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MULTI-EPOCH SPECTROPOLARIMETRY OF SN 2011fe

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ABSTRACT

We present multiple spectropolarimetric observations of the nearby Type Ia supernova (SN) 2011fe in M101, obtained before, during, and after the time of maximum apparent visual brightness. SN 2011fe exhibits time-dependent polarization in both the continuum and strong absorption lines. At all epochs, red wavelengths exhibit a degree of continuum polarizaiton of 0.2–0.4%, likely indicative of persistent asymmetry in the electron-scattering photosphere. However, the degree of polarization across the Si II λ6355 absorption line varies dramatically from epoch to epoch. Before maximum, Si II λ6355 shows enhanced polarization at the same position angle (PA) as the polarized continuum. During two epochs near maximum, however, Si II λ6355 absorption has a lower degree of polarization, with a PA that is 90° from the continuum. After maximum, the absorption feature has the same degree of polarization and PA as the adjacent continuum. Another absorption feature in the blue (either Si II λ5051 or a blend with Fe II lines) shows qualitatively similar changes, although the changes are shifted in time to an earlier epoch. This behavior is similar to that seen in broad absorption-line quasars, where the polarization in absorption features has been interpreted as the line absorbing some of the unpolarized continuum flux. This behavior, along with the 90° shifts of the polarization PA with time, imply a time-dependent large-scale asymmetry in the explosion.

Subject headings: supernovae: general

1. INTRODUCTION

Type Ia supernova (SN Ia) explosions convey information about the nucleosynthesis of the thermonuclear destruction of a CO white dwarf (Iwamoto et al. 1999), and they provide a way to measure the expansion of the universe by using their peak magnitudes as standardizable candles (Phillips 1993). The unexpected finding that the expansion of the universe is accelerating (Riess et al. 1998; Perlmutter et al. 1998) has focussed interest on a better understanding of the SN Ia explosion mechanism. It has long been recognized that there are variations within the SN Ia category. More luminous events rise to peak and decline from peak on a longer timescale than less luminous events (Branch, Fisher & Nugent 1993; Phillips 1993). The majority of events fall within a "normal" grouping, although some cases have been recognized where the luminosity does not correlate with peak width (e.g., Benetti et al. 2005; Wang et al. 2009; Foley & Kasen 2011). Asymmetries in the explosion may hold important clues to the explosion mechanism itself, as well as the consequent diversity in observed properties.

Spectropolarimetry has emerged as a powerful probe of SNe Ia (see Livio & Pringle 2011). The degree of polarization of the continuum emission is generally lower for SNe Ia than for core-collapse events, but it has been detected at significant levels for a range of SN Ia subclasses. Measured polarization at the wavelengths of observed absorption lines is particularly interesting, as it affords the opportunity to study the distribution of specific elements within the ejecta. This "line polarization" has been observed to change markedly near maximum light. The signature Si II λ6355Å line has exhibited line polarization in a number of SNe Ia: SNe 1999by (Howell et al. 2001), 2001el (Wang et al. 2003), 2002bf, 1997dt, 2003du, 2004dt (Leonard et al. 2005), 2004dt (Wang et al. 2006), and 2006X (Patat et al. 2009). Absorption lines of other elements have also been detected, notably Fe II lines (SN 1997dt: Leonard et al. 2005), and the Ca II IR triplet (SN 2001el: Wang et al. 2003; SN 2006X: Patat et al. 2009). For a review of polarimetric studies of SNe Ia, see Wang & Wheeler (2008).

SN 2011fe occurred in M101, and was discovered on 2011 August 24 by the Palomar Transient Factory (PTF: Brown et al. 2011, Nugent et al. 2011a, 2011b). The proximity of M101, ∼6.2 Mpc, and the location of the SN far from the host galaxy core and spiral arms, suggested that the SN would become the brightest SN Ia since SN 1972E. It was predicted to have a visual peak brighter than 10.0 mag. Studies of the light curve suggest that the SN was discovered just 0.5 days after the explosion, and the explosion time is constrained to very high precision (Nugent et al. 2011b). Optical spectra revealed SN 2011fe to be a normal SN Ia, with detections of C II λ6580 and λ7234 in absorption (Cenko et al. 2011). Studies of pre-explosion images of the site of SN 2011fe place the strictest upper limits yet on the luminosity of any SN Ia progenitor, arguing against a single-degenerate progenitor containing a giant donor star (Li et al. 2011).

SN 2011fe was the nearest Type Ia explosion in several decades, providing an unprecedented opportunity to obtain spectropolarimetry of a normal SN Ia with modest-aperture telescopes. We initiated a campaign to obtain multi-epoch spectropolarimetry of SN 2011fe at Steward Observatory (*SO*), using the 1.54-m Kuiper and 2.3-m Bok telescopes. We describe the results of these observations below.

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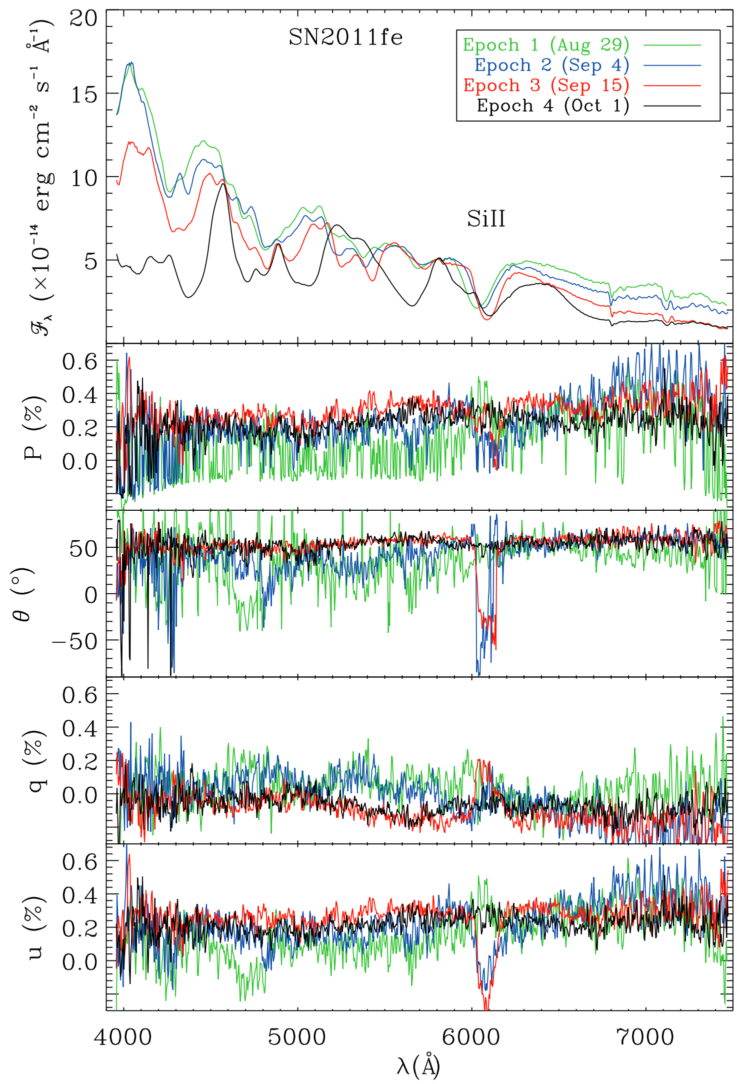

FIG. 1.— The four epochs (color coded) of flux, degree of polarization, angle, and normalized Stokes parameters q and u. The flux values have been scaled to the first epoch flux at 5800 Å using the following flux ratios: 1.0, 0.228, 0.148, 0.215. For the first epoch, angles less than $-45°$ have been rotated by 180° to remove confusion near the feature at 4700 Å.

2. OBSERVATIONS

The SPOL CCD Imaging/Spectropolarimeter (Schmidt et al. 1992a) mounted on the Steward Observatory 2.3-m Bok telescope (Kitt Peak, AZ) and the 1.54 Kuiper telescope (Mt. Bigelow, AZ) was used to obtain spectropolarimetry of SN 2011fe over 10 nights. We have grouped the 10 nights of observations into four Epochs in Table 1. Observations covered 4000–7550Å at a resolution of ∼20 Å (600 line mm^{-1} grating in first order, using a 5.″1×51″ slit and a Hoya L38 blocking filter). A rotatable semiachromatic half-wave plate was used to modulate incident polarization and a Wollaston prism in the collimated beam separated the orthogonally polarized spectra onto a thinned, anti-reflection-coated 800×1200 SITe CCD. The efficiency of the wave plate as a function of wavelength is measured by inserting a fully-polarizing Nicol prism into the beam above the slit. A series of four separate exposures that sample 16 orientations of the wave plate yields two independent, background-subtracted measures of each of the normalized linear Stokes parameters, q and u. Each night, several such sequences of observations of SN 2011fe were obtained and combined, with the weighting of the individual measurements based on photon statistics. The polarization results for September 15 and 16 were indistinguishable, so they were combined to yield the final result for the third observational epoch. Similarly, the polarization spectra from the six observations obtained between September 26 and October 6 (Epoch 4) were averaged together, since we detected no inter-night variations in Q or U over this time period.

We confirmed that the instrumental polarization of SPOL mounted on the Bok and Kuiper telescopes is much less than 0.1% through observations of the unpolarized standard stars BD+28°4211 and HD 212311 (Schmidt et al. 1992b) during each epoch. The linear polarization position angle on the sky (θ) was determined by observing the interstellar polarization standards Hiltner 960 and VI Cyg #12 (Schmidt et al. 1992b) during all epochs. Additional observations of the polarization

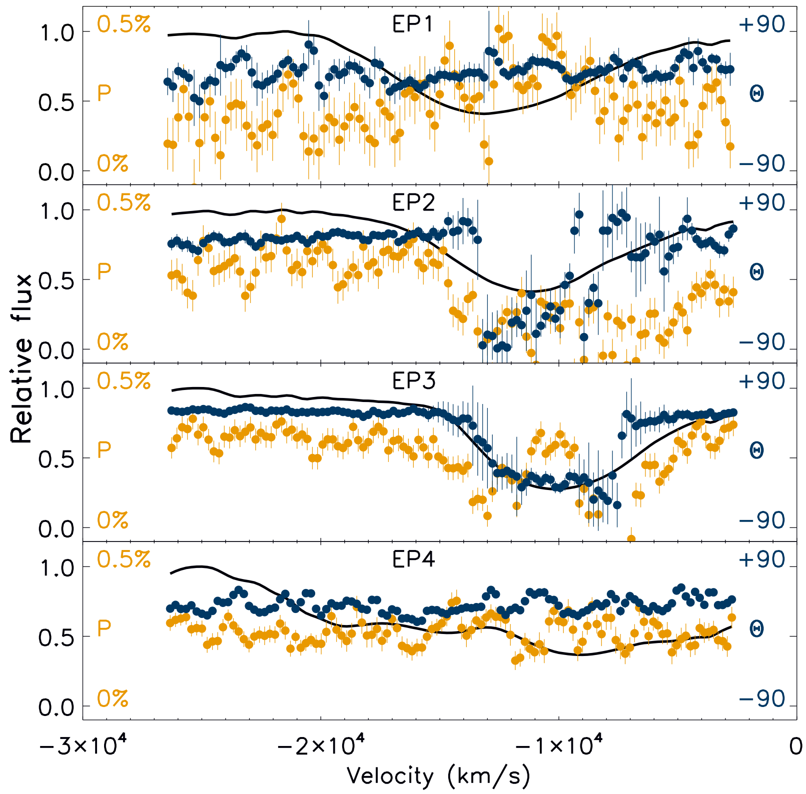

FIG. 2.— Plots of Si II λ6355 in velocity space for all four epochs. The flux is shown in black, P in orange and θ in blue. Flux spectra have been normalized to highest flux in wavelength range.

TABLE 1
OBSERVATION LOG FOR SN 2011FE

UT Date	days +exp[a]	days +B$_{max}$[b]	UT (start)	UT (end)	Exp (sec)	Epoch
2011-08-29	5.4	-12.0	03:32:02	04:47:55	3840	1
2011-09-04[c]	11.4	-6.0	02:51:44	04:33:19	4320	2
2011-09-15	22.4	5.0	02:53:41	03:40:45	1504	3
2011-09-16	23.4	6.0	02:48:08	03:58:29	2784	3
2011-09-26	33.4	16.0	02:41:28	03:14:17	1440	4
2011-09-28	35.4	18.0	02:53:44	03:13:46	800	4
2011-09-29	36.4	19.0	02:20:22	03:06:02	1920	4
2011-09-30	37.4	20.0	02:26:08	02:56:33	1920	4
2011-10-01	38.4	21.0	02:24:33	02:54:56	1280	4
2011-10-06	43.4	26.0	02:09:04	02:39:28	1280	4

[a]Epoch relative to explosion, 23.7 Aug. 2011, as estimated by averaging explosion dates of Brown et al. (2011) and Nugent et al. (2011).
[b]Epoch relative to the reported date of B$_{max}$, 10.1 +/ − 0.2 Sep. 2011, as reported by Matheson et al. (2011).
[c]This epoch of observations was obtained with SPOL mounted on the 1.54m Kuiper telescope at Mt. Bigelow, AZ. All other epochs used SPOL mounted on the 2.3-m Bok telescpe on Kitt Peak, AZ.

standard stars BD+59°389 and BD+64°106 were made during the third epoch (Table 1). The adopted correction from the instrumental to the standard equatorial frame for θ for all epochs was determined from the average position angle offset of Hiltner 960 and VI Cyg #12. Differences between the measured and expected polarization position angles were $< 0\farcs3$ for all of the standard stars.

During the first epoch, two field stars within $\sim 2'$ of SN 2011fe (2MASS J14031367+5415431 and 2MASS J14025413+5416288) were measured to check for significant Galactic interstellar polarization (ISP) along the line-of-sight to the SN. These stars yielded a consistent estimate for Galactic ISP, with $P_{max} = 0.11 \pm 0.03\%$ at $\theta = 114° \pm 7°$ for 2MASS J14031367+5415431 and $P_{max} = 0.16 \pm 0.03\%$ at $\theta = 109° \pm 6°$ for 2MASS J14025413+5416288, assuming that λ_{max}, the wavelength where the interstellar polarization is at a maximum (P_{max}) is 5550Å. The results for the field stars were averaged and $P_{max} = 0.13\%$ at $\theta = 112°$ was adopted as the Galactic ISP in the sightline to SN 2011fe. This low value for the Galactic ISP is consistent with the high Galactic latitude of M101 and the very low estimated amount of extinction for the supernova. The polarization spectra of SN 2011fe have been corrected for this level of Galactic ISP assuming that it is fit well by a Serkowski law (Wilking et al. 1980; Serkowski, Mathewson, & Ford 1975). No estimate or correction for ISP within M101 at the location of SN 2011fe has been made (although see §3). Our reported values for the degree of linear polarization, P, have been corrected for statistical bias (Wardle & Kronberg 1974).

3. POLARIZATION OF SN 2011fe

Our sequence of spectra are shown in the top panel of Figure 1, displaying the emergence of absorption features typical of SNe Ia. The continuum emission is polarized with the red wavelengths more highly polarized than the blue wavelengths at early epochs, reaching up to ∼0.4%. The polarization of the red continuum (6500-7500Å) exhibits a slight decrease with time, from about 0.4% down to 0.2%, while continuum polarization in the 5000-5900Å range increases from undetected up to 0.2%.

The polarization of absorption lines is clearly present in blueshifted Si II λ6355Å absorption, and it changes markedly with time. This line polarization of Si II is shown in velocity space in Figure 2. Before maximum at Epoch 1, Si II λ6355Å shows polarization at the same position angle (PA) as the continuum, but is roughly 0.2% stronger than the adjacent continuum in polarization degree. In the subsequent two epochs near maximum (Epochs 2 and 3), however, Si II λ6355Å absorption has ∼0.2% *weaker* polarization than the continuum, and the absorption-line PA changes by about 90° (Figure 2). Well after maximum in Epoch 4, the absorption trough returns to showing the same polarization and PA as the adjacent continuum — although note that the continuum polarization has increased since Epoch 1. The blueshift of the Si II feature decreases with epoch, consistent with a low velocity gradient event (LVG; Benetti et al. 2005).

Line polarization is also present in an absorption feature in the 4600-5000 Å region. This might be Si II λ5051, which may be blended with nearby Fe II lines. Similar blue features have been seen to exhibit line polarization in other SNe Ia (Leonard et al. 2005), although not necessarily the same absorption feature as in SN 2011fe. The polarization of this feature is also variable, exhibiting overall behavior similar to that of Si II λ6355, but shifted about one epoch earlier in time. In other words, this blue absorption feature shows line depolarization in Epoch 1, which then disappears in Epochs 2 and 3 when the same depolarization appears in the Si II λ6355Å line. Moreover, the apparent depolarization of the blue line approaches a PA that is nearly orthogonal to the continuum polarization PA, similar to what occurs later for the red absorption line. We speculate that the blue absorption feature traces the same asymmetric layers in the SN atmosphere that are seen in Si II λ6355 in Epochs 2 and 3, but at an earlier time. This may be an important clue to the changing structure in the receding SN photosphere, which can hopefully provide constraints on additional radiative transfer models of the observed polarization behavior.

4. SUMMARY AND INTERPRETATION

A key result of our spectropolarimetry is that Si II λ6355 absorption exhibits a polarization angle that changes with time, and more importantly, reaches a PA in the absorption line polarization that is roughly *orthogonal* to the adjacent continuum polarization angle for an extended time around maximum light when the line depolarization is strongest. This behavior can be approximated by two polarized components that have perpendicular PAs, and comparable amounts of polarization that do not completely cancel, leaving a net residual linear polarization. Small changes in the strength of the absorption line feature's polarization can shift the residual net polarization by 90°, because one or the other components dominates. This behavior is approximated by a simple two-component model of the spectrum at Epoch 3, shown in Figure 3, where the observed flux is composed of two such orthogonal components, but where one of the two has a different absorption equivalent width in Si II λ6355. There is a small amount (∼0.2%) of net residual continuum polarization dominated by one component, but this changes across the line feature due to absorption of the polarized continuum flux by the line.

The fact that these two components have orthogonal PAs that persist with time and are seen at the earliest epoch in a different absorption feature, is suggestive that there is some small amount of global asymmetry in the ejecta of SN 2011fe, perhaps even suggesting axial symmetry in the event. For example, the observations could be explained if the continuum polarization arises from an electron scattering photosphere that is slightly elongated in the polar direction, whereas the strongest Si II λ6355 absorption may occur in an equatorial belt. This is just one possible scenario. More definitive constraints on the SN ejecta geometry will require more detailed analysis with radiative transfer calculations.

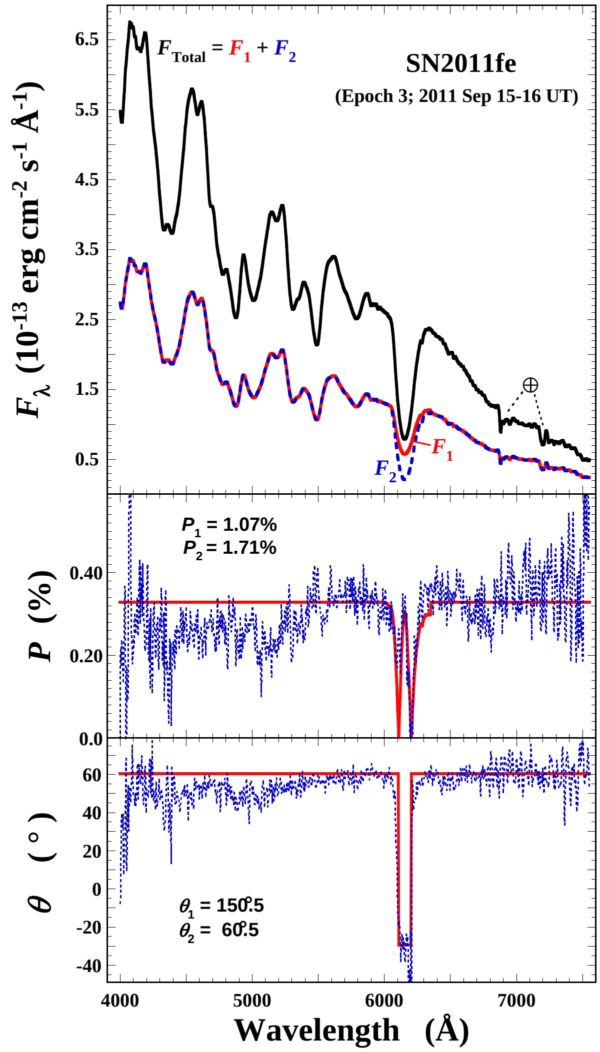

Fig. 3.— A simple non-unique model that can match the observed polarization at Epoch 3 using two scattering components with orthogonal PA. The two components have slightly different continuum polarization, and also have slightly different absorption equivalent widths in Si II λ6355 that result in different residual amounts of polarization in and out of the absorption line. The strong shift in PA occurs when one component dominates the polarization PA in the absorption line.

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