Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Fully 3D modelling of masers towards AGB stars - latest development and early results

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Abstract. We present new results from a 3D modelling code for maser flares which provides the user with control over the physical conditions; maser cloud geometry and orientation; and fast runtime via parallelisation. The statistics of simulated observables suggest that achievable amplification may be dependent on viewpoints of the source and that a randomly placed observer is likely to detect an unremarkable blue- or red-shifted maser unless the line-of-sight direction is optimal for maser amplification. A preliminary model of masers towards π^1 Gru based on SPH simulations also shows promising consistency with ALMA observations of high-J SiO transitions from the source.

Keywords. Masers, Molecular processes, Radiative transfer, Stars: AGB and post-AGB

1. Introduction

A 3D code for maser flares at VLBI scale (Gray *et al.* 2018) has been in development for constructing maser models with more realistic physical conditions e.g. 3D geometric consideration, multi-cloud systems, cloud shape and orientation, velocity profiles and multiple sources of radiation. Comparing the models to observations will shed some light on the observational conditions for maser emission in AGB stars.

2. Latest development on the 3D maser code

Since the previous reports (Gray *et al.* 2019, 2020b, 2020a), we have added new ray contributions from the central star to the calculation of population inversion and simulation of spectra and VLBI images. User control over the size and intensity (in terms of saturation intensity) of the star was introduced and the dynamical models for Miras called CODEX (Ireland *et al.* 2011) were employed for setting up 3D velocity fields. Better intrinsic depth scaling and parallelisation through OpenMP were also implemented for increased optimisation.

3. Statistics of observations of circumstellar masers

For a maser in a CSE, modelled by a group of shock-flattened maser clouds distributed in a spheroidal shell, it is important to understand what characteristics of the maser are likely to be detected in a given observation. 2000 observer's positions, defined by polar

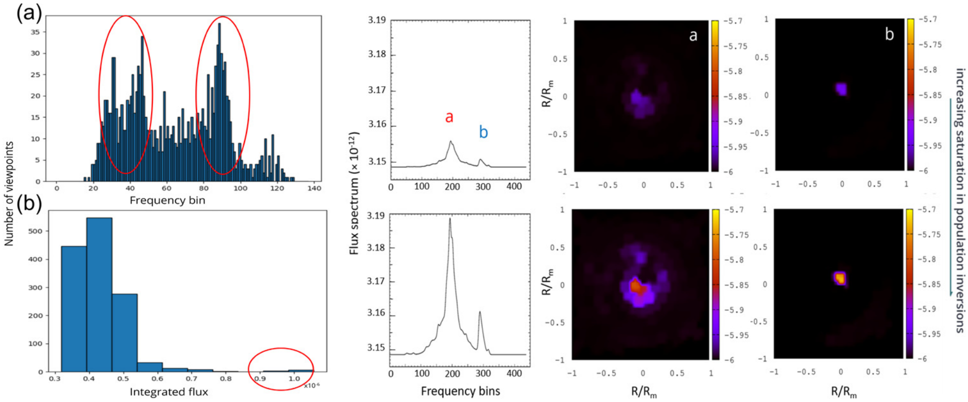

Figure 1. First simulated spectra and images of the π^1 Gru model (in model units). The red- and blue-shifted features are marked a and b, respectively. No effect from the star yet in these plots.

and azimuthal angles (with respect to the model axes), were randomly selected and flux densities were evaluated at the same distance of 1,000 model sizes from the star.

Fig. 1 shows histograms illustrating how the peak flux density per model is distributed in frequency bins (representing line-of-sight velocity) and the distribution of integrated flux. There is evidence to suggest that an observer is likely to detect the maser as being red- or blue-shifted with respect to the stellar velocity and its flux is unspectacular unless the observer's position is in the viewpoint that favours optimal maser amplification (i.e. the largest maser gain length). This is due to the geometry-dependent nature and the beaming effect of maser emission. A more extensive discussion on the maser statistics together with the code advancements in Section 2 is in progress (Pimpanuwat *et al. in prep.*).

4. Model of π^1 Gru

π^1 Gru was chosen as our first detailed attempt at a maser model for AGB stars based on the maser component maps (Homan *et al.* 2020) produced from ALMA Band 6 observations obtained as part of the ATOMIUM Large Programme (Decin *et al.* 2020; Gottlieb *et al.* 2022) and smoothed particle hydrodynamical (SPH) modelling work (e.g. Maes *et al.* 2021). The source is an S-type AGB star displaying SRb-type variability. It has a 197-day period, an effective temperature of 2300 K, a mass of 1.5 $M_\odot$, an angular diameter of 21 mas and a radial velocity (V_{LSR}) of -11.7 km/s (e.g. Gottlieb *et al.* 2022 and references therein).

The simulated spectra (with flux density in model units) and interferometric images of the π^1 Gru model (Fig. 1) can produce the characteristics of a typical maser flare observation. As the maser becomes more saturated, especially near and around the companion, a rise in maser intensity can be seen as per the maser component maps of high-J SiO masers reported in Homan *et al.* 2020; Fig. 11–12. Note, however, that only radiation from the background was considered and a model which includes maser pumping and seed radiation from the star is currently under investigation (Pimpanuwat *et al. in prep.*).

Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S1743921323002284

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