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The Spectropolarimetric Evolution of V838 Monocerotis

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Abstract.

I review photo-polarimetric and spectropolarimetric observations of V838 Mon, which revealed that it had an asymmetrical inner circumstellar envelope following its 2nd photometric outburst. Electron scattering, modified by pre- or post-scattering H absorption, is the polarizing mechanism in V838 Mon's envelope. The simplest geometry implied by these observations is that of a spheroidal shell, flattened by at least 10% and having a projected position angle on the sky of $\sim 37^\circ$. Analysis of V838 Mon's polarized flux reveals that this electron scattering shell lies interior to the envelope region in which H α and Ca II triplet emission originates. To date, none of the theoretical models proposed for V838 Mon have demonstrated that they can reproduce the evolution of V838 Mon's inner circumstellar environment, as probed by spectropolarimetry.

1. Diagnostic Capabilities of Polarimetry

Linear polarimetry can provide powerful diagnostic information regarding the geometry of unresolved astrophysical environments. Numerous literature resources (Nordsieck et al. 1992; Bjorkman 2000) eloquently discuss these diagnostic capabilities; for the purpose of this review I will simply summarize several fundamental principles.

The observed intrinsic polarization of unresolved sources is simply the net integrated polarization of the system. The density, geometrical distribution, and scattering properties of scatterers in a system are several factors which will influence the strength of the observed intrinsic polarization; systems which either lack an extended envelope of material or are characterized by a symmetrical envelope will exhibit zero net intrinsic linear polarization. Non-uniform illumination of an extended envelope, by sources such as star-spots and/or binary companions, may also produce a net intrinsic polarization.

Several factors may influence the wavelength dependence of observed intrinsic linear polarization, as discussed by Nordsieck et al. (1992) and Bjorkman (2000). These factors include: a) the scattering process (i.e. Thompson versus Mie scattering); b) the nature of the illuminating source; c) the dilution of polarized light by the presence of additional unpolarized (i.e. direct) light; and d) the preferential absorption of more scattered light than direct (unpolarized) light.

One is typically unable to directly measure the intrinsic polarization of astrophysical sources, as the actual observed polarization is comprised of interstellar (time independent) and intrinsic (possibly time dependent) components.

Identifying and removing interstellar polarization (ISP) from data is a critical, non-trivial exercise; however, several techniques have proven to be successful in this regard. The field star technique (McLean & Clarke 1979) is one method; successful implementation requires one to identify a suitable number of field stars which are a) intrinsically unpolarized; b) located at a similar distance as the target of interest; and c) located a small angular distance from the target of interest. If one assumes emission lines in the target of interest are intrinsically unpolarized (Harrington & Collins 1968), measuring the polarization in these lines can yield estimates of the ISP, although Quirrenbach et al. (1997) have shown that this assumption is not always valid. Finally, the wavelength dependence of ISP is known to follow the empirical Serkowski law (Serkowski et al. 1975); hence, measuring the wavelength dependence of the total observed polarization will, in certain cases, allow one to accurately parameterize the ISP.

2. Observational Datasets

Four groups have reported polarimetric observations of V838 Mon (Wisniewski et al. 2003a,b; Desidera et al. 2004; Rushton et al. 2005). While these studies generally yield similar results regarding the temporal polarimetric evolution of V838 Mon and the fundamental mechanism responsible for this polarization, there is some disagreement amongst the datasets. One likely source of these differences is the level of instrumental polarization which characterize these datasets and act as a source of systematic errors. The absolute accuracy of the Wisniewski et al. (2003a), Wisniewski et al. (2003b) and Rushton et al. (2005) datasets are 0.025% and 1 degree at V, < 0.05% and 1 degree, and 0.08% and \sim 1 degree at V respectively. The instrumental polarization of the Asiago data of Desidera et al. (2004) is quoted as 0.2% and 2 degrees, although Fornasier et al. (2006) quote an instrumental polarization of <0.4% for this instrument. The instrumental polarization of the Crimean data of Desidera et al. (2004) is quoted as ranging from 2.4% (U) to 0.5% (I), with a scatter of 0.1% (U) and 0.02% (other bands). In addition, Desidera et al. (2004) note an **additional 6 degree position angle offset** between their Asiago and Crimean datasets.

Interestingly, the polarization magnitude and position angle of the dataset of Desidera et al. (2004) is different by \sim 0.2% and \sim 6 degrees from other published polarimetry (Wisniewski et al. 2003a; Rushton et al. 2005), corresponding almost exactly to the additional level of instrumental polarization in their data. It is possible that the differences between these datasets are related to systematic errors present in the dataset of Desidera et al. (2004); the specific intrinsic polarization values reported by Desidera et al. (2004) might be suspect.

3. Spectropolarimetric Evolution: Timeline

V838 Mon exhibited clear evidence of variability in its total observed polarization in early 2002 (Wisniewski et al. 2003a; Desidera et al. 2004). Below I summarize the notable events in V838 Mon's spectropolarimetric behavior:

- 10 and 11 Jan 2002; The integrated V-band polarization is measured to be within $1-\sigma$ of the (later to be known) interstellar polarization value

(Desidera et al. 2004); it is unclear whether any intrinsic component existed at this early epoch.

- 4 Feb 2002; The integrated V-band polarization measured by Desidera et al. (2004) is well above the (later to be known) interstellar polarization value; this is the first clear evidence of the presence of an intrinsic polarization component.
- 8 Feb 2002; The first spectropolarimetric observations of V838 Mon confirm the presence of an intrinsic polarization component. The magnitude of the observed total polarization is clearly higher than (later to be known) interstellar values (see panel b of Figure 1). Wisniewski et al. (2003a) find the integrated R-band polarization to be 3.2% at a position angle (PA) of 149° . Observed line depolarization effects at $H\alpha$ and the Ca II triplet are also indicative of an intrinsic component. Subsequent spectropolarimetric observations on 11 Feb 2002 (Desidera et al. 2004) confirm these results.
- 13 Feb 2002; Spectropolarimetry by Wisniewski et al. (2003a) suggest that V838 Mon's intrinsic polarization component has disappeared. These data clearly exhibit a Serkowski-law (Serkowski et al. 1975) wavelength dependence, the best fit of which is shown as a solid line in Figure 2. Wisniewski et al. (2003a) measure the integrated R-band polarization to be 2.667% at a PA of 153° . Line polarization effects have disappeared (Figure 2), supporting the suggestion that the polarization is purely interstellar in origin.
- 14 Feb 2002; Spectropolarimetry by Rushton et al. (2005) confirm that V838 Mon's polarization appears to be purely interstellar in origin at this time. A second observation by this group on 7 Mar 2002 finds a similar result, although the authors do not rule out the possibility that a very small intrinsic component is still present.
- 15 Feb - 20 Mar 2002; Polarimetric observations by Desidera et al. (2004) detect no clear evidence of an intrinsic polarization component, rather the data appear to be characterized purely by an interstellar polarization component.
- 22-24 Oct 2002; Photo-polarimetric observations by Wisniewski et al. (2003b) suggest the renewed presence of an intrinsic polarization component. The position angle of this intrinsic polarization component is oriented 90° from that observed on 8 Feb 2002, suggesting either a fundamental change in the illumination of the system's scatterers or a fundamental change in the geometrical distribution of these scatterers.

4. Interstellar Polarization

Wisniewski et al. (2003a) fit a modified Serkowski-law (Serkowski et al. 1975; Wilking et al. 1982) to their 13 Feb 2002 data (Figure 2), yielding the ISP parameters: $P_{max} = 2.75 \pm 0.1\%$, $\lambda_{max} = 5790 \pm 37\text{\AA}$, $PA = 153.4 \pm 0.12^\circ$,

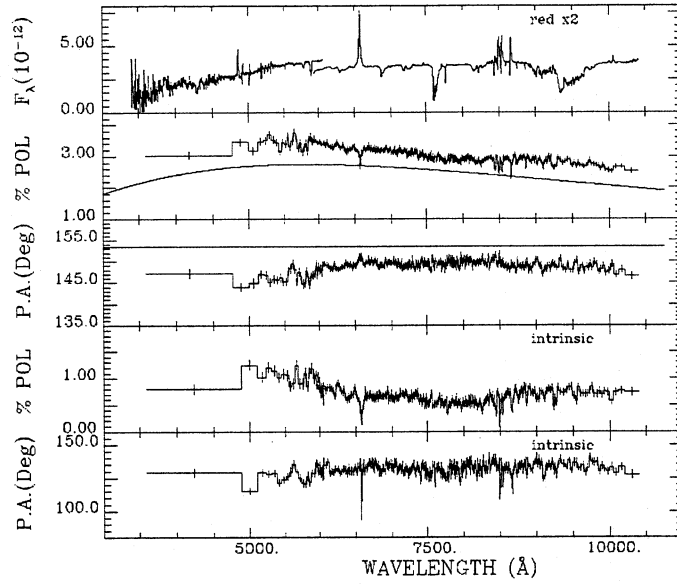


Figure 1. The flux (top panel), total polarization (panels 2 and 3), and intrinsic polarization (bottom 2 panels) of V838 Mon on 8 Feb 2002 (adopted from Wisniewski et al. 2003a). The solid line in the total polarization plots (panels 2 and 3) represent the best-fit interstellar polarization component of Wisniewski et al. (2003a).

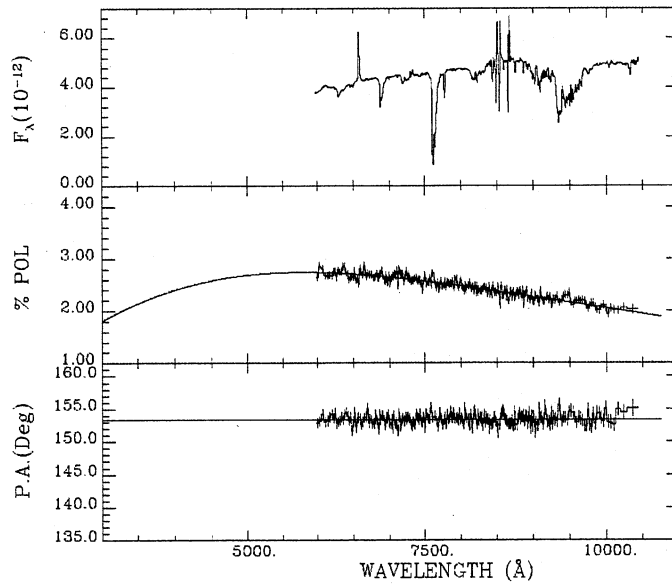


Figure 2. The flux (top panel) and total polarization (bottom 2 panels) of V838 Mon on 13 Feb 2002, along with the best-fit Serkowski-law interstellar polarization estimate (solid line), as adopted from Wisniewski et al. (2003a).

$K = 0.971$, and $dPA = 0$. Field star ISP measurements (Wisniewski et al. 2003b) and later epoch spectropolarimetry (Rushton et al. 2005) support this ISP determination. While it has been suggested in the literature (Desidera et al. 2004) that the line depolarization effects in the Wisniewski et al. (2003a) dataset do not visually fit their ISP determination, careful analysis of these data reveals this discrepancy is less than a $1\text{-}\sigma$ effect. Thus the line depolarization effects seen in Figure 1 do support the ISP determination of Wisniewski et al. (2003a). Desidera et al. (2004) suggest a modestly different ISP; however, as discussed in Section 2, systematic errors in their dataset are likely to be the source of this discrepancy.

4.1. Light Echo Material: Interstellar vs. Circumstellar

Interstellar polarization is produced by the dichroic absorption of starlight by aligned interstellar dust grains. During this conference, it was suggested that the large interstellar polarization component associated with V838 Mon supports the notion that its light echo material is interstellar in origin. However the observed interstellar polarization is merely a superposition of all absorption events which occur along a line of sight; thus, V838 Mon's interstellar polarization provides neither evidence for an interstellar nor a circumstellar origin of its light echo material.

5. Intrinsic Polarization

5.1. Polarizing Mechanism

The wavelength dependence of V838 Mon's intrinsic polarization (bottom 2 panels of Figure 1) exhibits several features: a) the polarization magnitude is nearly constant with wavelength, but does seem to slowly rise at blue wavelengths; b) there is $1\text{-}\sigma$ evidence of a polarization jump at the Paschen limit (Wisniewski et al. 2003a); and c) there is little evidence of intrinsic polarization in any of the strong emission lines. These unique spectropolarimetric signatures are similar to those observed for classical Be stars (Wood et al. 1996, 1997), leading both Wisniewski et al. (2003a) and Desidera et al. (2004) to suggest that the mechanism polarizing V838 Mon's environment is electron scattering, modified by pre- or post-scattering absorption by hydrogen. The behavior of the electron scattering wings in the $H\alpha$ line profiles of V838 Mon, which were present while V838 Mon exhibited an intrinsic polarization component and disappeared 1 day after the disappearance of this intrinsic polarization (Wisniewski et al. 2003a), further supports this interpretation. Other polarizing mechanisms such as Rayleigh scattering or scattering by dust grains would have produced a significantly different wavelength-dependent polarization signature than that observed.

5.2. Geometry of the Scatterers

The presence of an intrinsic polarization component implies that V838 Mon's circumstellar envelope deviates from spherical symmetry. Wisniewski et al. (2003a) note that one of the possible geometries of this envelope is that of a flattened spheroidal shell. Brown & McLean (1977) and Cassinelli et al. (1987) developed tools to estimate the polarization produced by optically-thin electron scattering

envelopes. Bjorkman et al. (1994) used this approach, introducing several assumptions regarding the structure and optical depth of the envelope, to obtain a rough estimate of the amount of flattening in the envelope of Nova Cygni 1992. To summarize these calculations (K. Bjorkman 2006, personal communication), the flattening required to produce a polarization p is

$$\frac{2(a-b)}{a} = \frac{(20 * p)}{\langle \tau \rangle \sin^2 i} \quad (1)$$

We used this technique to obtain a crude estimate of V838 Mon's environment; **the *minimum* amount of flattening of V838 Mon's spheroidal shell on 8 February 2002 is 10%**, given its intrinsic V-band polarization (0.98%, Wisniewski et al. 2003a). The intrinsic polarization PA on 8 Feb was 127° (Wisniewski et al. 2003a), indicating that the projected PA of this flattened shell on the sky was 37° . Interestingly, this position angle corresponds to the position angle derived from interferometric observations of V838 Mon, specifically the "binary" model of these data (Lane et al. 2005).

5.3. Location of the Polarizing Scatterers

Having established that electron scattering, modified by pre- or post-scattering absorption by hydrogen, is the mechanism responsible for V838 Mon's intrinsic polarization, we now consider the location of this material. The (intrinsic) polarized flux spectrum is merely the spectrum of the illuminating source as seen by the scatterer. Hence, any emission feature which is seen in the spectrum but not in the polarized flux must be external to the scatterer (K. Nordsieck 2006, personal communication). As seen in Figure 3, $H\alpha$ and the Ca II triplet are clearly in emission in V838 Mon's spectrum on 8 Feb 2002 (top panel), while these features are **absent** from the polarized flux (bottom panel). Thus, in early Feb 2002, the suggested flattened spheroidal shell of electrons responsible for producing V838 Mon's polarization must lie **interior** to the extended envelope producing the various emission features observed in V838 Mon's spectrum.

6. Intrinsic Polarization at Later Epochs

As noted in Section 3, Wisniewski et al. (2003b) reported photo-polarimetric observations taken on 22-24 Oct 2002 which strongly suggested that V838 Mon had redeveloped an intrinsic polarization component. Interestingly, the intrinsic PA of these data was oriented 90° from that observed on 8 Feb 2002. Wisniewski et al. (2003b) suggest that this renewed intrinsic polarization might arise from (1) a new source of asymmetrical scatterers in V838 Mon's envelope; (2) fundamental changes in the opacity of V838 Mon's envelope; (3) a change in the illumination source, possibly related to the emergence of the B-type binary in V838 Mon's spectrum during this time-period (Desidera & Munari 2002; Munari et al. 2005); or (4) a combination of these scenarios. Continued photo-polarimetric or spectropolarimetric monitoring may elucidate the source of this intrinsic polarization.

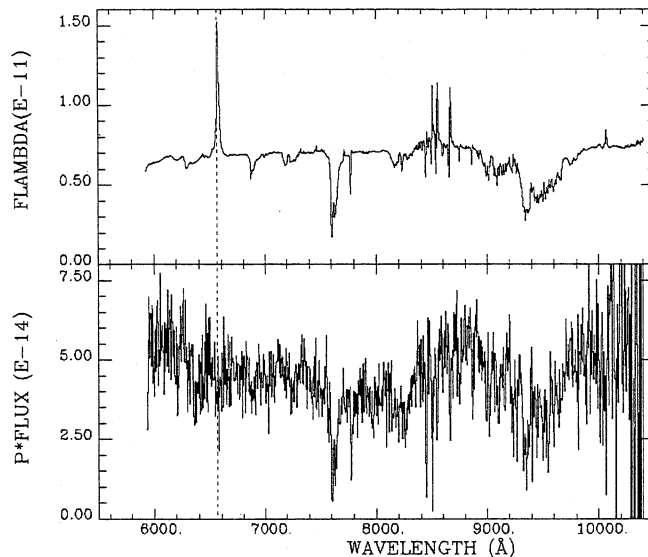


Figure 3. The flux (top panel) and polarized flux (bottom panel) of HPOL spectropolarimetry from 8 Feb 2002. Emission features present in the total flux but *absent* in the polarized flux spectrum, such as H α and the Ca II triplet, must be formed in regions external to the flattened spheroidal shell of electrons producing the observed polarization.

7. Summary

V838 Mon exhibited clear evidence of an intrinsic polarization component beginning at least on 4 February 2002; evidence of this intrinsic component disappeared by 13 February 2002. The wavelength dependence of this intrinsic polarization suggests that electron scattering, modified by pre- or post-scattering absorption by hydrogen, was the polarizing mechanism. The presence of an intrinsic component implies that V838 Mon's circumstellar envelope was asymmetrical; one possible geometry of this envelope is a spheroidal shell flattened by at least 10%. From V838 Mon's polarized flux, we know that this shell is located interior to the region of V838 Mon's envelope responsible for producing emission features at H α and the Ca II triplet. Current theoretical efforts to identify the mechanism responsible for V838 Mon's outburst have primarily focussed on explaining its photometric evolution. To date, none of these models have demonstrated that they can reproduce the evolution of V838 Mon's inner circumstellar environment, as probed by spectropolarimetry.

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Discussion

L. Bernstein: How non-spherical does the scattering shell need to be to be consistent with the polarization data?

J. Wisniewski: A crude estimate is that the shell is flattened by $\sim 10\%$, as detailed in Section 5.2 of this write-up.