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SPECTROPOLARIMETRY OF SN 1993J IN NGC 3031

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ABSTRACT

We have obtained low-resolution optical spectropolarimetry of SN 1993J which shows a high continuum linear polarization and a 0.5% drop in polarization across the Hα emission line accompanied by a $\sim 15°$ position angle rotation. From these data we infer the presence of two distinct polarization components and conclude that at least part of the polarization is intrinsic to the supernova. We propose that the polarization observed at Hα is due to interstellar polarization within NGC 3031, while the continuum polarization is intrinsic to the object. After correcting the observed Stokes parameters for interstellar polarization, we find that the intrinsic continuum polarization is high, $P = 1.6\% \pm 0.1\%$ at $\theta = 49° \pm 3°$, and is wavelength-independent. The Stokes flux displays blueshifted Hα absorption which suggests that the polarization is generated primarily in the underlying continuum source. Comparing our results to the scattering photosphere models of Shapiro & Sutherland we find that to produce the continuum polarization the ratio between the semimajor and semiminor axes of the scattering envelope must be ≥ 1.54 for the oblate case, and ≥ 2.0 for the prolate case. We also consider the point-source scattering envelope models of Brown & McLean, and find that for an oblate scattering envelope the models require that the inclination be close to edge-on unless the asymmetry is extreme. On the other hand, the prolate case can produce high polarization for a wide range of inclination angles.

Subject headings: supernovae: general — supernovae: individual (SN 1993J) — techniques: polarimetric — techniques: spectroscopic

1. INTRODUCTION

Most models of supernova explosions, light curves, and spectra assume spherical symmetry; however, both the evolution of supernovae and their use as cosmological distance indicators may be influenced by aspherical geometry (Shapiro & Sutherland 1982, hereafter SS82). Are supernova explosions really spherical? Observational evidence is needed to investigate the existence of aspherical structure in the ejecta of supernova and to constrain the degree of asymmetry present.

Polarimetry provides a unique observational tool to explore this question since it allows the study of the geometry of unresolved sources if the polarization mechanism is scattering. Before SN 1987A, broad-band polarization and spectropolarimetric observations of supernovae were rare (SS82; McCall et al. 1984; McCall 1985; Spyromilio & Bailey 1993). SN 1987A was the subject of several broad-band polarimetry and spectropolarimetry projects. Analyses of these data lead to the conclusion that the ejecta of this supernova possessed length-width asymmetry in the range 5%–30% (Mendez et al. 1988; Cropper et al. 1988; Barrett 1988; Höflich 1987; Jeffery 1991). The discovery of supernova 1993J in the nearby galaxy NGC 3031 presents an excellent opportunity to investigate another supernova using polarimetric techniques. In this paper we present high-quality, low-resolution spectropolarimetry of SN 1993J.

2. OBSERVATIONS

The observations were obtained with the McDonald Observatory 2.7 m telescope and spectropolarimeter (Goodrich 1991) on 1993 April 20.11. The detector was an 1024×1024 CRAF/Cassini CCD with 12 μm pixels binned 1×2 (dispersion times spatial). All spectra were taken using a slit width of 2″ and a slit length of 35″. The observations were taken through thin cirrus and with a typical seeing of 1″–2″. The resulting spectra cover the wavelength range 4450–6850 Å with a dispersion of 2.69 Å pixel^{-1}.

The sky-subtracted spectra of the supernova were obtained by co-adding all the rows that contained flux from the object. Wavelength calibration of the spectra was performed using neon and argon lamps. The zero points of the wavelength scales were adjusted using the [O I] night sky lines at λ5577.34 and λ6300.30. Absolute flux calibration of all spectra was obtained by observing Feige 34 (Stone 1977). Slit losses and sky conditions limit the accuracy of the absolute fluxes (30%). However, the relative fluxes within a given spectrum are quite reliable (5–10%). The data were reduced using VISTA and our standard polarimetric reduction package as outlined in Miller, Robinson, & Goodrich (1988).

3. RESULTS

We detect a relatively high degree of polarization $P = 0.9\% \pm 0.1\%$ at a position angle, θ, $33° \pm 3°$ (averaged over the range 4900–6800 Å). In addition, there is a 0.5% decrease in the polarization across the Hα emission line accompanied by a $\sim 15°$ position angle rotation (Trammell, Hines, & Wheeler 1993; see Fig. 1). These findings are consistent with those reported by Jannuzi et al. (1993) for data taken on April 26.12 UT, 6 days after our observations. Clearly there are two polarization components present. Because the line and continuum emission are both produced by the supernova, but their polarizations are different, the observed polarization we measure cannot be attributed entirely to interstellar polarization. At least part of the observed polarization is intrinsic to the supernova. If the polarization mechanism is scattering, as was the case for SN 1987A (e.g., Mendez et al. 1988), then this implies an aspherical geometry for the supernova ejecta.

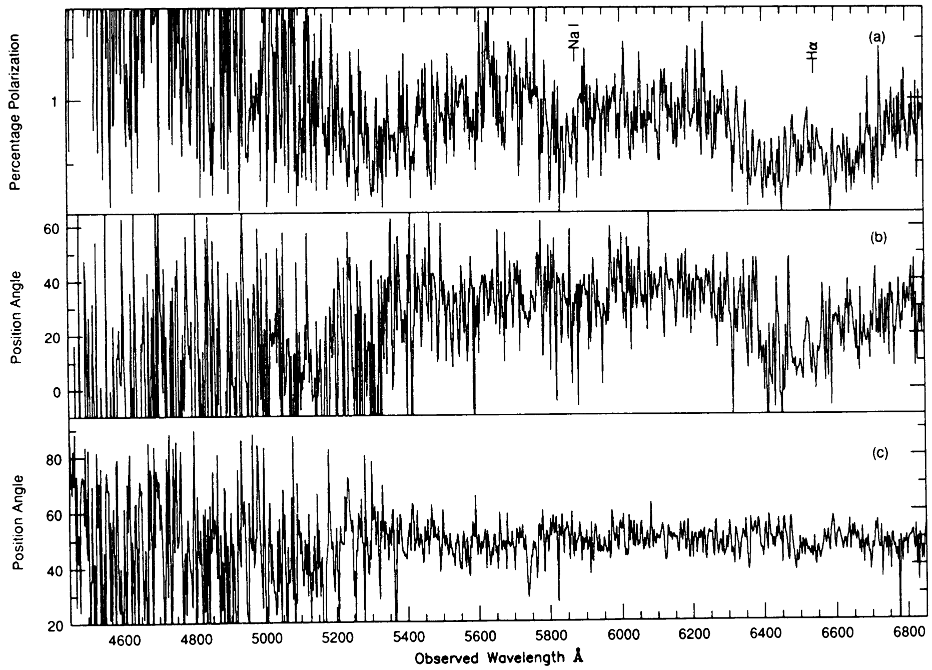

FIG. 1.—(a) Percentage polarization of SN 1993J as a function of wavelength. $P(\lambda)$ has not been corrected for interstellar polarization. Notice the dip in P coincident with the Hα emission line. (b) Position angle as a function of wavelength *before* correcting for the interstellar polarization. Notice the rotation in θ at the position of Hα. (c) Position angle as a function of wavelength *after* correcting for the interstellar polarization. Notice that the position angle is now wavelength-independent.

4. ANALYSIS: THE ORIGIN OF THE OBSERVED POLARIZATION

We propose that the continuum is intrinsically polarized, via electron scattering, while the Hα polarization is due entirely to interstellar polarization within NGC 3031. After removing the observed continuum polarization, we measure the polarization of the Hα emission alone to be $P = 1.1\% \pm 0.1\%$ at $\theta = 150° \pm 4°$. We note that resonance scattering may slightly depress the underlying continuum polarization at Hα, so the above value for the Hα polarization may slightly underestimate the true Hα polarization. Evidence described below suggests that this effect is probably very small and will not significantly change our results. While it is possible that the Hα polarization is caused by scattering or dichroic absorption local to the supernova, based on the following arguments we suggest that the Hα polarization is most likely interstellar in origin.

The total reddening along our line of sight to the supernova is estimated to be $E(B-V) = 0.15 \pm 0.02$ (Wheeler et al. 1993), which is sufficient to produce the 1% Hα polarization via dichroic absorption by intervening dust (e.g., Spitzer 1978). The Galactic latitude of the supernova is $+41\overset{\circ}{.}35$, well out of the plane of our Galaxy, implying that the interstellar polarization from our Galaxy is probably small. In addition, within a $20° \times 20°$ box around the supernova there are seven foreground stars with polarization measurements (Behr 1959). The average polarization of these seven stars is $P = 0.074\% \pm 0.02\%$ at $\theta = 63° \pm 15°$, further suggesting that the polarization due to dust in our Galaxy is small compared to, and has a different position angle than, the Hα polarization that we observe.

The SN occurred in a spiral arm. Optical imaging polarimetry of several face-on spirals (e.g., Elvius 1978; Scarrott et al. 1991) shows that the position angle of the polarized emission from the spiral arms is parallel to the arms and closely follows their morphology. The position angle of the Hα polarization, 150°, is within 15° of the projected position angle of the spiral arm of NGC 3031 near SN 1993J. Radio observations of NGC 3031 show that the direction of the magnetic field is parallel to the spiral arms, and the position angle at the location of the supernova is approximately 150° (Beck, Klein, & Krause 1985). The coincidence between the position angles of our measured Hα polarization, the spiral arm, and the magnetic field, coupled with the apparent lack of interstellar polarization in our Galaxy, suggests that this component of the polarization is caused by dichroic absorption by dust in the interstellar medium of NGC 3031. We conclude that the observed Hα polarization is consistent with being essentially entirely interstellar in origin. The behavior of P and θ at the wavelengths of the other emission lines (Na I, Fe II) is also consistent with this interpretation, but low signal-to-noise and difficulties in determining the continuum level prohibit a detailed investigation of these lines.

We thus identify two components of polarization in our data: an interstellar component due to dust within NGC 3031, which affects both the lines and the continuum, and a component intrinsic to the supernova which affects only the continuum. We must remove the interstellar component to study the intrinsic polarization of SN 1993J. To do this we assume that the Hα polarization is an accurate measure of the interstellar component. We remove a Serkowski law for the interstellar polarization (Wilking, Lebofsky, & Rieke 1982) using $P_{max} = 1.1\%$, $\theta = 150°$ (the Hα polarization) and $\lambda_{max} = 5500$ Å. After subtracting the interstellar component we find that the position angle is independent of wavelength—consistent with the presence of only one remaining polarization source (see Fig. 1).

The average continuum polarization after correction for the interstellar component is $P = 1.6\% \pm 0.1\%$ at $\theta = 49° \pm 3°$. The wavelength-independent nature of the continuum polarization implies that the continuum is polarized by scattering off electrons as was concluded for SN 1987A (e.g., Mendez et al. 1988).

Having removed the interstellar component, we isolate the scattered continuum radiation by forming the Stokes flux, which does not suffer from the biased error distribution inherent in polarized flux. The Stokes flux is formed by first rotating all the polarization into a single, rotated Stokes parameter (see Trammell, Dinerstein, & Goodrich 1993 for description). Stokes flux is then constructed by multiplying this rotated Stokes parameter by the total flux. The Stokes flux for SN 1993J is displayed in Figure 2*b*. There are no obvious emission lines present in the Stokes flux; in particular, by construction, there is no Hα emission. The blueshifted absorption trough associated with the Hα P Cygni profile is present, indicating that the polarized light propagates through the absorbing material. This fact, coupled with the knowledge that the Hα emission is probably intrinsically unpolarized, suggests that the continuum is scattered, thus polarized, interior to the region that emits Hα.

By isolating the absorption feature in the Stokes flux, we are able to analyze the absorption feature without the difficulties associated with the removal of the emission-line contamination in the total flux. We measure the relative velocity shift of the trough minimum from 6563 Å to be 10,500 km $s^{-1} \pm 500$ km s^{-1}, and the FWZI to be 18,700 km s^{-1}. Note that we did not correct for systemic or galactocentric velocity, but these quantities are both small and within our errors. The equivalent width for the Hα absorption is 197 ± 23 Å.

The best blackbody fit to the continuum in Stokes flux gives $T = 5800 \pm 900$ K. The large uncertainty is caused by the difficulty in determining the continuum shape at wavelengths shorter than 5000 Å, where our signal-to-noise in the Stokes flux is low. This temperature is consistent with those of other Type II supernovae, including SN 1987A (Swartz, Wheeler, & Harkness 1991).

Following the procedure outlined in Trammell et al. (1993), we calculate the unscattered flux spectrum by dividing the Stokes flux spectrum by the average continuum polarization and then subtracting this from the total flux. This assumes that all of the continuum emission is scattered. The resulting spectrum is displayed in Figure 2*c*. The Hα emission is isolated in this spectrum and thus is not affected by the adjacent absorption as it is in the total flux. Fitting a single Gaussian to the Hα emission in unscattered light, we find a FWHM = 16,000 km s^{-1} and a FWZI = 28,000 km s^{-1}. This is only an approximation since the Hα profile may not be best described by a single Gaussian.

5. INTERPRETATION: THE MORPHOLOGY OF THE SCATTERERS

What does the high degree of continuum polarization ($P = 1.6\% \pm 0.1\%$) tell us about the geometry of the supernova ejecta? Assuming that the polarization mechanism is scattering, the mere fact that we are measuring a net polarization implies aspherical geometry. A logical choice for modeling the distribution of scatters is a spheroidal shell. We compare our polarization results to two types of scattering models. In these models the scatterers are uniformly distributed in the shell. We note, however, that nonsymmetric, clumpy ejecta could also induce the observed polarization (e.g., Chugai 1992).

First we compare our results to the models of SS82. In these models the continuum source itself is aspherical and is surrounded by an optically thick, physically thin skin of scattering electrons. SS82 only calculate the edge-on case so that our

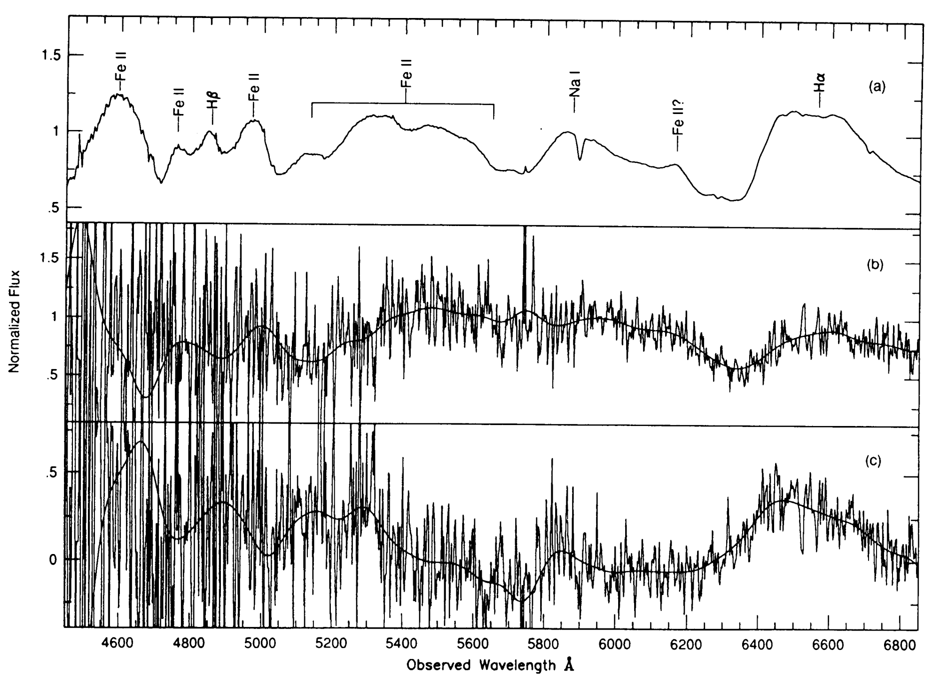

FIG. 2.—(*a*) Total flux spectrum of SN 1993J normalized to 1.5×10^{-13} ergs s^{-1} cm^{-2} $Å^{-1}$. (*b*) Stokes flux spectrum of SN 1993J. Notice the absorption dip in the continuum near 6400 Å (*see text*). Solid line is the Stokes flux smoothed by a 20 pixel Gaussian. (*c*) Unscattered flux spectrum for SN 1993J. Hα emission is isolated in this spectrum. Solid line is the unscattered flux smoothed by a 20 pixel Gaussian.

estimate of the degree of asymmetry is a lower limit. For the pure scattering case, the observed polarization can only be explained by an oblate geometry. To obtain 1.6% polarization, the ratio of the semimajor axis to semiminor axis, A, of the oblate spheroid is approximately 3.0. For the models that include absorption effects, A is reduced to 1.54 for the oblate case. If absorption is included, a prolate geometry can produce the observed 1.6% polarization with an implied axis ratio of 2.0. In these models the polarization is generated very close to the continuum source. This is consistent with our observation that the blueshifted Hα absorption is seen in Stokes flux, indicating that the polarized continuum must have passed through, and been absorbed by, the hydrogen envelope.

We also consider the pure scattering models of Brown & McLean (1977), which consist of an extended aspherical, optically thin shell of electrons illuminated by a central, unpolarized point source. The Brown & McLean oblate spheroid models were refined by Fox (1991) to include the effects of both an extended spherical illumination source and occultation of the back side of the shell by the central source. He found that the effects of occultation could, in general, be neglected for an oblate spheroid. In addition, any depolarization source would require that the asymmetry be larger for a given observed polarization as compared with the Brown & McLean model. Based on these arguments, we take the simplest approach and use the unmodified models of Brown & McLean to constrain the geometry of the supernova ejecta assuming a scattering optical depth of one. For the oblate case, our observed continuum polarization requires either that the ratio of the semimajor to semiminor axis, A, is between 1.1 and 3.0 and the inclination angle is between 1° and 8° (i.e., the scattering envelope is viewed very close to edge-on), or $A > 3.0$ for larger viewing angles. For the prolate case, a large range of inclination angles can produce the observed polarization without requiring large asymmetries. If the scattering envelope has $1 < A \leq 2.0$, the allowed inclination angles are between 15° and 90°. To produce the observed polarization, the oblate case must be viewed nearly edge-on unless the asymmetry is extreme, while the prolate case can produce high polarization for a wide range in inclination angles. This type of model is more difficult to reconcile with the Hα absorption seen in the polarized flux.

If the Hα polarization is not entirely due to interstellar polarization within NGC 3031, then the intrinsic continuum polarization may be slightly less than P = 1.6% (§ 4). However, this does not change our conclusion that the supernova is asymmetric, and our estimates of the implied asymmetry are only slightly altered. For example, if $P = 0.9\%$ (§ 4) this implies a slightly smaller degree of asymmetry in the SS82 models: $A = 2.3$ for the oblate case with no absorption, $A = 1.3$ for the oblate case with absorption, and $A = 1.5$ for the prolate case with absorption. The prolate case without absorption is still not possible. The range in the possible asymmetry implied by the Brown and McLean models is essentially unchanged.

Steinmetz & Höflich (1992) show that the explosion of rotating stars can lead to a configuration that evolves from oblate to prolate as the photosphere recedes through homologous, but asymmetrically, expanding portions of the ejecta. Such models would tend to favor prolate configurations at late times, and would be consistent with the source of the polarization being the embedded asymmetric continuum source (e.g., SS82). An expanding, asymmetric core could induce related asymmetries in an initially spherical envelope. Such an envelope could, however, be intrinsically asymmetric due to equatorial mass shedding or bipolar flow.

6. SUMMARY

We measure a high degree of polarization for SN 1993J. There is a dip in polarization at Hα accompanied by a position angle rotation. The Hα polarization alone is measured to be $P = 1.1\%$ at a position angle of 150°. We attribute this to an interstellar component due to dichroic absorption by dust in NGC 3031. After removing the interstellar polarization, we find a high degree of polarization in the continuum of SN 1993J, which is intrinsic to the source ($P = 1.6\% \pm 0.1\%$ at a position angle of $49° \pm 3°$). We suggest that the intrinsic continuum polarization is caused by electron scattering, thus the observed polarization implies an aspherical geometry for the SN ejecta. Using the scattering models of SS82 we find that to produce our measured continuum polarization, the ratio between the semimajor and semiminor axes of the scattering envelope must be ≥ 1.54 for the oblate case and ≥ 2.0 for the prolate case. The Brown & McLean scattering models require very small inclinations unless the asymmetry is extreme for an oblate scattering envelope. The prolate case can produce high polarization for a wide range of inclination angles.

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