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Maser Radiation from a Turbulent Keplerian Disk: NGC 4258

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Abstract. Calculations are summarized for the spectral and spatial distribution of maser radiation that emerges from a turbulent Keplerian disk when viewed nearly edge-on. A close comparison is made with the refined observational data about the masing accretion disk around the presumed massive black hole at the nucleus of the galaxy NGC 4258.

1. Introduction

Spectral line features associated with molecular gas in a variety of astronomical environments indicate that the medium is irregular. This can reflect irregularities in density, composition, excitation, temperature, and velocity—the relative importance of each in creating the spatial variations in the spectral line emission is unclear. Extensive studies of regions of star formation reveal small scale motions (turbulence or waves) with velocities that exceed the speed of sound by a factor of three or so. Together with magnetic fields, these seem to provide the main source of pressure in molecular clouds. In accretion disks, turbulence is closely related to the cause for the viscosity which allows matter to lose angular momentum and fall upon the central object to create luminosity. Because of the "exponential amplification" of maser radiation, its spectral and spatial variations are especially sensitive to irregularities in the masing gas. We have thus undertaken investigations to relate properties of the emergent maser radiation to likely turbulent velocity fields in the masing gas. Calculations for a turbulent slab of masing gas have been related to the 25 GHz methanol masers in OMC-1 for which our idealizations can be an adequate approximation (Sobolev, Wallin, & Watson, in preparation). Because of the refined observational data (Miyoshi et al. 1995) that are available and because of its general importance, we have mostly applied our calculations to the accretion disk around the presumed massive black hole at the nucleus of the galaxy NGC 4258. This disk is observed only in the 22 GHz masing transition of the water molecule.

2. Summary of Results

For the masing accretion disk, turbulent velocity fields are created by statistical sampling from Kolmogorov-like distributions for the power spectra of the velocities. Such distributions are suggested by numerical simulations for the viscosity in accretion disks. The calculations focus separately on the maser emission near the systemic velocity of NGC 4258 (Wallin, Watson, & Wyld 1997) and on the "high velocity" components from the sides of that accretion disk (Wallin, Watson, & Wyld, in preparation). The pumping for the masers is considered elsewhere (Neufeld, Maloney, & Conger 1994; Collison & Watson 1995; Wallin & Watson 1997) where it is found that the absorption of infrared radiation by dust grains increases significantly the volume of the disk that is likely to be masing.

(a) These calculations seem to resolve an apparent dilemma about the maser emission from NGC 4258 that has existed since it was recognized as a subparsec accretion disk (Watson & Wallin 1994). Emission appears from the center and sides of the disk in the characteristic triplet spectrum of a Keplerian disk seen edge-on. This requires that the dominant "coherence paths" as determined for a Keplerian disk play a role. Especially for the high velocity features, the maser emission consists of a number of narrow ($\simeq$ 1 - 2 km s^{-1} FWHM) features that are well separated in space and in Doppler velocity. This, in contrast, suggests that the emission occurs from clumps that are smaller than the coherence lengths of the Keplerian disk. Our calculated spectra demonstrate that these two qualitatively different aspects of the spectral distribution are, in fact, compatible when plausible turbulence is combined with Keplerian rotation. The calculations also demonstrate (i) that the spectral linebreadths of features can be only about 1 km s^{-1} (as observed) even though the rms turbulent velocity is 5 - 10 km s^{-1} and (ii) that the observed clumpiness in space and Doppler velocity of maser emission from NGC 4258, and by extension in astrophysics more generally, may thus be understandable in terms of plausible turbulence. The general appearance of the calculated spectra is similar to that of the observed spectra.

(b) Small differences do arise between the observed velocities of the maser radiation from NGC 4258 and an ideal Keplerian velocity curve. An aspect of our calculation focuses on utilizing this information to determine the magnitude of the turbulent velocities. Supersonic (rms velocity $\simeq$ 3 - 6 km s^{-1}), though probably still sub-Alfvenic, velocities are indicated. Such turbulence indicates high viscosity and a large dissipation of energy in the masing gas which may provide the heat necessary to create the masing environment (Desch, Wallin, & Watson 1997).

(c) A striking aspect of the observations of NGC 4258 is the change in the maser spectrum near the systemic velocity by factors of two or more on timescales of a year, in contrast with only slight changes in the spectrum of the high velocity features over the same period of time. Calculations have been performed as a function of time that include changes due to both the Keplerian rotation and to the evolution of the turbulent velocities. The resulting behavior of the spectrum is consistent with the contrasting time variations of the systemic and high velocity emission.

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