THE EIGHT 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: individual - stars: circumstellar shells - stars: abundances

I. INTRODUCTION

The dense cloud of gas and dust surrounding VY Canis Majoris is one of the brightest sources of maser emission and infrared continuum radiation in our Galaxy. The complex spatial and velocity structure of the maser emission from OH, H_2O and SiO has been studied by numerous authors (see e.g. Rosen et al. 1978 and references therein). The optical radiation from VY CMa, which is scattered by the surrounding nebula, consists of a photospheric, M-type spectrum, together with a number of low-excitation absorption and emission lines which originate outside the photosphere (see e.g. Wallerstein 1971; Herbig 1974). The optically derived radial velocity of the central star has been uncertain, and has appeared to change frequently by large amounts (Wallerstein 1977). This is presumably due to the Doppler shifting of the photospheric spectrum by scattering from different parts of the moving dust shell. Recently Reid and Dickinson (1976) deduced a stellar velocity of $+17.6 \pm 1.5$ km s^{-1} (LSR) from the centroid of what is believed to be the thermal component of the $v = 0$, $J = 2 \rightarrow 1$ millimeter line of SiO (Buhl et al. 1975) coming from the circumstellar cloud. This value lies approximately midway between the OH 1612 MHz maser features, and if correct, gives VY CMa the same velocity as the cluster NGC 2362, to which it may belong (Herbig 1969; Humphries 1975), and which is ~1.5 Kpc distant.

In the infrared, low-resolution observations between 2.9 μm and 14 μm (Gillett, Stein, and Solomon 1970) reveal a flat and rather featureless spectrum, showing that the dust must be present over a wider range of temperatures than in most M giants or supergiants. At higher resolution near 2.3 μm the stellar photosphere is still observed via the overtone bandheads of carbon monoxide (Hyland et al. 1969). However, the low excitation and blueshifted velocity of the observed fundamental band absorption lines of CO at 4.7 μm (Geballe, Wollman, and Rank 1973) indicate that by this wavelength only circumstellar material can be seen.

In order to learn more about the cloud around VY CMa, observations have been made near 8.3 μm of the fundamental vibration-rotation band of silicon monoxide. Although this band is quite complex in stellar atmospheres, the cool temperatures and low column densities in the circumstellar cloud of VY CMa permit only a relatively few lines to be prominent and have allowed a simplified 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 17 January and 26 January 1978. 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 beam diameter of 7″, combined with the exit aperture, produced a grating bandpass of ~3.5 cm^{-1}. 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

The measured absorption equivalent widths of the SiO lines were matched to isothermal shell line strengths to derive 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 model several of the ^{28}SiO 1-0 lines are saturated, with optical depths near 2. 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 both species of SiO are of nearly equal strength. $^{28}Si/^{29}Si$ was determined by three methods, none of which alone is foolproof. In order to facilitate the calculations, "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 $^{28}Si/^{29}Si = 17 \pm 4$. 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 giving 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 varies 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 are listed in Table 2. They 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. In order to verify that the different absorption velocities found for different bands of SiO in VY CMa are real, the molecular constants as well as the calibration procedure were checked by calculating the radial velocity of α Orionis 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.

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 *et al* 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 *et al* (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, a radius as large as ~0.21″ would result in observed temperatures at 8.3 μm near or below 400 K, which is somewhat lower than the temperatures found here. In conclusion, most of the SiO observed near 8 μm probably is located near a distance of 0.15″ from the central star, or just outside the region of radius ~0.1″ where H_2O maser emission is found (Rosen *et al.* 1978). The SiO masers, which require excitation temperatures of up to 3500 K (Buhl *et al.* 1974), probably originate closer to the star.

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 ~1.5 kpc) and an H_2 density of 4×10^{8} cm^{-3}. The density assumes the estimated density of 10^{9} cm^{-3} in the region of H_2O maser emission (Rosen *et al.* 1978) and a $1/r^{2}$ dependence. The result is [SiO]/[H] ~ 1×10^{-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 μm and 9.3 μm observed in a low-resolution spectrum of VY CMa obtained by Gillett, et al (1970). The feature seen by those authors has a depth of perhaps 30%, whereas the observed SiO band on the average depresses the continuum by only ~5%. In addition, the low temperatures found here indicate that the band is not as broad as the depression seen at low resolution. 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 STRUCTURE AND MOTION OF THE CLOUD

P Cygni line profiles were observed for at least five ^{28}SiO 1-0 band transistions. The emission features must arise in portions of the cloud not in the line of sight to the continuum source. The emission is always redshifted from the absorption (see Fig. 1), corresponding to an expanding cloud. Indeed, the line shape rules out rotation as a large component of the cloud motion in the region of SiO line formation.

The peak intensities and equivalent widths of the emission features generally appear much smaller than the corresponding absorption depths and equivalent widths. However, simple models of P Cygni profiles observed at the present spectral resolution show that the deconvolved emission and absorption equivalent widths are more nearly equal, with the ratio of emission to absorption as much as twice the observed ratio. For the few ^{28}SiO P Cygni lines observed, an inverse relation between the ratio of emission to absorption strength and the rotational level appears to exist. For example the emission to absorption ratio is about one-sixth for the P17 line in Fig. 1, but about one-half for the R3 line (which has a weaker absorption component than does the P17 line). The inverse correlation should be confirmed by observing more lines. If the inverse correlation were between emission strength and absorption strength, which is also consistent with the ^{28}SiO 1-0 band observations, then one would expect to observe emission features on the weak lines of the rare isotopes--this was not seen. The weak ^{28}SiO 2-1 band also does not show emission, but this may be expected since its absorption velocity and excitation indicate that it originates closer to the exciting source than do the other bands.

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 is simply reemission (resonant scattering). By using equations given by Millikan and White (1963) for computing collisonal 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, symmetry and conservation of energy require 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 is 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 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.

Clearly, a detailed model and observations at higher spectral resolution are necessary to better understand the observed line shapes. However, on the basis of the present observations, it is possible to draw some conclusions about the shape of the circumstellar 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. The resonant scattering mechanism, would, in the case of a disk of this orientation, 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 ~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. 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 present instrumental resolution). Thus, the observed velocity of peak emission (39 ± 4 km s^{-1}) implies a central velocity of 32 ± 7 km s^{-1} (LSR).

Two effects not included in the simple models could alter this result. Reabsorption by SiO in outer parts of an accelerating cloud (see below) will decrease the apparent emission from the front half causing the peak emission to occur behind the limb and be more redshifted than the central velocity. Absorbing dust within the line-forming region will have the opposite effect, reducing the contribution from the rear parts of the shell more than from the front. 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 normal size dust grains is negligible at 8 μm. To the extent that the first two effects are small or compensate, and for the cloud shapes which are either spheres or disks, the above velocity should represent the stellar velocity.

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 most redshifted 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.

The above arguments indicate that the stellar velocity, although in between the 1612 MHz OH features, is probably not central to them. Only the lower of the two lower limits, from the 2-1 SiO band, is consistent with Reid and Dickinson's (1976) proposed stellar velocity of 17.6 ± 1.5 km s^{-1}, which is central with respect to the maser velocity structures. The stellar velocity of ~32 km s^{-1} proposed here apparently requires some asymmetry in the expanding envelope, such that no 1612 MHz OH emission from the extreme rear of the envelope is directed towards us at present. In addition, it requires that most of the H_2O and SiO maser emission arises in the front half of the cloud.

It is interesting that the absorption line velocities of the various bands of SiO are not all the same (see Table 2). The velocity of the ground vibrational state lines of ^{28}SiO is blueshifted by about 13 km s^{-1} relative to that of the first vibrational state lines. The latter lines must arise in a region interior to the former lines; thus, the velocity difference corresponds to outward acceleration. This interpretation is consistent with that of the P Cygni lines. The intermediate velocity of the ^{29}SiO and ^{30}SiO lines indicates that they form largely in between the two ^{28}SiO bands. The expansion velocity at r ~ 0.15″ where 8 μm SiO lines originate is roughly half the expansion velocity at r ~ 1″ where OH 1612 MHz emission originates.

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 of 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 our 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.

SUMMARY

1. The 8 μm SiO lines in VY CMa are formed in ~600°K accelerating and expanding gas at a radius of ~0.15″. 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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TABLE 1

RESULTS OF ISOTHERMAL SHELL ANALYSIS

$T_{rot}(^{28}SiO\ 1\text{-}0)$ K	$T_{rot}(^{29}SiO,\ ^{30}SiO,\ ^{28}SiO\ 2\text{-}1)$ K	T_{vib} K	$NL(^{28}SiO)$ cm^{-2}	$\frac{^{28}Si}{^{29}Si}$	$\frac{^{29}Si}{^{30}Si}$
525±50	600±100	600±100	$(7 \pm 3) x 10^{17}$	20±5	1.0±0.3

TABLE 2

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

^{28}SiO 1-0 absorption	^{29}SiO, ^{30}SiO absorption	^{28}SiO 2-1 absorption	^{28}SiO 1-0 emission peak	^{28}SiO 1-0 midpoint of emission[1]	^{28}SiO 1-0 midpoint of profile	Deduced Stellar
+5 ± 3	+10 ± 3	+18 ± 4	39 ± 4	32 ± 7	25 ± 5	32 ± 7

[1] corrected for instrumental resolution

FIGURE CAPTION

Figure 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.

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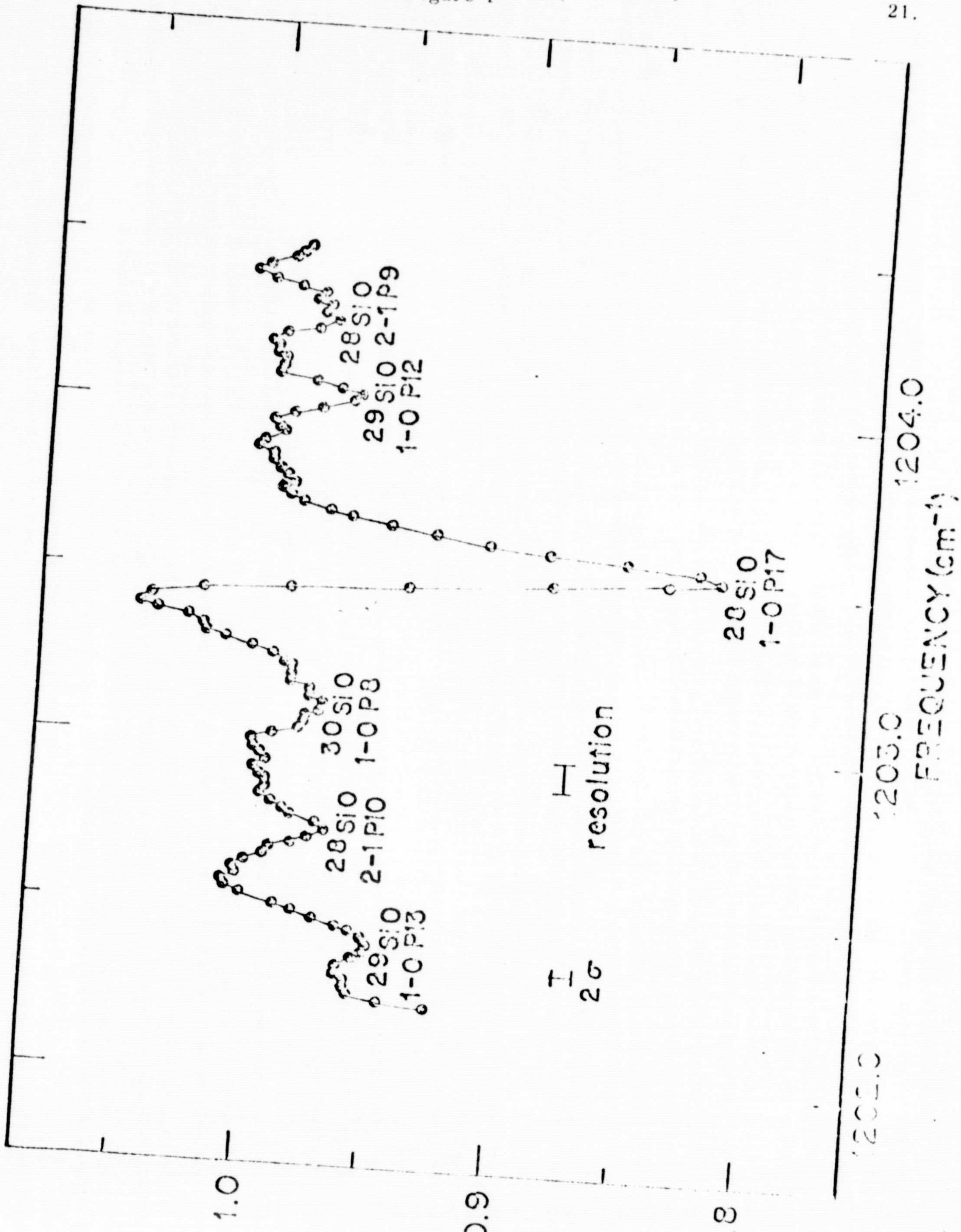
Figure 1


1.0
0.9
0.8
1202.0
1203.0
1204.0
FREQUENCY (cm⁻¹)
29SiO 1-0 P13
28SiO 2-1 P10
30SiO 1-0 P8
28SiO 1-0 P17
29SiO 1-0 P12
28SiO 2-1 P9
resolution
2σ