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THE 8 MICRON BAND OF SILICON MONOXIDE IN THE EXPANDING CLOUD AROUND VY CANIS MAJORIS

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ABSTRACT

Observations of vibration-rotation transitions of silicon monoxide in VY CMa show that the lines originate in accelerating, expanding, and cool (~600 K) layers of a circumstellar cloud at a distance of ~0″.15 from the central star. The central stellar velocity, as estimated from observed SiO P Cygni line profiles, is somewhat redshifted from the midpoint of the maser emission features. Most of the silicon is probably in the form of dust grains. The isotopic ratios of silicon are nearly terrestrial.

Subject headings: infrared: spectra — line profiles — stars: abundances — stars: circumstellar shells — stars: individual

I. INTRODUCTION

The cloud of dust and gas surrounding the peculiar object VY Canis Majoris is one of the brightest sources of infrared continuum radiation and maser emission in the Galaxy. The optical, infrared, and radio spectra as well as the spatial structure of the infrared continuum and radio line emission have been studied by numerous authors (see, e.g., Rosen *et al.* 1978 and references therein). Questions concerning the distance, central velocity, and evolutionary state of VY CMa, and indeed the class of objects to which it belongs, are not yet completely resolved.

In order to learn more about the circumstellar cloud of VY CMa, spectroscopic observations have been made near 8.3 μm of the fundamental vibration-rotation band of silicon monoxide. Previous observations at 4.7 μm of carbon monoxide in VY CMa (Geballe, Wollman, and Rank 1973) suggested that at the above infrared wavelengths the photosphere of the central exciting star is completely obscured by circumstellar dust. The cooler temperatures outside the opaque dust allow only a few infrared lines of SiO in the surrounding gas to be prominent and permit a relatively simple analysis.

II. OBSERVATIONS

Five frequency intervals of good atmospheric transmission which contain lines of the fundamental band of SiO were observed. The work was carried out at the Las Campanas Observatory 2.5 m du Pont telescope between 1978 January 17 and January 26. The spectrometer consists of a liquid nitrogen-cooled Fabry-Perot interferometer with one order scanned across the bandpass of a liquid helium-cooled tunable grating. The Fabry-Perot mirror spacing was set to give a resolution of 0.09 cm^{-1} (~23 km s^{-1}) at SiO wavelengths. The lines in VY CMa are partially resolved at this setting.

Figure 1 shows the spectrum of VY CMa in one of the observed intervals. The strongest line, which has a P Cygni shape, is from the ground vibrational state of ^{28}Si^{16}O. Weaker lines of ^{29}Si^{16}O, ^{30}Si^{16}O, and the 2–1 band of ^{28}Si^{16}O are also apparent. Lines of ^{28}Si^{17}O and ^{28}Si^{18}O were not detected and indeed are not expected, given the weakness of ^{29}Si^{16}O and ^{30}Si^{16}O.

In total, seven lines of the ^{28}Si^{16}O 1–0 band and somewhat fewer lines of the other detected bands were observed between 1167 cm^{-1} and 1235 cm^{-1} (8.1 μm and 8.6 μm). The rotational levels observed ranged from $J = 2$ to $J = 38$.

III. ANALYSIS

An isothermal shell analysis of the absorption lines results in the excitation temperatures (for each band), column density, and isotopic ratios shown in Table 1. While it is doubtful that the lines of each band of SiO arise in layers describable by a single temperature, there is insufficient information on the density and temperature structure of the circumstellar cloud to warrant the use of a more detailed model. In addition, the absorption line shape is not known and may be quite peculiar.

In the present analysis the stronger ^{28}SiO 1–0 lines are saturated. The column density in Table 1 was estimated using the transition probabilities calculated by Hedelund and Lambert (1972). Derivation of the isotopic ratio ^{29}Si/^{30}Si is straightforward since lines of

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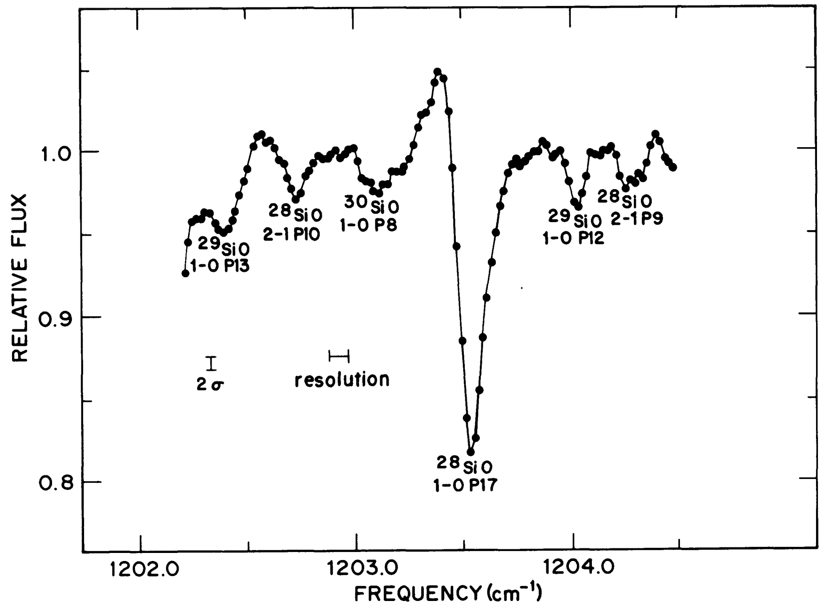

FIG. 1.—Observed spectrum of VY CMa near 1203 cm^{-1} (8.31 μm). The instrumental transmission has been removed. A weak telluric absorption line occurs near 1202.4 cm^{-1}. Spectral resolution and random noise are as shown.

both species of SiO are of nearly equal strength. In order to facilitate the determination of ^{28}Si/^{29}Si, "corrected" equivalent widths of the weakest ^{28}SiO 1–0 absorption lines (which are asymmetric due to nearby emission) were computed by doubling the equivalent widths of the high-frequency sides of these lines. By comparing these equivalent widths with those of ^{29}SiO, one obtains ^{28}Si/^{29}Si = 17 ± 4. If it is assumed that even the high-frequency sides of the ^{28}SiO lines are partially filled by emission, and the ^{28}SiO absorptions are widened by assigning to them the same central velocity as ^{29}SiO (see Table 2), one obtains the ratio 23 ± 5. Finally, isotopic lines and the weak 2–1 band lines of ^{28}SiO were compared, under the assumption that vibrational LTE holds. Values of ^{28}Si/^{29}Si were obtained ranging from 10 to 25 as the temperature was varied from 700 K to 500 K. A reasonable conclusion from the three results is that ^{28}Si/^{29}Si = 20 ± 5.

Velocities of maximum absorption and emission for each SiO band (Table 2) were determined by comparing measured frequencies to those calculated from molecular constants kindly furnished by D. N. B. Hall (1974). The frequencies were measured relative to observed atmospheric absorption lines and NH_3 lines. The frequency calibration and molecular constants were checked by calculating the radial velocity of α Ori from SiO spectra of it obtained during the same observing period as VY CMa. The 1–0 band and 2–1 band lines of ^{28}SiO independently gave the same radial velocity of 23 ± 3 km s^{-1} (heliocentric) for α Ori, which is in satisfactory agreement with the photospheric value.

TABLE 1

RESULTS OF ISOTHERMAL SHELL ANALYSIS

T_{rot} (^{28}SiO 1–0)	525±50 K
T_{rot} (^{29}SiO, ^{30}SiO, ^{28}SiO 2–1)	600±100 K
T_{vib}	600±100 K
NL(^{28}SiO)	(7±3)×10^{17} cm^{-2}
^{28}Si/^{29}Si	20±5
^{29}Si/^{30}Si	1.0±0.3

TABLE 2

SiO VELOCITIES (km s^{-1}, LSR)

^{28}SiO 1–0 absorption	5±3
^{29}SiO, ^{30}SiO absorption	10±3
^{28}SiO 2–1 absorption	18±4
^{28}SiO 1–0 emission peak	39±4
^{28}SiO 1–0 midpoint of emission*	32±7
^{28}SiO 1–0 midpoint of profile	25±5
Deduced stellar	32±7

* Corrected for instrumental resolution.

IV. LOCATION OF THE SiO AND PHYSICAL CONDITIONS IN THE CLOUD

The SiO excitation temperatures, which are near 600 K, imply that the 8 μm spectrum is formed well beyond the photosphere of VY CMa. Distances from the central star of between 0".13 and 0".18 for the SiO are obtained from Figure 2 of Herbig's (1970) gray-body model of the cloud and the range of SiO excitation temperatures in Table 1 of this paper. A second distance estimate, which uses the rotational temperature and estimated flux density at the deconvolved bottoms of saturated ^{28}SiO lines (using the continuum flux density given by Gillett, Stein, and Solomon 1970), gives a value of ~0".13. This value would be reduced if a significant fraction of the continuum radiation near 8 μm comes from the dust outside of the SiO. The measurement of 0".21 ± 0".06 by McCarthy, Low, and

Howell (1977) for the radius of VY CMa at 8.3 μm (assuming a uniform circular energy distribution) suggests that this may be the case. However, 0″.21 could not be the radius of the continuum source against which the SiO absorption is seen; otherwise observed excitation temperatures would be $\lesssim$400 K, somewhat lower than the temperatures found here. In conclusion, most of the SiO observed near 8 μm probably is located at roughly 0″.15 from the central star. That there is some range of distance over which absorption occurs is evident from the observation that different absorption bands of SiO have somewhat different radial velocities (see Table 2). The absorption band from the first excited vibrational state should occur closer to the continuum surface than that of the other observed bands. Therefore, the observed redshift of this band relative to the others implies outward acceleration of the envelope in the region of SiO line formation. The P Cygni line shapes (discussed later) also imply outward motion.

The abundance of SiO relative to hydrogen may be estimated roughly from the column density in Table 1, a distance of 1×10^{15} cm over which the ^{28}SiO lines are formed (assuming a distance to VY CMa of $\sim$1.5 kpc) and an H_2 density of 4×10^8 cm^{-3}. The density assumes the estimated density of 10^9 cm^{-2} at $r \approx 0''.1$ in the region of H_2O maser emission (Rosen *et al.* 1978) and a $1/r^2$ dependence. The result is [SiO]/[H] $\sim 1 \times 10^{-6}$, roughly 30 times lower than the solar value for [Si]/[H]. Although this result may not be very accurate, it does suggest that most of the silicon is in dust grains, a condition expected at this distance from the central star.

The present observations rule out SiO as the source of a broad depression between 7.6 and 9.3 μm observed at lower resolution by Gillett, Stein, and Solomon (1970) in VY CMa. The depression has a depth of perhaps 30%, whereas the observed SiO band on the average depresses the continuum by only $\sim$5%. Furthermore, the low temperatures found here indicate that the SiO band should not be as broad as the depression. The apparent depression may be a result of the emission spectrum characteristic of the circumstellar grains. Such emission features have been observed in several infrared sources (Russell, Soifer, and Willner 1977; see also Allamandola and Norman 1978).

V. P CYGNI LINES AND THE SHAPE AND VELOCITY OF THE CLOUD

P Cygni line profiles were observed for at least five ^{28}SiO 1–0 band transitions. The redshifted emission features are clear evidence for expansion of the circumstellar cloud and rule out rotation as a large component of its motion at radii of SiO line formation. The observed ratios of emission to absorption equivalent width range from $\sim\frac{1}{6}$ to $\sim\frac{1}{2}$. As is shown in Figure 2, however, convolution of a P Cygni line with the instrumental profile, although preserving the equivalent width of the entire line, weakens both the emission and absorption features. It is estimated, therefore, that the actual equivalent width ratios are somewhat larger than the observed values.

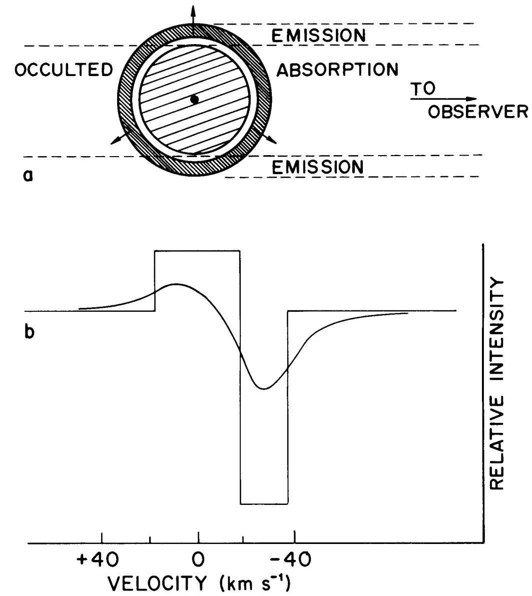

FIG. 2.—(*a*) Model for the production of P Cygni lines in VY CMa. A gas shell expands about a large continuum source. (*b*) P Cygni line shape associated with the above geometry, for the case of a central velocity of 0 km s^{-1} and an expansion velocity of 37 km s^{-1}. Convolution (*smooth curve*) with a Fabry-Perot transmission function of FWHM 23 km s^{-1} approximately halves the ratio of emission to absorption equivalent width and produces a peak in the emission component which is shifted $\sim+7$ km s^{-1} from the central velocity. The line shape is in acceptable agreement with observed ^{28}SiO P Cygni lines in VY CMa.

While in principle several mechanisms could lead to the observed emission from the first excited vibrational state lines of ^{28}SiO, the dominant one in this case must be reemission (resonant scattering). By using equations given by Millikan and White (1963) for computing collisional relaxation times, it can be shown that at the densities expected in the emitting part of the cloud ($\sim 10^9$ cm^{-3}) the collisional vibrational excitation rate is only $\sim 10^{-3}$ of the radiative excitation rate at 8 μm. Vibrational excitation by 4 μm or shorter-wavelength photons followed by relaxation via 8 μm emission is also relatively unlikely because of the low transition probabilities for overtone band absorption.

For resonant scattering in a spherically symmetric and expanding cloud without dust, conservation of energy requires that the line absorption and emission observed from any direction be equal, if the central continuum source is small. If, as may well be the case for VY CMa at 8 μm, the continuum source is not small compared to the SiO cloud, the emission is reduced due to the absorption of scattered radiation by the continuum source. Dust in the line-forming region absorbs photons reemitted by SiO, and further reduces the emission, most strongly for the optically deepest transitions. The limited data for the ^{28}SiO 1–0 band are in agreement with this model. However, the lack of emission for the optically thin transitions of ^{29}SiO and ^{30}SiO is puzzling. It is possible that much of the absorption equivalent widths of these lines may originate in dense layers which are close enough to the opaque surface that the emission is highly suppressed. In contrast, ^{28}SiO may absorb a substantial fractional amount of radiation in cooler outer layers, where reemitted photons are more likely to escape. The apparent existence of an inverse correlation between the ratios of emission to absorption equivalent width and the rotational levels of the P Cygni lines supports this hypothesis.

In addition to implying that the circumstellar cloud is expanding, the present observations contain evidence concerning the shape of the cloud and its central velocity. The presence of some emission features at least one-half as strong as the corresponding absorption lines limits the possible geometries of the expanding cloud. Some authors (Herbig 1969; Van Blerkom and Auer 1976) have proposed that the circumstellar material at certain distances from the central star is in the form of a disk seen nearly edge-on. In the case of a disk of this orientation, the resonant scattering mechanism would produce in our direction a very weak SiO emission line, whose maximum (small continuum source, dust free) equivalent width relative to the associated absorption would be roughly the ratio of the thickness of the disk to its diameter. Thus, the maximum observed ratio of $\sim\frac{1}{2}$ rules out a thin, nearly edge-on disk, near the radius of ^{28}SiO line formation ($r \sim 0''.15$).

The central stellar velocity may be estimated from the P Cygni profiles in the following way. For the case of a cloud expanding symmetrically about a continuum source and with the exceptions noted below, the central velocity of the emission feature corresponds to the velocity of that source (see Fig. 2). Fits to the observed profiles based on various simple models of P Cygni line formation show that the observed velocity of peak emission is redshifted by 7 ± 3 km s^{-1} from the central velocity of the emission feature due to the convolution with the instrumental resolution function. Thus, the observed velocity of peak emission (39 ± 4 km s^{-1}) implies a central velocity of 32 ± 7 km s^{-1} (LSR).

Two lower limits to the stellar velocity can be obtained from the 8 μm data and are consistent with the above value. The midpoint of the entire P Cygni profile (absorption and emission), averaged over several lines, is 25 ± 5 km s^{-1}. This value is a lower limit to the central velocity because emission from the most redshifted SiO is blocked by the continuum source. The second lower limit is the least blueshifted absorption velocity, 18 ± 4 km s^{-1}, which is that of the ^{28}SiO 2–1 band. Since the SiO lines are formed far from the stellar photosphere, the gas containing the observed SiO is expected to be moving away from the star. This implies that the stellar velocity is redshifted with respect to the velocity of the 2–1 band.

Two effects due to dust could affect the estimate of the stellar velocity. Scattering of radiation by dust external to the SiO could shift the 8 μm spectrum to the red in a manner similar to that proposed by Herbig (1969) and calculated by Van Blerkom and Van Blerkom (1978) for the optical spectrum of VY CMa. However, the scattering cross section of typical dust grains is thought to be negligible at 8 μm. Absorbing dust within the line-forming region will shift the emission shortward by reducing the contribution from the rear parts of the shell more than from the front. To the extent that these effects are small or compensate, and for cloud shapes which are either spheres or disks, 32 ± 7 km s^{-1} should represent the stellar velocity.

The above analysis suggests that the velocity of the central star of VY CMa, although between the velocities of the 1612 MHz OH features, perhaps is not central to them. The velocity derived here, however, is inconsistent with Reid and Dickinson's (1976) proposed stellar velocity of 17.6 ± 1.5 km s^{-1}, which was based on the broad and presumably thermal component of the $v = 0$, $J = 2 \rightarrow 1$ millimeter line of SiO (Buhl *et al.* 1975), and which is central to the maser velocity structures. The value proposed here for the stellar velocity would probably require some asymmetry in the radio-emitting envelope such that line emission from the extreme rear is suppressed. Alternatively, a stellar velocity of 17.6 km s^{-1} apparently would require that the smaller, infrared-emitting cloud be asymmetric, unless scattering of 8 μm radiation by dust is more important than presently thought. In either case it is clear that observations at higher spectral resolution and a more detailed model are necessary to understand better the SiO 8 μm spectrum.

VI. THE SILICON ISOTOPIC RATIOS

The terrestrial ratios ^{28}Si/^{29}Si and ^{29}Si/^{30}Si are 20 and 1.5, respectively. Within the uncertainties, the results for VY CMa differ from these only in a probable slight enhancement of ^{30}Si. Silicon isotopic ratios are available at present in only two other objects outside the solar system (Beer, Lambert, and Sneden 1974; Clark and Lovas 1977) and are also nearly terrestrial. The results are beginning to suggest a uniformity of these ratios over a large region of the Galaxy.

Isotopic abundances of silicon in a stellar interior are not expected to change until advanced stages of red giant stellar evolution are reached. Only as early as helium shell burning might *s*-process reactions change (increase) the abundances of the rare isotopes relative to ^{28}Si. In the still later stages of oxygen burning and silicon burning, cores are produced in which ^{28}Si/^{29}Si and ^{28}Si/^{30}Si are larger than their terrestrial values (Bodansky, Clayton, and Fowler 1968; Woosley, Arnett, and Clayton 1972). All of these mechanisms require some mixing process to alter the surface abundances.

Whether VY CMa is a newly formed star or an evolved object has been a matter of considerable discussion (e.g., see Herbig 1969; Hyland *et al.* 1970; Geballe *et al.* 1975). The observed isotopic abundances of silicon might restrict VY CMa to an evolutionary phase earlier than He shell burning, but certainly do not rule out earlier red giant phases. Thus, the present results in themselves leave open the question of the evolutionary state of VY CMa.

VII. SUMMARY

1. The 8 μm SiO lines in VY CMa are formed in $\sim$600 K accelerating and expanding gas at a radius

of $\sim 0\farcs15$. In this region, the gas is not in the shape of a thin disk seen nearly edge-on.

2. The radial velocity of the central star appears to be shifted by about $+15$ km s^{-1} from the midpoint of the 1612 MHz OH pattern.

3. Most of the silicon probably is in the form of dust grains.

4. The silicon isotopic ratios are roughly terrestrial.

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