Red Variables with and without OH Radio Emission

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Radio astronomers detected in 1963 hydroxyl molecules (first in absorption), in form of microwave lines at the frequencies 1612, 1665, 1667, and 1720 MHz (1612.231 + 1720.533 (=) 1665.401 + 1667.358), corresponding to a wavelength near 18 cm. Since 1968, some infrared stars have been known to be observable with radio telescopes as sources of such microwave lines, in emission with line widths of 2 kHz or less. In addition to the ground state, a Π state with $\Lambda = 1$, the OH molecule has three known electronic excited states, Σ states with $\Lambda = 0$, at about 30 000, 60 000, and 90 000 cm^{-1} above the ground state. These electric-dipole transitions are about 10^4 times stronger than the magnetic-dipole transitions which produce hydrogen or deuterium lines; the energy of the ${}^2\Pi_{3/2}$ state is less than that of the ${}^2\Pi_{1/2}$ state what indicates that the observed OH radio emission is subject to far infrared stellar radiation.

By the condition that the OH gas is in thermodynamic equilibrium and optically thin the predicted relative strengths of these ground-state lines should have been in the ratios 1:5:9:1. The observed intensities but give other ratios as was shown detailed in the preceding report. Therefore above-mentioned conditions appear not to be realized, it offers a stimulated emission of the type produced in laboratory masers, here infrared-pumped OH masers, initially proposed by SHKLOVSKYI (1967), later by LITVAK et al., and TURNER (both 1969). This theory of IR pumping explains the observation (satellite line 1612 MHz the strongest emission, weak main-line emission in most cases, and no OH emission at 1720 MHz, the other satellite-line frequence) if there is strong 2.8 μ IR radiation and if the OH gas has a large optical depth to provide for resonance trapping of the far-IR photons. Such a model (a molecule with a ground level and three excited levels, and radiation transfer with stimulated emission) gives transitions of left and right polarization what also is observed; but it is at present not clear whether polarization is a fundamental or incidental property.

On the other hand, OH sources lie mostly near the outer part of H II regions, in the ionization fronts. Here in the H II clouds there are very many H_2 molecules, hence the assumption:

$$H_2 + O \rightarrow OH + H \qquad \text{and}$$

$$n(OH) = 2\,T^{1/2}\,n(H_2)\exp(-3180/T)$$

The radiation is in this way thermal and the number density of OH about $10^{-6}/\text{cm}^3$; the temperature cannot be much above 100 °K. In contrast: The only 12 per cent of red giants which have intensive OH emission (probably lie many sources below the limit of measurement, 10^{-26} $\text{W/m}^2\text{Hz}$) are not concentrated in the galactic plane, their average latitude is about 20° what corresponds to evolved Population II objects.

Redness and light variability of giants (put the case that all red giants are more or less variable) seem to be necessary but not sufficient as conditions for OH emission, for most dwarfs (in front the T Tauri stars in the constellations Taurus, Auriga, Orion, and Monoceros) are without measurable OH emission. Only SU Aur and RY Tau exhibit 1667 MHz OH line emission, weak and near the limit (GAHM and WINNBERG, 1971); the authors find conformity with the optically measured radial velocities. Peculiar is the behaviour — *without* OH emission — of following variable red giants and supergiants: R And (S6e), Mira itself (M6e), TX Cam (M9), α Ori (M2I), α Sco (M1I), χ Cyg (M6e), and μ Cep (M2I). Peculiar analogously and of special interest are R Mon and FU Ori, first variable star a strong IR source and probably a preplanetary system composed by dense clouds (HERBIG, 1968), however: no OH emission; second star is a beginner as variable only in 1939, very young and also: no OH emission. The young stars appear not to meet the necessary conditions for a OH/IR masering, the low density and the low temperature.

Without surprise is the behaviour — *with* OH emission — of the variable red giants WX Ser (M8), R Aql (M6e, also H_2O), U Ori (M8e), VX Sgr (M4e), UX Cyg (M6e), and the most intense source VY CMa (M3e with reflection nebula, H emission and P Cygni structure, also H_2O). The integrated flux (right hand + left hand) at 1612 MHz

Variable Stars	Flux (10^{-22} W/m^2)
VX Sgr (semi-regular)	220
VY CMa (irregular)	1500
Mira stars (regular)	44

Further examples (TURNER, 1970), with OH emission: supernova remnants, dust clouds; without: Wolf-Rayet stars, planetary nebulae, globules, heavily reddened stellar clusters.

Only a peculiar case, observed by CASWELL and ROBINSON (1970): One of the 16 southern long-period variables, R Horologii (M7e, visual magnitude range of 5 to 14), shows a very different pattern of OH emission, here 1612 MHz remains absent while 1665 and 1667 MHz are present in nearly equal strengths. ROBINSON and his co-workers (1970) have observed these both main-line emissions also in VY CMa, with marked intensity and polarization changes while the 1.35 cm H_2O emission by BUHL et al. (1969) was established to be constant.

Models:

1. *Once more OH masering clouds, IR-pumped.* The observed IR and OH properties find their explanation by expanding, luminous (10^4 or 10^5 $L_\odot$), evolved giants/supergiants of the late spectralclasses. The OH masering clouds are located in the outest part of the stellar atmosphere, at a radius of 10^{15} cm where low density (10^{-17} g/cm^3) and low temperature (600 °K) predominate, the above-mentioned conditions for an OH maser. Here the OH masering originates by passage through stellar material, driven by the radiation pressure. A small amount of turbulence from separate clouds of material interprets — as an individual feature — the observed splitting-up in a shortward OH peak and in a longward OH peak, with a separation typically 20 to 60 km/sec of the radial velocity. This model has a very small change in mean radial velocity over a long period in time; however, small periodic changes during the cycle of variability are possible as in the optical lines. There is a calculation for the mass loss, equal to $4\,\pi\, r^2 \varrho\, v_r$ or $\sim 10^{-6}$ $M_\odot$/year, i. e. a rate somewhat less than that of planetary nebulae.

   Is the maser saturated? An answer lies in the search for emission of the isotope $O^{18}H$ in the IR sources. Are both, $O^{16}H$ maser and $O^{18}H$ maser, saturated their fluxes would be proportional to the abundance ratio (on Earth O^{16}/O^{18} about 500).

2. *Disk-shaped nebula,* a by-product of star formation (HERBIG, 1970). Young stars act as local sources of new dust and molecules and effect a dust concentration in their vinicity until such a cloud is disrupted by hot stars that ultimately will form within. Stars poor in mass return to the cloud (several per cent of the original condensation) with now heavier elements (Mg, Si, Fe, Ti, ...), bound up into solid particles. But also a certain part of the volatile elements (H, C, N, O) returns in form of diatomic and complex molecules; the inert gases (He, Ne, ..), however, retain their primary shape. So a strong concentration of interstellar molecules could arise (HEILES, 1968; CUDABACK and HEILES, 1969).

   The OH emission originates in the transparent peripheral regions of the expanding disk and the entire volume can contribute to this emission. An annular zone is responsible for the observed double-peaked profile. The shortward peak is produced in material rising toward the Earth; the velocity is similar to that of the shortward displaced absorption components of NaI and H lines in the optical spectrum of the star.

3. *Binary surrounded by a dust shell* (HYLAND et al., 1969). These authors have proposed a model (first for VY CMa) which consists of a pair of late supergiants (M5 Ib) with a thick circumstellar dust shell which is responsible for the lower radial velocity of the 1612 MHz emission, in accordance with the displaced lines in the optical spectrum. The higher velocity emission is attributed to the motion of the stars corresponding with the velocities of the normal-placed absorption lines in the common M spectrum.
4. *Zeeman splitting* (DAVIES et al., 1966). This conception would require a magnetic field of order of 10^{-3} gauss.
5. *Shock wave front* (WILSON and BARRETT, 1971). An expanding atmosphere, driven by radiation pressure, has a shock front in the outer regions; the OH emission could come from either side of this shock front, giving rise to the two separate velocities.

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Discussion to the paper of STROHMEIER

DE GROOT: If the radial velocity of one of the components coincides with the stellar radial velocity, this seems to me a severe problem for the first of two theories you mentioned, because in those cases the stellar radial velocity would be in between the two OH velocities.

SCHWARTZ: On the question of OH/H_2O radial velocities: The OH seems to come at two velocities in Mira and Semi-regular variables, the higher velocity corresponds to the star's velocity so most expanding shell or rotating ring models can be ruled out. VY CMa and NML Cyg seem to be different from the rest of the sources and for them, a rotating, expanding ring may be ok.

SAHADE: If I understood it right, Dr. SCHWARTZ mentioned that the two peaks of OH 1612 are separated by some 10—20 km/sec. How does this agree with the model of the two peaks coming from each side of an expanding rotating ring?

STROHMEIER: The velocity of an expanding ring is similar to that of the shortward displaced absorption components of Na and H lines in the optical spectrum. There are only such small velocities.

KELLOGG: What is the ratio of this OH emission for VY CMa to the total emission of the star?

STROHMEIER: That is difficult. OH emission is about $1500 \times 10^{-22} Wm^{-2}$ at 1612 MHz, the luminosity $3.6 \times 10^4 L_\odot$ with a distance of 400 pc, but $50 \times 10^4 L_\odot$ with the distance of 1500 pc which Dr. HERBIG has presented because of a probable kinematical association of VY CMa with the cluster NGC 2362.