Reports

Spectra, Variability, Size, and Polarization of H_2O Microwave Emission Sources in the Galaxy

Abstract. *Radio spectral line radiation of water molecules at a wavelength of 1.35 centimeters has been measured from eight sources in the galaxy. The sources are less than 1 arc minute in diameter, have extremely high brightness temperatures, and show many spectral features. Some spectral features are slightly polarized and some have changed greatly in intensity in a few weeks time.*

The emission spectrum of the rotational transition of water molecules at a wavelength of 1.35 cm was recently discovered by Cheung *et al.* (*1*) at the University of California in regions near the positions of the radio sources Sagittarius B2 and W49, the Orion Nebula, and the OH source (W3A) which is 17′ away from the W3 continuum source. These original observations, made with a radio telescope 20 feet in diameter having a beam width of 8.8′ and a spectral resolution of 350 khz, showed the diameters of the source regions to be less than 3′ and the lines to be unexpectedly intense, giving antenna temperatures up to 60°K.

Using a spectral resolution of 4 khz and an antenna beam width of 2.3′, we have observed the H_2O line emission from these four source regions and from four additional sources which were found near the positions of the OH sources in W51 (*2*), W75, Canis Major, and near the position of the bright continuum source W3. The observations were made with the 85-foot reflector at the Maryland Point Observatory of the Naval Research Laboratory which has an aperture efficiency of about 38 percent at a wavelength of 1.35 cm. The system noise temperature for single side-band operation was 2700°K. The backward-wave oscillator used as the local oscillator was phase-locked to an oscillator at 350 Mhz, which in turn was phase-locked to a lower-frequency crystal standard to give the required frequency stability of about 1 part in 10^8. The spectra were measured with a bank of 50 contiguous filters, each 4 khz wide. Since the source spectra were wider than the total width of the filter bank (200 khz), the local oscillator frequency was set at a number of frequencies to measure portions of the spectra each 200 khz wide which overlapped by 50 khz. Additional filter channels with widths of 100 khz were used for frequency scans and for polarization and size measurements.

The observed positions of the H_2O sources, which are accurate to 1′, are given in Table 1. Seven of the eight H_2O line emission sources which have been observed agree in position with known OH emission sources (*3*, *4*) to within the accuracy of measurement. The exception is the source near the position of the bright continuum source W3. The OH source near W3, which is separated from the bright continuum source by about 17′ (*5*), is also an H_2O source which we will call W3A. The H_2O source in Orion is in the position of the OH source (*6*), which coincides in position with an infrared point source found by Becklin and Neugebauer (*7*). The intense H_2O source in Canis Major was found at the position of the OH source recently discovered by Eliasson and Bartlett (*4*). They report this OH source to be near the position of a bright infrared object listed in the catalog of infrared objects of Neugebauer and Leighton which is identified with the irregular variable VY Canis Majoris. Infrared radiation has also been reported from near the positions of W3A, W51, and W75 (*3*).

The angular sizes of the H_2O source regions are small as compared with the telescope resolution of 2.3′. The diameters of the source regions of the more intense lines in W49, W3, and Orion were measured to be less than 0.7′. Size measurements for the weaker sources are less precise, but the diameters of all of the H_2O sources appear to be

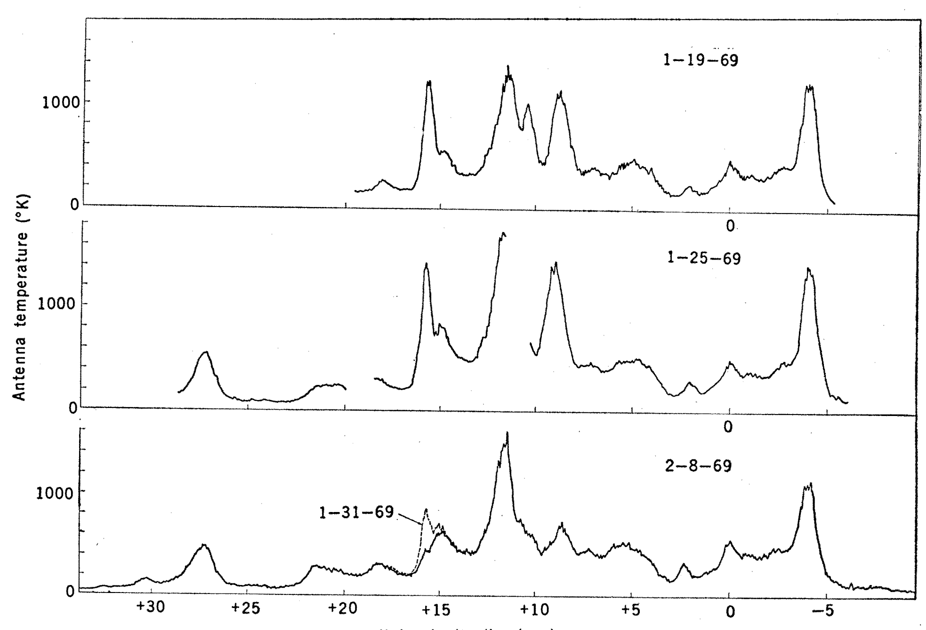

Fig. 1. Spectrum of the H_2O source in W49 measured on different dates which shows time variations of intense features.

less than 1′ with the possible exception of the source in Canis Major which may be slightly broader in declination. In W49 and Orion, where several intense, Doppler-shifted lines are observed, the positions of the source regions corresponding to the different lines coincide to within 0.1′.

The spectra of the W49 and Orion source regions, which were measured with a resolution of 4 khz, are shown in Figs. 1 and 2. Both have a number of sharp, Doppler-shifted lines with some line widths as narrow as 0.6 km/sec and some much broader features, spread over a range of radial velocities of 30 km/sec or more. The spectrum of W49 is broadened considerably further than shown in Fig. 1, with a low intensity tail-containing structure extending to Doppler shifts as great as −150 km/sec. This gives a total velocity spread as large as 185 km/sec. The spectra of the other sources shown in Fig. 2 are somewhat simpler, but all show more than one velocity component. The spectrum of Sagittarius B2, which is not shown, is weaker and was measured only with a coarser resolution of 100 khz. Two spectral features, separated by about 20 km/sec and with antenna temperatures of about 15°K, were observed. Although the positions and general range of Doppler velocities of the H_2O and OH sources agree for the seven sources for which OH is observed, the detailed spectral features of the H_2O sources show little similarity with those of the OH spectra.

Table 1. Positions of H_2O sources (1950.0 coordinates).

Source	Right ascension	Declination
W3	$2^h21^m51^s$	61°52.2′
W3A	$2^h23^m14^s$	61°38.5′
Orion	$5^h32^m47^s$	− 5°24.7′
VY Canis Majoris	$7^h20^m55^s$	−25°39.9′
Sagittarius B2	$17^h44^m05^s$	−28°22.1′
W49	$19^h07^m48^s$	9° 0.2′
W51	$19^h21^m25^s$	14°23.7′
W75	$20^h37^m12^s$	42°11.9′

Time variations of the spectrum of W49 are illustrated by the spectra shown in Fig. 1. Those in the upper and middle diagrams, which were measured on 19 January 1969 (during rain) and 25 January, show two strong lines at + 16 and + 9 km/sec which had nearly disappeared by 8 February when the lower spectrum was measured. A third feature at + 11 km/sec seen on the spectrum of 19 January and verified by spot checks, but missing from the spectrum of 25 January because of an error, also disappeared. A partial spectrum of the +16-km feature measured on 31 January and indicated by a dotted line on the spectrum of 8 February shows only a low intensity at this intermediate time. Additional spectra measured after 8 February confirm the disappearance of these lines. The extreme variability of these features in less than 3 weeks implies a diameter for the source region of less than 20 light-days, which, at a distance of 14.1 kpc for W49 (*8*), would correspond to an angular diameter for the H_2O source region of less than 0.005′. This observation of rapid variability of the H_2O line emission suggests that it is important to make direct measurements by long base-line interferometry to determine the sizes and structure of the source. Such measurements are practical because of the high intensity of the line radiation.

The observed H_2O line emission is very intense, with antenna temperatures for the strongest lines in the W49 source as high as 1700°K + 10 percent when corrected for atmospheric absorption of about 10 percent. This high intensity of received radiation, together with the measured source size of 0.7′ or less, implies a brightness temperature of 50,000°K or more. If the sizes of some of the intense source regions are two orders of magnitude smaller, as implied by the variability observed for W49, much higher brightness temperatures of the order of 10^9 °K are indicated.

Measurements made with circular and linear polarization show that the radiation in most of the observed spectral lines is not strongly polarized, at least not more than 10 percent. The line at +2.5 km/sec in the Orion spectrum was found to be 30 percent linearly polarized, and the strong line in the W3A spectrum is about 6 percent linearly polarized.

The groups of triplets in the Orion spectrum and the shapes of some lines suggest interesting systematic motions of H_2O clouds. The shapes of the pair at +5 and +1 km/sec and of the line at −4 km/sec are roughly consistent

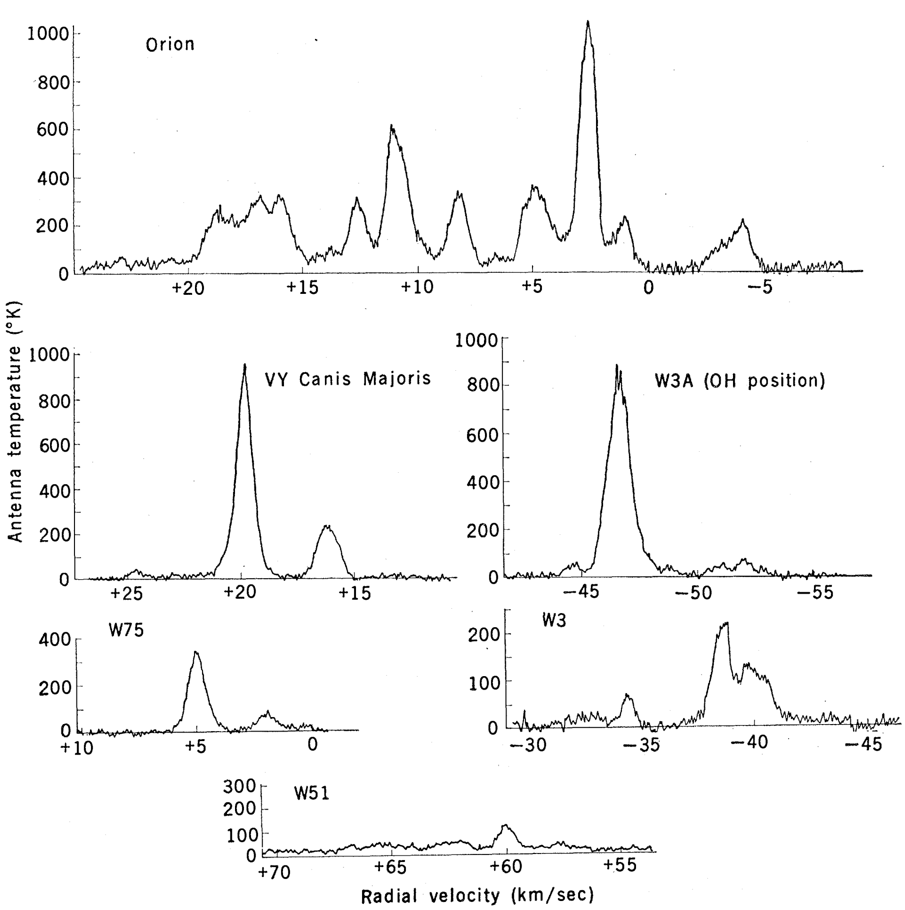

Fig. 2. Spectra of H_2O sources in Orion, Canis Major, W3, W51, and W75.

with a model in which a cloud containing H_2O in the shape of a ring rotates, expands, or contracts about a center. Such a model gives a spectral shape of

$$I\ (v) \propto \left(1-\frac{v^2}{V^2}\right)^{-1/2}$$

where I is the intensity, V is the speed of the ring, and v is the velocity component in the line of sight. Some turbulence or finite thickness would prevent any divergence at $v = V$ in a nonideal case. A spherically symmetrical and uniform shell would give only a flat spectrum; however, an asymmetry such as a bulge would also result in a spectral shape similar to that of a planetary ring.

A number of properties of this radiation indicate that it is caused by stimulated emission (maser action) rather than normal spontaneous or thermal emission. The molecular motions are clearly not in thermal equilibrium, since water would dissociate rapidly at 10^9 °K or even 50,000°K, the temperature of the radiation. Furthermore, line widths as narrow as 40 khz, which occur in some features, imply thermal kinetic energies corresponding to about 100°K, obviously not in equilibrium with the radiation temperatures. The actual kinetic energy seems likely to correspond to temperatures of at least several hundred degrees, since the rotational states involved are 447 cm^{-1} above ground. Hence these narrow line widths have probably been reduced by some small factor due to amplification by stimulated emission.

Finally, if the distance of W49 is 14.1 kpc and the photons are radiated isotropically, the total flux of microwave photons from this source would have to be 6×10^{48} sec^{-1} in order to produce the observed intensities. Since the spontaneous emission time is 5×10^8 seconds, this requires 3×10^{57} radiating molecules in the source, or 50 solar masses of H_2O molecules in the 6_{16} state. If we assume that not more than 10 percent of the molecules are in this particular state and assume the usual abundance ratio of H to O, a total mass of 5×10^4 solar masses is required in the emission region. This is excessive for regions as small ($\sim 10^{16}$ cm) as are indicated by the time variations in H_2O radiation. One must appeal to stimulated effects and maser-type amplification to account for the production of such copious radiation. In this case, the total number of H_2O molecules can be very much reduced and the total flux of microwaves is limited primarily by the excitation mechanism.

Even though the precise reasons for polarization of the H_2O radiation are not known, polarization can more naturally occur with maser amplification, as it does for the OH case, than with normal thermal emission. For spontaneous emission, linear polarization can occur simply through scattering. For example, if a source of infrared radiation excites water molecules from a $J = 5$ rotational level to the 6_{16} level and they reradiate microwave radiation by transitions to the 5_{23} level, the reradiated photons are linearly polarized for essentially the same reasons that Rayleigh-scattered radiation is polarized. A detailed calculation shows that reradiation in a direction perpendicular to the path of the original infrared quanta produces a polarization of about 30 percent. Thus the observed degree of polarization could be produced by spontaneous radiation. However, even a small net polarization of this type can provide a slight bias which produces a large amount of polarization if there is large amplification by stimulated emission.

Excitation of H_2O to the 6_{16} level by radiation alone is very unlikely, because there are not sufficient exciting quanta available from likely astronomical sources. For such excitation, each microwave photon requires a far-infrared photon to induce a transition to the 6_{16} rotational level and hence about 6×10^{48} infrared photon/sec. However, the total number of suitable infrared photons within an infrared Doppler width of 10 km/sec from an M5 star is less than 10^{43} sec^{-1}; hence the supply is inadequate by a factor of 6×10^5. The actual observed infrared radiation from Orion [including the infrared nebula (*9*)] near the OH emission regions also produces too few infrared photons by at least a factor of 10^3. Hence, the excitation mechanism cannot be simply photon absorption and must be collisions.

A complete list of transitions from the 6_{16} and 5_{23} levels and their strengths has been tabulated (*10*). Since the 6_{16} level decays by spontaneous emission in 1.4 seconds, and more rapidly than does the 5_{23} level, excitation by continuous radiation of more or less constant spectral intensity or by hard collisions with subsequent spontaneous emission cannot maintain the inverted population required for maser amplification. Various special excitation schemes which do invert the population can be imagined.

A large number of H_2O molecules also provides an effective mechanism for rapid cooling of the gas, in case an energy source is cut off, thus allowing time variations in the radiation. For a cloud of mass $1 M_{\odot}$, radius 10^{16} cm, and temperature 10^3 °K, the amount of cooling in 1 week caused by molecular infrared radiation could lower the kinetic temperature sufficiently to allow the observed time variations. This implies that the driving source of energy must vary with time.

It is evident that the H_2O occurs in regions where much energy is being released and where there are rapid changes with time. These might be due either to gravitational contraction of gas and dust or to rapid heating by other sources of energy. The large range of velocities, about 200 km/sec in W49, for example, coupled with an apparent size of less than about 10^{16} cm, suggest stellar formation or activity.

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References and Notes

1. A. C. Cheung, D. M. Rank, C. H. Townes, D. D. Thornton, W. J. Welch, *Nature* **221**, 626 (1969).
2. We were informed of the discovery at the M.I.T. Lincoln Laboratory of the H_2O source in W51 by M. L. Meeks.
3. E. Raimond and B. Eliasson, *Astrophys. J.*, in press.
4. B. Eliasson and J. F. Bartlett, *ibid.*, in press.
5. P. G. Mezger and A. P. Henderson, *ibid.* **147**, 471 (1967).
6. E. Raimond and B. Eliasson, *ibid.* **150**, L171 (1967).
7. E. E. Becklin and G. Neugebauer, *ibid.* **147**, 799 (1967).
8. P. G. Mezger and B. Höglund, *ibid.*, p. 490.
9. D. E. Kleinman and F. J. Low, *ibid.* **149**, L1 (1967).
10. M. Lichtenstein, V. E. Derr, J. J. Gallagher, *J. Mol. Spectrosc.* **20**, 391 (1966).
11. Work of the University of California was supported in part by NASA. We thank J. W. Boland for the mechanical design of the receiver; J. H. Nichols for valuable assistance with the radio telescope; B. S. Yaplee, D. L. Hammond, and R. E. Morden for the design and construction of the filter banks and integrator circuit; and David Stead of the Hewlett-Packard Company for assistance with stabilization of the backward-wave oscillator. Doppler velocities with respect to the local standard of rest were calculated by the Radio Astronomy Laboratory at Berkeley. We are grateful to Professor H. Weaver for this assistance and also for helpful discussion of the W3 source.

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