OPTICAL SPECTROPOLARIMETRY OF SN 2002AP: A HIGH VELOCITY ASYMMETRIC EXPLOSION

K. S. Kawabata, D. J. Jeffery, M. Iye, Y. Ohyama, G. Kosugi, N. Kashikawa, N. Ehizuka, T. Sasaki, K. Sekiguchi, K. Nomoto, P. Mazzali, J. Deng, K. Maeda, K. Aoki, Y. Saito, T. Takata, M. Yoshida, R. Asai, M. Inata, K. Okita, K. Ota, T. Ozawa, Y. Shimizu, H. Taguchi, Y. Yadoumaru, T. Misawa, F. Nakata, T. Yamada, I. Tanaka, and T. Kodama

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ABSTRACT

We present spectropolarimetry of the Type Ic supernova SN 2002ap and give a preliminary analysis: the data were taken at two epochs, close to and one month later than the visual maximum (2002 February 8). In addition we present June 9 spectropolarimetry without analysis. The data show the development of linear polarization. Distinct polarization profiles were seen only in the O I λ7773 multiplet/Ca II IR triplet absorption trough at maximum light and in the Ca II IR triplet absorption trough a month later, with the latter showing a peak polarization as high as ~ 2%. The intrinsic polarization shows three clear position angles: 80° for the February continuum, 120° for the February line feature, and 150° for the March data. We conclude that there are multiple asymmetric components in the ejecta. We suggest that the supernova has a bulk asymmetry with an axial ratio projected on the sky that is different from 1 by of order 10%. Furthermore, we suggest very speculatively that a high velocity ejecta component moving faster than ~ 0.115c (e.g., a jet) contributes to polarization in the February epoch.

Subject headings: polarization — supernovae: individual (SN 2002ap)

1. INTRODUCTION

SN 2002ap was discovered in the nearby spiral galaxy M74 (= NGC 628) on 29 January 2002 (Nakano et al. 2002) and reached its maximum of M74 (= NGC 628) on 29 January 2002 (Nakano et al. 2002) and reached its maximum of V ~ 12.4 mag on February 8 (Gal-Yam, Ofek, & Shemmer 2002). It has been classified as a Type Ic supernova (SN Ic) and suggested to be a hypernova (but at the low-energy end of the sequence of hypernovae) from the fact that its early spectra had very broad absorption lines (Mazzali et al. 2002 and references therein). Because of its apparent optical brightness, SN 2002ap provided us with a rare opportunity to carry out multi-epoch, high-quality spectropolarimetry of a peculiar supernova. Unfortunately, the supernova was lost behind the Sun from mid-March to early June, limiting our ability to observe it in the brightest phase.

2. SNE Ic, HYPERNOVAE, SUPERNova POLARization

A SN Ic is thought to be the result of the core collapse of a massive star that has either lost its hydrogen and helium envelopes prior to the explosion or has an intrinsic visible helium envelope due to low excitation. The details of the explosion mechanism are still under discussion (Nomoto, Iwamoto, & Suzuki 1995; Branch 2001 and references therein).

It has recently been recognized that there is a subgroup of SNe Ic whose members, tentatively called hypernovae, exhibit very broad absorption lines in their early spectra. Some hypernovae have had their spectra successfully modeled as the hyperenergetic explosion of a massive C+O star, with an explosive kinetic energy exceeding ~ 5–10 times as much as that of normal core-collapse SNe (Iwamoto et al. 1998; Nomoto et al. 2001 and references therein). SN 1998bw, the most luminous and energetic ‘hypernova’ to date, has been particularly well studied, and its probable connection with the γ-ray burst GRB 980425 has been pointed out (e.g., Galama et al. 1998). An aspherical hyperenergetic explosion has been suggested to explain the slowly-declining light curve of SN 1998bw and the narrowness of the [O I] λ6300, 6363 emission line in the nebular phase (Mazzali et al. 2001; Nakamura et al. 2001;...
Maeda et al. 2002). Alternatively, Höflich, Wheeler, & Wang (1999) suggested that the observed behavior could be explained by a moderate explosion ($2 \times 10^{51}$ ergs) if the ejecta had a prolate asphericity with an axial ratio of about 2 and were viewed close to the symmetry axis.

Since SNe are unresolved, intrinsic polarization is geometrically canceled out as long as the explosion is spherically symmetric: the presence of any polarization thus reveals asymmetry. It has been found that core-collapse supernovae are generally polarized in the continuum at levels of $p \simeq 0.5$–4 % and that the polarization increases after optical maximum light (e.g., Jeffery 1991b; Wang et al. 1996, 2001; Leonard et al. 2001); however, the polarization falls to zero at very late times, when the electron scattering opacity becomes very low (e.g., Jeffery 1991b). The typical line polarization profile, predicted theoretically (Jeffery 1989) and to some degree confirmed observationally in SN 1987A and other supernovae (Jeffery 1991a,b; Leonard et al. 2001), is an inverted P Cygni profile: strong polarization maximum at the flux P Cygni trough feature and polarization minimum at the flux P Cygni emission feature. However, line blending and other intrinsic effects may affect these profiles. For SN 1998bw, an intrinsic optical polarization of 0.4–0.6 % was found, suggesting an asymmetry of less than 2/1 in the axial ratio of the ejecta (Patat et al. 2001; Kay et al. 1998). However, no distinct polarization feature was revealed associated with the spectral lines, probably due to the poor S/N or the relatively narrow wavelength range of those observations.

3. Observations and Data Reduction

The spectropolarimetric observations were made with the 8.2-m Subaru Telescope equipped with the Faint Object Camera and Spectrograph (FOCAS, Kasihikawa et al. 2000; Yoshida et al. 2000). The observing log is shown in Table 1. The linear polarimetric module consists of a rotating superachromatic half-wave plate and a crystal quartz Wollaston prism, and both the ordinary and extraordinary rays are simultaneously recorded on two MIT/LL CCDs (2k×4k×15µm). A typical observing sequence consisted of four integrations at the $\psi = 0^\circ, 45^\circ, 22.5^\circ$ and 67.5° positions of the half-wave plate. Stokes $Q/I$ and $U/I$ were calculated as in §6.1.2 of Tibergen (1996). For polarimetric calibration, we obtained data for unpolarized and polarized standard stars, including measurements of flatfield lamps through fully-polarizing filters. Although the stability of instrumental polarization and depolarization in FOCAS on the Subaru Telescope have not yet been fully calibrated, our results indicate that the instrumental polarization ($\lesssim 0.1$ %) and the depolarization factor ($\lesssim 0.05$) are negligible at all wavelengths. The flux was calibrated using observations of G191B2B and BD+28°4211 (Oke 1990), and then was multiplied by a constant to match the VSNET14 photometric data.

4. Results and Discussion

Figure 1 shows the observed flux and polarization spectra. Several blueshifted broad absorption lines can be identified in the February flux spectrum (Mazzali et al. 2002). For March and June flux spectra a detailed analysis has yet to be done. However, we note that the March spectra resemble that of SN 1997ef at day 67 (Mazzali, Iwamoto, & Nomoto 2000), including the onset of net emission in Ca II λ8498, 8542, 8662 (i.e., the Ca II IR triplet). The significant emission line at $\sim 6300$Å in the June spectrum is identified as [O I] λ6300, 6363 as in SN 1997ef (Mazzali et al. 2001). The flux is generally polarized by $p \gtrsim 0.5$ % at a position angle (PA) of $\theta = 120^\circ \pm 20^\circ$ over the observed wavelengths. Significant day-by-day variation is not seen in the polarization spectra within each month. Here we will only analyze monthly averages and leave a day-by-day analysis for future work.

4.1. Interstellar Polarization

The level of an interstellar polarization (ISP) varies slowly with wavelength in the optical, and is well approximated by the empirical formula: $p_{\text{ISP}}(\lambda) = p_{\text{max}} \cdot \exp[-1.15 \theta^2 (\lambda_{\text{max}}/\lambda)]$, where $p_{\text{max}}$ is the peak polarization level occurring at wavelength $\lambda_{\text{max}}$ (Serkowski, Mathewson, & Ford 1975). In March the emission feature of the Ca II IR triplet line profile shows strong net emission due to NLTE processes. Such NLTE line flux is necessarily unpolarized on emission. Since the line profile is still broad (absorption minimum at a $\sim 14,000$ km s$^{-1}$ redshift, corresponding to an enclosed mass of $2 M_\odot$ in model CO100/4, which has a total mass of $2.4 M_\odot$ (Mazzali et al. 2002)), much of the emission is probably coming from far out in the ejecta, where the electron optical depth is low. We conclude that the flux from this emission line is mostly unscattered by electrons and unpolarized, and that it dilutes the polarized electron scattered flux. If this were the only effect, then the intrinsic polarization should show a distinct minimum nearly exactly at the wavelength of the flux emission maximum. Since, in fact, the polarization is roughly constant across the P Cygni emission feature (8400–9000 Å), apart from small variations that may be mostly noise, we conclude that the line is not only diluting the polarized flux but is also strongly depolarizing it. Thus the intrinsic polarization across the emission feature is probably close to zero, and the observed level of polarization in this region is close to the ISP level. We will assume that the observed polarization in this region is all due to ISP: thus $p_{\text{ISP}}(8600$ Å) $\approx 0.5$ %. Now Serkowski, Mathewson, & Ford (1975) find that $\lambda_{\text{max}}$ for 30 stars with $p_{\text{max}}/E_{B-V} \geq 7.0$ has a median value of 5370 Å and an rms deviation of 400 Å. We adopt this median value to derive our ISP estimate from a non-linear regression: $p_{\text{max}} = 0.64 \pm 0.20$ % and $\theta_{\text{ISP}} = 120^\circ \pm 10^\circ$. (The uncertainties are crude estimates based on the alternative assumption that only line flux dilution, and not line depolarization, occurs in the region of the Ca II IR triplet emission feature.) Since Takada-Hidai, Aoki, & Zhao (2002) derive a color excess for SN 2002ap of $E_{B-V} = 0.09$ (a sum of 0.07 within our Galaxy and 0.02 within M74) from interstellar Na D absorptions, our assumption of the Serkowski, Mathewson, & Ford (1975) $\lambda_{\text{max}}$ is consistent: $p_{\text{max}}/E_{B-V} = 0.64/0.09 \approx 7$.

The estimated ISP is consistent with other observational indications. In the recently compiled ISP catalog (Heiles 2000), 16 stars are recorded within $10^\circ$ of SN 2002ap. The data for these stars suggest a possible positive correlation.

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between polarization level and the distance along the line of sight toward SN 2002ap. The two most distant stars among them, HD8919 (d = 525 pc) and HD9560 (d = 437 pc) show (p, θ) = (0.32±0.10 %, 99°±9°) and (0.48±0.09 %, 123°±5°), respectively. On the other hand, it has been found that p_{max}(%) has an empirical upper limit of 9E_{B−V} (Serkowski, Mathewson, & Ford 1975). From the derived E_{B−V} = 0.09, an upper limit on the ISP toward the supernova is 0.81 %. The estimated ISP is nicely sandwiched between the possible lower bounds of the cited stars and the empirical upper limit. The estimated ISP position angle is also consistent with the position angle of the spiral arm in M74 at the position of SN 2002ap, 110°–140° (cf. DPOSS images).

The polarization spectrum obtained on June 9 has only low S/N. It is noted, however, that the polarization values at the peak of the strong emission flux at the [O I] λ6300, 6363 forbidden line is roughly consistent with the estimated ISP (Figure 1c). In the following, we analyze only the higher S/N polarization spectra of the earlier two epochs.

4.2. Intrinsic Polarization

Figure 2 shows the intrinsic polarization (calculated using the estimated ISP) plotted on a QU diagram: the polarization points are connected according to their wavelength ordering. Given the uncertainty in the estimated ISP, points within 0.2 % of the origin must be considered very uncertain when drawing conclusions about the intrinsic position angle.

If one assumes that the intrinsic supernova polarization is produced by a single axisymmetric component in the ejecta, then the intrinsic polarization plotted on a QU diagram should lie on a line passing through the origin. It can be seen that the polarization in February has two clear position angles, PA less than or ~ 120° (associated with the O I/Ca II line trough) and PA ~ 80° ± 20° (associated with the continuum from ~ 5700–8200 Å), joined by a somewhat complicated transition. The polarization in March has a clear position angle PA ~ 150° associated with the Ca II line trough and with at least some of the continuum. We conclude that there are multiple asymmetric components in the supernova, and that their contribution varies with time. It is likely that the recession of the supernova photosphere uncovers different asymmetries.

4.3. Possible Models

Figures 3a, b, and c show the flux corrected for heliocentric redshift \(v_{\text{helio}} = +631 \text{km s}^{-1}\) (Smartt & Meikle 2002) and interstellar extinction \(E_{B−V} = 0.09\) (Takada-Hidai, Aoki, & Zhao 2002) and the polarization for the estimated ISP. The figures show that polarization is low and barely significant (given the uncertainty in the estimated ISP), except in the regions ~ 6700–8000 Å for February and ~ 6700–8300 Å for March.

The low level of the continuum polarization blueward of ~ 6700 Å in both epochs may be due to the depolarizing effect of lines (Howell et al. 2001): in supernova spectra, lines generally become stronger further to the blue. The level of the continuum polarization, where it is significant (a relatively small region) is ~ 0.4 % in both epochs. If the asymmetry is assumed to be an axisymmetric, global prolate or oblate asymmetry, then a continuum polarization of this level can be explained by an axial ratio (assuming there is a main axis) projected on the sky that is different from 1 by of order 10 %. This asymmetry estimate is a crude one based on realistic, but parameterized, calculations (Höflich 1991, 1995). The estimate is also crude because, as noted above, the asymmetry cannot be completely axisymmetric. The estimated asymmetry is not large, compared to those estimated for some other supernovae (e.g., Wang et al. 2001).

The three distinct line polarization profiles seen in Figure 4 (at the O I/Ca II flux absorption in February and the O I and Ca II flux absorptions in March) can partially be accounted for by the inverted P Cygni profile (cf. § 2): the polarization maxima associated with line trough features are clear. Without detailed modeling more information probably cannot be extracted from these profiles.

For the polarized continuum observed in February, we can suggest a radically different origin from the bulk asymmetry assumed in prolate/oblate models or element inhomogeneity models (see below). In Figure 3d we show the intrinsic polarized flux \((p \times F)\) compared to the observed flux scaled down by a factor of 0.0018 and non-relativistically redshifted by a velocity of 0.23c: i.e., \(\lambda_{\text{redshifted}} = \lambda/0.77\). There is fair agreement over the range ~ 5000–8000 Å. This agreement suggests that a large component of polarized flux comes from electron scattering in an ionized clump (i.e., a jet) thrown out of the supernova explosion. In the simple non-relativistic picture we adopt, the scattered light is redshifted by \(v_{\text{red}} \sim v_{\text{jet}}(1 + \cos i)\), where, \(v_{\text{red}} = 0.23c\), \(v_{\text{jet}}\) is the characteristic velocity of scattering relative to the supernova center, and \(i\) is the inclination angle of jet to the line of sight measured from the far side of the supernova. The jet polarization component is calculated from

\[
P_{\text{jet}}(\lambda) = f \cdot \frac{F[\lambda(1 - v_{\text{red}}/c)]}{F(\lambda)},
\]

where \(F(\lambda)\) is the corrected flux (Figure 3a), \(1 - v_{\text{red}}/c\) is the blueshift back to the origin of the scattered flux observed at \(\lambda\), and the scale factor \(f = 0.0018\): \(f\) accounts both for the polarization of the jet scattered flux and the fraction scattered. We note the polarization is wavelength dependent even though electron scattering is wavelength-independent since the scattered flux vanishes from a bluer part of the spectrum. Electron scattering depends on scattering direction: e.g., maximum polarization occurs for \(i = 90°\); half as much for \(i = 45°\) or 135°; zero for \(i = 0°\) or 180°. The jet velocities corresponding to \(i = 90°, 45°,\) and 0° are 0.23c, 0.135c, and 0.115c, respectively. Thus 0.115c is a lower bound on the jet velocity and \(i \gtrsim 90°\) would require a somewhat relativistic jet.

The existence of high velocity jet-like clumps has been proposed in some hydrodynamic explosion models for SNe, hypernovae and GRB’s (e.g., Nagataki et al. 1997; MacFadyen & Woosley 1999). If the jet is thrown out of the core of the exploding supernova, then it is plausible that it carries some radioactive 56Ni. The gamma-rays from decay would keep the jet ionized to some degree just as they keep the nebular phase bulk ejecta ionized.

If the jet picture is indeed correct, then the position angle of the jet on the sky is ~ 170° (or ~ 350°) since
the jet polarization component has position angle \( \sim 80^\circ \) and electron scattering polarizes perpendicularly to the scattering plane. The O I/Ca II line polarization maximum in the February data cannot easily be associated with the jet. In reality, the observed position angle makes an excursion from \( \sim 80^\circ \) up to \( 120^\circ \) across the polarization maximum. Some of the line polarization may then arise in the bulk asymmetry of the supernova. It is possible that the position angle of \( \sim 120^\circ \) is the net result of a jet polarizing at \( \sim 80^\circ \) and a bulk asymmetry polarizing at \( \sim 150^\circ \) (i.e., at the position angle observed in the March data). To test this model we have eliminated the jet polarization component from the February intrinsic polarization. The residual polarization and position angle spectra are plotted in Figures 3e,f. The position angle of the residual polarization for February from the region of significant polarization (i.e., \( \sim 6700-8000 \, \text{Å} \)) is now approximately centered on \( 150^\circ \) and deviates by more than 30\(^\circ\) only in a few isolated points. The results in Figure 3f are thus consistent with the jet model.

The jet may not be a completely separated amount of ejecta, but rather a blob rich in \(^{56}\text{Ni}\) moving at \( \geq 0.115c \). A high-velocity, \(^{56}\text{Ni}\)-rich region is required both in theoretical hypernova explosion models (Nakamura et al. 2001; Maeda et al. 2002), and in SN 2002ap (Mazzali et al. 2002) in order to reproduce the light curve. Note that, the maximum ejecta velocity indicated by spectrum synthesis of SN 2002ap is \( \sim 0.22c \). A blob would affect the ionization balance differently in different regions of the outer ejecta and hence the electron scattering optical depth would be different in different directions. The ionization would likely be increased by radioactive \(^{56}\text{Ni}\) and this would make the blob more polarizing than other parts of the ejecta at the same velocity. The net effect of a blob is difficult to estimate. Other chemical inhomogeneities in the ejecta at varying velocities are also possible (Maeda et al. 2002) and would affect polarization in complicated ways.

5. CONCLUSIONS

In this Letter we have presented spectropolarimetry for SN 2002ap and given its first order interpretation. We suggest that the supernova has a bulk asymmetry with an axial ratio projected on the sky that is different from 1 by of order 10\% and speculatively a polarizing jet moving at \( \geq 0.115c \). The jet can make a significant contribution to the polarization only in the February observational epoch. Undoubtedly more realistic modeling is necessary for a more definitive understanding of the polarization. The degree of the bulk asymmetry predicted in this model may be tested with the line widths and their ratios in the nebular spectrum (Maeda et al. 2002).

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Table 1
LOG OF OBSERVATIONS FOR SN 2002ap

| Date (UT)   | Grism\(^a\) | λλ (Å)\(^b\) | λ/∆λ | ∆t (s) |
|------------|-------------|---------------|-------|--------|
| 2002 Feb 9.2 | 300/5500    | 4750–8300     | 1200  | 1200   |
| 2002 Feb 9.3 | 300/5500    | 3850–6050     | 1200  | 2800   |
| 2002 Feb 10.3| 300/5500    | 4750–8300     | 1200  | 1200   |
| 2002 Feb 11.3| 300/5500    | 4750–8300     | 1200  | 1600   |
| 2002 Feb 11.3| 300/5500    | 3850–6050     | 1200  | 1600   |
| 2002 Feb 12.3\(^c\) | 300/5500 | 4750–8300     | 1200  | 1200   |
| 2002 Mar 8.2 | 300/7500    | 4850–9050     | 650   | 960    |
| 2002 Mar 10.2| 300/7500    | 4850–9050     | 650   | 1080   |
| 2002 Jun 9.6 | 300/5500    | 4750–8300     | 1200  | 1200   |

\(^a\) Grooves per millimeter/central wavelength in angstroms

\(^b\) Effective wavelength range of the observation, which depends on the combination of the grism and the order-cut filter used.

\(^c\) On February 12 we could not carry out the whole sequence of polarimetry because of unstable weather, and so obtained only flux data.
Fig. 1.— Flux and polarization spectra of SN 2002ap. Heliocentric redshift, interstellar extinction and polarization have not been corrected for. From top to bottom, we plot (a) total flux, (b, c) polarization level $p$ and position angle $\theta$ on each observation night. The polarimetric data are binned to a constant photon noise of 0.05% which is shown by the error bars of polarization points. The estimated ISP component is shown by a dashed curve in (b,c).

Fig. 2.— $QU$-diagram of the monthly-averaged intrinsic polarization for February and March epochs. The estimated ISP has been removed and the data are binned to a constant photon noise of 0.04%. It can be seen that the polarization in February has, at least, two preferred axes: PA$\sim120^\circ$ (associated with the O I/Ca II line trough) and PA$\sim80^\circ$ (associated with the continuum). The polarization in March has a clear position angle PA$\sim150^\circ$ associated with the Ca II line trough and the significantly polarized continuum. These position angles are indicated by thick arrows. Note that the position angle on the sky is half the angular location on a $QU$ diagram.

Fig. 3.— Polarization spectra corrected for heliocentric redshift and interstellar extinction. The estimated ISP component has also been removed. From top to bottom, we plot (a) total flux in erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, (b) polarization level $p$, (c) position angle $\theta$, (d) polarized flux, and (e,f) $p$ and $\theta$ of the residual polarization after the jet polarization component has been subtracted from the February data. The February flux is the mean of Feb 9 and 11, and the March flux is the mean of Mar 8 and 10. We adopt a heliocentric redshift +631 km s$^{-1}$ for M74 (Smartt & Meikle 2002), a color excess of $E_{B-V}=0.07$ in our Galaxy and 0.02 in M74 (Takada-Hidai et al. 2002) and the normal interstellar extinction curve (Cardelli, Clayton, & Mathis 1989). Deep absorption bands due to the terrestrial atmosphere and the interstellar medium have been removed by interpolation using nearby continuum levels. The polarimetric data are binned in the same manner as in Fig. 2. The solid curve in (d) is the February flux multiplied by 0.0018 and redshifted by +0.23c (see §4.3).
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-0.5 0 0.5 1

-2

-1.5

-1

-0.5

0

0.5

1

$Q$ (%)

-2

-1.5

-1

-0.5

0

0.5

1

$U$ (%)

PA~80° (February continuum)

PA~150° (CaII trough in March)

PA~120°

(OI / CaII trough in February)

Average in February

Average in March
