Supernovae and Their Massive Star Progenitors

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Abstract. I briefly describe the Lick Observatory Supernova Search with the 0.76-m Katzman Automatic Imaging Telescope. I then present an overview of optical observations of Type II, IIb, Ib, and Ic supernovae (SNe), all of which are thought to arise from core collapse in massive progenitors that have previously experienced different amounts of mass loss. SNe IIb are distinguished by relatively narrow emission lines with little or no P-Cygni absorption component; they probably have unusually dense circumstellar gas with which the ejecta interact. Some SNe IIb, however, might actually be super-outbursts of luminous variable stars; rarely, they may even be SNe Ia in disguise. Plausible detections of the progenitors of a few SNe II have been made. Spectropolarimetry of core-collapse SNe reveals that asphericity increases toward the core.

1. The Lick Observatory Supernova Search

In 1989, my team began to work on developing a robotic telescope for CCD imaging of relatively faint objects. The history of the project is discussed in several papers (e.g., Filippenko et al. 2001; Richmond, Trefers, & Filippenko 1993), and several prototypes were used over the years. In 1996, we achieved first light with our present instrument, the 0.76-m Katzman Automatic Imaging Telescope (KAIT) at Lick Observatory on Mt. Hamilton, California. It took the better part of another year to eliminate most of the remaining bugs in the system, and useful scientific results started appearing in 1997. Absolutely vital contributions to the programming and to the observing strategy were made by Dr. Weidong Li, who joined my group in 1997.

KAIT is a fully robotic instrument whose control system checks the weather, opens the dome, points to the desired objects, acquires guide stars (in the case of long exposures), exposes, stores the data, and manipulates the data automatically, all without human intervention. We reach a limit of $\sim 19$ mag ($4\sigma$) in 25-s unfiltered, unguided exposures, while 5-min guided exposures yield $R \approx 20$ mag. KAIT acquires well-sampled, long-term light curves of SNe and other variable or ephemeral objects — projects that are difficult to conduct at other observatories having a large number of users with different interests.

One of our main goals is to discover nearby SNe to be used for a variety of studies. Special emphasis is placed on finding them well before maximum brightness. Although the original sample of our Lick Observatory Supernova Search (LOSS; Li et al. 2000; Filippenko et al. 2001) had only about 5000 galaxies, in the year 2000 we increased the sample to $\sim 14,000$ galaxies (most with redshift $< 10,000$ km s$^{-1}$), separated into three subsets (observing base-
lines of 2 days for about 100 galaxies, 3–6 days for \( \sim 3000 \) galaxies, and 7–14 days for \( \sim 11,000 \) galaxies). We are able to observe \( \sim 1000 \) galaxies per night in unfiltered mode. Our software automatically subtracts new images from old ones (after registering, scaling to account for clouds, convolving to match the point-spread-functions, etc.), and identifies SN candidates which are subsequently examined and reported to the Central Bureau for Astronomical Telegrams by numerous undergraduate research assistants in my group, working with W. Li. Interested astronomers elsewhere are also notified immediately.

A Web page on LOSS is at http://astro.berkeley.edu/~bait/kait.html. LOSS found its first supernova in 1997 — SN 1997bs; ironically, it might not even be a genuine SN (Van Dyk et al. 2000). In 1998, mostly during the second half of the year, LOSS discovered 20 SNe, thereby breaking the previous single-year record of 15 held by the Beijing Astronomical Observatory Supernova Search. In 1999, LOSS doubled this with 40 SNe. In 2000, LOSS found 38 SNe, even though we spent a significant fraction of the observing time expanding the database of monitored galaxies rather than searching for SNe. With this expanded database, LOSS discovered 68 SNe in 2001, 82 in 2002, 95 in 2003, and 71 in 2004 through October. We discovered SN 2000A and SN 2001A, and hence the first supernova of the new millennium, regardless of one’s definition of the turn of the millennium! During the past few years, KAIT has discovered \textit{well over half} of all nearby SNe reported world-wide, from all searches combined. Thus, KAIT/LOSS is currently the world’s most productive search engine for nearby SNe.

At the Lick and Keck Observatories, we spectroscopically confirm and classify nearly all of the SNe that other observers haven’t already classified. Thus, the sample suffers from fewer biases than most. We have started to determine the Hubble types of the host galaxies of the SNe (van den Bergh, Li, & Filippenko 2002, 2003), as a first step in the calculation of rates of various types of SNe. Already, our observations and Monte-Carlo simulations have shown that the rate of spectroscopically peculiar SNe Ia is considerably larger than had previously been thought (Li et al. 2001).

Follow-up observations for the discovered SNe are emphasized during the course of LOSS. Our goal is to build up a multicolor database for nearby SNe. Because of the early discoveries of most LOSS SNe, our light curves usually have good coverage from pre-maximum brightening to post-maximum decline. Moreover, LOSS SNe are automatically monitored in unfiltered mode as a by-product of our search; these can sometimes be useful for other studies (e.g., Matheson et al. 2001). The positions of SNe in KAIT images were used to identify the same SNe at very late times in \textit{Hubble Space Telescope (HST)} images (Li et al. 2002), allowing us to determine the late-time decline rates.

LOSS also discovers novae in nearby galaxies (e.g., M31), cataclysmic variable stars, and occasionally comets (e.g., Li 1998). Although it records many asteroids, we don’t conduct follow-up observations, so most of them are lost.

2. Supernova Types

Supernovae occur in several spectroscopically distinct varieties; see Filippenko (1997) for a review. Type I SNe are defined by the absence of obvious hydrogen in their optical spectra, except for possible contamination from superposed H II
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regions. SNe II prominently exhibit hydrogen in their spectra, yet the strength and profile of the Hα line vary widely among these objects. At early times (within a few weeks of maximum brightness), SNe Ia are characterized by a deep absorption trough around 6150 Å produced by blueshifted Si II λ6355. Members of the Ib and Ic subclasses do not show this line. The presence of moderately strong optical He I lines, especially He I λ5876, distinguishes SNe Ib from SNe Ic. In almost all SNe the lines are broad, due to the high velocities of the ejecta, and most of the lines have P-Cygni profiles formed by resonant scattering above the photosphere.

The late-time ($t > \sim 4$ months) optical spectra of SNe provide additional constraints on the classification scheme. SNe Ia show blends of dozens of Fe emission lines, mixed with some Co lines. SNe Ib and Ic, on the other hand, have relatively unblended emission lines of intermediate-mass elements such as O and Ca. At this phase, SNe II are dominated by the strong Hα emission line; in other respects, most of them spectroscopically resemble SNe Ib and Ic, but with narrower emission lines. The late-time spectra of SNe II show substantial heterogeneity, as do the early-time spectra.

To a first approximation, the light curves of SNe I are all broadly similar, although SNe Ib usually have slower decline rates than SNe Ic. The light curves of SNe II exhibit much dispersion (e.g., Patat et al. 1993), but it is useful to subdivide the majority of them into two relatively distinct subclasses (Barbon, Ciatti, & Rosino 1979; Doggett & Branch 1985). The light curves of SNe II-L (“linear”) generally resemble those of SNe I, with a steep decline after maximum brightness followed by a slower exponential tail. In contrast, SNe II-P (“plateau”) remain within $\sim 1$ mag (in VRI) of maximum brightness for an extended period. The light curve of SN 1987A, albeit atypical, was generically related to those of SNe II-P.

Theoretical models are generally successful at explaining the basic observed properties of SNe (e.g., Woosley & Weaver 1986; Arnett et al. 1989; Wheeler & Harkness 1990; Woosley, Langer, & Weaver 1995; Burrows 2000). SNe Ia are white dwarfs in binary systems undergoing mass transfer. When the mass of the white dwarf reaches the Chandrasekhar limit, $\sim 1.4 M_\odot$, the entire star is incinerated by a thermonuclear runaway. Controversial issues are the nature of the burning front (subsonic, supersonic, or a mixture?), the mass of the progenitor (can it be sub-Chandra?), and the nature of the companion (a dwarf, giant, or white dwarf?). SNe II, on the other hand, result from the violent collapse of an iron core, and the subsequent ejection of surrounding layers (largely due to neutrino interactions), in stars having initial mass $\gtrsim (8-10) M_\odot$. SNe Ib/Ic are probably produced by core collapse of massive stars that have lost their outer layer of H/He, either via winds or mass transfer to a companion.

3. Subclasses of Type II Supernovae

Most SNe II-P seem to have a relatively well-defined spectral development, as shown in Figure 1a for SN 1999em (from Leonard et al. 2002). At early times the spectrum is very blue, indicating a high color temperature ($\gtrsim 12,000$ K; Fig. 1b), and in some cases nearly featureless. The temperature rapidly decreases with time due to the adiabatic expansion and associated cooling of the ejecta,
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reaching ~ 7000 K after a few weeks (Fig. 1b). It then decreases more slowly during the plateau (the photospheric phase), while the hydrogen recombination wave moves through the massive (~ 10 M⊙) hydrogen ejecta and releases the energy deposited by the shock. At this stage strong Balmer lines and Ca II H&K with well-developed P-Cygni profiles appear, as do weaker lines of Fe II, Sc II, and other iron-group elements. The spectrum gradually takes on a nebular appearance as the light curve drops to the late-time tail; the continuum fades, but Hα becomes very strong, and prominent emission lines of [O I], [Ca II], and Ca II also appear.

![Figure 1: (a, left) Optical spectra and (b, right) photospheric radius and temperature of SN II-P 1999em, from Leonard et al. (2002).](image)

Few SNe II-L have been observed in as much detail as SNe II-P. Branch et al. (1981) show the spectral development of SN 1979C, an unusually luminous member of this subclass. Near maximum brightness the spectrum is very blue and almost featureless, with a slight hint of Hα emission. A week later, Hα emission is more easily discernible, and low-contrast P-Cygni profiles of Na I, Hβ, and Fe II have appeared. By t ≈ 1 month, the Hα emission line is very strong but still devoid of an absorption component, while the other features clearly have P-Cygni profiles. Strong, broad Hα emission dominates the spectrum at t ≈ 7 months, and [O I] λλ6300, 6364 emission is also present. Several authors (e.g., Wheeler & Harkness 1990; Filippenko 1991a; Schlegel 1996) have speculated that the absence of Hα absorption spectroscopically differentiates SNe II-L from SNe II-P, but the small size of the sample of well-observed objects precluded definitive conclusions.

The progenitors of SNe II-L are generally believed to have relatively low-mass hydrogen envelopes (a few M⊙); otherwise, they would exhibit distinct plateaus, as do SNe II-P. On the other hand, they may have more circumstellar gas than do SNe II-P, and this could give rise to the emission-line dominated spectra. Also, the light curves of some SNe II-L reveal an extra source of energy: after declining exponentially for several years, the Hα flux of SN 1980K reached a steady level, showing little if any decline thereafter (Uomoto & Kirshner 1986; Leibundgut et al. 1991). The excess almost certainly comes from the kinetic energy of the ejecta being thermalized and radiated due to an interaction with
circumstellar matter (Chevalier 1990; Leibundgut 1994). SNe II-L are often radio and X-ray sources, providing further evidence for circumstellar interaction.

During the past 15 years, there has been the gradual emergence of a new, distinct subclass of SNe II (e.g., Schlegel 1990; Filippenko 1991a,b; Leibundgut 1994) whose ejecta are believed to be strongly interacting with dense circumstellar gas, even at early times (unlike SNe II-L). The derived mass-loss rates for the progenitors can exceed $10^{-4} M_\odot$ yr$^{-1}$ (Chugai 1994). In these objects, the broad absorption components of all lines are weak or absent throughout their evolution. Instead, their spectra are dominated by strong emission lines, most notably H$\alpha$, having a complex but relatively narrow profile. Although the details differ among objects (e.g., Filippenko 1997), H$\alpha$ typically exhibits a very narrow component (FWHM $\lesssim 200$ km s$^{-1}$) superposed on a base of intermediate width (FWHM $\approx 1000$–2000 km s$^{-1}$; sometimes a very broad component (FWHM $\approx 5000$–10,000 km s$^{-1}$) is also present. This subclass was christened “Type IIn” (Schlegel 1990), the “n” denoting “narrow” to emphasize the presence of the intermediate-width or very narrow emission components.

In some cases, there is evidence that much of the circumstellar material of SNe IIn was produced quite suddenly, just a short time before the SN explosion. For example, Chugai et al. (2004) found that the plateau-like light curve of SN IIn 1994W is powered by the combination of the internal energy leakage after the explosion of an extended progenitor ($\sim 10^{15}$ cm) and subsequent luminosity from circumstellar interaction. The recovered pre-explosion kinematics of the circumstellar envelope is close to homologous expansion with an outermost velocity of $\sim 1100$ km s$^{-1}$ and a kinematic age of $\sim 1.5$ yr. The high mass ($\sim 0.4 M_\odot$) and kinetic energy ($\sim 2 \times 10^{48}$ erg) of the circumstellar envelope, combined with the small age, strongly suggest that the circumstellar envelope was violently ejected $\sim 1.5$ yr prior to the SN explosion.

As briefly mentioned in Section 1, in some cases a SN IIn is probably not a genuine supernova (the final explosion of a star at the end of its life), but rather an “impostor” — the powerful outburst of a very massive, evolved star such as a luminous blue variable. Examples of these objects, to be discussed more fully in the contribution by Schuyler Van Dyk, are SN 2000ch (Filippenko 2000; Wagner et al. 2004) and SN 2002kg (Schwartz et al. 2003). This idea has been discussed since the work of Goodrich et al. (1989) on SN 1961V.

More recently, it has been suggested that a small subset of SNe IIn are actually SNe Ia whose ejecta are interacting with dense circumstellar material. Specifically, the early-time spectrum of SN 2002ic (Hamuy et al. 2003) resembled that of the peculiar SN Ia 1991T, but as the object aged its spectrum transformed into that of a SN IIn. A likely interpretation is that the progenitor of SN 2002ic had an asymptotic giant branch companion that produced a dense circumstellar environment. Other SNe IIn that may have been similarly “cloaked” SNe Ia are SN 1997cy and SN 1999E (Wang et al. 2004).

4. Stripped Core-Collapse Supernovae

Although core-collapse SNe present a wide range of spectral and photometric properties, there is growing consensus that much of this variety is due to the state of the progenitor star’s hydrogen and helium envelopes at the time of explosion.
Those stars with massive, intact envelopes produce Type II-plateau SNe, those that have lost their entire hydrogen envelope (perhaps through stellar winds or mass transfer to a companion) result in SNe Ib, and those that have been stripped of both hydrogen and most (or all) of their helium produce SNe Ic; see Filippenko (1997) for a review.

A large, comprehensive study of SNe Ib and SNe Ic was completed by Matheson et al. (2001). The relative depths of the helium absorption lines in the spectra of the SNe Ib appear to provide a measurement of the temporal evolution of the SN, with He I λ5876 and He I λ7065 growing in strength relative to He I λ6678 over time. Some SNe Ic show evidence for weak He I absorption, but most do not. Aside from the presence or absence of the helium lines, there are other spectroscopic differences between SNe Ib and SNe Ic. On average, the O I λ7774 line is stronger in SNe Ic than in SNe Ib. In addition, the SNe Ic have distinctly broader emission lines at late times, indicating either a generally larger explosion energy and/or a lower envelope mass for SNe Ic than for SNe Ib. These results are consistent with the idea that the progenitors of SNe Ic are massive stars that have lost more of their envelope (i.e., much of the helium layer) than the progenitors of SNe Ib.

The general hypothesis that SNe Ib/Ic have “stripped” progenitors is greatly supported by the discovery of links between SNe II and SNe Ib/Ic. For example, as discussed by Filippenko (1988), near maximum brightness SN 1987K was undoubtedly a SN II, but many months later its spectrum was essentially that of a SN Ib. The simplest interpretation is that SN 1987K had a meager hydrogen atmosphere at the time it exploded; it would naturally masquerade as a SN II for a while, and as the expanding ejecta thinned out the spectrum would become dominated by emission from deeper and denser layers. The progenitor was probably a star that, prior to exploding via iron core collapse, lost almost all of its hydrogen envelope either through mass transfer onto a companion or as a result of stellar winds. Such SNe were dubbed “SNe IIb” by Woosley et al. (1987); had the progenitor of SN 1987K lost essentially all of its hydrogen prior to exploding, it would have shown the optical characteristics of SNe Ib.

The data for SN 1987K were rather sparse, making it difficult to model in detail. Fortunately, the Type II SN 1993J in NGC 3031 (M81) came to the rescue, and was studied in greater detail than any supernova since SN 1987A (see Filippenko & Matheson 2004 for a review). Its light curves and spectra amply supported the hypothesis that the progenitor of SN 1993J probably had a low-mass (0.1–0.6 $M_\odot$) hydrogen envelope above a $\sim 4 M_\odot$ He core. Filippenko, Matheson, & Ho (1993) illustrate several early-time spectra of SN 1993J, showing the emergence of He I features typical of SNe Ib. Considerably later (Filippenko, Matheson, & Barth 1994), the Hα emission nearly disappeared, and the spectral resemblance to SNe Ib was strong. After correcting pre-explosion images for contamination from foreground stars, Van Dyk et al. (2002) found that the energy distribution of the SN 1993J progenitor is consistent with that of an early K-type supergiant star with $M_V = -7.0$ mag and an initial mass of 13–22 $M_\odot$. A star of such low mass cannot shed nearly its entire hydrogen envelope without the assistance of a companion star. Thus, the progenitor of SN 1993J probably lost most of its hydrogen through mass transfer to a bound companion 3–20 AU away. Very recently, Maund et al. (2004) reported the probable detection of
hydrogen Balmer lines from the putative companion of the progenitor of SN 1993J, thereby providing strong evidence for the binary-star hypothesis.

In a related study, Matheson et al. (2000) suggested a possible spectroscopic link between SNe Ib and SNe Ic: the spectrum of the SN Ic 1999cq exhibited intermediate-width emission lines of helium, but with no corresponding hydrogen, much as would be expected if the ejecta of the SN were interacting with dense clumps of helium in the circumstellar medium. These clumps are probably from the nearly pure helium layer of the massive progenitor, lost prior to the explosion either through winds or via mass transfer to a companion star. The remaining progenitor of the SN may have had little (if any) helium in a shell around the C-O core. In any case, there is now little doubt that most SNe Ib, and probably SNe Ic as well, result from core collapse in stripped, massive stars, rather than from the thermohnuclear runaway of white dwarfs.

5. Evidence for CNO Processing in SN II Progenitors

One of the most important indicators of the extent of pre-supernova mass loss in massive stars is the relative abundances of the CNO elements. Depending on the mass lost and the degree of mixing, CNO burning products may be seen in either the circumstellar medium or the outer parts of the progenitor, and therefore in the SN. Evidence for such CNO processing has earlier been seen in SN II-L 1979C (Fransson et al. 1984) and SN II-P 1987A (Fransson et al. 1989). More recently, a combination of HST and ground-based observations have revealed CNO processing in SN IIb 1993J and SN IIn 1998S (Fransson et al. 2004), as well as in SN IIn 1995N (Fransson et al. 2002).

Table 1. Summary of CNO Abundances in SNe II

| Object   | Type | Environment | N/C | N/O | Notes               |
|----------|------|-------------|-----|-----|---------------------|
| SN 1979C | II-L | ejecta      | 8   | >2  |                     |
| SN 1987A | II-P | circumstellar | 7.8 | 1.6 | nebular analysis    |
|          |      |             | 5.0 | 1.1 | photoionization model|
| SN 1993J | IIb  | ejecta      | 12.4 | >0.8 |                     |
| SN 1995N | II   | ejecta      | 3.8 | 0.2 | uncertain           |
| SN 1998S | IIn  | circumstellar | 6.0 | >1.4 |                     |
| Solar    |      |             | 0.25 | 0.12 |                     |

Table 1 (from Fransson et al. 2004) summarizes the derived CNO ratios for these SNe. Because of blending, the broad-line (i.e., ejecta) determinations are affected by a larger uncertainty (especially in the case of SN 1995N), compared to values from the narrow circumstellar emission lines in SN 1987A and SN 1998S. In all cases, the N/C ratio is considerably larger than the solar value, N/C = 0.25 (Grevesse & Sauval 1998). The N/O ratio is more uncertain due to the problems with O III] λ1664, but again it appears to be much larger than the solar value N/O = 0.12.

All of the SNe in Table 1 are believed to have had progenitors that underwent extensive mass loss prior to the explosion. Thus, it is tempting to see the nitrogen enrichment as being a result of the mass loss. A more quantitative comparison, however, is not straightforward (see Fransson et al. 2004, for more
details and references). Stellar evolutionary models of massive stars, including effects of mass loss, rotation, and binarity, have been calculated by several groups. In particular, rotation can have a large effect on the CNO abundances by increasing the mixing from the CNO burning region already in the main-sequence phase. Binary mass exchange produces a result which, unfortunately, is not easily distinguished from that of rotation.

6. The Progenitors of Core-Collapse SNe

Identifying the massive progenitor stars that give rise to core-collapse SNe is one of the main pursuits of SN and stellar evolution studies. Using ground-based images of recent, nearby SNe obtained primarily with KAIT, astrometry from the Two Micron All Sky Survey, and archival images from HST, we have attempted the direct identification of the progenitors of 16 Type II and Type Ib/c SNe (Van Dyk, Li, & Filippenko 2003a).

We may have identified the progenitors of the Type II SNe 1999br in NGC 4900, 1999ev in NGC 4274, and 2001du in NGC 1365 as supergiant stars with \( M_V \approx -6 \) mag in all three cases. We may have also identified the progenitors of the Type Ib SNe 2001B in IC 391 and 2001is in NGC 1961 as very luminous supergiants with \( M_V \approx -8 \) to \(-9 \) mag, and possibly the progenitor of the Type Ic SN 1999bu in NGC 3786 as a supergiant with \( M_V \approx -7.5 \) mag.

Additionally, we have recovered at late times SNe 1999dn in NGC 7714, 2000C in NGC 2415, and 2000ew in NGC 3810, although none of these had detectable progenitors on pre-supernova images. In fact, for the remaining SNe only limits can be placed on the absolute magnitude and color (when available) of the progenitor. The detected Type II progenitors and limits are consistent with red supergiants as progenitor stars, although possibly not as red as we had expected. Our results for the SNe Ib/c do not strongly constrain either Wolf-Rayet stars or massive interacting binary systems as progenitors.

New images of SN 2001du (in NGC 1365) available in the HST archive allowed us to pinpoint the exact location of the SN on the pre-explosion images (Van Dyk, Li, & Filippenko 2003b; see also Smartt et al. 2003). We showed that the SN occurred in very close proximity to one of our blue candidate stars, but we argued that this star is not the actual progenitor. Instead, the progenitor was not detected on the pre-SN images, and we constrained the progenitor’s initial (zero-age main sequence) mass to be less than \( 13^{+7}_{-4} M_\odot \).

HST archival images obtained within one year prior to the explosion of the nearby Type II-P SN 2003gd in M74 have been analyzed, and two plausible candidates for the progenitor star were found (Van Dyk, Li, & Filippenko 2003c). The most likely of the two progenitor candidates is a red supergiant with initial mass of \( 8-9 M_\odot \). Independently, Smartt et al. (2004) identified the same star as the plausible progenitor of SN 2003gd. They had the benefit of an additional, late-time HST image of SN 2003gd showing the SN to be positionally coincident with the red supergiant. Their derived mass for the progenitor, \( 8^{+1}_{-2} M_\odot \), agrees with that of Van Dyk et al. (2003c). These mass estimates are somewhat lower than, but relatively consistent with, recent limits placed on the progenitor masses of other SNe II-P, suggesting that such SNe arise from the iron core collapse of massive stars at the lower extreme of the possible mass range.
7. Spectropolarimetry of Supernovae

As first pointed out by Shapiro & Sutherland (1982; see also McCall 1984), polarimetry of a young SN is a powerful tool for probing its geometry. A hot young SN atmosphere is dominated by electron scattering, which by its nature is highly polarizing. Indeed, if we could resolve such an atmosphere, we would measure changes in both the position angle and strength of the polarization as a function of location in the atmosphere. For a spherical source that is unresolved, however, the directional components of the electric vectors cancel exactly, yielding zero net linear polarization. If the source is aspherical, incomplete cancellation occurs, and a net polarization results. In general, linear polarizations of $\sim 1\%$ are expected for moderate ($\sim 20\%$) SN asphericity.

Filippenko & Leonard (2004) review the results of our group’s spectropolarimetric studies of SNe. Briefly, we find that SNe IIn tend to be highly polarized, perhaps in part because of the interaction of the ejecta with an asymmetric circumstellar medium. In contrast, SNe II-P are not polarized much, at least shortly after the explosion. At later times, however, there is evidence for increasing polarization, as one views deeper into the expanding ejecta. Moreover, stripped core-collapse SNe tend to show substantial polarization; the deeper we probe into these objects, the greater the asphericity.

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