THE 'ISOTHERMAL' PHASE OF NOVA DUST SHELLS

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Abstract

We describe a model for the evolution of the infrared spectrum of the dust shell of nova NQ Vul. The effects of nucleation and grain growth, together with extended, but diminishing, mass loss from the nova, are included. The variations in the effective temperature of the dust shell that occur near infrared maximum may be understood in terms of varying optical depth in a dust shell having significant temperature gradient. However, a more consistent picture is shown to combine interrelated optical depth and grain size variations.

The development of an infrared excess in classical novae some weeks after visual maximum is well known. The excess appears at the time of nova transition and for novae having dust shells that are optically thick in the infrared, its appearance also coincides with the break in the visual light curve. This behaviour led Clayton & Wickramasinghe (1976; CW) to consider the nucleation and growth of graphite grains in nova ejecta.

For NQ Vul and LW Ser, the dust shell temperatures deduced from the photometry of Ney & Hatfield (1978;NH) and Gehrz et al (1980), reveal an initial decrease prior to infrared maximum, followed by a rise, a 'levelling out' and finally a decline after $\sim$ 200 d. Gehrz et al (1980) interpreted this behaviour in terms of an initial phase of grain growth, followed by grain destruction and finally a period of cooling as the dust shell expands. However this scenario merits closer inspection because (a) in a dust shell that is optically thick to the illuminating radiation, temperature gradients arise even if the shell is geometrically thin and (b) grain destruction may be expected to occur sooner rather than later as the nova environment presumably becomes less hostile with time.

Here we present a preliminary report of a detailed treatment of the dust shell of NQ Vul, accurately solving the radiative transfer

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problem for a series of quasi-static spherically symmetric models. These are based on the quasi-diffusion method of Leung (1975, 1976), as described by Mitchell & Robinson (1978). Our work was prompted by the hope that changes in the infrared opacity of the expanding dust shell would suffice to account for the temperature behaviour of the dust shell, for the following reason. In an optically thick shell, the dust shell temperature will essentially be that at the surface of unit optical depth; at first this surface will be located well away from the nova but as the shell expands and thins out, the surface will contract and the dust shell temperature will rise.

The expansion velocity v of the principal spectrum (from which the grains would be expected to condense) was ~ 1000 km s^{-1} for NQ Vul (Klare & Wolf 1978), while dust condensation began ~ 60 d after visual maximum (NH); the condensation distance $R_{min} \approx 5.2 \times 10^{14}$ cm. We assume (Shara 1981), that the mass loss rate declines exponentially with decay constant k. Hence the gas density ρ in the circumnova environment varies as

$$\rho(r,t) \propto r^{-2} \exp\{-k\,(t-r/v)\} \quad . \tag{1}$$

We assume that grain nucleation and growth occur instantaneously at R_{min} (cf. CW). The ρ^2 dependence of nucleation rate at R_{min} leads to a grain number density distribution

$$n(r,t) \propto r^{-2} \exp\{-2k\,(t-r/v)\} \tag{2}$$

while the grain size distribution is

$$a(r,t) \propto \exp\{-k(t-r/v)\} \quad . \tag{3}$$

We assume graphite grains with the following dependence of absorbing efficienty Q_{abs} on wavelength λ:

$$\begin{aligned} Q_{abs} &= \text{const.} \qquad (\lambda \lesssim 2\pi a) \\ &\propto \lambda^{-1.8} \qquad (\lambda > 2\pi a) \end{aligned} \tag{4}$$

The bolometric luminosity of the nova is assumed constant throughout the period of interest (Bath & Shaviv 1976), with the value $L = 9 \times 10^{37}$ erg s^{-1}. At day 60, the nova temperature is expected to be $\sim 4 \times 10^4$ K and to increase thereafter. For such temperature behaviour, the radiative power of the nova is emitted mainly at wavelengths at which the dust opacity is flat; thus the temperature behaviour is not critical and we assume a constant value of 5×10^4K.

We use the visual light curve of NH to help deduce the time-dependence of the optical depth of the dust distribution. This procedure demands prior knowledge of the time dependence of the unreddened visual flux. We have considered several forms for the latter,

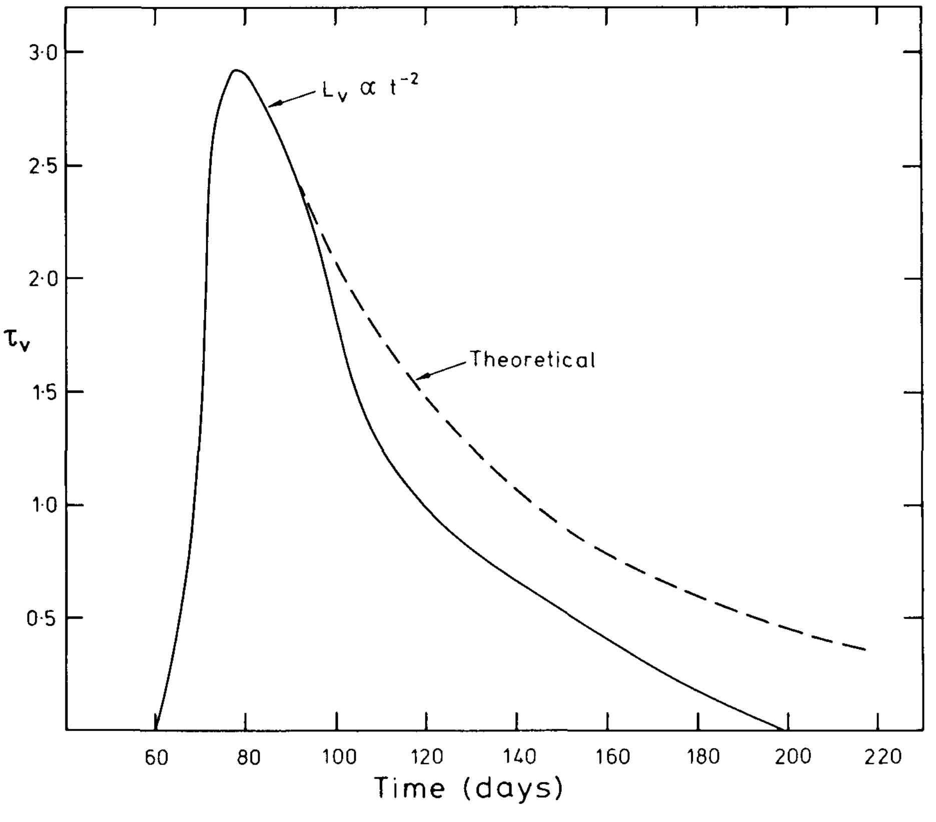

Fig. 1 Time variation of visual optical depth, based on (i) observed light curve and assumed t^{-2} dependence of unreddened visual flux (solid curve) and (ii) theoretical variation of grain number density and radius in dust shell (see text)

but the most satisfactory behaviour comes from a dependence of the form $L_V \propto t^{-2}$, characteristic of the free-free emission from an optically thin, expanding gas shell of uniform thickness. Indeed, this behaviour has been observed in a number of other novae. Fig. 1 shows the time dependence of optical depth derived from this assumption, together with the theoretical variation which follows from the grain size and number density distribution given in Eqs. (2) and (3) above.

From the work of NH, six sets of photometry were selected to cover all phases of dust-shell temperature variation. Grain radius at the outer edge of the dust shell, a_{max}, was adjusted to provide the best fit to the data at infrared maximum (80.8 d after visual maximum). Model computations performed assuming the theoretical $\tau_V(t)$ dependence shown in Fig. 1 together with a_{max} = 0.6 μm, succeed in reproducing the initial temperature fall and subsequent rise after infrared maximum.

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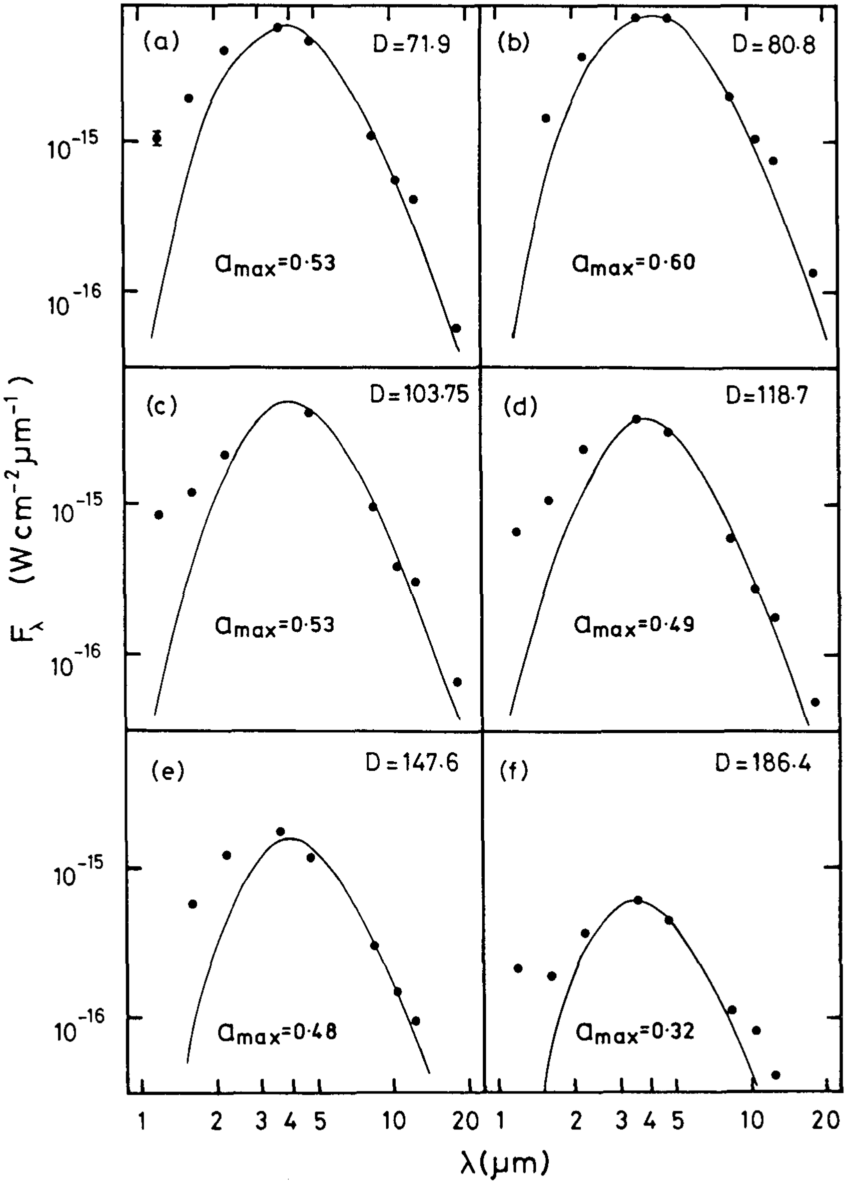

Fig. 2 Model fits to the evolving infrared energy distribution for NQ Vul; time in days (D) and a_{max} (µm) values as indicated

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However, the model dust shell was found to cool more rapidly than the observational data suggest is the case for $t \gtrsim 120$ d.

The required temperature behaviour at later times may be achieved if reductions in grain size occur after $t \gtrsim 120$ d. Gehrz et al (1980) invoked grain destruction to explain the dust temperature rise in LW Ser; here the effect is required to arrest the rate of cooling of the shell at later times. A reduction in grain size from $a_{max} = 0.6$ μm to amax = 0.4 μm would produce the effect required. The impact of subsequently ejected, higher velocity material (e.g. 'Orion' ejecta) on grains condensed from the principal ejecta would result in grain sputtering, but probably not of the magnitude required. The interaction of outflowing grains with gas in the nova environment is currently being investigated.

If we interpret the data in terms of a change in grain size, an indication of the reduction required may be derived from the optical depth: if grain radii are reduced throughout the shell by the factor α the optical depth is reduced by α^2; α may be derived from the ratio of empirical ($L_V \propto t^{-2}$) to theoretical optical depth (cf. Fig. 1). A sequence of models based on changing grain size and the empirically derived optical depth variation of Fig. 1 is shown in Fig. 2; the good agreement between theory and observation is evident (the excess flux at short wavelengths is due to contamination by free-free emission). This suggests that the following phases occurred in the ejecta of NQ Vul : (a) a short ($\sim$ 20 d) period of grain growth, leading to (b) an optically thick shell of grains, ranging in grain size up to 0.6 μm, followed by (c) an extended period of grain destruction, resulting in $\sim$ 50% reduction in grain size. In this scenario, the temperature rise following infrared maximum is due to the combined result of (a) the higher temperatures attained by the smaller grains and (b) the shrinking of the infrared pseudophotosphere, primarily caused by the interrelation of optical depth and grain size discussed above.

It seems that the establishment of an infrared 'pseudophotosphere' as discussed here, can indeed provide a satisfactory explanation of the optically thick dust shells of novae. On the other hand, a complete explanation seems to require some interaction of the outflowing grains with circumnova gas. This work emphasises again (Bode & Evans 1981) the potential usefulness of a detailed treatment of the infrared development of novae in understanding the eruption as a whole.

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DISCUSSION FOLLOWING R. MITCHELL'S TALK

KING: You had a persistent excess of flux at short wavelength which you said was due to free-free, I think you have a possible way of checking that, because at least if the Balmer lines are optically thin you can relate any Balmer emission to the free-free you would expect from the system.

MITCHELL: Yes.

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