SN 1987A at the end of its second decade

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Abstract. After nearly two decades at least five emission mechanisms can be found in SN 1987A. The ejecta continue to glow as a result of the radioactive decay of long-lived nuclei (mostly $^{44}$Ti), but is fading continuously because of the expansion and the reduced opacity. The nearly stationary rings around SN 1987A are still fluorescing from the recombination of matter originally excited by the soft X-ray emission from the shock breakout at explosion. The supernova shock reached the inner circumstellar ring about ten years ago and the forward shock is moving through the inner ring and leaves shocked material behind. This material is excited and accelerated. The reverse shock illuminates the fast-moving supernova ejecta as it catches up. And, finally light echoes in nearby interstellar matter can still be observed. We present here high resolution spectroscopy in the optical and integral-field spectroscopy in the near infrared of SN 1987A and its rings.

Keywords: Astronomical observations (SN 1987A); Supernovae; Supernova remnants

PACS: 95.85.-e; 95.85.Kr; 95.85.Jq; 97.60.Bw; 98.38.Mz

INTRODUCTION

Monitoring the evolution of a supernova beyond a few years is very rare. Only a handful of objects have been observable for longer than a year or two (Leibundgut 1994, Weiler et al. 2002). The clear exception to the rule is SN 1987A, for which a continuous observational record since its explosion exists (Arnett et al. 1989, McCray 1993, 2005). It has been observed in nearly all wavelengths and with the shock now reaching the circumstellar rings is starting to increase in luminosity again in the radio (Manchester et al. 2005), X-rays (Park et al. 2004, 2005, 2006) and the optical (Michael et al. 2000, 2002, Pun et al. 2002).

The collision of the ejecta of SN 1987A with its circumstellar ring is creating a series of emission sites in addition to the glow of the ejecta, the fluorescence of the ring (Fransson et al. 1989, Jakobsen et al. 1991, Panagia et al. 1991) and light echoes (e.g. Newman & Rest 2006). Emission from the ring collision has been observed in the radio (Gaensler et al. 1997, Manchester et al. 2005), in X-rays (Park et al. 2004, 2005, 2006) and the optical (Michael et al. 2000, 2002, Pun et al. 2002).

High spatial resolution imaging and high resolution spectroscopy are the tools of choice for further investigations of SN 1987A. Imaging with HST continues regularly (Sugerman et al. 2002) and we have been following the emergence of the emission lines from the shocked material and the reverse shock with the VLT (Gröningsson et al. 2006, 2007, Kjær et al. 2007).

The extended nature of the ring (and by now the ejecta) limits slit spectroscopy to individual regions of the ring (cf. Figure 1). Hence we had to compromise by placing the slit for the high-resolution spectroscopy across the ejecta and spot 1 (Michael et
FIGURE 1. SN 1987A with its inner circumstellar ring as seen in the K-band by SINFONI at the VLT. The nearby unrelated stars 2 and 3 are marked.

al. 2000). With an integral field unit, it is now possible to measure the ring and the supernova ejecta without losses and to reconstruct the ring emission in individual lines (Kjær et al. 2007). It allows us to cleanly separate the ejecta from the ring as well.

**CORONAL EMISSION FROM THE SHOCKED CIRCUMSTELLAR RING**

We have monitored SN 1987A with a resolution of 40-50,000 since October 1999 using the Ultraviolet and Visual Echelle Spectrograph (UVES) at the ESO/VLT (Gröningsson et al. 2006, 2007). Fig. 2 shows a spectrum from 2002 around the Hα line. The spectrum consists of three different components described above. The narrow lines (FWHM $\sim 10$ km s$^{-1}$) are from the unshocked, fluorescing ring material, the broader lines (FWHM $\sim 250$ km s$^{-1}$) stem from the shocked ring and the very wide component (FWZI $\sim 15000$ km s$^{-1}$) is the signature of the reverse shock, i.e. material in the supernova ejecta. These three components can clearly be distinguished.

The reverse shock has been discussed in detail by Michael et al. (2002), Smith et al. (2005) and Heng et al. (2006). The excitation of Hα is uncertain, but charge exchange is a likely mechanism. The shock emission continues to increase, but it is possible that the hydrogen atoms will be ionised by emission from the forward shock before the reverse shock reaches it and the Hα emission from the reverse shock may stop (Smith et al. 2005, Heng et al. 2006).

In Fig. 3 we display a compilation of line profiles from the intermediate velocity component, where we have removed the narrow lines as well as blends with other lines. The lines from the intermediate velocity component show asymmetric line profiles extending to FWHM $\sim 300$ km s$^{-1}$. There are about 190 lines, among which roughly 160 from the intermediate-velocity component, in the spectrum from 310 nm to 1000 nm identified in our spectra (Gröningsson et al. 2007). Several of these lines are coming
The region around Hα for SN 1987A 5704 days after explosion. The velocity scale is centred on Hα. Note the very broad component originating in the reverse shock, extending to ∼15,000 km s$^{-1}$. Superimposed on this are the narrow (FWHM ∼ 10 km s$^{-1}$) and intermediate (FWHM ∼ 300 km s$^{-1}$) velocity components, coming from the unshocked and shocked ring material, respectively. In addition several other low and intermediate ionisation lines, as well as the coronal [Fe X], are visible.

from highly ionised atoms, in particular [Fe X], [Fe XI], [Fe XIV], [Ne V] and [Ar V]. These arise in the collisionally ionised gas behind the shock propagating into the dense protrusions of the ring. In Gröningsson et al. (2006) we presented a detailed analysis of the coronal lines and derived the temperature required for their formation. The gas must be heated to about 2 · 10$^6$ K, corresponding to a shock velocity of ∼350 km s$^{-1}$. The fact that also lines of low ionisation ions, like O I-III and Fe II, are seen shows that most of the emission is coming from radiative shocks. We can, however, not exclude that some of the emission in the coronal lines of FeX–XIV arise from shocks which have not had time to cool yet. This is indicated by the larger blue extent of these lines (Fig. 3).

According to the radiative shock model of Gröningsson et al. (2006) the [Fe XIII] $\lambda$ 1.075 line should be observable in emission. We indeed could confirm this line in emission in our ISAAC observations.

A comparison of the evolution of the line fluxes and the X-ray emission reveals an interesting correlation. The line fluxes of the coronal Fe lines increased exactly like the soft X-ray (0.5–2 keV) emission as measured by Chandra (Park et al. 2005; Fig. 4).
FIGURE 3. Compilation of line profiles from the intermediate velocity component from day 5702 to 5705 after explosion. The narrow component, as well as other blends, have been subtracted. Note the larger blue extent of the coronal lines compared to the low and intermediate ionisation lines (from Gröningsson et al. 2006).

FIGURE 4. Flux evolution of the coronal lines as measured in optical spectroscopy (left) and the flux increase of the X-ray emission from SN 1987A (Park et al. 2005). The fluxes have been normalised to the ones observed in October 2002 (see Gröningsson et al. 2006 for more details).

This, together with similar shock velocities required to produce the coronal lines, led Gröningsson et al. (2006) to argue that the coronal lines form in the same region as the soft X-rays. The coronal lines therefore offer a complementary view to the X-rays of the shock interaction. In this respect the high resolution spectrum of Chandra (Zhekov et al. 2005) is especially interesting, showing lines from, e.g., Fe XVII.

INFRARED EMISSION LINES

Using early Science Verification data of SINFONI, the infrared integral-field spectrograph at the VLT (Gillesen et al. 2006), we obtained J, H and K data cubes of SN 1987A and its inner ring 6490 days after explosion. With these data we can determine the in-
tegrated emission of the complete ring or trace the spatial extent of individual emission lines around the ring. In addition, we can cleanly separate the ejecta from the ring emission, although the spectral resolution was not sufficient to separate the narrow and intermediate components. In Fig. 5 we show the K-band spectrum of the integrated ring. He I $\lambda$2.06 and Br$\gamma$ are the most prominent lines, but there are several [Fe II] lines in the near-IR spectrum (see Kjær et al. 2007 for a detailed list).

Previously, the best NIR spectrum from the AAT (Fassia et al. 2002) is of much lower spectral resolution than the SINFONI one. The ejecta and ring contributions could therefore not be resolved. It also is a further combination of supernova ejecta and circumstellar ring, although it can be expected that the line emission from the ring did dominate. The SINFONI spectrum is an integration of the ring emission, excluding the central part. The two spectra are displayed in Fig. 5.

Due to the higher spectral resolution the narrow He I and Br$\gamma$ lines appear to have a higher central intensity than some 14 years before. Part of this is due to the fact that the earlier spectroscopy could not resolve the narrow lines. However, as is seen in the optical UVES spectrum the flux in the intermediate velocity component – and both these strong lines should have a contribution from this component – has increased in flux. Many other lines have appeared in the SINFONI spectrum. Almost all of them are forbidden transitions of Fe II. However, we also tentatively identify Na I, O I and Ni II lines in this spectrum. The situation in the other IR bands is similar with several new identifications (Kjær et al. 2007).

The spectral resolution of SINFONI is $\sim 150$ km s$^{-1}$ and hence we cannot distinguish between the fluorescing gas and the shocked matter. Nevertheless, we are able to trace the velocity dispersion and the radial velocity around the ring. Figure 6 shows the
azimuthal velocity distribution for the three prominent lines in the ring (Paβ, Brγ and He I λ2.06).

It is now possible to determine the rest frame velocity of the ring assuming that the acceleration around the ring has been constant. This is clearly not the case, as the flat-topped velocity distribution of Paβ shows. There is a clear deviation from the expected sine curve for a tilted ring. The reason is, of course, that the density of the ring protrusions and the shock interaction are not the same around the ring. The eastern part has had the first interaction and hence a higher shock velocity is expected in these regions. Also, the ring is not simply inclined perpendicular to the line of sight but also rotated out of the plane of the sky with the eastern sector more distant than the western part. We derive from the velocity curve a rotation angle of $\sim 10^\circ$, consistent with the offset seen in the major axis of the ring on the sky (Jakobsen et al. 1991, Panagia et al. 1991). Nevertheless assuming that the asymmetries average out over the complete ring, we can find the systemic velocity of the ring, and presumably of SN 1987A itself. A first, preliminary analysis yields $v_{SN1987A} = 283 \pm 8$ km s$^{-1}$, which is consistent with the value derived from the high-resolution UVES spectroscopy, 286.7 ± 0.1 km s$^{-1}$.

**THE EJECTA SPECTRUM**

The UVES spectra clearly show a broad Hα line extending to $\sim 15,000$ km s$^{-1}$ (Fig.2). This is discussed in detail by Smith et al. (2005) and Heng et al. (2006), who show
that this originates from the reverse shock, propagating back into the ejecta. In addition, there is also a component in this line, as well as in [Ca II] $\lambda 7324$, coming from the radioactively excited core.

Detection of emission from the supernova ejecta are more difficult in the SINFONI spectrum. The only line we securely can identify as coming from the ejecta is [Fe II] $\lambda 1.64$. It has a velocity width of about 4000 km s$^{-1}$, which corresponds to the nickel core of SN 1987A. Unfortunately, the early science verification data do not have sufficient spatial resolution to allow us to investigate the shape of the ejecta. However, there are strong indications from HST observations that the supernova ejecta is deviating strongly from a spherical distribution (Wang et al. 2002). With deeper spectroscopy and adaptive optics supported observations, we hope to obtain a clearer picture of the ejecta in the coming years.

**CONCLUSIONS**

It is clear that with the kinematic information we will be able to further investigate the evolution of the supernova shock as it envelopes the circumstellar ring in the coming years. SN 1987A is living up to being a true teenager. It is transforming itself into a mature supernova remnant, but on the way has to go through some turbulent times as the supernova shock overtakes the circumstellar ring. SN 1987A represents a fascinating laboratory to study how a supernova interacts with its surrounding.

We continue our spectroscopic monitoring of the emission in the optical and near-infrared. Integral-field spectroscopy is an ideal tool to investigate the many emission sites.

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