HIGH-RESOLUTION OBSERVATIONS OF DUST IN SN1987A

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With the ALMA SN1987A Collaboration

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ABSTRACT

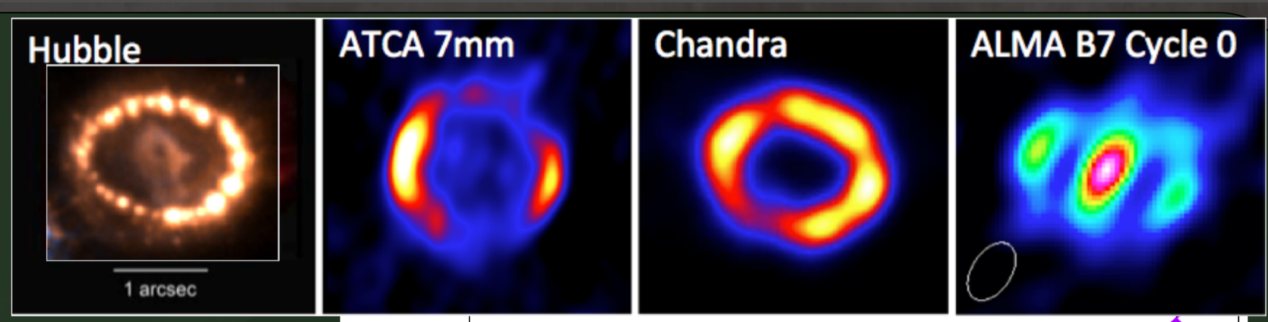
Interstellar dust is important for a variety of fundamental astrophysical processes and yet the origin of this dust is not particularly well-constrained. Dust can form in the envelopes of evolved stars, but not efficiently enough to overcome destruction rates and yield the abundances observed in our galaxy. Supernovae, which dominate the mechanical evolution of the ISM, can help balance the dust production budget. SN1987A, being relatively young as well as the brightest supernova observed in over 400 years, is a unique and exciting laboratory for studying supernova ejecta dust production. We have obtained new high-resolution observations of the continuum emission from the SN1987A system with ALMA, which we present here. We analyze the location and morphology of the dust, and compare with resolved emission at different wavelengths. In the future, we will use the relative distributions of dust and molecular species such as CO and SiO to help determine the dust composition and constrain the physics of supernova dust formation.

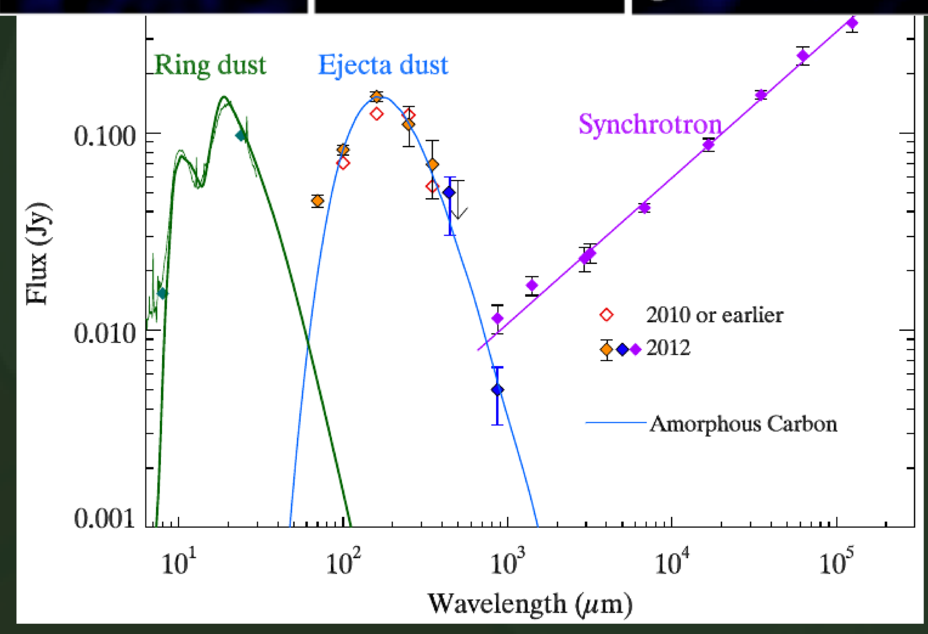
MOTIVATION

Dust is a crucial component of the ISM: among much else, it can effectively sequester much of the metal content of a galaxy and release it upon destruction for future generations of star formation, directly affecting ISM evolution. Supernovae - major drivers of change in the ISM - are also an important source of dust (Indebetouw+2014, Matsuura+2011,2015). SN 1987A, due to its youth and proximity, is an excellent laboratory for studying the relation between SNe and dust.

ALMA Cycle 0 observations (Indebetouw+2014) directly imaged a large mass of dust located within the central region with roughly spherical distribtution. Their observations agreed with Matsuura et al. (2011,2015) who proposed ~0.45M$_\odot$ of dust in the ejecta at T=23K. However, the baselines available then were not long enough to resolve the structure within the ejecta or ring. With our new 2015 observations, we can finally start to push down to the scale of the clumpy dust distribution. This work is intended as a first look at the morphology of the ring and ejecta as seen in the new data. We also utilize here our team's Cycle 1 Band 6 spectra (Matsuura+, in prep.).

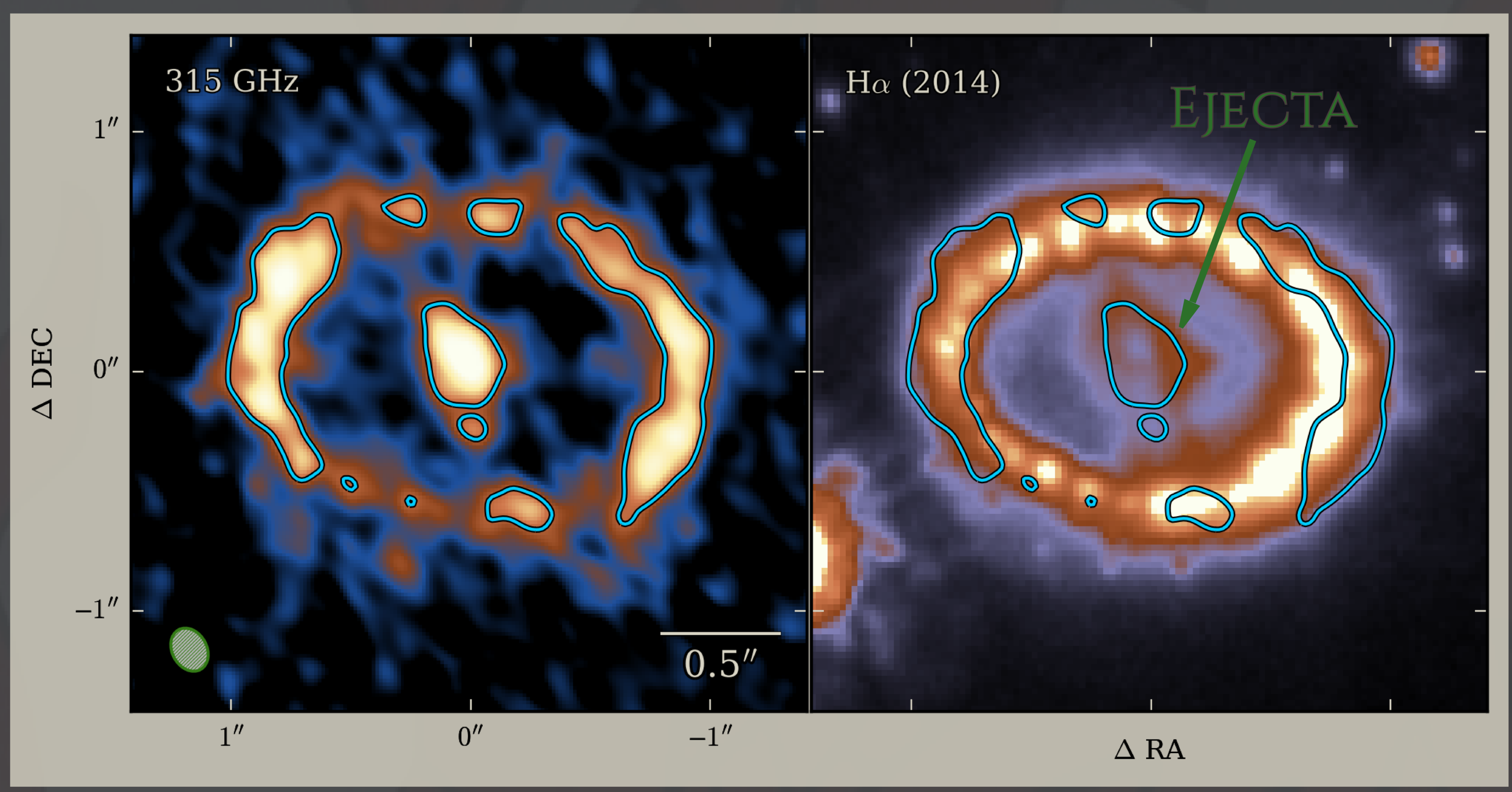
The optical imaging of SN 1987A clearly shows a distinct ring of circumstellar material (made bright in the submm as the shockwave accelerates electrons which produce synchrotron radiation, and bright in the IR due to shock heating of pre-existing dust swept up by the blast wave) and an inner ejecta component (the expanding remnant of the star's metal-rich core). The ejecta emission has a complex structure, somewhat resembling an old-fashioned keyhole in the HST images.





Top: SN 1987A over many wavelengths. Credits: STScI-2011-21, Zanardo+2014, Helder+2013, Indebetouw+2014
Bottom: SED of SN 1987A (image: Matsuura+2015) from ATCA mm (Zanardo+2014) and unresolved PACS and SPIRE observations.

OBSERVATIONS



Above: ALMA 315 GHz Continuum, compared with HST (F625W filter, which includes Hα emission). ALMA images used here were produced with natural weighting, to optimize flux recovery. Contours represent the 315 GHz 0.2mJy/beam level. Hα: Fransson+2015

The Cycle 2 ALMA observations were taken in the second half of 2015, in bands 7 and 9. The data were reduced in CASA with extensive checks on astrometry and flux/phase calibration. Final images were CLEANed with natrural weighting to optimize sensitivity. Continuum windows centered at roughly 307, 315, 350, 360, and 679 GHz were defined to exclude molecular line contamination. When the submm continuum emission is compared to other wavelengths, such as optical/Hα, several notable traits about the dust morphology become apparent.

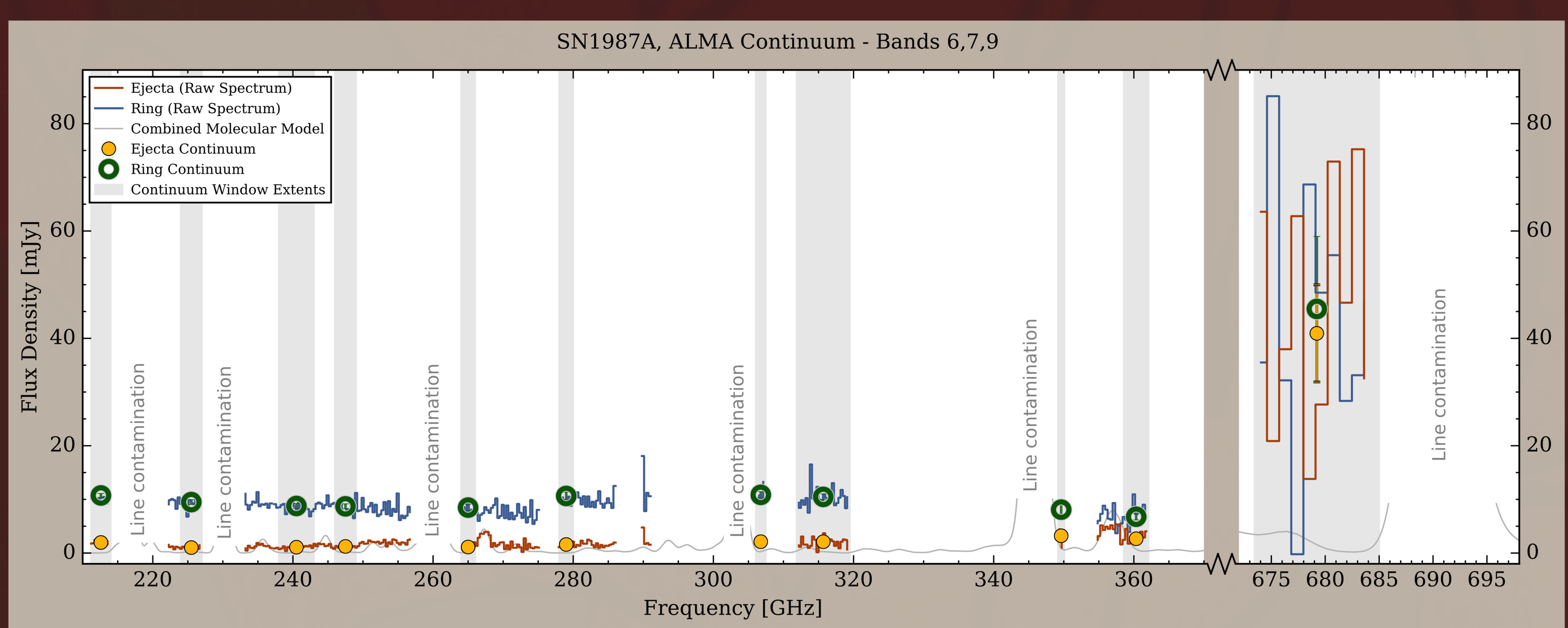
EJECTA

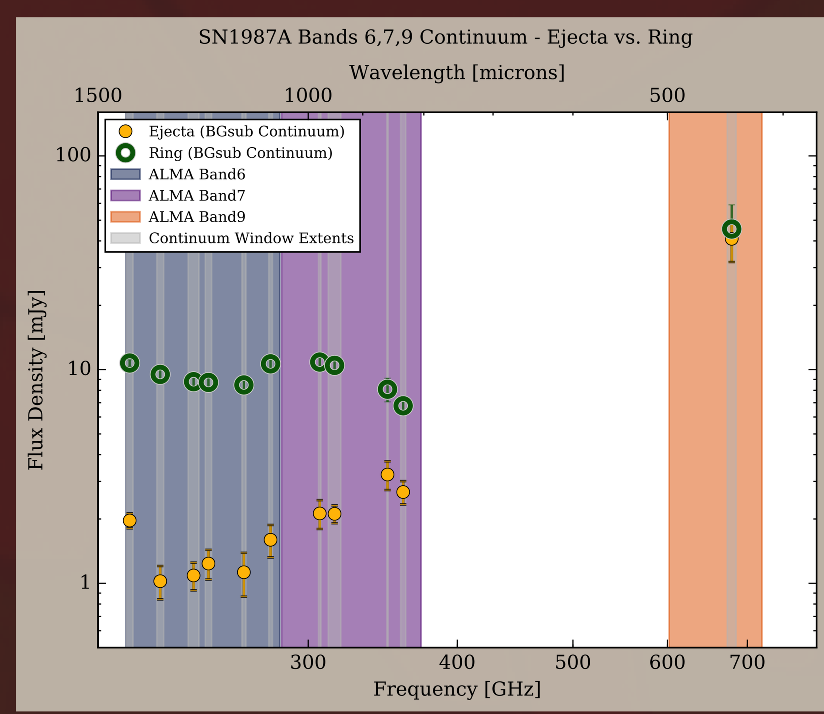
The majority of the submm ejecta continuum comes from a roughly symmetrical ellipsoid, with fainter asymmetrical emission protruding W and S. There is a conspicuously separate clump of emission south of the main body, seen most clearly in wide windows: at 315 and 679 GHz. Both the primary ejecta material and the smaller clump appear to fill in the gaps seen in the optical, like a 'lock in the keyhole'. Since the ejecta continuum is primarily thermal emission (see below), we are seeing cool dust produced in the supernova ejecta, less than 30 years after the explosion (c.f. Matsuura+2015).

RING

The submm continuum mirrors the basic properties of the optical: within the overall torus shape, there are several brighter clumps of emission. The far eastern and western slices of the shell are the brightest components, the latter of which is particularly pronounced in the most recent Hα image. Most of the ring continuum is due to synchrotron (see below), with a component of warmer (T~134K) silicate dust (Bouchet+2006 and Matsuura+2015).

ANALYSIS





Left: Continuum spectra over ALMA bands 6,7,9, with molecular line intensity models
Right: Continuum flux densities in the ejecta and ring

Continuum levels were estimated in windows with no molecular line contamination, according to the models of Matsuura et al. (in prep.). For simplicity, the same spectral windows were used for the ejecta and ring. Uncertainties (~15%) were calculated as a quadratic sum of the background level and aperture uncertainties. The aperture uncertainty is a measure of the variation in the integrated emission due to the aperture's properties. This was estimated empirically as the standard deviation of integrated flux from identical source apertures placed in many random off-source regions of the image.

The three physical mechanisms primarily responsible for emission in this region of the spectrum are thermal (greybody; ~IR) emission, nonthermal (synchrotron; ~radio/mm) emission due to relativistic electrons accelerating in magnetic fields, and a lesser contribution from free-free (Bremsstrahlung; ~mm/submm) emission from hot ionized material. See Zanardo+2014 for a detailed discussion of these components including ATCA and ALMA Cycle 0 data.

The new ALMA data show the ejecta are primarily emitting thermal (dust) radiation, all the way into the mm (confirming the result of Indebetouw+2014). The ring emission, on the other hand, is primarily characterized by synchrotron emission, roughly consistent with the spectral index of -0.8 seen previously, though the continuum at 679 GHz is higher than predicted.

We can also estimate the average expansion velocity of the ejecta dust by simple geometry: $v_{avg} = \Delta x \,/\, \Delta t$. The ALMA observations occurred 10,352 days after the initial explosion. The majority of the continuum in the ejecta (excluding the southern clump) can be approximated as an ellipse with semimajor axes of roughly 0.24″ and 0.16″, with a 115° PA. Assuming a distance of 50kpc, the physical extent is 0.116 × 0.078 pc (diameter), yielding v_{avg} = 1338 km/s on the minor axis, and 2008 km/s on the major axis. If the southern clump is also included in the major axis, v_{avg} = 2510 km/s.

DISCUSSION

These results are of note:

- The velocity derived from the physical extent matches the previously observed spectral line width of ~2000 km/s
- The general picture from the ALMA Cycle 2 observations suggests that the expanding volume of dust is just interior to the optical shell. That is, trailing the initial ejecta shell.
- One curious feature in the ring continuum is a 'bump' or local enhancement spanning ~280-350 GHz - much too wide to be due to line emission, and too narrow for standard power law emission. Peaking around 1000μm, this is too cool to be a cold dust component.

FUTURE WORK:

- We will fit the ring and ejecta components to determine the dust properties
- Create resolved spatial *maps* of ring and ejecta properties such as spectral indices
- Spatial comparison of dust and molecular emission, to study the production and mixing of dust

ACKNOWLEDGEMENTS

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