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CATALOG OF SN 1987A POLARIMETRY CORRECTED FOR INTERSTELLAR POLARIZATION

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ABSTRACT

A catalog of SN 1987A polarimetry is given that covers the period from day 2 to day 262. The catalog includes broad-band and narrow-band polarimetry and spectropolarimetry. The polarimetry has been corrected for the interstellar polarization along the line of sight to SN 1987A. Since the interstellar polarization is of the same order as the SN 1987A polarization, a correction for the interstellar polarization is essential for observing the intrinsic behavior of the SN 1987A polarization. It is hoped that the catalog will aid and encourage further analyses of the SN 1987A polarimetric data.

Subject headings: polarization — spectrophotometry — stars: individual (SN 1987A) — stars: supernovae

1. INTRODUCTION

Polarimetric observations of Type II SN 1987A in the LMC revealed a significant polarization of the supernova's flux. Since the polarization is time-dependent and its wavelength dependence is correlated with the flux line features, it is clear that there is significant intrinsic polarization and therefore that the supernova had some form of asymmetry. However, a priori a significant interstellar polarization (ISP) in the direction SN 1987A must be expected. Galactic foreground ISP for the region where SN 1987A is located has been found by Schmidt (1976) to be 0.40 ± 0.13% at position angle 20°. In the LMC, most of the significantly polarized stars with polarization due to LMC ISP lie in the 30 Doradus region where SN 1987A is located; the polarization of these stars due to LMC ISP ranges at least as high as 4% (Clayton, Martin, & Thompson 1983, hereafter CMT). Stars within ~15′ of SN 1987A have LMC ISP of order 1% (Cropper et al. 1988, hereafter CBM). To obtain intrinsic polarization of the supernova flux requires that the ISP Stokes Q and U parameters be subtracted from the observed Stokes Q and U parameters (see, e.g., Martin 1974). The intrinsic polarization is then given by

$$P = \sqrt{(Q_{\rm obs} - Q_{\rm ISP})^2 + (U_{\rm obs} - U_{\rm ISP})^2} \qquad (1a)$$

$$= (Q_{\rm obs} - Q_{\rm ISP}) \cos 2\chi + (U_{\rm obs} - U_{\rm ISP}) \sin 2\chi, \qquad (1b)$$

where the fractional Q and U parameters (i.e., the conventional Q and U parameters divided by the flux and multiplied by 100%) are used here and

$$\chi = \frac{1}{2} \arctan \left(\frac{U_{\rm obs} - U_{\rm ISP}}{Q_{\rm obs} - Q_{\rm ISP}} \right) + k\pi/2 \qquad (2)$$

is the position angle (p.a.) of polarization measured clockwise from one of the perpendicular axes (the l axis in the notation of Chandrasekhar 1960, p. 26) of the coordinate system being used for measuring the Stokes parameters. The k factor in equation (2) is an integer chosen in order to make equations (1a) and (1b) consistent. Note the position angles differing by π (180°) are physically identical. Since the observed SN 1987A broad-band polarization is of order 1% or less (e.g., Barrett 1988) and significant line polarization features in the observed SN 1987A spectropolarimetric data range from ~0.1% to ~3% (CBM), equations (1) and (2) make it clear that the observed polarization behavior will be a greatly distorted version of the intrinsic polarization behavior unless the SN 1987A ISP is unexpectedly small. A particularly unwelcome effect is that bumps (dips) in the intrinsic polarization spectra can give rise to dips (bumps) in the observed polarization spectra. Clearly, analyses of the SN 1987A polarimetry that are better than very qualitative require a fairly accurate knowledge of the ISP.

Analyses of SN 1987A spectropolarimetry or narrow-band polarimetry have been given by Schwarz (1987b), CBM, Bailey (1988), and Jeffery (1987, 1988, 1989, 1991a, b). Significant analyses of SN 1987A broad-band polarimetry are given by Barrett (1988), Méndez et al. (1988), and Höflich, Sharp, & Zorec (1989). A main goal of these analyses is to try to understand the nature of the SN 1987A asymmetry. The authors of the analyses use various ISP corrections estimated in various ways. Recently, a new and probably quite accurate SN 1987A ISP determination has been reported. Therefore, it seemed useful to prepare a catalog of all readily available SN 1987A polarimetry corrected using this new ISP determination in order to encourage and aid further analyses of the SN 1987A polarization and asymmetry. The catalog has already been used by Jeffery (1991b) as the basis for an interpretation of the evolution of the SN 1987A polarization.

The new ISP correction used for preparing the catalog is introduced in § 2 where arguments for its accuracy are given. The catalog is discussed and presented in § 3; it includes most of the published data of which the author is aware. Since Barrett (1988) finds no evidence for significant circular polarization of the SN 1987A flux, circular polarization is not considered in this paper. Note that throughout this paper the epoch of SN 1987A is given in days from the neutrino event of 1987 February 23.316 UT (Bionta et al. 1987; Hirata et al. 1987).

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2. THE SN 1987A INTERSTELLAR POLARIZATION

Méndez (1990) in a private communication describes broad-band polarimetry of SN 1987A taken at the La Plata Observatory during the period of late 1988 and earlier 1989. These observations show a polarization spectrum that is consistent with a Serkowski-law spectrum for interstellar polarization and that is unvarying over a 6 month period. The Serkowski empirical ISP law is given by

$$P = P_{\max} \exp\left[-K \ln^2 (\lambda_{\max}/\lambda)\right], \qquad (3)$$

(see, e.g., Serkowski 1973). For the La Plata SN 1987A polarization spectrum, Méndez reports that $P_{\max} \sim 1.05\%$, $\lambda_{\max} \sim 5400$ Å, $K \sim 1.1$, and the position angle is $\sim 34°$. The reported value of $\lambda_{\max}$ is consistent with the ranges of 4500–5500 Å and 5100–6500 Å reported by CMT for the foreground Galactic ISP and the LMC ISP, respectively. The reported K and $\lambda_{\max}$ values are not quite consistent with the empirically determined Galactic relation

$$K = (1.86 \pm 0.09)\lambda_{\max} - (0.10 \pm 0.05), \qquad (4)$$

(Wilking, Lebofsky, & Rieke 1982) where $\lambda_{\max}$ is measured in microns. This relation may, of course, need to be modified for the LMC. The constant position angle of the La Plata SN 1987A polarization spectrum is consistent with what one expects for an ISP spectrum (e.g., CMT). Both the shape of the reported La Plata SN 1987A polarization spectrum and its time-independence argue for the hypothesis that this spectrum is due entirely to ISP. That the intrinsic SN 1987A polarization would have vanished by about day 650 (approximately the epoch of the La Plata observations) should not be unexpected. Sometime of order day 300, the electron opacity optical depth to the center of the ejecta should have fallen to less than 1 (see, e.g., Axelrod 1988) and the supernova will have entered the nebular phase. Therefore, by about day 650, it is plausible that the electron opacity optical depth through the ejecta has fallen to much less than 1. With such a low electron opacity optical depth, little flux will be scattered by electrons and the electron polarizing effect will vanish. The polarizing effect of line scattering should also have vanished by this epoch if it had ever been present at all (Jeffery 1991b). The strength of these arguments makes it probable that the La Plata SN 1987A polarization spectrum is in fact the SN 1987A ISP, and therefore this spectrum (in a Serkowski-law parameterized form) has been adopted for correcting the SN 1987A polarimetric data displayed in § 3. Figure 1 displays the adopted ISP and its fractional Q and U parameters.

Two further points should be made. First, any contamination of the La Plata observations of SN 1987A by light from other field stars, especially stars 2 and 3, would not alter the argument that the La Plata spectrum is the SN 1987A ISP provided all the light sources were unpolarized and the ISP was constant over the field of observation. (Stars 2 and 3 are within 3″ of SN 1987A; e.g., White & Malin 1987). Second, the SN 1987A ISP actually results from ISP components due to the Galaxy and the LMC. Therefore, in principle , a two-component Serkowski law treatment is needed for the SN 1987A ISP correction. However, since the La Plata spectrum is consistent with a one-component Serkowski law spectrum (Méndez 1990) and since only the net SN 1987A ISP is required here, the need for a two-component treatment is obviated.

3. THE CATALOG OF SN 1987A POLARIMETRY CORRECTED FOR INTERSTELLAR POLARIZATION

All the SN 1987A broad-band polarimetry of which the author is aware, except for the yet unpublished broad-band polar-

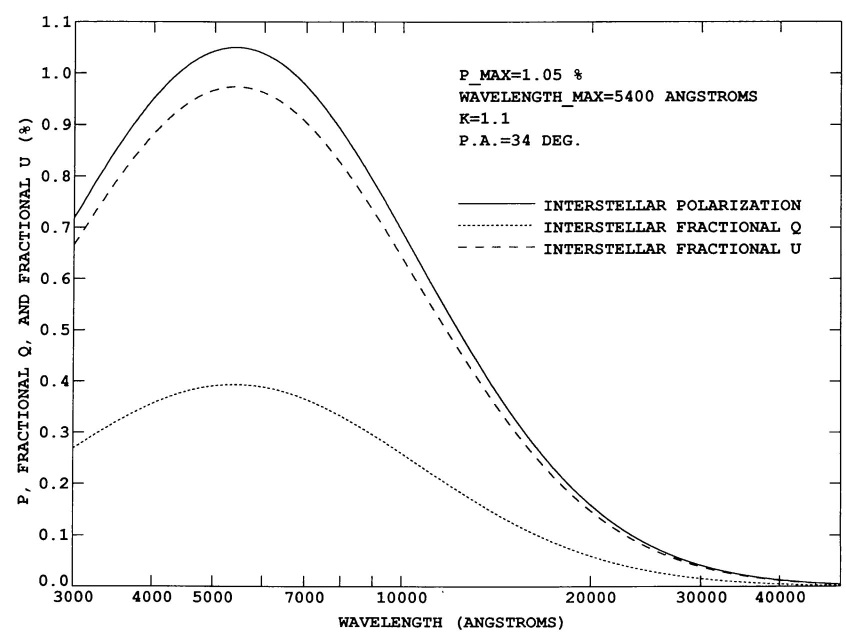

FIG. 1.—Adopted ISP for the direction toward SN 1987A. The ISP fractional Q and U parameters are also displayed.

imetry described by Méndez (1990), is reported by Cropper et al. (1987), Rao et al. (1987), Schwarz (1987b, c), Bailey, Ogura, & Sato (1987), Benvenuto et al. (1987), Magalhaes & Velloso (1987), Barrett (1988), Clocchiatti & Marraco (1988), Bailey (1988), and Méndez et al. (1988). Barrett (1988) and Méndez et al. (1988) give large collection of data that include their own observations and those of others. There is a large number of observations for the *BVRI* bands, somewhat fewer observations from the *U* band, three observations from each of the *JHK* bands, and one observation from the *L* band. The time evolution of the polarization and position angle for each band, except the *L* band, corrected using the La Plata ISP appears in Figures 2–7. The data attributed in the figures to Barrett (1988) and Méndez et al. (1988) are their own data, not merely data they have collected from the literature. The uncertainties displayed with the data points were obtained using the usual first-order error propagation formulae and the uncertainties provided by the authors. The data reported by Schwarz (1987b, c) are not assigned uncertainties by the author. Uncertainties for Schwarz's first set of observations (1987 March 6–7 UT) were obtained from Schwarz (1987a). (The data values for these observations in Schwarz 1987a are not quite the same in Schwarz 1987b; the data probably had not been given final reduction in Schwarz 1987a.) These uncertainties were used for calculating uncertainties for the figures; for the later data from Schwarz, no uncertainties have been calculated. No uncertainty has been assigned to the La Plata ISP correction since no uncertainty has yet been reported for this ISP. Since in many cases the observers have not reported the time of day of their observations, many of the data points have a maximum horizontal uncertainty of 1 day. The dates and supernova epochs given by Barrett (1988) for his data for the period after day 100 are not consistent. Here his dates have been assumed to be correct and the supernova epochs used for the figures have been calculated from those dates.

In order to use the Serkowski law for the correction of a broad-band polarization, a band wavelength had to be assigned to each broad-band filter. For the *UBVRI* bands, the band wavelength used was the central wavelength of the FWHM region of the broad-band filter. For the *JHKL* bands the effective wavelengths taken from the literature were used. Since the Serkowski law polarization is rather slowly varying with wavelength (see Fig. 1) the exact assignment of a band wavelength is not too important as long as a wavelength fairly central to the band is used. A minor complication in assigning a band wavelength is that it is not entirely clear exactly what filter system was used for obtaining each set of data. From what the observers report, however, it seems that there is small error in assuming that the *UBV* and *JKL* filters are from the Johnson system, the *RI* filters are from the Cousins system, and the *H* filter is the common standard *H* filter. The band wavelengths assigned to the filters are given in Table 1.

Some data are omitted from the figures. Only a selected sample of the closely spaced in time *BVRI* data from Méndez et al. (1988) appears. The *R* band observations for the days 5–32 epoch reported only graphically by Bailey (1988, Fig. 5) have been omitted since this band in this epoch is well covered by observations from other sources. The three *U* band observations given by Benvenuto et al. (1987) are omitted; these observations taken at the La Plata Observatory were not included in the collection of La Plata broad-band observations reported by Méndez et al. (1988) and two of these *U* band data are quite inconsistent, by being too large in uncorrected form, with other *U* band observations taken from near the same epochs (see, e.g., Barrett 1988, Table 1a). The *L* band has been omitted altogether from the figures since only one observation, taken on about day 262, has been reported (Bailey 1988). Corrected for ISP, the *L* band polarization and position angle are 1.62% ± 0.09% and 111° ± 3°, respectively. Of course, for the *L* band which has a band wavelength of 34000 Å, the Serkowski law gives a very small ISP correction (see Fig. 1).

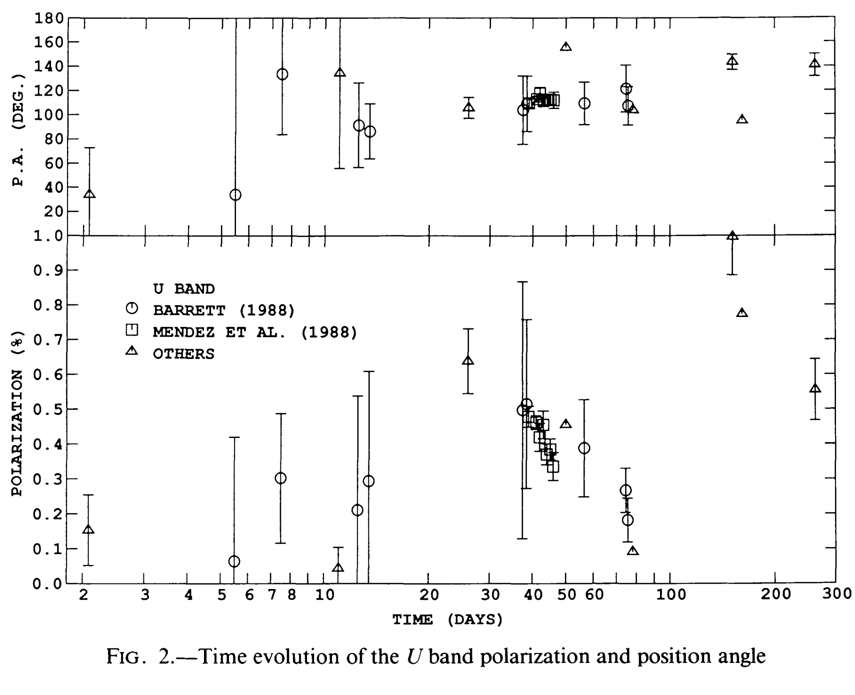

FIG. 2.—Time evolution of the *U* band polarization and position angle

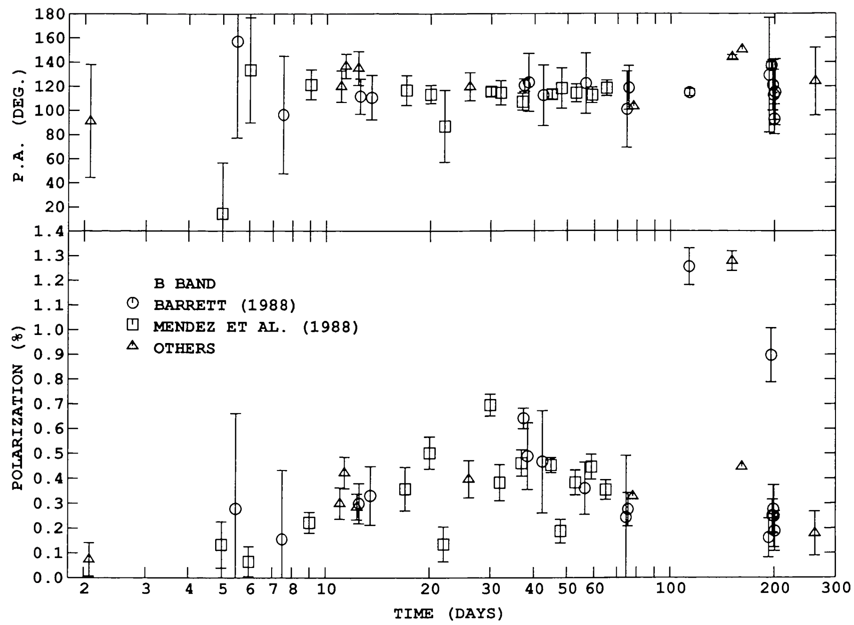

FIG. 3.—Time evolution of the B band polarization and position angle

Figures 8 through 24 present the SN 1987A spectropolarimetry and narrow-band polarimetry corrected with the La Plata ISP. For each observation, a figure shows the polarization and position angle of polarization as functions of wavelength. The freedom to add and subtract multiples of 180° from the position angles was used in creating the figures in order to try to minimize oscillations in the position angle data. The flux spectra of or nearly of the polarimetry observation epochs are also presented, except for the flux spectrum of the days 161–162 epoch (see Fig. 24) which was not available to the author. The dates, supernova epochs, and some of the details about the observations are given in the figure legends. Since the sources for the observations do not give the time of day of the observations, the supernova epochs given in the figure legends have an uncertainty of 1 day, except the epoch given in the figure legend for Figure 8 which is more accurate.

In addition to correcting for the ISP, the polarimetry displayed in Figures 8–24 is also corrected for the redshift due the radial velocity of SN 1987A with respect to the sun. The value of the radial velocity used is 286 km s^{-1} which has been determined by Wampler & Richichi (1989) from SN 1987A circumstellar lines. The displayed flux spectra are also corrected

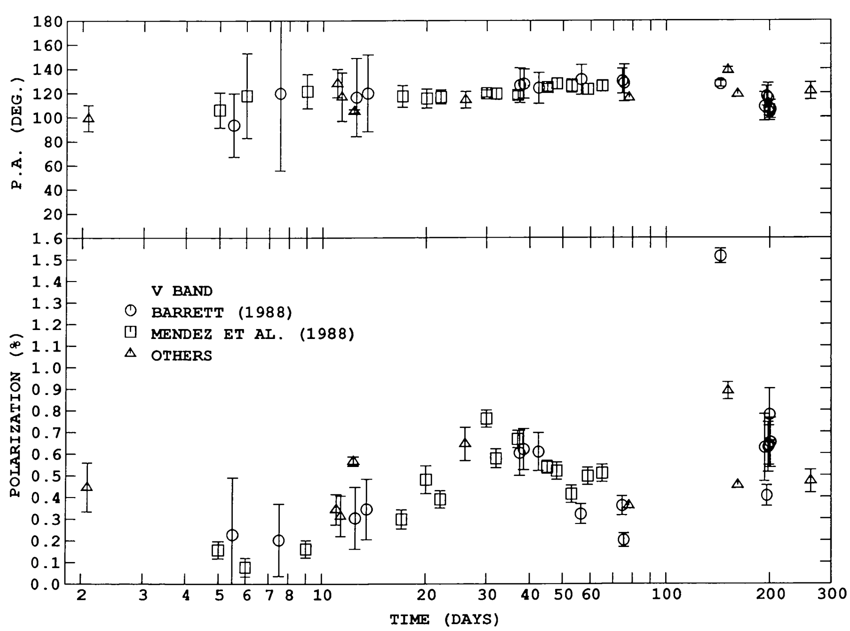

FIG. 4.—Time evolution of the V band polarization and position angle

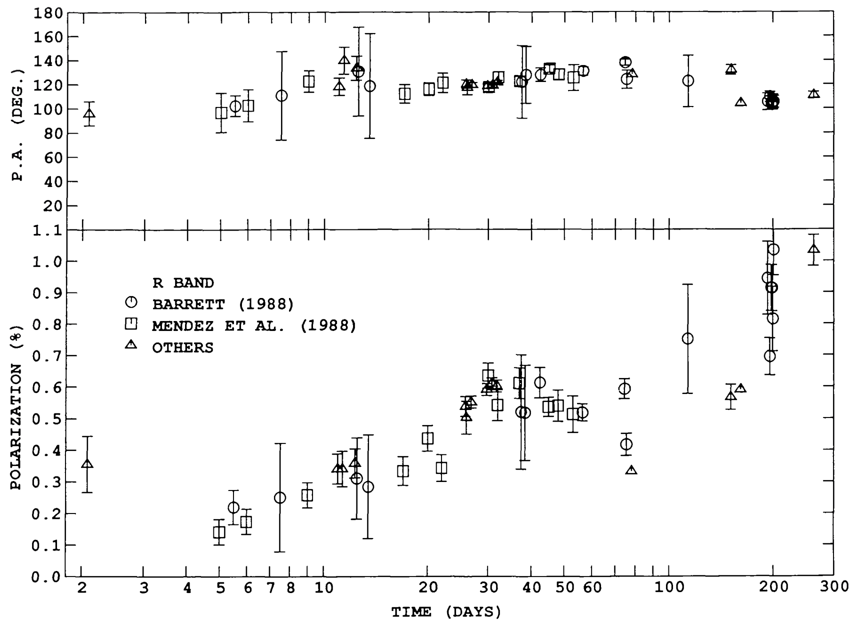

FIG. 5.—Time evolution of the R band polarization and position angle

for the redshift due to the radial velocity. Additionally, the flux spectra are corrected for interstellar reddening using the $E(B-V)$ value 0.17 mag reported for the field of SN 1987A by Walker & Suntzeff (1990) and the interstellar reddening law given by Code et al. (1976). Note that the polarization maximum of the La Plata ISP and the adopted $E(B-V)$ are consistent with the empirical relation $P_{\max} \leqslant 9.0\,E(B-V)$ found for Galactic stars (Serkowski, Mathewson, & Ford 1975). The highest flux on every figure is normalized to 1.

The spectropolarimetry is reported in CBM where it is displayed uncorrected for ISP. As far as the author is aware, the CBM spectropolarimetry is the only true spectropolarimetry from the pre-day 162 epoch (i.e., before 1987 August 4 UT). Bailey (1988) has reported spectropolarimetry from 1987 September 1 UT, 1988 January 4 UT, and 1988 February 8 UT. In CBM spectropolarimetry was binned in wavelength in order to keep the statistical uncertainty (i.e., the standard deviation) of the polarization less than 0.08%, except for the 1987 February 27 UT data (here displayed in Fig. 8) which was binned so that the statistical uncertainty was 0.3%. The corrected spectropolarimetry is binned in order to roughly preserve the same statistical uncertainty as a CBM; the corrected data, of course, also

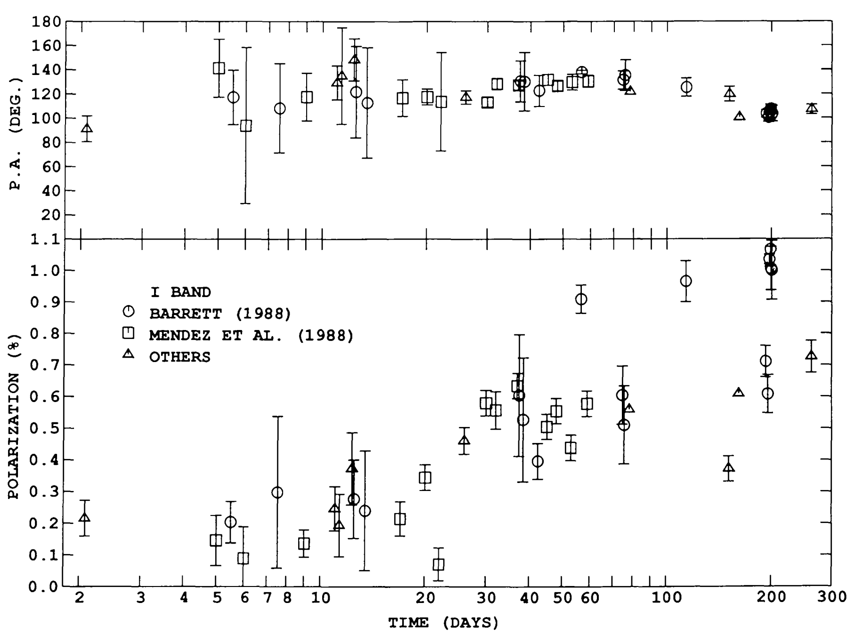

FIG. 6.—Time evolution of the I band polarization and position angle

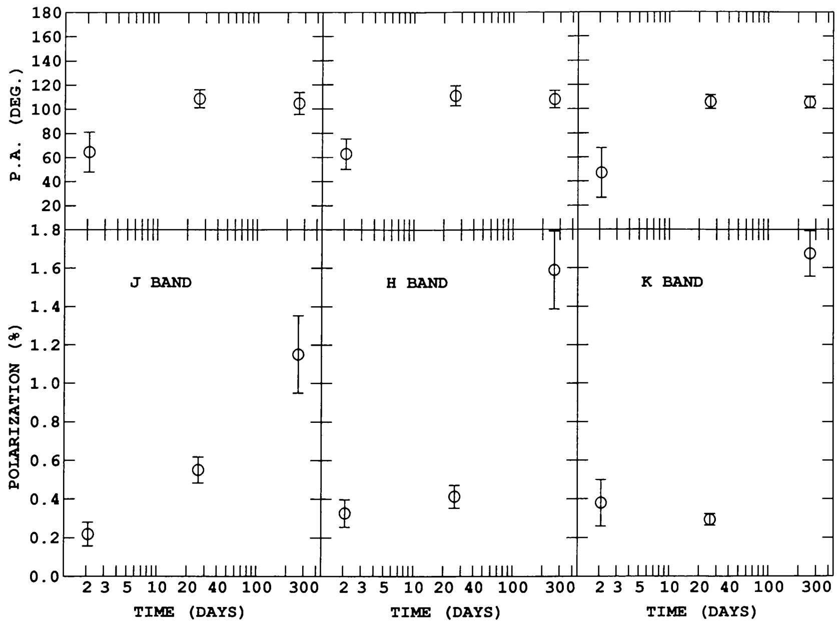

FIG. 7.—Time evolutions of polarization and position angle of the *J* band (*left*), *H* band (*center*), and *K* band (*right*). The day 2.08 (1987 February 25.39 UT) data comes from Cropper et al. (1987), the day 26 (1987 March 21 UT) data from Bailey et al. (1987), and the day 262 (1987 November 12 UT) data from Bailey (1988).

TABLE 1

ASSIGNED BAND WAVELENGTHS AND WIDTHS

Filter	Assigned Band Wavelength (Å)	Assigned Band Width (Å)
U	3500	700
B	4350	950
V	5500	850
R	6550	1350
I	8100	1650
J	12500	3800
H	16500	...
K	22000	4800
L	34000	7000
Hγ absorption	4188	33
Hγ emission	4340	28
Hβ absorption	4697	10
Hβ emission	4867	34
Na D absorption	5757	20
Na D emission	5897	56
Hα absorption	6251	33
Hα emission	6565	10

NOTES.—For the *UBV* (Johnson system) and *RI* (Cousins system) bands, the assigned band wavelength and width are the central wavelength of the filter FWHM region and the filter FWHM, respectively. The data for these bands was taken from Lamla 1982. For *JKL* (Johnson system) bands the effective wavelengths and effective widths given by Allen 1973 are used as the assigned band wavelengths and widths, respectively. The *H* band assigned band wavelength is the effective wavelength given by Greenstein, Neugebauer, & Becklin 1970. The assigned band wavelengths and widths of the narrow-band filters are the central wavelengths and FWHMs, respectively, given by Schwarz 1987b.

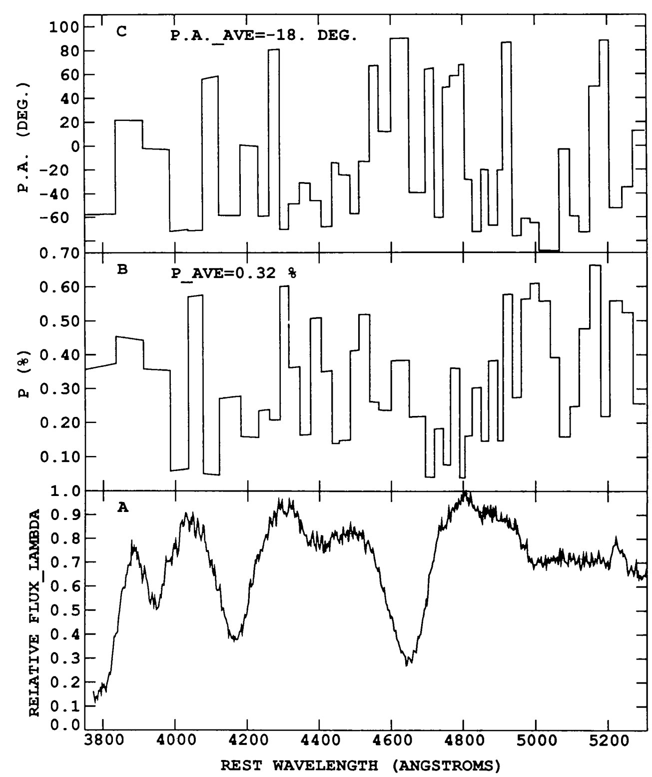

FIG. 8.—ISP-corrected spectropolarimetry (3750–5310 Å) for 1987 February 27.55 UT (day 4.23) from CBM. The precise epoch for this data is known from Walsh, Bailey, & Ogura (1987). Since the uncorrected spectropolarimetry for this figure was obtained already binned in wavelength, some of the binned regions are not flat-topped after ISP correction. The statistical uncertainty in the polarizations are of order 0.3%. The flux spectrum is for 1987 February 28.02 UT (day 4.70) and is taken from Phillips et al. (1988). The emission feature in the flux spectrum centered on about 5230 Å is spurious (Phillips 1990); no unusual behavior is present near 5230 Å in the well-displayed spectra reported by other observers for the period near days 4–5 (see, e.g., CBM, Fig. 2).

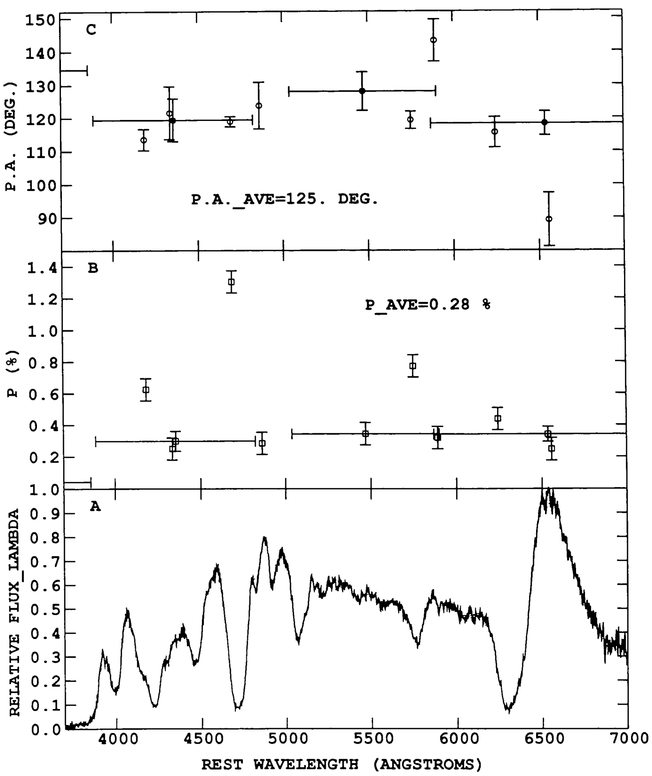

FIG. 9.—ISP-corrected narrow-band and broad-band polarimetry (3700–7000 Å) for 1987 March 6–7 UT (days 11–12) from Schwarz (1987b). The flux specrum is for 1987 March 6.08 UT (day 11.76) and is taken from Phillips et al. (1988).

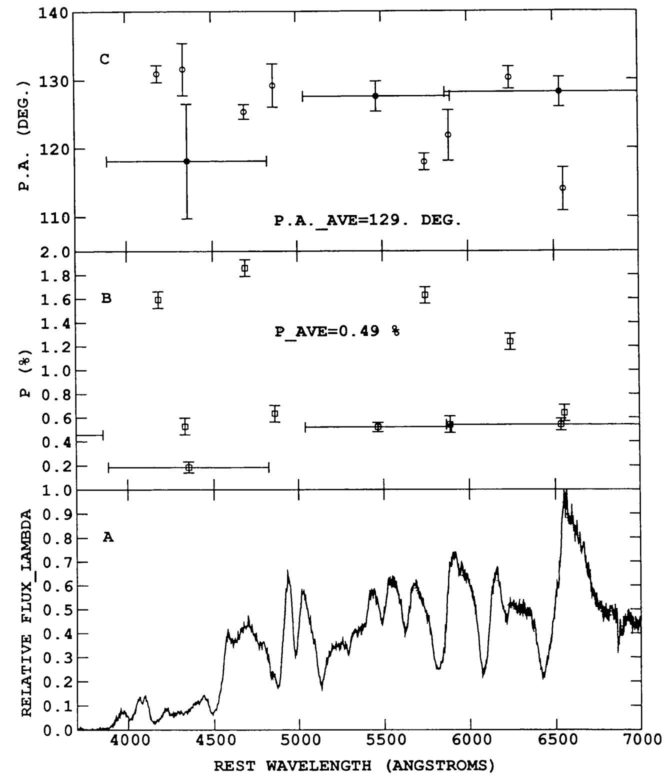

FIG. 11.—ISP-corrected narrow-band and broad-band U polarimetry (3700–7000 Å) for 1987 April 14–15 UT (days 50–51) from Schwarz (1987b). The broad-band BVR polarimetry is for 1987 April 12 UT (day 48) and is taken from Méndez et al. (1988). The flux spectrum is for 1987 April 14.00 UT (day 49.69) and is taken from Phillips et al. (1988).

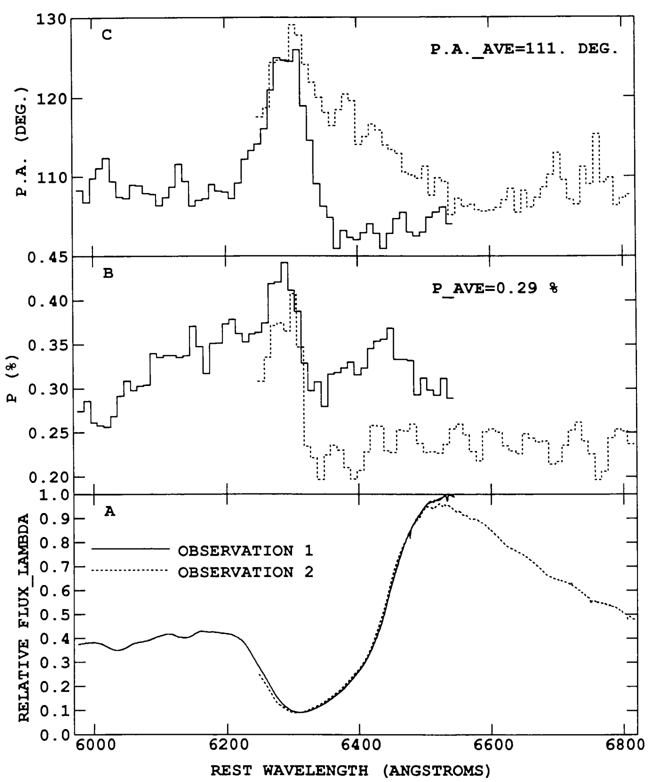

FIG. 10.—ISP-corrected spectropolarimetry and flux spectrum (5970–6820 Å) for 1987 March 7 UT (day 12) from CBM. The polarization data are binned in 10 Å wavelength intervals. The statistical uncertainty in the polarizations shown in this and subsequent spectropolarimetry figures is of order 0.1%.

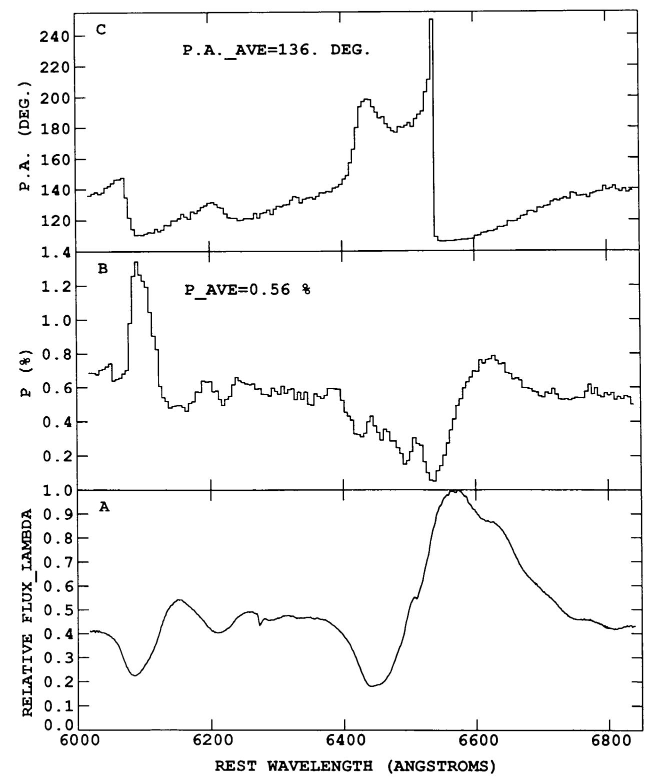

FIG. 12.—ISP-corrected spectropolarimetry and flux spectrum (6000–6850 Å) for 1987 May 5 UT (day 71) from CBM. The polarization data are binned in 5 Å wavelength intervals.

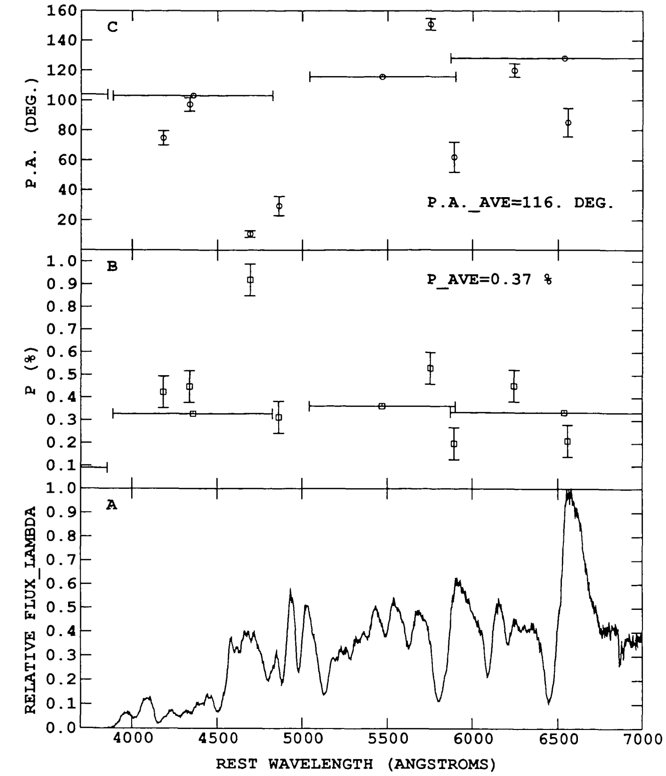

FIG. 13.—ISP-corrected narrow-band and broad-band polarimetry (3700–7000 Å) for 1987 May 12 UT (day 78) from Schwarz (1987b). The flux spectrum is for 1987 May 11.97 UT (day 77.65) and is taken from Phillips et al. (1988).

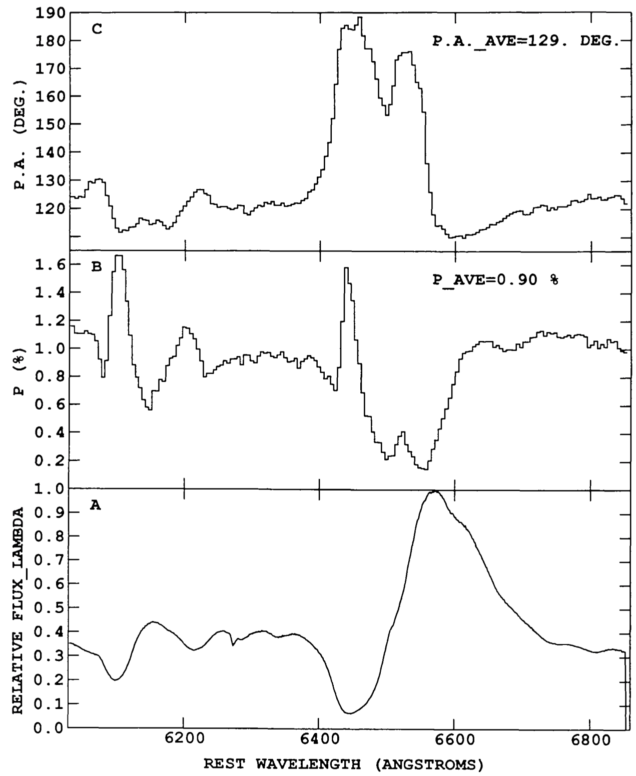

FIG. 15.—ISP-corrected spectropolarimetry and flux spectrum (6030–6860 Å) for 1987 June 3 UT (day 100) from CBM. The polarization data are binned in 5 Å wavelength intervals.

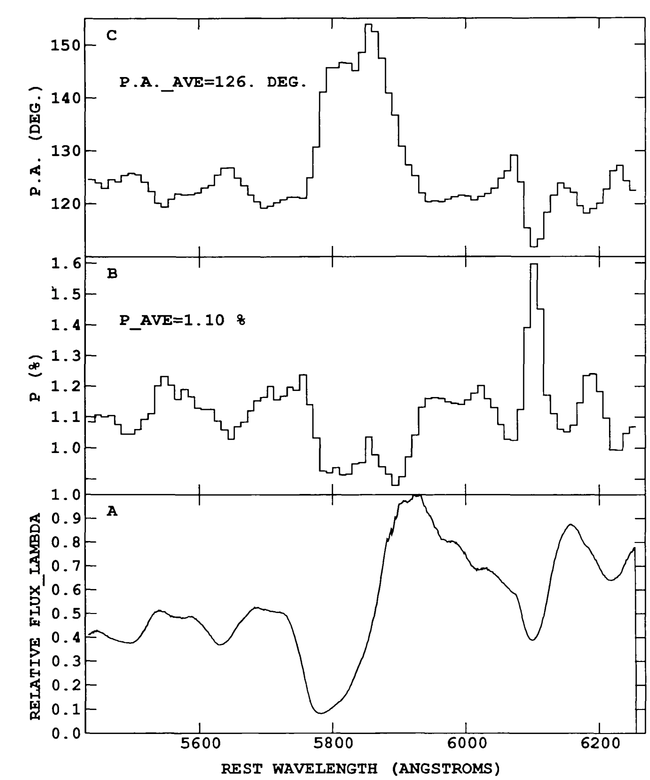

FIG. 14.—ISP-corrected spectropolarimetry and flux spectrum (5430–6270 Å) for 1987 June 3 UT (day 100) from CBM. The polarization data are binned in 10 Å wavelength intervals.

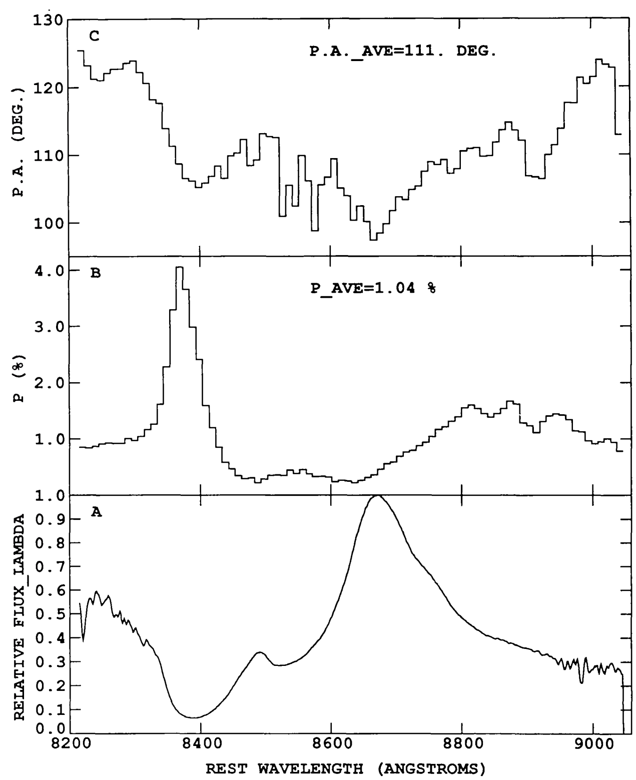

FIG. 16.—ISP-corrected spectropolarimetry and flux spectrum (8200–906 Å) for 1987 June 3 UT (day 100) from CBM. The polarization data are binned in 10 Å wavelength intervals.

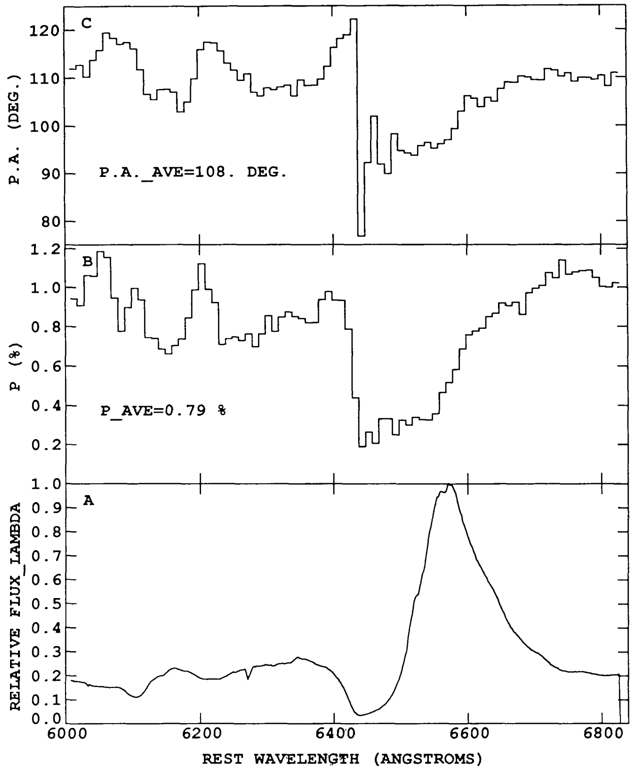

FIG. 17.—ISP-corrected spectropolarimetry and flux spectrum (6000–6840 Å) for 1987 June 28 UT (day 125) from CBM. The polarization data are binned in 10 Å wavelength intervals.

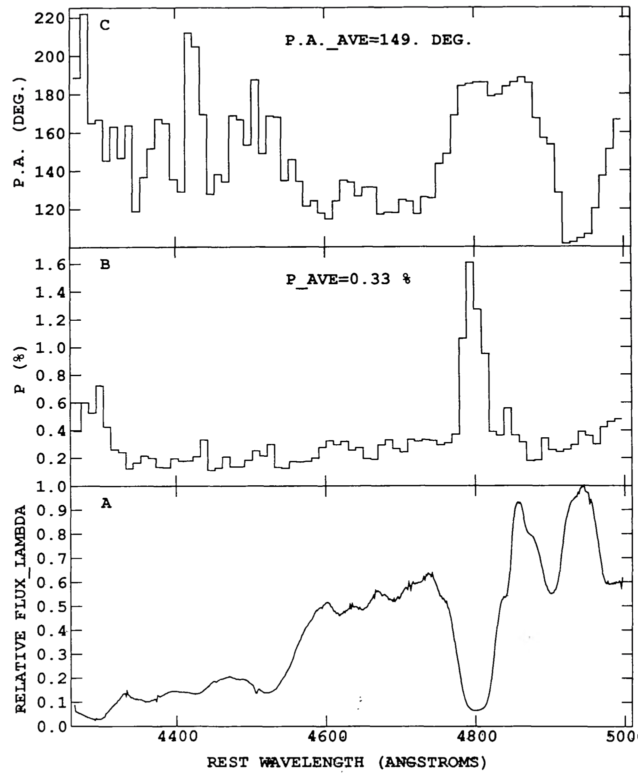

FIG. 19.—ISP-corrected spectropolarimetry and flux spectrum (4260–5010 Å) for 1987 July 3 UT (day 130) from CBM. The polarization data are binned in 10 Å wavelength intervals.

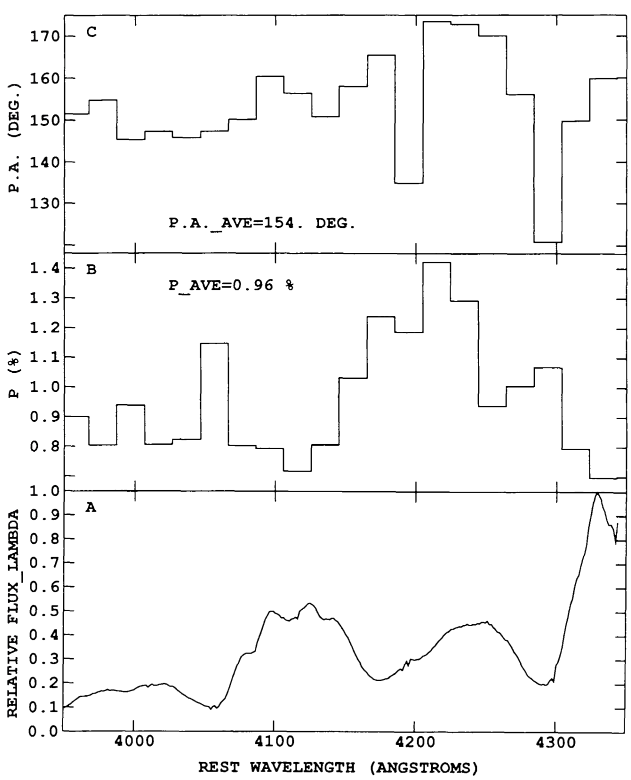

FIG. 18.—ISP-corrected spectropolarimetry and flux spectrum (3950–4350 Å) for 1987 July 3 UT (day 130) from CBM. The polarization data are binned in 20 Å wavelength intervals.

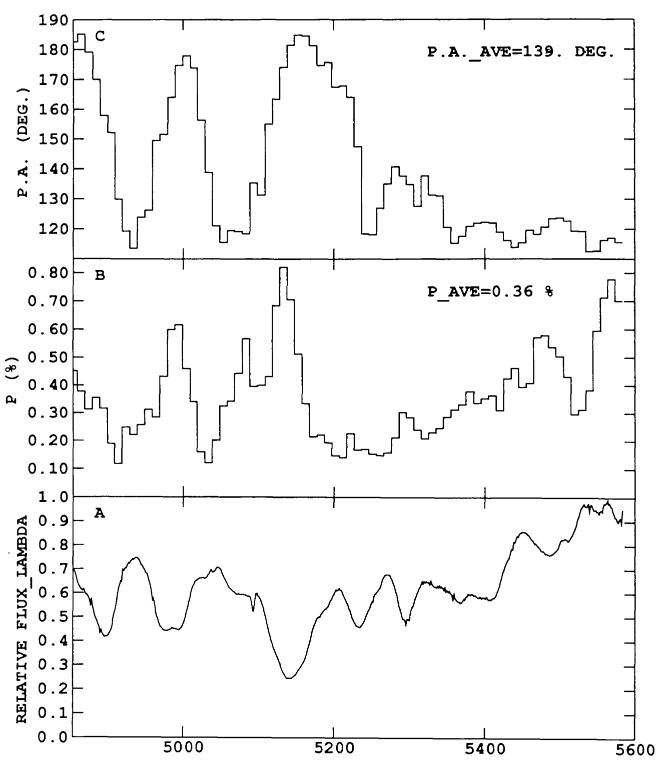

FIG. 20.—ISP-corrected spectropolarimetry and flux spectrum (4855–5600 Å) for 1987 July 4 UT (day 131) from CBM. The polarization data are binned in 10 Å wavelength intervals.

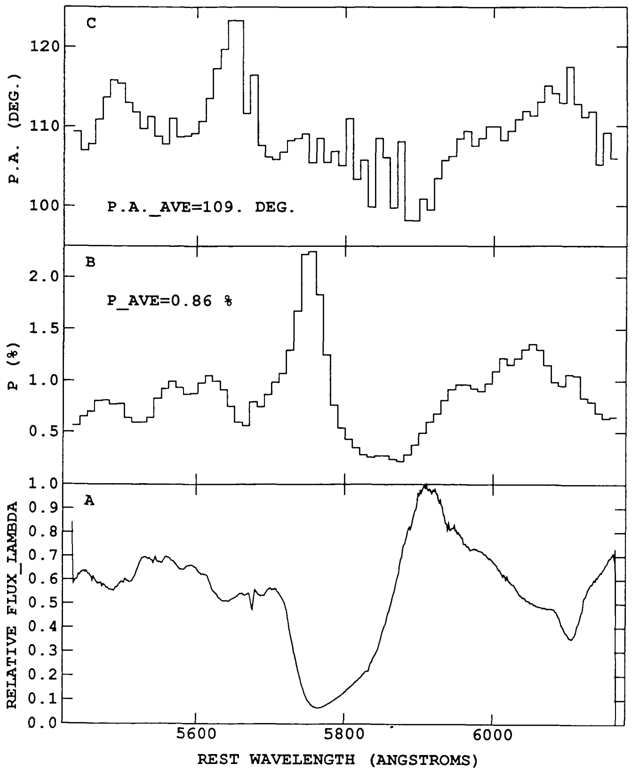

FIG. 21.—ISP-corrected spectropolarimetry and flux spectrum (5420–6180 Å) for 1987 July 5 UT (day 132) from CBM. The polarization data are binned in 10 Å wavelength intervals.

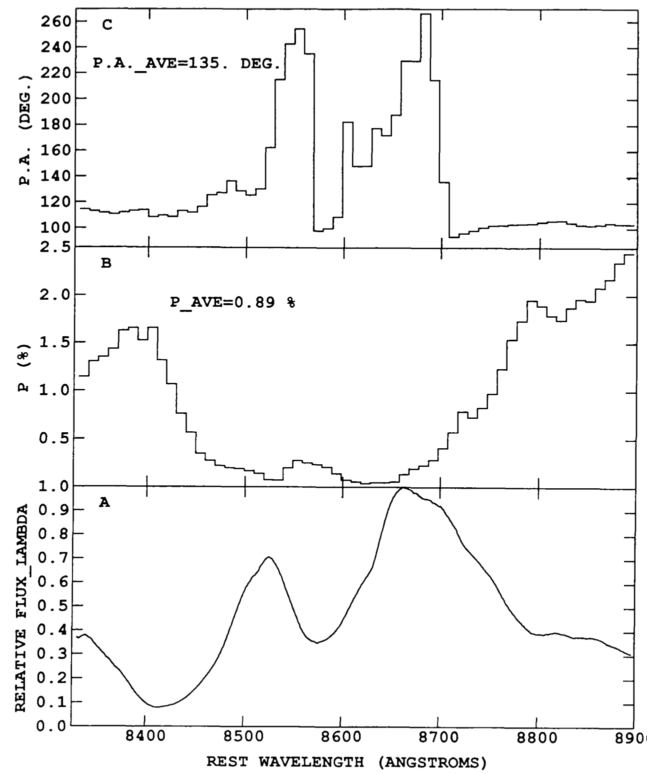

FIG. 23.—ISP-corrected spectropolarimetry and flux spectrum (8350–8900 Å) for 1987 July 8 UT (day 135) from CBM. The polarization data are binned in 10 Å wavelength intervals.

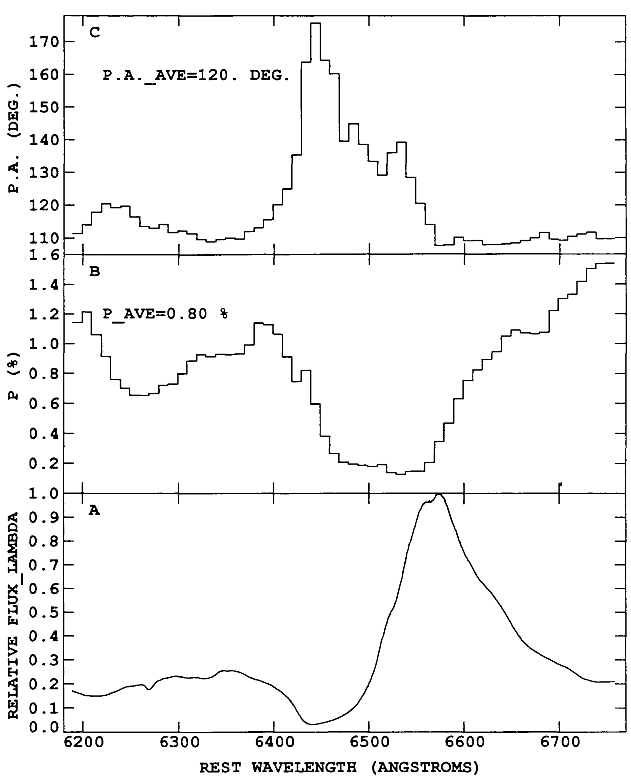

FIG. 22.—ISP-corrected spectropolarimetry and flux spectrum (6180–6770 Å) for 1987 July 8 UT (day 135) from CBM. The polarization data are binned in 10 Å wavelength intervals.

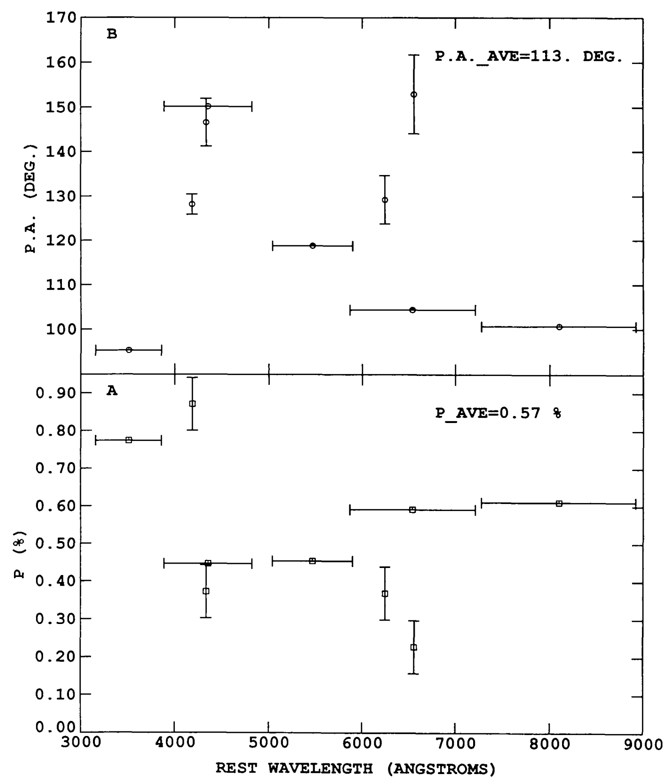

FIG. 24.—ISP-corrected narrow-band and broad-band polarimetry (3000–9000 Å) for 1987 August 3–4 UT (days 161–162) from Schwarz (1987c).

has a systematic uncertainty due to the uncertainty in the La Plata ISP. When the statistical uncertainty of the polarization is large relative to the size of the polarization, the position-angle statistical uncertainty can become large and rather rapid oscillations in position angle can occur (see, e.g., Figs. 8 and 19). The average polarization and average position angle given on each spectropolarimetry figure are simply the wavelength averages of the displayed polarizations and position angles, respectively. Because of the large statistical uncertainty of the data shown in Figure 8, the displayed averages are somewhat misleading; averages obtained from the average Q and U values are 0.13% for polarization and 120° for position angle.

The narrow-band polarimetry is displayed in Figures 9, 11, 13, and 24 as a function of band wavelength. Except for the data in Figure 24, all the narrow-band polarimetry is taken from Schwarz (1987b); in that paper an ISP correction for the data is used that is somewhat different from the La Plata ISP. The data in Figure 24 (the 1987 August 3–4 UT data) comes from a private communication (Schwarz 1987c). The band (i.e., central) wavelengths and bandwidths (i.e., FWHMs) of Schwarz's narrow-band filters are given in Table 1. Each filter is labeled by a P Cygni line feature (e.g., Hα absorption) that at least in some epoch of the SN 1987A evolution is sampled by that filter. The uncertainty in Schwarz's narrow-band Q and U parameters is taken to be 0.07%; this is the value given by Schwarz & Mundt (1987) as a typical uncertainty in the earliest data reported by Schwarz (1987b, c). The vertical error bars of the narrow-band data points are calculated using the 0.07% value and the usual first-order error propagation formulae.

A few narrow-band polarimetric observations known to the author have been omitted from the catalog. Schwarz (1987b) reports 1987 March 7 UT narrow-band data for unspecified Hα emission and absorption filters; no obvious reference is given for this data. Schwarz (1987c) reports 1987 March 6–7 UT narrow-band data for an unspecified [O III] line filter. Magalhaes & Velloso (1987) report five Hα line center wavelength narrow-band observations from the period 1987 March 21–27 UT; these observations, corrected for ISP, give polarizations and position angles in the ranges 22%–32% and 105°–120°, respectively.

In order to give some idea of the continuum polarization for the days when narrow-band polarization data exists, ISP-corrected broad-band polarization data from those days or from near those days are plotted on the figures containing narrow-band data. The horizontal coordinate used for the broad-band data are assigned band wavelengths (see Table 1 and above). The horizontal error bars of the broad-band data points display the assigned bandwidths which in all displayed cases are the band filter FWHMs (see Table 1). Most of the broad-band data comes from Schwarz (1987b, c). However, the *BVR* data for Figure 11 is taken from Méndez et al. (1988). The uncertainties in the broad-band data, when available, were treated as described above for Figures 2–7. The average polarizations and average position angles given on the narrow-band figures are simply the wavelength averages for each epoch of all the narrow-band and broad-band data, including the broad-band data that are out of the display range of the figures.

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