DUST FORMATION TIME SCALES IN NOVAE.

NOVA	TYPE	δ mag day^{-1}	$L_{peak}/10^4 L_\odot$	$L_{CL}/10^4 L_\odot$	V km s^{-1}	t_d days	t_i days	t_{break} days		Comments
V1500 Cyg 1975	CP Pup	0.8	38 (1)	6 (a)	1500 (1)	> 52	< 38	none	(1)	
V603 Aql 1918	very fast	0.6	38 (2)	6 (a)	1700 (2)	> 46	< 34	none	(3)	
CP Pup 1942	CP Pup	0.4	35 (2)	6 (a)	700 (2)	>112	< 82	none	(3)	[FeII] present at t=63-125 days (3).
DK Lac 1950	fast	0.14	13 (3)	6 (a)	900 (2)	> 87	< 64	none	(3)	
EU Sct 1949	FH Ser	0.1:	7 (5)	6 (a)	400 (2)	>196	<140	60	(3)	For δ=0.06, t_d=134.
V1301 Aql 1975	?	0.095	6 (5)	6 (a)	1000 (8)	> 78	< 57	$t_{discovery}$+10	(8)	If $L_{IR}=L_{CL}=5\times10^3$ (8), t_d=23. Spectrum in (8) suggests $t_{discovery}\approx50$.
V1229 Aql 1970	FH Ser?	0.08	5 (5)	2 (f)	800 (10)	57	103	30	(10)	
IV Cep 1971	DK Lac?	0.08	5 (5)	3.8 (b)	1000 (11)	62	67	32	(9)	For M= -8.3 (11); t_d=78; t_i=57. No thermal IR excess on days 8-11 (12).
FH Ser 1970	FH Ser	0.04	2.2 (4)	1.6 (b)	700 (4)	58	130	60	(4)	
DQ Her 1934	DQ Her	0.03	1.4 (2)	1.4 (c)	290 (2)	131	320	110	(3)	[FeII] grows in strength after t=95 (3).
V450 Cyg 1942	DQ Her	0.03:	2 (e)	2 (c)	500 (2)	91	165	110	(3)	[FeII] strong during steep decline (3).
T Aur 1891	DQ Her	0.025	2.4 (2)	2.4 (c)	460 (2)	108	170	90	(3)	
RR Pic 1925	RR Pic	0.025	7.2 (2)	6 (a)	410 (2)	> 191	< 42	none	(3)	[FeII] and [FeIII] after day 20.
V373 Sct 1975	RR Pic	0.03:	7 (e)	6 (a)	1400 (1)	> 56	< 41	none?	(1)	
HR Del 1967	very slow	<0.01	2.2 (6)	0.5 (d)	500 (7)	45	260	none	(6)	[FeII] not strong during decline (6,14).

Notes:
(a) $L_{CL} = L_{Eddington} \approx 6 \times 10^4 L_\odot$.
(b) $L_{CL} = 0.75 L_{peak}$, cf FH Ser.
(c) for slow novae, $L_{CL} \approx L_{peak}$.
(d) Sanyal (1974) gives $V_{mean} = 5$.
(e) L_{peak} estimated from type.
(f) L_{CL} estimated from infrared luminosity given by Geisel *et al.* (1970).

Sources: (1) Gallagher and Ney (1974), IAU Circulars and unpublished observations; (2)McLaughlin (1960); (3) Payne-Gaposchkin (1957); (4)Gallagher and Code (1974); (5)estimated from calibration of δ given by Rosino (1963); (6)Sanyal (1974); (7)Gallagher and Anderson (1976); (8) Vrba, Schmidt and Burke (1976); (9) Kohoutek and Klawttler (1973); (10)Ciatti and Rosino (1974); (11)Thomas et al. (1973); (12)Sato et al. (1973); (13)Sanford (1945); (14)Hutchings (1970).

imum. However, if their *V, K, M,* and *N* magnitudes are plotted, the energy distribution can be fit by a hot thermal blackbody at short wavelengths and a cool free–free source at $\lambda > 2\ \mu$, thus there is no substantial evidence that dust formation played an important role in HR Del.

Although HR Del is a somewhat unique object, the absence of a dust break appears to be typical of the very slow novae (PG). The assumption that the physical conditions can be scaled from FH Ser breaks down for these objects. A likely point of difficulty is our assumption that the ejecta will always support grain formation. Since the radius of the photosphere is primarily controlled by the mass-loss rate and expansion velocity (Grotrian 1937; Bath and Shaviv 1976), the long visual plateau in very slow novae requires that there be an extended period of nearly constant mass loss. The principal ejecta could then have lower mean density than in a nova such as FH Ser where the bulk of the mass loss occurs at or near the time of the initial outburst. It is therefore possible that the density is below a critical limit for successful nucleation and growth of grains. Yamamoto and Nishida (1977) also find there is a critical monomer density for successful formation of dust. Another difference between very slow and other novae could be the radiation field at t_d. Forbidden emission lines from species with ionization potentials of 13.6 eV are seen in FH Ser- and DQ Her-type novae *before* the slope break in visual light (PG,ML). Thus, the substantial ultraviolet luminosity observed in FH Ser before day 60 is probably typical (cf. Grotrian 1937). In contrast, the early emission spectrum from HR Del is mostly from singly ionized metals, and the photosphere is therefore probably cool ($\sim$5000 K). The lower ionization may act to raise the threshold density at which nucleation begins. Alternatively, these differences could sufficiently limit the growth of grains so that their effect on the energy balance would be small.

III. SUMMARY AND CONCLUSIONS

We have developed an idealistic model for predicting the time of grain formation in novae by scaling from the well-observed nova FH Ser. By assuming that the condensation of grains is controlled by the radiation field alone, we derived Eq. (4b) which gives the time t_d after maximum for the appearance of observable circumstellar dust. If all novae develop circumstellar dust shells, it should be possible to find a t_d at which dust becomes important. This hypothesis is in conflict with both direct and indirect observational evidence. Although there are several mechanisms which could be responsible for the absence of grains in luminous (very fast and fast) novae, we have argued that disruption of the nucleation process by ultraviolet photons seems at present to be the most likely cause. Grain formation would therefore be halted by the ionization of the ejecta and Eq. (11) gives an approximate estimate for the time t_i required for ionization. The ratio of t_i/t_d is independent of the expansion velocity, and therefore depends only on the luminosity or speed class of the novae. For the fast and very fast novae, $t_i < t_d$ and dust does not form; in slower novae $t_i > t_d$ and dust should be present. For novae of the FH Ser and DQ Her type, Eq. (4b) also gives a reasonable estimate for the time at which dust may have actually appeared (see Table I).

HR Del is an example of the low-luminosity, very slow novae for which our assumptions are invalid. This object should have become an infrared source after about 45 days, but in fact remained a bright visual nova for more than a year. In the very slow novae both lower mean density and reduced ionization may prevent effective nucleation. Thus, the slow to moderate novae with peak luminosities of (3–5) $\times\ 10^4 L_\odot$ are the best candidates for developing circumstellar dust shells.

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REFERENCES

Aller, L. H. (1954). "Nuclear Transformations, Stellar Interiors, and Nebulae," *Astrophysics* (Ronald, New York).

Andersen, P. H., Borra, E. F., and Dubas, O. V. (1971). Publ. Astron. Soc. Pac. **83,** 5.

Arp, H. C. (1956). Astron. J. **61,** 15.

Bath, G. T., and Shaviv, G. (1976). Mon. Not. R. Astron. Soc. **175,** 305.

Cassinelli, J. P., and Haisch, B. H. (1974). Astrophys. J. **188,** 101.

Ciatti, F., and Rosino, L. (1974). Astron. Astrophys. Suppl. **16,** 305.

Clayton, D. D., and Hoyle, F. (1976). Astrophys. J. **203,** 490.

Clayton, D. D., and Wickramasinghe, N. C. (1976). Astrophys. Space Sci. **42,** 463.

Ennis, D., Becklin, E. E., Beckwith, S., Elias, J., Gatley, I., Mathews, K., Neugebauer, G., and Willner, S. P. (1977). Astrophys. J. To be published.

Friedjung, M. (1966). Mon. Not. R. Astron. Soc. **132,** 317.

Gallagher, J. S., and Code, A. D. (1974). Astrophys. J. **189,** 303.

Gallagher, J. S., and Oinas, V. (1974). Publ. Astron. Soc. Pac. **86,** 952.

Gallagher, J. S., and Anderson, C. M. (1976). Astrophys. J. **203,** 625.

Gallagher, J. S., and Ney, E. P. (1976). Astrophys. J. Lett. **204,** L35.

Gallagher, J. S., and Starrfield, S. G. (1976). Mon. Not. R. Astron. Soc. **176,** 53.

Gehrz, R. D., Ney, E. P., Becklin, E. E., and Neugebauer, G. (1973). Astrophys. Lett. **13,** 89.

Geisel, S. L. (1970). Astrophys. J. Lett. **161,** L105.

Geisel, S. L., Kleinmann, D. E., and Low, F. J. (1970). Astrophys. J.

Lett. **161,** L101.

Gilman, R. C. (1969). Astrophys. J. Lett. **155,** L185.

Gilman, R. C. (1974). Astrophys. J. Suppl. **28,** 397.

Gratton, L. (1963). In *Stellar Evolution,* edited by L. Gratton (Academic, New York), p. 297.

Grotrian, W. (1937). Z. Astrophys. **13,** 215.

Grygar, J., Smolinski, J., and Hutchings, J. B. (1971). Publ. Astron. Soc. Pac. **83,** 15.

Hummer, D. G., and Mihalas, D. M. (1970). JILA Rep. No. 101.

Hutchings, J. B. (1970). Publ. Dom. Astrophys. Obs. **13,** No. 14.

Hutchings, J. B., Smolinski, J., and Grygar, J. (1972). Publ. Dom. Astrophys. Obs. **14,** No. 2.

Hutchings, J. B., and Fisher, W. A. (1973). Publ. Astron. Soc. Pac. **85,** 122.

Hyland, A. R., and Neugebauer, G. (1970). Astrophys. J. Lett. **160,** L177.

Kohoutek, L., and Klawittler, P. (1973). Astron. Astrophys. Suppl. **11,** 347.

Kraft, R. P. (1964). Astrophys. J. **139,** 457.

Malakpur, I. (1973). Astron. Astrophys. **24,** 125.

McLaughlin, D. B. (1936). Publ. Am. Astron. Soc. **8,** 145.

McLaughlin, D. B. (1960). In *Stellar Atmospheres,* edited by J. L. Greenstein (Univ. Chicago P., Chicago), p. 676.

Mustel, E. R., and Boyarchuk, A. A. (1970). Astrophys. Space Sci. **6,** 183.

Ney, E. P., Stoddart, J., and Hubbard, R. (1977). IAU Circ. No. 3023.

Osterbrock, D. E. (1974). *Astrophysics of Gaseous Nebulae* (Freeman, San Francisco).

Paczynski, B. (1965). Acta Astron. **15,** 197.

Payne-Gaposchkin, C. (1957). *The Galactic Novae* (North-Holland, Amsterdam).

Robinson, E. L. (1976). Astrophys. J. **203,** 485.

Rosino, L. (1963). In *Novae, Novoids, et Supernovae* (Centre National de la Recherche Scientifique, Paris), p. 126.

Salpeter, E. E. (1974). Astrophys. J. **193,** 579.

Sanford, R. F. (1945). Astrophys. J. **102,** 357.

Sanford, R. F., and Greenstein, J. L. (1957). Publ. Astron. Soc. Pac. **69,** 75.

Sanyal, A. (1974). Astrophys. J. Suppl. **28,** 115.

Sato, S., Maihara, T., and Okuda, H. (1973). Publ. Astron. Soc. Jpn. **25,** 571.

Sparks, W. L., Starrfield, S. G., and Truran, J. W. (1976). Preprint.

Stratton, F. J. M. (1945). Mon. Not. R. Astron. Soc. **105,** 275.

Thomas, J. C., Cowley, A. P., MacConnell, D. J., and Toney, J. (1973). Publ. Astron. Soc. Pac. **85,** 309.

Vrba, F. J., Schmidt, G. D., and Burke, E. W. (1976). Preprint.

Wu, C. C., and Kester, D. (1976). Preprint.

Yamamoto, T., and Nishida, S. (1977). Preprint.

Zellner, B. (1971). Astron. J. **76,** 651.

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