In previous calculations for the luminosities of 22 GHz water masers, the pumping is reduced and ultimately quenched with increasing depth into the gas because of trapping of the infrared (\(\approx 30-150\) \(\mu m\)), spectral line radiation of the water molecule. When the absorption (and reemission) of infrared radiation by dust grains is included, we demonstrate that the pumping is no longer quenched but remains constant with increasing optical depth. A temperature difference between the grains and the gas is required. Such conditions are expected to occur, for example, in the circumnuclear masing environments created by X-rays in active galaxies. Here, the calculated 22 GHz maser luminosities are increased by more than an order of magnitude. Application to the well-studied, circumnuclear masing disk in the galaxy NGC 4258 yields a maser luminosity near that inferred from observations if the observed X-ray flux is assumed to be incident onto only the inner surface of the disk.

**Subject headings:** circumstellar matter -- galaxies: active -- masers

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### 2. CALCULATIONS

To illustrate the influence of the grains, we present a direct comparison with the previous calculations. We thus use methods similar to those of NMC to calculate the emissivity \(\Phi_{\text{em}}\) (photons s\(^{-1}\) cm\(^{-2}\)) of a saturated maser as a function of depth into a thick slab of gas that is infinite in the directions parallel to the planar interface. Escape of the infrared radiation involved in determining the populations of the masing states is only allowed to occur through the interface and is treated using the “escape probability” approximation, in which there is no velocity gradient. To perform these computations, we have modified the code described elsewhere (Anderson & Watson 1990) to incorporate the emission and absorption of infrared radiation by dust grains, to utilize static (rather than large velocity gradient [LVG]) escape probabilities, and to utilize more recent cross sections (Green, Maluendes, & McLean 1993). By straightforward analysis, we find that the influence of the dust grains can be incorporated by modifying the usual rate equations (e.g., Anderson & Watson 1993, eq. [11]) for the populations in the escape probability approximation to read

\[
\sum_{i<j} (g_i C_i n_i - g_j C_j n_j) + \sum_{j>i} g_j A_j [n_i (\beta_j + \beta_j) + (n_i - n_j) S_i \beta_j] - \sum_{j>i} g_j A_j [n_i (\beta_j + \beta_j) + (n_i - n_j) S_i \beta_j] = 0, \quad (1)
\]

in which \(n_i\) and \(n_j\) refer to the populations (per magnetic substate) of states \(i\) and \(j\) of H\(_2\)O in the gas, \(g_i\) and \(g_j\) to the...
The general agreement between our comparison, we also show the results of similar calculations performed in the manner described above. For disk (0.1 pc). In Figure 1, we present the results of our calculations for \( \beta_0 \) and \( \beta_0' \):

\[
\beta_0 = \left[ 1 + \tau_i \left( 2\pi \ln \left( 2.13 + \tau_i \right) \right)^{1/2} \right]^{-1},
\]

(2)

where

\[
\delta_i = \frac{2 \alpha_i}{1 + 2 \alpha_i} \left( \ln \left( \frac{2.72 + \frac{1}{\pi \alpha_i}}{1} \right) \right)^{1/2},
\]

(3)

in which \( \tau_i \) is the optical depth to the surface of the slab at the center of the \( \nu_i \) spectral line of H\(_2\)O, \( \tau_i \) is the optical thickness to the edge of the slab due to dust at the wavelength of the \( \nu_i \) line, and \( \alpha_i = \tau_i / \tau_{i0} \). For \( \tau_i \) we use an approximation based on Laor & Draine (1993; see their Fig. 6) as a benchmark: \( \tau_i = \tau_{i0} n(H)/10^{23} \text{ cm}^{-2} \), \( \lambda < 50 \mu \text{m} \) and \( \tau_i = \tau_{i0} (50 \mu \text{m} / \lambda)^3 n(H)/10^{23} \text{ cm}^{-2} \), \( \lambda > 50 \mu \text{m} \), in which \( n(H) \) is the column density of hydrogen nuclei to the edge of the slab and \( \tau_{i0} = 1 \).

Calculations are also performed with different \( \tau_i \) and wavelength dependences to verify that modest uncertainty in the assumed properties of the grains leads to only modest changes in our results. There is, of course, uncertainty in \( \tau_i \). To obtain \( \Phi_{\text{sat}} \), the radiative terms in the rate equations (1) that represent the 22 GHz maser transition are replaced by \(-R(n_{i0} - n_i)\) in the equation for the upper state (\( i = u \)) and by \( R(n_{i0} - n_i) \) in the equation for the lower state (\( i = l \)). Equations (1) are then solved numerically as a function of \( R \) to obtain the limiting constant value \( \Phi_{\text{sat}} = R(n_{i0} - n_i) \) as \( R \to \infty \). In previous investigations, \( \Phi_{\text{sat}} \) has been obtained by first computing \((n_{i0} - n_i)\) from the rate equations in the unsaturated limit (\( R = 0 \)) and then multiplying this quantity by an effective loss rate. Potential ambiguities arise (at least to us) in determining an effective loss rate. However, with the loss rate as specified in Anderson & Watson (1993), we find that the two methods yield similar \( \Phi_{\text{sat}} \) values for the regions of most interest here.

To perform the calculations, the gas density, kinetic temperature, and H\(_2\)O fractional abundance within the slab of gas must be specified. Fortunately, these quantities have already been computed by NMC (see their Fig. 2) for an incident X-ray flux that is essentially identical with that inferred for the X-ray luminosity of NGC 4258 \( \left( \approx 10^{44} \text{ ergs s}^{-1} \right. \) above 1 keV; Makishima et al. 1994) incident onto a gas with a pressure of \( 10^{11} \text{ K cm}^{-3} \) at the distance of the inner radius of the masing disk (0.1 pc). In Figure 1, we present the results of our calculations performed in the manner described above. For comparison, we also show the results of similar calculations from Figure 2 of NMC. The general agreement between our calculations for \( \Phi_{\text{sat}} \) with no dust and the analogous calculations by NMC is evidence of the general consistency of the calculational methods (but see below).

The influence of dust on \( \Phi_{\text{sat}} \) is illustrated by our other calculations presented in Figure 1. It is seen most clearly by comparing the two solid lines which, when integrated to an appropriate depth to obtain the maser luminosity, differ by a factor of about 20 (see § 3). Calculations are also presented in which the dust temperature is 300 K and in which it is equal to the gas kinetic temperature \( T_K (\text{gas}) \) and differs from \( T_K \) by 10 K. Modest changes (up to a factor of 3 or so) in the velocity dispersion \( \Delta v \) or the dust parameter \( \tau_{i0} \) will result in comparable fractional changes in \( \Phi_{\text{sat}} \). In § 3 we reason that the gas kinetic temperature should be about 200 K in the masing gas for NGC 4258, and thus the presence of dust can cause a major increase in the total maser luminosity. The result in Figure 1 that \( \Phi_{\text{sat}} \) is essentially constant (except near the boundary) when dust is present reflects the fact that absorption is more important than escape for infrared spectral line radiation. Once the column density of H\(_2\)O to the boundary is large enough to cause sufficient scatterings that the accumulated path length of a photon becomes equal to the mean free path for absorption by dust (which occurs when \( \tau_e \approx 0.1 \)), further increase in the column density of H\(_2\)O (and hence the depth into the slab) is unimportant. After this number of scatterings, the photon is destroyed through absorption by dust grains.

The result that \( \Phi_{\text{sat}} \) becomes constant can also be seen in equations (1), (3), and (4). With increasing depth into the slab, \( \beta_0 \) dominates \( \beta_{0'} \) and becomes independent of depth, 

\[
\beta_0 \to \frac{2 \alpha_i}{1 + 2 \alpha_i} \ln \left( \frac{2.72 + \frac{1}{\pi \alpha_i}}{1} \right)^{1/2},
\]

since the ratio \( \tau_e / \tau_i \) is independent of depth. Equation (1) and its solutions must then also become independent of depth into the slab, as seen in Figure 1. The presence of dust thus results in a lower limit to the escape probability. In detail, our calculations for \( \Phi_{\text{sat}} \) in Figure 1 are somewhat different from...
those of NMC. This is partly compensated by our use of $\Delta v = 2 \text{ km s}^{-1}$ versus their $\Delta v = 1 \text{ km s}^{-1}$. After the original version of this Letter was submitted, D. Neufeld and P. Maloney kindly made available the exact variation with depth of the physical conditions used for calculating $\Phi_{\text{out}}$. When these are used, we have verified that the effect of dust is changed negligibly from that indicated in Figure 1.

3. DISCUSSION

Most of the radiation from a compact nuclear source (optical, ultraviolet, soft X-rays) will be absorbed near the inner interface when the slab of gas has an optical depth greater than a few at 50 $\mu$m, as is relevant here. This energy will be processed into infrared radiation that will be absorbed (and re-emitted) to maintain the temperatures of the dust grains in the slab. The benchmark temperature for the dust grains is then the effective blackbody temperature of the grains in the slab. The benchmark temperature for the dust (and re-emitted) to maintain the temperatures of the dust will be processed into infrared radiation that will be absorbed near the inner interface when the slab of gas has an optical depth (optical, ultraviolet, soft X-rays) will be absorbed near the inner interface when the slab of gas has an optical depth.

Beyond the depth at which the optical depth $\tau_{\text{opt}}$ of the masing gas is recognized to be greater than $\tau_{\text{opt}} = 0.13$ pc from the compact source in NGC 4258. In contrast, when this X-ray flux is incident onto the interface of the slab of gas used in Figure 1, it creates the gas kinetic temperatures of $\approx 400-600$ K that are used in the calculations for Figure 1. Although the grains and the gas exchange energy through collisions and through the emission and absorption of infrared radiation, the additional energy input to the gas due to photoionization by the X-rays causes the calculated temperature difference. Based on the above information, this difference in temperature between the grains and the gas is large enough that the $\Phi_{\text{out}}$ values calculated in the “cold dust” limit are adequate approximations.

To obtain the true (i.e., integrated over angles of emission) maser luminosity to compare with observations, $\Phi_{\text{out}}$ must be integrated over the masing volume. For a ring of thickness $h$ with an inner radius $R$, the maser luminosity is

$$L_\text{m} = 2 \pi h v R h \int \Phi_{\text{out}} dR,$$

where the radial extent of the masing gas is recognized to be much less than $R$. Beyond the depth at which the optical depth for Thomson scattering is about 1 [$N(\text{H}) = 1.5 \times 10^{18}$ H nuclei cm$^{-2}$], the X-ray heating is significantly decreased. We thus terminate the integral in equation (5) at this depth, which corresponds to $4 \times 10^{18}$ cm in Figure 1. For the “cold dust” curve in Figure 1, $h v \Phi_{\text{out}} dR$ is thus 3800 $L_\odot$ pc$^{-2}$. Then, from the published observations of the disk in NGC 4258 [$R = 0.13$ pc and $(h/R) < 0.02$, $L_\text{m} \approx 8 L_\odot$, in agreement with the observed luminosity of $7 L_\odot$ based on the inferred beaming angle (Miyoshi et al. 1995, Table 1). Our value for $h v \Phi_{\text{out}} dR$, and hence for $L_\text{m}$, as well, exceeds that of NMC ($\approx 180 L_\odot$ pc$^{-2}$), which was computed for similar conditions, by a factor of 20. From a similar analysis, NMC concluded that their lower value of $h v \Phi_{\text{out}} dR$ is compatible with the observations. The discrepancy arises in part because the beaming angle adopted by NMC ($\Omega = 2 \pi h/R$) is smaller than that inferred from the observations of NGC 4258. In the interpretation of Miyoshi et al. (1995), the beaming angle is determined by the size of a nuclear continuum source, which is being amplified by the central masers. This source is larger than the thickness of the disk. Since the continuum source has not yet been detected, potential uncertainty remains about this interpretation for the beaming angle. However, $\Omega \approx 2 \pi h/R$ is based on the premise that the gas that creates most of the observed maser flux (the nearly radial central emission) is distributed roughly uniformly over a radial extent of the disk that is comparable to $R$. In contrast, Miyoshi et al. (1995) seem to find that the radial extent of this uniform distribution is much smaller than $R$.

Because of the narrowness of the observed spectral lines of the circumnuclear water masers (as small as a few kilometers per second), the calculations to date have generally utilized similarly small velocity dispersions in calculating escape probabilities. If velocity fields with larger dispersion are present that are not reflected in the observed spectral line profiles, the calculated maser luminosities will be increased. Adopting a larger velocity dispersion in directions orthogonal to the line of sight is evidently one such possibility. The thickness of the observed disk and the apparent need for hydrostatic equilibrium does, however, limit such additional velocity dispersion. The foregoing analysis is based on the premise (as was NMC) that a significant X-ray flux is incident only on the inner surface of the disk of thickness $h$. If X-rays incident on the upper and lower surfaces of the disk due to scattering by the halo or to incidence at grazing angles directly from the central source are important, it is evident that the maser volume will be increased over that included in equation (5) and the maser luminosity will be appropriately increased. However, quantitative assessments of these possibilities do not yet appear to have been presented.

At gas pressures greater than the $10^{14}$ K cm$^{-3}$ observed in Figure 1, the extent (in column density of hydrogen) of the molecular gas created by X-rays that is warm enough for masing is reduced. According to NMC, at (pressure/k) $= 10^{12}$ K cm$^{-3}$ the gas is cool enough that masing is unimportant at depths into the slab for which absorption by dust is important in the pumping. Finally, the absorption and emission by dust at the wavelengths of the spectral lines of the gas can influence the cooling of the gas, as well as the pumping of the maser. However, examination of the cooling rates (Fig. 6 of Neufeld & Kaufman 1993) suggests that this will be of minor importance for the conditions on which Figure 1 is based.

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