OBSERVATIONAL CHARACTERISTICS OF MASERS ASSOCIATED WITH STARS

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OH, H_2O and SiO are the 3 known molecular masers associated with stars. The known transitions, their line profiles, radial velocities, temporal intensity variations and polarization properties are discussed. Current work on determination of circumstellar shell sizes is reviewed. Possible future research topics are outlined.

I. INTRODUCTION

Only 11 years ago, Wilson and Barrett (1968) discovered the first maser emission associated with late-type stars. Their OH observations led the way to other molecular searches of stars and today both early-type emission line stars and late-type stars have been observed. Davis, Seaquist, and Purton (1979) have listed the few early-type objects which have been observed in OH maser emission. Because much more is known about maser emission from circumstellar shells associated with late-type stars, our discussion will be concentrated here. The observations prior to and through 1976 have been summarized by Olnon (1977), Snyder (1977), and Winnberg (1976); hence the more recent developments will be emphasized here. Hydroxyl (OH), water (H_2O) and silicon monoxide (SiO) are the three molecular species found in strong maser emission from circumstellar shells associated with late-type stars. The best values for the maser rest frequencies (Lovas, Snyder and Johnson 1979) are: $OH^2\Pi_{3/2}$ J=3/2, F=1-2, 1612.2310 MHz; F=1-1, 1665.4018 MHz; F=2-2, 1667.3590 MHz: H_2O $J_{K-K+} = 6_{16}-5_{23}$, F=5-4, 22,235.120 MHz (central hyperfine component): SiO v=1, J=3-2, 129,363.262 MHz; J=2-1, 86,243.350 MHz; J=1-0, 43,122.027 MHz; v=2, J=1-0, 42,820.539 MHz; v=3, J=1-0, 42,519.34 MHz. The SiO v=3, J=1-0 transition is the most recently detected (Scalise and Lepine 1978) and hence was not included in previous circumstellar maser reviews. A catalog of more than 300 stellar objects showing maser line radio emission from OH, H_2O and/or SiO has been compiled by Engels (1979). About 200 of these objects have been identified with optical or infrared stars (mostly M-supergiants, Mira or semiregular variables), and they may be described by Turner's (1970) OH classification scheme as extended by Wilson (1973).

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Type II OH maser stars have stronger 1612 MHz emission than main line emission; 1720 MHz OH emission is never observed. These stars tend to have excess infrared radiation at 10 μm, and there may be no detectable H_2O maser emission. There usually are two OH emission groups separated by 20 km s^{-1} or more. Type I stars have stronger main lines than 1612 MHz emission; again, 1720 MHz emission is not observed. There is less excess radiation at 10 μm and, usually, detectable H_2O maser emission. The two OH emission groups are typically separated by about 10 km s^{-1}. A third group includes the supergiant OH masers such as VY CMa, VX Sgr and NML Cyg. Representative spectra from Type II masers stars are shown in Figure 1.

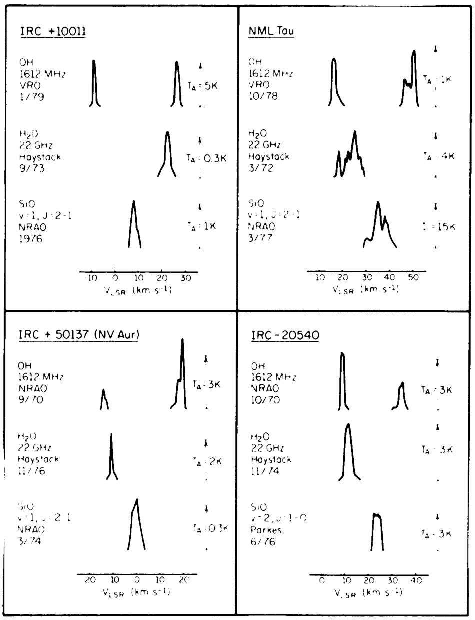

Figure 1. Representative OH, H_2O and SiO maser emission spectra from Type II maser stars. Ordinates: antenna temperature T_A. Abscissae: radial velocity with respect to the LSR.

2. CURRENT OBSERVATIONAL PROGRAMS

2.1 Line profile and radial velocity studies

The work of Reid (1976), Reid and Dickinson (1976) and Dickinson et al. (1978) has shown that the two OH emission groups are displaced symmetrically about the stellar radial velocity. This evidence supports an expanding shell model for late-type maser stars and has helped define the goals of many current observational programs. Earlier, Dickinson, Kollberg, and Yngvesson (1975) had confirmed the correlation

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between the velocity separation of the characteristic double-peaked OH spectrum and stellar period. This correlation can be used to establish the approximate periods and types for OH stars. The situation for H_2O and SiO maser line profile studies is not as well defined. Knowles and Batchelor (1976) have identified symmetrical H_2O radial velocity structure in VY CMa and Orion as well as in several H II region H_2O maser sources. Both these profiles and symmetrical SiO maser profiles in VY CMa and possibly NML Cyg (Buhl et al. 1974; Snyder and Buhl 1975) have been studied by Van Blerkom and Auer (1976) and Van Blerkom (1978) as possible examples of rotating disk geometries where the disk fragments into a system of concentric rings. These studies suggest that perhaps the existence of emerging planetary systems could be inferred from the maser line profiles they produce, with the precaution that a symmetrical maser spectrum does not uniquely define the ring geometry. In other studies, Snyder et al. (1978) have found broad, weak SiO maser emission pedestals underlying the principal SiO maser peaks in the v=1, J=1-0 transition. This emission pedestal appears to be an intrinsic part of the spectral signature of SiO maser emission from late-type stars: the width of the pedestal is usually somewhat less than the expansion velocity and often its center velocity may be used to determine stellar radial velocities. Dinger, Dickinson and Snyder (1978) have also observed the SiO pedestal in the v=1, J=2-1 transition where it appears to be an assembly of several individual features. Schwartz, Waak and Bologna (1979) have detected broad emission pedestals in both v=1 and v=2, J=1-0 SiO maser transitions but none has been found in the v=3 J=1-0 transitions detected to date. Elitzur (1979) interprets the weak SiO maser emission pedestal as emission from the circumstellar shell, while the more easily observed, strong, sharp main emission spikes would come from convective cells located much closer, possibly in the upper atmosphere of the star itself. Fortunately, extensive radial velocity measurements of high dispersion optical spectra now exist for many of the important maser emission stars (e.g., Wallerstein 1975, 1977; Hagen 1978). These optical data are being utilized in conjunction with the radio maser velocity data to build consistent physical pictures of the excitation processes in the atmospheres of these stars.

2.2 Intensity variations and intensity correlation studies

The optical, infrared and OH maser emission from late-type stars usually varies in intensity in a regular or semi-regular manner. Harvey et al. (1974) found that the intensity of the 1612 MHz satellite line of OH followed the infrared luminosity changes closely and agreed qualitatively with available optical data. A correlation has been established between the intensity variations of the OH main lines at 1665 and 1667 MHz and the optical emission (Fillit, Proust and Lepine 1977; Jewell et al. 1979). These studies support the theory that the OH level populations are inverted by a radiative pump which is intimately related to the optical output of the central exciting star. The temporal intensity variations of H_2O and SiO have not behaved as nicely. Schwartz, Harvey and Barrett (1974) studied the time variability of both H_2O and 2.2 μm emission from 8 late M stars. For the 3 strongest

H_2O emitters (R Aql, U Her and W Hya) they found a correlation between optical and infrared variations and no phase difference greater than about 30 days between H_2O and infrared variations. Cox and Parker (1979) included these 3 stars in their study of H_2O emission from 9 stars during the period 1974 September-1977 May. In several the H_2O intensities were very different from those found by earlier observers and they concluded that stellar H_2O masers are often not stable for more than a few cycles of the stellar luminosity. The SiO maser time variation studies reported to date with regular sample monitoring over part or all of a cycle include only o Cet, R Cas and R Leo. Spencer and Schwartz (1975) found phase dependent SiO time variations in o Cet and R Cas, similar to OH and H_2O variations, which suggest a partially saturated maser. Hjalmarson and Olofsson (1979) found good correlation between SiO and the 2.7 μm infrared intensity as well as a distinct phase lag with respect to the visual light curve for R Leo and o Cet. On the other hand, Troland et al. (1979) observed 7 regular variable stars 3 years after Kaifu, Buhl and Snyder (1975) and found substantial changes in the line profiles and integrated fluxes. Most of the changes were thought to be real (and not due to the linear polarization effects discussed in 2.4), but they could not be related to the optical phases of the stars. Hence time variation studies of the SiO maser often are complicated by polarization and perhaps by the pedestal-spike line shape discussed in 2.1. Time variations have also been observed in the Orion SiO maser by Snyder et al. (1978), Schwartz, Waak and Bologna (1979), and Troland et al. (1979).

Maser luminosities have been used successfully in several statistical correlation studies. Nguyen-Q-Rieu et al. (1979) point out that about 75% of the OH Mira masers detected within ∿ 1 kpc of the sun are Type I sources. They found that OH intrinsic luminosity varies from star to star and that Type II OH Mira masers generally are more distant and have higher OH luminosities than Type I OH Mira masers. This generally supports the results of systematic surveys which suggest that many optically unidentified Type II OH/IR maser sources are situated at large distances in the central part of the galaxy (e.g. Johansson et al. 1977; Bowers 1978; Baud et al. 1979). Cahn and Wyatt (1978) have developed a period-luminosity-spectral type scheme which had led to a successful correlation between SiO maser luminosities and stellar luminosities in long-period variables (Cahn 1977; Cahn and Elitzur 1979). This correlation suggests that SiO masers are radiatively pumped by direct stellar radiation, saturated, and occur at roughly the same distance from the star.

2.3 Determination of circumstellar shell sizes

OH VLBI observations of late-type stars, both M supergiants and long-period variables, have been made by Masheder, Booth and Davies (1974), Moran et al. (1977), Reid et al. (1977), Reid and Muhleman (1978), Reid et al. (1979), and Mutel et al. (1979). Typical OH maser shell radii for supergiants are $\sim 10^{17}$ cm for 1612 MHz emission and apparently somewhat less for the main-line emission. Typical Mira variable stars have 1612 MHz radii of $\gtrsim 3 \times 10^{15}$ cm. H_2O VLBI observations have been made by Rosen et al. (1978) and by Spencer et al. (1979). Typical late-type stars and the supergiant VY CMa have an H_2O masing region with radius $\sim 10^{15}$ cm. Figure 2 (from Moran et al. 1979b) shows the distribution of 1612 MHz OH and H_2O masers near VX Sgr.

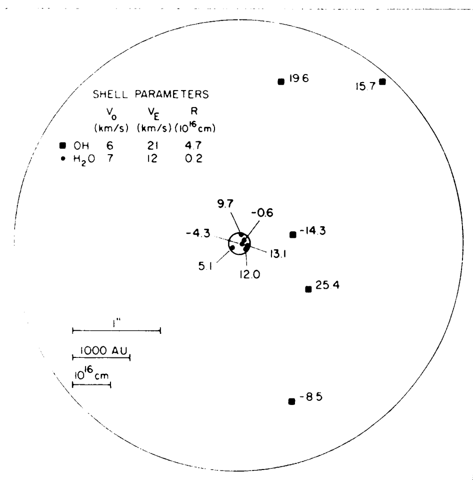

Figure 2. The distribution of 1612 MHz OH and H_2O masers near VX Sgr (from Moran et al. 1979b).

Recently Moran et al. (1979a) performed the first successful VLBI measurements of SiO stars. They found the radius of the SiO masering region to be $\sim 10^{14}$ cm for the Mira variable R Cas and $\sim 10^{15}$ for VY CMa. The VLBI technique measures the angular diameter of the maser emission region. Recently another technique has been used to attempt to measure the OH radial diameter. If the OH at all points in the shell emits and varies in phase relative to the star, then emission from different parts of the shell will be out of phase relative to Earth because of the difference in distance the emission travels. Thus the blueshifted line, from the front of the star, should lead the redshifted line, from the back of the star, by a phase corresponding to the light travel time across the shell. Through careful monitoring, it should be possible to determine shell diameters. Shultz, Sherwood, and Winnberg (1978) investigated a number of maser sources but, owing to their small number of data, only an indication of shell sizes could be determined. Jewell et al. (1979) have monitored 8 OH maser stars over a time base of several years, and their data suggest OH shell dimensions on the order of a few $\times 10^{16}$ cm. However, both sets of observations demonstrate that it is imperative to obtain a high density of data points, perhaps 20 or more over a cycle, if reliable measurements with small standard errors are to be forthcoming.

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2.4 Polarization studies

Maser polarization measurements are necessary for correctly calibrated line intensities and for placing constraints on proposed pumping models. To date, there have been no sensitive, large scale surveys of the polarization of stellar masers associated with late-type stars. On the basis of somewhat limited observational sampling, it has been found that some OH stellar masers have linear and/or circular polarization; stellar H_2O maser emission shows little or no polarization and SiO masers have linear but no observable circular polarization. Reid et al. (1979) have measured the 1612 MHz OH polarization of U Ori and IRC+10420. Their results suggest that the magnetic fields of the central exciting stars in stellar OH masers are of the order of 10-100 gauss. Troland et al. (1979) have determined the Stokes parameters for 8 SiO masers using the v=1, J=2-1 transition. No circular polarization was found and the typical linear polarization was 15 to 30% except that R Cas has one feature with $\sim$ 100% linear polarization and Stokes parameters which changed over $\sim$ 1 day. At this meeting, Clark et al. (1979) have reported linearly polarized SiO v=1, J=2-1 emission spread over 12 km s^{-1} from R Leo. The position angle of linear polarization changes uniformly over the underlying emission pedestal but undergoes an abrupt change at the strong principal emission peak; hence this promises to be an important technique for separating the spectrum of the SiO pedestal from that of the stronger main emission spike.

3. FUTURE RESEARCH

Several interesting directions are suggested for future research. New molecular masers are hard to find. Morris (1979) interprets the CO emission from CIT-6 as a possible weak maser. Buxton et al. (1977) searched 132 sources without finding methanol maser emission. Orion A remains the only known methanol maser but it may not be intrinsically unique because the other sources may be too far or too weak to be detected. The Orion region has other interesting properties. Of all the known SiO maser sources, only the Orion A maser is associated with a molecular cloud region. None of the other OH/H_2O maser IR sources associated with molecular clouds have been found to be SiO maser sources. Bieging et al. (1979) have interferometrically determined that the Orion SiO maser is coincident with the infrared point source IRC2, in agreement with the suggestion of Genzel et al. (1979). It remains to be determined whether IRC2 really is a unique object or just another late-type star. Other interesting objects have been revealed by OH time monitoring. One such object, U Ori, has been found to behave like a damped oscillator in its 1612 MHz OH emission (Jewell et al. 1979). Undoubtedly other important results will be found from the SiO maser monitoring programs now underway at places such as the Naval Research Laboratory, the Five College Radio Astronomy Observatory and the Onsala Space Observatory. The results from programs like these might be used to search for multiple systems associated with late M giants, as suggested by Zuckerman (1979). Finally, we need to know more observational detail about mass loss in maser stars. For example, it has been suggested (e.g., Bowers and Kerr, 1977) that OH maser stars have high mass loss rates while non-OH maser stars have low mass loss rates. It is clear from discussions presented at this meeting that this is a rich area for further investigation. This work was supported in part by NSF Grant AST 79-07830.

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DISCUSSION FOLLOWING SNYDER

Zuckerman: The SiO masers could be used to study the frequency of binary systems containing late M giants if accurate maser positions could be obtained with conventional or VLB interferometers.

Slysh: Mira is a binary star. What influence might the white dwarf companion Mira B have on the maser emission?

Snyder: We have found some unusual temporal behavior in the intensities and velocities of the SiO maser emission from Mira (o Cet). The period of Mira B appears to be too long to explain these changes. However we are still examining the possibility.

Winnewisser: You mentioned that it would be important to have predictions for new masers. Are you prepared to make a more qualitative statement about what you think is the most important area for predictions?

Snyder: Yes.

Booth: Careful comparison of the spectra of SiO, H_2O and OH in Orion show several features which overlap in velocity and which fall into distinct velocity ranges. Furthermore, our interferometric measurements at Jodrell Bank show that Orion is the only HII region where OH and H_2O emissions are coincident. Do you think we are seeing a late-type star in the Orion complex?

Snyder: To my knowledge, all of the other known SiO masers can be associated with some sort of late-type star. Also, none of the other large molecular clouds associated with HII regions have shown SiO maser emission. These points suggest that if the SiO maser in Orion is not associated with a late-type star, then it is a unique object.

Gold: Let us be quite clear and specific, in this session, whether we are discussing the physical size of a masering region, or what we measure with radio telescopes and interferometers here on Earth, the curvature of a phase-front and its irregularities. The two quantities may be totally different, or have little relation to each other for sources of coherent radiation. The angular size of a maser region as observed by interferometer refers in reality only to the irregularities within the region, which cause a slight scatter in direction of the amplified wavefronts. It has no direct relation to the physical size.

Snyder: I assumed that the listeners are familiar with these points about coherence. Those who are not may wish to read Professor Gold's discussion on p. 747 of Interstellar Ionized Hydrogen, ed. Y. Terzian (W.A. Benjamin, Inc., New York 1968).