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abstract

General solutions of the maser polarization problem are presented for arbitrary absorption coefficients. The results are used to calculate polarization for masers permeated by magnetic fields with arbitrary values of x_B, the ratio of Zeeman splitting to Doppler linewidth, and for anisotropic (m-dependent) pumping. In the case of magnetic fields, one solution describes the polarization for overlapping Zeeman components, $x_B < 1$. The $x_B \to 0$ limit of this solution reproduces the linear polarization derived in previous studies, which were always conducted at this unphysical limit. Terms of higher order in x_B have a negligible effect on the magnitude of q. However, these terms produce some major new results: (1) The solution is realized only when the Zeeman splitting is sufficiently large that $x_B > \sqrt{S_0/J_s}$, where S_0 is the source function and J_s is the saturation intensity (pumping schemes typically have $S_0/J_s \sim 10^{-5}$–10^{-8}). When this condition is met, the linear polarization requires $J/J_s x_B$, where J is the angle-averaged intensity. This condition generally requires considerable amplification, but is met long before saturation ($J/J_s \geq 1$). (2) The linear polarization is accompanied by circular polarization, proportional to x_B. Because x_B is proportional to the transition wavelength, the circular polarization of SiO masers should decrease with rotation quantum number, as observed. In the absence of theory for $x_B < 1$, previous estimates of magnetic fields from detected maser circular polarization had to rely on conjectures in this case and generally need to be revised downward. The fields in SiO masers are $\sim$ 2–10 G and were overestimated by a factor of 8. The OH maser regions around supergiants have fields of $\sim$ 0.1–0.5 mG, which were overestimated by factors of 10–100. The fields were properly estimated for OH/IR masers (0.1 mG) and H_2O masers in star-forming regions ($\sim$ 15–50 mG). (3) Spurious solutions that required stability analysis for their removal in all previous studies are never reproduced here; in particular, there are no stationary physical solutions for propagation at $\sin^2\theta < \frac{1}{3}$, where θ is the angle from the direction of the magnetic field, so such radiation is unpolarized. These spurious solutions can be identified as the $x_B = 0$ limits of non-physical solutions and they never arise at finite values of x_B, however small. (4) Allowed values of θ are limited by bounds that depend both on Zeeman splitting and frequency shift from line center. At $x_B 10^{-3}$, the allowed phase space region encompasses essentially all frequencies and $\sin^2\theta > \frac{1}{3}$. As the field strength increases, the allowed angular region shrinks at a frequency-dependent rate, leading to contraction of the allowed spectral region. This can result in narrow maser features with linewidths smaller than the Doppler width and substantial circular polarization in sources with $x_B 0.1$. When $x_B \geq 0.7$, all frequencies and directions are prohibited for the stationary solution and the radiation is unpolarized.

Another solution describes the polarization when the Zeeman components separate. This occurs at line center when $x_B > 1$ and at one Doppler width when $x_B > 2$. The solution is identical to that previously identified in the $x_B \to \infty$ limit, and applies to OH masers around HII regions. A significant new result involves the substantial differences between the π- and σ-components for most propagation directions, differences that persist into the saturated domain. Overall, HII/OH regions should display a preponderance of σ-components. The absence of any π-components in W3(OH) finds a simple explanation as maser action in a magnetic field aligned within $\sin^2\theta < \frac{2}{3}$ to the line of sight.