Supernovae and the VLT: More Light to Examine*

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Abstract: Supernovae constitute ideal laboratories for the investigation of the end phases of stellar evolution. The explosion mechanisms are fairly well understood in general, but the individuality of supernovae needs to be explored in more detail. The opportunity provided by these bright point sources to study the interstellar medium of external galaxies has not been fully exploited to date. The future 8m telescopes will provide the means for such investigations with profound implications for the chemical composition and evolution of galaxies. In addition to the expected extensions of existing observing programs to fainter and more distant supernovae, four specific projects for original observations of supernovae and the interstellar medium are described. Asymmetries in the explosions can be detected through spectropolarimetry and structure in emission lines. Interstellar dust properties can be inferred from polarimetry and light echoes, and very high-resolution spectroscopy probes gas in the halo, external galaxies, and intergalactic space. All these programs require the light gathering power of 8m class telescopes to investigate a fair sample of supernovae. Suitable instruments in the VLT program are identified.

1. Introduction

Characteristic signatures of supernovae (SNe) are their distinct light curves, spectral appearance and evolution, and high luminosities. Spectroscopy near maximum light forms the main classification mechanism (e.g. Harkness & Wheeler 1990). The presence (SNe II) or absence (SNe I) of hydrogen lines distinguishes the two main types. The absorption due to the Si II doublet (rest wavelength 6355 Å) near 6100 Å defines the subclass of SNe Ia and separates it from the other clear subtype of SNe Ib/c (Harkness & Wheeler 1990). A further separation into SNe Ib (He-rich) and SNe Ic (He-poor) is proposed (Wheeler & Harkness 1990, Wheeler et al. 1994), but an easy and clear identification scheme is still missing. Optical spectra are often too complicated to identify the He I series in them and the rather quick spectral evolution makes classification after a few weeks past maximum a difficult proposition. The breakdown of the current classification system is illustrated

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by the association of SNe II and SNe Ib/c with core collapse explosions, while SNe Ia most probably result from thermonuclear explosions. The decoupling of the explosion mechanism from the light emission at the surface has been most readily demonstrated by the close resemblance of SN 1987K (Filippenko 1988) and SN 1993J (see Wheeler & Filippenko 1994 for a review of the early observations and models), which as a type II displayed many characteristics (light curves and spectra at late times) of SNe Ib/c. We are thus confronted with the problem of connecting the internal explosion physics with the external appearance (intimately related to the structure of the progenitor star). The creation of additional subclasses of supernovae does not contribute to the discussion of the underlying physics but may lead to atomization of the issues.

There exists fair agreement on the global picture and variations among individual supernovae can be traced back to differences in the evolutionary stage of the progenitor star at explosion. The optical display from core collapse supernovae starts with the shock breaking out the surface of the progenitor star. Soft X-ray and extreme UV emission ionizes a large volume around the supernova (Fransson et al. 1994a). The object itself, i.e. the shock-heated stellar material, can brighten by $\sim$10 magnitudes in a few hours. The duration of this peak is determined by the size of the progenitor star before explosion (Falk & Arnett 1977, Klein & Chevalier 1978). After the passing of the shock the envelope immediately starts to cool and the supernova bolometric luminosity drops rapidly. This phase has so far been observed only in SN 1987A (Arnett et al. 1989) and SN 1993J (Schmidt et al. 1993a, Lewis et al. 1994, Richmond et al. 1994, Benson et al. 1994, Van Driel et al. 1993). The decline stops when the recombination wave moving inward in mass coordinates is balanced by the expansion of the envelope which creates a spatially nearly stationary photosphere and the light curve settles on a prolonged plateau (e.g. Eastman et al. 1994). Such a plateau can last for several months depending on the envelope size and mass, and the energy generated in the explosion (Chugai 1991, Popov 1993). The luminosity of the supernova until this phase is completely dominated by the interaction of the shock with the envelope. When the photosphere has receded deep enough into the envelope, radioactive heating begins to dominate the energetics. ^{56}Ni, produced in the shock moving through dense, hot material deep inside the progenitor star, decays to radioactive ^{56}Co, which in turn decays to stable ^{56}Fe. As a result the plateau phase might be extended as long as the envelope remains optically thick to optical photons.

Once the ejecta have thinned out enough to allow thermalized photons to escape easily, we observe a brightness decline. For supernova progenitors with large envelopes almost all energy is converted to optical photons and the decline follows the radioactive decay time of ^{56}Co (111.3 days; the ^{56}Ni decay time [8.80 days] is so short that it all has been converted to ^{56}Co by this phase). Many SNe II have masses high enough to trap most of the energy and display decline rates matching closely the cobalt decay times (Turatto et al. 1990, Schmidt et al. 1993b). In cases of low ejecta masses γ-rays from the ^{56}Co decay can escape and only a fraction of the energy is deposited in the ejecta. Since the column density decreases due to the expansion, the escape fraction increases and the decline of the light curve is steeper than the decay times (Leibundgut & Pinto 1992). The contribution of e^+ depositing energy locally in the ejecta is a small fraction for several hundred days. A prime example is SN 1993J (Shigeyama et al. 1993, Woosley et al. 1994) and most SNe Ib/c (Vacca & Leibundgut 1994, Leibundgut 1994a).

More detailed descriptions have to include the amount of mixing which occurs when the shock crosses density steps in the envelope (Müller et al. 1991, Herant &

Woosley 1994). Rayleigh-Taylor instabilities can bring radioactive material to the surface and some of the envelope is sunk into the core (Herant et al. 1992). The density variations also lead to clumping in the ejecta, which has been observed in a few supernovae (Stathakis et al. 1991, Spyromilio 1994).

Supernovae do not explode in a vacuum. The intense radiation field and shocks have profound environmental impacts. Many effects from such interactions have been observed, including narrow emission lines, intense X-ray and radio emission, and non-thermal continua. In some supernovae this interaction completely dominates the optical evolution (Leibundgut 1994b). Several years after explosion the conversion of shock energy into radiation can be observed (Fesen & Becker 1990, Leibundgut et al. 1991).

A dramatic change in the filter light curve occurred $\sim$500 days after explosion in SN 1987A (Suntzeff & Bouchet 1990), when dust formed in the ejecta. Most of the emission shifted to infrared wavelengths at this point.

The light curve tracks the energy deposition, since the time scale for energy release is much shorter than for the deposition. After about 900 days, however, the light curve of SN 1987A flattened out (Bouchet et al. 1991, Suntzeff et al. 1991). The recombination time for very thin material ionized at early phases becomes comparable to the age of the supernova, which causes the flattening of the light curve (Fransson & Kozma 1993).

The optical display of thermonuclear explosions (SNe Ia) is very similar to the one just described. Since the supernova here is the result of explosive burning and the progenitor star is a very compact object, the ejecta are not heated by a shock wave (Woosley & Weaver 1986). The light curve is powered solely by the decay of radioactive nuclei produced in the burning of material to nuclear statistical equilibrium. The photon diffusion in the expanding material creates a peak phase of about 40 days (Arnett 1982, Woosley et al. 1986). The small mass and rapid expansion of the ejecta as well as the relatively complete burning of the progenitor star result in small column densities for the γ-rays. Thus, only a small fraction of the available energy is thermalized (Leibundgut & Pinto 1992). The light curve at these phases is powered by exactly the same mechanism as in core collapse supernovae. A rapid cooling of the ejecta due to (infrared) fine structure lines of iron peak elements is expected at late phases (Fransson et al. 1994b). Also predicted is a freeze-out phase similar to that in SN 1987A (Fransson et al. 1994b). Neither of these effects has been observed to date.

Current problems of supernova research are apparent from the above description. Prominently missing is the link between progenitor star evolution and the supernova explosion (Branch et al. 1991). Which stars blow up and what in their evolution determines the appearance of the supernova? Stellar evolution theory provides many ways to produce a star which *may*, when exploded, appear similar to what we observe (e.g. Woosley et al. 1993, 1994, Nomoto et al. 1994, Wheeler et al. 1994). Supernovae provide the unique opportunity to observe the results of stellar evolution. The stellar interior is exposed in the explosion and shock interaction with the remnant of the stellar wind unravels the mass loss history (Fransson & Chevalier 1989, Chevalier & Fransson 1994). The explosion models are not able to fully describe the propagation of the burning fronts for SNe Ia (Woosley 1990, Khokhlov 1994, Arnett & Livne 1994). The explosions produce instabilities in the ejecta mixing various layers and favoring clumping (Müller et al. 1991). Detailed analysis of explosive nucleosynthesis is necessary to explore the chemical enrichment of galaxies. An important new field is the investigation of the effect supernovae have on their local environments. The radiation field and shock wave from the explosion interact with the circumstellar material in various observable ways (Fransson et al. 1994a, Cumming et al. 1994, Lundqvist 1994). Several years after outburst some supernovae are still emitting light through such processes (Fesen & Matonick 1994, Leibundgut 1994b).

For galaxies beyond the Local Group supernovae are the only light beacons which allow us to study the local interstellar medium. This is one of the few ways we can learn about the chemical compositions of the ISM in external galaxies. The dust-to-gas ratio can be inferred from selective absorption (reddening) and interstellar lines in the spectra.

Supernovae have been in popular use as distance indicators (cf. Branch & Tammann 1991). One determination of the Hubble constant is based on the use of SNe Ia (see Hamuy et al. 1994 for the best controlled and most distant set of supernovae). With the availability of absolute calibrations (Saha et al. 1994) H_0 will be reliably determined in the next few years. An independent way towards H_0 is provided by the expanding photosphere method (Schmidt et al. 1994a).

2. Supernovae and ESO's Very Large Telescope

There are various obvious ways in which 8m-class telescopes will improve supernova studies. The spectral evolution at optical wavelengths can be followed to much later phases and for fainter supernovae. Infrared wavelengths will become as easily accessible as the optical region is today.

Important observations include the direct determination of the radioactive decay through the evolution of the [Co II] 10.52μm line (Aitken et al. 1988, Danziger et al. 1991), the Fe/Co ratio measured at late phases from the [Co II] ($\lambda 1.547\,\mu$m) and the [Fe II] ($\lambda 1.533\,\mu$m) lines (Varani et al. 1990) and the [Fe III] and [Co III] blends in the optical (Kuchner et al. 1994). The comparison of the the optical and IR multiplets will probe the physical conditions in the supernova ejecta. With some more spectral modeling the Ni mass can be deduced (Ruiz-Lapuente & Lucy 1992). Detailed mapping of the 1–3 μm spectral range of SNe Ia (Spyromilio et al. 1994) is required for a further understanding of the opacities and temperatures in the ejecta. Direct observation of dust formation (Lucy et al. 1991) as well as the IR catastrophe and the freeze-out (Fransson & Kozma 1993, Fransson et al. 1994b) will further constrain the models for the ejecta and the close environment of the supernovae.

The list of supernovae observable several years past maximum (Leibundgut 1994b) will enlarge. One of the main questions here are the shapes of the emission lines which indicate the origin of the emission (forward shock in the CSM and reverse shock in the ejecta; Chevalier & Fransson 1994).

Spectroscopic studies of distant SNe will be common place. They will provide important clues on the cosmic distance scale well beyond most other distance indicators (e.g. Jacoby et al. 1992). The expanding photosphere method of SNe II and the empirical use of SNe Ia as distance indicators require good spectral and photometric (not necessarily from the VLT) coverage to identify peculiarities and the decline parameter for SNe Ia (Phillips 1993, Hamuy et al. 1994). Determination of the Hubble constant beyond any currently known bulk flows could be achieved (Turner et al. 1992, Lauer & Postman 1994). The measurement of the deceleration of the Universe might be feasible with accurate data (cf. Cappellaro in this volume).

To perform the studies mentioned above many of the foreseen and planned VLT instruments will be needed. We anticipate use of FORS, ISAAC, and MIIS. Observational requirements will be as large a wavelength coverage as possible, flexible and frequent observations, and accurate background subtraction.

In the following, we will concentrate on a few projects which are not simple extensions of existing programs but try to illustrate observations which become feasible with 8m telescopes.

2.1 Polarization

Current models for core collapse indicate large asymmetries emerging at the inner hot bubble above the proto-neutron star (Herant et al. 1992). How strongly these asymmetries imprint themselves on the surface is as yet unknown but certainly depends on how the shock is restarted by the neutrinos. Critical measurements of asphericities in the explosion are obtained with spectropolarimetry. Since any asymmetries are expected to dampen out very quickly, early phase observations are crucial.

To date spectropolarimetry has been obtained for a few objects only. The strong polarization found in SN 1987A (Bailey 1988, Cropper et al. 1988) is still mostly unexplained, but has been interpreted as due to an asphericity of the material (Jeffery 1991). The evolving polarization of SN 1993J requires an aspherical scattering surface below the region where Hα forms, i.e. inside the supernova (Trammel et al. 1993). Asymmetry has also tentatively been reported for a third core-collapse supernova, the type Ib SN 1983N (McCall 1985). All SNe Ia with spectropolarimetric observations appear to be spherical to the measurement limits (McCall et al. 1987, Spyromilio & Bailey 1994). For explosions of compact objects like SNe Ia asymmetries are expected to disappear rapidly and only observations at very early phases can detect them. Such a measurement would be of paramount importance for the current discussion on the explosion mechanism for white dwarfs (e.g. He shell detonation models; Livne 1990, Woosley & Weaver 1994).

A second polarization component, which arises from interstellar dust grains, is often present in the observations. It provides a way to measure the size and orientation of interstellar dust grains in other galaxies (Trammel et al. 1993). Supernovae near maximum are for many galaxies the only available point sources to obtain such a measurement. The implication for our understanding of the chemical history of galaxies and the mechanisms orienting the grains is profound. All the supernovae mentioned above have determinations of the interstellar polarization along the line of sight. Most interestingly, the value for the total to selective absorption found from SN 1986G for the dust lane in NGC 5128 is lower than the canonical one for the solar neighborhood, indicating smaller characteristic grain sizes (Hough et al. 1987).

Spectropolarimetry will be possible for several supernovae per year with FORS. Polarimetry in the infrared would be advantageous since the interstellar contamination is low and a more direct measurement of the source is possible. Hence, the polarimetric functionality of ISAAC is an asset.

2.2 Probing the ISM

Interstellar (and intergalactic) narrow absorption lines are also seen in supernova spectra. The most prominent ones are Na I D and Ca II H and K. In addition, diffuse interstellar bands have been observed in at least two objects (SN 1987A: Vidal-Madjar et al. 1987, Pettini 1988, SN 1986G: di Serego Alighieri & Ponz 1987).

The spectral resolution of most supernova observations are not high enough to separate contributions of different absorbers along the line of sight. The few exceptions have yielded fairly surprising results. Towards SN 1987A up to 24 components have been identified in the Ca II line, some of intergalactic nature (Vidal-Madjar et al. 1987). These measurements probe the gas distribution in the outer Galaxy and the LMC. A similar study of SN 1993J detected intergalactic gas possibly stripped from a companion galaxy of M 81 (Vladilo et al. 1993). Currently, such observations can be obtained for SNe Ia at maximum in the Virgo cluster (SN 1991T; Meyer & Roth 1991). Surprisingly, the supernova sight line contains three additional, galactic absorption components compared with the one towards 3C 273, situated only 1.4° from the supernova (Meyer & Roth 1991). They might be the metal counterparts of high-velocity H I clouds (Robertson et al. 1991).

High resolution spectroscopy with high signal-to-noise ratio is required for such investigations. The 8m telescopes will substantially increase the limiting magnitudes. Not only more distant supernovae can be observed, also the time for which a supernova stays bright enough for such a study is extended. Supernovae in the Coma cluster can be observed with the same signal-to-noise (spectral resolution 20000, S/N$\sim$10) with UVES in 1 hour (Dekker 1994), while it took 10 hours on a 4m telescope for a supernova in Virgo (Meyer & Roth 1991). For brighter supernovae detailed studies at spectral resolutions of a few 100000 and S/N of better than 30 can be envisaged with a very high resolution spectrograph.

2.3 Clumping in the supernova ejecta

Evidence for fragmentation of the ejecta come from the early γ-ray detections and light curve shapes (e.g. Shigeyama et al. 1988). Models have identified Rayleigh-Taylor instabilities when the shock wave passes the O/He layer interface (Müller et al. 1991) as responsible for this mixing. The mixing scale length, however, remains largely speculative. Polarization can possibly trace large scale clumping, but an alternative method is detailed analysis of very high S/N spectral of emission lines (typically the [O I] ($\lambda\lambda$ 6300,6364 Å doublet) at late phases. This has been attempted for SN 1987A (Stathakis et al. 1991), SN 1985F (Filippenko & Sargent 1989), and SN 1993J (Spyromilio 1994). In all cases, several velocity components could be identified providing evidence for rather large (and dense) clumps. Connecting such observations with polarization measurements promise great advances in understanding the internal structure of the progenitor star.

Very high S/N is required for an unambiguous detection of the different velocity components. The resolution should be at least 3000, just at the limit of FORS 2. Higher resolution might be warranted for certain interesting cases, but no instrument for such a resolution ($\sim$10000) could be identified in the VLT program.

2.4 Light Echoes

Light we observe has not always reached us on the shortest possible way. Detection of very faint light echoes arising from dust, however, has rarely been observed. We can distinguish to kinds of echoes: radiation from dust heated by the intense radiation field and scattered light. The two effects have distinctly different observational signatures. Heated dust primarily emits at infrared wavelengths and the light echo is observed at early times. Scattering tends to make the spectrum bluer at very late phases.

The first form of light echo has been observed in SN 1982E (Graham et al. 1983, 1986) and possibly SN 1980K (Dwek 1983). The infrared excess emission in these supernovae has been observed near maximum light and is associated with material close to the supernova.

In the case of SN 1987A scattered light has been observed as spatially resolved "expanding" rings. For certain objects the scattered light can add up to dominate the direct emission from the supernova after it faded. SN 1991T seems to remain at B$\approx$21.3 and the observed spectrum after $\sim$900 days matches remarkably well that expected from scattering the integrated light of the supernova through the peak phase (Schmidt et al. 1994b). Several years after explosion the extend of the echoes might be large enough to be resolved. The calculated angular size of the light echo around SN 1991T is of the order of 0.1 arcsecond three years after explosion. Although this is too small for ground-based telescopes, we might be able to resolve echoes from closer supernovae, like SN 1993J and SN 1994I, in a few years. The light echoes from SNe II will resemble their spectrum in the plateau phase.

Spectroscopic observations of (spatially unresolved) light echoes open a new window on studies of interstellar material in external galaxies. The scattering characteristics and hence the grain size can be determined from comparison of the observed spectrum with calculated integrated light spectra modified by a scattering model, thus yielding a completely independent method to infer dust properties in external galaxies.

The faintness of light echoes puts spectroscopic observations in the realm of 8m class telescopes. With a typical magnitude difference between peak light and the integrated light echo of $\sim$9 magnitudes (Schmidt et al. 1994b), we have to expect the light echoes below $20^{\rm th}$ magnitudes for almost all supernovae. The spectral evolution should be monitored to detect changes in the scattering properties of the dust as the light front expands. Low-resolution spectroscopy is the best we can hope for and FORS will certainly deliver the data required for detailed investigations.

3. Summary

Many of the proposed research projects reproduce observations which have been obtained for SN 1987A in the LMC and SN 1993J in M 81 for supernovae at significantly larger distances. Although this statement appears trivial, it is of vital importance for supernova studies. While with the current instrumentation we are able to perform a comprehensive analysis on objects which are among the half a dozen in the last century with apparent peak magnitude less than 10, the 8m telescopes will be able to observe supernovae with the same detail out to the Virgo cluster and beyond. In other words, we can expect to observe a supernova with a comparable wealth of information as was gathered for SN 1987A about once every year!

Rapid access to the telescopes through flexible scheduling will be a very important asset of the VLT. With a wide variety of instrumentation a newly discovered supernova can be observed with several techniques simultaneously. The interesting early epochs have been quite elusive due to rapid evolution of supernovae and the difficulties encountered in supernova searches. As more searches come on line and communications improve, we can expect more supernovae to be discovered very early.

All core collapse supernovae with spectropolarimetric measurements exhibit intrinsic asymmetries. It is paramount for the explosion models to confirm these gross asymmetries. Similarly, the link between the evidence for clumping from spectral lines at late times and the polarimetric observations near maximum almost certainly will shed new light on the fragmentation mechanisms.

Supernovae will provide convenient light beacons for studies of the interstellar material in the outer halo of the Galaxy and in external galaxies. The determination of total to selective absorption is an important input for the chemical history of the galaxies. Independent determination of reddening and absorption also improve the knowledge of the supernova parameters (e.g. temperature, luminosity).

Supernova observations yield a heap of tangled information. Explosion ejecta, excited circumstellar matter, and scattered light from material in the line of sight are observed simultaneously. We can learn about the material synthesized in the explosion and by the progenitor star's internal processes, the mass loss history of the progenitor star and its evolutionary state at explosion, and interstellar as well as intergalactic material. To disentangle this information is the great trick. The VLT will provide a powerful platform to separate the effects and enhance the sample for which such studies can be performed.

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