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ALMA Observations of Supernova 1987A

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Abstract. The explosion of Supernova (SN) 1987A was detected in the Large Magellanic Cloud, only 50 kpc away from the Solar system. This was the nearest SN explosion detected in 400 years. Due to its close distance, SN 1987A has enabled us to investigate the evolution of supernovae in unprecedented detail.

With its superb sensitivity and angular resolutions at submillimeter and millimetre wavelengths, ALMA is discovering new aspects of Supernova 1987A. The ALMA high angular resolution images showed thermal emission from cold dust thermal confined in the SN ejecta, proving that SN can form nearly a solar mass of dust from its newly synthesised elements. The ALMA helps our understanding of dust formation in SNe, and further helps answering the question whether SN dust can be an important source of dust in galaxies or not.

ALMA also discovered unexpectedly strong CO and SiO rotational lines in SN 1987A. These detections provide a key to understand molecular chemistry in SNe in the time scale of 20 years.

Further, the ALMA covers the low frequency range of the synchrotron radiation arising from SN 1987A. The comparison of 213 and 345 GHz images taken from ALMA at with 44–108 GHz ATCA images showed that the spectral power indices of the synchrotron radiation varies within the SN. This suggests the presence of a range of strengths in shock interactions within the system.

1. Introduction

The explosion of Supernova (SN) 1987A was detected in the Large Magellanic Cloud, only 50 kpc away from the Solar system. This was the nearest SN explosion detected in 400 years. Due to its close distance, SN 1987A has enabled us to investigate the evolution of supernovae in unprecedented detail.

Our four ALMA programmes of SN 1987A have investigated four different aspects of this SN: 1. dust, 2. molecules, 3. shocks and 4. gas dynamics. This contribution of the proceedings highlights some of the finding we made from the ALMA programmes.

2. Dust studies

Theoretical works of dust evolution have proposed that supernovae can be an important source of dust in galaxies, if supernovae can form a significant mass of dust (0.1–1 $M_\odot$; Morgan & Edmunds 2003; Dwek & Cherchneff 2011; Valiante et al. 2009). So far, dust has been measured in over ten supernovae, but the reported dust masses in early days (up to ~600 days after the explosion) tend to be much lower than the predicted value, with typical measured dust masses of less than 1×10^{-3} $M_\odot$. Twenty six years after explosion, the Herschel Space Observatory detected SN 1987A at far-infrared wavelength, with an estimated dust mass of ~0.5 $M_\odot$ (Matsuura et al. 2011; Matsuura et al. 2015). A surprisingly large dust mass found in SN 1987A triggered many debates, including the origin of dust in SN 1987A. Matsuura et al. (2011) claimed that the large mass of dust was from the ejecta. An alternative possibility proposed by the community was that the ring is the location of the large mass of dust. The ring is associated with progenitor's mass loss during the red-supergiant phase, and in this case, dust is not made by the SN itself. The emission from dust grains have been found in the ring before (Bouchet et al. 2006), so that it was thought to be the natural choice. As the Herschel pixel size was 3 arcsec at best it could barely resolve the ejecta and ring, as the ejecta diameter is about 1 arcsec and the ring diameter is ~2 arcsec (Larsson et al. 2013).

In order to resolve the origin of the dust in SN 1987A, we have requested the ALMA image of the thermal dust emission in SN 1987A at 450 and 870 μm. With the angular resolution of 0.3–0.7 arcsec, the ALMA was able to spatially resolve the ejecta and the ring at these wavelengths.

Fig.1 shows the ALMA image of SN 1987A at 450 μm, together with Hα white contour lines (Indebetouw et al. 2014). While Hα emission arises from both from the ejecta in the centre, and the surrounding ring, the thermal emission from dust grains at 450 μm were only found in the ejecta. This image showed that the dust grains have indeed formed from the material ejected from SN.

3. Molecules

The ALMA has made the discovery of the first millimetre molecular lines from SNe (Kamenetzky et al. 2013). The detected molecules were CO and SiO. This shows that cold material in the ejecta form not only dust but also molecules.

In the early days (day 100 up to 600 after the explosion), the formation of molecules in SN 1987A was reported by Spyromilio et al. (1988) and Roche et al. (1991). These past detections were also for CO and SiO but in rotational-vibrational transitions at near- and mid-infrared wavelengths. The estimated CO mass at that time was 5×10^{-5}–10^{-3} $M_\odot$ (Spyromilio et al. 1988; Liu et al. 1992), which was supported by chemical models (Rawlings & Williams 1990). The excitation temperature was over 1000 K in early days. Now, the ALMA observations together with the Herschel detection of J=7–6 and 6–5 transitions suggested that the CO mass was at least 0.01 $M_\odot$, at the time of 26 years after the explosion (Kamenetzky et al. 2013). The temperature dropped approximately below 150 K. This is consistent with theoretical prediction

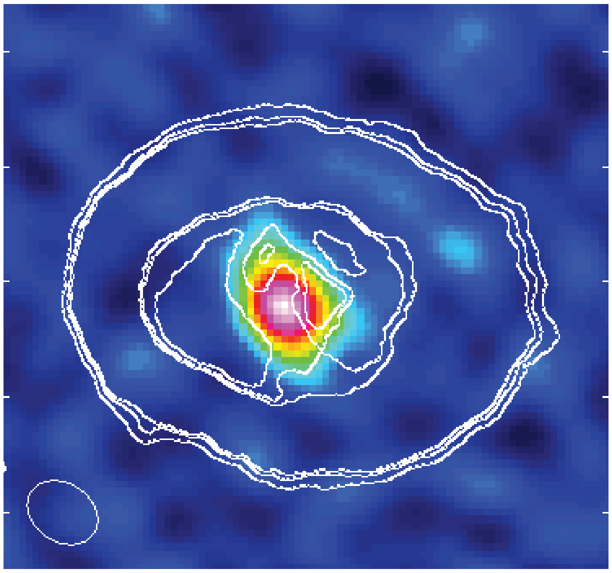

Figure 1. ALMA 450 μm image is indicated in the colour scale, overlaid with the Hα contour plot in white lines. The Hα contour traces the location of the ejecta at the centre, with circumstellar-ring around it. The 450 μm thermal dust emission is detected only from the ejecta, indicating that the cold dust has formed from SN ejected material. The original images were published by Indebetouw et al. (2014).

that the molecular mass gradually increases in time, while the gas in the ejecta cools down after the SN explosion (Sarangi & Cherchneff 2013).

4. Shocks

At longer wavelength bands, the ALMA detected synchrotron radiation from the ring. The synchrotron radiation arises from the shocked region, where the fast expanding SN waves are colliding with the slowly expanding dense circumstellar medium.

Zanardo et al. (2014) showed the comparison of the spatial distribution of the power indices from the synchrotron radiation at different frequency. The extract of the images are plotted in Figure 2. The left panel shows that at 44 GHz the power index has the peak at the west side of the ring, while the peak is slightly shifted to north-west at 213 GHz. Zanardo et al. (2014) suggested that the synchrotron lifetime is shorter at high frequencies.

5. Closing remark

The ALMA has found and will find new aspects of SN evolution. This includes recent delivery of cycle-2 data, which shows the dynamical evolution within the ejecta. The ALMA has opened an exciting window of SN research.

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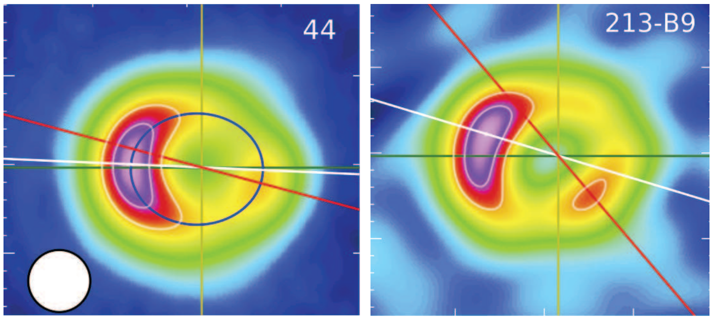

Figure 2. The spatial distribution of power indices of synchrotron radiation from the ATCA 44 GHz image (left panel), compared with that from ALMA 213 GHz image (right panel). The images taken from Zanardo et al. (2014).

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