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Spectral evolution of V838 Monocerotis in the optical and near-infrared in early 2002

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ABSTRACT

We report optical and near-infrared spectroscopy, and optical spectropolarimetry, of the peculiar variable V838 Mon during the multiple outburst phase in early 2002. The spectral evolution is exceptional. Our earliest spectra (2002 January) are noteworthy for their strong absorption lines of barium and strontium in the optical, and bands of CO and circumstellar H_2O in the near-infrared. All but the CO weaken or are absent in later spectra. The behaviour of the CO band during this phase is extraordinary: initially in absorption, it was observed two months later in optically thick emission. The excitation of the CO is probably the result of the propagation of a shock wave at the third maximum. The two spectropolarimetric epochs were taken 6 and 27 d after the second outburst on 2002 February 8. The polarization at both times was measured to be $p_V \approx 2.7$ per cent. Nearly all of the measured polarization is believed to be due to interstellar dust, a conclusion that is consistent with previous studies. At both epochs, however, a weak and variable intrinsic component is thought to be present. Between January and March of 2002 the luminosity of V838 Mon increased by a factor of 15 and the apparent diameter increased fourfold.

Key words: stars: evolution – stars: individual: V838 Mon.

1 INTRODUCTION

V838 Mon was discovered (Brown 2002) in outburst on 2002 January 6, and its subsequent evolution has defied attempts at interpretation and classification.

Its visual light curve displayed three distinct maxima (Munari et al. 2002; Crause et al. 2003), each of which was accompanied by spectral changes in the optical and near-infrared (near-IR) (Munari et al. 2002; Banerjee & Ashok 2002; Kolev et al. 2002; Lynch et al. 2002). Photometric observations from 2002 mid-April showed a rapid decline in the visual, accompanied by the development of a M III-I spectrum. Optical spectroscopy obtained on 2002 April 22 showed an even cooler M6/7 star (Henden et al. 2002b). Near-IR spectra obtained on 2002 May 3 and 2002 May 14 showed that the star had cooled further still, with blackbody-curve temperatures of $T_{\rm eff} = 2600$ and 2400 K (respectively) best fitting the *JHK* fluxes (Banerjee & Ashok 2002). The overall trend during this period is towards lower effective temperatures and higher luminosities, and has been interpreted in terms of an expanding photosphere (Rauch, Kerber & van Wyk 2002). The star then evolved to become one of the coolest stars known, displaying molecular features most commonly seen in the spectra of very late L and T brown dwarfs (Evans et al. 2003; Lynch et al. 2004).

Ejection of matter is implied by the occurrence of several lines with P-Cygni profiles, suggesting outflow speeds of 100–500 km s^{-1} (Wisniewski et al. 2003a; Kipper et al. 2004). Immediately after eruption the object resembled a K giant or supergiant. However, a major spectral change, consisting primarily of a shift towards a state of higher ionization and an increase in P-Cygni emissions (Wisniewski et al. 2003a), coincided with the second photometric outburst (∼2002 February 6).

The extraordinary nature of this object was underlined by the appearance of a light echo, first detected on 2002 February 17 (Henden, Munari & Schwartz 2002a), with apparently superluminal expansion (Bond et al. 2003). The light echo seems to reside within a dusty environment around V838 Mon, the existence of which is

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suggested by possible *Infrared Astronomical Satellite* (*IRAS*) (Kato 2002) and *Midcourse Space Experiment* (*MSX*) (van Loon et al. 2004) detections. Monitoring of the light echo led to a distance determination of $d \approx 700$ pc (Munari et al. 2002; Kimeswenger et al. 2002). Using this distance, the predicted interstellar reddening $E(B - V) = 0.5$ mag, and archive measurements, Munari et al. (2002) estimated that the progenitor was of spectral type F and close to the main sequence. However, the distance is now thought to be much larger: Wisniewski et al. (2003a) determined $d \gtrsim 2.5$ kpc using spectroscopic data, while Bond et al. (2003) and Tylenda (2004) have reassessed the distance as determined from the light echo and suggested $d \gtrsim 6$ kpc, implying a progenitor with luminosity $L \gtrsim 92\,L_{\odot}$.

The nature of V838 Mon is an enigma, although there are similarities with the eruptive variables M31 RV (Rich et al. 1989) and V4332 Sgr (Martini et al. 1999). Early interpretations of V838 Mon included a nova and a He shell flash, but there are severe difficulties with both of these scenarios (Munari et al. 2002; Kimeswenger et al. 2002): the spectral evolution is contrary to the behaviour of normal novae, and there are compositional difficulties with the He-flash interpretation. More exotic possibilities have therefore been explored. Soker & Tylenda (2003) suggested that these objects could be explained by the merging of two main-sequence stars, while Retter & Marom (2003) proposed the swallowing of planets by a giant star.

The bizarre behaviour displayed by V838 Mon does not sit comfortably with any conventional stellar evolution scenario and may represent a new and hitherto unknown category of stellar behaviour.

In this paper we present optical and near-IR spectroscopy together with spectropolarimetry, obtained on numerous occasions in early 2002, which record the remarkable changes highlighted above, as well as some that were not seen by other observers. Such studies, in conjunction with others, will be useful in deciphering the nature of V838 Mon.

2 OBSERVATIONS

The observational details are shown in Tables 1 and 2. Fig. 1 shows the times of the 2002 observations with respect to the visual light curve of V838 Mon.

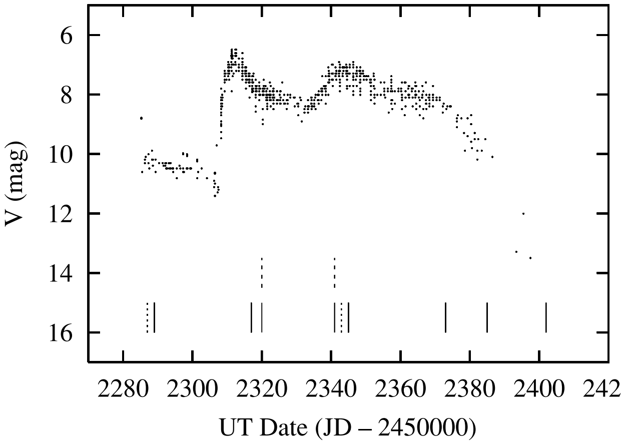

Figure 1. Visual light curve of V838 Mon from the Association Française des Observateurs d'Étoiles Variables (AFOEV) covering the period of observations. Vertical lines mark the dates of the optical (solid line), near-IR (dotted), and polarimetry (dashed) observations described here.

2.1 Optical spectra

Optical spectra were obtained on six separate occasions over a four-month period between 2002 January and May. We used the Kast double spectrograph (Miller & Stone 1993) mounted at the Cassegrain focus of the Shane 3-m telescope at Lick Observatory. A 2-arcsec slit was utilized, and its position angle (PA) was generally aligned along the parallactic angle to reduce light losses arising from atmospheric dispersion (Filippenko 1982). Details are given in Table 1.

All data were reduced using standard techniques as described by Li et al. (2001) and references therein. Flat-fields for the red CCD were taken at the position of the object to reduce near-IR fringing effects. The spectra were corrected for atmospheric extinction and telluric bands (Bessell 1999; Matheson et al. 2000), and then flux-calibrated using standard stars observed at similar airmass on the same night as V838 Mon.

2.2 Near-IR spectra

The near-IR spectra of V838 Mon were taken at the 3.8-m United Kingdom Infrared Telescope (UKIRT). The observations employed the cooled grating spectrometer CGS4 (Mountain et al. 1990). They covered the *JHK* bandpasses and were obtained on two occasions, the first following the initial maximum, and the second near the optical peak following the third outburst (Fig. 1).

To remove telluric features and the effects of instrumental response, the raw spectra of V838 Mon were ratioed with the spectrum of the selected standard star HIP33819 (type F5 V). The standard was observed at a similar airmass to that of the target to ensure that the removal of telluric features was reasonably complete. The only major intrinsic spectral features in the standard are H I lines, which we removed prior to ratioing.

Flux calibration was achieved by multiplying the ratioed spectra by a blackbody function scaled to be representative of the energy distribution of an F5 V star. The accuracy of the calibration was estimated from the discrepancy between the overlapping *H* and *K* spectral segments, and is thought to be ~15 per cent. The wavelength calibration, which is accurate to ± 0.0003 μm($\pm 2\sigma$), was accomplished by obtaining the spectra of arc-lamps immediately prior to observing the target.

2.3 Optical spectropolarimetry

We obtained spectropolarimetry of V838 Mon on 2002 February 14 and March 7, using the low-resolution imaging spectrometer (Oke et al. 1995) with polarimeter on the 10-m telescope at the W. M. Keck Observatory. The slit PA was set close to the parallactic angle for all observations, and the total-flux spectra from all epochs were corrected for continuum atmospheric extinction and telluric absorption bands. A log of observations is given in Table 2.

The polarimetry data were reduced according to the methods outlined by Miller, Robinson & Goodrich (1988), and detailed by Leonard et al. (2001) and Leonard & Filippenko (2001). The polarization angle offset between the half-wave plate and the sky coordinate system was determined for all polarimetry epochs by observing the polarized standard star BD+59°389 and setting its *V*-band polarization PA (e.g. θ_V, the de-biased, flux-weighted average of the polarization angle over the wavelength range 5050–5950 Å; see Leonard & Filippenko 2001) equal to $98\overset{\circ}{.}09$, the value catalogued by Schmidt, Elston & Lupie (1992). An extensive discussion of the observations and an analysis of the data obtained specifically on these two nights can be found in Leonard et al. (2002).

Table 1. Log of optical and near-IR observations of V838 Mon.

2002 date (UT)	Grism/grating (lines mm^{-1}/blaze)	Res[a] (Å)	Flux std	Wavelength range (Å)	Exposure (s)	PA[b] (deg)	Parallactic[c] angle (deg)	Airmass[d]	Seeing[e] (arcsec)
Jan 12	40	12.5	HIP33819	10300–13400	256	0	–	1.26	0.8
Jan 12	40	25	HIP33819	18900–25300	128	0	–	1.20	0.5
Jan 12	40	25	HIP33819	14400–20600	184	0	–	1.14	0.6
Jan 14	600/4310	6	BD +284211	3300–5400	20	179	179	1.33	3
Jan 14	300/7500	11	BD +174708	5200–10400	20	179	179	1.33	3
Feb 11	600/4310	6	Feige 34	3300–5400	5	17	17	1.38	2
Feb 11	300/7500	11	BD +262606	5200–10400	5	17	17	1.38	2
Mar 9	40	25	HIP33819	14200–20600	160	90	–	1.09	1.0
Mar 9	40	25	HIP33819	18900–25300	256	90	–	1.12	0.8
Mar 9	40	12.5	HIP33819	10300–13400	256	90	–	1.18	1.4
Mar 11	600/4310	6	Feige 34	3300–5400	3	15	17	1.40	2.5
Mar 11	300/7500	11	HD19445	5200–10400	3	15	17	1.40	2.5
Apr 8	600/4310	6	BD +284211	3300–5400	15	32	32	1.56	1.5
Apr 8	300/7500	11	BD +262606	5200–10400	15	32	32	1.56	1.5
Apr 20	600/4310	6	BD +284211	3300–5400	5+15	37	37	1.77	2
Apr 20	300/7500	11	BD +171708	5200–10400	5+3	37	37	1.77	2
May 7	600/4310	6	BD +284211	3300–5400	30+300	46	47	1.77	∼7
May 7	300/7500	11	BD +171708	5200–10400	30+300	46	47	1.77	∼7

Optical observations were obtained at the Lick 3-m telescope with a 2-arcsec slit; IR observations were obtained at UKIRT with a 1-arcsec slit. [a]Resolution determined from the width of night-sky lines. [b]Position angle of the spectrograph slit. [c]Parallactic angle (Filippenko 1982) near mid-point of the exposures. [d]Airmass near mid-point of each set of observations. [e]The approximate full width at half-maximum (FWHM) of the spatial profile for each set of observations.

Table 2. Log of spectropolarimetric observations of V838 Mon.

2002 date (UT)	Grating (lines mm^{-1}/blaze)	Res[a] (Å)	Flux Std	Wavelength range (Å)	Exposure (s)	PA[b] (deg)	Parallactic[c] angle (deg)	Airmass[d]	Seeing[e] (arcsec)
Feb 14	300/5000	13	HD 84937	3930–8830	4 × 5	22	28	1.13	2
Feb 14	400/8500	9	HD 84937	6420–10100	4 × 5	22	20	1.11	2
Mar 7	300/5000	13	BD +262606	3900–8800	4 × 1	56	57	1.45	1

All observations were obtained at the Keck-I 10-m telescope with a 1.5-arcsec slit. [a]Resolution determined from the width of night-sky lines. [b]Position angle of the spectrograph slit. [c]Parallactic angle (Filippenko 1982) near mid-point of the exposures. [d]Airmass near mid-point of each set of observations. [e]The approximate FWHM of the spatial profile for each set of observations.

3 OPTICAL SPECTRA

The evolution of the optical spectrum is shown in Fig. 2. These spectra and those in Fig. 3 have been dereddened using $E(B - V) = 0.7$ mag. This value is intermediate between those obtained by Wagner & Starrfield (2002) [$E(B - V) = 0.54$ mag] and Zwitter & Munari (2002) [$E(B - V) = 0.8$ mag]. In addition, it is supported by Kimeswenger et al. (2002) and the extinction maps of Neckel & Klare (1980) for distances $\gtrsim$1 kpc. The value adopted by Munari et al. (2002) [$E(B - V) = 0.5$ mag] had been chosen as a mid-point between $E(B - V) = 0.8$ mag and the implied reddening from the lower distance estimate.

3.1 2002 January

On 2002 January 14, the optical spectrum of V838 Mon was characterized by strong neutral atomic lines and weak hydrogen lines. The only persistent molecular feature detected in this range was the G band (CH) centred at ∼4300 Å (2002 January 14 to March 11). While the dereddened continuum resembles that of an early G-type star, the presence of marginal absorption in the $\upsilon' = 0$ sequence of the TiO γ' system is more typical of an early to mid-K giant or supergiant (Turnshek et al. 1985; Jacoby, Hunter & Christian 1984).

In addition to Hα, Na I D, O I (7774 Å), and the Ca II triplet, three multiplets of Fe I (Multiplet 1254, 168 and 60) definitely display P-Cygni characteristics; mean outflows at a given epoch are listed in Table 3. The Ba II lines at 5852, 6142 and 6497 Å (Multiplet 2) first reported with prominent emissions on 2002 January 8 and 9 (Wagner, Halpern & Jackson 2002; Della Valle & Iijima 2002) are also seen, along with Ba II (4554 and 4934 Å; Multiplet 1). However, only Ca I, Fe I, and the Ba II (6497 Å) blend show an appreciable emission component. Furthermore, we detect two strong absorption lines centred at 10 030 and 10 329 Å. Their relative strengths and wavelengths, together with features at 4077 and 4215 Å, suggest that they may be due to Sr II (10 037 & 10 327 Å; Multiplet 2).

The 2002 January optical and *JHK* spectra were taken nearly simultaneously. Assuming a negligible change in T_{eff} between these two data sets, the spectra can be combined to give a continuous spectrum covering 0.33–2.5 μm. The resulting spectra show a smooth transition between the optical and near-IR ranges, and the flux at a given bandpass is in agreement with the concurrent photometric data (Munari et al. 2002; Kimeswenger et al. 2002; Crause et al. 2003).

The effective temperature has been estimated, in both spectra, by fitting Kurucz solar composition model atmospheres (Kurucz 1991, 1993) to the dereddened continua, and the best fits are obtained with $T_{\mathrm{eff}} = 5250 \pm 250$ K, with the uncertainty dominated by the 250-K intervals of the models.

We have attached a Rayleigh–Jeans tail at the estimated effective temperature to the region longward of 2.5 μm, and calculated the

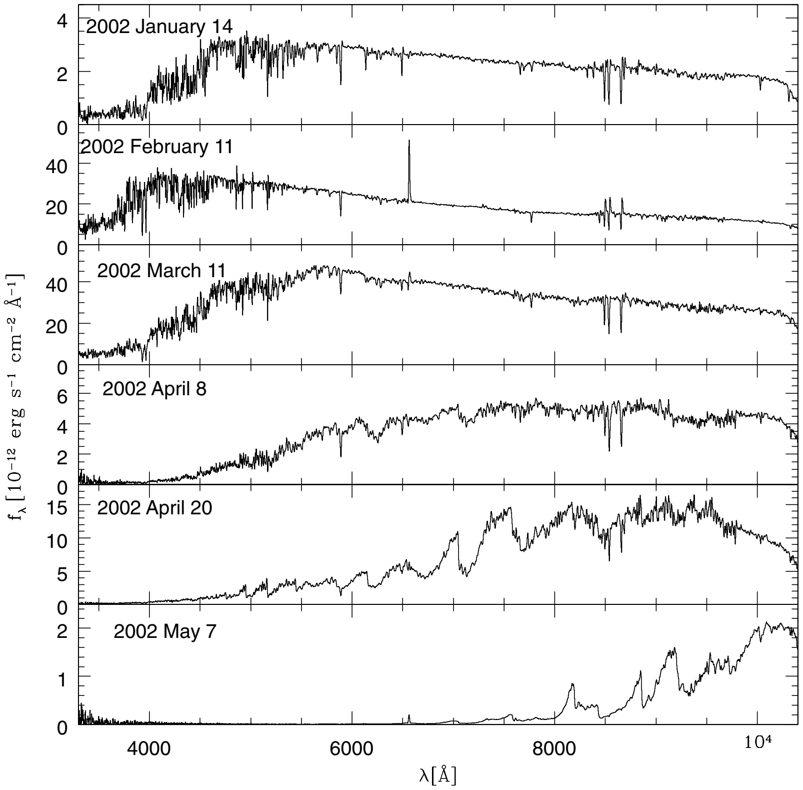

Figure 2. Optical spectra of V838 Mon on the dates indicated. The vertical lines correspond to the rest wavelengths of the identified lines. The spectra are ordered chronologically, with the upper spectrum corresponding to the earliest epoch.

Table 3. Mean outflow velocities.

	Mean velocity (km s^{-1})		
Spectral line	2002 Jan 14	2002 Feb 11	2002 Mar 11
Hα	−200	−450	−400
Ca II (8498 Å)	−200	−300	−250
Fe II (4924 Å)	–	−300	–
Fe I (6192 Å)	−200	–	–
Fe I (6394 Å)	−350	–	−400
Fe I (6678 Å)	−200	–	−300
Fe I (8387 Å)	−200	–	–

bolometric luminosity for an assumed distance of 6 kpc (Table 4). Using the combined spectra, we estimate the apparent diameter of V838 Mon by assuming that V838 Mon emits like a blackbody; these values are included in Table 4.

3.2 2002 February

The 2002 February 11 spectrum is marked by a weakening of the low-excitation neutral metals and the Ba II and Sr II lines, and a corresponding increase in other singly ionized and higher-excitation neutral species. The continuum is now more typical of a late F-type star, although this is inconsistent with the persistence of the G band: as with the earlier spectra, this underlines the difficulty of classifying the spectrum of this object. Prominent P-Cygni profiles arise from Fe II (Multiplet 42), and fluxes in the emission components have increased by a factor of ∼3 in the Ca II triplet and Hα, the core of which is saturated in this spectrum. The higher members of the Balmer series, Hβ–Hδ, and the Paschen series in the range Paδ–Pa19 (maybe as high as Pa25) are resolved, but Pa18, Pa16–Pa15 and Pa13 are blended with the Ca II triplet and O I (8446 Å). Of these, emission components are seen in Hβ (0.07 × Hα emission), Paδ and, possibly, Hγ.

3.3 2002 March

The 2002 March optical and *JHK* spectra were also taken nearly simultaneously, and, although the 2002 January and March data show similar energy distributions, the dereddened integrated fluxes between the two epochs are markedly different. We again find $T_{\rm eff} = 5250 \pm 250$ K (Table 4), but the stronger low-excitation and weaker higher-excitation lines in 2002 January point to a higher temperature in 2002 March.

Despite the crudeness of our analysis, our data suggest that the luminosity and radius increased by factors of ∼15 and ∼4 (respectively) between 2002 January and March. Assuming a uniform

Table 4. V838 Mon parameters (d = 6 kpc assumed for L and R).

	$T_{\rm eff}$ (K)	Flux (W m^{-2})	Apparent diameter (arcsec)	Luminosity (L$_\odot$)	Radius (R$_\odot$)
2002 January	5250(±250)	$2.3(\pm0.5) \times 10^{-11}$	$3.2(\pm0.2) \times 10^{-2}$	$2.6(\pm0.6) \times 10^{4}$	$2.0(\pm0.6) \times 10^{2}$
2002 March	5250(±250)	$3.5(\pm0.6) \times 10^{-10}$	$1.2(\pm0.9) \times 10^{-1}$	$3.9(\pm0.7) \times 10^{5}$	$7.6(\pm0.2) \times 10^{3}$

expansion rate, the outward velocity is ~60 km s^{-1} at 6 kpc, lower than the mean P-Cygni outflows (Table 3).

The lines from low-excitation neutrals, Ba II and Sr II have recovered somewhat in the 2002 March 11 data, although they are weaker than in the corresponding 2002 January 14 spectrum. The changes in the line spectrum are mirrored in the energy distribution, which again resembles that of an early-G giant or supergiant. P-Cygni profiles are evident in two multiplets of Fe I (Multiplet 1254 and 268), while the emissions from Hα and the Ca II triplet have receded.

3.4 2002 April and 2002 May

Fig. 2 shows the 2002 April–May evolution of the optical spectra, illustrating the emergence of the molecular features and the rapid evolution towards later spectral types. Conspicuous TiO absorption is already visible in the 2002 April 8 spectrum and is very prominent by 2002 April 20. The strengthening of the TiO absorption continues until 2002 May 7, when VO B–X is distinct – indicating a spectral type later than M7 (Turnshek et al. 1985) – and the H_2O band at ~9200 Å is obvious. A comparison of the relative sizes of the depressions with the representative spectra presented in various stellar libraries (Jacoby et al. 1984; Serote Roos, Boisson & Joly 1996) suggests the following classifications: M0 III-I (2002 April 8), M5 III-I (2002 April 20), and M9 III-I (2002 May 7).

The 2002 May 7 spectrum stands out with its pure emission in Hα. The presence of this feature may be related to the emergence of the series of Ti I emission lines observed in the *K* band, which has been suggested to be a result of an interaction between more recent and previously ejected material (Banerjee & Ashok 2002).

4 NEAR-IR SPECTRA

The evolution of the near-IR spectrum is shown in Fig. 3, which also includes expanded spectra in order to show greater detail in the individual *JHK* bandpasses. The spectra are noisy in the region around 1.8 μm because of telluric water vapour. No data were obtained between 1.33 and 1.48 μm, another interval in which telluric H_2O absorption is strong.

Our 2002 January 12 spectrum shows broad and shallow H_2O absorption centred at 1.4 μm ($\upsilon_1 + \upsilon_3$) and 1.9 μm ($\upsilon_2 + \upsilon_3$) (Fig. 3). These features are characteristic of late M-type stars, contradicting the K giant or supergiant classification adopted in the optical (see Section 3). This suggests that these bands cannot be photospheric in origin, but arise in the circumstellar material or extended envelope. Their presence makes it difficult to detect the 1.6-μm excess expected in the atmospheres of G–K giants because of the minimum

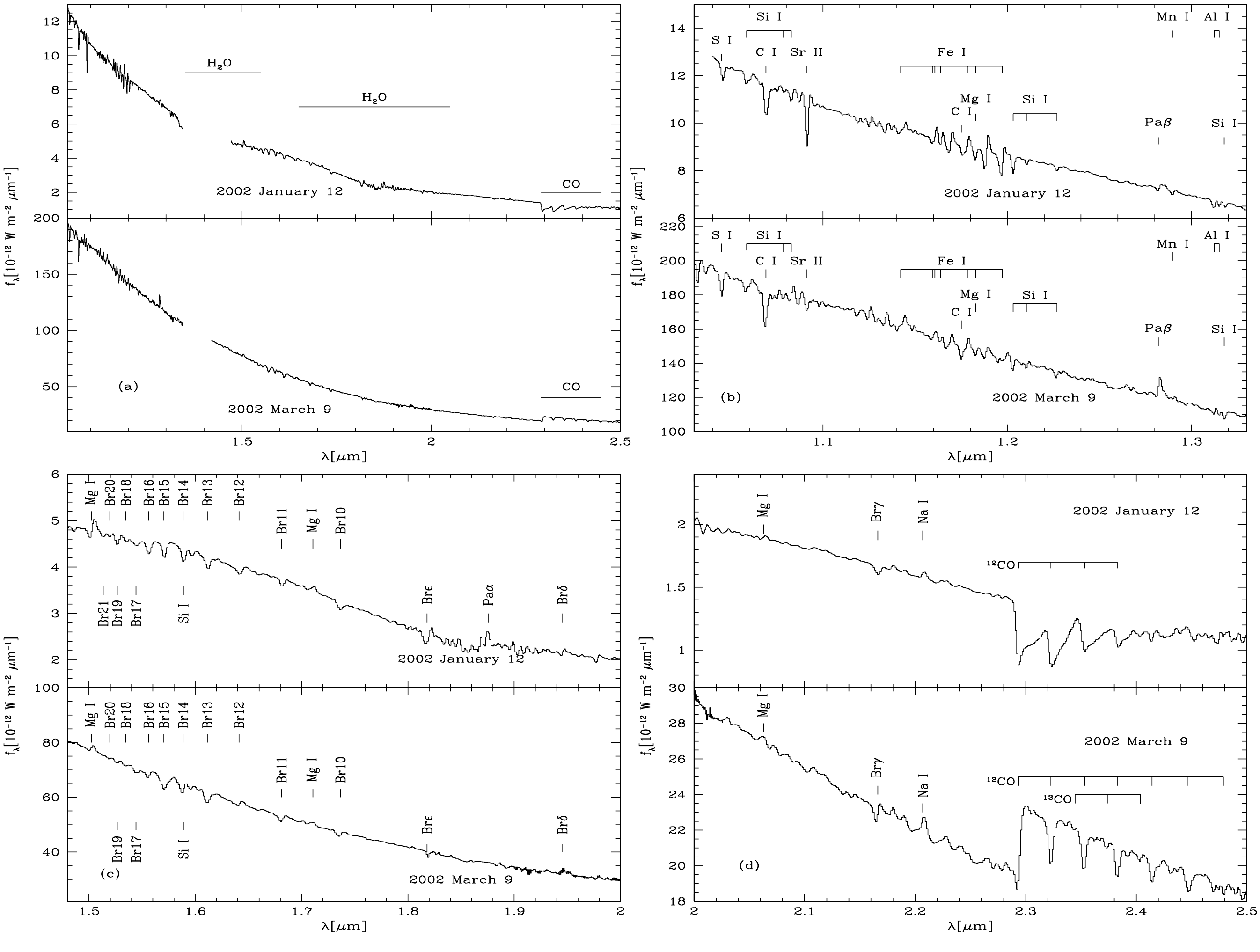

Figure 3. (a) Near-IR spectrum of V838 Mon, showing the locations of the molecular features on the dates indicated; the horizontal lines denote the approximate width of the observed molecular bands. (b), (c), (d) Detailed views of the near-IR spectra of V838 Mon in the wavelength ranges indicated.

in the absorption coefficient of H^- (Lançon & Rocca-Volmerange 1992) that had been reported in a 2002 January 28 spectrum of V838 Mon (Lynch et al. 2002). However, the water bands were absent in the 2002 March 9 data and any spectral effect due to H^- was not evident at that time.

The ^{12}CO first-overtone ($\Delta\upsilon = 2$) absorption is visible and prominent longward of 2.3 μm (2002 January 12). The individual bandheads are visible at least up to $\upsilon = 5 \rightarrow 3$, with the $\upsilon = 2 \rightarrow 0$ and $\upsilon = 3 \rightarrow 1$ bandheads being the strongest and comparable in strength (0.6 of the continuum level). The strengths of these bandheads are consistent with K5 III, or somewhat earlier for a supergiant (Kleinmann & Hall 1986). Remarkably, between this epoch and our 2002 March data the ^{12}CO has switched from absorption into a combination of absorption and emission. This has given rise to an extraordinary raised 'plateau' (1.16 times the continuum level), with distinct absorptions in the region of the individual ^{12}CO bandheads superimposed; weaker absorptions arising from ^{13}CO (16 times weaker than ^{12}CO absorptions) are now also resolved (Fig. 3). These are all remarkably symmetric and narrow, quite unlike the asymmetric shape of a bandhead, with deconvolved FWHM ≈ 0.005 μm. Note that the ^{12}CO $\upsilon = 2 \rightarrow 0$ band produces a depression in the continuum at 2.294 μm, suggesting that the absorptions are blueshifted relative to the emission. It should be mentioned that the peculiar CO profile is clearly visible in the raw data and is not an artefact created by the reduction process. The ^{12}CO second-overtone ($\Delta\upsilon = 3$) bands are not detected in our spectra, but they are in the spectra reported by Banerjee & Ashok (2002).

As illustrated in Fig. 3, the *J* band is dominated by atomic line transitions in both January and March. The strongest line seen on 2002 January 12 is attributed to Sr II (1.091 μm; Multiplet 2) absorption, which is consistent with the optical data (see Section 3). Other alternative identifications with Mg II (1.091 μm) and Paγ are far less likely. The former is not consistent with the absence of features at 1.745 and 2.143 μm; moreover, the implied velocity shift (-700 km s^{-1}) and strength relative to Paβ, a weak emission feature, discount Paγ as a credible candidate. The remaining prominent absorption lines in the *J* band are typical of *K–M* giants (Wallace et al. 2000). In addition to weaker features of Si I, Al I, and Mn I, the prominent absorption line at 1.069 μm is due to a blend of several C I (Multiplet 1) transitions. P-Cygni profiles are seen in Fe I (Multiplet 58; 1.14–1.20 μm) and, in the *H* band, in Ca I (1.977 μm). All of the spectra detailed in Banerjee & Ashok (2002) show Mg I (1.7711 μm), but the authors doubted this identification because the line was seen in emission. In our spectra this and Mg I (1.150 μm) have P-Cygni profiles, and, together with the presence of the $^2S{-}^2P^0$ Na I doublet (2.2056 and 2.2084 μm) in the *K* band lend support to this identification. The low-excitation neutral metal and Sr II lines are all weaker in the 2002 March 9 spectrum, although the Na I doublet is persistent in emission and is a factor of 1.3 more intense.

Although absent in the Banerjee & Ashok spectra, most of the spectral lines observed here in the *H* band arise from the hydrogen Brackett series. The detected transitions range from Brδ to at least Br20 in both spectra, and as high as Br21 on 2002 January 12. The transitions around upper quantum numbers of 15 are most prominent in both spectra. The strength of Br19 (2002 January 12) is probably the result of blending with a nearby Fe I (1.529 μm) line, but the origin of the anomalous strength of Br15 (2002 March 9) is unclear. From Br10 to Brγ there is some weakening between the two epochs. Such changes, however, may reflect not changes in absorption strength if the lines are blends of absorption and emission, but rather a change in the velocity profiles of these lines.

5 OPTICAL SPECTROPOLARIMETRY

Spectropolarimetry of V838 Mon has been described by Wisniewski et al. (2003a) and by Desidera et al. (2004), who also presented broad-band polarimetry. These authors conclude that the polarization is primarily interstellar, with maximum polarization $P_0 = 2.75$ per cent at $\lambda_{\max} = 5790$ Å (Wisniewski et al. 2003a). A further study by Wisniewski, Bjorkman & Magalhães (2003b) confirmed this interstellar component estimate by demonstrating that several field stars near to the line of sight of V838 Monocerotis are polarized by this same amount.

There is also, however, a small, and variable, intrinsic component. Wisniewski et al. (2003a) presented spectropolarimetry obtained on 2002 February 8 and 13 and concluded that the intrinsic component was negligible at the later date (within a day of our first epoch of spectropolarimetry); they used these data to determine the interstellar polarization. In a subsequent paper Wisniewski et al. (2003b) argued that there was a significant intrinsic component shortly after the second 'outburst', in 2002 February, but subsequent observations showed that the intrinsic polarization component was negligible until 2002 October, when it reappeared with a 90° shift in position angle.

The spectropolarimetry obtained here, shown in Fig. 4, is broadly in line with previous work (Wisniewski et al. 2003a; Desidera et al. 2004). For example, a least-squares fit of our February 14 data (taking the observed polarization to be interstellar; Wisniewski et al. 2003a) with a Serkowski law (e.g. Whittet 2003, and references therein) gives $P_0 \approx 2.7$ per cent and $\lambda_{\max} \approx 5802$ Å, in agreement with the values obtained by Wisniewski et al. (2003a). Our second epoch, taken 21 d later, shows a broadly similar degree of polarization. However, the wavelength dependence of the polarization of both epochs deviates somewhat from a Serkowski-law dependence, particularly at wavelengths below $\sim$4600 Å. In addition, the wavelength dependence of the PA changes between the two epochs, becoming much steeper in 2002 March. This indicates that a small, and variable, intrinsic component exists during this time.

6 DISCUSSION

6.1 CO

Perhaps the most remarkable behaviour reported here has been that observed in the CO first overtone. Variable CO emission is a rare phenomenon, one example being found in the star IRAS 2272+543, which switched from absorption into emission within three months (Hrivnak, Kwok & Geballe 1994). Although CO first-overtone emission in itself is not unusual, having been observed in supernovae (Gerardy et al. 2000), novae (Evans et al. 1996), post-AGB stars (Oudmaijer et al. 1995), and young stellar objects (YSOs) (Scoville et al. 1983), the 'plateau profile' of the emission in V838 Mon is extraordinary, being unlike that observed in any of these sources. CO emission tends towards such a flat-topped profile as the optical depth approaches very high values (Kraus et al. 2000). The emission profile seen in V838 Mon could therefore be explained by extremely optically thick CO emission, and if so the superposed absorption must arise outside the emission. This may be difficult to reconcile with the high vibrational excitation of the observed absorption bands (visible up to at least $\upsilon = 7 \rightarrow 5$), which suggests

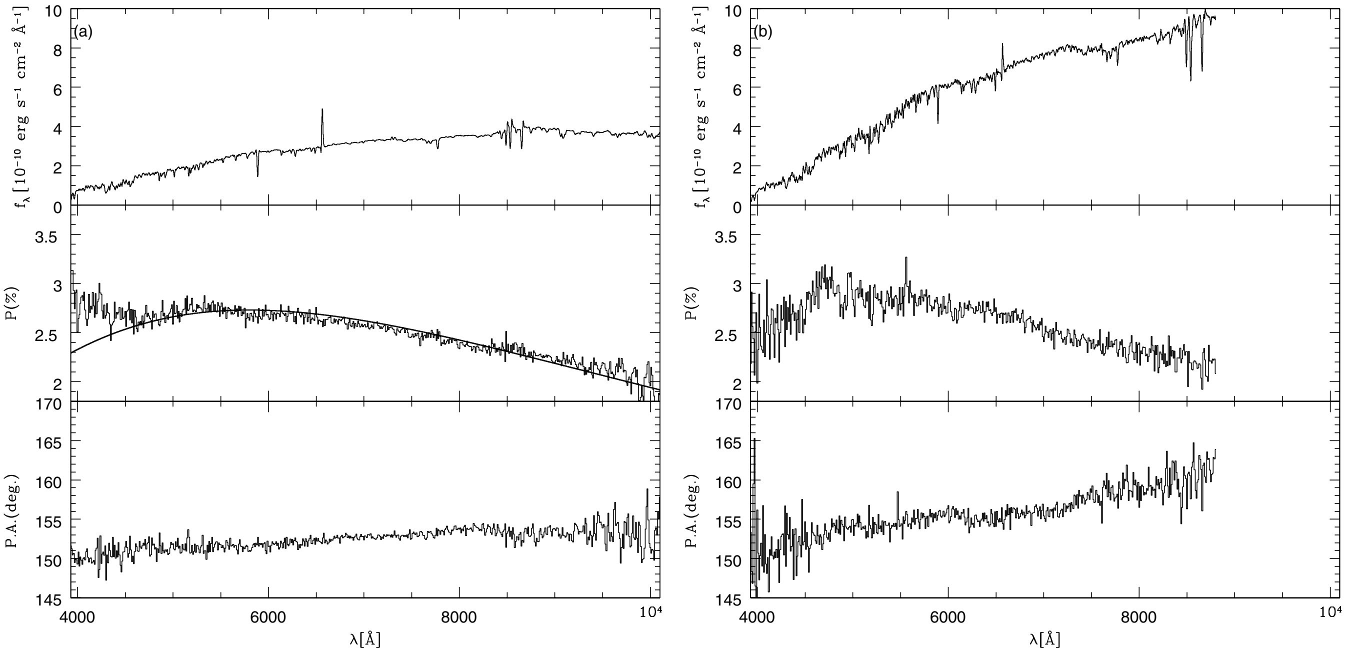

Figure 4. (a) Spectropolarimetry of V838 Mon on 2002 February 14: top frame, total flux spectra; middle frame, degree of polarization; bottom frame, position angle. The curve is a best-fit Serkowski law to the wavelength dependence of polarization for $4500 < \lambda < 9500$ Å. (b) As (a) but for 2002 March 7.

that they are formed very close to the star. To our knowledge, this type of composite CO spectrum has not been observed in any object.

Remarkable first-overtone ^{12}CO behaviour in V838 Mon has also been reported by Banerjee & Ashok (2002). They, too, observed an initial absorption phase followed by a phase of emission and absorption. Even in the initial absorption stage the CO was varying rapidly. In our spectrum (2002 January 12) there is some evidence of a cool CO component superposed onto the photospheric bands, which had become much more prominent by their 2002 February 2 observation. Later they observed the tail end of the emission phase observed here, which had ended by 2002 May 14.

CO first-overtone emission has been well documented in YSOs (Scoville et al. 1983; Carr 1989; Geballe & Persson 1987). It has been shown (Scoville et al. 1979; Scoville, Krotkov & Wang 1980; Scoville et al. 1983) that collisional excitation in a compact, warm (2500–4500 K), and dense ($n_H > 10^{10}$ cm^{-3}) region is required in order to populate the rotational levels. Suggestions for the location of such an environment have been a stellar wind or a circumstellar disc (Scoville et al. 1983; Carr 1989). The formation of shocks due to the interaction of a stellar wind with previously ejected circumstellar material has been considered as a possibility (Thompson 1985). Given the timing of the CO emission, near the peak of the third outburst, and the rapid change in the CO spectrum, shock excitation of the CO is the most attractive mechanism. Although we do not detect the well-known H_2 $\upsilon = 1 \rightarrow 0$ S(1) shock signature at 2.122 μm in our spectra to a 3σ upper limit of 1.2×10^{-16} (2002 January 12) and 1.6×10^{-15} W m^{-2} (2002 March 9), it is not expected, since H_2 cannot emit at the high densities required to excite the CO.

We also note that SiO emission is seen in strongly pulsating red giants, in which shocks propagate through a dense molecular envelope (Yamamura, de Jong & Cami 1999; Matsuura et al. 2002). The presence of SiO emission, as well as CO emission, in V838 Mon (Lynch et al. 2004; Rushton et al. 2005) lends further support to the shock mechanism in V838 Mon.

6.2 The nature of V838 Mon

Although the Li I resonance line at 6708 Å is unconfirmed at the resolution of our data, several authors have drawn attention to its presence (Munari et al. 2002; Goranski et al. 2002; Kipper et al. 2004). Lithium detection in stellar objects is usually confined to YSOs and a small sample of highly evolved AGB stars. The depletion of the primordial Li that occurs during and after the main sequence suggests that the latter objects produce the observed Li, which is then transported to the surface. This is thought to occur in the high-mass AGB stars with $M \gtrsim 4$–6 $M_\odot$ via 'hot bottom burning' (Sackmann & Boothroyd 1992). These objects also show s-process enhancement resulting from the synthesis of heavy elements during thermal pulses.

Using static local thermodynamic equilibrium (LTE) models, Kipper et al. (2004) have estimated an abundance for Li in V838 Mon in excess of the cosmic value, and the s-process elements (Ba and La) also show enhancement. These authors emphasize that their values are only very crude estimates because static LTE models are not an appropriate representation of the expanding atmosphere of V838 Mon. An analysis of abundances requires expanding model atmospheres, incorporating highly non-LTE physics, and knowledge of the velocity field in the atmosphere and the radial velocity of the object. Therefore we have made no attempt to model the abundances in this study.

The strong Sr II lines seen here, particularly in 2002 January (see Fig. 2), do lend credence to an enhancement in the s-process elements. This (if confirmed), together with the high luminosity and *IRAS*/*MSX* detections of the progenitor, would appear to imply that V838 Mon had evolved to at least the AGB stage. For this reason the possibility that V838 Mon underwent a thermal pulse event is an attractive one, but, as has been pointed out (Munari et al. 2002; Kimeswenger et al. 2002), the luminosity of V838 Mon in outburst was higher than that of known thermal pulse events and the evolution was much faster.

If what we are seeing is the surface dredge-up of the products of He burning, one might expect V838 Mon to be a C-rich star. We know that, as yet, this is not the case (Evans et al. 2003). It is known that O-rich thermally pulsating AGB stars exist (van Loon et al. 1999), but they are restricted to the most luminous of these objects. With absolute magnitudes of $M_{\rm bol} = -6$ to -7, we would not expect the progenitor of V838 Mon to rank among them. Moreover, an AGB progenitor for V838 Mon cannot accommodate the possible B3 V companion (Munari & Desidera 2002), unless the progenitor was very massive.

An equally crucial pointer to the evolutionary status of V838 Mon is its ^{12}C/^{13} C isotopic ratio. We can only constrain a lower limit of $^{12}\mathrm{C}/^{13}\,\mathrm{C} > 16$ (the terrestrial ratio is ~90) at the resolution of our data. Tightening this ratio will be important in deciphering the nature of V838 Mon.

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