SERKOWSKI: Can the observed wavelength dependence of polarization be explained by the electron scattering and hydrogen absorption?

HARDORP: I don't know. However, dust must be in the shells because of the large IR-excess, and if dust particles are the explanation for the polarization as well, the particle size must be of the order of 4000 Å.

GEYER: Is the membership of these stars safe? Are there radial velocity measurements or proper motion determinations?

HARDORP: Yes, there are. According to the radial velocity and proper motion studies the stars discussed are members or probable members.

BEHR: What is known about the foreground (interstellar) polarization in the region of the cluster and what is the amount of interstellar reddening?

HARDORP: There are not many foreground stars; the reddening of the stars in the cluster is some hundredths of a magnitude.

Microwave Emission from Stars

PH. R. SCHWARTZ (Washington D.C.)

I. Introduction

During the past several years, the radio astronomical detection of a large number of complex organic and inorganic molecules has led to an entirely new concept of the chemical composition, kinematics and excitation of the interstellar medium. The microwave molecular transitions detected thus far fall into two natural categories: 1. „normal" (i. e. nearly LTE) emission and absorption lines, and 2. anomalous or „masered" emission lines. The first category includes molecules found in both high and low excitation regions whose intensity, linewidth and other characteristics may be described in terms of a physically realistic excitation temperature. Nearly all of the known microwave lines fall into this category. Typically, molecular lines of this type are found in HII regions, dark nebulae and, occasionally, extended circumstellar shells. Only two molecules populate the second category: OH and H_2O. Emission from OH lambda doublet transitions in several rotational states and from the 6_{16}—5_{23} rotational transition of H_2O exhibits many strange characteristics: tremendous intensity, narrow linewidth, non LTE distribution of hyperfine intensities, linear and circular polarization, and rapid variability. OH and H_2O emission originates from extremely localized regions, often as small as a few A.U. in diameter, in or near some HII regions and some cool, late type stars. The behavior of OH and H_2O emission lines is best explained by assuming that the microwave radiation is amplified by some narrow band non-linear process in the sources.

OH and H_2O lines, alone, exhibit masered emission with characteristics that are remarkably similar and usually originate from the same localized regions. That two chemically related molecules should behave in this way is, itself, puzzling; but, when the fact that many of the sources of masered emission are late type stars is also considered, the problem takes on even more interest and challenge. In the following sections, I will attempt to summarize the observations of masered emission from stars and, hopefully, outline some basic conclusions that can be drawn from the data. It should be obvious that this problem represents the proverbial „two edged sword". The association of masered microwave emission with well studied objects like stars allows us to use the information gathered by conventional optical observations to attack the general masering problem and, conversely, the radio observations may be used to obtain information about a star not readily accessable optically such as the mass loss rate or the physical conditions in a circumstellar shell.

II. OH Emission from Stars

The first observations of OH emission from stars were made by W. J. WILSON and A. H. BARRETT of MIT in 1968. WILSON and BARRETT observed several of the reddest objects in the CIT Two Micron Sky Survey at the 1612 MHz $^2\Pi_{3/2}$ J = 3/2 1—2 transition in an attempt to test the hypothesis put forward by M. M. LITVAK of MIT Lincoln Laboratory that far infrared radiation could selectively pump this transition (1). The first observations met with spectacular success; several sources were detected and an enormously powerful emission source in NML Cygnus, a highly reddened M supergiant, was detected and studied (2). In a subsequent survey nearly 500 „infrared stars" were observed for OH emission at the 1612 MHz line and 29 new sources were detected. The infrared star/OH sources were found to form a very definite class of objects with consistent radio and infrared properties. WILSON and BARRETT characterize these objects as follows:

1. The 1612 MHz transition is always the strongest of the four OH ground state transitions. The 1720 MHz ($^2\Pi_{3/2}$ J = 3/2 2—1) as always absent.
2. The OH emission is concentrated into two distinct velocity ranges and the two features tend to have similar shapes. The velocity separation of the two features is 10—30 km/s and, in the cases where the stellar absorption line velocity has been measured, it seems to agree with the higher OH velocity.
3. Weak main line emission sometimes accompanies the 1612 MHz emission. There appears to be a preference for the 1667 MHz ($^2\Pi_{3/2}$ J = 3/2 2—2) over the 1665 MHz (1—1) line.
4. The OH emission is essentially unpolarized.
5. There is no detectable radio continuum.
6. In almost all cases the OH emission is coincident with a star of large I-K color index. The average infrared star/OH source has I-K = 6.4 while the average star in the whole survey has I-K = 4.9. Over 20% of all stars with color index greater than 6.0 are OH sources.
7. The infrared star/OH sources tend to have strong infrared excesses at 5 and 10 microns possibly indicating the presence of circumstellar shells (3).

In Figure 1 the radio spectrum of a typical infrared star/OH source is shown illustrating some of the characteristics listed above. Of particular interest is the symmetry of the OH emission and the rather sharp edges of the features at the highest and lowest velocities.

It is important to stress that most of the sources detected in the WILSON and BARRETT OH survey are associated with late M stars either of very late spectral types or highly reddened by circumstellar material. In only a few cases is there any indication that anything other than a late type star is involved. Positive proof of the identification of the OH source with the star has been given by recent interferometric observations of the OH positions made by WILSON and HARDEBACK (4). In the sources studied thus far, the OH source and star are coincident to within about 5 arc sec, the limit of the precision of the interferometer used.

Since most of the stars associated with OH sources are known or suspected long period variables, their OH emission has been monitored for possible time variation. Unfortunately, OH sources are not usually time variable but, preliminary studies by J. A. BALL and K. BECHIS of Harvard University indicate that the 1612 MHz emission from many infrared stars is variable and in some cases the variation tends to be periodic and related to the associated star's infrared variation (5).

III. OH and H_2O Emission from Stars

Masered emission from the 6_{16}—5_{23} rotational transition of H_2O at 22 235 MHz shares many characteristics with OH emission and is often found in the same objects. Initially it was thought that since late type stars are often 1612 MHz OH sources and since H_2O is known to be an abundant constituent of the atmospheres of these stars, H_2O emission might be detected in infrared star/OH sources. In late 1969, P. R. SCHWARTZ and A. H. BARRETT began a survey of infrared stars for H_2O emission similar to the WILSON and BARRETT OH survey. Of over 300 stars surveyed, only 8 were found to be H_2O sources and, interestingly enough, most of the H_2O sources were not associated with 1612 MHz emission (6). In fact, H_2O emission seemed to be found in stars which exhibit strong main line (1665 or 1667 MHz) emission rather than 1612 MHz emission. Reobservation of a number of stars at the OH main lines rather than the satellite line by WILSON has led to the conclusion that

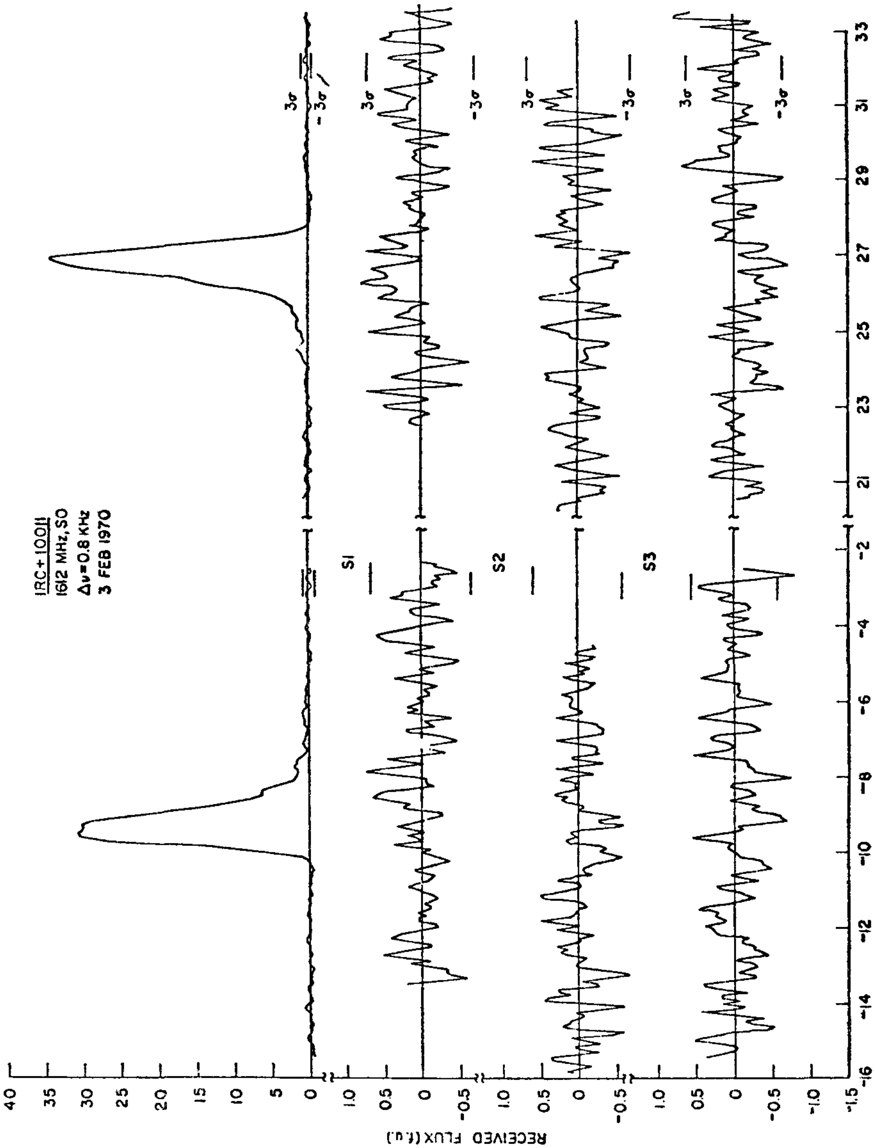

Fig. 1: 1612 MHz OH Emission from IRC +10011.

https://doi.org/10.1017/S0252921100032656 Published online by Cambridge University Press

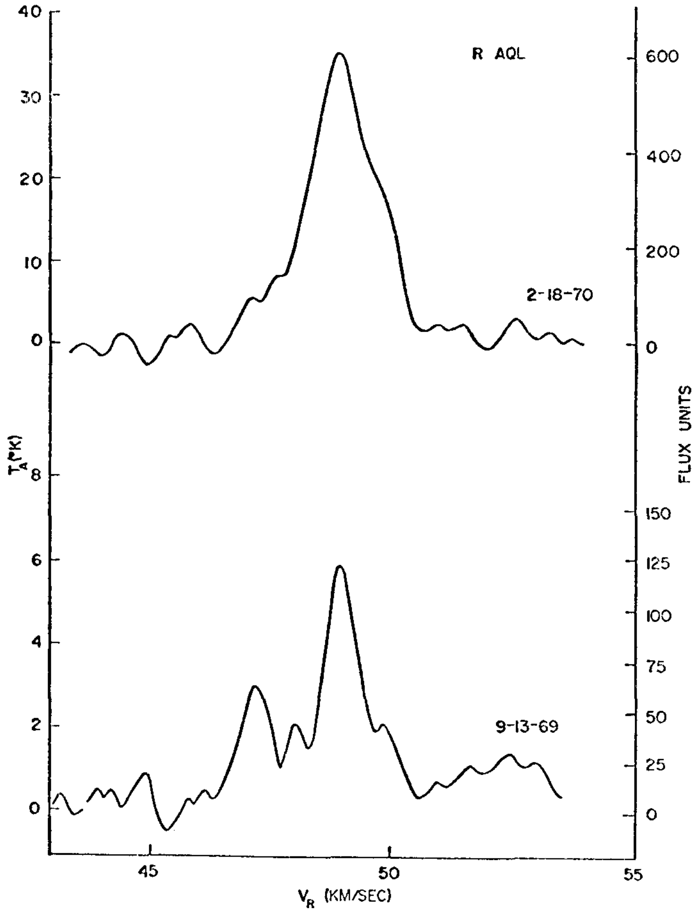

Fig. 2: Variable H_2O Emission from R Aql.

stars with H_2O emission are also OH sources but of a new type. Although the sample is small, infrared star/H_2O and OH sources seem to have rather definite characteristics that are quite different from those of infrared star/OH sources. These characteristics may be summarized as follows:

1. H_2O emission seems to imply OH emission but the main lines (1665 or 1667 MHz) are usually stronger and in some cases the 1612 MHz lines are absent. The H_2O emission is 10 to 100 times more intense than the OH emission.
2. The OH emission usually has two features and the higher OH velocity seems to agree with the stellar absorption line velocity but the separation of the two OH velocities is only 5—10 km/s. The H_2O emission velocity lies between the two OH velocities.
3. 1720 MHz OH emission is always absent.
4. There is no detectable radio continuum.

5. The stars associated with the microwave emission are almost always bright late M type variables with typical I-K values of 5.4 or less.

6. No large 5 or 10 micron infrared excess is observed (7).

The most interesting characteristic of these objects is the dramatic time variation of the H_2O emission. Most H_2O sources are variable on time scales of from a few days to years and in general the variations tend to be random although there is a tendency for the brighter features to change the most rapidly. In Figure 2 two spectra of the H_2O emission associated with the star R Aql are shown. The variation, however, is anything but random since the two spectra were taken at maximum and minimum light and indicate that the microwave emission seems to be more intense at maximum light. Periodic observations of the H_2O emission from a number of stars over the last two years indicate that in the most cases the microwave emission line varies in phase with the star's light cycle. In Figure 3 the observations of three stars that behave in this way are shown; the peak flux of the brightest H_2O feature is plotted against optical phase. It is clear that the intensity of the masered microwave radiation is

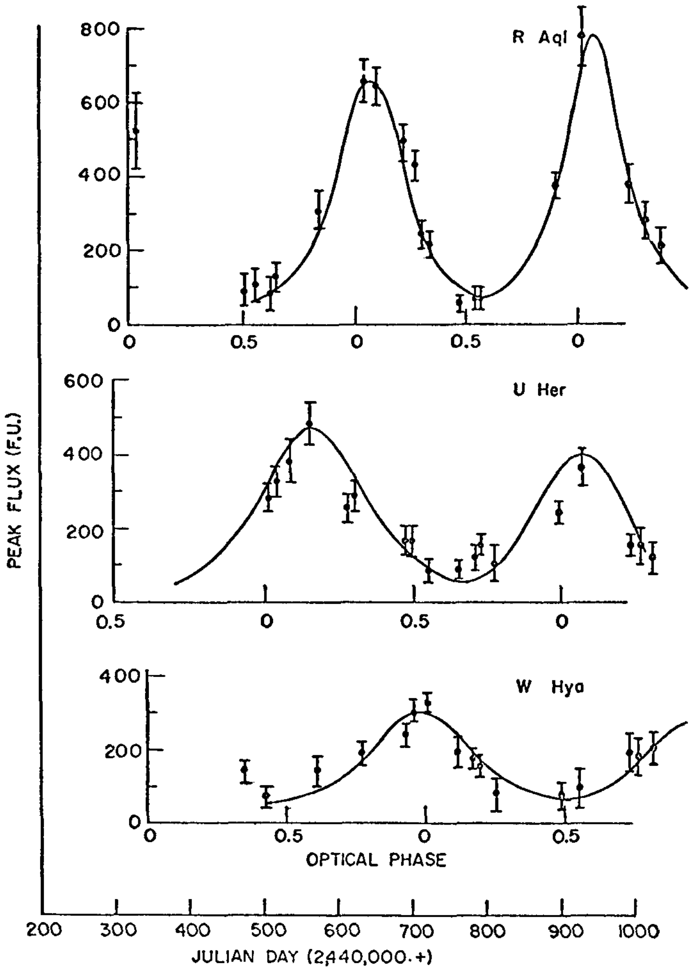

Fig. 3: Time Variation of the Peak H_2O Flux from Three Late Type Stars.

https://doi.org/10.1017/S0252921100032656 Published online by Cambridge University Press

directly related to the optical or infrared flux from the star or to some other parameter which varies with stellar phase. Although the OH data on stars of this type is less complete, observations by BALL and BECHIS indicate that the OH emission also varies in phase with the optical radiation.

IV. Interferometric Observations of Stars

In addition to measurements of the position of OH sources associated with stars made with conventional radio interferometers, a number of OH and H_2O sources have also been studied with Very Long Baseline Interferometry (VLBI). The 1612 MHz OH emission from NML Cygnus was resolved by WILSON, BARRETT and MORAN in 1968 and the structure of the source was demonstrated to be constant over a period of about one year. The typical angular size of the velocity features appears to be on the order of 0.008 arc sec implying a linear size of about 40 A.U. The brightness temperature of the OH source is thus found to be about 10^{11} °K (8).

Similar VLBI observations of the H_2O source in VY Canis Majoris have failed to resolve the source at fringe spacings up to about 0.001 arc sec implying that the linear size of the source is less than a few A.U. This is not a particularly unexpected result since most H_2O sources exhibit source structure that is unresolvable on terrestrial baselines (9). Unfortunately, both the OH and H_2O experiments to date have not been able to determine the spatial relationship of the various velocity features observed in sources associated with stars. Since, as discussed previously, this velocity structure has many interesting characteristics which seem to relate to the kinematics of the regions near the associated star, high resolution determinations of the microwave structure are of great interest to the study of mass loss and other circumstellar phenomena. The spatial relationship of OH and H_2O emission could possibly also be determined by VLBI observations but, at present, experiments of this type are still in the planning stage.

V. Basic Conclusions

Several rather simple conclusions can be drawn from the observations that are, by themselves, startling and unexpected. The most obvious point is that microwave emission is a relatively common attribute of cool red stars and, in fact, stars represent the most common source of anomalous OH and H_2O emission. Of equal importance is the fact that OH and H_2O sources associated with stars seem to represent a distinct class of anomalous emission source with common qualities that are not shared by other sources. Within the class of sources associated with stars there seems to be a natural division between objects which show both H_2O and OH emission and those which have only OH emission lines.

1612 MHz OH emission apparently originates from the reddest objects and especially from stars with circumstellar dust shells in excellent agreement with the LITVAK infrared pumping theory. The emission is found in two distinct velocity ranges corresponding to emission regions at rest with respect to the star and moving toward the observer. This behaviour undoubtedly represents a situation where the physical conditions necessary to amplify the microwave radiation are satisfied either on both sides of a shock wave in a stellar wind or on the inner and outer edge of a condensed shell. In either case the masering region is close to the star but mechanically decoupled from the short term stellar variation since only the pump rate (intensity) but not the velocity varies with stellar phase. From the velocity of the OH emission it can be deduced that substantial amounts of material flow away from many late type stars at velocities up to 30 km/s since fairly high densities of molecules are required to support the maser mechanism. The details of the mass loss implied by OH emission depend, of course, upon the exact mechanism involved but the rate may easily be as high as 10^{-6} $M_\odot$/yr (10).

The main line OH and H_2O emission from stars possibly represents a process that is more intimately related to pure mass loss than to the formation of a circumstellar shell and the maser mechanism is probably pumped by near infrared radiation, probably between two and four microns, since the H_2O emission seems to be so highly sensitive to stellar phase. Since the „hotter" stars not only have more near infrared flux but also less highly developed circumstellar shells to down convert radiation, it is not surprising that main line OH and H_2O emission is favored over 1612 MHz OH emission in these stars. The assertion that the maser is pumped by near infrared radiation is, of course, an assumption but is based upon the fact that both OH and H_2O have vibration-rotation bands in this spectral region (11). If the infrared pump lines were directly observable, their optical depth should vary in phase with the star making it unlikely that the known infrared H_2O lines in late M stars are the actual pump lines.

It is probably clear, at this point, that the understanding of the phenomenon of microwave emission from stars has not progressed much beyond the stage of classification and simple generalizations from the data. Those of us who have worked on this problem have mainly concerned ourselves with the „ground work" and some of the simple extrapolations of other theories that can be found in most observational papers. New experiments are being planned; in particular, the monitoring of OH and H_2O lines is being carried on and a series of VLBI experiments on this class of source will be performed this winter but what is really needed are more infrared observations and a fresh theoretical approach that makes use of the known properties of late type stars and the relatively well developed theory of stellar mass loss.

Acknowledgements

In composing this brief review, the author is grateful to his collaborators Prof. A. H. BARRETT and Dr. W. J. WILSON for allowing him to use their data before publication and for their helpful comments. The experimental work outlined in this paper was performed under research contracts from the National Aeronautics and Space Administration and the National Science Foundation to the MIT Research Laboratory of Electronics.

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Discussion to the paper of SCHWARTZ

BAKOS: Is there a difference of the emission between Mira variables and semiregular?

SCHWARTZ: There is no difference, as far as we can tell, between the OH and/or H_2O emission from Mira and semi-regular variables. The OH and H_2O emission from peculiar variables such as VY CMa and NML Cyg is different, however; the variations of these two sources seem to be random.

GEYER: Is there a correlation between the optical radial velocity changes of these late type stars and those of OH radial velocity changes?

SCHWARTZ: No. The OH and/or H_2O velocities do not seem to change significantly with phase.

SINVHAL: Do we know anything about these emissions (OH and H_2O) in these stars, and of their relation to the flares themselves?

SCHWARTZ: Broadly speaking, no. Actually, so far all we know is that late type long period variables alone have these emissions.