A Spectropolarimetric Comparison of the Type II-Plateau Supernovae SN 2008bk and SN 2004dj

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Abstract.
   The Type II-Plateau supernova (SN II-P) SN 2004dj was the first SN II-P for which spectropolarimetry data were obtained with fine temporal sampling before, during, and after its fall off of the photometric plateau – the point that marks the transition from the photospheric to the nebular phase in SNe II-P. Unpolarized during the plateau, SN 2004dj showed a dramatic spike in polarization during the descent off of the plateau, and then exhibited a smooth polarization decline over the next two hundred days. This behavior was interpreted by Leonard et al. (2006) as evidence for a strongly non-spherical explosion mechanism that had imprinted asphericity only in the innermost ejecta. In this brief report, we compare nine similarly well-sampled epochs of spectropolarimetry of the Type II-P SN 2008bk to those of SN 2004dj. In contrast to SN 2004dj, SN 2008bk became polarized well before the end of the plateau and also retained a nearly constant level of polarization through the early nebular phase. Curiously, although the onset and persistence of polarization differ between the two objects, the detailed spectropolarimetric characteristics at the epochs of recorded maximum polarization for the two objects are extremely similar, feature by feature. We briefly interpret the data in light of non-Local-Thermodynamic Equilibrium, time-dependent radiative-transfer simulations specifically crafted for SN II-P ejecta.

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INTRODUCTION

Spectropolarimetry offers a direct probe of early-time SN geometry since a hot, young SN atmosphere is dominated by electron scattering, which by its nature is highly polarizing. For an unresolved source that has a spherical distribution of scattering electrons, the directional components of the electric vectors of the scattered photons cancel exactly, yielding zero net linear polarization. Any asymmetry in the distribution of the scattering electrons, or of absorbing material overlying the electron-scattering atmosphere, results in incomplete cancellation, and produces a net polarization [see, e.g., 1].

Type II-Plateau supernovae (SNe II-P) are the canonical core-collapse events that arise from isolated red supergiant stars [2]. The precise nature of the mechanism responsible for the stellar explosion, however, remains the subject of considerable debate [3]. One

key diagnostic is explosion geometry. A global asphericity of SN ejecta will manifest itself through two main spectropolarimetric signatures. First, there will be significant polarization in spectral regions not dominated by line opacity. For SNe II-P, this includes the broad spectral region 6800–8200 Å. Strong emission lines should generally be unpolarized, since directional information is lost as photons are absorbed and reemitted in a line [4] [see, however, 12]. Finally, polarization increases are anticipated in the troughs of strong P-Cygni absorption lines. This results primarily from selective blocking of more forward-scattered and, hence, less polarized, light in the trough regions. A critical point to bear in mind is that the longer one waits after the explosion, the deeper into the ejecta one can see. For SNe II-P, the story unfolds over an extended time period as the photosphere recedes (in mass coordinates) back through the ejecta as the hydrogen recombination front progresses from the outside inwards through the thick hydrogen envelope. The transition from the opaque, "photospheric" phase to the transparent, "nebular phase" is signaled by the sudden drop in luminosity that marks the end of the photometric plateau.

In initial studies, SNe II-P were found to have minimal intrinsic polarizations at the generally early times at which they were observed. Low-contrast line features were sometimes seen in the data, but no obvious strong continuum polarization was found [e.g., 5, 6]; for a recent review of SN spectropolarimetry of all types, see [7]. The situation changed dramatically with observations of SN 2004dj, however, for which a sudden "spike" in polarization was seen during the steepest part of the descent off of the plateau [8]. Using existing models [9], it was concluded that the late onset of the polarization suggested a fundamentally non-spherical explosion, with the asphericity cloaked at early times by the massive, opaque, hydrogen envelope.

An obvious observational question presented itself: Was SN 2004dj a unique (or rare) event? Or, would other similarly well-observed SNe II-P display similar behavior? Chornock et al. [10] and Leonard et al. [11] provide partial answers from analysis of four additional SNe II-P: Three (SNe 2006my, 2006ov, and 2007aa) exhibit large, late-time (end of photometric plateau and beyond;) polarization [10], while one (SN 2004et) exhibits strong and temporally increasing polarization that began at least three months before the end of its plateau phase [11]. Detailed comparison of these datasets with that of SN 2004dj is hindered, however, by modest temporal sampling or phase coverage.

SPECTROPOLARIMETRY OF SN 2008BK

Here we show initial results from our program to obtain critically sampled spectropolarimetry of SNe II-P with the European Southern Observatory Very Large Telescope. Figure 1 presents nine spectropolarimetric epochs for our most well observed SN II-P, SN 2008bk, along with the data of SN 2004dj from [8]. Unlike the case for SN 2004dj, SN 2008bk was strongly polarized well *before* the end of the plateau (much like SN 2004et), with the level rising through the plateau. Despite the different temporal behavior, it is intriguing that at the point of maximum recorded polarization (i.e., day 31 with respect to the end of the plateau for SN 2004dj and day -21 for SN 2008bk) the spectropolarimetric *signatures* of SN 2008bk are virtually identical to those of SN 2004dj. This similarity may suggest a common cause — or, at least, geometry. Following the plateau drop-off, the polarization of SN 2008bk remains remarkably constant. In fact,

although not shown in Figure 1, the spectropolarimetry from days 9 through 120 post-plateau (epochs 5 through 9) are virtually indistinguishable from one another. This is quite different from the behavior of SN 2004dj.
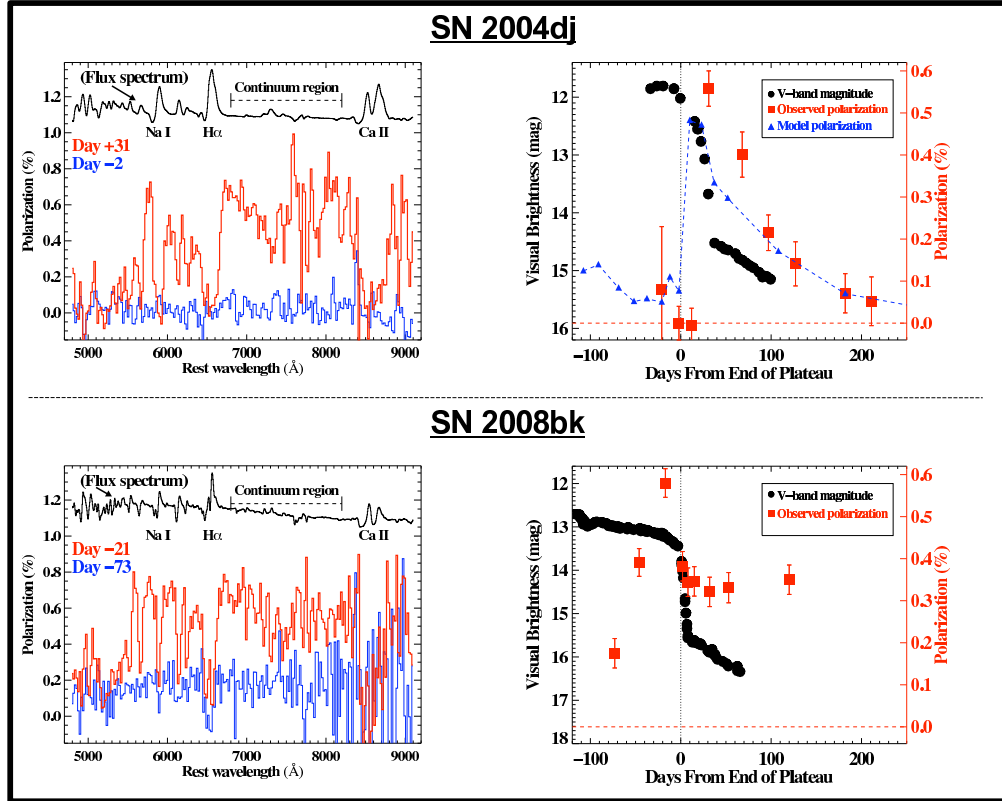

FIGURE 1. Comparison of the polarization of SN 2004dj with SN 2008bk. **Top, left**: Linear polarization of SN 2004dj at two representative epochs with respect to the end of the plateau phase (labels indicate the phase in days from the end of the plateau, defined as the point where the light curve begins a precipitous drop). **Top, right**: Continuum polarization (from the spectral region 6800 Å— 8200 Å) and *V*-band magnitude of SN 2004dj; the expected polarization derived from the models of [12] and discussed in the text is also shown (filled triangles connected by a dashed line). **Bottom:** Same as the top, but for SN 2008bk. Note that an interstellar polarization (ISP) of $\sim 0.29\%$ has been removed from the SN 2004dj data [8], whereas no ISP has been removed from the SN 2008bk data, because it is estimated to be $\lesssim 0.1\%$ from the depolarizations seen across strong emission lines (e.g., Hα, Ca II) at all epochs.

Theoretical Modeling

We have developed non-Local-Thermodynamic Equilibrium, time-dependent radiative-transfer simulations specifically crafted for SNe II-P [12]. The simulations, based on the one-dimensional SN II-P models of [13], compute the expected polarization (in both lines and continuum) as a function of time for an asphericity generated by a latitudinal density enhancement. A significant finding is that temporal polarization changes in SNe II-P do not *necessarily* implicate a change in the asymmetry of the ejecta. For instance, in Figure 1 (top, right) we include the expected temporal evolution of the continuum polarization for an SN II-P with an oblate equator-to-pole density enhancement of 1.67, viewed edge-on. This model reproduces what is observed

for SN 2004dj quite well, with the sudden "spike" in polarization now explained not by a dramatic increase in asphericity but, rather, by the sharp reduction in optical depth (i.e., fewer electron scatters for outgoing photons) that occurs at the plateau's end. The post-plateau polarization decline is also reproduced as a consequence of the expected $1/t^2$ dependence of the ejecta optical depth during the nebular phase [8, 12].

While models with a dominant and fixed large-scale asymmetry fit the polarization behavior of SN 2004dj, the substantial early time polarization seen in SN 2008bk (and SN 2004et) is not replicated; in fact, current models with equator-to-pole density enhancements as extreme as 5.0 are unable to produce significant (i.e., $> 0.1\%$) polarization during the mid-plateau [12]. The persistent late-time polarization seen in SN 2008bk also presents a modeling challenge.

It is worth noting that, in addition to their spectropolarimetric differences, SNe 2008bk, 2004dj, and 2004et also exhibit photometric and spectroscopic differences [14, 15], some of which are clearly evident for SN 2004dj and SN 2008bk in Figure 1, such as the rapidity of the plateau drop-off. These differences may be associated with explosion physics but might also be related to the progenitor's core structure and the ^{56}Ni-mixing properties (morphology, amount, depth below the hydrogen-rich envelope; see [16]) as well. It is hoped that with the benefit of further modeling we may begin to connect all of these parameters and develop a consistent interpretation of the asymmetries indicated by the polarization of SNe II-P.

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