EPISODIC DUST FORMATION IN ASTROPHYSICAL SOURCES

MICHAEL F. BODE
Astrophysics Group, Liverpool John Moores University, U.K.

Abstract. At first sight, it is surprising that dust nucleation and growth can occur in the harsh environment of a Wolf-Rayet star wind. However, we know that episodic formation occurs in several different types of astrophysical source. Of particular relevance to our efforts to gain a fuller understanding of the process in WC stars is the extensive work that has been performed on classical novae. Thus, although episodic dust formation in other types of object is briefly described, this review concentrates on a comparison with this process as observed in novae in particular. It is argued that for efficient grain growth, clumping of ejecta (perhaps following shock-interactions) is essential.

Key words: stars: Wolf-Rayet – RCB – novae – supernovae – circumstellar dust

1. Introduction

Episodic dust formers can give us more precise information on the conditions under which grain formation occurs than can sources of continuous production of cosmic dust grains (Bode 1988). For example, in such objects, the distance from the central source at which grains condense can be pinpointed simply from time from an ejection event to the appearance of an infrared excess, coupled with knowledge of the ejection velocity in addition to methods employing consideration of radiative balance.

Following initial formation, there are several methods by which we can identify grain parameters. These include use of the extinction law; spectral features (particularly in the infrared part of the spectrum); condensation temperature (although this is probably less reliable); absorption efficiency of the grains (from either the shape of a continuum flux distribution or, in episodic dust formers, from the time dependence of grain temperature etc.); elemental abundances in the gas from which grains subsequently form; degree of crystallinity of the grains (from consideration of migration time of atoms on the grain surface to energetically favourable sites, versus the impact time-scale of impinging atoms); polarization studies; and studies of immediate grain precursors (atoms and molecules).

I will now review the various types of object in turn from which we might find analogues useful in unravelling the physical conditions necessary for grain formation and growth in Wolf-Rayet stars.

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2. R Coronae Borealis stars

These hydrogen deficient, carbon rich objects undergo unpredictable decreases in brightness due to the formation of dust grains in outflowing clouds of carbon rich gas along our line of sight. Ultraviolet to infrared observations of a few of these stars (*e.g.*, Evans *et al.* 1985; Drilling & Schönberner 1989) have resulted in the construction of extinction curves fitted by grains of characteristic size of order 0.1μm. Certain carbon rich RV Tauri stars may also undergo episodic dust formation evidenced by dips in their visual light curves which are rather less dramatic than for the RCB stars (Shenton *et al.* 1994).

However, although the elemental abundances in RCB stars in terms of the very high C/H ratio, may be approaching those of the WC stars, in most RCBs the effective photospheric temperature is much lower than in the WR stars. This is an important factor in terms of the chemistry of the formation of nucleation centres as we shall see below. More importantly, because there is no appreciable change in overall infrared excess at the time of grain formation, and it is difficult to ascribe condensation to a particular ejection event, the physical conditions under which grain formation occurs are less well defined than in other types of episodic dust former.

3. Supernovae

Supernovae have been proposed as major contributors to the interstellar grain population (*e.g.*, Dwek & Scalo 1980). Indeed there is strong evidence from isotopic anomalies in meteorites that supernovae at some stage in their outburst must form large quantities of grains (Clayton 1988). However, only in the case of supernova 1987A has unambiguous idenification of rapid grain formation been made (Meikle *et al.* 1993). The infrared excesses of other supernovae seen around a year from outburst have usually been attributed to a 'Light Echo' from grains which pre-date the outburst and are associated with the wind of the progenitor star, as first proposed by Bode & Evans (1980). Physical conditions at the time of grain formation in a supernova are in any case very different from those in WR stars. For example, the effective photospheric temperature at this time is an order of magnitude less than that in WC stars, and the elemental abundances in the gas phase are of course very different.

4. Classical Novae

It is in these objects that we may find the closest analogue to dust formation in WC stars. A classical nova system comprises a short period ($\sim$hrs) binary in which a late type main sequence star overflows its Roche Lobe and transfers material via an accretion disc on to the surface of a white dwarf. Outbursts occur every $10^4 - 10^5$ years due to a thermonuclear runaway on the white dwarf surface. The luminosity subsequently rises to near the Eddington limit. Material with a total mass of between 10^{-5} and 10^{-4} $M_\odot$ is ejected at velocities of order 1000 km s^{-1} (Warner 1989). These ejecta are enriched in heavy elements, with for example carbon comprising a few percent by mass (actual abundances do however vary from nova to nova — see *e.g.,* Truran & Livio 1986).

Novae are characterised in the visual by a rapid rise to maximum brightness and then a gradual decline. However the visual light-curve disguises the underlying energetics. For moderate speed novae, thermonuclear runaway models predict (and observations confirm) the existence of a constant bolometric luminosity phase. The fall in the visual light curve is then due to a change in bolometric correction as the photospheric temperature increases with time. Indeed from the models of Bath and Shaviv (1976) at the time of dust condensation (which gives rise to an infrared flux increase coincident with a dramatic fall in visual flux for moderate speed novae) the photospheric temperature is of order 4×10^4 K and increasing.

4.1 DUST FORMATION

There is no doubt that the infrared excesses observed in classical novae at the time of the break in the visual light curve are due to emission from dust grains. Indeed, a simple picture in which condensation distance is defined by the distance from the central star at which a hypothetical condensation nucleus reaches a condensation temperature is usually consistent with the product of the time to transition break in the visual light curve and the known expansion velocity of the ejecta. We now know of around 20 classical novae that have shown evidence of dust production. There are suggestions that the faster novae are less able to produce dust and the reasons for this may be related to the fact that speed class determines not only peak luminosity but also the ejection velocity (for reviews see Gehrz 1988; Bode & Evans 1989; Evans 1990). Simple (and detailed!) modelling suggests that the total mass of dust formed is $\leq 10^{-6}$ $M_\odot$ and that the grains at this time have typical radii of order 0.1μm and are composed in the first instance of amorphous carbon.

4.2 IDENTIFICATION OF GRAIN TYPE

As outlined in the introduction, we can identify grain type from spectral features in the infrared. In nova QV Vul (1987) for example, Gehrz *et al.* (1992) observed a smooth continuum between 2 and 8μm consistent with emission of carbon dust at all times. Around 100 days after outburst a silicon carbide feature was evident. Far more surprisingly, there were silicate features at 9.7 and 19.5μm dominating these spectral regions on day 561. The presence of both C and O-rich grains had previously been noted in V846 Cen (Smith *et al.* 1994). Simplistically one would expect that the formation of CO would mop-up whichever of C or O atoms were less abundant in the gas phase to leave the other species to proceed to participate in dust formation. Thus after the formation of CO, if carbon was more abundant than oxygen only carbon grains should form. Conversely, if O is more abundant than C then one would expect O-rich grains (silicates) to form. The formation of both types of grains in a nova suggests that there is some differentiation of these elements in the ejecta, or that CO formation is not fully efficient before grains form.

Grain nucleation has been investigated in some detail for carbon grains in nova ejecta. *Homogeneous nucleation* (that is formation of nucleation centres from carbon molecules) proceeds at a very low rate and has not been considered as an effective nucleation process. This is also consistent with the findings of Cherchneff-Parrinello in the context of WC stars (these proceedings). *Heterogeneous nucleation* on the other hand (*i.e.,* the formation of grains on other than pure carbon molecules) has been considered as a more promising route. Work by Rawlings (1988) and Rawlings & Williams (1989) has concluded that a neutral carbon region at the outer edge of the ejecta is essential for chemistry to proceed. In addition the temperature of the gas needs to be $\leq$ 4000 K and the only route to the formation of a significant number of nucleation sites is via a hydrocarbon chemistry. The strong UV field of the central star inhibits the chemistry and depletion of O into CO is essential if the hydrocarbon molecules are not to be 'burnt'. Finally, the abundance of H_2 needs to be very high in the region of formation of nucleation centres. Of course, this latter criterion is not fulfilled in the wind of a WC star, unless mixing with mass lost from a binary companion can somehow occur (see below). The formation of nucleation centres in the conditions prevailing in the harsh environment of the outflowing ejecta of a nova is however still a finely balanced process.

4.3 EVIDENCE FOR PRECURSORS OF DUST

Evidence for the formation of molecules which could be the precursors of dust is strong. Carbon monoxide has been detected in several novae including V1500 Cyg (Ferland *et al.* 1979, although this nova did not subsequently go on to produce a dust shell), and most recently the dusty Nova Cas 1993 (Scott *et al.* 1993a,b). Unidentified infrared features have also been seen in at least two novae (V842 Cen, Wichmann *et al.* 1991, Smith *et al.* 1994; Nova Cas 1993, Scott *et al.* 1993b). Once nucleation has been successful, grain growth can proceed. Simple kinetic growth can then be investigated to determine the number density of condensable atoms needed to give rise to the observed final grain size. Using appropriate parameters, the required carbon gas number density is however around 100 times that which one would derive from a steady flow of ejecta. This is a lower limit as it does not take into account limits on grain size imposed by both dilution of the ejecta and depletion of the condensate by the grains (see *e.g.*, Evans 1993). Hence the ejecta must be clumpy. The question then is, could such a shell of clumps of grains intercept all the luminosity of the central star as is obviously the case for moderate speed novae where the infrared luminosity of the dust shell at peak can equate to the underlying bolometric luminosity of the hot source? Simple arguments show that for a covering factor of unity the radius of a blob is around 10^{12}cm and each blob can easily be optically thick if the grains are 0.1μm radius carbon and a few percent of the total gas phase carbon condenses into grains.

Clumping of the ejecta, due perhaps to dynamical instabilities in the gas, helps both nucleation and growth. For example, the homogeneous nucleation rate is proportional to the condensable atom number density squared and clumps are efficient at shielding their interiors from the ultraviolet radiation field. Such clumps may also be well-cooled and this aids the chemistry. Growth is obviously enhanced by the increased number density of monomers, and in addition dilution may proceed more slowly than r^{-2} in the clumps. However depletion of the condensate will still limit grain size but it can be shown that formation of 0.1μm grains is still straightforward.

The question then is, is there any evidence for clumping in nova ejecta? Images of the remnants of novae decades after the explosion clearly show that the ejecta are clumped. However, we are concerned with what is happening in the days and weeks after an outburst prior to dust formation. Here again there is evidence of clumping, albeit more indirect. Emission line profiles (for example in Nova Her 1991, Ingram *et al.* 1992; Nova Cyg 1992, Shore *et al.* 1993) show multiple components. The infrared emission of Nova Her 1991 observed by Woodward *et al.* (1992) showed that grain formation had commenced within ten days of the outburst and was coincident with a fall of 0.9 magnitudes in the visual light curve. However the ratio of the infrared luminosity to the bolometric luminosity of the underlying source was only approximately 0.05, therefore the dust cloud could not cover the whole of the sky as seen from the central object. The existence of a break in the visual light curve thus suggests that the ejecta were very clumpy and that one of these clumps condensed along our line of sight. We should also note that Lynch *et al.* (1992) later found that silicates had formed where again intially there was carbon dust.

What is the mechanism that might lead to instabilities in the shocked material that would cause clumping? *ROSAT* observations of Nova Her only five days from outburst are fitted by gas at temperatures of between 10^7 and 10^8K. The origin of this shock-heated gas is likely to lie in interactions between different velocity systems of ejecta (Lloyd *et al.* 1992; O'Brien *et al.* 1994). This situation might then lead to the formation of a Rayleigh-Taylor and thermally unstable shell, providing a natural mechanism for clumping to occur. This contrasts with the outburst of the recurrent nova RS Oph (Bode 1987) in which the X-ray emission arose from interaction of the ejecta with the pre-existing wind of the red giant star. The lack of any significant dust formation in this case may be due to the near-solar abundances in the shocked region.

5. Closing thoughts

The episodic dust-forming WC stars have the advantage over novae of the potential predictability in the timing of their bouts of dust formation. This enables co-ordinated observing campaigns to be mounted to explore the conditions under which grains form and the type of grains that result. Searches for precursors of grains should be made both in the optical (where, according to a suggestion made at this symposium by Martin Cohen, the Swann bands of carbon may be evident) and in the infrared, where features such as that seen at 7μm in the survey of Cohen *et al.* (these proceedings) may be detectable. Unfortunately at present there seem to be very few signatures of such precursors observed, or (particularly if the WC wind is unmixed with its H and O-rich companion) to which we might in future appeal. 'Occultation' studies using archival *IUE* data for example may however be worthwhile. In this context it is interesting to note the dips in visual light-curves reported at this meeting for several WC star systems.

Simple calculations of the growth of 0.01–0.1 μm-sized grains in WR140 suggest that this requires gas densities only one to two orders of magnitude higher than those presumed to exist at the interface between the WR and O star winds. However, this is unlikely to be the site of formation initially. More likely, this will be downstream of this region and hence the density enhancement over and above that of the steady stellar wind at this point will be higher (as emphasised for the efficient formation of grain nucleation centres by Cherchneff-Parrinello, these proceedings) for the efficient formation of grain nucleation centres. As in novae, such density enhancements would be a natural consequence of clumping in well-cooled material which had previously undergone shock-heating. Mixing of hydrogen from the O star wind in the turbulent regions of the bow-shock will also obviously help the chemistry.

In conclusion, much better understanding of grain nucleation and growth would ideally stem from a coupling of observations of grain precursors and grain parameters; hydrodynamic modelling to explore temperature and density in downstream regions of the bow-shock, and exploration of the chemistry in these regions leading to the formation of nucleation centres from which grains can grow.

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DISCUSSION:

Shaviv: Mike, if a small grain manages to form, then it will change the flow around it. Thus, using the mean flow conditions may be inappropriate (overestimate or underestimate - I really do not know).

Bode: This may be one of several complicating effects, although it has not been considered. Certainly, grain charge is an effect that has been addressed by some workers.

Nussbaumer: We have heard from Cherchneff how difficult it is to form dust and that dust formation is a slow process. Mike Bode has shown us examples of fast dust formation and he has outlined plausible conditions for fast dust formation. How do dust formation theoreticians see the scenario?

Cherchneff: Dust growth may be fast, but the limiting step is the formation of precursors. In novae, the physical conditions appear more favourable to precursor nucleation than in WR environments. Also, hydrogen is present and therefore the chemistry will be different. However, the problem of dust nucleation still needs to be addressed and treated with a full chemical kinetic approach.

Moffat: Has anyone actually followed the time evolution of the spectral subpeaks you mentioned? If they behave as do subpeaks on WR emission lines, the clumps would come and go on a timescale of ~10 hours (depending on their size: larger ones last longer), so it might be difficult to have clumps last long enough to enhance dust formation.

Bode: As far as I am aware, the fine structure in nova emission lines has not been followed in any detail, though gross features in spectra taken at outburst in several novae map well onto images of the ejecta taken decades later. The type of study your question suggests is, I believe, very important.