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Spectropolarimetry of Core-Collapse Supernovae

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Abstract. We briefly review the young field of spectropolarimetry of core-collapse supernovae (SNe). Spectropolarimetry provides the only direct known probe of early-time supernova geometry. The fundamental result is that asphericity is a ubiquitous feature of young core-collapse SNe. However, the nature and degree of the asphericity vary considerably. The best predictor of core-collapse SN polarization seems to be the mass of the hydrogen envelope that is intact at the time of the explosion: those SNe that arise from progenitors with large, intact envelopes (e.g., Type II-plateau) have very low polarization, while those that result from progenitors that have lost part (SN IIb, SN IIn) or all (SN Ib) of their hydrogen (or even helium; SN Ic) layers prior to the explosion tend to show substantial polarization. Thus, the deeper we probe into core-collapse events, the greater the asphericity seems to be, suggesting a fundamentally asymmetric explosion with the asymmetry damped by the addition of envelope material.

1. Introduction

Since extragalactic supernovae are spatially unresolvable during the very early phases of their evolution, explosion geometry has been a difficult question to approach observationally. An exciting, emerging field is supernova (SN) spectropolarimetry, an observational technique that allows the only *direct* probe of early-time SN geometry. As first pointed out by Shapiro & Sutherland (1982), polarimetry of a young SN is a powerful tool for probing its geometry. The idea is simple: 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 position 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. The exact polarization amount varies with the degree of asphericity, as well as with the viewing angle and the extension and density profile of the electron-scattering atmosphere. Through comparison with theoretical models, the early-time geometry of the expanding ejecta may be derived (Fig. 1).

Recent interest in SN morphology has been heightened by the strong spatial and temporal association between some "hypernovae" (SNe with early-time spectra characterized by unusually broad line features) and gamma-ray bursts (GRBs; see T. Matheson's contribution to these Proceedings). These associations have fueled the proposition that some (or, perhaps all) core-collapse SNe explode due to the action of a "bipolar" jet of material (Wheeler et al. 2002; MacFadyen & Woosley 1999), as opposed to the conventional neutrino-driven mechanism (Colgate & White 1966; Burrows et al. 2000, and references therein). Under this paradigm, a GRB is only produced by those few events in which the progenitor has lost most or all of its outer envelope material (i.e., it is a "bare core" collapsing), and is only observed if the jet is closely aligned with our line of sight. Such an explosion mechanism predicts severe distortions from spherical symmetry in the ejecta.

Largely due to the difficulty of obtaining the requisite signal-to-noise ratio for all but the brightest objects, the field of SN spectropolarimetry remained in its infancy until quite recently. Indeed, prior to our efforts and those of a few other groups, spectropolarimetry of core-collapse events existed only for SN 1987A in the LMC (see Jeffery 1991, and references therein) and SN 1993J in M81 (Tran et al. 1997). The situation has changed dramatically in the last 5 years. Detailed spectropolarimetric analysis now exists for nearly a dozen core-collapse events (Leonard et al. 2000, 2001, 2002a,b,c; Leonard & Filippenko 2001; Kawabata et al. 2003; Wang et al. 2001, 2003; for a review of earlier broadband studies, see Wang et al. 1996), and the basic landscape of the young field is becoming established. In this review we discuss the spectropolarimetric characteristics of core-collapse SNe; for a review of SNe Ia spectropolarimetry, please see the contribution by L. Wang in these Proceedings.

2. Interstellar Polarization

It is important to first note that a difficult problem in the interpretation of all SN polarization measurements is proper removal of interstellar polarization (ISP), which is produced by directional extinction resulting from aspherical dust grains along the line of sight that are aligned by some mechanism such that their optic axes have a preferred direction. The ISP can contribute a large polarization to the observed signal. Fortunately, ISP has been well studied in the Galaxy and shown to be a smoothly varying function of wavelength and constant with time (e.g., Serkowski, et al. 1975), two properties that are not characteristics of SN polarization. This has allowed us to develop a number of techniques to eliminate ISP from observed SN spectropolarimetry, the simplest of which is to assume that specific emission lines or spectral regions are intrinsically unpolarized, and derive the ISP from the observed polarization at these wavelengths; a demonstration of how this is accomplished is given in Fig. 2a.

3. Type II-Plateau Supernovae

Type II-plateau supernovae (SNe II-P) are the classic variety of core-collapse events that result from isolated, massive stars with thick hydrogen envelopes intact at the time of explosion. The most thoroughly observed SN II-P is

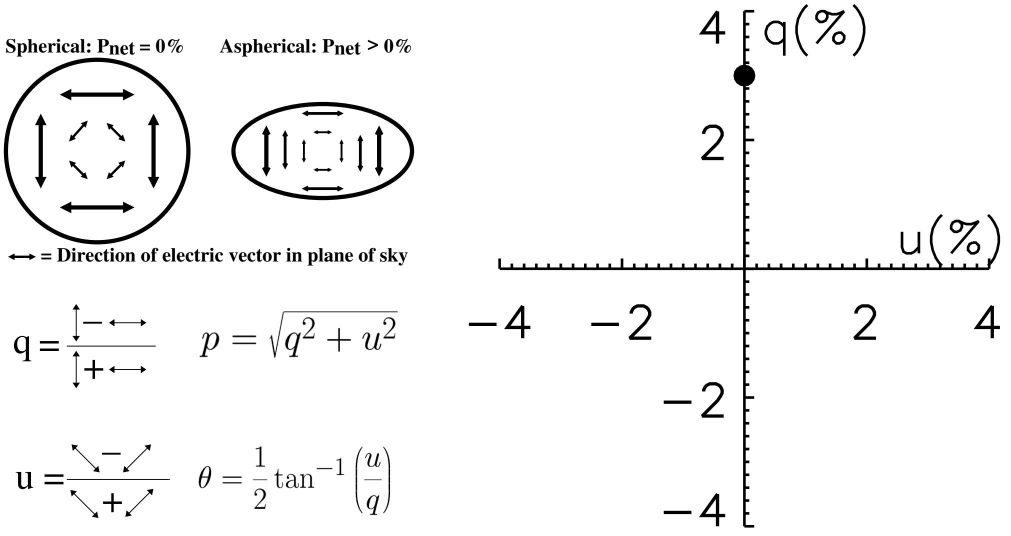

Figure 1. How polarization is produced and measured for an aspherical SN atmosphere. (*Upper left*) Polarization magnitude and direction (in the plane of the sky) for a resolved electron-scattering atmosphere; for an unresolved source (i.e., a supernova), only the *net* magnitude and direction can be measured. Note that the more highly polarized light (longer arrows) comes from the limb regions in this simple model. (*Bottom left*) By comparing the strengths of the electric vector of the supernova flux at four different position angles, the normalized Stokes parameters, q and u, are derived, from which the total polarization, p, and polarization angle, θ, may be determined. As an example, if a young SN actually had the asymmetry depicted by the "aspherical" example in the upper left figure (approximate axis ratio of 2.0) and was viewed edge-on, a net polarization of $\sim 3\%$ would result according to the oblate, electron-scattering models of Höflich (1991). This result is indicated by the filled circle in the q-u plane plot shown on the right.

SN 1999em, for which we obtained rare, multi-epoch spectropolarimetry – three epochs during the plateau and one during the early nebular phase. We found a very low polarization, $p \approx 0.1\%$, at early times that increased with time to $p \approx 0.5\%$ by the early nebular phase while maintaining a relatively fixed polarization angle in the plane of the sky throughout (Leonard et al. 2001). This implies a substantially spherical geometry at early times that may become more aspherical at late times when the deepest layers of the ejecta are revealed. This result provides some support for the jet-induced explosion models of Höflich et al. (2001), in which a low but temporally increasing degree of polarization and, hence, asphericity is predicted for SNe II-P. A similar temporal polarization increase was observed for SN 1987A at early times as well (Jeffery 1991). In fact, for SN 1987A, the expanding ejecta have now been resolved, and the direction of the observed asymmetry is in accord with the early-time morphology implied by the photospheric-phase polarimetry data (Wang et al. 2002).

After correcting for ISP, all of the SNe II-P in our database are found to have low intrinsic polarization during the plateau (Fig. 2b). We note that

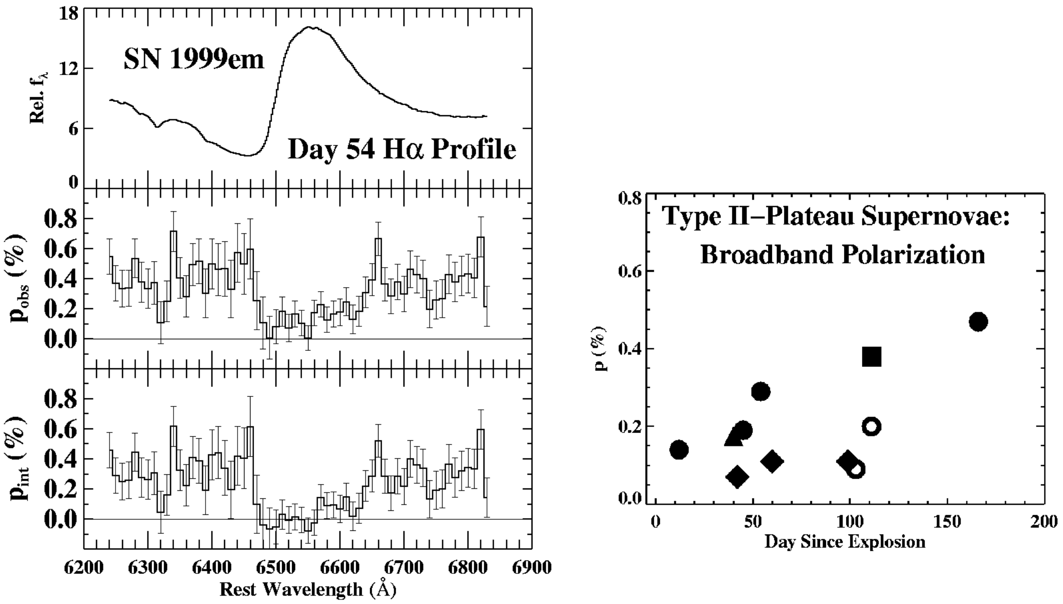

Figure 2. (*a*, left) Removal of ISP from SN spectropolarimetry. Total flux (*top*, Relative f_λ), observed polarization (*middle*, $p_{\rm obs}$), and inferred intrinsic polarization (*bottom*, $p_{\rm int}$) after removal of an ISP of $\sim 0.1\%$, for the region around the Hα P-Cygni profile of SN 1999em, 54 days after explosion. The sharp depolarization at the location of the strong emission component is a typical signature of SN spectropolarimetry and is expected from theoretical investigations that demonstrate that directional information is lost as photons are absorbed and reemitted in an optically thick line (e.g., Höflich et al. 1996). The ISP was therefore derived by assuming the spectral region near the peak of the Hα line to be intrinsically unpolarized. (*b*, right) Broadband polarization of SNe II-P, after correction for ISP derived under the assumption of an intrinsically unpolarized spectral region near the Hα emission peak. The ISP removed, and the plotting symbol used, for each object are as follows: 0.1% for SN 1999em (*closed circle*); 1.0% for SN 1997ds (*closed triangle*); 5.4% for SN 1999gi (*closed square*; for a detailed study of the extraordinarily high polarization efficiency inferred for the dust along the line-of-sight in the host galaxy of SN 1999gi, NGC 3184, see Leonard et al. 2002b); 0.2% for SN 2001X (*closed diamond*); and 1.0% for SN 2003gd (*open circle*).

SN 2001X, for which we obtained multiple spectropolarimetric epochs, does not show any substantial temporal polarization increase as was seen in SN 1987A and SN 1999em. This suggests either a constant degree of asphericity or, alternatively, a viewing angle (nearly) along an axis of symmetry (e.g., an SN shaped as a prolate ellipsoid, if viewed pole-on, will show zero polarization at all times). The basic result of our investigation into early-time SN II-P geometry is that *no* event has thus far been found to show large ($\gtrsim 0.5\%$) intrinsic polarization.

However, evidence does exist in some cases for increasing polarization as one views deeper into the expanding ejecta.

4. Stripped-Envelope Supernovae

SNe that have lost a substantial part of their envelopes prior to explosion display dramatically different polarization signatures than SNe II-P. These events tend to be highly polarized, often with significant polarization changes in magnitude and/or direction in the absorption troughs of the P-Cygni line profiles. Well-studied examples include SN 1993J (IIb, $p \approx 1\%$; see Tran et al. 1997), SN 1998S (Type IIn, $p \approx 2\%$; much of the polarization for this object may result from the interaction of the ejecta with an asymmetric CSM, see Leonard et al. 2000; Wang et al. 2001), and SN 2002ap (Ic-peculiar, $p \approx 1.5\%$; see Leonard et al. 2002a; Kawabata et al. 2003; Wang et al. 2003). The high polarization observed for stripped-envelope SNe implies rather extreme departures from spherical symmetry.

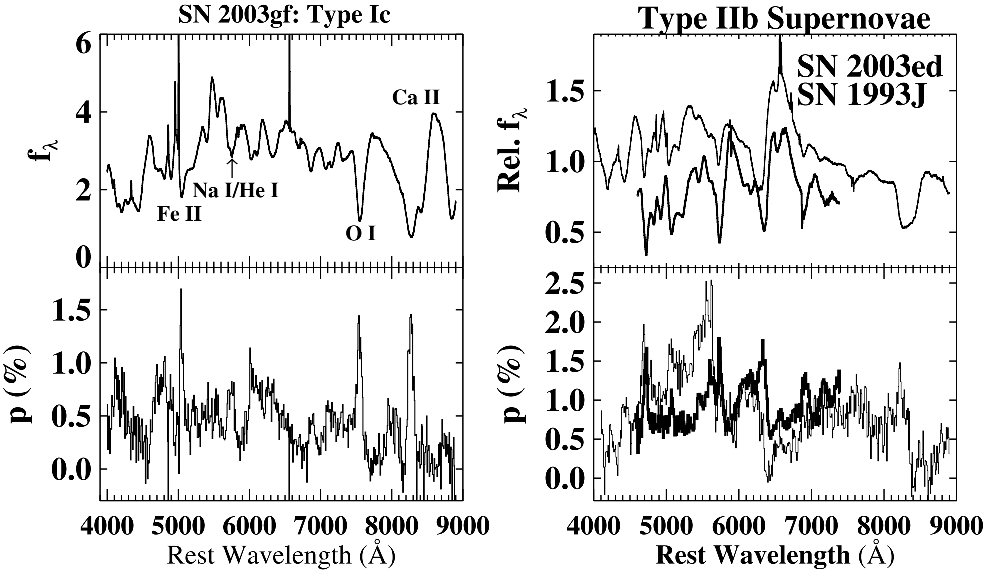

Figure 3. (*a*, left) Spectropolarimetry of SN 2003gf, obtained about 30 days after explosion. An ISP of 0.5%, derived by assuming zero intrinsic polarization at the location of the Ca II near-IR emission peak, has been removed. (*b*, right) Spectropolarimetry of SN 2003ed (*thin line*, wider spectral range) and SN 1993J (*thick line*, narrower spectral range), taken roughly 26 and 34 days after explosion, respectively. An ISP of 1.2% has been removed from the SN 2003ed data (derived by assuming an unpolarized Ca II near-IR emission region). The data for SN 1993J are taken from Tran et al. (1997), and have been corrected for the ISP ($\sim 0.6\%$) derived in that paper.

Two recent examples of stripped-envelope SNe for which we have obtained spectropolarimetry are SN 2003gf (Type Ic) and SN 2003ed (Type IIb); they are shown in Figures 3a and 3b, respectively. For SN 2003gf, note the sharp polarization increases at the location of strong P-Cygni absorptions. A simple explanation may be that P-Cygni absorption selectively blocks photons coming from the central, more forward-scattered (and thus less polarized) regions, thereby enhancing the relative contribution of the more highly polarized photons from the limb regions (see Fig. 1). Clumpy ejecta, or elemental density asymmetries, probably also play a role in producing these features.

The similarity seen in Figure 3b between the polarization characteristics of SN 2003ed and SN 1993J at similar epochs is quite remarkable, especially when coupled with the fact that the only other SN IIb for which spectropolarimetry has been obtained, SN 1996cb, also displayed spectropolarimetric characteristics astonishingly similar to those of SN 1993J (Wang et al. 2001). The similarity among these three events is somewhat puzzling, considering the rather wide range of envelope masses that SNe IIb can be expected to possess, as well as the effect that random viewing orientations should have on the resulting spectropolarimetry. As additional data on SNe IIb are obtained, it will be interesting to see if the similarities persist.

5. Conclusion

The bottom line is that for core-collapse events the closer we probe to the heart of the explosion, the greater the polarization and, hence, asymmetry. The small, but temporally increasing polarization of some SNe II-P coupled with the high polarization of stripped-envelope SNe implicate an explosion mechanism that is highly asymmetric. The current speculation is that the presence of a thick hydrogen envelope dampens the observed asymmetry. We propose that explosion asymmetry, or asymmetry in the collapsing Chandrasekhar core, may play a dominant role in the explanation of pulsar velocities, the mixing of radioactive material seen far out into the ejecta of young SNe, and even GRBs.

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