Supernova 1987A:30 years later - Cosmic Rays and Nuclei from Supernovae and their aftermaths
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High-Resolution Observations of Dust in SN 1987A

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Abstract. The dust produced by supernovae is an important topic for understanding supernova physics and the chemical evolution of galaxies. Recent ALMA observations of SN 1987A have allowed us to peer into the inner ejecta to the cool dust, with spatial resolution from $0''.3$ at $\sim$300 GHz down to $0''.09$ at $\sim$680 GHz – an improvement over the previous 300 GHz Cycle 0 observations at $0''.69$. Comparison of the dust location and morphology with other multiwavelength emission presents an interesting picture of the role dust plays in the ejecta. The mm–FIR SED is compared to radiative models to study the dust composition 30 years after the initial explosion. Fits to the ring emission also probe the drift of the center of the system over time.

Keywords. dust, supernovae: individual (SN 1987A)

1. Introduction

The youngest known supernova (SN) remnant in the Milky Way Galaxy is G1.9+0.3, at roughly 100 years old (Reynolds et al. 2008). SN 1987A, located roughly 50 kpc away in the Large Magellanic Cloud, is the nearest supernova detected since then, and is the first supernova whose structure is able to be resolved with modern instrumentation less than 30 years after its initial explosion. Among many other areas in astrophysics, SN 1987A has made for an unprecedented target of study – new spatially resolved images of dust and molecules can reveal the chemistry resulting in SN dust formation.

Models in the literature predict that core-collapse supernovae (CCSN) can be an important source of dust in galaxies if they produce at least moderate (0.1–1.0 $M_\odot$) amounts of dust (Morgan & Edmunds 2003; Nozawa et al. 2003; Gomez et al. 2012b; Gall et al. 2014; Dwek & Cherchneff 2011). Likewise, CCSN could be a major source of interstellar medium (ISM) dust in general (e.g., Matsuura et al. 2009; Dwek & Cherchneff 2011). Low-metallicity galaxies also provide insight into the requirements for dust sources. Their typically low dust-to-gas ratios can at least partially be due to low condensation rates in the ISM; subsequently, dust from stars could be responsible for a significant amount of dust on short timescales (Zhukovska 2014).

These nearby dwarfs are often taken as analogues to early galaxies in the universe, but direct observations of high redshift galaxies are also important for piecing together the puzzle of dust formation across cosmic timescales. The so-called dust budget crisis (e.g., Morgan & Edmunds 2003; Rowlands et al. 2014b; Schaerer et al. 2015), similar to the case of low-Z dwarfs, highlights the need to be able to build up large amounts of dust relatively quickly. Sources beyond just AGB stars are needed to account for the dust observed, and supernovae such as SN 1987A are excellent candidates.

All of this leads to two big questions regarding the role of SN in dust production: How much dust do SNe really produce? And for matching any resolved observations to models, how is dust distributed in SN ejecta? The following work presents some developments in the effort to provide answers to these questions using new ALMA observations of SN 1987A.

2. History of Dust in SN 1987A

A brief history of the dust in SN 1987A is useful for context. From day 260–1316, the dust emission was dominated by mid-infrared (MIR) thermal emission (Bouchet et al. 1991; Wooden et al. 1993). During this time, $\sim 10^{-4}$ $M_{\odot}$ dust was inferred from the observed signal, presumed to be from the ejecta.

23 years later, between days 8467 and 8564, the dust had cooled down enough to be studied in the far-infrared (FIR). Thermal emission was detected with Herschel from 100–350 μm (Matsuura et al. 2011), where a quite massive quantity of 0.4–0.7 $M_{\odot}$ of dust was inferred. The dust emission was confirmed to originate in the ejecta by Indebetouw et al. (2014). This result raised questions, as the mass was quite a bit larger than those previously inferred from Spitzer MIR emission. However, Herschel observations of Cas A (Dunne et al. 2003, 2009; Barlow et al. 2010; De Looze et al. 2017) and the Crab Nebula (Gomez et al. 2012b; Owen & Barlow 2015) also showed high masses of $M > 0.1 M_{\odot}$.

More recently during day 9090 in 2012, fresh Herschel observations presented by Matsuura et al. (2015) confirmed SN 1987A's large mass of dust of around 0.8 $M_{\odot}$. The best model of the emission was comprised of 0.3 $M_{\odot}$ of amorphous carbons and 0.5 $M_{\odot}$ of silicates. Crucially, these new observations used the 70 μm band to constrain the lower wavelength end of the thermal distribution and show that the dust temperature was cool, with $T < 30$ K.

3. Preliminary Results

The Atacama Large Millimeter Array (ALMA) brings to bear a game-changing capability to observe targets such as SN 1987A in the FIR to sub-millimeter. A full discussion of our observations, reduction, analysis, and implications is provided in our forthcoming paper (Cigan *et al., in preparation*). The new ALMA observations in bands 7 (275–373 GHz) and 9 (602–720 GHz) give spatial maps at $0.''3$ and $0.''09$ resolution, respectively. This is an improvement over the previous Cycle-0 ALMA maps at $0.''69$ resolution presented by Indebetouw et al. (2014).

Qualitatively, the ring is visible in the ALMA submm windows in synchrotron radiation, while the ejecta follows a thermal greybody profile. The dust emission peaks near the notable gap in the optical *HST* map (Fransson et al. 2015). Figure 1 shows the SN 1987A 315 GHz image in comparison to several other wavelength bands.

Integrating the signal in each continuum window, it is possible to build spectral energy distributions (SEDs) for the separate ring and ejecta components. Unfortunately, the ALMA bands only cover the Rayleigh-Jeans tail of a cool thermal distribution, so modified blackbody fits would be relatively unconstrained. However, we can utilize the recent Herschel flux densities fromMatsuura et al. (2015) as upper limits to the current SED (not as fully-weighted data points) and therefore constrain the fits. See Figure 2 for the integrated flux densities in the ring and ejecta. As an initial analysis of the ejecta dust, we fit a single modified blackbody function to the integrated ALMA ejecta flux densities. We use $\kappa_{850} = 0.07$ m^2 kg-1 from James et al. (2002) for the absorption coefficient. The maximum likelihood estimation (MLE) fit yields a dust mass of 0.82 ± 0.40 $M_{\odot}$, consistent with the previous findings of a large dust mass in the system. The integrated fitted dust profile is also cool, at 22.8 ± 5.0 K.

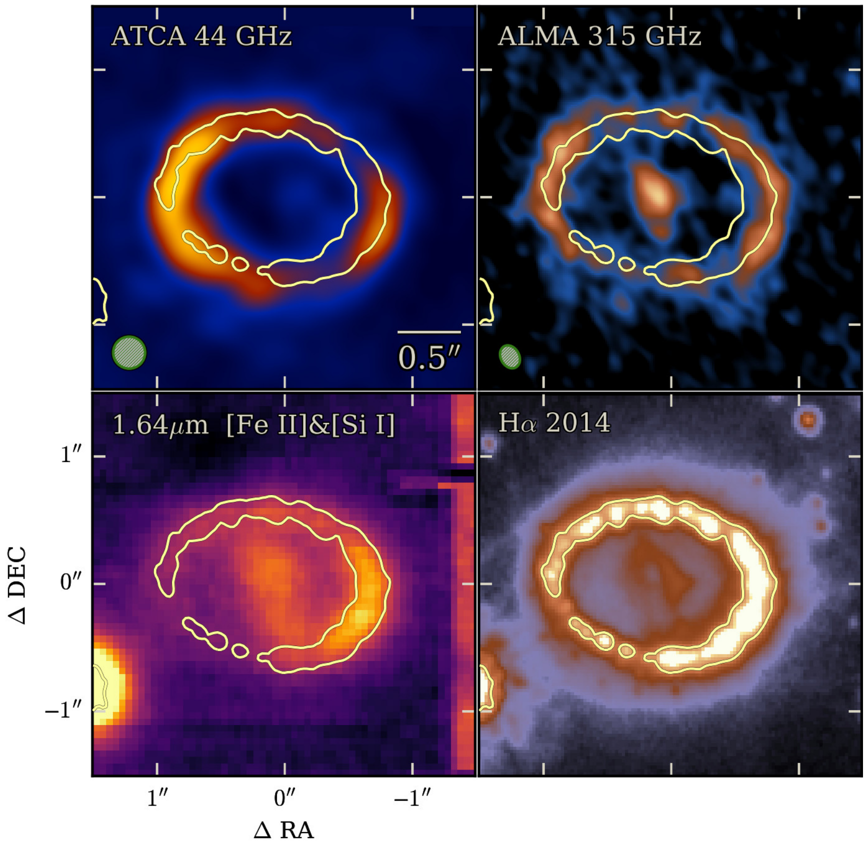

Figure 1. Multi-wavelength view of SN 1987A: ATCA 44 GHz (Zanardo et al. 2013), ALMA 315 GHz (this work), 1.64 μm [Fe II]&[Si I] (Fransson et al. 2016), and Hα (Fransson et al. 2015). The yellow contours trace the optical ring emission.

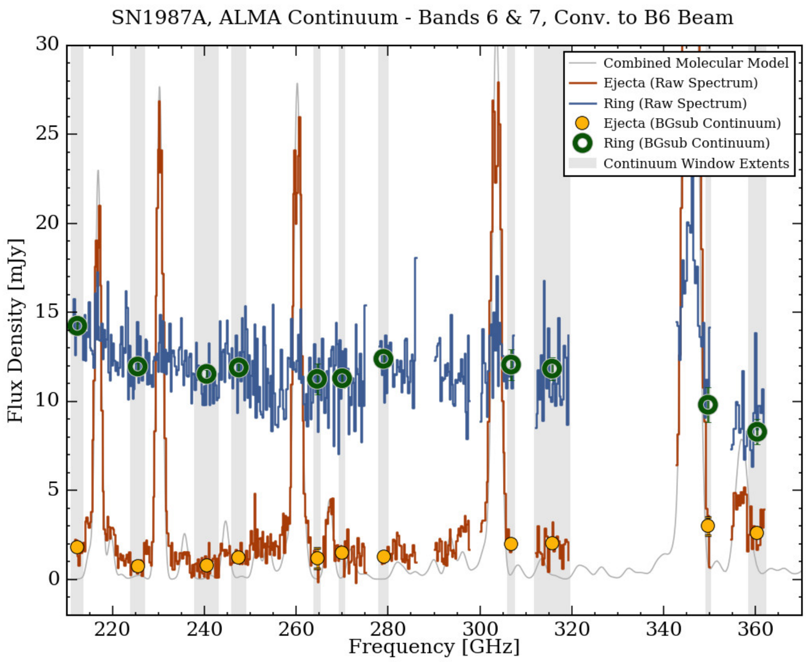

Figure 2. Raw (without background subtraction) band 6–7 spectra and integrated continuum flux densities in the ring and ejecta. Continuum windows selected to be relatively free of emission based on molecular models from Matsuura et al. (2017).

4. Conclusions

These new results confirm the previous findings of Matsuura et al. (2015) that SN 1987A has created a large amount of dust, $\sim$0.8 $M_\odot$, within 30 years of its initial explosion. This lends evidence to the picture of CCSN being able to provide large amounts of dust in the ISM on short timescales. However, it should be noted that this is not the final word, as this will almost certainly not be the final yield of dust into the ISM from this object – that will depend on exactly how much ejecta dust is destroyed by the reverse shock, among other factors. Further monitoring and models will be required to verify the final dust yield. A spatially-resolved study of the thermal profiles in the ejecta is required for comparison with detailed models of the chemical evolution. We provide this spatially-resolved treatment in our second forthcoming paper, where we also compare the resolved dust emission to several molecular species from Abellán et al. (2017).

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