THE INTERPRETATION OF HIGH VELOCITY H_2O MASERS

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ABSTRACT

Kinematic and physical models of high velocity H_2O masers are briefly discussed.

INTRODUCTION

In some sources of maser emission associated with compact HII regions H_2O maser features are spread in velocity up to ±200 km s^{-1} from the central features. If these high velocity features (HVF) are attributed to the Doppler effect, the corresponding sources cannot be gravitationally bound to a central body as the central mass required, $\sim 10^5 M_\odot$, would be too big. This mass would in some way or other manifest itself, which is not the case. Therefore the HVF are an interesting phenomenon in the physics of galactic masers. The latest VLBI observations (Genzel et al. 1978, 1979) have discovered new peculiarities of the spatial distributions of the maser features, namely their grouping around centers of activity. The low velocity (±15 km s^{-1}) most intense maser features form the centers of activity. High velocity H_2O maser features cluster around the centers of activity at both positive and negative velocities, occupying a large spatial area. The HVF vary in time (Morris 1976, Gammon 1976, Little et al. 1977, White 1979, Genzel et al. 1979). It is now obvious (Genzel and Downes 1977a) that our first naive models of maser sources related to HII regions should be considered as an evolutionary sequence. Maser sources may exist in the expanding shell of a recently born star of high luminosity. It is evident that the maser sources are cloudlets formed due to fragmentation of the medium in which they are immersed. The medium can fragment as the result of thermal instability caused by the passage of a shock wave (Burdyuzha and Ruzmaikina 1974, 1975) or due to Rayleigh-Taylor instability (Norman and Silk 1979). H_2O maser behaviour increases the inhomogeneity of the medium because the maser emission is a quite powerful cooling source (Burdyuzha and Ruzmaikina 1977, Norman and Silk 1979).

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In addition to the assumption that the low velocity and high velocity features are clouds radiating as masers (Strelnitskii and Sunyaev 1972, Norman and Silk 1979, Elmegreen and Morris 1979) another interpretation was proposed involving a various and sometimes amazing distribution of radial velocities. This interpretation is associated with the physics of line splitting (Stark effect-Slysh 1973; induced by Compton scattering - Galeev and Sunyaev 1972, Montes 1977; Raman scattering - Radhakrishman et al. 1975, Boyd 1977; and scattering from plasma noise - Fernandez and Reinisch 1978, Burdyuzha 1978, Burdyuzha et al. 1979).

All models of "high velocity H_2O masers" (about ten) can be divided into two types: kinematic, and physical.

KINEMATIC MODELS

The basis for the interpretation of all kinematic models is the Doppler effect. The high velocity clouds radiating as masers may be accelerated either by a stellar wind or by radiation pressure. Strelnitskii and Sunyaev (1972) were the first to draw attention to this fact.

As has been shown by many authors, a young massive star of high luminosity radiates an intense stellar wind: the outflow rate is 10^{-5}-$10^{-6}M_\odot$/year. The stellar wind can accelerate maser clouds up to rather high velocities $\sim$200-300 km s^{-1} and carry them from a distance of $R_0 \sim 10^{14}$cm from the central star to a distance of $R \sim 10^{17}$cm and farther. $R_0 \sim 10^{14}$cm appears to be the minimum distance at which the maser clouds could originate due to the fragmentation of the medium, and to be the minimum distance at which there are appropriate conditions for the H_2O maser to operate ($n \sim 10^7$-$10^{11}cm^{-3}$ and $T \sim 3 \cdot 10^2$-10^3K). The criterion for this mechanism to be efficient is

$$\dot{M}V\sigma/2\pi R_0 mv^2 \sim 1 \qquad (1)$$

where $\dot{M}$ is the outflow rate (g s^{-1}), V is the stellar wind velocity (cm s^{-1}), σ is the cross-sectional area of the maser cloud (cm^2), m is the maser cloud mass (g), and v is the maser cloud velocity (cm s^{-1}).

In the case of acceleration by radiation pressure, the criterion may be written as

$$L_* \sigma/2\pi R_0 cmv^2 \sim 1 \qquad (2)$$

where L_* is the central star luminosity (erg s^{-1}), and c is the speed of light (cm s^{-1}).

Quite recently, more specific and elaborate models have been suggested. In the paper by Norman and Silk (1979) a new mechanism was proposed in which the magnetic field plays an essential part in the acceleration of the cloud. When the intense stellar wind interacts with gas in the magnetic field of the shell, a Rayleigh-Taylor instability is developed which leads both to fragmentation of the medium and to the acceleration of the clouds thereby formed. In these processes the magnetic field is the energy source. Later these high velocity clouds ("bullets") are ejected into the environment, thus providing an explanation of the phenomenon of Herbig-Haro objects. A rather large magnetic field ($B \gtrsim 10^{-2}$G) is required to make this mechanism efficient. With increasing distance from the central star the "bullets" slowly lose their velocity. However this prediction is contradicted by the observations in Orion (Genzel and Downes 1977b), making the interpretation of the high velocity H_2O masers as "bullets" seem rather doubtful.

Shell and disk kinematic models of cloud acceleration are similar in many ways. In these models the clouds are also accelerated by either the stellar wind or the radiation pressure. In the shell model, the spherical shell is expanding together with its low velocity features (LVF). In the disk model, the disk with the immersed LVF is also expanding and rotates differentially. The authors of the models of this type are R. Genzel and D. Downes.

The most developed model among the kinematic models is that of a Keplerian disk (Elmegreen and Morris 1979). In this model, the LVF are maser regions moving in orbit together with the disk around a star of mass $M \sim 30\ M_\odot$. The HVF are clouds blown by the stellar wind out of the inner parts of the Keplerian disk, which is a stable formation as far as its expansion or compression is concerned. In this model the high velocity clouds should be either smaller in size or warmer than the low velocity clouds.

Summing up this brief survey of the kinematic models, I should like to note that in Doppler interpretations of the H_2O HVF a few aspects still remain obscure:

1. Why do the HVF appear only in the H_2O molecule emission? (Of course there always remains the possibility that moving H_2O features can radiate as masers).
2. With several years or even months of attentive "patrolling" of the high velocity H_2O features of a source, changes in the distance between them as well as the velocity of their separation should be determinable. It is not clear why these motions have not yet been detected.
3. It is not quite clear how the high velocity H_2O maser operates when there are rather high velocity gradients in the cloud.

PHYSICAL MODELS

Physical models of high velocity H_2O masers are based either on there being a splitting and a shift of features in frequency caused by the influence of electric or magnetic fields, or on there emerging satellite lines as a result of interaction between the maser emission and a plasma. For H_2O maser emission, 1 MHz separation in frequency corresponds to 13.5 km s^{-1} in velocity.

The hyperfine structure of the $6_{16} \to 5_{23}$ line of water vapor has been investigated by Kukolich (1969). The interaction between rotational angular momentum and nuclear spin splits the 22 GHz transition into six lines with a total spread in velocity of ~ 5.9 km s^{-1}. Note that of the six hyperfine components, three correspond to a transition with the same value of the projection of the total angular momentum F, and have an intensity two orders smaller than that of the basic components, so it is more correct to speak about the hyperfine interaction resulting in a split in velocity of order 1 km s^{-1}.

The splitting in frequency caused by the Zeeman effect is also very small in the magnetic fields ($\sim$10mG) that are characteristic of maser regions (Moran et al. 1978).

According to Slysh's calculations (1973) the electric component of the electromagnetic field of maser radiation may be set equal to

$$E_0 = (4\pi W^t)^{1/2} = (8\pi k \nu^2 \Delta\nu_{dop}\ T_b \Omega / c^3)^{1/2} \sim 10^{-2} \text{esu} \qquad (3)$$

where W^t is the radiation energy density (if we assume an isotropic maser at $T_b \sim 10^{15}$K). Satellite lines due to the Stark effect are observed at $\pm\Delta\nu_{st} = \mu E_0/\hbar$, and their splitting may exceed the Doppler width $\Delta\nu_{dop} \sim 50$ kHz $\mu = 0.125 \times 10^{-18}$ esu is the electric dipole moment of the H_2O molecule. Since it has become apparent that the H_2O masers are anisotropic ($\Omega/4\pi \sim 10^{-2}$) a splitting of a few km s^{-1} is difficult to explain by the Stark effect (much larger brightness temperatures are required, but are not observed).

Since $T_b \gg T_e$, and the density of plasma through which the maser radiation passes is close to that required for the generation of Compton solitons, Compton scattering may be essential for the creation of the high velocity maser features and for their variability (Galeev and Sunyaev 1972, Montes 1977). It should be noted that Compton solitons are formed only at positive velocities (red features) while the maser features are observed both at positive and negative velocities relative to the central structures.

Radhakrishnan et al. (1975) noted that satellite radiation that is essentially HVF may appear as a result of stimulated Raman scattering of maser radiation. Raman scattering is the inelastic scattering of radiation from molecules. A photon can gain or lose an energy ΔE in this scattering process, where ΔE is the energy separation of two of the molecular levels. Boyd (1977) investigated this idea. He found that the best candidate for the scattering agent is the ammonia molecule. He showed that there are some difficulties in the Raman interpretation of high velocity H_2O features. The main difficulty seems to lie in the fact that there is very little chance of the features occurring at negative velocity (anti-Stokes scattering). Besides, a very high density of ammonia ($n_{NH_3} \sim 10^{11} cm^{-3}$) is required, and the population of the hyperfine levels must be in equilibrium. The models of HVF with both Compton solitons and stimulated Raman scattering have one more important limitation connected to the fact that the HVF produced in such a way must be generated in the same spatial region as the low velocity maser features, a requirement that again contradicts the observations (Genzel et al. 1978).

Burdyuzha (1978), Fernandez and Reinisch (1978), and Burdyuzha et al. (1979) suggest that HVF are the Langmuir satellites of maser radiation at frequencies $\omega_0 \pm \omega_e$ (ω_0 is the cyclic frequency of the maser radiation, ω_e is the plasma frequency). Langmuir satellites arise from the interaction between maser emission and turbulent plasma as a result of merging and decay processes. In the paper by Fernandez and Reinisch (1978), the possibility of satellite generation by maser emission itself is considered within the limits of a one-dimensional model without blue-shifted satellites. We have considered the case where the plasma is excited by external turbulence i.e. a shock wave. We resort to the shock wave model because the plasma turbulence level W^ℓ which is excited by maser emission is very small ($W^\ell \sim 6 \times 10^{-25}$ erg cm^{-3} for $W^t \sim 10^{-11}$ erg cm^{-3}). A plasma turbulence level $W^\ell \sim 10^{-3} n_e k\, T_e$ is produced by the shock waves which occur in the vicinity of a newborn O star (Burdyuzha and Ruzmaikina 1974, Cochran and Ostriker 1977). We assume that the symmetric LVF and HVF were formed while maser emission passed through the turbulent medium. Various electron densities from $n_e \sim 10^4$ to $n_e \sim 10^6$ cm^{-3} are necessary. The relation between the plasma density and the separation of features in velocity takes the form:

$$n_e \sim 0.7 \times 10^2 \times (\Delta V \text{ km s}^{-1})^2 \text{cm}^{-3} \tag{4}$$

The approximate formula correlating the turbulent plasma length with its density n_e and temperature T_e is

$$\Delta Z \sim 2.5 \times 10^{24} \times A^{-1} B\ n_e^{-3/2} T_e^{-1/2} \text{ cm} \tag{5}$$

where A is the degree of excitation of the cosmic plasma, and B is the ratio of the intensity of the H_2O satellites to the intensity of the radiation at the basic frequency. The observed ratio of intensities is $\sim 10^{-2}$ (Goss et al. 1976). The Langmuir satellites propagate in a direction which differs from the direction of propagation of the basic signal. The approximate formula describing the angle between the direction of propagation of scattered and incident radiation is

$$\Theta/2 \sim 0.005 n_e^{1/2} T_e^{-1/2} \tag{6}$$

An H_2O maser with the dimensions ($10^{13} \times 10^{13} \times 10^{15}$) cm appears as a small elongated cloudlet in the gas-dust shell of a young O star. The H_2O maser radiation propagating in a region with $n_e \sim 10^4$ cm^{-3} and $T_e \sim 10^3$K produces symmetric features with $\Delta V \sim 12$ km s^{-1}. With $n_e \sim 10^4$ cm^{-3} and $T_e \sim 10^3$K the angle of scattering is still rather small, and the interferometric picture shows the low velocity maser features in regions with an area of $10^{15} \times 10^{16}$ cm^2 (the centers of activity). As the maser radiation propagates through a region with higher density, $n_e \sim 10^6$ cm^{-3} (the region behind the dust front of the shock wave) the angle of scattering and the plasma frequency ω_e increase. This creates HVF at frequencies $\pm\omega_e$, i.e. velocities $\Delta V = \pm 40$ to 200 km s^{-1}. These HVF are spread over a much larger area ($10^{16} \times 10^{17}$ cm^2 and more) around the LVF. The observed asymmetry in the distribution of LVF (Goss et al. 1976, Morris 1976) may be due to the inhomogeneity of the electron density and plasma velocity behind the shock wave front at 10^{16}-10^{17} cm in the spatial plane. An observer sees the integrated effect caused by inhomogeneities of density or velocity. Of all the predictions made on the basis of this model the most interesting is that superhigh velocity features with $\Delta V \sim \pm 1200$ km s^{-1} must be present in the H_2O radiation from IR stars.

Summing up this brief survey, I should like to say that for a better understanding of the phenomenon of "high velocity H_2O masers" we need more information on the movement of both high velocity and low velocity features.

REFERENCES

Boyd, R.W.: 1977, Publ. Astron. Soc. Pacific 89, pp. 141-146.

Burdyuzha, V.V., and Ruzmaikina, T.V.: 1974, Astron. Zh. 51, pp. 346-353.

Burdyuzha, V.V., Ruzmaikina, T.V.: 1974, Astron. Zh. 51, pp. 346-353.

Burdyuzha, V.V., Ruzmaikina, T.V.: 1975, Astron. Astrophys. 40, pp. 233-236.

Burdyuzha, V.V., Ruzmaikina, T.V.: 1977, Proceedings of IAU pp. 53-56. Eds. E. Basinska-Grzesik, M. Mayor.

Burdyuzha, V.V.: 1978, Pis'ma Astron. Zh. 4, pp. 555-558.

Burdyuzha, V.V., Charugin, V.M., Tomozov, V.M.: 1979, Astron. Astrophys. (in press).

Cochran, W.D., Ostriker, J.P.: 1977, Astrophys. J. 211, pp. 392-399.

Elmegreen, B.G., Morris, M.: 1979, Astrophys. J. 229, pp. 593-603.

Fernandez, J.C., Reinisch, G.: 1978, Astron. Astrophys. 67, pp. 163-174.

Galeev, A.A., and Sunyaev, R.A.: 1972, Zh. Eksper. Teor. Fis. 63, pp. 1266-1282.

Gammon, R.H.: 1976, Astron. Astrophys. 50, pp. 71-77.

Genzel, R., Downes, D., Moran, J.M., Johnston, K.J., Spencer, J.H., Walker, R.C., Haschick, A., Matveyenko, L.I., Kogan, L.R., Kostenko, V.I., Ronnang, B., Rydbeck, O.E.H., Moiseev, I.G.: 1978, Astron. Astrophys. 66, pp. 13-29.

Genzel, R., Downes, D., Moran, J.M., Johnston, K.J., Spencer, J.H., Matveyenko, L.I., Kogan, L.R., Kostenko, V.I., Ronnang, B., Haschick, A.D., Reid, M.J., Walker, R.C., Giuffrida, T.S., Burke, B.F., Moiseev, I.G.: 1979, Astron. Astrophys. 78, pp. 239-247.

Genzel, R., Downes, D.: 1977a, Astron. Astrophys. Suppl. 30, pp. 145-168.

Genzel, R., Downes, D.: 1977b, Astron. Astrophys. 61, pp. 117-126.

Goss, W.M., Knowles, S.H., Balister, M., Batchelor, R.A.: 1976, Mon. Not. R. astr. Soc. 174, pp. 541-549.

Kukolich, S.G.: 1969, J. Chem. Phys. 50, pp. 3751-3756.

Little, L.T., White, G.I., Riley, P.W.: 1977, Mon. Not. R. astr. Soc. 180, pp. 639-656.

Montes, C.: 1977, Astrophys. J. 216, pp. 329-337.

Morris, M.: 1976, Astrophys. J. 210, pp. 100-107.
Moran, J.M., Reid, M.J., Lada, C.J., Yen, J.L., Johnston, K.J., Spencer, J.H.: 1978, Astrophys. J. (Letters) 224, pp. L67-L71.
Norman, C., Silk, J.: 1979, Astrophys. J. 228, pp. 197-205.
Radhakrishnan, V., Goss, W.M., Bhandari, R.: 1975, Pramana 5, pp. 49-57.
Slysh, V.I.: 1973, Astrophys. Letters 14, pp. 213-216.
Strelnitskii, V.C., Sunyaev, R.A.: 1972, Astron. Zh. 49, pp. 704-711.
White, G.J.: 1979, Mon. Not. R. astr. Soc. 186, pp. 377-381.

DISCUSSION FOLLOWING BURDJUZHA

Field: If I understand you correctly, you postulate a high concentration of electrons and H_2O molecules. It is known that vibrational excitation of H_2O by electrons proceeds at a high rate. Would it not be corroboration of your theory if vibrational transitions in H_2O could be observed? Furthermore, could it possibly be that some of the rotational lines seen in H_2O maser sources (e.g. those with apparently very high Doppler velocities) arise from stimulated emission in vibrationally excited H_2O (1,0,0; 0,1,0 or 0,0,1)?

Burdjuzha: The scattering of H_2O maser radiation occurs in the external plasma, where there may be no H_2O molecules. Thus to speak about excitation by electrons may not be necessary.

Lepine: I made a rough estimate of the frequencies of the 6_{16}-5_{23} rotational transition in excited vibrational states of H_2O. These frequencies fall off by several GHz from the ground vibrational transition at 22 GHz, and thus cannot explain high velocity features. However a search for these lines could be interesting, if accurate vibration-rotation interaction constants were available.

Burdjuzha: This idea is interesting, but it requires accurate calculation. Possibly the shift will be only to one side. A shift of a few GHz is very big.

de Jong: The central region in your model has an electron density of $\sim 10^4 cm^{-3}$ and a radius of $\sim 10^{16}$cm. Such a region should be a strong source of free-free radio emission, which in spite of several attempts has never been detected. How do you account for this?

Burdjuzha: If the low velocity features are interpreted as satellite lines of the maser emission then really rather high emission measures ($\sim 3.10^5 cm^{-6}$pc) must be present. In general it is more realistic to say that the low velocity features are identified with the cloudlets and that only the high velocity features are satellite lines. However, according to this model there must be weak free-free radiation from maser sources.