C.M. CALLUS, J.S. ALBINSON and A. EVANS
Department of Physics, Keele University, Keele,
Staffordshire, U.K.

ABSTRACT. We consider the possibility that dust grains in novae could nucleate on ions. We examine how different ejected masses and different elemental abundances effect the availability of nucleation centres, and we show how this model could explain why only novae of intermediate speed classes form dust.

1. Introduction

In novae, the observation of a decline in the optical light accompanied by a simultaneous rise in the infrared flux some weeks after outburst has been attributed to the rapid formation and growth of dust grains in the nova ejecta (Clayton & Wickramasinghe 1976). We consider here the mechanism of grain formation, in particular the nature of the nucleation centres of the grains. For simplicity we assume a carbon based dust.

2. Nucleation Rates

The condition for the formation of grains is that the partial pressure of the monomer gas exceeds the saturated vapour pressure of the grain forming material i.e.

$$nkT_c > p_o \exp(-T_o/T_c) \qquad (1)$$

Here k is Boltzmann's constant, T_o, p_o are constants, n is the number density of condensing monomers and T_c is the condensation temperature. For a condensation temperature of 2000K carbon grains are formed when the number density is $\sim 3 \times 10^7$ cm^{-3}, corresponding to the upper end for ejecta densities.

Observationally we are able to estimate the nucleation rate J using

$$J = 2L_f/(\pi a^2 v \Delta t^2) \qquad (2)$$

Here L_f is the fraction of infrared luminosity compared to the total

Paper presented at the IAU Colloquium No. 93 on 'Cataclysmic Variables. Recent Multi-Frequency Observations and Theoretical Developments', held at Dr. Remeis-Sternwarte Bamberg, F.R.G., 16–19 June, 1986.

Astrophysics and Space Science **131** (1987) 437–441.

luminosity, a is the grain radius, v the ejection velocity, and Δt the ejection time. This leads to a value of $J \sim 10^{-10}$ cm^{-3} s^{-1} when average numbers for typical dusty novae are substituted.

From Donn et al. (1968) the nucleation rate for *homogeneous* nucleation is

$$J = 4\pi r^{*2} \eta P/(2\pi mkT)^{1/2} \; Z \; n \; \exp(- G_i^*/kT) \qquad (3)$$

where η is the sticking coefficient for vapour impinging on the cluster, $4\pi r^{*2}$ is the surface area of the "critical-sized" cluster and $P/(2\pi mkT)^{1/2}$ is the impingement rate of a single carbon atom on unit area of the cluster. ΔG_i^* is the Gibbs free energy of formation of the cluster and Z is a "non-equilibrium factor". Again using typical values we find $J \sim 6\times10^{-26}$ cm^{-3} s^{-1}, implying that homogeneous nucleation is not relevant in the case of novae.

Various studies have shown that there is ionization stratification in nova ejecta (Ferland et al. 1979). We suggest that heterogeneous nucleation, with ions as nucleation centres, could be a possible grain formation mechanism in novae. Theoretically the heterogeneous nucleation rate is calculated using Equation (3) with the modification of the Gibbs free energy factor to include an electronic term. Thus we obtain $J \sim 3.3\times10^{-12}$ cm^{-3} s^{-1}, which is within an order of magnitude of the observed nucleation rate. We therefore proceed on the hypothesis that nucleation on ions is the grain formation mechanism in novae.

3. Nucleation On Ions

When considering the ion onto which carbon grains could nucleate we need an element that would be ionized when carbon is neutral and also a species that is abundant enough to provide adequate numbers of nucleation centres; sulphur, silicon, magnesium and iron fit both these requirements in novae. We calculate the time at which the radius of the Stromgren sphere for species i, r_i, "catches up" with the radius of the ejecta, r_{ej}, as it is at this point that the element will be totally ionized.

Applying the method in Mitchell & Evans (1982) we have

$$r_i = (3S_i/(4\pi n_H^2 \alpha_i f_i^2))^{1/3} \qquad (4)$$

Here f_i is the abundance by number relative to hydrogen in the ejecta, α_i is the recombination coefficient, n_H is the hydrogen number density and S_i is the rate of emission of ionizing photons. The latter quantity is calculated using the fact that the bolometric luminosity of the nova is constant until after the grain growth period (Bath & Shaviv 1976). We fit curves of the form

$$S_i = S_{oi} \Delta t_v \theta_i^{\beta} \exp(-\theta_i) \; s^{-1} \qquad (5)$$

(where S_{oi} and β are constants for a given ion, $\theta_i = h\nu_i/kT$ and $h\nu_i$ is the ionization potential) to the time dependence of S_i. The hydrogen

https://doi.org/10.1017/S0252921100105172 Published online by Cambridge University Press

number density at time t is given by

$$n_H = 3M_{ej}/4\pi v^3 t^3 m_H \quad (6)$$

m_H being the mass of a hydrogen atom, M_{ej} the mass of the ejecta, and v the velocity given by $v = 2630\dot{m}_V^{1/2}$ where $\dot{m}_V$ is the speed class in mag day^{-1}

Using $r_{ej} = vt$ we solve for t when $r_i \geq r_{ej}$.

4. Results

For typical relative nova abundances of H=8000, C=120, S=60, Si=10, Fe=5 and Mg=40, we find that, regardless of ejected masses, all the species of interest are ionized before carbon (see Figs 1 & 2). In fact for all elemental abundances (with the exception of very low hydrogen abundances) carbon is always the last of the relevant elements to be ionized. If there were no other parameters to consider then carbon would always have an ion onto which it would condense; however there are other factors to be taken into account (see below).

Observationally only novae of intermediate speed class produce large quantities of dust; this model provides some explanation for this observational phenomenon. Firstly in fast novae no dust is produced because carbon is ionized well within the radius of condensation. The fact that there is a period when carbon is neutral while all other elements are ionized is not relevant to dust formation in fast novae as dust will obviously not form until the ejecta reaches the radius of condensation. At the slowest end of the speed class range, (e.g. HR Del), nucleation on ions becomes extremely inefficient as the density is too low (cf. Equation (1)) by the time the nucleating species are significantly ionized.

In the case of the intermediate speed classes it seems likely that carbon atoms could nucleate onto sulphur, magnesium, iron or silicon ions. The total ionization time for the first three elements ∿ 30 days, about the time dust is observed to appear in the dusty novae. However silicon is ionized ∿ 8 days in these medium class novae, which suggests that silicon may not be important in carbon grain nucleation.

5. Conclusions

In novae of intermediate speed class there exist regions where carbon is neutral and suitable elements are ionized. In these regions carbon atoms can nucleate onto ions as a start to dust growth in the ejecta. By the time all the various "Stromgren spheres" have enveloped the ejecta, grains will have had time to nucleate and grow. Furthermore on this model fast novae do not produce dust because carbon is completely ionized before the condensation radius is reached; while the slowest novae do not produce dust as the density in the ejecta is too low by the time the elements providing the nucleation centres are completely ionized. Nucleation on ions seems to satisfy the observational

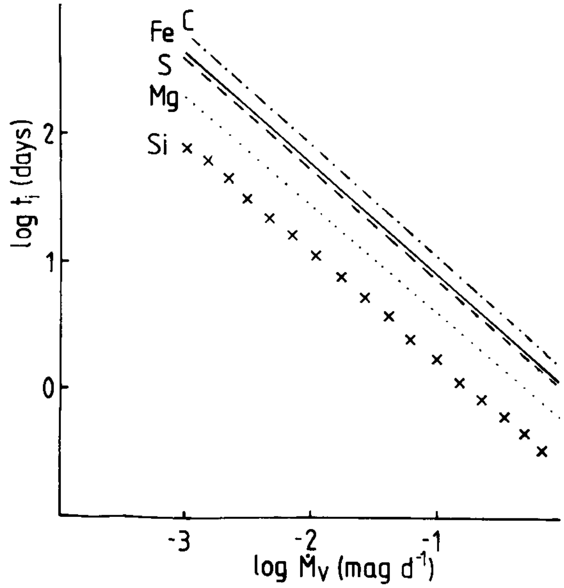

Fig. 1: Ionization time for various species in nova ejecta, as a function of speed class. Ejected mass = 10^{-4} $M_\odot$, abundances as in text.

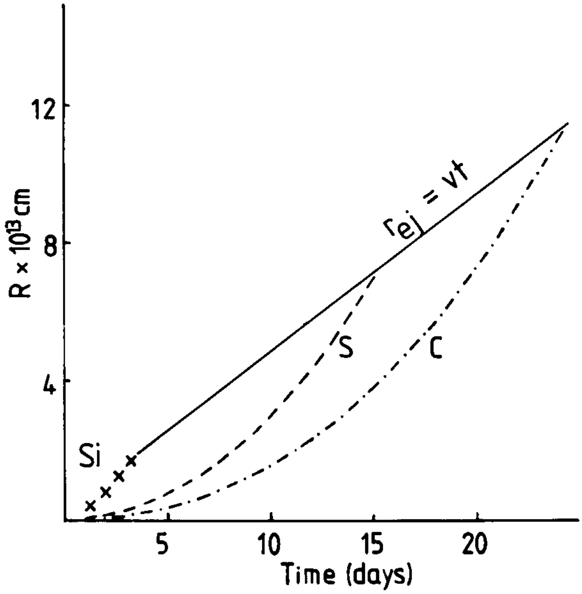

Fig. 2: Radius of "Strömgren spheres" for Si, S and C for nova with speed class 0.04 mag d^{-1}, other parameters as Fig. 1.

https://doi.org/10.1017/S0252921100105172 Published online by Cambridge University Press

and thermodynamic constraints on grain formation in novae. Furthermore, nucleation on ions may occur in other environments (e.g. WR stars, planetary nebulae) where grains form in an ionizing radiation field.

ACKNOWLEDGEMENTS

CMC and JSA are supported by the United Kingdom Science and Engineering Research Council.

References

Bath G.T., & Shaviv G., 1976, M.N.R.A.S., 175, 305.
Clayton D.D., & Wickramasinghe N.C., 1976, Astrophys. Space Sci., 42, 451.
Donn B., Wickramasinghe N.C., Hudson, J.P., & Stecher T.P., 1968, Ap. J., 153, 451.
Ferland G.J., Lambert D.L., Netzer H., Hall D.N.B., & Ridgway S.T., 1979, Ap. J., 227, 489.
Mitchell R.M., & Evans A., 1984, M.N.R.A.S., 209, 945.

https://doi.org/10.1017/S0252921100105172 Published online by Cambridge University Press