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DUST IN SUPERNOVAE

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A brief review is given on what we know observationally about dust formation in supernovae. The main focus will be on SN1987A where dust formation was first observed. The detection ad analysis of the presence of dust in this object still remains the most complete of all SNe where dust has been subsequently detected. The importance of supernovae for dust production in the nearby and distant universe will be briefly alluded to.

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1. Sites of Dust Formation

The following sources of dust have been established in our Galaxy and beyond: 1. Envelopes of Red Giant stars. 2. Circumstellar material surrounding hot stars and luminous blue variables (LBV). 3. Novae ejecta. 4. Core- collapse supernovae (the basis of this talk). We note that it is also anticipated that dust should be destroyed in some astronomical environments, although there is little direct observational evidence confirming this expectation. We note that dust formation was hypthesized in supernovae 20 years earlier than it was discovered by Cernuschi et al.[1], Hoyle and Wickramasinghe[2] and subsequently discussed by Dwek. Dust is an important constituent of the Milky Way although its composition is still a cause for investigation. Whether dust is the cause of the large IR fluxes observed from galaxies at cosmogical distances is a question bringing extra interest to the study of its origin and composition. In what follows special emphasis is given to SN1987A not simply because it was the first supernovae in which dust was observed to form, but also because the subsequent analysis of the evidence at various wavelengths still remains the most complete. This is partly due to the brightness of SN1987A and therefore the detail and frequency of observations at the late phases when conditions in the expanding envelope were such as to make dust formation inevitable.

2. Observational Manifestations of Dust

There are several ways in which the presence of dust may be shown to be associated with supernovae. Each individually may not be unequivocal concerning its precise location and time of origin. For example dust may form and has been seen to form in the ejecta or in the surrounding circumstellar material or may be already present in the CSM before the explosion. The following indicators of dust have been exploited in the case of SN1987A. 1. Blueward shifts of emission line peaks - arguably the most unequivocal indicator of dust in the expanding envelope. 2. Decrease in the visual light curves - actually a manifestation of the same effect as in (1) above. 3. Increase in the IR emission and particularly the thermal IR. 4. Effects on the bolometric light curve. 5. Presence of molecules prior to the observed presence of dust.

In SN1987A the CO and SiO molecules were observed earlier than 150 days after explosion in IR spectra. In fact the temporal evolution of the first overtone band of CO at 2.3 micron was followed from 100 to 650 days and the mass of the CO molecule determined by various groups using different degrees of sophistication. The flux in this band began to decrease after 200 days some of which being due to a decrease in temperature in the ejecta.

A blue shift of the blended [OI]λ6300,6363 doublet was first observed near day 530 by Danziger et al.[3], and the shift continued to increase for some 200 days demonstrating that dust was continuing to form for this period. This shift and the profile shapes were shown via analytic modelling to be consistent with dust forming and uniformly distributed in the ejected at expansion velocities less than 1870km/sec (Lucy et al.)[4]. The apparent shift is caused by the fact that emission from the far side of the envelope which is receding is more obscured by the dust than the near side approaching the observer. Dust in a thin shell would produce flat-topped profiles not observed, while the constancy of the blue wing of the profile defines the 1870km/sec limit of dust formation in the metal-rich interior of the ejecta. The profile shape also allows a determination of the optical depth and albedo of the dust. Line shifts were also found to be greater for the MgI]λ4571 line and smaller for the [CI]λ9843 line, clear evidence that there was an amorphous component of the dust with grain sizes of the order of or less than the wavelength of these emission lines. A similar effect is seen in the broad-band light curves where the slope of the light curve started to change near day 530 or before with the maximum change occuring at shorter wavelengths.

There was evidence of dust formation in the Type IIP SN1999em from both line shifts and light curves (Elmhamdi et al.)[5] but at somewhat earlier phases and within a more compact region of the envelope. Other examples are discussed below.

The thermal IR emission near 10μ and beyond began to increase at day 530 which would happen if the dust had absorbed shorter wavelength radiation and was re-emitting at its ambient temperature. At day 1316 for example a black-body (BB) fit to the IR revealed a temperature of 155K. If this BB radiation came from dust in the ejecta then it should be included in the energy budget produced by radioactive decay of, at this phase, ^{56}Co. In fact this inclusion showed that the bolometric light curve followed the ^{56}Co decay slope, whereas without this inclusion the optical light curves decreased progressively more below the radioactive decay line.

Thus there was a consistent picture of dust formation in the ejecta with a mass of amorphous dust estimated to be 3x10^{-4} $M_{\odot}$ (lucy et al.)[6].

Recently evidence has emerged that dust formation may in fact have started in SN1987A nearer day 430 (Elmhamdi, private communication). This is suggested by dividing a composite UBVRI-JHK by a composite UBVRI light curve showing a small bump beginning near day 430 growing and then fading. Could this be dust forming at a temperature to show emission in the near IR JHK bands and then fading as the dust cooled. Other possibilities might have to do with formation of emission lines, a matter requiring investigation with IR spectra and modelling. However this earlier date is also consistent with close inspection of the extremely accurate Geneva photometry. The difference in the derived dates of the commencement of dust formation probably lies in the fact that acquistion of spectra was far less frequent than those of the accurate photometry mentioned above.

The composition of the dust in the ejecta has been a point of contention since the thermal IR observations after dust formation were not of sufficient quantity or quality to discriminate between silicates and amorphous carbon grains. Of possible relevance was the occurrence near day 450 of a small dip in the light curve of MgI]λ4571 suggestive of depletion due to silicate formation. It should also be noted that starting near day 530 the possible [SiI]1.64μ line began to decrease at a faster rate than the nearby continuum [7] which possibly suggests that this resulted from formation of silicate grains. If, however,the mass of silicate dust were 3x10^{-4} $M_{\odot}$, the amount of Mg, Si,and O depleted into grains would not be sufficient to detect a diminution of the strengths of lines emitted by ions of these 3 elements. There remain other possible explanations for this decrease such as a sudden drop in temperature (or IR catastrophe). The most likely explanation for the behaviour of this feature at 1.64μ results from its being a blend of [SiI]1.6445μ and an [FeII]1.6435μ line, both of which originate from lower levels near the ground state. While they would not have very different temperature sensitivity, they would have a different dependence on the ionization equilibrium. If FeII was recombining to FeI, in principle quite possible at this phase, this would cause an additional weakening of the 1.65μ feature in addition to the dust absorption. Both lines have been proposed as identifications in other supernovae and supernova remnants. Modelling is required to settle this problem.

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Recently the IR spectrum of the Type II SN2004et (Kotak et al.)[8] has been fitted with a 3-component spectrum at day 464 due to optically thick gas, a red IR echo and silicate dust emission from dust inside (∼1600km/sec) the ejecta. The silicate dust emission gives a significantly better fit to the spectrum than amorphous carbon. Since the estimated mass of dust was $10^{-4}\ M_\odot$ these results are somewhat similar to those of SN1987A.

There is also evidence for dust formation in Type Ib SNe such as SN1990I (Elmhamdi et al.)[9]. In this case we have only the visual light curve starting to fall faster than the radioactive decay rate near day 230. The earlier start of dust formation could have been due to the more metal-rich environment of a Type Ib stripped of hydrogen before the explosion. A more recent Type Ib supernova with dust is SN2006jc (Smith et al.)[10] where there is also circumstellar material with dust.

It would hardly be surprising then if most or all Type IIP and other core-collapse SNe produce dust, since after the explosion the ejecta pass through a phase where the physical conditions for dust formation are similar. Nevertheless SN2004dj (Meikle et al.)[11] is an example of a Type IIP SN whose behaviour in forming dust is different from those discussed above. Firstly there seems to have been dust formation of non-silicate dust in a surrounding shell much earlier than in SN1987A and then a non-silicate dust formation in the expanding envelope at a much later phase. These differences in place and time remain a puzzle to be solved by knowing more about the progenitors.

The following is a list (now probably incomplete) whose members show evidence for the possible presence of dust. For some the evidence is from spectra, others from IR emission and others from both:

SN1987A, SN1999em, SN1990I, SN1998S, SN1980K, SN2003gd, SN2002hh, SN2005bf, SN2004et, SN2005ip, SN1979C, SN1985L, SN1994Y, SN1997ab, SN1999e, SN2004dj, SN2006jc.

There is of course a growing number of young SN remnants showing IR emission from associated dust: Tycho, Kepler, Crab, Cas A as well as older SN remnants. There are also theoretical attempts to demonstrate how very large masses of dust are produced in SNe to explain high z IR luminosities. Some of this modelling requires progenitor masses for SNe that so far have never been clearly identified observationally.

3. Circumstellar Dust

Again SN1987A has also provided us with a good example of dust in the nearby CSM illuminated and excited by the interaction with the expanding ejecta. In order to elucidate the role and behaviour of dust we confine our remarks to IR and Xray observations. Starting in 2003 (with Gemini South and the VLT) midIR imaging revealed dust emission from the the inner ring at a BB temperature of 180K (Bouchet et al.)[12],[13]. The IR brightening followed the Xray, visual and radio brightening which had begun much earlier, about 1200 days for Xray and radio, and 3600 days for the visual. The actual start of the IR brightening was almost certainly earlier than 2003 but limited by availability of instrumentation capable of detecting and isolating it. The temporal evolution of the IR ring emission reveals several unexplained properties. One is the fact that the brightening occurred first predominantly on the eastern side of the ring and after 4 years it dominates the south-western side. Another is the fact that although there seems to be a reasonable coincidence of the IR with the visual position and shape, and both show clumpiness in the structure, there is not a good one-to-one coincidence of IR clumps with visual clumps clearly outlined by the HST. Broad band IR observations could not discriminate the various types of dust that might be in the ring. But SPITZER could and did (Dwek et al.)[14].

A temporal series of spectra in the range 5-30μ clearly showed the double peaked structure produced only by silicate emission in this wavelength range. These observations confirmed the temperature and gave a mass of visible ring dust of $10^{-6}M_{\odot}$. Concurrent soft Xray emission occurring as a result of shock interaction with the ring allowed one to test whether this emission could be responsible for destroying dust in the ring. Therefore both IR and soft Xray fluxes obtained during the period 6000-8000 days provided ratios that were constant within the uncertainties, whereas dust destruction would require a decrease in the IR/Xray ratio(Dwek et al.)[15]. In the fit of silicate emission to the SPITZER spectra there remained an excess at wavelengths shorter than 8 microns which could be fitted with amorphous carbon emission at a temperature of 400K. Whether these two temperature domains are possible in such an environment is a matter of concern.

What has been tacitly assumed until now is that all the dust seen in the ring was present before the explosion. However the formation of dust near to, but outside the expanding envelope in subsequent SNe might suggest that at least part of the ring dust was formed following the initial UV burst and cooling or following the impact and shock interaction with the very outer parts of the envelope impacting the gas in the ring. Important thermal IR imaging observations are lacking in the interval 1600-4000 days when dust might have formed. Dust formation in a surrounding shell after outburst has been reported for SN2005ip (Smith et al.) [16] while dust formation in both the expanding ejecta and a surrounding shell has been noted for SN2006jc (Smith et al.) [10].

4. The HERSCHEL Dust

There is a recent detection with HERSCHEL (Matsuura et al.)[17] of cold dust (17-23K) with a mass of 0.4-0.7 $M_{\odot}$ centred on SN1987A and ascribed to the ejecta. With this mass which is about 1000 times that estimated for the mass of dust which formed near day 530 one immediately recognises its significance for the origin of large IR luminosities of galaxies at cosmological distances. There are however some difficulties with associating this cold dust with the ejecta (debris). One is the very low temperature in this environment. Another is the fact that to obtain this mass virtually all the available refractory material must go into grains. In addition if absorption of dust in the visual region scales as its mass the absorption of the HERSCHEL dust should be 1000 times (7.5 magnitudes) that caused by the original dust forming near day 530 or before. The HST photometry of the debris up to 21 years (Kirshner)[18] shows no evidence of such absorption. Nor do HST spectra from the central regions show blue shifts consistent with such a huge mass of dust even if some effects of obscuration are probably observed.

5. Conclusions

The association of dust with SNe has resulted in a number of questions requiring future elucdation. We need to know the range of masses of dust produced in different types of SNe as well as the range in types of dust grains. Another question is why thermonuclear SNe do not seem to produce dust and whether this is simply a lack of the appropriate refractory elements. Still begging an explanation is the origin of the large HERSCHEL dust mass and at what phase it formed. Thus from the above discussion it is clear that we are not yet in a position to conclude whether supernovae contributions to dust production are sufficient to account for a major portion of IR fluxes from galaxies at cosmological distances. Indeed recent modelling work by Valiante et al.[19] and Dwek and Cherchneff [20] shows that AGB stars could be the dominant provider with also grain growth in molecular clouds playing a role.

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