DOI: doi.org/10.18727/0722-6691/5005

Supernova 1987A at 30

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Thirty years on, SN 1987A continues to develop and, over the last decade in particular, has: revealed the presence of a large centrally concentrated reservoir of dust; shown the presence of molecular species within the ejecta; expanded such that the ejecta structure is angularly resolved; begun the destruction of the circumstellar ring and transitioned to being dominated by energy sources external to the ejecta. We are participating in a live experiment in the creation of a supernova remnant and here the recent progress is briefly overviewed. Exciting developments can be expected as the ejecta and the reverse shock continue their interaction, the X-rays penetrate into the cold molecular core and we observe the return of the material into the interstellar medium. We anticipate that the nature of the remnant of the leptonisation event in the centre will also be revealed.

In the preface to the first SN 1987A conference thirty years ago (Danziger, 1987), Lodewijk Woltjer, then Director General of ESO, welcomed the participants with the prescient statement “It is very well possible that […] SN 1987A will remain observable for thousands of years to come.”

Introduction

If an observational astronomer was allowed to pick the parameters of the object of study, then ideally the angular size would be matched to the resolution of the telescope, the dimensions of the physical processes would be matched to the angular size and the variability matched to the proposal cycles for telescope time. If, in addition, the physics ranged across astroparticles and all wavelengths of the electromagnetic spectrum, then one might consider one had found the perfect source.

SN 1987A is just such a heavenly object! That it is circumpolar for the more southern astronomical sites adds to its optimality. Located in the Large Magellanic Cloud (LMC), it is near enough to be resolved, yet far enough to not be a threat, along an almost unextinguished line of sight, in a relatively uncluttered part of its host galaxy. It is evolving on a human timescale. Many articles on 1987A have appeared in the pages of The Messenger over the years and therefore we will not dwell here on the past but rather focus on the current state and ponder an exciting future. A comprehensive review (McCray & Fransson, 2016) appeared recently and covers SN 1987A over the past 10 000 days.

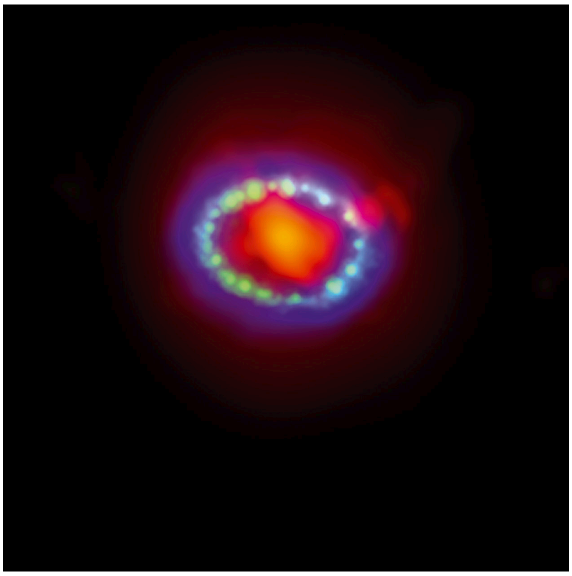
Despite fading by seven orders of magnitude from its peak, the supernova and its surroundings remain readily observable. Lengthy exposure times are still necessary to study the details and, critically, the timescales over which the supernova changes remain of order half a year (approximately the light travel time of the ejecta at this epoch); therefore continued vigilance is needed. ESO, together with the Hubble Space Telescope (HST) and the Australia Telescope Compact Array (ATCA), are the sole observatories that, thanks to the evolution of their observing capabilities, have provided the necessary continuous ultraviolet/optical/near-infrared/radio coverage of the supernova, and fortunately the fireworks are still continuing. Together with similar monitoring by the Chandra and X-ray Multi-Mirror Mission (XMM-Newton) space telescopes in X-rays, these facilities have provided a nearly complete multi-wavelength coverage of the development of the supernova. These telescopes are providing a legacy dataset for this object that cannot be repeated.

The progenitor star (Sanduleak –69°202) of SN 1987A cleared a volume around itself, sweeping-up material blown off in earlier evolutionary stages (about 8000 years ago) into an hour-glass structure dominated by an equatorial ring. This structure, first observed with the New Technology Telescope (NTT) in 1989, and made famous by HST, Chandra and ATCA images (see Figure 1, left), is readily visible in images from NAOS-CONICA (NACO), and the Spectrograph for INtegral Field Observations in the Near-Infrared (SINFONI) as well (Larsson et al., 2016). Figure 1 right shows a very recent NACO image at 2.15 μm (*Ks*-band). The flux in the *Ks*-band is dominated by Brackett-γ emission at 2.165 μm illuminated from the outside. The illumination of the ring at the earliest times, by the ultraviolet (UV) light emerging as the shock broke the surface of the progenitor star, was used to determine a geometric distance to the LMC and remains one of the anchors of the extra-galactic distance ladder. The ring illumination also provided the first evidence of the radiation from the shock break-out, lasting only a few minutes but with a temperature of about a million degrees.

Later, when the fastest ejecta, moving at ~10 % of the speed of light, reached the ring, the shocked gas emitted brightly at wavelengths from radio to X-ray. Recently, observations from HST have been used to show that the ring is beginning to suffer from the effects of the ejecta colliding into it (Fransson et al., 2015). It will take a while, but the ring is currently being destroyed. A simple extrapolation estimates this process will be complete by ~2025. However, new spots of emission outside the ring have appeared and continued observations may yet provide surprises about the surrounding structure. We get to watch in real time as a shock wave with well-defined characteristics impinges on a well-understood structure (both in density and composition); a text book illustration of shock theory.

Radioactivities

Inside the ejecta, radioactive species freshly synthesised in the explosion provide gamma rays and energetic positrons that deposit their energy into the ejecta, provided they do not escape. Which isotopes are present, and how much of each, are critical to our understanding of the emerging spectrum. The isotope mix also places limits on the mass cut (the mass coordinate in the proto-neutron star where the ejection starts and the collapse ends) and provides a measure of the



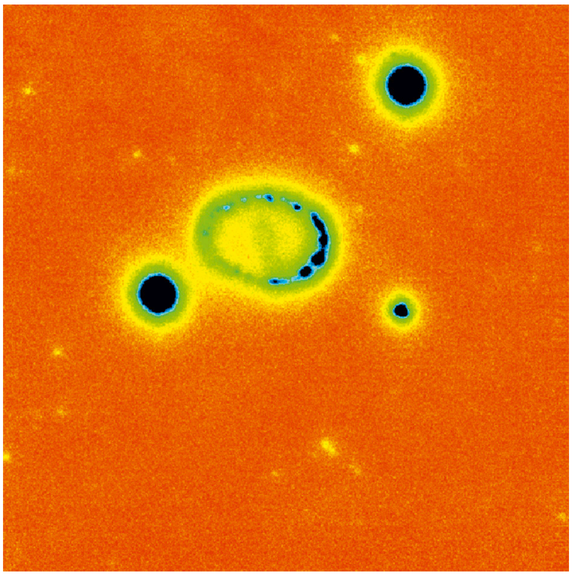


Figure 1. Left: combined HST (green), Chandra (blue) and ALMA (red) image of SN 1987A. Right: NACO data taken in January 2017 in the *Ks*-band. The ejecta emission in the centre of the ring is well resolved in both images; the short axis of the ring projects to 1 arcsecond on the sky. The west side of the ring can now be seen to be significantly brighter than the east side.

nucleosynthetic yield of the supernova. The presence of ^{56}Ni (source of ^{56}Fe) had long been confirmed in SN 1987A, as had ^{57}Co. Theory predicted that ^{44}Ti should also be made in the explosion of supernovae. Combining Very Large Telescope (VLT) and HST spectra with time-dependent non-local thermodynamic equilibrium (LTE) radiative transfer calculations, it was determined that ^{44}Ti had taken the role of key energy supplier to the supernova eight years after the explosion (Jerkstrand et al., 2011).

It was consequently exciting to see both the Nuclear Spectroscopic Telescope ARray (NuSTAR) detection (Boggs et al., 2015) and the INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) detection by Grebenev et al. (2012) of hard X-ray lines from ^{44}Ti. Observations with SINFONI (Kjaer et al., 2010; Larsson et al., 2016) and HST (Larsson et al., 2011) have revealed a complex structure of emission from atomic species that, in some cases, are collocated with the radioactive species and in others are illuminated by external sources. In particular, the SINFONI observation of the 1.644 μm [Si I] + [Fe II] line gives a three-dimensional view of the ^{44}Ti distribution in the ejecta, responsible for powering the inner core. This distribution is one of the main diagnostics of the explosion dynamics during the first seconds.

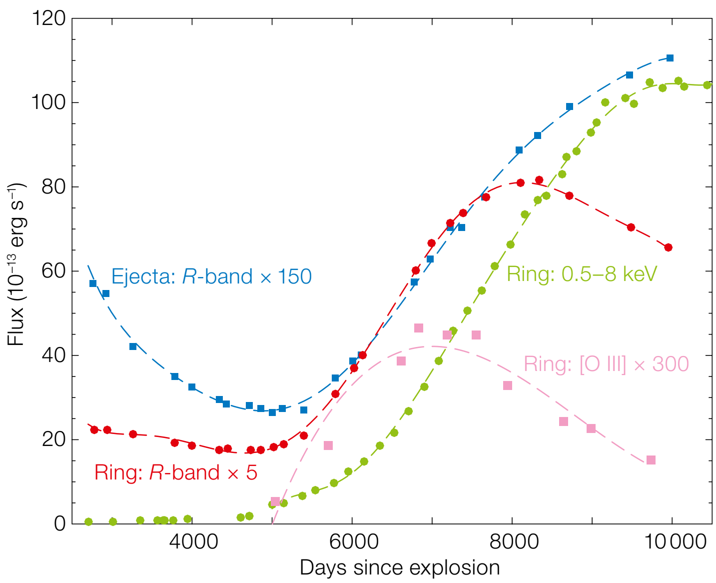


Figure 2. The light curve of the supernova over the past 5000 days. Different components and wavelengths are identified. The dimming of the ring in optical emission and the brightening of the emission from the ejecta, consequent on the input of energy from the reverse shock, are evident.

Shocks

While the forward shock moves through the ring, slowing down the ejecta and accelerating the ring material, the reverse shock is formed by the supernova ejecta hitting the decelerated medium behind the forward shock. The reverse shock is formed in successfully slower and denser regions in the supernova ejecta.

The supernova ejecta are being exposed from the outside to X-rays from the ring interaction and at some point during the supernova's teenage years the dominant source of energy became the conversion of kinetic energy from the supernova ejecta with the surroundings. Quite elegantly, just as the radioactive elements whose decay had powered the emission of the junior supernova exponentially decreased, the X-rays from the interaction with the inner ring provided the energy for an outside-in look at the ejecta. These X-rays are mainly absorbed in the hydrogen rich envelope and the metal core is still powered by decay of ^{44}Ti.

The different emission sites (ionised but unshocked ring material, shocked ring gas, reverse shock, inner supernova ejecta) account for the vastly different velocities, and are easily separated in the

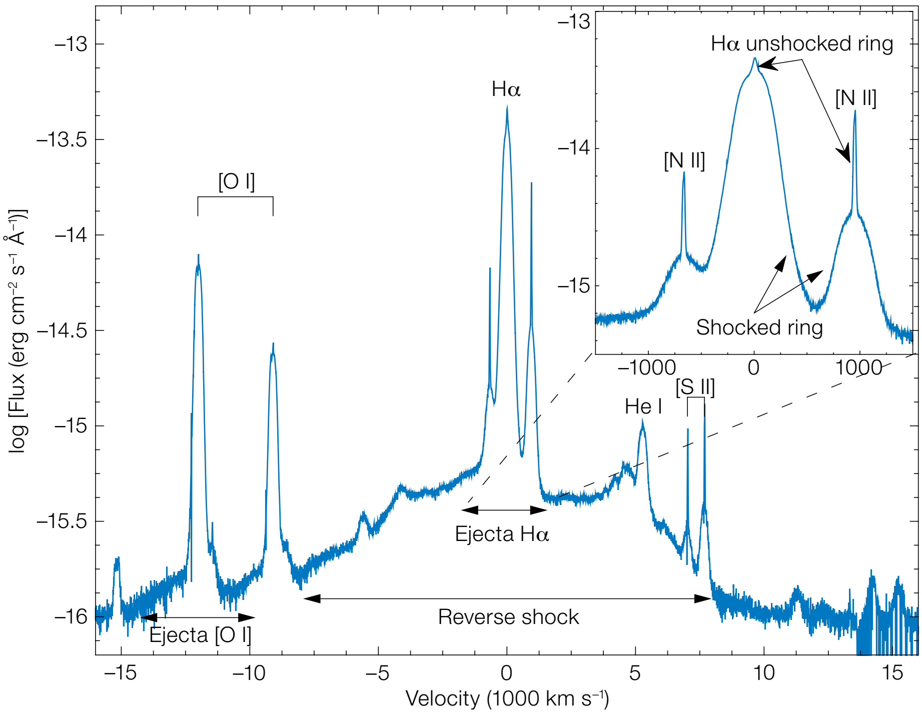


Figure 3. The UVES spectrum of SN 1987A around the Hα line in different zooms; spectrum taken in January 2012. The UVES slit covers the whole supernova, sampling the emission from all components; see text for details.

optical and infrared spectrum of the supernova. The UV-Visual Echelle Spectrograph (UVES) spectroscopy complements the HST imaging by providing separation of the different velocity components, and is perfectly suited both in wavelength coverage and resolution (see Figure 4 for the different velocity components in the Hα region). Spectra such as this have allowed us to follow the evolution of both the ring and ejecta emission continuously.

The dominant feature of the velocity profile from the whole supernova shown in Figure 4 is the ~500 km s^{-1} emission from the shocked ring, seen in Hα and the [N II] lines either side of it. The narrow feature on top of the broader profile is emission from the ionised ring gas at the systemic velocity of the supernova, +287 km s^{-1}. Over a range of 10 000 km s^{-1} and at a flux level less than 1 % of the peak of the ring emission, we see a strong box-like emission of Hα. This is emission from the supernova ejecta passing through the reverse shock. The emission from the inner core can be seen as the rising blue emission for velocities less than about 2500 km s^{-1}.

The ejecta continue to be observed across the optical and near-infrared spectral region. SINFONI with adaptive optics has been critical in providing a view of the near-infrared emission at a spatial resolution comparable to that of HST. This work has established the geometry of the emission in the lower ionisation lines of [Fe II] and [Si I]. These "core" elements play a critical role in cooling the ejecta while at the same time tracing the radioactive energy deposition. However, the SINFONI data also provided us with the ability to find previously undetected molecular gas.

Before construction of the VLT had even been approved, the discovery of hot (2000 K) molecular emission (CO and SiO) from within the ejecta of 1987A initiated the discussion of supernova chemistry. Chemical models also predicted formation of molecular hydrogen (Culhane & McCray, 1995). H_2 is notoriously shy and challenging to detect in the part of the spectrum approaching the thermal infrared, and therefore it was a pleasant confirmation to detect the emission (Fransson et al., 2016) in SINFONI data some 20 years after the explosion. Except for its very presence, the fact that the observed distribution reaches almost to the centre means that hydrogen was mixed by the Rayleigh-Taylor instabilities shortly after the explosion, as predicted by explosion models (for example, Wongwathanarat et al., 2015).

Dust and molecules

As new facilities come online, SN 1987A is not only a natural target but also a

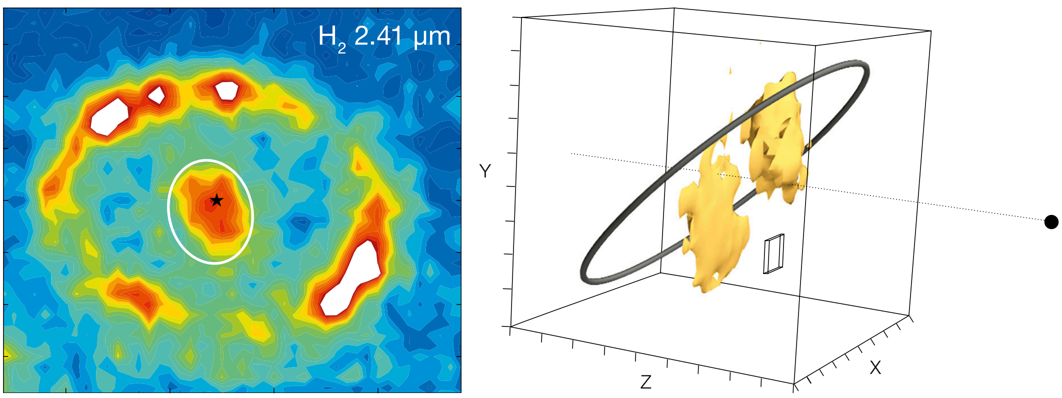


Figure 4. Left: SINFONI spectral image in the molecular hydrogen line at 2.40 µm (from Fransson et al., 2016). The bright ring is the continuum emission from the shocks and is not related to the molecular hydrogen in the inner ejecta. Right: 3D distribution of the 1.64 µm [Si I] + [Fe II] line from SINFONI. The ring is shown for reference and the tick marks on the box are at steps of 1000 km s^{-1}.

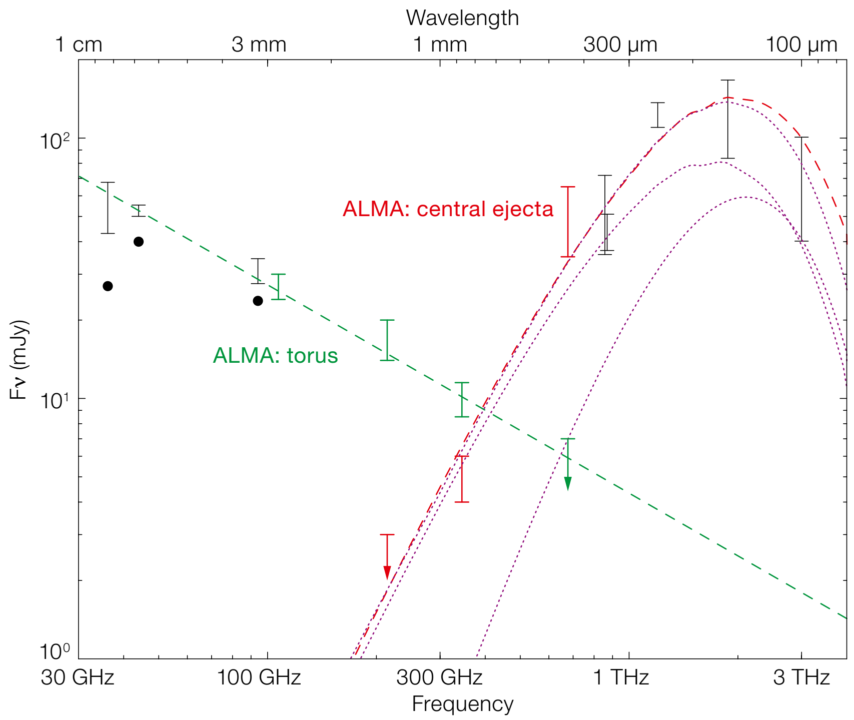


Figure 5. ALMA's angular resolution permits the separation of the continuum dust emission from the synchrotron power law radiation resulting from shocks in the ring. The measurements shortward of 400 μm are from Herschel (Matsuura et al., 2011) and APEX (Lakicevic et al., 2012) At low frequencies data come from ATCA (Potter et al., 2009; Zanardo et al., 2014). From Indebetouw et al. (2014).

source of new understanding. The Spitzer Space Telescope observed the supernova out to 30 μm and detected the presence of warm dust. Observations with the Gemini South telescope and the VLT in the 10 μm band showed that the thermal infrared emission comes from the equatorial ring. In 2010 the Herschel satellite observed the supernova in the far infrared and detected an enormous excess of emission longward of 100 μm (Matsuura et al., 2011). Contemporaneously, Lakićević et al. (2012) used APEX to detect emission from the supernova at 300 and 870 μm. Combining the flux with models of dust, Matsuura et al. (2011) concluded that between 0.1 and 1 $M_\odot$ of dust formed in the supernova.

Given the angular resolution of Spitzer and Herschel, the location of the cold dust remained uncertain. Observations in 2013 with ALMA at 1 mm and 450 μm at an angular resolution of ~ 0.5 arcseconds proved the unambiguous association of the cold dust with the inner ejecta of 1987A (Indebetouw et al., 2014; see Figure 5). The mass of the dust, however, remains "stubbornly high", above 0.5 $M_\odot$ (Matsuura et al., 2015). If the dust survives travelling through the reverse shock, then core-collapse supernovae may be a significant contributor to the dust budget in the early Universe.

The ALMA spectra provided further excitement in that, in addition to the dust observations, they revealed strong emission from CO 2–1 and SiO 5–4 transitions. Combined with a detection by Herschel of the CO 6–5 and 7–6 transitions, the temperature and mass determination could be refined by Kamenetzky et al. (2013). Approximately 0.01 $M_\odot$ of CO emits at a temperature of ~ 20 K and at an expansion velocity of 2000 km s^{-1}. It remains to be seen whether this is the same CO that was detected at 2000 K and 2000 km s^{-1} during the supernova's first year or represents new formation.

Fascinating new ALMA observations at high angular resolution are in the process of being published (Abellan et al., 2017, submitted). The cold CO and SiO in the centre of the supernova are seen to be separated into clumps. These are unique observations of the birth of a supernova remnant before the reverse shock disturbs the environment. We will need to remain vigilant to see whether the dust and molecules survive or are destroyed. Supernovae are certain to be prolific polluters of the early Universe in metals. Whether they also contribute dust and molecules to the mix, we will see in the experiment taking place before our telescopes.

The future

What can we expect for the future? The holy grail is certainly the nature of the compact object in the centre. The length of the neutrino burst indicated the formation of a neutron star, but with later fallback it is also possible that a black hole could have been formed. ATCA has been giving us a detailed view of the material around the supernova (Potter et al., 2009) and combining these radio data with ALMA mm/sub-mm data provides an interesting constraint set for the presence of a plerion, a region ionised by the strong magnetic field of the neutron star, in the centre of the remnant (Zanardo et al., 2014). Higher angular resolution observations with ALMA will help greatly.

From X-ray observations there is a strong upper limit to the luminosity in the 3–10 keV band of 3×10^{33} erg s^{-1} (Frank et al., 2016). The absorption of the X-rays by the ejecta may, however, still be large (Fransson & Chevalier, 1987; Orlando et al., 2015), although this decreases rapidly with the expansion of the ejecta. The clumpiness of the ejecta, as revealed by SINFONI and ALMA, is the main uncertainty. The optical/infrared may also provide an interesting window, since any absorbed X-rays may be reprocessed into this wavelength range. The infrared sensitivity of the James Webb Space Telescope (JWST) and the superior spatial resolution of the Extremely Large Telescope (ELT), will be especially exciting here. With the new and old facilities, we will, hopefully, during the coming decade reveal whether the leptonisation event that was responsible for the neutrinos ended in a neutron star or a black hole.

As for the ejecta and circumstellar medium, we are already seeing the decaying ring emission. The shock wave, however, continues out into the circumstellar medium beyond the ring, and will hopefully reveal more of the several solar masses of material thought to have been lost by the progenitor star. The mass of the ring is only ~ 0.06 $M_{\odot}$. The X-ray emission is expected to decay more slowly than the optical ring emission. It will therefore continue to illuminate more and more of the ejecta, and thus also give a new view of the abundance and hydrodynamic structure of the ejecta. The supernova will then gradually transform into a supernova remnant similar to other young remnants. We can follow this in real time for hundreds of years, perhaps longer, as suggested by Lo Woltjer. In all these aspects ESO can continue to play a leading role.

Ten years ago we were already musing about the future development of SN 1987A (Fransson et al., 2007). We predicted exciting events — the destruction of the inner ring and the illumination of material outside the ring. We were also hoping to find the compact remnant inside SN 1987A and hopefully other surprises. The ring has started to fade, indicating that it will be destroyed in the near future, and the first traces of material beyond the ring have also been found. The neutron star has so far defied detection.

There have indeed also been great surprises. Tracing the explosion mechanism by directly observing the geometry of the element distribution in the inner ejecta confirms the non-spherical explosion models. The illumination of the inner ejecta by X-rays from the ring is a new feature in the development of SN 1987A. It provides a novel and unexpected window on parts of the ejecta that have so far been unobservable. The molecules in the inner ejecta were predicted early on and have finally been found. ALMA, with its first observations, together with Spitzer and Herschel, have told us more about the dust in SN 1987A than we could have guessed two decades ago. The reverse shock has been firmly observed and adds another important aspect to the evolution of the supernova.

Acknowledgements

It is a pleasure to thank all the staff at the various observatories and in particular those involved in the Paranal and ALMA operations, both in preparing the observations in Garching and in executing them on the sites. They have all contributed through their expertise and enthusiasm to generating this beautiful and unique data set. We also want to thank the time allocation committees over the decades who have recognised the uniqueness of the supernova and have supported this research.

The authors thank the current editor, himself a naked eye observer of SN 1987A, for improving the article and wish the next editor a Galactic supernova for herself.

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A wide-field image (about 4 degrees in extent) of the Large Magellanic Cloud and 30 Doradus taken by the ESO 1-metre Schmidt telescope in 1986, before the appearance of SN 1987A.