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# STIMULATED RAMAN SCATTERING AND THE EXTREME HIGH-VELOCITY $H_2O$ MASER FEATURES IN W49

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Stimulated Raman scattering of the intense 22.2 GHz water-vapor maser radiation within W49 is examined as a possible explanation of the extremely broad spectrum of W49 extending to ± 200 km $sec^{-1}$ apparent Doppler velocity. Under the most favorable conditions, Raman scattering from ammonia molecules is calculated to be observable. It is unlikely that the Raman process contributes appreciably in the case of W49, as it fails to predict the observed spatial and spectral distribution of the radiation.

*Key words:* Raman scattering — nonlinear propagation — $H_2O$ masers — high-velocity features — W49

## Introduction

It has been recognized for some time that the very great intensities associated with the strong water-vapor masers could induce various nonlinear effects in the propagation of the maser radiation. Brightness temperatures as high as $10^{15}$° K have been inferred from very long baseline interferometer (VLBI) observations of the $6_{16} \rightarrow 5_{23}$ transition of $H_2O$ at 22.23522 GHz in the source W49. This temperature implies photon occupation numbers as large as $10^{15}$ and electric field strengths of about 0.0076 esu. As these values are comparable to the output of laboratory lasers, the possibility of nonlinear effects is suggested.

In this connection, it is intriguing to try to interpret the extremely broad spectrum of the water-vapor emission in W49 as the result of some nonlinear effect. Figure 1 shows the spectrum of the water-vapor emission from W49 A. The spectrum is composed of a series of components, each about 2 km $sec^{-1}$ wide, within a spectral region of some 400 km $sec^{-1}$. The asymmetry is striking, in particular the negative velocity part of the spectrum is both stronger and has a higher background level between spectral components.

One is hard pressed to explain this 400 km $sec^{-1}$ apparent width as a true Doppler effect (Radhakrishnan, Goss, and Bhandari 1975). The asymmetry of the spectrum is not readily explained by systematic or by turbulent motions. Furthermore, 400 km $sec^{-1}$ is an unprecedented velocity dispersion for a small region of interstellar space where 20 km $sec^{-1}$ is a more conventional random velocity.

We can calculate the total mass required for W49 to be gravitationally bound and yet maintain a velocity dispersion of ± 200 km $sec^{-1}$. Assuming a distance of 14 kpc to W49, the interferometric observations of Knowles et al. (1974) yield a size for the entire masing region of about 0.1 pc. Then the virial theorem requires that

$$\mathfrak{M} \sim \frac{v^2 r}{G} = 10^6 \, \mathfrak{M}_\odot \quad .$$

The total density would be $10^9 \, \mathfrak{M}_\odot$ $pc^{-3}$ or $10^{11}$ atoms $cm^{-3}$, which is unusually high for extended regions of space.

Conversely, if the W49 cloud is not bound, we would expect it to disrupt in a time approximately equal to its size divided by its velocity dispersion or about 500 years.

While these arguments cannot completely rule out the Doppler effect as the source of the wide emission spectrum of W49, they do suggest that the Doppler interpretation is perhaps not correct, and encourage us to turn to somewhat more exotic explanations.

## Nonlinear Effects

Slysh (1973) considered the resonance Stark effect and concluded that the effect could produce frequency splittings of about 2 km $sec^{-1}$ in the 22.2 GHz water vapor lines of W49. This is comparable to the observed line width of individual components, and hence could produce measurable results. However, this effect is much too small to account for the 400 km $sec^{-1}$ total width of the spectrum.

Stimulated Raman scattering in astronomical masers has been considered by Litvak (1971), Sullivan (1973), and Radhakrishnan et al. (1975). The latter authors make the interesting suggestion that the broad emission spectrum of W49 is in fact due to this effect. The main purpose of the present paper is to explore this suggestion and to estimate the expected magnitude of the effect. It will be shown that the stimulated Raman effect is sufficiently intense to be observable under the most favorable of conditions, but that it cannot account for the detailed spatial and spectral distribution observed in W49. The wide spectrum of W49

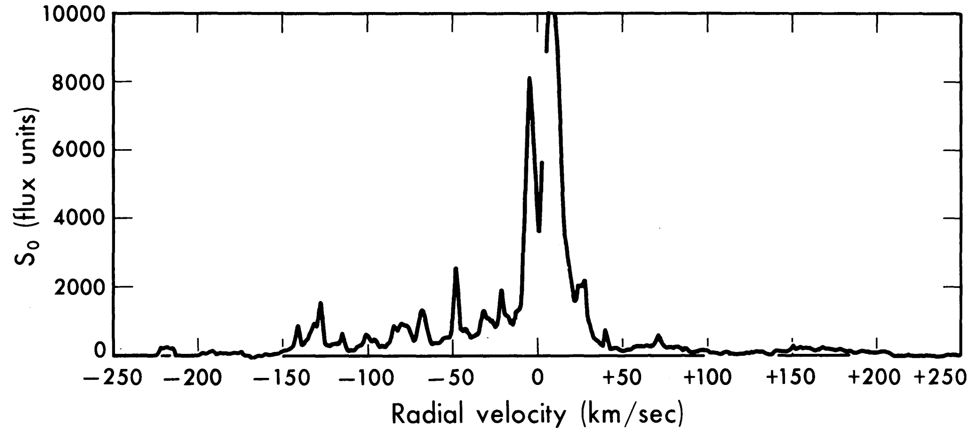


FIG. 1 — High-velocity $H_2O$ emission profiles of W49 taken 1969 May 29 to 1969 June 8 by Sullivan (1973).

thus remains something of a mystery.

### Stimulated Raman Scattering

Raman scattering is the inelastic scattering of radiation from molecules; a photon can gain or lose the energy $\Delta E$ in this scattering process where $\Delta E$ is the energy separation of two of the molecular levels. Raman scattering could thus provide a very natural explanation for the wide spectrum of W49 if, for example, the high-intensity maser field were Raman scattering from molecules near the maser and creating the lines in the wings of the spectrum of Figure 1. Raman scattering is usually characterized by small transition probabilities and hence low efficiency of converting radiation from the original frequency to the Raman-shifted frequencies. However, for the case of large field intensities, the closely related process of stimulated Raman scattering can become important. Stimulated Raman scattering is often characterized by frequency conversion approaching unit efficiency. As the field strengths associated with the astronomical masers are well within the range where the stimulated Raman effect is important, only this case will be considered in the following.

Consider the energy level diagram of Figure 2. The molecule makes a transition from level $i$ to level $f$ by absorbing a photon of energy $\hbar\omega_p$ and emitting a photon of energy $\hbar\omega_s$. This process in which the photon loses energy is called Stokes emission; anti-Stokes emission, to be discussed later, is the process in which the photon gains energy by Raman scattering. For stimulated Raman scattering (Ducuing 1969), the intensity grows exponentially according to

$$I_s(z) = I_{s0} e^{gz} \quad , \tag{1}$$

where the gain coefficient is given by

$$g = \frac{2\pi^2 E_p{}^2 \Delta N}{\lambda_s \hbar^3 \Delta\omega_{if}} \left| \sum_n \frac{(\mu_{fn} \cdot \epsilon_s)(\mu_{ni} \cdot \epsilon_p)}{\omega_{ni} - \omega_p} \right|^2 \quad . \tag{2}$$

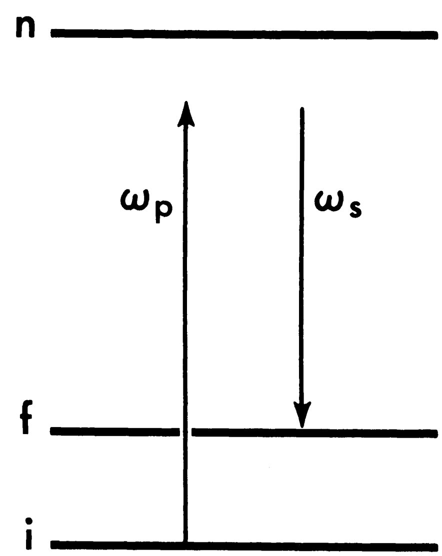


FIG. 2 — The Raman scattering process is illustrated. An incident photon of energy $\omega_p$ is Raman scattered to a photon of energy $\omega_s$. Simultaneously, the molecule makes a transition from level $i$ to level $f$. The transition rate for this process is enhanced as the photon energy $\omega_p$ approaches the energy difference between level $i$ and level $n$.

The intensity grows exponentially from the initial value $I_{s0}$, which could be the intensity of a thermal source imbedded in the maser, or could be the isotropic 3° K background if no such source is present. The gain coefficient actually contains additional terms involving $(\omega_{ni} + \omega_p)^{-1}$, but these terms are negligible compared to the term involving $(\omega_{ni} - \omega_p)^{-1}$ when $\omega_p$ is near resonance. Only the resonant term will be considered in this calculation. $E_p$ is the electric field amplitude of the water vapor maser, $\Delta N$ is the difference in the populations of a magnetic sublevel of level $i$ and a magnetic sublevel of level $f$, and $\lambda_s$ is the wavelength of the Stokes radiation. The $\mu_{jk}$ are the appropriate dipole matrix elements. $\epsilon_p$ and $\epsilon_s$ are polarization unit vectors for the pump and Stokes waves, respectively, $\hbar\omega_{ni}$ is the energy separation of levels $i$ and $n$, and $\Delta\omega_{if}$ is equal to $\omega_{fi} - (\omega_p - \omega_s) + i\Delta\omega$, where $\Delta\omega$ is the natural line width of the $f \rightarrow i$ transition. Equations (1) and (2) as written pertain to the case of monochromatic pump and Stokes waves. In the present case, the line width of the pump radiation is much broader than the natural line width of typical microwave transitions, and is no narrower than the spread in $\Delta\omega_{if}$ due to Doppler broadening. Thus, to good approximation, equations (1) and (2) can be applied to the present case by taking $\Delta\omega_{if}$ equal to the observed line width of the pump radiation.

In order to proceed, the molecule involved in the Raman transition must be specified. We have no direct evidence of what molecule this is, but we note from equation (2) that the gain coefficient will be particularly large if the molecule has a transition frequency near $\omega_p$, the water-vapor maser frequency. In fact, the (3, 1) inversion transition of ammonia is remarkably close to this frequency. There is no other molecule which is a better candidate than $NH_3$, since $NH_3$ is a reasonably abundant molecule, and is closer to resonance than any more abundant molecule. In the discussion to follow, it will be assumed that ammonia is the molecule actually responsible for the Raman scattering, although the analysis is more general and would apply to any of a number of molecules.

The $NH_3$ energy levels under consideration are shown in Figure 3. The inversion splitting of $NH_3$ for the (3, 1) level is 22.234 GHz, which is only 0.69 MHz off resonance from the water-vapor maser frequency. Each of these levels is further split by the electric quadrupole hyperfine interaction. If, for example, we take the lower $F = 3$ level as the initial state, and the lower $F = 2$ level as the final state, the sum over intermediate states will extend over the upper $F = 2$ and $F = 3$ states. In order to calculate the gain coefficient, we take $E_p = 7.6 \times 10^{-3}$ esu, $\lambda_s = 1.35$ cm, $\omega_{ni} - \omega_p = 2\pi$ (690 KHz), and $\Delta\omega_{if}/2\pi = 75$ KHz (the observed width of the W49 emission lines). For the present case involving unpolarized pump and Stokes radiation, the quantity $|\mu_{fn}{}^2\,\mu_{ni}{}^2|$ can be shown to be equal to $9.7 \times 10^{-4}\,\mu_0{}^2$, where $\mu_0 = 1.468 \times 10^{-18}$ esu is the permanent dipole moment of ammonia (Townes and Schawlow 1955, Appendix I). We then calculate

$$g = 3.8 \times 10^{-16}\,\Delta N \quad .$$

Stimulated Raman scattering will be intense only if $gL \gg 1$, and in fact the observations suggest $gL \sim 30$. Here $L$ is the size of an individual emitting region, and VLBI measurements indicate that $L$ is about $10^{14}$ cm. In order to estimate $\Delta N$, let us first assume that the energy levels of ammonia are popu-

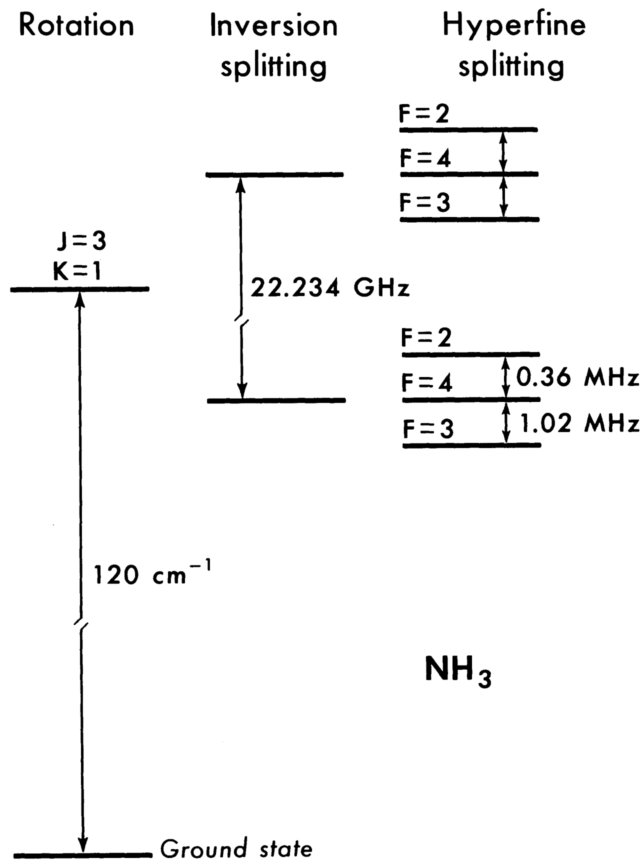


FIG. 3 — The energy levels of $NH_3$ considered in this paper are illustrated.

lated according to thermal equilibrium at 300° K, a temperature commonly assumed for a masing region. At this temperature nearly all of the ammonia will be in the ground vibrational state; the fraction of ammonia in the (3, 1) rotational state will be 0.05 (Townes and Schawlow 1955, p. 76) and the fractional difference in population between upper and lower hyperfine levels will be $h\nu/kT = 1.6 \times 10^{-7}$. Then $\Delta N$ will be related to the total ammonia density $N$ by $\Delta N = 8.0 \times 10^{-9}\,N$, and the condition for sufficiently intense Raman scattering requires the extremely large ammonia density of $1.0 \times 10^{11}$ cm$^{-3}$.

The required density can be considerably reduced if the requirement of thermal equilibrium is removed. It is well established that thermal disequilibrium can exist in interstellar clouds, and indeed the astronomical masers are one of the more impressive consequences of this occurrence. In the present case, we hypothesize that the populations of the hyperfine levels are out of equilibrium in such a way as to yield a fractional population difference closer to one than to the value of $1.6 \times 10^{-7}$ obtained in the thermal equilibrium calculation. Disequilibrium population of hyperfine levels is somewhat less usual than other types of disequilibrium, as radiative pumping is almost certainly required to produce the effect, but examples of this phenomenon are known. Anomalies in the hyperfine structure of the $J = 0 - 1$ transition of HCN in the Orion nebula have been studied by Snyder and Buhl (1973) and Wannier et al. (1974), and have been interpreted by Kwan and Scoville (1975). Recently, Matsakis et al. (1977) observed the (1, 1) inversion transition of $NH_3$ in DR21 and found that the population of the hyperfine levels was out of thermal equilibrium with fractional population differences as large as 0.06.

If it is assumed that the fractional population difference between the relevant hyperfine levels is 0.01 for the present case, the ammonia density required for intense Raman scattering must be approximately $1.6 \times 10^6$ cm$^{-3}$. This is probably not an impossibly large ammonia number density. The ammonia-to-total-particle number-density ratio could be as large as $10^{-4}$ if the entire cosmic abundance of nitrogen in the masing region were in the form of ammonia, although $10^{-5}$ is probably a more realistic upper limit. If the ratio were $10^{-5}$ the total density would be $1.6 \times 10^{11}$ cm$^{-3}$, and in fact densities this large or larger seem to be required to account for the high intensity output of the water-vapor masers. This follows from assuming that at least one collision is involved in producing each microwave photon, and using normal valves for collisional cross sections and temperatures. At a density of $1.6 \times 10^{11}$ cm$^{-3}$ the collision rate per molecule is 24 sec$^{-1}$ at 300° K. This creates some difficulty in obtaining disequilibrium hyperfine populations, as the $A$ coefficients for the allowed rotational transitions involving the masing levels are in the range of 0.1 sec$^{-1}$, and the greater frequency of collisions would be expected to equilibrate the hyperfine populations. Furthermore, the thermal Doppler width of the rotational transitions is about 10 MHz, and hence these transitions could produce only small fractional differences in the populations of hyperfine levels whose separations are about 1 MHz. It thus appears unlikely, but not completely impossible, that sufficient disequilibrium could exist in the case of W49.

## Discussion

It was shown in the previous section that, under the assumption of disequilibrium populations of the initial and final hyperfine levels, sufficient gain exists for Stokes emission to be present in the spectrum of W49. In this section a number of effects will be considered, each of which tends to complicate this simple analysis. The general conclusion, however, will be that the Raman model does not in any simple form appear to be consistent with the observations.

The Raman model has difficulty in predicting all of the spectral features which appear in Figure 1. This observed spectrum shows subsidiary features on both sides of the main peak. Stimulated Stokes scattering would produce features only on the positive velocity side. In laboratory experiments, stimulated anti-Stokes scattering can produce intense components shifted to higher frequency, but stimulated anti-Stokes cannot be an efficient process for astronomical masers. This is because stimulated anti-Stokes scattering is a phase-matched process, and thus the anti-Stokes wave can interact with (i.e., extract energy from) only that part of the Stokes and pump fields which is in the same spatial mode as it. This is to say that the anti-Stokes process requires the wave vectors $\mathbf{k}$ of all three waves to be colinear, whereas the Stokes process allows the Stokes wave vector to have any direction. In order of magnitude, the anti-Stokes process would be expected to be less intense than the Stokes process by the total number of spatial modes into which the Stokes can radiate. This number is of order $A/\lambda^2$, where $A$ is the cross-sectional area of a maser, yielding a ratio of about $10^{28}$.

The Raman scattering model thus is unable to account for the high negative velocity features, unless it is assumed that these features originate in regions where the initial and final Raman states are actually inverted. In this case, the theory for stimulated Stokes scattering would apply, but the frequency shift would be positive. In any case, the largest frequency shift available from ammonia is 19 km sec$^{-1}$. Thus, the observed shift of 200 km sec$^{-1}$ would have to result from tenth-order Raman scattering, i.e., the first-order Stokes wave, which we have been considering until now, grows in intensity until it can act as a pump and scatter into a second-order Stokes wave at an even longer wavelength, etc. In fact, high-order stimulated Raman scattering is observed in laboratory experiments (Garmire, Pandarese, and Townes 1963). However, the water-vapor maser would have to be sufficiently intense to supply energy to all of the masing orders, and this places a difficult constraint on the Raman model.

Up to this point, it has been implicitly assumed that the masers radiate nearly isotropically, and have the sizes indicated by the VLBI measurements. The predictions are modified if these assumptions are not valid and, in fact, there has been some question as to the relation between the true size of an astronomical maser and the size inferred from VLBI measurements. The true size of an astronomical maser could be larger than the size inferred from VLBI if the radiation from a small region were being coherently amplified in passing through a larger region (Litvak 1971). Conversely, scattering of the maser radiation from inhomogeneities in the electron density near the source or in the in the interstellar medium could distort the maser wavefronts and make the inferred size larger than the true size. This effect is not expected to be important at wavelengths as short as 1.35 cm (Boyd and Werner 1972). If the true maser size is $\alpha$ times the size as determined by VLBI, the true electric field strength will be $\alpha^{-1}$ times as large as the value previously given, and $gL$, the total gain, will be $\alpha^{-1}$ times as large. If the maser radiates into a solid angle $\Omega$ less than $4\pi$ steradians, the electric field strength will be decreased by the factor $(\Omega/4\pi)^{1/2}$. It is unlikely that either of these effects would produce more than a factor of 10 correction to the predicted Raman intensities, as rather special geometries are required for either effect to be large.

Saturation effects, while present, should not play a great role in limiting the Raman output of the maser cloud. A collision rate comparable to the Raman transition rate will insure that saturation is not too severe a problem. However, as mentioned previously, the collision rate must be at least comparable to the average net transition rate for the masing $H_2O$ molecules. Thus, it is insured that the $NH_3$ transitions are not badly saturated, at least to the extent that the $NH_3$ and $H_2O$ densities are comparable.

An important difficulty with the Raman model is provided by the high spatial resolution maps of the negative high-velocity features provided by Knowles et al. (1974), one of which is shown in Figure 4. In general, each frequency component is seen to come from a different direction in the sky. In its simplest form, the Raman model would predict that all the frequency components originate in the same source, in contradiction to what is observed. One could explain these observations in terms of a Raman scattering model if the maser radiation were highly directional. Then one would simply hypothesize that the not-observed low-velocity pumping frequencies are not beamed in our direction. Furthermore, the particulars of the relaxation processes operating in each masing cloud would determine which order of Raman scattering would be most intense for that cloud. This would explain why different frequencies are seen from different clouds.

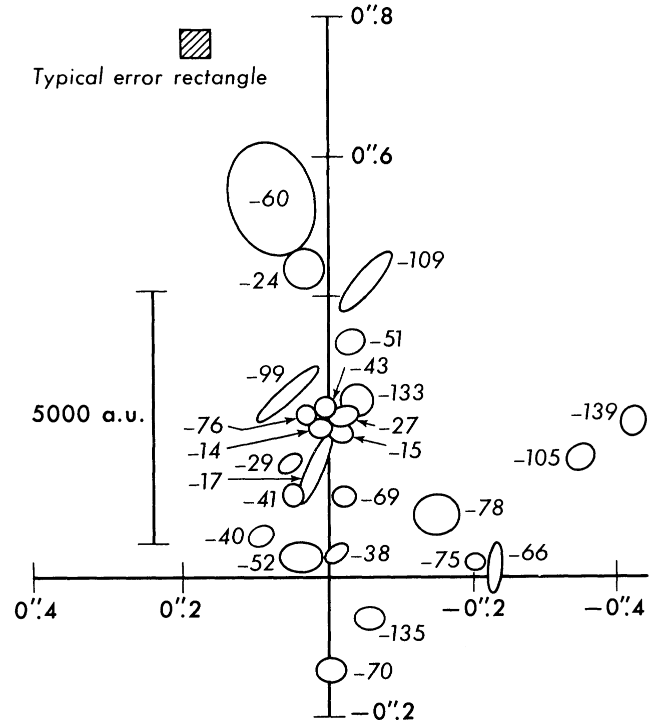


FIG. 4 — Negative high-velocity map of W49 taken in December 1972 by Knowles et al. (1974). Numbers within or near each ellipse refer to the radial velocity of that feature.

## Conclusions

If the W49 maser sources are of the size indicated by VLBI measurements, and if the initial and final Raman states are in thermal equilibrium at any reasonable temperature, the stimulated Raman effect is orders of magnitude too weak to provide the observed intensity at high apparent velocities. However, if the initial and final states are out of equilibrium by amounts comparable to the observed disequilibrium of ammonia in DR21, the Raman gain becomes large enough to provide the observed intensities. Even if this is the case, it is very difficult for the Raman model to explain the observed spectral dependence and spatial dependence of the masers unless rather contrived assumptions are made regarding pumping rates and source geometry. Thus, while stimulated Raman scattering appears to be a possible astronomical process, it does not provide an acceptable model for the W49 maser. This conclusion regarding W49 was recently stated independently by Heckman and Sullivan (1976) using somewhat different arguments.

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