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SPECTROPOLARIMETRY OF NOVA CYGNI 1992: EVIDENCE FOR AN ASYMMETRIC GEOMETRY

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ABSTRACT

We present the first study of the spectropolarimetric evolution of a fast neon nova from outburst through the decline of the light curve, showing the initial presence and gradual disappearance of intrinsic linear polarization. The observations of Nova Cygni 1992 were obtained at the Pine Bluff Observatory of the University of Wisconsin from 1992 March through 1993 May. The emission lines and the continuum show quite different linear polarization behaviors, with the line emission essentially unpolarized and the continuum showing intrinsic polarization. The data provide evidence for an asymmetric geometry in the initial explosion and evidence for clumping in the subsequent nova ejecta.

Subject headings: novae, cataclysmic variables — polarization — stars: individual (Nova Cygni 1992)

1. INTRODUCTION

One of the few novae that has an extensive history of linear polarimetric observations is Nova Cygni 1975. Many observers, such as Belokon & Larionov (1977), Efimov, Narizhnaya, & Shakhovshoi (1977), and Hull (1977) made independent linear polarimetric measurements of that nova shortly after its rise to visual maximum. Despite some dissension among the various studies about whether an intrinsic component to the polarization existed, the majority of the studies found evidence of a small level of intrinsic polarization shortly after visual maximum. Other novae studied via linear polarization include Nova Cyg 1978 (Blitzstein et al. 1980; Piirola & Korhonen 1979), Nova Cyg 1986 (Whitney & Clayton 1989), Nova Vul 1976 (Martin, Maza, & Angel 1977), Nova Vul no. 1 1968 (Zellner & Morrison 1971), RS Oph (Cropper 1990), T Pyx (Eggen, Mathewson, & Serkowski 1967), Nova Del 1967 (Zellner & Morrison 1971; Arsenijevic & Alexsander 1970), Nova Ser 1970 (Zellner & Morrison 1971), and Nova And 1986 (Kikuchi, Kondo, & Mikami 1988).

All of these studies (except for Whitney & Clayton 1989) used broad-band filter (*UBV*) linear polarization measurements, which do not allow for complete understanding of how the polarization correlates with the spectral features. Strong unpolarized line emission can dilute any polarized continuum in filter polarimetry, making it difficult to determine whether an intrinsic component is present, especially if it is dominated by an interstellar component. Spectropolarimetry permits separation of the line and continuum regions, providing a more accurate way to find the interstellar and intrinsic components of the observed linear polarization. The outburst of Nova Cygni 1992 (V1974 Cyg) in 1992 February provided a unique opportunity to obtain a homogeneous time series of observations using this technique.

2. OBSERVATIONS

From 1992 March through 1993 May, 29 spectropolarimetric observations of Nova Cyg 1992 were obtained at the Pine Bluff Observatory (PBO) of the University of Wisconsin. A log of observations is given in Table 1. The data were taken with the PBO 0.9 m telescope, which has a dedicated spectropolarimeter attached. The spectropolarimeter consists of a spectrograph modified to include polarization analyzing optics; the orthogonally polarized spectra are recorded simultaneously with a dual reticon array. The design of the instrument allows for simultaneous measurements of the spectrum and the polarization from 3300 to 7600 Å.

Typical observations required about 2 hours of exposure to obtain adequate signal-to-noise for polarization measurements. A 12″ slit was used to ensure accurate spectrophotometry over the entire wavelength band, resulting in a spectral resolution of ∼25 Å. The polarimetric stability of the PBO instrument is estimated at better than ±0.005% broad band. For a description of the instrument, see Nordsieck et al. (1992). The spectral analysis of these observations is discussed in a separate paper (Barger et al. 1993; hereafter Paper I); here we present the polarization analysis only.

3. DATA REDUCTION

The data were reduced with standard software developed for PBO observations. Flux calibration was based on flux standards observed on the same nights as the nova. Instrumental polarization is removed using a calibration based on observations of polarization standards. Figure 1 shows an early PBO observation of Nova Cyg 1992. This observation was made 9 days after the discovery of the nova (Collins 1992). The polarization in Figure 1 is a combination of the intrinsic polarization of the nova plus a component of interstellar polarization.

3.1. *Interstellar Polarization*

Interstellar polarization (ISP) is produced by the extinction of starlight by aligned dust in the interstellar medium along the line of sight to the object of interest. Several techniques for estimating the part of the measured polarization due to ISP have been developed; for a discussion of some of these techniques, see McLean & Clarke (1979). In the case of Nova Cyg 1992, we used three different techniques to estimate the ISP. First, we assumed that the quiescent polarization measurements in the later phases of the nova observations (after 1992 July 11, when no further changes were seen in the polarization

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TABLE 1

LOG OF PBO OBSERVATIONS OF NOVA CYGNI 1992

Date	JD (2440000+)	Exposure Time (s)	Line Polarization	Line P.A.	Continuum Polarization	Continuum P.A.
1992 Mar 1	8683	7883	1.072% ± 0.022%	1.6	1.487% ± 0.008%	1.2
1992 Mar 11	8693	3686	1.085 ± 0.071	170.9	1.284 ± 0.037	178.9
1992 Mar 12	8694	6554	1.127 ± 0.041	179.4	1.626 ± 0.015	2.0
1992 Mar 21	8703	4710	1.314 ± 0.069	178.3	1.147 ± 0.024	176.7
1992 Apr 5	8718	2048	1.001 ± 0.096	177.6	0.999 ± 0.058	176.8
1992 Apr 6	8718	9830	1.234 ± 0.055	172.8	1.116 ± 0.022	173.3
1992 Apr 30	8743	4915	1.549 ± 0.085	170.0	1.214 ± 0.094	167.4
1992 May 6	8749	8192	1.343 ± 0.106	166.9	1.354 ± 0.101	168.7
1992 May 19	8762	8192	1.313 ± 0.029	1.3	1.043 ± 0.066	175.3
1992 May 27	8770	3277	1.035 ± 0.081	0.2	1.985 ± 0.113	160.3
1992 May 29	8772	6554	1.002 ± 0.024	178.7	1.840 ± 0.059	175.5
1992 Jun 7	8781	1638	0.996 ± 0.048	1.8	1.690 ± 0.155	178.0
1992 Jun 13	8787	6554	0.994 ± 0.036	2.2	0.298 ± 0.095	12.2
1992 Jun 29	8803	8192	1.071 ± 0.023	177.6	0.177 ± 0.075	151.3
1992 Jul 11	8815	8192	0.913 ± 0.026	178.6	1.389 ± 0.073	173.8
1992 Jul 19	8823	9421	1.197 ± 0.024	179.8	1.280 ± 0.079	173.6
1992 Aug 1	8836	8192	1.045 ± 0.026	178.3	1.367 ± 0.070	170.4
1992 Aug 6	8841	9830	1.104 ± 0.023	178.9	1.344 ± 0.061	170.1
1992 Aug 21	8856	9830	0.993 ± 0.027	1.3	1.776 ± 0.081	9.5
1992 Sep 4	8870	9830	1.249 ± 0.025	4.2	0.475 ± 0.093	23.8
1992 Sep 9	8875	1638	0.977 ± 0.112	172.7	2.593 ± 0.505	163.3
1992 Sep 12	8878	4915	1.221 ± 0.060	7.7	2.185 ± 0.282	165.3
1992 Oct 1	8897	7782	1.114 ± 0.025	178.0	1.612 ± 0.075	1.1
1992 Oct 19	8915	8192	1.098 ± 0.033	173.4	1.510 ± 0.094	173.9
1992 Dec 20	8977	1638	[a]	[a]	[a]	[a]
1992 Dec 22	8980	2355	[a]	[a]	[a]	[a]
1993 Jan 16	9005	4860	[a]	[a]	[a]	[a]
1993 Mar 13	9061	1229	[a]	[a]	[a]	[a]
1993 May 17	9141	1638	[a]	[a]	[a]	[a]

[a] Spectrum only: too faint for useful polarization measurements.

level) were solely due to ISP. Averaging these observations then provided an estimate of the ISP. Second, we fitted a Serkowski law ISP profile (Serkowski, Mathewson, & Ford 1975, hereafter SMF) to the polarization values at the hydrogen Balmer lines, assuming that the lines were not intrinsically polarized and polarization in the lines was only due to ISP. We allowed the position angle of the ISP to rotate slightly as a function of λ^{-1}, as discussed by Moffat & Piirola (1993). Third, we compared these results with published polarization measurements for stars in a 5° radius around the position of the nova (excluding known Be stars, which could be intrinsically polarized).

The first two methods produced consistent estimates for the ISP in the direction of Nova Cyg 1992, and those estimates are also consistent with a preliminary estimate of the reddening toward Nova Cyg 1992 from the spectral information (Paper I). The third method gave a somewhat different position angle (P.A.), but it is also less reliable due to the small number of stars in the region with measured polarization, most of which are several degrees away from the position of the nova. Adopting the second method, we find a maximum ISP, $P_{\max} = 1.25\% \pm 0.01\%$, at a wavelength $\lambda_{\max} = 5635 \pm 50$ Å, with a position angle $\theta_i = 177.4 \pm 0.2$. These are the SMF parameters, with the parameter $K = 0.95$ calculated from the formula of Wilking et al. (1980). The rotation in the fit is $\mathrm{dPA} = 3\overset{\circ}{.}4 \pm 0.4$ per λ^{-1} (where λ is in μm). The estimated ISP is shown in Figure 1. The derived value for $\lambda_{\max}$ gives a value of $R_v = 3.2 \pm 0.2$, using the formula of Whittet & van Breda (1978); this is consistent with published R_v values for the region.

3.2. *Continuum and Line Polarization*

To separate the continuum and line polarization, we defined artificial filters to split our data into two parts. The continuum filter was defined to include flux and polarization from only those regions of the spectrum that were determined to be free of strong line emission. In this case, the filter definition was the line-free regions from 5280 to 5495 Å and from 6005 to 6115 Å. The line filter definition included the flux and polarization from the lines of [Ne v], [Ne III], Hα, Hβ, Hγ, [O III], and He I (see Paper I). Since there were no significant differences in behavior between the individual line polarizations, we chose to include all the lines in a single filter definition. The total amount of polarization within each filter was measured; the line polarization measurements were made without removing the continuum contribution from the lines.

4. RESULTS AND DISCUSSION

Figure 2 shows the polarimetric variations in the continuum and lines. The ISP has not been removed from these data; since the ISP is assumed constant, a variable observed polarization indicates the presence of a variable intrinsic polarization component. Continuum measurements later than 1992 October are not shown in Figure 2, since the nova became too faint to measure the continuum polarization accurately. The line polarization is essentially constant at the ISP level, despite large changes in the line fluxes, which indicates that the lines are apparently nearly unpolarized. The change in polarization across the emission lines (see Fig. 1) is consistent with unpo-

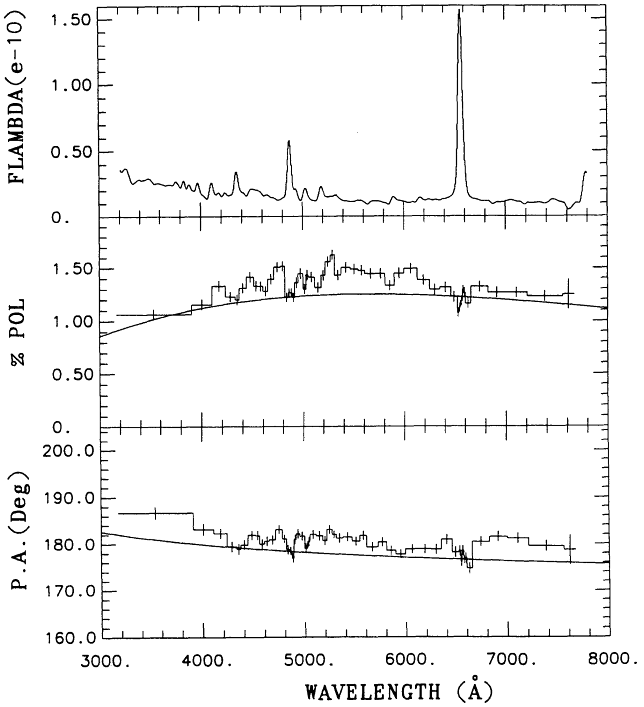

FIG. 1.—PBO observation on 1992 March 1, 9 days after discovery. The plot shows, from top to bottom panels respectively, the flux (F_λ, in units of ergs cm^{-2} s^{-1} Å^{-1}), polarization (% Pol.), and position angle (P.A.) as a function of wavelength (Å). The polarization and position-angle data have been binned to a constant error of 0.05% (shown by the error bars). Note the polarization change across the emission lines. The solid line indicates the estimated interstellar polarization contribution derived from the entire data set (see Text).

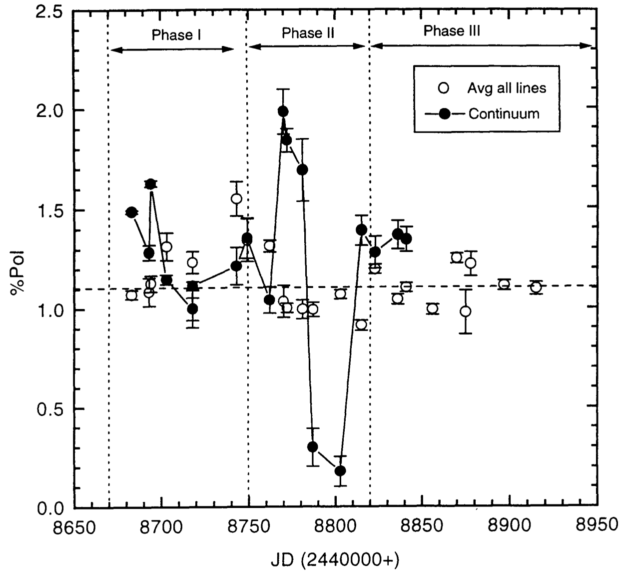

FIG. 2.—Polarimetric variations of the continuum and lines. The continuum points (*solid circles*) represent the combined data from line-free continuum areas. The line points (*open circles*) represent the data from all the emission line regions combined. Interstellar polarization, which has not been removed, is approximated by the dashed line. Note that the continuum polarization varies while the line polarization does not. The three phases are described in the text.

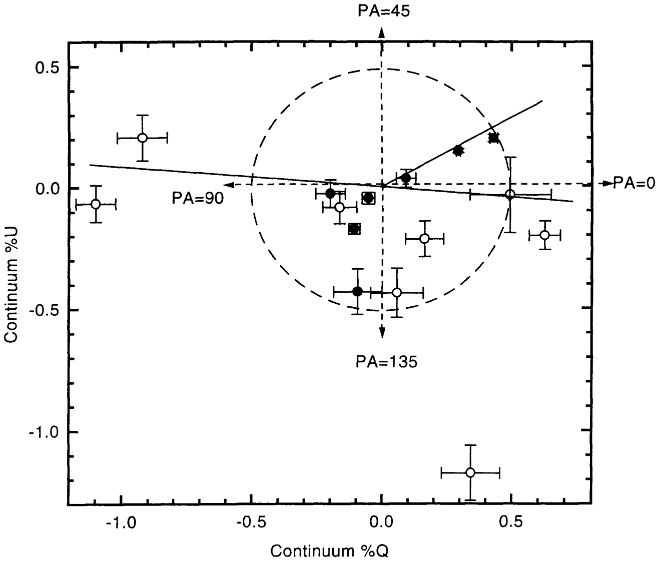

FIG. 3.—QU diagram for the continuum data. The interstellar polarization has been removed, so (0, 0) corresponds to zero intrinsic polarization. The dashed circle indicates a constant 0.5% intrinsic polarization. The points are coded according to the phases of the polarimetric evolution of the nova (see Fig. 2). Note the well-defined position angle, P.A. ~ 15°, of the points in phase 1 (*solid circles*), indicating a flattened ejection shell with a preferred direction. In phase 2 (*open circles*), as the nova becomes optically thin, intrinsic polarization develops briefly near P.A. ~ 175° (*far right*), then flips to P.A. ~ 85° (*far left*). Note that the P.A. rotates twice as fast in a *QU* diagram as it does on the sky, as shown by the P.A. indicators.

larized line emission. We interpret this to mean that the lines are produced in a very extended region and are not subject to large amounts of electron scattering. The continuum polarization is quite different from the lines and is variable. We discuss the continuum variations in terms of three distinct phases, indicated in Figure 2. Figure 3 is a vector plot of Q and U (Stokes parameters) for the phase 1 and 2 observations (when most of the variability occurred).

In phase 1 the continuum polarization starts out with an intrinsic component of about 0.5% above the ISP level. It then generally decreases over the first 47 days to the ISP level, where it remains for a time. In our interpretation, during this phase the continuum radiation from the small pseudo-photosphere of the nova is scattered off electrons in the initial ejection shell, producing a polarized continuum.

Using the techniques of Brown & McLean (1977) for an optically thin electron-scattering envelope, and including the finite-disk correction factor for illumination by a uniform spherical source (Cassinelli, Nordsieck, & Murison 1987), we find that the intrinsic polarization level implies an asymmetry in the ejection shell which could be explained, for instance, by a spheroidal shell with greater than 10% flattening. Since polarization is proportional to the electron-scattering optical depth, the decline of the intrinsic polarization is simply a result of the expansion of the shell, which gradually decreases the scattering optical depth. The P.A. of the continuum polarization in phase 1, shown in Figure 3, corresponds to the ejection axis, and is well defined at P.A. = 15°. Note that this is dependent on our assumption of optically thin electron scattering; for the optical thick case, or in the case where there is a velocity asymmetry in the scattering shell, the P.A. could be perpendicular to the

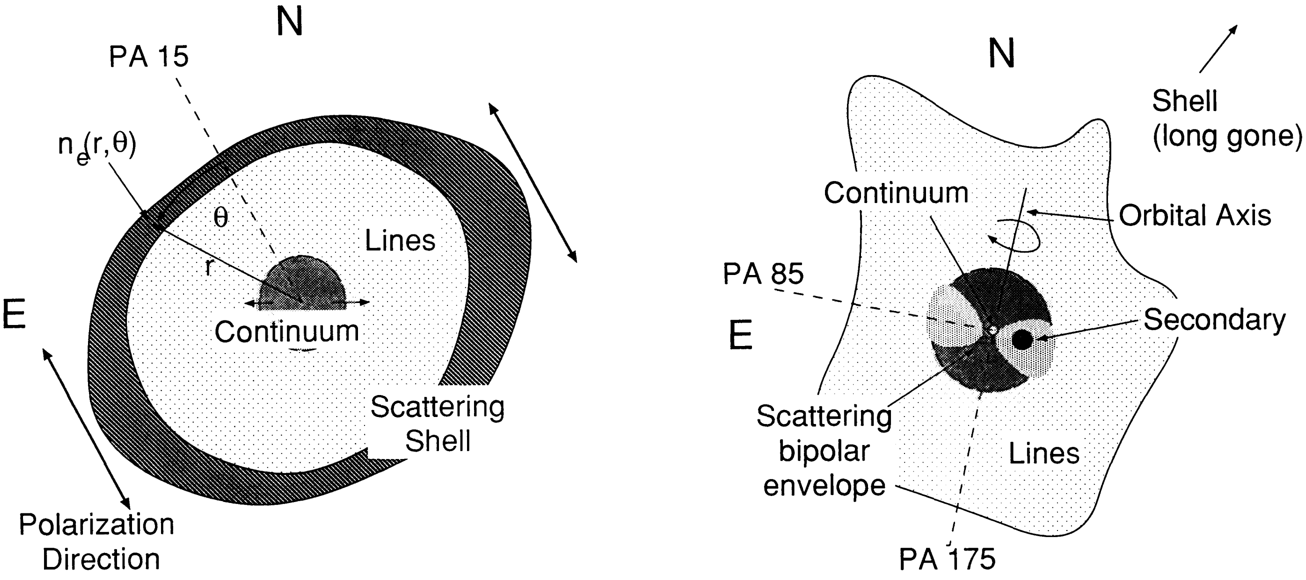

FIG. 4*a*

FIG. 4*b*

FIG. 4.—Schematic representation of two phases in the nova evolution as inferred from the polarization measurements: (*a*) phase 1; (*b*) phase 2. Note that in phase 1, the line-forming region is more extended than the continuum region, extending even into the scattering region itself, so the lines will be significantly less polarized than the continuum.

ejection axis. Figure 4*a* shows a schematic representation of our interpretation of phase 1.

At about 70 days after visual maximum, the nova enters phase 2, when the continuum polarization undergoes two large changes (~0.8% in the polarization) relative to the ISP. The P.A. of the continuum polarization during these times is rapidly variable and rather chaotic (see Fig. 3), but seems to show two orthogonal values: first near P.A. = 175° and then near P.A. = 85°. The rapid timescale over which these variations occur, about a week, suggests changes in the illuminating source rather than changes in the geometry of the scatterers. Interestingly, the start of these changes in the continuum polarization in phase 2 corresponds to the onset of the nebular phase as seen in the spectrum (Paper I).

Our current interpretation of phase 2, which is admittedly speculative, involves the emergence of the underlying binary as the pseudo-photosphere becomes transparent. The rapid changes in the continuum polarization level and P.A. could be produced by beams of light emerging from the hot companion along (or perpendicular to) the binary axis, illuminating electrons in the dispersing wind. The rapid changes are evidence of clumping in the ejection, which is supported also by radio (R. M. Hjellming 1993, private communication) and ultraviolet (Shore et al. 1993) observations and by spectral analysis (Paper I). Such clumping would result in an uneven change in the apparent illuminating source as the pseudo-photosphere becomes transparent in an irregular fashion. Our interpretation is illustrated schematically in Figure 4*b*. This picture is similar to what is seen in the polarization behavior of bipolar objects such as pre–main-sequence stars with disks and jets (Schulte-Ladbeck et al. 1992). Although this interpretation is much less well defined than that of phase 1, it would imply that the ejection axis (P.A. = 15°, as seen in phase 1) does not align with the binary axis (P.A. = 85°, seen late in phase 2).

The final polarimetric phase, phase 3, which the nova entered about 180 days after visual maximum, shows the continuum polarization nearly constant at the ISP level with no further changes. There is apparently little intrinsic polarization present in phase 3, which implies that the remaining electron scattering opacity is small. Spectropolarimetric observations in this phase are quite difficult, as the nova spectrum is completely dominated by line emission, and the continuum is very faint. We have continued to monitor the polarization and the spectrum to watch for the possible formation of dust, which might result in a large increase in the polarization; however, later observations show no evidence for dust formation. This is consistent with other observations and with predictions for fast novae (Gallagher 1977; R. D. Gehrz 1992, private communication).

These results show that spectropolarimetry provides a more powerful probe of the geometry of nova outbursts than traditional filter polarimetry. It provides a means to separate continuum and line polarization, which is critical for seeing changes in the shell evolution. It also permits polarization changes to be compared directly with simultaneous information on the spectral changes. Unfortunately the technique can only be used on relatively bright novae, although future spectropolarimeters on larger telescopes using CCD detectors should improve the magnitude limits. Future bright nova outbursts should be monitored spectropolarimetrically if possible, especially during the first 3–4 months after visual maximum.

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