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Infrared spectroscopy of carbon monoxide in V838 Monocerotis during 2002–2006★

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ABSTRACT

Aims. We report spectra of the overtone and fundamental bands of CO in the eruptive variable V838 Mon, which trace the recent evolution of the star and allow its ejecta to be characterized.
Methods. The data were obtained at the United Kingdom Infrared Telescope on fourteen nights from 2002 January, shortly after the first outburst of the star, to 2006 April.
Results. Although the near-infrared stellar spectrum superficially resembled a cool supergiant after both the first and third of its outbursts in 2002, its infrared "photosphere" at that time consisted of highly blueshifted gas that was moving outward from the original stellar surface. A spectrum obtained during the third outburst reveals a remarkable combination of emission and absorption in the CO first overtone bands. The most recent observations show a composite spectrum that includes a stellar-like photosphere at a temperature similar to that seen just after the initial outburst, but at a radial velocity redshifted by 15 km s^{-1} relative to the stellar velocity determined from SiO maser emission, suggesting that the atmosphere is now contracting. Three shell components, corresponding to expansion velocities of 15, 85, and 145 km s^{-1}, also are present, but absorption is seen at all expansion velocities out to 200 km s^{-1}. Weak absorption features of fundamental band lines of ^{13}CO have been detected. However, the large uncertainty in the value of $^{12}C/^{13}C$ does not constrain the evolutionary status of the progenitor.

Key words. line: formation – stars: individual: V838 Monocerotis – stars: late-type – stars: mass-loss – stars: variables: general – stars: peculiar

1. Introduction

V838 Monocerotis literally burst upon the scene in early 2002 January, when its visual brightness increased by nearly two orders of magnitude over its pre-eruption value, $V \sim 16$ mag (Brown et al. 2002). Two additional outbursts occurred, in 2002 February and March (see Munari et al. 2005, and references therein for optical and infrared light curves). In early February the visual brightness increased by an additional order of magnitude, making the overall increase a factor of ~5000. During the third outburst, in March, the star nearly regained its February peak optical brightness. No further eruptions have occurred and after 2002 mid-March the visual magnitude quickly declined to close to the pre-eruption value. However, the near-infrared flux from V838 Mon, which also was very strong after the January eruption and underwent large fluctuations during the subsequent outbursts in the first few months of 2002, has only declined slowly since then. The optical and infrared behavior of V838 Mon, coupled with the presence of P Cygni and (later) inverse P Cygni profiles (Zwitter & Munari 2002; Geballe et al. 2002; Kipper et al. 2004; Rushton et al. 2005a) suggest that considerable material was ejected from the star, but that some of the material was being returned.

A prominent light echo surrounding V838 Mon (Hemden et al. 2002) appeared shortly after the second outburst. Polarimetry of it has led to an estimated distance to V838 Mon of 5.9 kpc (Sparks 2006). The fading optical spectrum of V838 Mon, which resembled that of a late type star during the early months of 2002 (e.g., Zwitter & Munari 2002; Kipper et al. 2004) eventually revealed the presence of a B3 V component (Desidera & Munari 2002; Wagner & Starrfield 2002; Munari & Desidera 2002), which is very likely a companion. Afsar & Bond (2007) have classified three nearby stars, first seen by Wisniewski et al. (2003), as B-types, and determined their mean distance to be 6.2 ± 1.2 kpc, similar to that of V838 Mon, suggesting that V838 Mon belongs to a young cluster.

The behaviors of only two other erupting variables, M31 RV (Rich et al. 1989) and V4332 Sgr (Martini et al. 1999) resemble the very detailed light curve and spectral energy distribution of V838 Mon. However, key portions of the light curves of these objects do not exist: the actual outburst (or outbursts) of V4332 Sgr were not observed and observations of M31 RV were very few and the source is now too faint to be observed. Thus the degrees of similarity are uncertain. Various scenarios have been suggested to account for the behaviors of these objects, invoking nova-like outbursts, thermonuclear shell events in a massive stars, He-shell flashes in post-asymptotic giant branch stars, and both star-planet and star-star mergers (see e.g. Lawlor 2005; Munari et al. 2005; Tylenda et al. 2005; Retter et al. 2006; Tylenda & Soker 2006, and references therein).

★ Based on data obtained at the United Kingdom Infrared Telescope, which is operated by the Joint Astronomy Center on behalf of the UK Particle Physics and Astronomy Research Council.

This paper reports infrared spectra of the fundamental and first overtone vibration-rotation bands of carbon monoxide (CO) in V838 Mon, obtained at the United Kingdom 3.8 m Infrared Telescope (UKIRT) on Mauna Kea, from shortly after the initial outburst of the object to 2006. We use the CO spectra to follow the evolution of the star and its ejecta during and after its three outbursts in 2002 and to attempt to constrain some of the basic properties of the progenitor, including the value of $^{12}C/^{13}C$.

The first vibrational overtone ($\Delta v = 2$; where v is the vibrational quantum number) bands of CO at 2.3−2.5 μm are among the the most prominent and characteristic spectral features of cool ($T_{\rm eff} \lesssim 5000$ K) stars of all luminosity classes. Typical stellar spectra containing these bands are shown in Wallace & Hinkle (1997). At low-medium resolution the stellar CO absorption breaks up into a number of individual asymmetric and partially overlapping features corresponding to 2−0, 3−1, 4−2,... vibrational transitions, shifted to successively longer wavelength. The bands of different isotopic species also are shifted in wavelength, with heavier species shifted longward. Each feature consists of a multitude of individual vibration-rotation lines that can be resolved from one another at high spectral resolution.

In cool stellar photospheres a sharp edge, or band head, occurs at the short wavelength limit of each vibrational feature, due to the coincidence of many vibration-rotation lines. For $^{12}C^{16}O$ the 2−0 band head is at 2.2935 μm and marks the short wavelength onset of CO absorption in the K band. Each $\Delta v = 2$ band head occurs near rotational quantum number $J = 50$. Because the excitation temperature of this rotational level is ~7000 K, $\Delta v = 2$ band heads can be prominent only if the absorbing gas has $T \gtrsim 1500$ K). At lower temperatures only absorption lines from lower J levels will be present. High densities ($n > 10^8$ cm^{-3} for $v = 0$ and $n > 10^{10}$ cm^{-3} for $v > 0$) also are required for the ro-vibrational levels producing the band heads to be populated; normally these conditions are only found in or very close to stellar photospheres. The CO bands usually are seen in absorption against the stellar continuum; however, if the sufficiently high temperatures and densities exist outside the photosphere the overtone bands can be in emission.

In low-medium resolution spectra of cool stellar photospheres the fundamental ($\Delta v = 1$) band of CO is apparent as a broad and fairly structureless depression from ~4.5 μm to ~5.0 μm. The band heads of the fundamental occur near $J = 90$; their wavelengths (4.3–4.5 μm for the several lowest vibrational levels) are inaccessible from ground-based telescopes and in any event the lines forming them are very weak owing to the high rotational excitation (~22 000 K). Einstein A values of fundamental band transitions are 10–100 times larger than those of first overtone transitions from the same levels. Hence it is possible to detect much lower column densities of CO by observing fundamental band lines than by observing overtone band lines from the same ro-vibrational levels. This is particularly important when observing cool circumstellar or interstellar CO.

2. Observations

Spectroscopy of CO in V838 Mon began at UKIRT on 2002 January 12 and has continued into 2006, with data obtained on fourteen separate nights (see Table 1). Most of the spectra were acquired in the 2.0–2.5 μm band using the 40 lines/mm grating of the facility 2-dimensional array spectrograph, CGS4 (Mountain et al. 1990), or the HK grism in the imager/spectrograph UIST (Ramsay Howat et al. 2004), at resolving powers of $R \sim 850$. Some spectra of specific narrow wavelength intervals were obtained at $R \sim 18\,000$ using CGS4's echelle. Some of the data has been reported previously by Evans et al. (2003) and Rushton et al. (2005b). Other observers have also obtained low resolution spectra covering CO bands during this period (Banerjee & Ashok 2002; Lynch et al. 2004; Banerjee et al. 2005). In particular, Banerjee & Ashok (2002) and Banerjee et al. (2005) have reported the detection of both the first and second ($\Delta v = 3$) overtone bands of CO in their spectra obtained during 2002–2004. We have been unable to identify the latter bands, which are located near 1.6 μm, in our UKIRT data. We note that the weak absorption features they identify as CO, although corresponding in wavelength to some of the second overtone CO bands, do not have the characteristic sharp short wavelength edges (due to band head formation) and the overall asymmetries of CO vibrational bands. Because of the uncertainty as to the presence of these bands, and their weakness if they are present, we restrict this study of CO to its first overtone and fundamental bands.

Table 1. CO observing log.

UT Date	Resolution	Band
2002 Jan. 12	Low[a]	$\Delta v = 2$
2002 Mar. 09	Low	$\Delta v = 2$
2002 Oct. 29	Low and High[b]	$\Delta v = 2$
2002 Dec. 17	Low	$\Delta v = 2$
2003 Feb. 05	High	$\Delta v = 1, 2$
2003 Apr. 04	Low	$\Delta v = 2$
2003 Oct. 06	Low	$\Delta v = 2$
2003 Dec. 06	High	$\Delta v = 2$
2005 Jan. 05	Low	$\Delta v = 2$
2005 Feb. 25	High	$\Delta v = 2$
2005 Mar. 02	High	$\Delta v = 1$
2005 Mar. 04	High	$\Delta v = 1$
2006 Feb. 13	Low	$\Delta v = 2$
2006 Apr. 18	High	$\Delta v = 2$

[a] Resolution ≈350 km s^{-1}, accuracy ≈20 km s^{-1}.
[b] Resolution ≈17 km s^{-1}, accuracy ≈3 km s^{-1}.

All of the UKIRT spectra reported here were taken in the conventional stare/nod-along-slit mode. Extracted spectra were flat-fielded, de-spiked, and wavelength-calibrated using telluric absorption lines or emission lines from arc lamps. Accuracies in absolute wavelength are better than 0.00017 μm (20 km s^{-1}) for the low resolution spectra and 3 km s^{-1} for the echelle spectra. Spectra of early type standard stars were obtained nearly simultaneously with and close to the same airmass as the spectra of V838 Mon, in order to accurately remove telluric features.

3. Results and discussion

Here we provide descriptions of the most significant spectra of CO obtained during 2002–2006 and use them to derive velocity information, temperatures, and physical locations of the CO, and to constrain the $^{12}C/^{13}C$ ratio. We attempt to physically relate the different spectral features and velocity components to the recent evolution of the source. A subsequent paper (Rushton et al., in preparation) will present detailed modeling of some of these spectra.

Because of the high speeds of the ejected gas, even at the low resolution of these spectra, the accuracy of the wavelength calibration is sufficient for using the band heads to constrain the locations of the principal line-forming regions, by comparison of wavelengths at which the observed band heads occur to the wavelengths expected for gas at the stellar velocity. In particular,

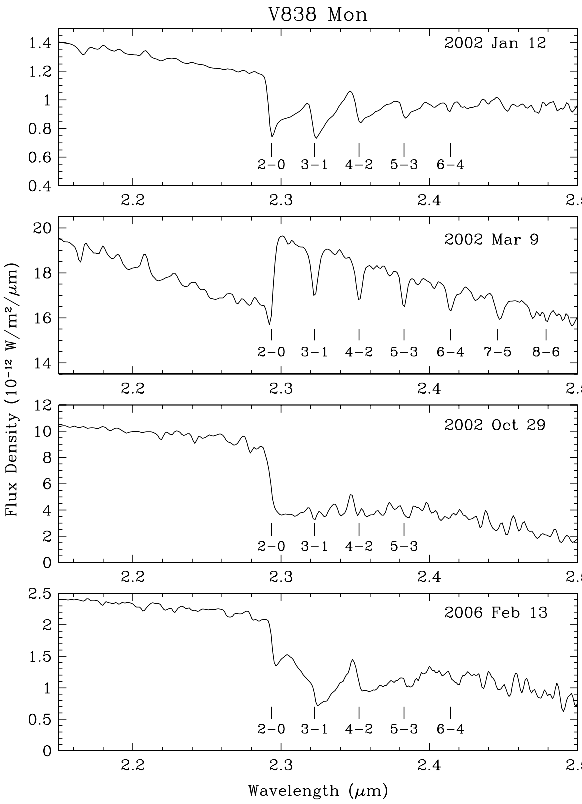

Fig. 1. Low resolution spectra of the first overtone bands of CO in V838 Mon. The positions of band heads of ^{12}CO are indicated.

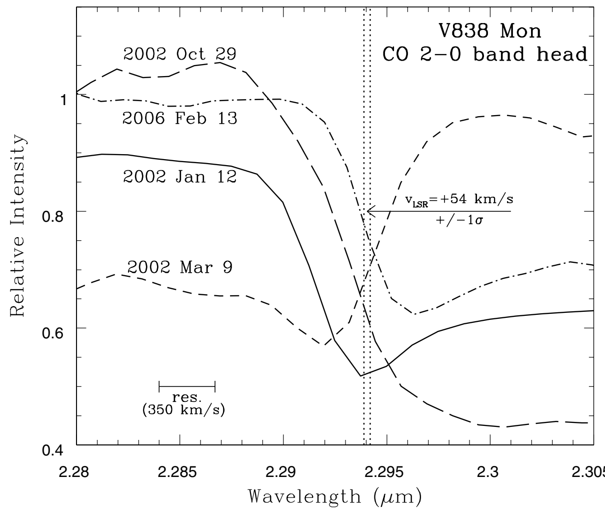

Fig. 2. Details of the low resolution spectra in Fig. 1 near the CO 2−0 band head. The dashed vertical lines are 20 km s^{-1} (1σ) to either side of the wavelength that the band head would appear for CO at the stellar radial velocity, and would bisect the absorption edge if the band head were formed at that velocity.

the 2−0 band head is an accurate velocity indicator, unless it is extremely saturated, which should not be the case here.

Based on measurements of two SiO maser transitions at millimeter wavelengths, Deguchi et al. (2005) has determined the radial velocity of V838 Mon to be +54 km s^{-1} LSR (+71 km s^{-1} heliocentric; LSR velocities are used hereafter). Their result assumes that amplification tangential to the circumstellar material dominates the emission, which is generally true in late-type stars (e.g., Jiang et al. 1995), but we note that V838 Mon is a highly unusual case, and also that it may be in a binary system.

3.1. Low resolution spectroscopy of the $\Delta v = 2$ bands

Figure 1 shows low-resolution 2.15–2.50 μm spectra of V838 Mon obtained on three dates in 2002 and one date in 2006. Figure 2 shows details of the same spectra near the wavelength of the 2−0 band head of ^{12}CO.

The spectrum in the top panel of Fig. 1 was obtained on 2002 January 12, roughly two weeks after the initial outburst. Superficially it looks similar to that of a stellar photosphere. However, a detailed examination of the spectrum near the 2−0 band head (see Fig. 2) reveals that the CO absorption edge is highly blueshifted relative to the radial velocity of the star. This is also the case for the 3−1, 4−2, and 5−3 band heads. Thus, the hot CO contributing to these absorption bands is in dense gas that was moving outward at speeds of up to a few hundred km s^{-1}.

The second spectrum in Fig. 1, obtained on 2002 March 9, during the second outburst, may be the most unusual example of CO first overtone band emission ever reported. When in emission the $\Delta v = 2$ bands commonly have peaks near their heads, and decreasing emission to longer wavelengths (e.g., see Chandler et al. 1993). The 2002 March 9 emission does not resemble this in any respect. Assuming that the continuum level may be extrapolated from its slope at 2.15–2.29 μm, the CO line emission longward of each band head is nearly constant with wavelength. Narrow absorption features are located at the wavelengths of the band heads, absorbing out much of the emission there. To our knowledge neither the constancy of the emission between the band heads nor the absorption dips at the band heads have been observed previously in an astronomical object. This remarkable CO emission did not last long, as the spectrum of Banerjee & Ashok (2002) obtained two weeks later shows only CO absorption.

Figure 2 indicates that on 2002 March 9 the maximum absorption at the 2−0 band head was shifted by more than −200 km s^{-1} relative to the stellar velocity. However, the low resolution of the spectrum and the presence of strong emission on only the long wavelength side of the absorption conspire to cause the observed absorption maximum to be blueshifted from the actual velocity of peak absorption. The peak absorptions at each of the other band heads, where the CO emission on each side is of comparable strength, are blueshifted by 80 ± 20 km s^{-1}, which we take as a more reliable value of the velocity shift of the absorbing CO relative to the star.

Between the band heads the spectrum of 2002 March 9 must be a superposition of CO emission and absorption, because it is physically impossible for absorption to be present only near the band heads at $J \sim 50$ and not at other values of J. If both the emission and absorption lines were optically thin, in most cases the composite spectrum, as viewed at low resolution, would approach closer to the level of the (extrapolated) continuum further from the band head, because the increasing line spacing with increasing wavelength across each band leads to the both the emission and absorption per unit wavelength decreasing steadily. That behavior also would be observed even if the CO emission lines were optically thick, as long as the lines were narrow, because of the increasing line spacing. Separately CO absorption and emission normally behave in this manner; see Wallace & Hinkle (1997) and Chandler et al. (1993). Thus, the dominance of emission over absorption and especially the "flatness" of the emission between the band heads indicate that on 2002 March 9 the CO emission lines were optically thick over a sufficiently wide range of velocities (∼200 km s^{-1}) to fill the gaps between lines far from the band heads. The similar slopes of the CO emission and the continuum shortward of the 2−0 band head and the ∼20% excess of the emission over the continuum indicates that the two were emitted by gas at similar temperatures and that the CO radius was roughly 10% larger than the stellar radius at that time.

Because on 2002 March 9 CO absorption was present up to at least the v = 7−5 band, the gas producing it was quite dense and was at least as hot as the CO observed in 2002 January. Yet, if the emission was optically thick, as we believe, the absorption features must have formed outside of the emitting region. The absorbing CO may have been located on the outer surface of the gas producing the emission. Alternatively, it may have been ejected earlier than 2002 March 9, for example during the major outburst in early 2002 February. Unfortunately no CO data were obtained precisely at the time of the February outburst; however, roughly one week later Hinkle et al. (2002) detected broad and shallow CO absorption lines blueshifted by 80 km s^{-1} relative to the (now known) heliocentric velocity, thus approximately the velocity of the CO absorption features that we observed on March 9. Nevertheless, it is difficult to understand how such a separate hot and dense circumstellar component could persist for even one month, and therefore we believe that the CO line emission and absorption on March 9 occurred in close physical proximity to one another.

The third spectrum in Fig. 1 was obtained in 2002 October, approximately ten months after the initial eruption. In strong contrast to the previous spectrum, it shows what may be the deepest CO overtone absorption ever observed in a star, as well as a remarkably broad 2−0 band head absorption edge. The great depth is indicative of the presence of a large column density of cool absorbing gas. Model spectra by Rushton et al. (2006) suggest a mean CO temperature of 1300 K. The observed spectrum contains only marginal indications of the 3−1, 4−2, and 5−3 band heads of CO, even though from the overall breadth of the absorption it is likely that those bands contribute and thus that a somewhat warmer gas component also was present. In an oxygen-rich star such low temperatures imply that in addition to CO lines of H_2O constituted a significant part of the absorption beyond 2.3 μm. For V838 Mon this inference is supported by the even deeper absorption bands of H_2O at 1.1, 1.4, and 1.9 μm in the full 1–2.5 μm spectrum from 2002 October (Evans et al. 2003), which together with the strong CO first overtone band led Evans et al. (2003) to refer to the object as an "L supergiant". The CO 2−0 absorption edge in the 2002 October spectrum shown in Fig. 2 is considerably broader than in the other spectra in the figure and is much broader than the resolution; it indicates that CO absorbing over a wide range of velocities (perhaps 600 km s^{-1}) as well as at a wide range of temperatures contributed to the spectrum at that time.

From 2002 October to the date of the most recent low-resolution spectrum (an interval of 3.5 years) the CO Δv = 2 absorption has changed much more slowly than it did during 2002. In the most recent low-resolution spectrum from 2006, shown at the bottom of Fig. 1, at least four bands can be seen in absorption, clearly demonstrating the presence of dense molecular gas at temperatures typical of an M-type stellar photosphere. It is unlikely that the gas ejected at high velocities in 2002 could still be sufficiently hot and dense to populate the ro-vibrational levels that produce these features. Thus, even in the absence of radial velocity information, one would have to conclude that the band heads are formed in the stellar photosphere or very close to it. Radial velocity data for the CO are available, however, both at low and high resolution. The portion of the low resolution spectrum shown in Fig. 2 demonstrates that the velocity of the 2−0 band head is no longer blueshifted and is in fact close to that of the star. Moreover, the absorption edge is considerably sharper than in 2002 October (the drop in flux density, from 10% to 90% of peak absorption, occurs over ∼350 km s^{-1}, compared to ∼700 km s^{-1} earlier) and is unresolved. Both of these findings suggest that in 2006 the CO forming the band heads was photospheric or near-photospheric. A cool and presumably detached circumstellar component is still present, clearly revealed in Fig. 1 by the excess absorption from 2.31 μm to 2.34 μm where R branch lines from low lying J levels in the CO v = 2−0 band are located; note that the level of flux density decreases longward of 2.31 μm and is lower at the 3−1 band head than at the 2−0 and 4−2 band heads. The gas producing this excess is too cool to contribute significant absorption at $J \sim 50$, where the 2−0 band head is formed. It seems likely that the cool gas was ejected at higher velocity and is now far from the star, but spectra at much higher resolution, some of which are presented and discussed below, are required to clearly demonstrate this, as well as accurately measure the velocity of the hot, band head-forming CO.

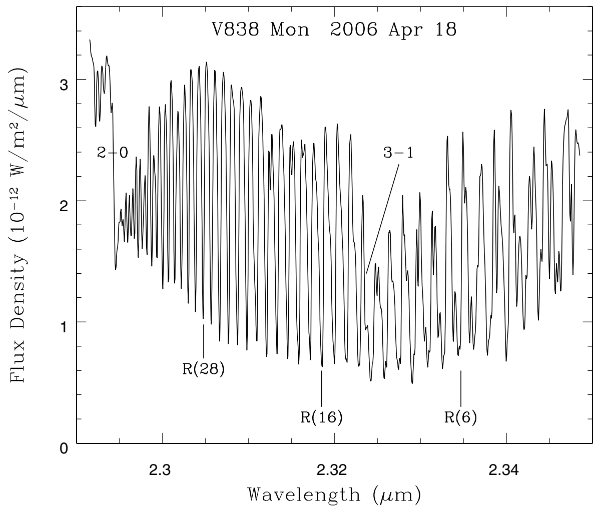

Fig. 3. High-resolution spectra of first overtone bands of CO. The locations of the 2−0 and 3−1 band heads of ^{12}CO are indicated. The three lines of CO, whose velocity profiles are shown in Fig. 4, are indicated.

3.2. High resolution spectroscopy

The first high resolution spectra of CO were obtained more than seven months after the final outburst of V838 Mon (see Table 1). These early spectra are very complex, with broad and blended absorption components, and are still being analyzed. The CO line profiles in spectra from 2005 and 2006 are less blended, although still highly structured, and do allow some understanding of conditions in the absorbing gas. In the following we present and discuss only these most recent high resolution spectra.

Figure 3 shows the 2.28–2.35 μm spectrum of V838 Mon obtained in 2006 April at a resolution of 17 km s^{-1}. Many individual CO lines can be seen. The spectrum is consistent with the low resolution spectrum obtained two months earlier and shown in the bottom panel of Fig. 1. In particular the 2−0 and 3−1 band

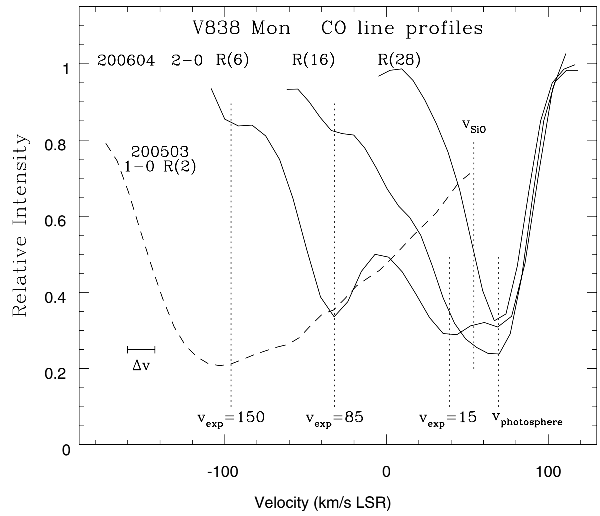

Fig. 4. Velocity profiles of three 2−0 band lines and one 1−0 band line of CO. Velocities of maximum absorption are indicated by vertical dashed lines, as is the stellar radial velocity obtained from SiO maser measurements by Deguchi et al. (2005). Expansion velocities (relative to SiO) of the cool CO components are given.

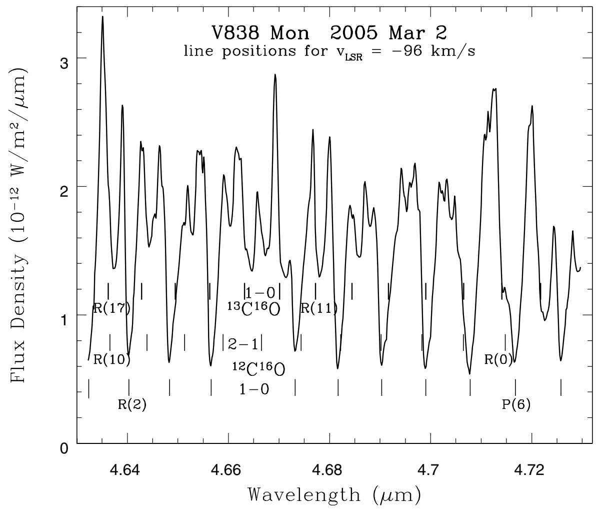

Fig. 5. High resolution spectrum of a portion of the CO fundamental, showing strong lines near the center of the 1−0 band of ^{12}CO. Line positions are indicated at the bottom of the figure. Also indicated are line positions of the 2−1 band of ^{12}CO and the 1−0 band of ^{13}CO.

heads are clearly present; in Fig. 3 the latter can be seen in the midst of a forest of lines from the 2−0 band.

Examination of Fig. 3 reveals that the low J lines of the 2−0 band have more complex profiles than the high J lines, which are presumably largely formed in or close to the photosphere. Figure 4 shows velocity profiles of three 2−0 lines from this spectrum, R(28), R(16), and R(6), with widely different lower state energies (corresponding to temperatures of 2240 K, 752 K, and 116 K, respectively). Note that the velocity coverage is less for the higher J lines, because of the decreasing spacing of adjacent lines in the band with increasing J. These specific lines were chosen to minimize contamination by other CO lines. The R(28) line is coincident with the 2−0 R(73) line, which should be very weak. The R(16) line is equidistant from the extremely weak 2−0 R(84) and R(85) lines. The R(6) line, which should be negligibly contaminated by the nearly coincident 2−0 R(95) line, is coincident within a few km s^{-1} with the 3−1 R(27) line which, because its lower vibrational level is excited, should only contribute absorption in the warm and dense photosphere.

The high J lines such as R(28) are slightly asymmetric, with blueshifted shoulders, and are dominated by a single velocity component at $\upsilon_{\rm LSR}$ = +69 km s^{-1}. The same velocity is derived from the wavelength of the 2−0 band head at J = 51. One would normally expect these lines to arise in the photosphere of the star. However, they are redshifted by 15 km s^{-1} with respect to the velocity of peak SiO maser emission, which we have taken (with the aforementioned caveats) to be the stellar radial velocity. This suggests that gas cotaining this CO is falling back onto the star or the star's photosphere is contracting to approximately its pre-outburst radius. If so the velocity of this component and possibly also the strength of the CO overtone absorption could change noticeably in the next few years. Eventual contraction of the envelope is predicted by Tylenda & Soker (2006) following the merger of a low mass star with an 8 $M_\odot$ main sequence star.

The peak absorption of the R(16) velocity profile is at the same radial velocity as that of the R(28) profile, but the blue asymmetry of the R(16) profile is much more pronounced. In addition, a weak absorption component is present at −32 km s^{-1} (shifted by −85 km s^{-1} from the nominal stellar velocity). In the R(6) profile the −85 km s^{-1} component is much stronger. In addition, the R(6) profile contains a deep absorption at +38 km^{-1}, corresponding to an expansion velocity of 15 km s^{-1}. It is barely resolved from the photospheric component at +69 km s^{-1}. The blue asymmetries of the higher J lines are probably caused by the +38 km s^{-1} component, which is weaker at higher J, but spectral modeling at high resolution is required to confirm this.

The 2–0 R(6) profile also contains evidence for a third and even more blueshifted component at approximately −96 km s^{-1}. A spectrum of a portion of the fundamental (1–0) band of CO near 4.7 μm, shown in Fig. 5, obtained a year earlier, demonstrates that this component is real and that it is the dominant absorber in the $\Delta\upsilon$ = 1 band. The spectrum is highly complex and likely contains numerous lines of H_2O in addition to CO. However, the strongest lines by far are the CO 1–0 lines. The peak absorptions in these lines are uncertain because the continuum level is unknown, but based in Fig. 5 they must be at least 80%.

Figure 4 includes the velocity profile of the 1−0 R(2) line, one of the least contaminated of these fundamental band lines, in addition to the profiles of the three 2−0 band lines disussed previously. The profile is remarkably broad and asymmetric, characteristics that are present in all of the ^{12}CO 1−0 lines in Fig. 5. The CO at the velocity of maximum absorption is moving outward from V838 Mon at roughly 150 km s^{-1} and absorption is present at least to expansion velocities of 200 km s^{-1}. Information at higher velocities is unavailable because of contamination from other lines. The decrease in absorption toward lower expansion velocites is smooth and more gradual, with little or no evidence for the discrete velocity components seen in the 2−0 band line profiles. The differences between the fundamental and overtone indicate that the continuum-forming regions at 2.3 μm and 4.7 μm are located at different radii. In particular, much of the gas producing the prominent absorption features in the 2−0 band lines at expansion velocities of 15 and 85 km s^{-1} must be located inside the 4.7 μm continuum-forming region. The broad 1−0 profile also demonstrates that gas at a remarkably wide range of expansion velocities lies outside of the 4.7 μm continuum-forming surface, far from the star.

Thus, four discrete velocity components are identified in these CO spectra, three of which are in ejected gas. Rough excitation temperatures can be estimated for all but the most blueshifted component and CO column densities can be estimated for the +38 and −32 $\mathrm{km\,s^{-1}}$ components. From the relative strengths of the $\Delta\upsilon = 2$ band heads in synthetic spectra (Rushton et al. 2006), the temperature of the photospheric (+69 $\mathrm{km\,s^{-1}}$) component was ∼2000 K in 2002 January, but has been difficult to determine since then due to contamination from the other components. At +38 $\mathrm{km\,s^{-1}}$ and −32 $\mathrm{km\,s^{-1}}$ the relative strengths of the three overtone lines shown in Fig. 4 imply excitation temperatures ($T_{\rm ex}$) of ∼500 K and ∼200 K, respectively. The kinetic temperatures could be significantly higher, particularly in the case of the cooler (−32 $\mathrm{km\,s^{-1}}$) component. Both the low temperatures and the expansion velocities imply that by 2006 the blueshifted absorption components were far from the star. The distances that the gas producing them would have traveled from the star since early 2002 at the measured velocities are 12 AU, 70 AU, and 120 AU. In view of its low expansion velocity and the probability of significant deceleration during the four years since it was ejected, the innermost (+38 $\mathrm{km\,s^{-1}}$) component may have been considerably more distant than 12 AU from V838 Mon in 2006.

Rough estimates of column densities can be derived from CO overtone spectra for those shell components whose temperatures are known. We find $N_{\rm CO}$ in both the +38 (500 K) and the −32 $\mathrm{km\,s^{-1}}$ (200 K) component is $\sim 1 \times 10^{19}$ $\mathrm{cm^{-2}}$, indicating hydrogen column densities of $\sim 4 \times 10^{22}$ $\mathrm{cm^{-2}}$ if C/H is normal. The extinction normally associated with such column densities, ≈20 mag in each shell, is more than an order of magnitude greater than that observed (Afsar & Bond 2007), indicating that either little dust has formed as a result of the outbursts or that dust-forming elements are severely depleted relative to carbon. For normal C/H and assuming spherical symmetry and the above radii for the shells, the masses associated with the +38 $\mathrm{km\,s^{-1}}$ and −32 $\mathrm{km\,s^{-1}}$ components are $\sim 1 \times 10^{-5}$ $M_\odot$ and $\sim 4 \times 10^{-4}$ $M_\odot$, respectively.

3.3. ^{12}C/^{13}C

The ^{12}C/^{13}C ratio is a diagnostic of stellar evolution in oxygen-rich stars, with giants and supergiants having ratios far below the solar value (89) and typical interstellar values of 60–100 (e.g., Merrill & Ridgway 1979). Currently V838 Mon has the luminosity and temperature of a cool giant or supergiant. If it were a giant or supergiant prior to its outburst, and if the bulk of the ejected gas belonged to it (rather than to a merged companion) prior to the outburst, one would expect that its value of ^{12}C/^{13}C would be low compared to the above values.

The 2−0 and 3−1 band heads of ^{13}C^{16}O, at 2.345 μm and 2.374 μm, respectively, are not present in any of the low resolution spectra in Fig. 1 or any of the other K-band spectra we have obtained[1]. In most late-type stars these band heads are readily apparent, even when ^{12}C/^{13}C ∼ 30. Comparisons of some of these spectra with simple model overtone spectra (Rushton et al. 2006) have also failed to identify lines of ^{13}CO. Realistic synthetic spectra are needed, but are difficult to construct due to the complexities of the star and its multiple ejected gas shells.

[1] Rushton et al. (2005b) reported the detection of weak absorption bands of ^{13}CO in the 2002 March 9 spectrum. We have re-examined this spectrum and conclude that the wavelengths of the weak features do not match those of ^{13}CO.

The spectrum of part of the fundamental band shown in Fig. 5 covers the wavelengths of a number of individual lines of ^{13}CO from its 1−0 band. The ^{13}CO 1−0 transitions from the lower J levels in this spectral interval are the same ones that are prominent in ^{12}CO. Because the spectrum is badly contaminated by lines of H_2O, some of which approach the strengths of the ^{12}CO lines, only the ^{12}CO 1−0 lines and the water lines are readily identified. Nevertheless, from detailed examination of the spectrum at the ^{13}CO line wavelengths which do not coincide with strong ^{12}CO or H_2O lines, we believe we detect the presence of ^{13}CO in absorption at $\upsilon_{\rm LSR} \approx -96$ $\mathrm{km\,s^{-1}}$, the velocity of peak ^{12}CO absorption. The absorptions are ∼10% below the average of the flux levels at adjacent wavelengths, implying that the optical depths at the centers of these absorption lines are at least 0.1.

It is not straightforward to determine a reliable value of ^{12}C/^{13}C from these data. The best opportunity for a constraint on the ratio comes from comparison of the fundamental band lines of ^{13}CO and −96 $\mathrm{km\,s^{-1}}$ components of the overtone lines of ^{12}CO. From Fig. 4, the peak optical depth of the −96 $\mathrm{km\,s^{-1}}$ component of the 2−0 R(6) line of ^{12}CO was ∼0.15 in 2006 April. It would have been somewhat greater than that a year previous when the fundamental band lines of ^{13}CO shown in Fig. 5 were observed. Assuming that this component is formed completely outside of both the 2.3 μm and 4.7 μm continuum surfaces, the peak optical depths of the ^{12}C^{16}O 1−0 band lines from $J \sim 6$ in Fig. 5 should be ∼10. Thus, if ^{12}C/^{13}C were 10 or less, absorption lines of the ^{13}C^{16}O 1−0 band from $J \sim 6$ probably would have optical depths near unity and ought to have been seen easily in the spectrum of the fundamental band; that they are not suggests that ^{12}C/^{13}C ∼ 100. However, in view of the complexity of the spectrum, we feel that values as low as 10 cannot be excluded.

Due to the large uncertainty in ^{12}C/^{13}C we cannot rule out any of the proposed scenarios for the outburst of V838 Mon. We note that in the only late He-shell flash object where this isotopic ratio is measured, Sakurai's Object, the ratio is approximately 4 (Pavlenko et al. 2004; Asplund et al. 1999), a value that is inconsistent with the V838 Mon spectra. However, it is not known if such a low value applies to all cases of stars undergoing late thermal pulses. The stellar merger model (Tylenda & Soker 2006), which invokes main sequence stars, predicts a solar/interstellar value for ^{12}C/^{13}C, whereas in the giant star – planet merger model (Retter et al. 2006) ^{12}C/^{13}C probably would be considerably lower. More stringent observational constraints for V838 Mon should be possible from future infrared spectroscopy, as the CO spectrum simplifies due to the cooling of the expanding circumstellar shells and the decrease of CO column densities in them, or possibly from measurements of pure rotational transitions of CO arising in the cool extended envelope.

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