ALMA confirms dust in supernova 1987 A

Prateek Sharma

Atacama Large Millimeter Array (ALMA), the largest telescope observing in the far infrared (FIR) and sub-millimetre bands, has confirmed[1] the presence of substantial dust (> 0.2 solar mass) in the core of supernova 1987 A. Three years ago Herschel, the space-based FIR observatory, had reached a similar conclusion, but because of a lower spatial resolution it was not possible to distinguish dust formed in supernova ejecta from that formed in shells launched by the progenitor star before explosion[2]. ALMA uses its large array of antennae to attain much higher spatial resolution than achievable from space. Recall that the resolving power of a telescope is proportional to its diameter, and that an array of radio telescopes can be arranged such that its effective diameter is not the size of an individual dish but the distance between the dishes. The FIR radiation from ALMA is unambiguously localized to the centre of the supernova remnant. These observations reveal the importance of high resolution that we can attain from large ground-based telescopes.

Supernova 1987 A (so named because it was the first supernova observed in 1987) is the nearest recent supernova which went off in our neighbouring galaxy, the Large Magellanic Cloud. The optical transient was preceded by neutrino events detected at a few underground neutrino observatories. This confirmed the predicted neutronization of the core and was the beginning of neutrino astronomy. Being so close (50 kpc), 87 A gives us a chance to study various aspects of supernovae at close range, and therefore it has been observed in all wavebands by all major telescopes. Currently, on average ~250 supernovae are discovered annually, mostly in nearby galaxies. 87 A is a core-collapse supernova resulting from the death of a massive star. Another class of supernovae, called the type Ia's, has been calibrated as a distance indicator. Ia's have shown that the universe is not a only expanding, it is expanding at an accelerating rate. This discovery was awarded the physics Nobel Prize in 2011.

Coming back to the subject matter, dust consists of just 1% (by mass) of the interstellar medium (ISM), but it plays a fundamental role in astrophysics. Extinction due to dust is responsible for the dimming of UV/optical emission of stars. Most star-forming regions are enshrouded by dust, which reprocesses the UV emission into IR. Therefore, most star-forming galaxies are copious IR emitters. Dust plays a crucial role in heating and cooling of the ISM. Dust particles are believed to aggregate collisionally to form planetesimals, which eventually become self-gravitating and form planets. In fact, the most abundant elements on Earth are the ones also trapped in dust, not the most abundant elements in stars – and the universe as a whole for that matter. Dust particles can absorb momentum from photons, can collisionally couple to gas, and lead to galaxy-scale outflows powered by radiation. Such outflows disperse metals on scales much larger than the size of the galaxy.

Despite its importance, there is no firm understanding of how and where this inter-stellar dust forms. Traditionally it is believed that most of the dust is produced by cool outflows of evolved sun-like stars known as asymptotic giant branch (AGB) stars. The abundant refractory elements (aluminum, silicon, iron, etc.) condense out in the form of dust grains consisting of amorphous carbon, polycyclic hydrocarbons, etc. Supernovae are not usually considered to be dominant dust producers because the shock heated gas is too hot; even if dust condensed out it will be evaporated by the hot gas. However, the observations of high-redshift ($z \sim 6$; when the universe was just 1 billion years old) galaxies show copious emitters of millimetre radiation due to dust. Ordinary stars simply do not have enough time to evolve to the phase in which they can produce cool outflows conducive to forming dust[3]. Production in supernova ejecta and in cool outflows of massive stars is the only viable alternative. Moreover, the lower-mass (< 8 solar mass) stars, which do not lead to supernovae, do not synthesize heavier elements in their cores. Therefore, while dust consisting of carbon is predominantly formed in AGB outflows, dust with heavy elements like silicon and iron is likely manufactured in supernova ejecta[3].

Indebetouw *et al.*[1] made use of the exquisite spatial resolution of ALMA to separate out the emission from the supernova core and a surrounding ring. The ring emits radio synchrotron emission and X-rays due to forward and reverse shocks driven by the explosion. Figure 1 shows that the centrally concentrated FIR emission (~0.5 arcsec) is due to cold (~20 K) dust condensing in the supernova ejecta. Both components (ring and core) are spatially and spectrally distinct. A combination of amorphous carbon and silicate dust fits the FIR blackbody-like emission. The dust composition is not

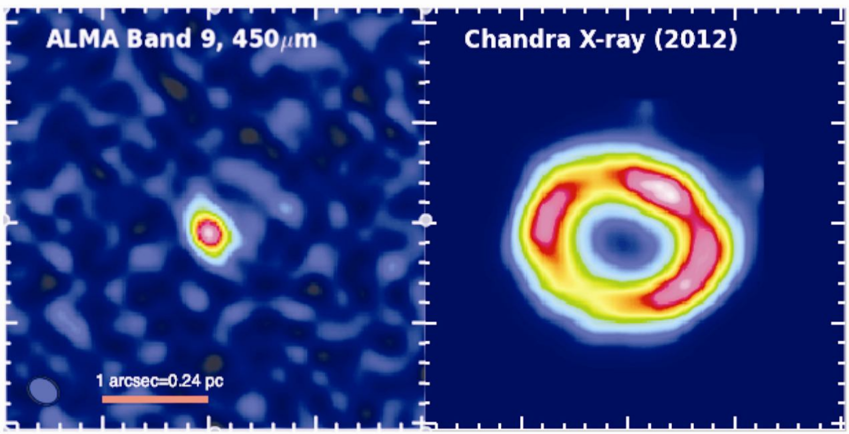

Figure 1. A comparison of FIR and X-ray images from supernova 1987 A. X-ray emission is confined to the ring formed by inner and outer shocks, but the FIR emission comes from dust in the cool inner ejecta (©AAS. Reproduced with permission).

uniquely constrained, but the total amount of dust is definitely > 0.2 solar mass. The mass of carbon condensed in dust is comparable to the nucleosynthetic yield in the supernova shock, and hence some refractory elements can efficiently condense into dust over a short timescale.

The optical and X-ray maps of 87 A show the location of the forward and reverse shocks. It is clear that the centrally concentrated cold dust is not yet engulfed by the reverse shock. The survival of dust in the shocked hot gas is not well understood and depends on several parameters (size distribution of dust, ISM density, etc.)[3], but if most of this dust is dispersed into the ISM without being destroyed, then supernovae should be substantial producers of dust, especially at high redshifts. It should be possible to observationally settle this issue by measuring the amount of dust in older supernovae in which the reverse shock has hit the core. Since there is not definite prediction from theoretical models, observations will play a decisive role in advancing this field.

Sensitive sub-millimetre and IR telescopes have become available recently and the issue of dust formation and survival in supernovae has been revolutionized. Observations of supernovae and supernova remnants (see note 1) have shown several correlations[4]. The amount of dust within ~10 years of explosion is observed to be always less than 0.001 solar mass; most of this is also warm (100–1000 K) dust emitting in mid-IR. At later (>10 years) phases some supernovae show high (~0.1 solar mass) incidence of dust and others much smaller (<0.001 solar mass). A correlation which is fairly strong is that cold dust emitting in far-IR/sub-millimetre, when present, is substantial (> 0.001 solar mass). Warm dust, on the other hand, is always present in much smaller quantities and predominantly in early stages (see note 2). Such robust correlations, combined with the models of nucleosynthesis, and dust condensation and survival, should lead to advances in understanding the production and destruction of the most enigmatic component of ISM.

Notes

1. Astronomers distinguish between the early and later phases of supernovae. The early phase, powered by radioactive decay of elements synthesized in supernova shock, is called a supernova. The later time lightcurve, after a few years, called the remnant phase, is powered by the thermal energy produced by the shock.
2. In fact, from before the discovery of cold dust, a much smaller amount of warm dust (~10^{-5} solar mass) is being observed from 87 A.

1. Indebetouw, R. *et al.*, *Astrophys. J. Lett.*, 2014, **782**(1), L2.
2. Matsuura, M. *et al.*, *Science*, 2011, **333**, 1258.
3. Dwek, E., In Proceedings of the Spectral Energy Distribution of Gas-Rich Galaxies: Confronting Models with Data (eds Popescu, C. C. and Tuffs, R. J.), AIP Conference Series, Heidelberg, 4–8 October 2004; doi: 10.1063/1.1913921.
4. Gall, C., Hjorth, J. and Andersen, A. C., *A&A Rev.*, 2011, **19**, 43.

Prateek Sharma is in the Department of Physics, Indian Institute of Science, Bangalore 560 012, India.
e-mail: prateek@physics.iisc.ernet.in