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POLARIZATION PROPERTIES OF THE 86.2 GHz $v = 1$, $J = 2 \rightarrow 1$ SiO MASER

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ABSTRACT

Complete Stokes parameters have been measured for a small sample of SiO masers associated with variable stars. These sources were found to be typically 15–30% linearly polarized and to exhibit no circular polarization above limits of as low as a few percent. The Orion Molecular Cloud source exhibited no linear or circular polarization greater than 3% during the present observing period. The Stokes parameters for R Cas, not necessarily including the total intensity, were found to vary over short periods. Comparison of the new profiles for regular variable stars with those obtained several optical periods earlier reveals substantial changes. No apparent correlation exists between these changes and the optical variations of the stars.

Subject headings: interstellar: molecules — masers — polarization — stars: long-period variables — stars: supergiants

I. INTRODUCTION

Approximately 50 sources of vibrationally excited SiO maser radiation are now known. These sources are almost always associated with cool, evolved, long-period variables such as Mira-type stars and irregular supergiants; most exhibit OH and H_2O maser emission as well. (See Dickinson *et al.* 1978 for a list of sources and references.)

Polarization is a distinctive characteristic of many interstellar OH and some H_2O masers. Yet little is known observationally about the polarization properties of SiO masers, in part because of the scarcity of millimeter wavelength polarimeters. Theoretical knowledge of maser polarization is also incomplete. Goldreich, Keeley, and Kwan (1973*a*, *b*), among others, have carefully formulated a theoretical framework for the subject; nonetheless, many uncertainties still exist.

In this paper we present further observational data on the subject of maser polarization, a search for linear and circular polarization in the 86.24328 GHz (3.5 mm) $v = 1$, $J = 2 \rightarrow 1$ transition of SiO. These measurements were made with a switchable linear/circular polarimeter on the NRAO[1] 11 m telescope. Our results indicate that linear polarization at the 15–30% level (and occasionally higher) is common in SiO maser emission but circular polarization is not. These findings are in qualitative agreement with the maser polarization theory.

We also present a modest additional contribution to the subject of SiO maser variability. While it was not our primary intent to consider this question, we did detect variations in one source, R Cas, over a 24 hour interval. Finally, we have investigated longer-term variations and their relationship to optical phase in the Mira variables by comparison of our line profiles with those obtained earlier by other investigators. This comparison reveals numerous changes in the 86.2 GHz lines, changes which bear no obvious relationship to the optical phases of the stars.

II. OBSERVATIONAL TECHNIQUES

a) Data Acquisition

We observed during the interval 1977 March 19–21 with the NRAO 11 m telescope and cooled Cassegrain receiver. Under typical conditions at 86.2 GHz, this receiver and telescope are equivalent to a 1000 K single side-band system located above the Earth's atmosphere. At this same frequency the telescope has a half-power beamwidth of about 80″; the 256 channel 100 kHz filter bank provides a velocity coverage and resolution of 89 and 0.35 km s^{-1}, respectively, and the 128 channel 30 kHz filter bank provides coverage of 13.4 and 0.10 km s^{-1}, respectively. We calibrated the receiver using the standard vane calibration procedure for the NRAO Cassegrain system. In this technique the calibration signal is the difference between power received with and without an ambient-temperature absorbing vane placed in front of the feed horn. All temperatures quoted below are in terms of T_A^*, the antenna temperature corrected for both atmospheric

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

and antenna losses in the manner described by Ulich and Haas (1976).

For this experiment we used a remotely switchable polarimeter designed and constructed by J. M. Payne and R. K. Howard of the NRAO. This device, also used by Clark *et al.* (1978) and Hobbs, Maran, and Brown (1978), provides opposite senses of linear or circular polarization through the use of one (circular polarizations) or two (linear polarizations) quarter-wave plates mounted immediately in front of the dual-linear feed horn. By rotating one of the plates 90°, the polarization senses can be switched between right- and left-hand circular or between horizontal and vertical linear polarizations as fast as once per second. This fast-switching capability represents a considerable improvement over the earlier, manually switchable polarimeter used by Johnson and Clark (1975).

We initially attempted to obtain polarization-switched spectra by switching the polarimeter rapidly (1 Hz). However, these spectra had highly unsuitable baselines that could not be removed by subtracting equivalent off-source spectra. In an alternate technique we recorded a succession of 5 minute position-switched spectra, switching the sense of polarization and recalibrating the receiver for each. This procedure yielded exceptionally flat baselines. Furthermore, telescope gain in the opposite polarization senses (opposite linears or circulars) proved to be the same to within a few percent, so we had no need to correct the spectra for this effect. We did not use the Fabry-Perot sideband rejection filter because of uncertainties in the effect of the filter on polarimeter performance.

Antenna-temperature scaling errors are often significant at millimeter wavelengths where atmospheric opacity is nonnegligible and sometimes variable, where the antenna aperture efficiency is sensitive to small thermal deformations in the dish, and where accurate pointing of the telescope is difficult. Figure 1 illustrates the magnitude of these effects in the spectrum of the Orion Molecular Cloud (OMC-1). The ordinate g of each point is defined as

$$g \equiv \frac{1}{G_{\max}}\left[\int_{v_1}^{v_2}(T_A{}^*)^+ dv + \int_{v_1}^{v_2}(T_A{}^*)^- dv\right], \quad (1)$$

where $(T_A{}^*)^+$ is the line profile as observed during one 5 minute scan, $(T_A{}^*)^-$ is the line profile as observed during the next 5 minute scan in the orthogonal sense of polarization, and $G_{\max}$ is the maximum value of the quantity in brackets for any pair of scans on the source. For OMC-1 we take $v_1 = 9$ km s^{-1} and $v_2 = 20$ km s^{-1}. Since g is proportional to the Stokes parameter I, its value is unaffected by polarization in the source. It is only affected by scale errors as described above. The points plotted in Figure 1 show about a 15% peak-to-peak variation and little dependence on telescope elevation or time; they are representative of the results obtained by applying this same analysis to all other sources. However, the overall accuracy of the polarization measurements for a given source is considerably better than 15% since the temperature-scale variations shown in Figure 1 tend to cancel out when data taken over several hours are combined. This conclusion follows from the observed absence of apparent circular polarization in most sources, often down to the 2–3% level, and from the observed absence of linear polarization in OMC-1 down to a level of 3%. (See §§ III*a* and III*c*, and Tables 1 and 2.)

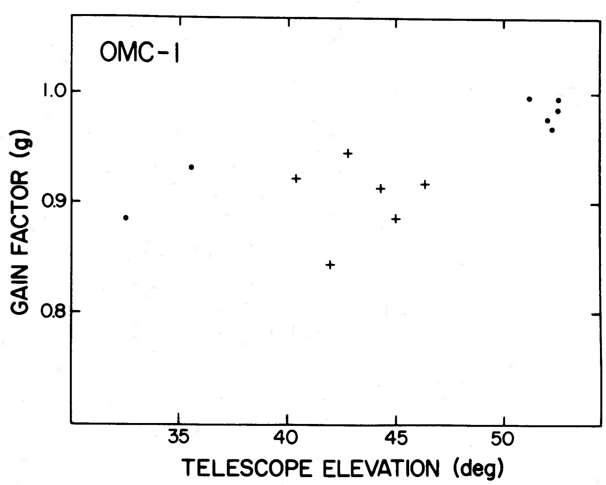

FIG. 1.—Gain factors (see eq. [1] in text) versus telescope elevation for OMC-1. Filled circles represent circular polarization data (1977 March 19) and crosses represent linear polarization data (1977 March 20).

b) *Derivation of Polarization Parameters*

We have computed the Stokes parameters for all positions with detectable line emission. The linear polarization parameters, Q and U, are derived from a least-squares fitting procedure which makes use of the rotation in position angle of the polarimeter as the altitude-azimuth–mounted telescope tracks a source. In this procedure, we fit the n position-switched line temperatures for channel i (where n is the number of linearly polarized spectra recorded for a given source) to a function of the form

$$T_i(\theta) = \tfrac{1}{2}I_i + \tfrac{1}{2}Q_i \cos 2\theta + \tfrac{1}{2}U_i \sin 2\theta . \quad (2)$$

$T_i(\theta)$ is the line temperature for channel i, θ is the position angle of the linear polarimeter measured as usual from the north toward the east. The Stokes parameters I, Q, U, V are identical to the parameters S_0, S_1, S_2, and S_3, respectively, as defined by Ball and Meeks (1968). We have also computed the fractional (or "degree" of) linear and circular polarizations and the position angles of linear polarization, again as defined by Ball and Meeks.

In Tables 1–3 we summarize our results for each source as well as other pertinent data. Additional characteristics of many of these sources (OH and H_2O emission, optical properties, etc.) are listed by Kaifu, Buhl, and Snyder (1975, hereafter KBS) and by Snyder and Buhl (1975). In Figure 2 we present the Stokes parameters as well as the fractional linear polarizations and position angles of linear polarization where

TABLE 1

LINEARLY-POLARIZED 86.2 GHz SiO SOURCES

Source	α(1950) δ(1950)	Variable Type[a]	Flux (10^{-20} W m^{-2})	Fractional Linear Polarization (max)	Fractional Circular Polarization (at line peak)	Optical Phase (present data)	Optical Phase[b,c]
o Ceti	$02^h16^m49^s.0$ $-03°12'13''$	M	540	0.40	< 0.20	0.2	not observed
NML Tau	03 50 43.7 11 15 30	M	520	0.25	< 0.10	?	?
VY CMa	07 20 54.6 −25 40 12	unclassified	1280	0.15	< 0.03	...	...
R Leo	09 44 52.2 11 39 42	M	250	0.30	< 0.14	0.95	0.4
W Hya	13 46 12.2 −28 07 06	SR*a* (M?)	1080	0.25	< 0.02	?	?
U Her	16 23 34.6 19 00 18	M	115	0.55	< 0.50	0.7	0.95
χ Cyg	19 48 38.0 32 47 12	M	100	0.25[d]	< 0.20	0.65	0.9
R Cas	23 55 51.7 51 06 36	M	640	0.25	...	0.15	0.4

[a] Kukarkin *et al.* 1969.
[b] Optical data were provided by AAVSO; optical maximum is at phase 1.0; phases are rounded to nearest 0.05.
[c] Kaifu *et al.* 1975.
[d] Polarization detection is uncertain.

TABLE 2

86.2 GHz SiO SOURCES[a]

Source	α(1950) δ(1950)	Variable Type	Flux (10^{-20} W m^{-2})	Fractional Linear Polarization (max)	Fractional Circular Polarization (at line peak)	Optical Phase (present data)	Optical Phase[b]
S Per	$02^h19^m16^s.0$ $58°21'30$	SR*c*	65[c]	...	...	...	...
OMC-1	05 32 47.8 −05 24 08	...	1740	< 0.03	< 0.03	...	...
U Ori	05 52 51.0 20 10 06	M	30	...	...	0.55	0.55
RX Boo	14 21 58.0 25 55 53	SR*b*	51	...	...	...	...
S CrB	15 19 21.4 31 32 45	M	16	...	< 0.75	0.20	0.9, 0.05
VX Sgr	18 05 03.0 −22 13 56	SR*c*	610	...	< 0.14	...	...
R Aql	19 03 57.7 08 09 11	M	51	...	< 0.50	0.20	0.25
NML Cyg	20 44 33.8 39 55 57	...	290	...	...	...	...

[a] See notes to Table 1.
[b] Kaifu *et al.* 1975.
[c] Line may not be real.

TABLE 3

POSITIONS WITH UNDETECTED 86.2 GHz SiO EMISSION[a]

Source	α(1950) δ(1950)	Variable Type	Velocity Range (km s^{-1})	$\Delta T_A{}^*$ [b] (°K)	Optical Phase (present data)
IRC+10216........	$09^h45^m14^s.8$ 13°30′ 41″	...	−70, 18	0.7	...
CIT-6..............	10 13 12.0 30 49 24	...	−44, 44	0.5	...
R Hya.............	13 26 59.0 −23 01 30	M	−53, 35	0.5	0.98
WX Ser............	15 25 32.0 19 44 24	M	−37, 51	0.7	?
RR Aql............	19 55 01.0 −02 01 12	M	−13, 75	0.8	0.64

[a] See notes to Table 1.

[b] Peak-to-peak noise in 100 kHz resolution spectra.

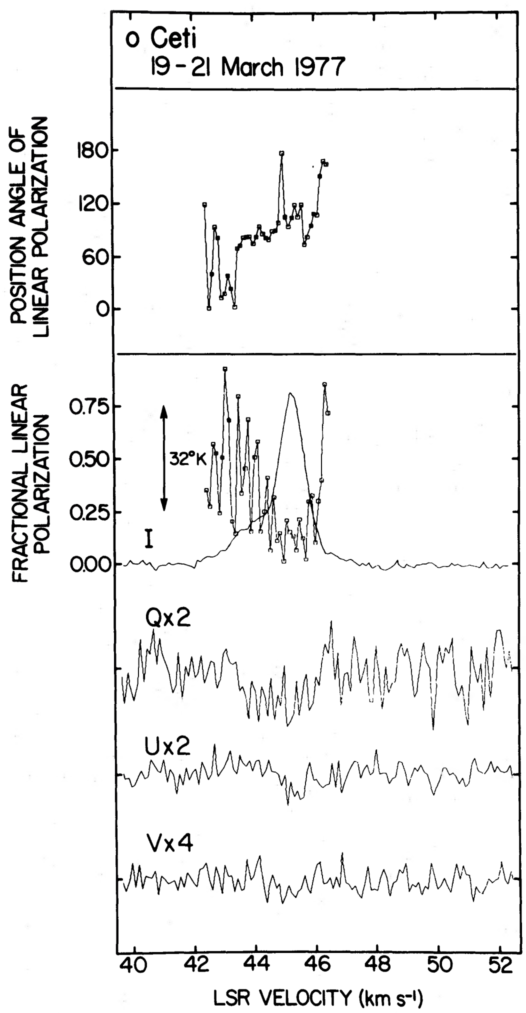

FIG. 2a

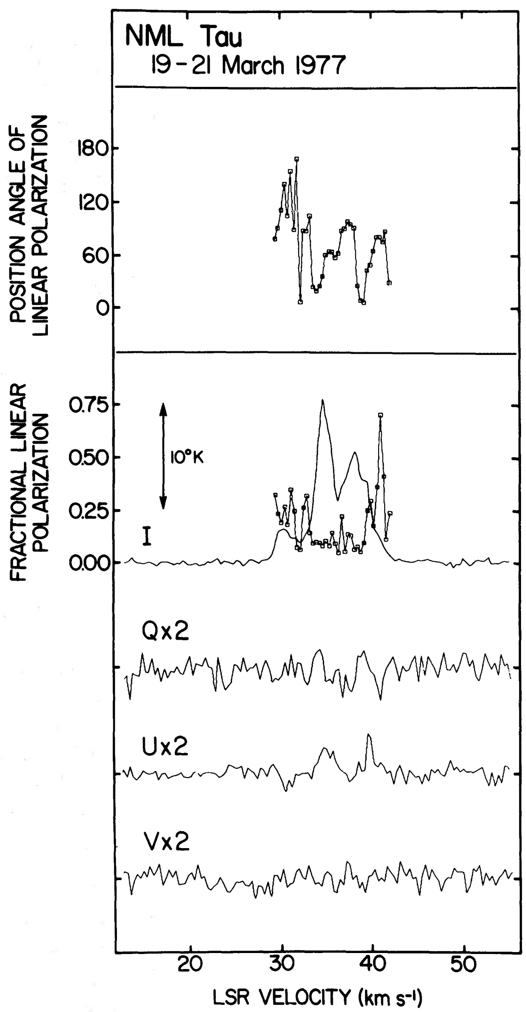

FIG. 2b

FIG. 2.—Stokes parameters for sources for which polarization properties were measured. Figures 2*a*, 2*f*, and 2*j* are 30 kHz resolution spectra; others have 100 kHz resolution. Note that the total intensity *I* is the sum of two spectra taken in orthogonal polarizations and is therefore twice as intense as a typical spectrum showing $T_A{}^*$.

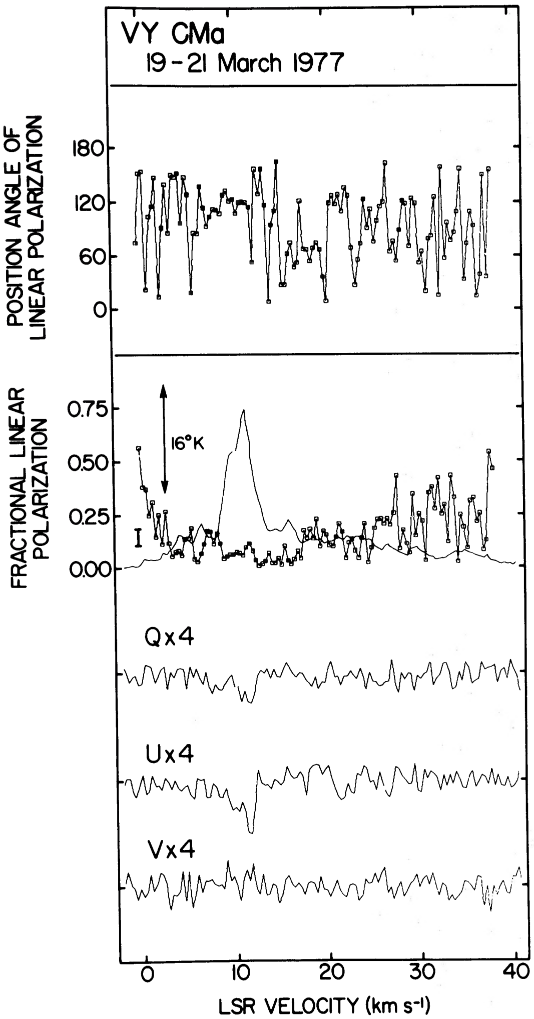

FIG. 2c

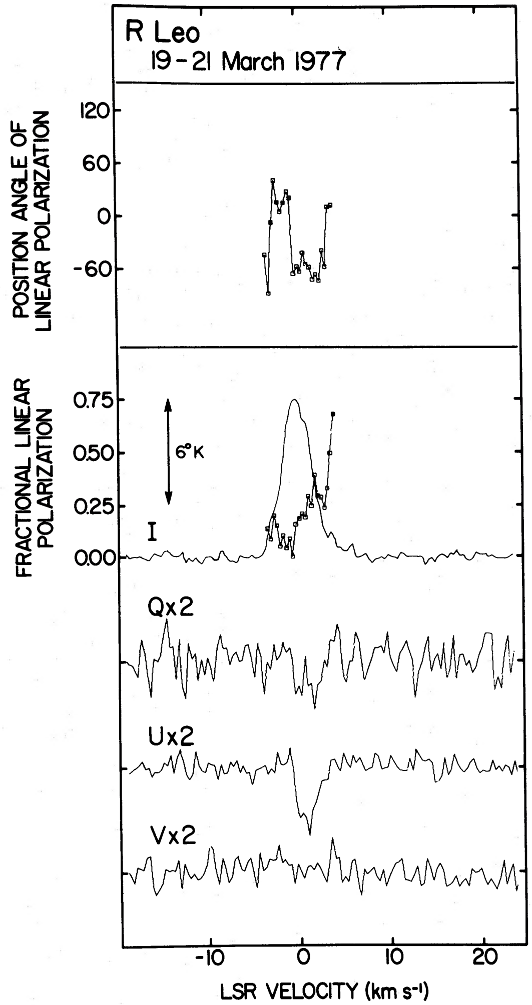

FIG. 2d

FIG. 2—*Continued*

appropriate. Figure 3 presents total intensity (I) spectra for those sources for which we were unable to derive meaningful polarization properties.

III. RESULTS

a) General Characteristics of SiO Polarization

We detected 86.2 GHz lines in 16 sources, all previously known SiO masers. Our observations of 11 of these sources are sufficient to establish circular polarization properties; none is circularly polarized above our sensitivity level, which is in some cases as low as a few percent. W Hya appears to be circularly polarized. However, this source exhibits the strongest linear polarization in our list, and we tentatively ascribe the circular polarization to the presence of a slight ellipticity in the circularly polarized response of the polarimeter. For sensitivity reasons, only nine sources were observed adequately to establish linear polarization properties; all had $T_A^* \geq 1.6$ K. Seven of these nine sources show clear evidence of 15% or more linear polarization; one source, χ Cyg, shows possible 25% linear polarization, and the remaining source, OMC-1, displays no linear or circular polarization greater than 3%. The small amount of linear and circular polarization apparent in the Stokes parameters profiles for OMC-1 is probably not real because the polarization is constant across the entire line profile, a circumstance which can result from small calibration errors or gain errors between opposite senses of polarization. Taken as a whole, these results suggest that at least 15% linear polarization and little or no circular polarization is a characteristic property of many, perhaps all, 86.2 GHz stellar SiO masers; the unpolarized OMC-1 source is an anomaly. Linear polarization has also been detected in the 43 GHz $J = 1 \rightarrow 0$ transitions of some SiO sources (J. H. Spencer, private communication); Moran *et al.* (1977) report less than about 20% linear polarization in OMC-1 at 43 GHz.

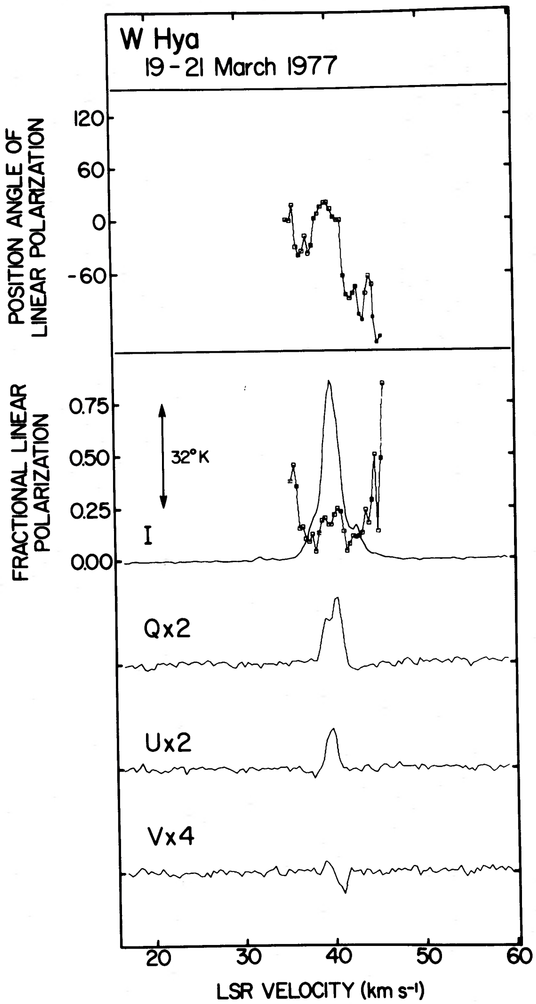

FIG. 2e

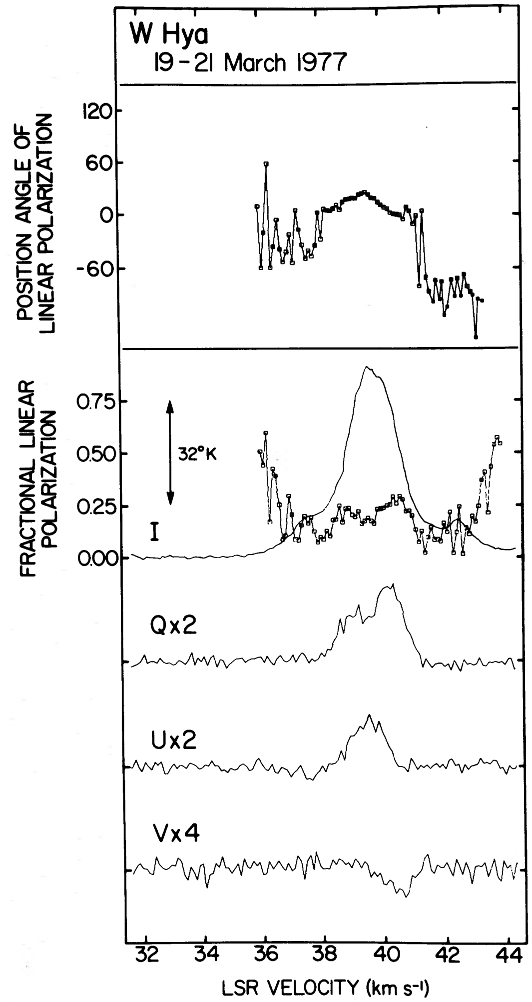

FIG. 2f

FIG. 2—*Continued*

b) Variation of Polarization across Line Profiles

The polarization properties of the linearly polarized sources often change significantly across the line profiles. R Cas and W Hya show this behavior quite noticeably. In the spectra of *o* Ceti, R Leo, U Her, and VY Cma, only parts of the profiles are polarized. This effect has also been observed in OH profiles of W Hya (Wilson *et al.* 1972) and in the profiles of OH sources associated with H II regions (see, e.g., Manchester, Robinson, and Goss 1970). For these latter sources, Goldreich, Keeley, and Kwan (1973*a*) have suggested that the variation in linear-polarization angle across the profiles may be caused by magnetorotation within the masers. It is very unlikely, however, that magnetorotation of the type described by Goldreich, Keeley, and Kwan is important in the SiO masers, since the differential rotation of position angle per unit frequency in these sources is about six orders of magnitude smaller than for OH sources.

A second explanation for the variation in linear-polarization parameters across line profiles is that the radiation from these sources comes from several emitting regions, each having different polarization properties. In this model the *I*, *Q*, and *U* profiles are represented as the sums of Gaussians:

$$I(f) = I_1 a_1(f) + I_2 a_2(f) + \cdots ,$$

$$Q(f) = Q_1 a_1(f) + Q_2 a_2(f) + \cdots ,$$

$$U(f) = U_1 a_1(f) + U_2 a_2(f) + \cdots ,$$

$$a_i \equiv e - \frac{(f - f_i)^2}{\Delta_i} .$$

In addition, we require that $Q_i^2 + U_i^2 \leq I_i^2$ and $I_i > 0$. As a test of this model we individually fit the *I*, *Q*, and *U* spectra of three sources with Gaussians. These sources, chosen for their strong, relatively simple

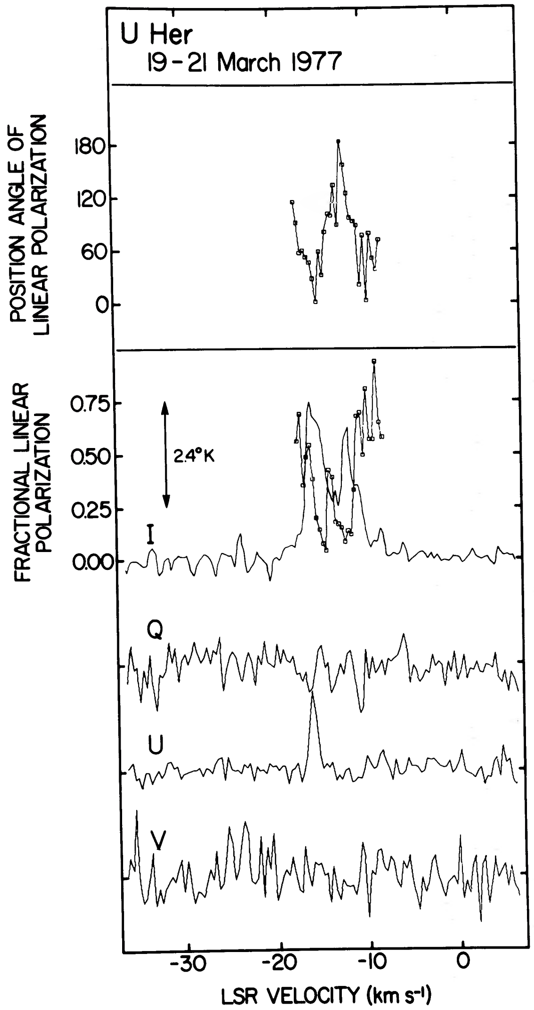

FIG. 2g

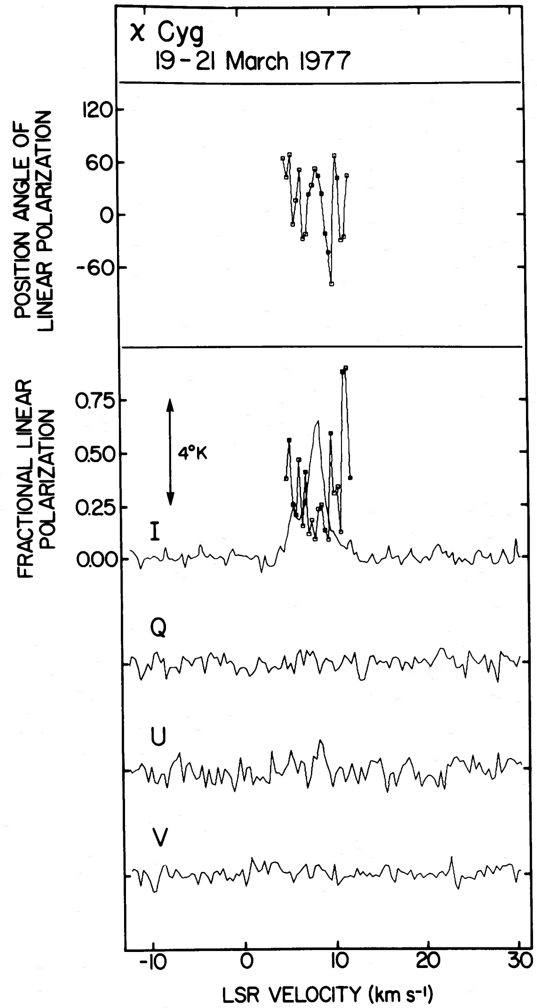

FIG. 2h

FIG. 2—*Continued*

line profiles, are W Hya, R Cas, and R Leo. We find that the I, Q, and U profiles for each source are fitted very well by one to three Gaussians having FWHM between 1 and 3 km s^{-1}, corresponding to thermal broadenings of 10^3–10^4 K. However, the center velocities of the Gaussians fitted to the I, Q, and U spectra for a given source do not match even approximately; and the widths fitted to the Q and U spectra are 40% narrower than those fitted to the corresponding I spectra. These discrepancies in the Gaussian parameters fitted separately to the I, Q, and U spectra strongly suggest that this simple model is inadequate. (In this model, it is improper to fit the fractional polarization spectrum, $[Q(f)^2 + U(f)^2]^{1/2}$, to Gaussians, since this profile contains non-Gaussian cross terms.) As a further test of the model, we fitted the I profiles for each source with a combination of the Gaussians fitted to the Q and U spectra (allowing variable amplitudes) plus several additional unpolarized Gaussians. Between two and four additional unpolarized Gaussians were required for each source in order to achieve a reasonable fit to the I profiles, and even then the fit was poorer than with the initial fits to I of one to three Gaussians. We conclude that this simple model of separate uniquely polarized emitting regions cannot adequately represent the data for these three sources unless an unduly large number of free parameters is allowed.

c) *Polarization of OMC-1 Source*

The present observations indicate that OMC-1 had less than 3% circular polarization in 1977 March, whereas Johnson and Clark (1975) observed three narrow ($\sim$1 km s^{-1}) circularly polarized features at about the 10% level in 1974 October. A detailed comparison of the total-intensity line profiles obtained during the two periods (Fig. 4) indicates that significant changes have occurred in the narrow ranges of

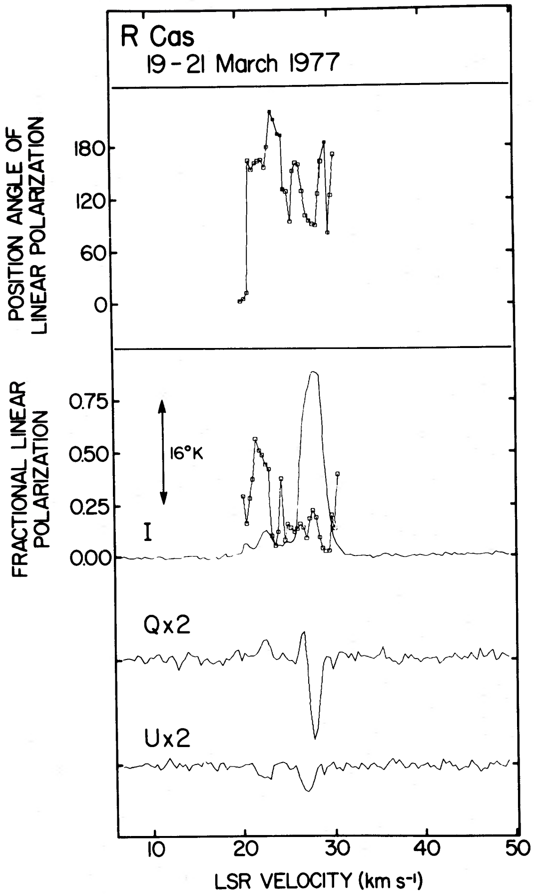

FIG. 2i

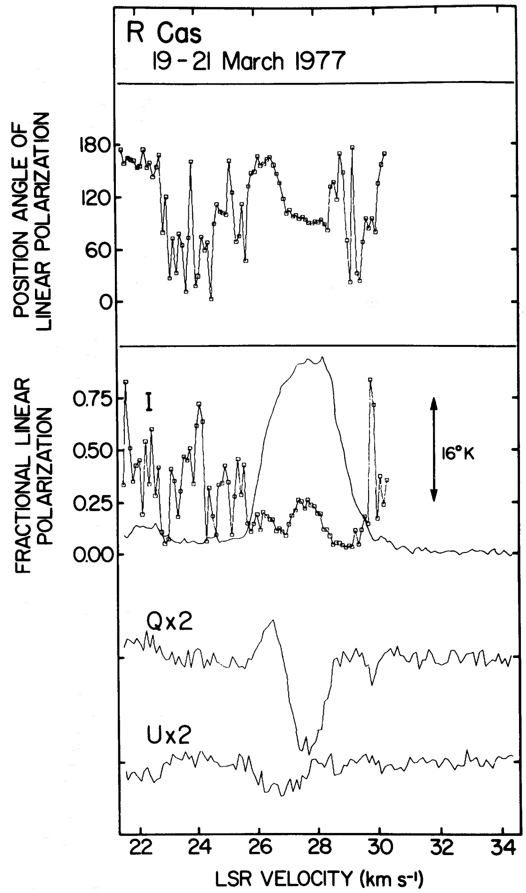

FIG. 2j

FIG. 2—*Continued*

velocity covered by two of the apparent circular-polarization features of Johnson and Clark. At the velocity of the third and weakest feature, the total intensity is virtually identical in the two spectra. The absence of circular polarization in the present data may be indicative of time variability in the polarization properties of the Orion source. Alternatively, the earlier result may be in error. It is difficult, however, to conceive of a source of error which would account for apparent polarization in several adjacent spectral channels, but not over the line as a whole. The origin of the apparent polarization of Johnson and Clark could lie in instabilities in the local oscillator which artificially broadened the line profile during the observations of one sense of circular polarization and not the other. In this circumstance, the difference between the right-hand and left-hand polarized profiles would contain residual "polarization" components narrower than the line itself. Despite careful attempts by Johnson and Clark to eliminate such systematic effects, this earlier observation was inherently more susceptible to these errors since the polarization switching rate was so much slower (§ II*a*).

d) *Short-Term Variability*

Time variability in R Cas was discovered while examining the residuals to the fit of equation (2). The residuals were found to be abnormally high for the 22 km s^{-1} feature but not for the stronger feature at 28 km s^{-1}. Subsequent examination of the residuals for all the other sources revealed no further evidence for variability.

In Figure 5 we present two successive 5 minute scans of R Cas taken in opposite senses of linear polarization. The feature at 22 km s^{-1} is close to 100% linearly polarized. Evidence for the time variability appears in Figure 6, where we plot T_A* for two narrow velocity ranges as a function of position angle of the polarimeter. Various symbols are used to designate different blocks of data, as described in the figure caption. Time-independent linear polarization produces a sinusoidal distribution of data points, as suggested by the least-squares fitted solid curves. The 28 km s^{-1} data (*upper figure*) are well represented by the curve, especially in view of the 15% peak-to-peak calibration errors expected for each 5 minute scan (§ II*a*). In the

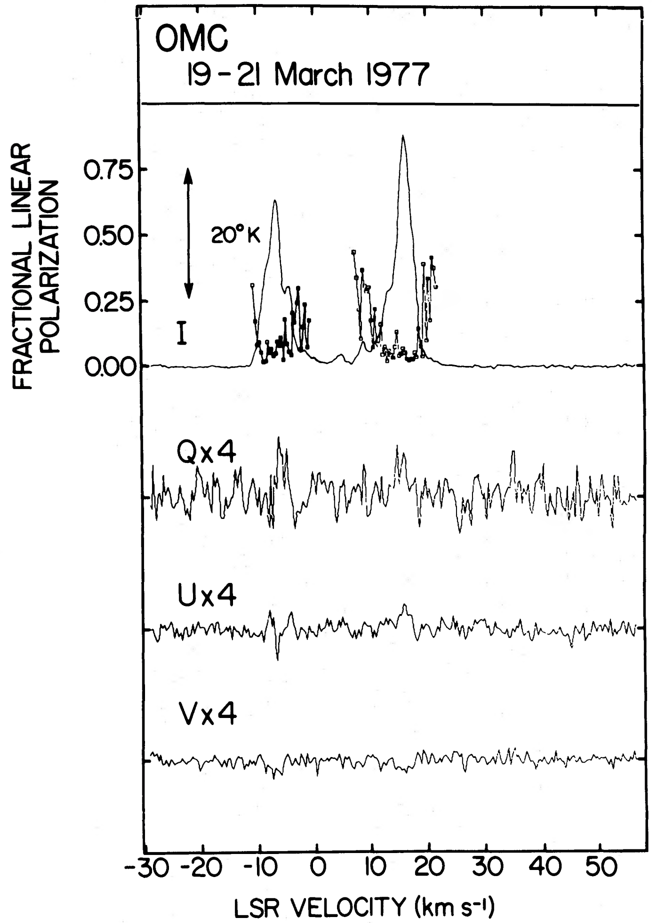

FIG. 2*k*

FIG. 2—*Continued*

lower half of Figure 6 we present an equivalent plot for the 22 km s^{-1} time-variable component. Here, the curve has been fitted only to the first and second sets of data points (shown as * and +). This same curve does not fit the data obtained the following day (shown as filled circles). No curve can simultaneously fit all of the data points with reasonable errors. We conclude that the Stokes parameters, possibly not including the total intensity, of the 22 km s^{-1} component have changed over a period of 1 day. Balister *et al.* (1977) report day-to-day variations in the 43 GHz $v = 1$ and 2, $J = 1 \rightarrow 0$ transitions from at least two sources, the semiregular variables R Dor and AH Sco.

e) *Long-Term Variability*

Apart from variability on time scales of days or less, longer-term SiO variations have been reported by Spencer and Schwartz (1975) and by Balister *et al.* (1977) in the 43 GHz $v = 1$ and 2, $J = 1 \rightarrow 0$ transitions. Spencer and Schwartz, observing in north-south linear polarization (equatorial telescope), found variations in R Cas and *o* Ceti that appeared to be correlated with the optical phases of these stars. Observed at several epochs during the same optical period, the SiO line strengths of these stars increased from 2 to 10 times or more near the optical maximum. However, this simple relationship between optical phase and SiO emission strength is not so apparent when comparisons are made between profiles obtained at intervals of one or more optical periods. Balister *et al.* compared their 43 GHz spectra for nine regular variables with those obtained by Snyder and Buhl (1975) two years (1–2 optical periods) earlier, and they found that peak flux densities in the profiles had changed by factors of 0.1–2. These changes bear no compelling relationship to the optical phases. However, the two sets of data were obtained in linear polarization on altitude-azimuth–mounted telescopes; hence the received polarizations were elliptical with parameters depending on the ranges of hour angle of the individual observations. Some of the differences between the profiles of Balister *et al.* and those of Snyder and Buhl may arise from linear polarization in the sources combined with differences in the received polarizations in the two series of observations.

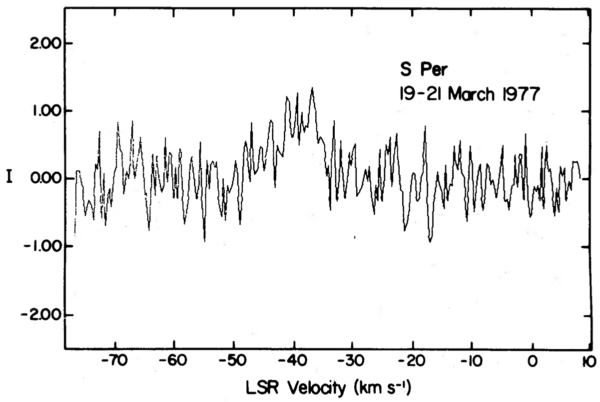

FIG. 3*a*

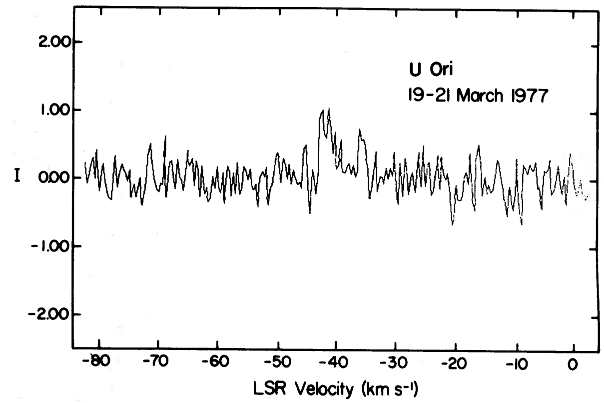

FIG. 3*b*

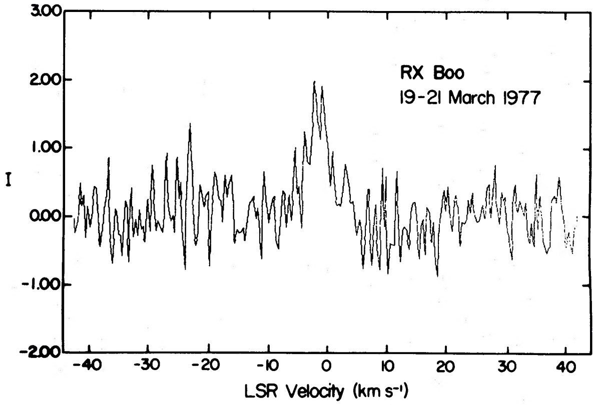

FIG. 3*c*

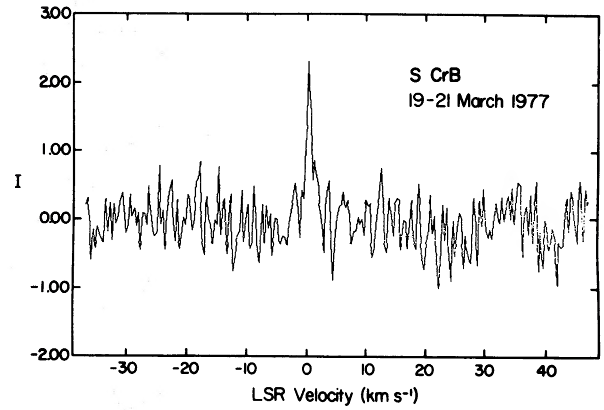

FIG. 3*d*

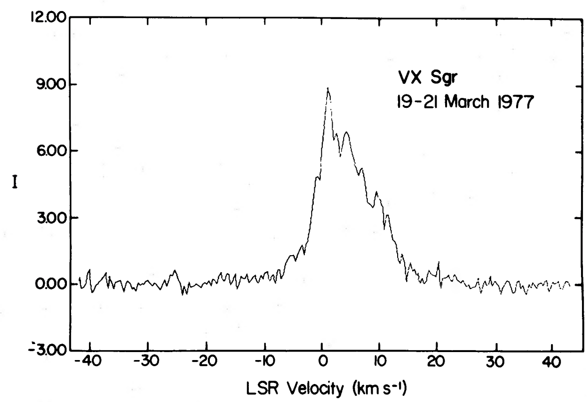

FIG. 3*e*

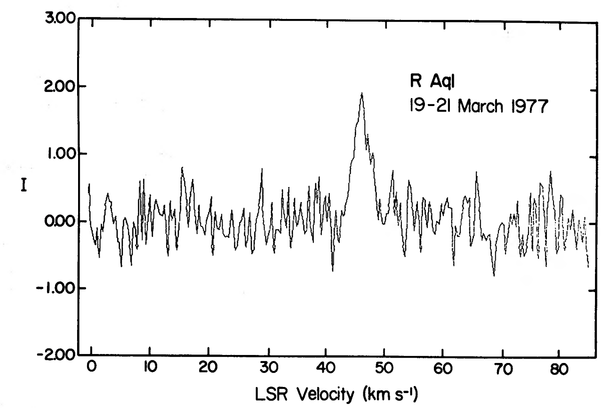

FIG. 3*f*

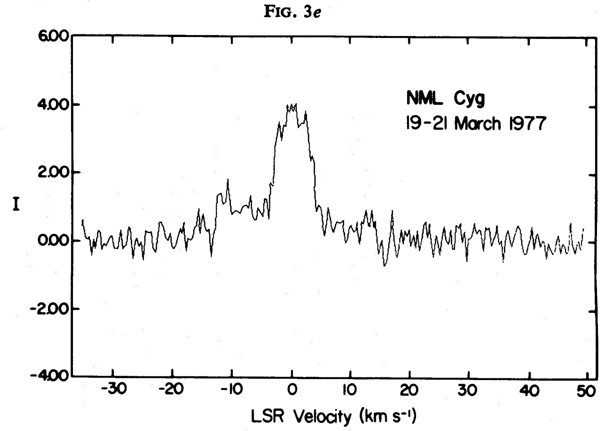

FIG. 3*g*

FIG. 3.—Total intensity I for sources which were too weak to derive meaningful Stokes parameters. Spectral resolution is 100 kHz. Note that I is the sum of two spectra taken in orthogonal polarizations, and it is therefore twice as intense as T_A*.

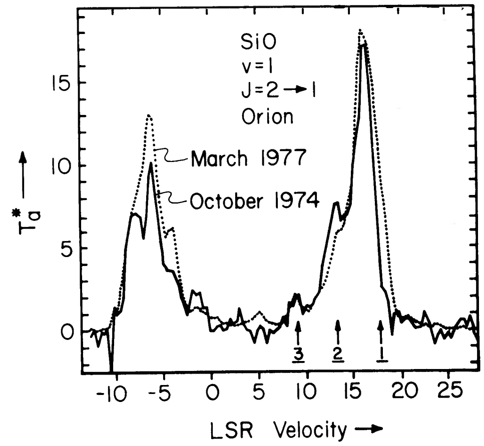

FIG. 4.—Comparison of the total intensity I for OMC-1 for the two observing periods, illustrating the significant changes which occurred in the narrow ranges of velocity occupied by two of the apparent circular-polarization features of Johnson and Clark (1975).

We have performed a similar comparison of our 86.2 GHz profiles with those of KBS. The KBS profiles were obtained three years earlier at the same frequency, again using linear polarization on the altitude-azimuth–mounted NRAO 11 m telescope. Thirteen sources are common to both sets of observations, while seven of these are regular variable stars with known optical phases. We find that substantial changes have occurred in the line profiles and in the integrated fluxes from most of these SiO sources. Most of the changes cannot be explained as polarization

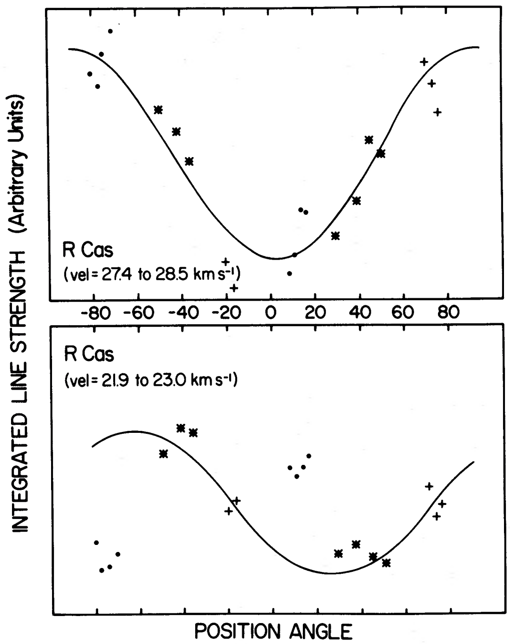

FIG. 6.—Plotted points show T_A* integrated over the indicated velocity ranges versus position angle (PA) of the linearly polarized feed. Points shown as * and + were taken on 1977 March 20, about 4 hours apart. Points shown as filled circles were taken on 1977 March 21. The smooth curves show the functional dependence of T_A* on PA as predicted from least-squares fits of eq. (2) to the data. The 28 km s^{-1} curve has been fitted to all of the data points. The 22 km s^{-1} curve has been fitted only to the 20 March data points; no fit with reasonable errors could be obtained by using all of the data points.

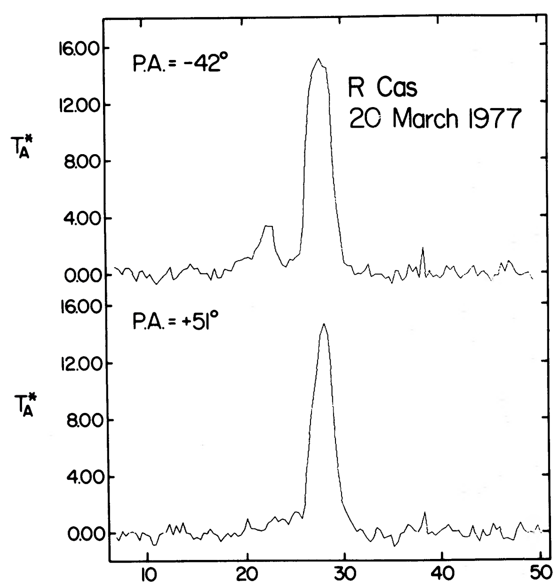

FIG. 5.—Two successive scans of R Cas taken in nearly orthogonal linear polarizations. The short time-variable feature at 22 km s^{-1} was close to 100% polarized on 1977 March 20.

effects of the type described above unless the fractional polarizations of the lines were much higher in the KBS data than in our own. Since this circumstance is unlikely, we conclude that most of the observed differences between the two sets of profiles are real, and these differences have no obvious relationship to the optical phases of the regular variables.

Tables 1 and 2 list optical phases[2] of the stars when observed by us and when observed by KBS. The integrated line fluxes, also listed in the tables, may be compared with the corresponding fluxes in Table 1 of KBS. A few specific cases illustrate the nature of the differences between the two sets of profiles. R Cas was observed near optical minimum by KBS and near maximum by us. The integrated flux in the KBS spectrum is 25 times smaller, and the intense 28 km s^{-1} feature appearing in our spectrum is absent. This comparison supports the supposition that line strengths increase near optical maximum. Yet in the case of R Leo, also observed near optical minimum by KBS and near maximum by us, the integrated fluxes at the two epochs are comparable, although the line peaks occur at different velocities. The integrated fluxes of

[2] All data on the optical fluxes of variable stars have been kindly provided by the American Association of Variable Star Observers.

χ Cyg and U Her, derived from our spectra near optical minimum, are comparable to or greater than those of KBS near maximum, and U Ori, sampled by both groups near optical minimum (optical fluxes the same to within 50%), radiated 3 times more integrated line flux at the time of the KBS observations. Clearly, it is impossible to discern any correlation between SiO line strengths and optical fluxes in this limited group of seven regular variable stars sampled over a three-year interval.

Finally, we consider time variations in two other sources. VY CMa, a supergiant irregular variable, has not varied in visual optical flux by more than 50% since the observations of KBS. The integrated SiO line flux, however, has increased twofold in the more recent data. For the OMC-1 source, three earlier 86.2 GHz spectra have appeared in the literature, those of Snyder and Buhl 1974 (1973 December, hereafter SB), Ulich and Haas 1976 (May 1974), and Johnson and Clark 1975 (October 1974). Ulich and Haas and Johnson and Clark have already discussed differences between their respective spectra and those of SB. Relative to the SB component 1 ($\sim$17 km s^{-1}), SB component 2 ($\sim$15 km s^{-1}) became about 40% weaker in the interval 1973 December to 1974 October. Comparing our present spectrum with that of Johnson and Clark, we also find differences; relative to SB component 1, SB component 7 (~ -8 km s^{-1}) has increased in strength by about 20%. At 43 GHz Snyder *et al.* (1978) find changes of comparable or greater magnitude over an interval of 1 year. Spencer and Schwartz (1975) report short-term ($\sim$1 hr) variations in this source at 43 GHz, yet Moran *et al.* (1977) were unable to detect similar changes over periods of 30 minutes to 4 days.

The stringent upper limits we have placed on linear polarization in the OMC-1 source strongly suggest that the 86.2 GHz time variations discussed above are not merely an effect of differences in received polarization. We note, however, that erroneous conclusions can easily be drawn about time variations in SiO sources if two data sets are compared and proper account is not made of receiver polarization. We suggest that authors who report on SiO observations be careful to include a description of the feed-horn polarization, the telescope mounting, and the observing procedures relevant to the received polarization for each source. Whenever possible, such observations should be made in orthogonal polarization modes so that the total intensities of the lines can be derived.

IV. DISCUSSION

a) Polarization

If the present results are representative of all 86.2 GHz stellar SiO masers, then these sources consistently show linear but not circular polarization. Few systematic data have appeared in the literature regarding polarization of stellar OH and H_2O masers. Nevertheless, the general pattern appears to be one of only occasional linear and circular polarization in OH (Wilson, Barrett, and Moran 1970; Wilson and Barrett 1972; Wilson *et al.* 1972) and little or no polarization in H_2O (Dickinson, Bechis, and Barrett 1973; Moran 1976; Moran, private communication). Of the three maser species associated with stars, SiO is perhaps the only one consistently characterized by polarization.

The OMC-1 maser is distinguished in the current observations by its lack of polarization at 86.2 GHz. This source may be intrinsically quite different from the stellar sources, for little is known about its physical environment, or about its relationship to OH and H_2O masers and infrared sources in OMC-1. Moran *et al.* (1977) suggest that the SiO masers may be associated with a discrete group of H_2O masers having velocities near -6 and $+16$ km s^{-1}. These particular H_2O masers are themselves unusual. Unlike other H_2O masers in OMC-1, they show little time variation and little if any polarization (Moran *et al.* 1977; Sullivan 1973). Other discussions of the physical nature of the OMC-1 SiO masers can be found in Habing *et al.* (1975), Genzel and Downes (1977), and Snyder *et al.* (1978). We will not consider this anomalous source in the discussion that follows.

The existence of linear polarization in the radiation from SiO masers places constraints on physical conditions within them. In order to investigate these constraints we have found it useful to consider the theory of maser polarization developed by Goldreich, Keeley, and Kwan (1973*a*, *b*). This theory is based on several simplifying assumptions (e.g., plane-wave propagation through a homogeneous medium), and it makes some predictions that are at variance with observation. Still, the formulation provides a useful if not definitive framework for interpreting our data.

According to this theory, maser radiation from non-paramagnetic molecules (e.g., SiO, H_2O) which are immersed in magnetic fields of less than several tens of gauss will emit no circular polarization. Linear polarization of up to 100% can be generated if the following conditions are satisfied:

1. The maser is saturated. That is, $R > \Gamma$, where R is the rate of stimulated emission and Γ is the "decay rate" of the maser, the rate at which population in the maser levels is transferred to other unspecified (non-maser) levels.
2. The Zeeman splitting, $g\Omega$ (where g is the Landé g-factor and $\Omega = eB/m_e c$), is greater than $(R\Gamma)^{1/2}$.
3. R is greater than the "cross-relaxation" rate γ. Cross-relaxation, described by Goldreich, Keeley, and Kwan (1973*b*), is a process in which population differences among the magnetic sublevels of the upper maser state are smoothed out by optically thick infrared line radiation coupling that state to yet higher levels. If cross-relaxation occurs at a rate faster than the stimulated emission rate, polarization of the maser is suppressed.

According to condition (1), the 86.2 GHz SiO transition must be saturated; we assume this to be the case. Cahn and Elitzur (1979) argue that the $v = 1$, $J = 1 \rightarrow 0$ maser (43 GHz) is also saturated. Condition (2) sets a lower limit on the magnetic field in the emitting region provided that R and Γ can be estimated.

Although neither rate is known, a possible lower limit on B may be derived given that an upper limit to Γ is set by the rate of spontaneous decay to the ground vibrational state (Kwan and Scoville 1974). Since $A \approx 5\ \mathrm{s}^{-1}$ for the $v = 1 \rightarrow 0$ transitions (Hedelund and Lambert 1972), we have $\Gamma \lesssim 5\ \mathrm{s}^{-1}$, and if Γ is set equal to its upper limit with $R > \Gamma$ (saturated maser), the result is $R > 5\ \mathrm{s}^{-1}$; hence $(R\Gamma)^{1/2} \gtrsim 5\ \mathrm{s}^{-1}$ and $B \gtrsim 400$ microgauss.

To explore constraints placed upon the maser by condition (3), we have estimated cross-relaxation rates for the $v = 1, J = 2$ level (the upper maser level). The rate of cross-relaxation can be estimated from the equation

$$\gamma = C\frac{A}{30(e^{h\nu/kT} - 1)}\ .$$

In this equation, equivalent except for the factor C to equation (16) of Goldreich, Keeley, and Kwan (1973*b*), A is the spontaneous transition rate from the upper nonmaser level to the upper level of the maser, and ν is the frequency of this transition. The factor C represents the total number of couplings that exist between all of the magnetic sublevels in the maser level and magnetic sublevels in the nonmaser level. For example, if a transition responsible for cross-relaxation connects the maser level to a higher rotational level, there are $2J + 1$ sublevels in the maser level, each of which is coupled to three sublevels in the upper rotational level, and $C = 3(2J + 1)$. In practice, several transitions may be involved in the cross-relaxation process, and the total cross-relaxation rate is then the sum of several terms, each of which is calculated from the equation above.

Considering all possible upper levels to which the upper maser level is coupled, we find that the fastest possible cross-relaxation occurs from the $v = 2$ ($J = 3$ and $J = 1$) levels for which the combined $\gamma \approx 2\ \mathrm{s}^{-1}$. Cross-relaxation rates for other levels are all less than or equal to $10^{-2}\ \mathrm{s}^{-1}$. This result, together with condition (3), implies that $R > 2\ \mathrm{s}^{-1}$. R is approximately limited to Γ since R increases linearly rather than exponentially with distance once $R \sim \Gamma$ and the maser saturates. If we take $R \sim \Gamma$, then condition (2) becomes $g\Omega > R$, and with $R > 2\ \mathrm{s}^{-1}$ we have $B > 150$ microgauss. This second field limit is independent of the more stringent limit derived above. However, the pump model of Kwan and Scoville (1974) requires that the 8μ $v = 2 \rightarrow 1$ transitions be optically thin. If this model is correct, the cross-relaxation rate calculated above is much too large and the 150 microgauss limit does not apply.

If the theory of Goldreich, Keeley, and Kwan is adequate to explain the observed polarization in SiO, the theory should also explain the apparent absence of polarization in H_2O. Like SiO, the water molecule is nonparamagnetic and the absence of linear polarization in most of the H_2O masers should indicate a failure to meet one or more of the three conditions outlined above. Unfortunately, our knowledge of the parameters of the maser emitting regions, specifically R, Γ, and γ, is too slight to permit a definitive application of the theory. Condition (1) is probably met since the general correlation between H_2O maser output and periodic IR flux changes (Schwartz, Harvey, and Barrett 1974) implies that these sources are at least partially saturated. Presumably, the absence of polarization in the H_2O masers is a consequence of failure to meet conditions (2) and/or (3).

If the lack of polarization is a result of cross-relaxation among the magnetic sublevels in the upper maser state (i.e., failure to meet condition 3), then we must have $R/\gamma < 1$. We estimate that $\Gamma \lesssim 1\ \mathrm{s}^{-1}$, using the same reasoning applied by Kwan and Scoville (1974) in estimating this parameter for SiO. (That is, we assume that the most important contribution to Γ is spontaneous decays to lower rotational states for which $A \sim 1\ \mathrm{s}^{-1}$; de Jong 1973.) In practice, Γ could be much less than A since photon trapping in the optically thick rotational lines will reduce the effective rate of spontaneous emission out of the maser levels; the rotational lines are indeed very likely to be optically thick owing to their high transition probabilities relative to that of the maser transition. As for the stimulated emission rate R, its value is roughly limited to Γ since once the maser becomes saturated, R increases only linearly with increased gain length rather than exponentially. Goldreich, Keeley, and Kwan (1973*b*) estimate that $\gamma \sim 2\ \mathrm{s}^{-1}$ for H_2O masers operating at a few hundred degrees K. Therefore, very crudely, we have $R \sim \Gamma \lesssim 1\ \mathrm{s}^{-1}$, hence $R/\gamma \lesssim \frac{1}{2}$. The ratio could be very much smaller than $\frac{1}{2}$ given the photon trapping effects discussed above. In short, a violation of condition (3) is consistent with our limited knowledge of the parameters of the H_2O masers; cross-relaxation may be responsible for the absence of polarization in these sources.

Alternatively, the unpolarized nature of the H_2O maser emission may be the result of failure to meet condition (2); that is, the magnetic fields in the emitting regions may be too small to affect the polarization of the radiation. Since no firm upper limit can be set on R, we can set no firm upper limit on the magnetic fields in the emitting regions. However, following the reasoning above, we take upper limits for R and Γ of $1\ \mathrm{s}^{-1}$. Condition (2) then requires that $B \lesssim 70$ microgauss. This limit is somewhat smaller than that derived for the SiO masers. A smaller field would be expected in the H_2O maser regions if they are situated further from the exciting star, as discussed in the next section.

An upper limit on the magnetic field in regions surrounding these sources can also be inferred from the small amount of observed circular polarization in the OH maser emission. Although at least one star, W Hya, is highly circularly polarized at 1665 and 1667 MHz, most other stellar OH sources are less than 25% circularly polarized at all observed ground-state frequencies. (See references at beginning of § IV*a*.) If the percent circular polarization is less than P, we have

$$B \lesssim \frac{1.4\Delta f \times P/100}{G}\ ,$$

where $G = 3.3$, 2.0, and 1.3 Hz per microgauss at

1665, 1667, and 1612 MHz, respectively. The FWHM is Δf Hz. For $P < 25\%$ and $\Delta f = 8$ kHz, the upper limit on the magnetic field in the OH emitting regions is between 1 and 2 milligauss.

b) Long-Term Variability

The 1612 MHz OH flux and the H_2O flux from some Mira and periodic infrared stars is known to vary periodically. The maxima and minima of the OH and H_2O fluxes are roughly repeatable from period to period, and they appear to coincide with the maxima and minima of the infrared variations which, in turn, lag behind the optical variations by typically 0.1–0.2 periods (Harvey *et al.* 1974; Fillit, Proust, and Lepine 1977; Schwartz, Harvey, and Barrett 1974).

As discussed in § III*e*, the pattern of SiO variability at 43 and 86 GHz appears to be more complicated, although available statistics are meager. In particular, the line profiles show no obvious pattern of repeatability from one optical period to another. There may even be a tendency for individual velocity components to come and go from one period to the next (e.g., the 7 km s^{-1} feature in the KBS spectrum of R Leo has been replaced by a -0.5 km s^{-1} feature in our spectrum; the dominant 28 km s^{-1} feature in our spectrum of R Cas is nonexistent in the KBS data).

If the SiO variations are indeed more erratic than their OH and H_2O counterparts, this behavior may reflect a comparative proximity of the SiO masers to the stars. Alternatively, the SiO masers may be unsaturated and the OH and H_2O masers saturated. In this case, the outputs of the SiO masers would be a much more sensitive function of the path lengths of amplification (exponential rather than linear), and their erratic variability might be much more pronounced. Nonetheless, we have argued on theoretical grounds that the SiO masers are at least partially saturated, and the more attractive explanation for their variability is relative proximity to the stars.

No observational information exists to directly establish the locations of the SiO masers about their exciting stars, and we know very little about the relative locations of the different masing species. However, the models of Kwan and Scoville (1974) locate the SiO emission in a shell of radius roughly 2–5 R_*. *VLBI* measurements of the 1612 MHz masers suggest sizes on the order of 3×10^{15} cm (Reid *et al.* 1977) or about 50 R_*, and the close correspondence in the velocities of OH and H_2O emission in many sources (Kleinman and Dickinson 1977) implies that these H_2O masers are similarly removed from the star. Lepine *et al.* (1976) and Lepine and Paes de Barros (1977) discuss a model in which the order of masing species with increasing distance from the star is SiO, H_2O, and OH. In any case, we suspect that erratic behavior of SiO masers reflects erratic variations in physical conditions close to the star, conditions which affect the maser pumping, geometry, or both. These variations in physical conditions could be related to changes in the amounts or velocities of material ejected by the star from one period to another, or to fragmentation of an expanding shell. Such effects may be more effective in controlling the nature of maser emission close to the star (i.e., SiO) than they are in controlling the masers further removed from the star (i.e., OH and H_2O).

c) Short-Term Variability

In § III*d* we described the short-term (a few hours to a day) variations in the 22 km s^{-1} feature of R Cas. Since the stronger 28 km s^{-1} feature in the spectrum of this source displayed no such variability, it is unlikely that the short-term variations at 22 km s^{-1} can be related to variations in the radiative pump power from the star. Another possible explanation involves mass motions in the emitting regions which might affect the maser gain length or the angle of beamed radiation (lighthouse effect). The circumstellar expansion velocity derived for this source from the "thermal" SiO emission is 9 km s^{-1} (Reid and Dickinson 1976). From this velocity and from the time scale of variation, we derive a size scale for the variable mass element of (10 km s^{-1}) $\times$ (12 hours) $\sim 4 \times 10^{10}$ cm. This length is $\sim 10^{-4}$ times the gain length in the model of Kwan and Scoville (1974); therefore, in the context of this model, mass motions of the order of the circumstellar expansion velocity are unlikely to measurably affect the masers. Other sources of variability must therefore be responsible. Two straightforward possibilities are variations in excitation rate to the $v = 2$ level, and variations in SiO abundance caused by variations in the rate of SiO production or destruction. Both would have their origin in density variations in the region in which the SiO is located. Such variations could be caused by localized density increases resulting from shock fronts generated by turbulence within the stellar atmosphere or in the circumstellar shell. Such localized perturbations could affect one maser emitting region and not another.

V. SUMMARY AND CONCLUSIONS

The major conclusions drawn from the current experiment can be summarized as follows:

1. The $v = 1, J = 2 \rightarrow 1$ SiO maser transition from a small sample of long-period variable stars shows a consistent pattern of 15–30% linear polarization with polarization properties changing considerably across the line profiles. No circular polarization is apparent in the radiation from these sources.
2. A single set of a limited number of gaussians cannot simultaneously fit the *I*, *Q*, and *U* profiles for the strongest few sources.
3. The narrow, circularly polarized features reported in the OMC-1 spectrum by Johnson and Clark (1975) were not observed in this more-recent series of observations. Instead, OMC-1 was found to have no linear or circular polarization greater than 3%.
4. The Stokes parameters for R Cas, not necessarily including the total intensity, were found to vary over a period of 1 day.
5. Comparisons of SiO line profiles obtained for the same stars over intervals of one or more optical

periods show no pattern of variation that is related to the optical cycles of these stars.

6. The existence of linear polarization and the absence of circular polarization in the SiO stellar sources is in agreement with the polarization theory of saturated masers developed by Goldreich, Keeley, and Kwan (1973*a*, *b*). Subject to various assumptions, this theory, together with the current observations, implies a lower limit to the magnetic field in the emission regions of a few hundred microgauss.

Systematic observations of SiO maser lines, especially over several optical periods of the stars, will be needed to understand the nature of variations and polarization in these sources. The theoretical framework necessary to interpret observations is also not yet adequate, and it will require further development.

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