The Astrophysical Journal, 598:L43–L46, 2003 November 20

EVOLUTION OF THE INNER CIRCUMSTELLAR ENVELOPE OF V838 MONOCEROTIS

J. P. Wisniewski,[1] K. S. Bjorkman,[1] and A. M. Magalhães[2]

Received 2003 September 11; accepted 2003 October 8; published 2003 October 31

ABSTRACT

We present imaging polarimetry observations of the eruptive variable V838 Monocerotis and its neighboring field obtained in 2002 October. The polarization of field stars confirms the previously determined interstellar polarization along the line of sight to V838 Mon. While V838 Mon showed intrinsic polarization shortly after its second outburst on 2002 February 8, all subsequent observations only showed a quiescent interstellar polarization component. We find that V838 Mon once again showed significant intrinsic polarization in 2002 October, suggesting the presence of an asymmetrical geometry of scattering material close to the star. Furthermore, an observed 90° position angle flip in the intrinsic polarization from 2002 February to October suggests that the distribution of nearby circumstellar material has experienced significant changes. We discuss the opacity changes in the evolving circumstellar cloud around V838 Mon that may explain these observations.

Subject headings: circumstellar matter — stars: individual (V838 Monocerotis) — techniques: polarimetric

On-line material: machine-readable table

1. INTRODUCTION

The eruptive variable V838 Monocerotis, first reported as a possible nova on 2002 January 6.6 (Brown et al. 2002), experienced three significant photometric outbursts in early 2002 (Munari et al. 2002b; Kimeswenger et al. 2002). From preoutburst to its maximum brightness during the second outburst, V838 Mon brightened by over 9 mag in *V*, from 15.85 to 6.66 (Goranskii et al. 2002). V838 Mon also exhibited significant spectroscopic variability in early 2002: neutral metal and *s*-process lines were observed following the first outburst (Zwitter & Munari 2002), ionized metal lines were noted following the second outburst (Iijima & Della Valle 2002; Morrison et al. 2002), and neutral metal and molecular lines were observed following the third outburst (Rauch, Kerber, & van Wyk 2002; Banerjee & Ashok 2002). V838 Mon exhibited intrinsic polarization on 2002 February 8 (Wisniewski et al. 2003). Polarimetric observations after 2002 February 13 only detected the presence of an interstellar polarization (ISP) component (Munari et al. 2002c; Wisniewski et al. 2003).

V838 Mon developed a light echo by 2002 February 17 (Henden, Munari, & Schwartz 2002). Bond et al. (2003) obtained imaging polarimetry of this light echo with the *Hubble Space Telescope* (*HST*) Advanced Camera for Surveys (ACS) and suggested a distance of 3–7 kpc to V838 Mon, although a wide range of other distances have been estimated (e.g., see discussion in Wisniewski et al. 2003 and Tylenda 2003). In late September and early October of 2002, V838 Mon's spectral type had evolved to "later than the M10-III star U Her" (Desidera & Munari 2002). Furthermore, a weak blue continuum was detected by several groups, suggesting that a binary component of spectral type B3 V might be present (Desidera & Munari 2002; Wagner, Starrfield, & Hauschildt 2002; Munari, Desidera, & Henden 2002a). Recent Multiple Mirror Telescope spectra confirm this secondary component (S. G. Starrfield 2003, private communication).

Given the magnitude and complexity of the variability exhibited by V838 Mon, it is not surprising that there is still great uncertainty regarding the exact nature of this object. In this Letter, we present imaging polarimetry observations of V838 Mon and its surrounding field obtained in 2002 October. These observations allow us to further interpret the evolution of the circumstellar matter near V838 Mon since its major outbursts.

2. OBSERVATIONS

We obtained polarimetric measurements of V838 Mon and its field in 2002 October at the Cerro Tololo Inter-American Observatory (CTIO) 1.5 m telescope. The standard Cassegrain focus imaging camera with the f/13.5 ($0''.24$ pixel^{-1}) configuration was modified by the addition of a rotatable half-wave plate followed by a fixed analyzer placed before the second filter wheel. The analyzer was a double-calcite block whose optical axes had been crossed to minimize astigmatism and color effects, which produced two orthogonally polarized images of each object in the field. One polarization modulation is covered for each 90° rotation of the wave plate. For our *V*, *R*, and *I* observations of V838 Mon, we took images with the wave plate rotated through eight positions $22^\circ.5$ apart. Further details about this polarimeter can be found in Magalhães et al. (1996), Melgarejo et al. (2001), and Pereyra & Magalhães (2002).

After basic image processing in IRAF,[3] we performed aperture photometry on the fields. The reduction package PCCDPACK (Pereyra 2000), which calculates linear polarization from a least-squares solution of the photometry in the eight wave-plate positions (ψ_i), was then applied. The residuals at each wave-plate position with respect to the expected $\cos 4\psi_i$ curve constitute the uncertainties in our data; these are consistent with the theoretically expected photon noise errors (Magalhães, Benedetti, & Roland 1984). Each object whose polarization is reported has been carefully checked for contamination effects due to close neighbors; objects that contained such contamination were excluded from the present study.

Polarized and unpolarized standard stars were monitored nightly throughout the 11 nights of our observing run, and the stability of the polarimeter was reflected in the consistency of

[1] Ritter Observatory, Department of Physics and Astronomy, University of Toledo, Mail Stop 113, Toledo, OH 43606-3390; jwisnie@physics.utoledo.edu, karen@physics.utoledo.edu.

[2] Instituto Astronomico e Geofisico, Universidade de São Paulo, Caixa Postal 3386, SP 01060-970 São Paulo, Brazil; mario@astro.iag.usp.br.

[3] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

TABLE 1
Summary of Our Observations of V838 Mon and Polarimetric Observations from the Literature

Filter (1)	Date (2002) (2)	Polarization (%) (3)	Error (%) (4)	P.A. (deg) (5)	Intrinsic Polarization (%) (6)	Error (%) (7)	Intrinsic P.A. (deg) (8)	Ref. (9)
B	Feb 8	2.840	0.081	146.6	0.703	0.081	117.0	1
V	Feb 8	3.412	0.012	146.7	0.983	0.012	127.0	1
*V**	Feb 13	2.729	0.009	153.4	…	…	…	1
V	Oct 24 (08:12 UT)	2.49	0.12	162.3	0.90	0.12	32.0	2
	Nov 12	3.05	0.35	159.7 ± 3.9	…	…	…	3
5500 Å	Feb–Mar	2.6	…	150 ± 2	…	…	…	4
R	Feb 8	3.226	0.004	149.0	0.714	0.004	131.2	1
	Feb 13	2.667	0.004	153.4	…	…	…	1
	Oct 22 (08:57 UT)	2.24	0.21	163.2	0.93	0.21	36.7	2
I	Feb 8	2.910	0.003	149.5	0.578	0.003	131.9	1
	Feb 13	2.458	0.003	153.5	…	…	…	1
	Oct 24 (08:46 UT)	2.23	0.04	156.3	0.32	0.04	42.1	2

Notes.—The asterisk denotes a spectropolarimetric observation that did not span the entire wavelength range of the Johnson *V* filter; thus, the *V*-band polarization for this observation is only an estimate. Wisniewski et al. 2003 suggested that the polarization of V838 Mon on 2002 February 13 was purely interstellar in origin, which the present field star measurements support. We determined the intrinsic polarization present on 2002 October 22–24 by subtracting the observed polarization on 2002 February 13 from our data.

References.—(1) Wisniewski et al. 2003; (2) this study; (3) Giro et al. 2002; and (4) Munari et al. 2002c.

these standard star observations. Comparing our observations of polarized standard stars with available literature data, we transformed our polarization measurements to a standard equatorial system. This transformation is accurate to a position angle (P.A.) of better than 1°. Instrumental polarization was consistently less than 0.05%. Note that the simultaneous observation of the dual orthogonally polarized images of each target in each wave-plate position allows for accurate polarimetry to be performed even under nonphotometric skies, as all-sky polarization is practically canceled (Magalhães et al. 1996). We summarize our observations of V838 Mon, along with polarimetry of this object from the literature, in columns (1)–(5) of Table 1.

3. RESULTS

3.1. *Polarization of Field Stars*

Over small spatial regions, where variations in the distribution of dust and magnetic fields can be assumed to be small, field stars located at similar distances exhibit similar levels of ISP. To study the intrinsic polarization of an astrophysical object, it is often beneficial to examine the polarization of spatially nearby field stars, located at similar distances, to get a statistical measure of the ISP along a particular line of sight.

We measured the polarization in *V*, *R*, and *I* of most of the field stars surrounding V838 Mon; a sample of these results is given in Table 2, and a complete listing of these data is available on-line. The left panel of Figure 1 shows a *V*-band image obtained on 2002 October 16 at the CTIO 0.9 m telescope and includes numerical references to stars shown in the right panel of Figure 1 and tabulated in Table 2. A plot of the spatial distribution of the polarization of these field stars in the *V* band is shown in right panel of Figure 1. We note that three stars near V838 Mon show very similar polarizations, stars 2, 3, and 5. Furthermore, these stars exhibit very similar polarizations to the ISP previously estimated for V838 Mon (Wisniewski et al. 2003). We plot the wavelength dependence of the polarization of these three objects in Figure 2 and overlay the modified Serkowski law (Serkowski, Mathewson, & Ford 1975; Wilking, Lebofsky, & Rieke 1982) description of V838 Mon's ISP with $P_{\rm max} = 2.746\% \pm 0.011\%$, $\lambda_{\rm max} = 5790 \pm 37$ Å, P.A. = 153°.43 ± 0°.12, δP.A.(λ) = 0, and $K = 0.971$ (Wisniewski et al. 2003). The good agreement shown in this figure supports the previously determined ISP, derived entirely from spectropolarimetry. Furthermore, these results imply that stars 2, 3, and 5 are located at similar distances to V838 Mon. Future efforts to determine the distance to V838 Mon should ensure consistency with these three neighboring objects.

TABLE 2
Filter Polarimetry of Targets Shown in Figure 1

R.A. (2000)	Decl. (2000)	Fig. 1 Ref.	Filter	Polarization (%)	Error (%)	P.A. (deg)
7 04 05	−3 50 50	1	*V*	2.486	0.118	162.3
…	…	…	*R*	2.236	0.209	163.2
…	…	…	*I*	2.230	0.043	156.3

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The reference numbers in the third column refer to the labels in Fig. 1. Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

3.2. *Intrinsic Polarization of V838 Mon*

We subtracted the ISP along the line of sight (Wisniewski et al. 2003) from our observations of V838 Mon to determine its intrinsic polarization. The nonzero results (cols. [6]–[8], Table 1) show that on 2002 October 22–24, V838 Mon once again exhibited a significant intrinsic polarization component. Interestingly, the magnitude of intrinsic polarization present on 2002 October 22–24 is similar to that observed on 2002 February 8; however, the position angle of this scattered light differs by roughly 90° (i.e., a P.A. "flip" has occurred).

The presence of an intrinsic polarization component can be interpreted as a signature of light scattering off circumstellar material that is distributed in an asymmetrical geometry. The intrinsic polarization reported here and by Wisniewski et al. (2003) is produced in a region immediately surrounding the unresolved central star and, as such, is different from the reported polarization of V838 Mon's light echo (Bond et al. 2003). In our observations of the unresolved source, the observed polarization is roughly the ratio of the scattered to total (i.e. direct plus scattered) light received. Thus, the renewed intrinsic polarization component suggests that either (1) a new source of asymmetrical circumstellar material, i.e., a new source of scatterers, formed around V838 Mon in 2002 October; (2) the opacity of the circumstellar envelope surrounding

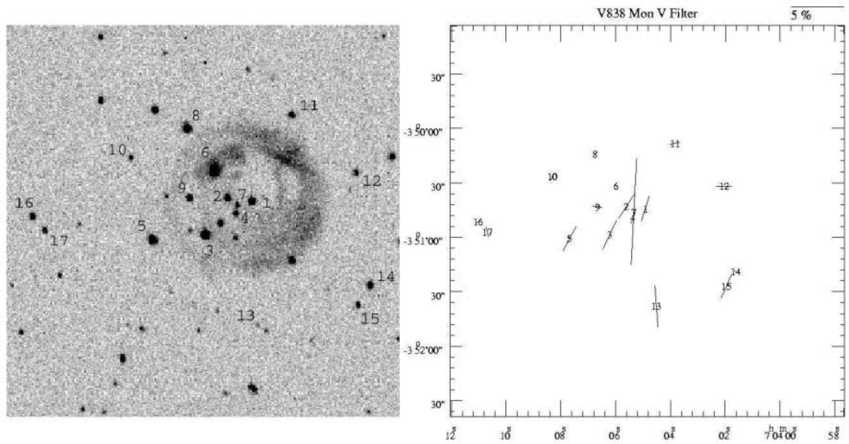

FIG. 1.—*Left*: Locations of the field stars cited in the right panel and in Table 2 are overlaid on a *V*-band image of the field of V838 Mon, taken with the CTIO 0.9 m telescope. V838 Mon is labeled as number 1. *Right*: Polarization of V838 Mon and surrounding field stars.

V838 Mon evolved significantly between February 5–13 and October 22-24, thereby changing the dominant source of scattered light over time; (3) the illuminating source had changed; or (4) a combination of the aforementioned scenarios.

4. DISCUSSION

Schulte-Ladbeck et al. (1992) interpreted an observed wavelength-dependent P.A. flip in polarimetric observations of an unresolved B[e] star as evidence of a bipolar nebula. These authors argued that at short wavelengths, an optically thick circumstellar disk blocked out most of the starlight, and thus little scattered light (with a P.A. aligned along the polar axis) originated from the equatorial disk. Most of the polarized light at short wavelengths originated from the polar regions, where the resulting P.A. would be aligned with the equatorial disk. At long wavelengths, where the disk was optically thin, the dominant source of scattered light was the equatorial disk region, not the polar regions. The net effect of such a wavelength-dependent opacity effect was the production of a 90° P.A. flip in the polarization signal at the wavelength where the equatorial and polar regions contributed equal amounts of scattered light.

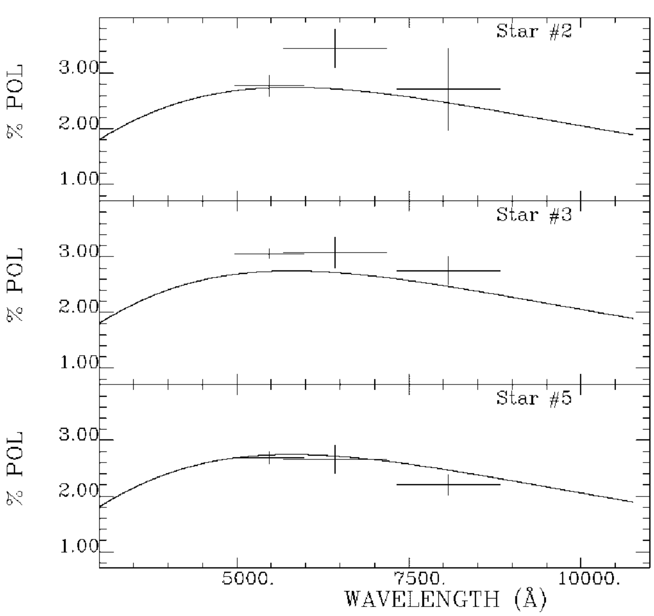

FIG. 2.—Wavelength dependence of three nearby field stars of V838 Mon, along with an overlay of the ISP Serkowski fit derived by Wisniewski et al. (2003) from spectropolarimetry in early 2002. These field stars are consistent with this previously determined ISP.

We suggest that a similar type of scenario might explain the renewed intrinsic polarization component and P.A. flip in V838 Mon. On 2002 February 8, V838 Mon had an intrinsic polarization component, indicating the presence of an asymmetrical distribution of circumstellar material, initially suggested to be a flattened circumstellar envelope (Wisniewski et al. 2003). We postulate that at this initial stage, the observed scattered light originated primarily from specific physical locations, e.g., the polar region. As the opacity of the circumstellar material evolved over time, specifically as the opacity of the equatorial material decreased, we suggest that the contribution of scattered light from the polar and equatorial regions were nearly equivalent. Thus, viewed as an unresolved object, the scattered light from the circumstellar envelope would appear to be unpolarized, consistent with observations in late 2002 February and March (Wisniewski et al. 2003; Munari et al. 2002c). As the envelope continued to evolve and as the equatorial region experienced a further decline in opacity, one would expect the equatorial region to slowly emerge as the dominant source of scattered light. This reemergence of a dominant (and secondary) scattering region would produce an intrinsic polarization component oriented 90° from the original position angle. The projection of the intrinsic P.A. of this envelope onto the sky ($2\theta \sim 75°$, measured north to east) is not inconsistent with the overall morphology seen in the *HST* ACS images (Bond et al. 2003). The intrinsic P.A. of the polar region is also not inconsistent with the direction of the hole in the *HST* ACS light echo images.

We note that the opposite relative opacity changes would produce a similar P.A. flip. The scattered light in the circumstellar envelope could have initially been dominated by an optically thin disk. As this equatorial material dispersed, the scattered light from the equatorial and polar regions could have balanced, producing zero intrinsic polarization. Over time, expansion of the disk could have evacuated the equatorial region, causing the polar region to emerge as the dominant source of scattered light.

Follow-up infrared (IR) imaging polarimetry would be valuable in providing additional constraints on the nature of V838 Mon's circumstellar envelope. Based on IR light and color curves, Crause et al. (2003) suggest that a dust shell had formed around the central star by 2002 April. If in early 2002 this dust formed in the equatorial regions as described in the aforementioned first scenario, i.e., an initial thick equatorial and thin polar region, then the IR polarization position angle would be the same as that quoted in this Letter.

As described in § 1 of this Letter, V838 Mon appears to have a binary companion. Polarimetric observations of mass transfer binary systems show some degree of periodicity and scattering at a constant P.A., defined by the orbital plane of the system (Hoffman, Nordsieck, & Fox 1998). The observed P.A. flip in V838 Mon's intrinsic polarization along with the lack of any apparent periodicity suggest that binarity is not the dominant source of scatterers responsible for the observed intrinsic polarization component.

In summary, the polarization of field stars confirms the previously suggested interstellar polarization along the line of sight to V838 Mon. We find strong evidence of a renewed intrinsic polarization component in V838 Mon, at a position angle of nearly 90° from that present on 2002 February 8. We suggest that these observations indicate an evolution of the circumstellar environment of V838 Mon, possibly characterized by (1) an initially optically thick equatorial disk that contributed a limited amount of scattered light; (2) a subsequent decline in disk opacity that resulted in a balance of scattered light produced by the polar and equatorial regions; and (3) the further decline in the opacity of the equatorial disk that finally allowed the equatorial region to become the dominant source of scattered light. Continued spectropolarimetric monitoring of V838 Mon is strongly encouraged since such observations would enable detailed modeling of the circumstellar environment of this unique object to be performed.

We thank the referee, S. Starrfield, for his suggestions on improving this Letter. We also thank Antonio Pereyra and Brian Babler for assisting with the data reduction. This work has been supported in part by NASA LTSA grant NAG5-8054 to the University of Toledo. K. S. B. is a Cottrell Scholar of the Research Corporation and gratefully acknowledges their support. J. P. W. is supported by a NASA GSRP fellowship and thanks NOAO for supporting his travel to CTIO. A. M. M. acknowledges travel support by FAPESP; he is also partially supported by CNPq. Polarimetry at the University of São Paulo (USP) is supported by FAPESP. A. M. M. and K. S. B. acknowledge partial travel support by USP.

REFERENCES

Banerjee, D. P. K., & Ashok, N. M. 2002, A&A, 395, 161
Bond, H. E., Henden, A., Panagia, N., Sparks, W. B., Starrfield, S., & Wagner, R. M. 2003, Nature, 422, 405
Brown, N. J., Waagen, E. O., Scovil, C., Nelson, P., Oksanen, A., Solonen, J., & Price, A. 2002, IAU Circ. 7785
Crause, L. A., Lawson, W. A., Kilkenny, D., van Wyk, F., Marang, F., & Jones, A. F. 2003, MNRAS, 341, 785
Desidera, S., & Munari, U. 2002, IAU Circ. 7982
Giro, E., Desidera, S., Munari, U., Pernechele, C., & Baume, G. 2002, IAU Circ. 8036
Goranskii, V. P., Kusakin, A. V., Metlova, N. V., Shugarov, S. Yu, Barsukova, E. A., & Borisov, N. V. 2002, Astron. Lett., 28, 691
Henden, A., Munari, U., & Schwartz M. 2002, IAU Circ. 7859
Hoffman, J. L., Nordsieck, K. H., & Fox, G. K. 1998, AJ, 115, 1576
Iijima, T., & Della Valle, M. 2002, IAU Circ. 7822
Kimeswenger, S., Lederle, C., Schmeja, S., & Armsdorfer, B. 2002, MNRAS, 336, L43
Magalhães, A. M., Benedetti, E., & Roland, E. H. 1984, PASP, 96, 383
Magalhães, A. M., Rodrigues, C. V., Margoniner, V. E., & Pereyra, A. 1996, in ASP Conf. Ser. 97, Polarimetry of the Interstellar Medium, ed. W. G. Roberge & D. C. B. Whittet (San Francisco: ASP), 118
Melgarejo, R., Magalhães, A. M., Carciofi, A. C., & Rodrigues, C. V. 2001, A&A, 377, 581
Morrison, N. D., Bjorkman, K. S., Miroshnichenko, A., & Wisniewski, J. P. 2002, IAU Circ. 7829
Munari, U., Desidera, S., & Henden, A. 2002a, IAU Circ. 8005
Munari, U., Henden, A., Corradi, R. L. M., & Zwitter, T. 2002b, in AIP Conf. Proc. 637, Classical Nova Explosions: Int. Conf. on Classical Nova Explosions, ed. M. Hernanz & J. José (Melville: AIP), 52
Munari, U., et al. 2002c, A&A, 389, L51
Pereyra, A. 2000, Ph.D. thesis, Univ. São Paulo
Pereyra, A., & Magalhães, A.M. 2002, ApJS, 141, 469
Rauch, T., Kerber, F., & van Wyk, F. 2002, IAU Circ. 7886
Schulte-Ladbeck, R. E., et al. 1992, ApJ, 401, L105
Serkowski, K., Mathewson, D. S., & Ford, V. L. 1975, ApJ, 196, 261
Tylenda, R. 2003, A&A, submitted (astro-ph/0306555)
Wagner, R. M., Starrfield, S. G.. & Hauschildt, P. H. 2002, BAAS, 34, 1161
Wilking, B. A., Lebofsky, M. J., & Rieke, G. H. 1982, AJ, 87, 695
Wisniewski, J. P., Morrison, N. D., Bjorkman, K. S., Miroshnichenko, A. S., Gault, A. C., Hoffman, J. L., Meade, M. R., & Nett, J. M. 2003, ApJ, 588, 486
Zwitter, T., & Munari, U. 2002, IAU Circ. 7812