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WATER ABSORPTION IN THE INFRARED SPECTRUM OF LONG-PERIOD VARIABLE STARS AND ASSOCIATED MICROWAVE EMISSION

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ABSTRACT

Long-period Mira-type variables which have water emission at 1.35 cm are found also to have strong water absorption at 1.9 μ. The variation in the strengths of these two features are anticorrelated with one another. A possible physical model for this phenomenon is proposed, based on the concept of mass loss from late-type stars.

I. INTRODUCTION

Recently, Schwartz and Barrett (1970*b*) reported observations of H_2O emission at 1.35 cm from several late-type stars. The purpose of this Letter is to present correlations between this radio emission line and the broad H_2O absorption band at 1.9 μ. This is a report of one aspect of a general study of medium-resolution spectra in the 2.2-μ region of long-period variables and other late-type stars now under way (Frogel and Hyland 1970).

II. OBSERVATIONS

The spectra discussed in this paper were obtained with a 0.5-m Ebert-Fastie spectrometer which has been described previously by McCammon, Münch, and Neugebauer (1967). Telluric absorption features have been eliminated, and the spectra have been reduced to an absolute flux scale by calibrating them with α Lyr, α CMa, or α CMi. Broad-band photometric observations from 1.25 to 3.5 μ were made by using the photometer described by Becklin and Neugebauer (1968).

The light curve of the flux in the 2.25-μ region as measured directly on the calibrated spectra is, in general, indicative of the total-luminosity light curve of the long-period variables reported in this Letter. This is because the 2.25-μ region is relatively free of absorption by stellar water vapor, has negligible terrestrial absorption, and has a flux comparable to that of the region of maximum emission—around 1.6 μ for the objects considered here. This is not true of the visual light curve since the flux in the visual region is typically reduced by a factor of 10 relative to the 1.6-μ region and also is severely affected by absorption bands of metallic oxides. The phase shift between the visual and 2.25-μ light curves is a function of the amplitude at 2.25 μ; typically, the 2.25-μ maxima lag behind the visual maxima by one-fifth of a period for stars with large variations in amplitude. A more detailed description of this phenomenon is in preparation.

Seventeen long-period variables for which good observations have been obtained over the past 18 months show large variations in the strength of the 1.9-μ H_2O absorption band, both from one variable to another at the same temperature or phase, and as a function of phase for a given variable. Such variations were first noted by Spinrad *et al.* (1966) in a study of H_2O bands in the photographic infrared.

A measure of the strength of the 1.9-μ band may be obtained by considering the ratio of fluxes at 2.25 and 2.10 μ. While the 2.10-μ region has negligible terrestrial absorption, as does the 2.25-μ region, it lies well within the 1.9-μ water absorption band at the temperatures characteristic of the regular long-period variables. The observations given

TABLE 1

1.9μ H_2O BAND ABSORPTION

STAR	MAXIMUM OBSERVED				MINIMUM OBSERVED				PHASE SHIFT
	$\log\left(\frac{F_\lambda=2.25\mu}{F_\lambda=2.10\mu}\right)$	COLOR TEMPERATURE	PHASE 2.25μ	PHASE visual	$\log\left(\frac{F_\lambda=2.25\mu}{F_\lambda=2.10\mu}\right)$	COLOR TEMPERATURE	PHASE 2.25μ	PHASE visual	(visual-2.25μ)
a) Strong 1.9μ absorption; 1.35cm emission									
U Her	.15	1800° K	∿.31	.53	-.04	2200° K	.9	.1	∿.22
U Ori	.14	2000	.45	.65	-.02	2400	.0	.2	.20
R LMi	>.08	2100	>.23	>.43	-.06	2300	.8	.0	.20
R Aql	.06	2100	.40	.47	-.07	2500	.0	.1	.07
b) Strong 1.9μ absorption; no 1.35cm emission									
NML Tau	.15	<1600	-	-	.04	∿1600	-	-	-
Mira	.11	2000	.29	.54	-.08	2400	.8	.0	.25
R Cas	>.10	<1900	-	<.71	-	-	-	-	-
R Ser	.08	2100	>.27	.52	-.07	2500	>.7	.9	<.25
R Leo	>.05	<2300	>.18	>.40	<-.05	2400	>.6	>.8	.22
c) Weak 1.9μ absorption; no 1.35cm emission									
X Oph	.04	2300	.45	.49	-.06	2600	.9	.0	.04
R Cnc	>.03	<2300	>.19	>.36	.10	2400	.7	.9	.17
RS Lib	.03	2300	.19	.46	-.07	2500	.8	.1	.27
R Aur	.03	2100	∿.24	.41	-.06	2500	∿.0	.2	∿.17
R Aqr	>.01	<1900	<.61	<.81	-.03	2300	.9	.1	.20
T Cep	-.01	2500	∿.41	.44	-.10	2600	>.7	>.7	∿.03
χ Cyg	-.02	1900	.38	.55	-.08	2300	.8	.0	.17
T Cas	-.03	2400	.56	.61	-.09	2500	.9	.0	.05

in Table 1 and illustrated in Figure 1 are the maximum and minimum H_2O absorption strengths observed in the seventeen stars. Unless it is otherwise noted, these strengths are judged to be very close to the actual maximum and minimum during the cycles through which the stars were observed. The color-temperature scale was established with the photometry done here and the work of Johnson (1966), Mendoza V. and Johnson (1965), and Smak (1966); it will be discussed in detail by Frogel and Hyland (1970). The phases of the observations listed in Table 1 are the fractions of a period after the maximum in both the visual and 2.25-μ region. With the exception of R Aql, the stars with the strongest 1.9-μ band are among the stars whose 2.25-μ maxima lag their visual maxima by the greatest amount.

The behavior of the 1.9-μ absorption band with respect to the 2.25-μ light curve may be summarized as follows: It is at maximum strength shortly before minimum light; decreasing rapidly, it reaches minimum strength and remains relatively constant over one-fifth of a period; in most of the stars, the strength begins to increase between one-fifth and

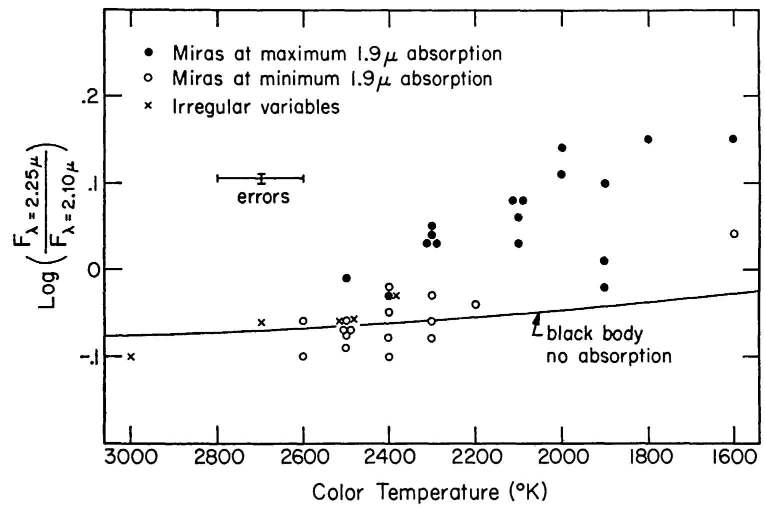

FIG. 1.—Color temperature is based on observed $J - L$ colors. In stars with little or no H_2O absorption, the continuum is determined by H^- and is steeper than a blackbody of the same temperature.

one-tenth of a period before maximum light and increases steadily until maximum strength is reached. It thus appears that the 1.9-μ band behaves in a manner similar to that of emission lines observed in the visual region of Mira by Joy (1954).

The H_2O microwave emission line has been observed in five long-period variables: U Her and R Aql (Schwartz and Barrett 1970*b*), U Ori, S CrB, and (provisionally) R LMi (Schwartz and Barrett 1970*a*). On all but S CrB, good infrared data have been obtained and it is clear from Table 1 that these have strong H_2O absorption. Only a single spectrum of S CrB was obtained, and it shows the 1.9-μ band to be of comparable strength to that of R Aql when the latter is at the same phase. The remaining long-period variables listed in Table 1 may be divided into two groups depending on the strength of the 1.9-μ absorption band. All have been observed in the radio region, with the exception of R Ser, but no H_2O emission lines have been detected. Three factors may contribute to this: (1) the star has no emission; (2) the star has emission but is too faint; (3) the star was insufficiently observed at the time of maximum emission. It should be emphasized, however, that *no star with a weak infrared absorption band has been found to have microwave emission.*

The radio data are still too limited to show whether the microwave emission is correlated more strongly with the 2.25-μ or visual light curve, but it apparently is at a maximum near the maxima of the two light curves (Schwartz and Barrett 1970*a*).

Schwartz and Barrett (1970*a*, *b*) have also detected 1.35-cm emission in the irregular variables VY CMa, W Hya, and RX Boo. These stars have weak or moderate 1.9-μ absorption bands.

III. DISCUSSION

The limited number of infrared and radio data available at present is strongly suggestive of a correlation between long-period variable stars which show 1.35-cm H_2O emission and those which have strong 1.9-μ absorption.

The similarity in behavior of the 1.9-μ absorption band and the visual emission lines noted previously suggests one possible physical model which could account for the observed behavior of the H_2O emission and absorption. As the variable passes through light maximum, a considerable quantity of hot material is expelled and cooled as it rises above the photosphere. Below $T = 2500°$ K, water becomes fully associated (Tsuji 1964), independent of pressure in the relevant range (Vardya 1966). The drop in absorptivity of H_2O with decreasing temperature (Auman 1967) would initially be more than offset by the increasing amount of H_2O above the photosphere. As the mass expulsion rate drops and the material continues to cool, the strength of the 1.9-μ absorption band will begin to decrease rapidly, but the H_2O will remain associated. Near maximum luminosity the star's energy output finally becomes sufficient to excite the pumping action suggested by Schwartz and Barrett (1970*b*) to account for the microwave emission. It would seem, then, that maser amplification of 1.35-cm microwave emission can take place to an observable degree only in stars which fulfill two conditions: (1) a sufficient quantity of H_2O must have been produced in previous parts of their cycle; (2) the stars' energy output at some point during their cycles must become great enough to initiate the maser action. The strength of the 1.9-μ water band is an indication of how well the first criterion is satisfied; from the data in Table 1 we would therefore expect 1.35-cm emission to be found in NML Tau, R Ser, R Cas, and possibly R Leo. These stars seem to produce at least as much water vapor as do the known H_2O sources.

In addition, there are probably close ties between the phenomena of H_2O emission and OH emission. Although there is evidence for mass loss occurring in both types of emission objects (Wilson, Barrett, and Moran 1970; Schwartz and Barrett 1970*b*), the much greater abundance of H_2O than of OH in the atmospheres of the stars (Tsuji 1964) implies that the amount of mass loss required for the H_2O sources need not be as great as for the OH sources. This is supported by photometric observations of both types of sources (Hyland *et al.* 1970) which can be interpreted as showing that the OH emitters typically have much thicker circumstellar shells than do the H_2O emitters. We are thus led to predict that most of the OH sources should also be H_2O sources.

IV. CONCLUSION

The physical reason for the apparently necessary condition in long-period variables of strong 1.9-μ absorption in order to have 1.35-cm H_2O emission is not yet clear. Mass loss in late-type stars has been suggested by Deutsch (1960) and Weymann (1963) on the basis of phenomena observed in the optical region. Therefore, it is suggestive that we are dealing with a further aspect of mass loss in these objects. Geisel (1970) has discussed recent evidence for the mass-loss phenomenon in emission-line objects including Mira-type stars which show infrared excesses. In the particular case of the long-period variables, water molecules formed at low levels in the atmosphere could be forced outward, perhaps by energy derived from the large-amplitude pulsations that occur in these giant stars (Keeley 1970). Emission from the irregular variables, which seem to have less water vapor produced during their cycles than the regular variables discussed above, could be due to their much smaller pulsation amplitudes which in turn would allow expelled water molecules to accumulate in circumstellar regions in larger quantities,

Because of the closeness in time of the visual and infrared maxima, we do not feel that the limited number of radio observations allows one to determine conclusively which maximum the 1.35-cm emission agrees with. Also, more observations in both the infrared and radio are needed to investigate strength correlations between the absorption and emission features.

Note added in proof.—Dr. P. Schwartz has informed me that R LMi and NML Tau have been very heavily observed. Neither source showed any detectable H_2O emission above about 10 f.u.

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