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A Unified Maxwell-Bloch Framework to Model Flaring Behaviour in Maser-Hosting Regions

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Introduction

Maser lightcurves exhibit diverse variability which cannot be easily explained with the classical maser theory. Previous work has shown that the Maxwell–Bloch equations (MBEs), operating in the superradiance regime, can reproduce asymmetric burst-like flares as well as periodic variability observed in maser-hosting regions. Here, we summarize those results and extend the framework to demonstrate that symmetric, sinusoidal flares can also be reproduced within the same physical model.

Method: MBEs

population inversion density
$$\frac{\partial n'}{\partial \tau} = \frac{i}{\hbar}\left(P^+E^+ - P^-E^-\right) - \frac{n'}{T_1} + \Lambda_n$$

polarization density
$$\frac{\partial P^+}{\partial \tau} = \frac{2id^2}{\hbar}E^-n' - \frac{P^+}{T_2} + \Lambda_p$$

Electric field
$$\frac{\partial E^+}{\partial z} = \frac{i\omega_0}{2\epsilon_0 c}P^-$$

d: transition dipole moment
ω_0: frequency of the field
Λ_n: phenomenological inversion pump
Λ_p: polarization pump due to vaccuum fluctuations
T_1: population relaxation timescale
T_2: polarization dephasing timescale

- The relaxation timescales depend on the physical environment
- Inversion pump is required to produce periodic flares, and its amplitude and period must be properly tuned.

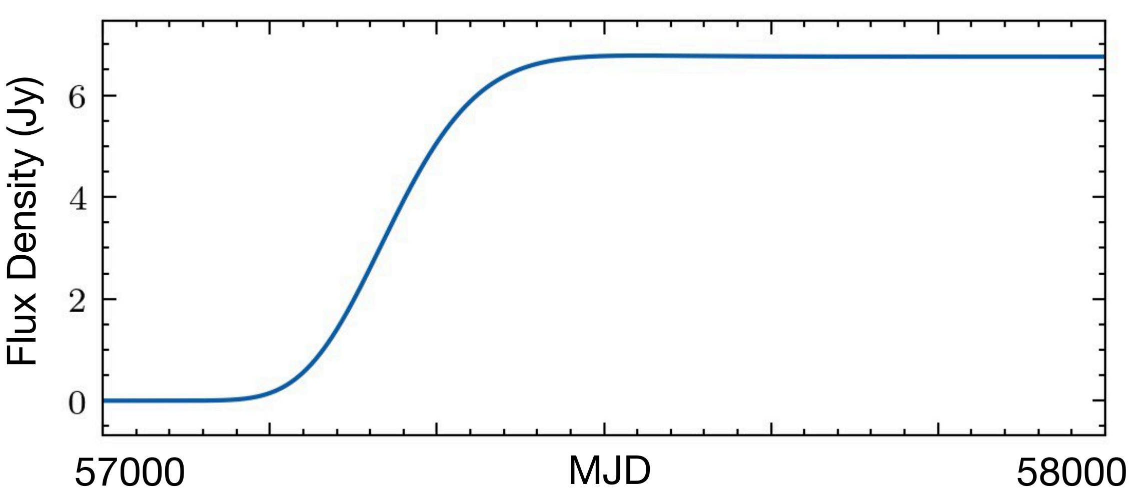
Results

The Maxwell–Bloch framework reproduces the main classes of observed behaviour:

1. Steady-state maser emission [1]

Constant inversion pump and short T_1 and T_2:

$$\frac{\partial n'}{\partial \tau} \ll \frac{n'}{T_1}, \quad \frac{\partial P}{\partial \tau} \ll \frac{P}{T_2}$$



2. Superradiance emission [1, 2]

$$\frac{\partial n'}{\partial \tau} \gg \frac{n'}{T_1}, \quad \frac{\partial P}{\partial \tau} \gg \frac{P}{T_2}$$

All parameters similar to case 1, but longer T_1 and T_2:

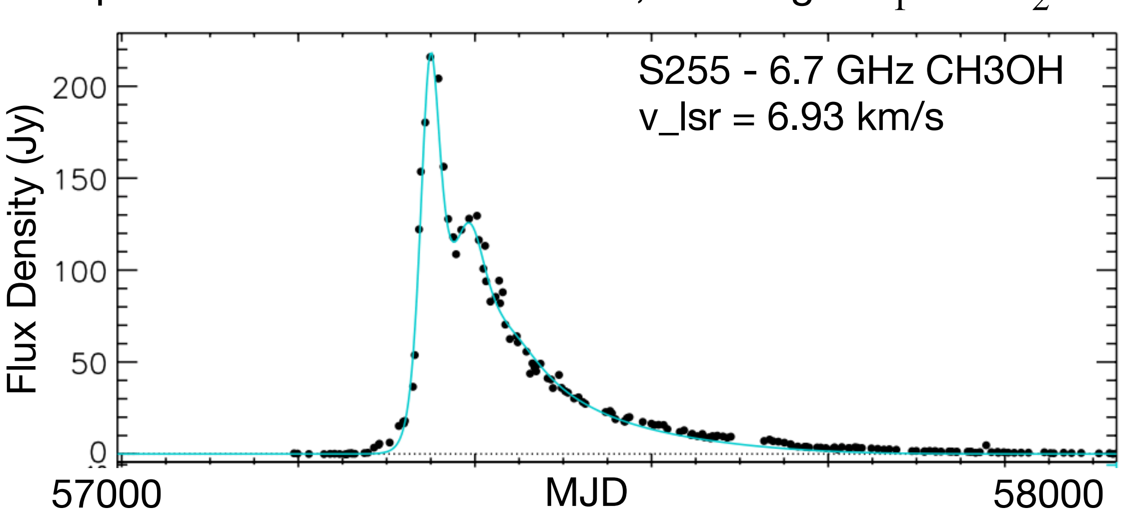


Figure credit: [3], Data: Szymczak et al. (2018)

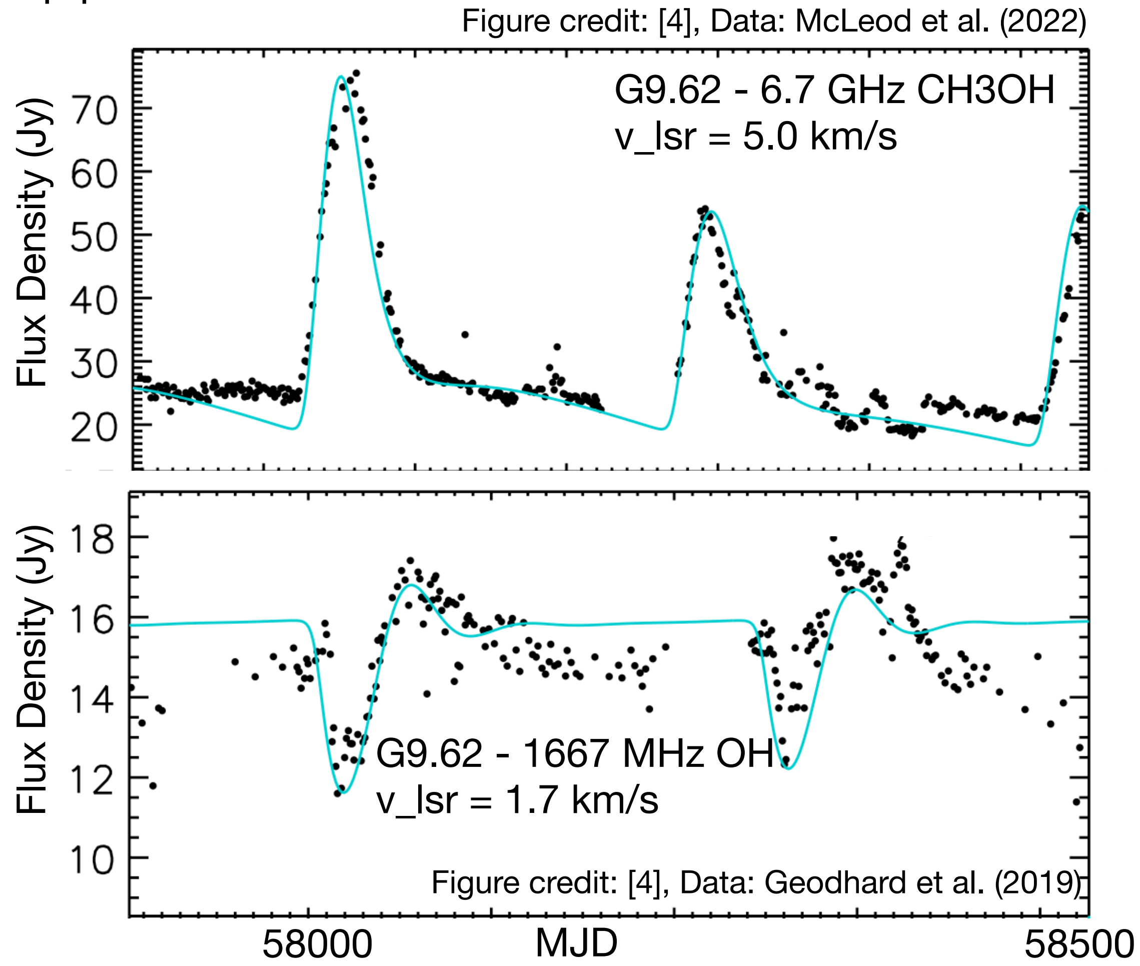
3. Periodic flaring

By periodically inverting the medium, periodic flaring can be realized as superradiant transient phases superposed on a steady-state maser baseline.

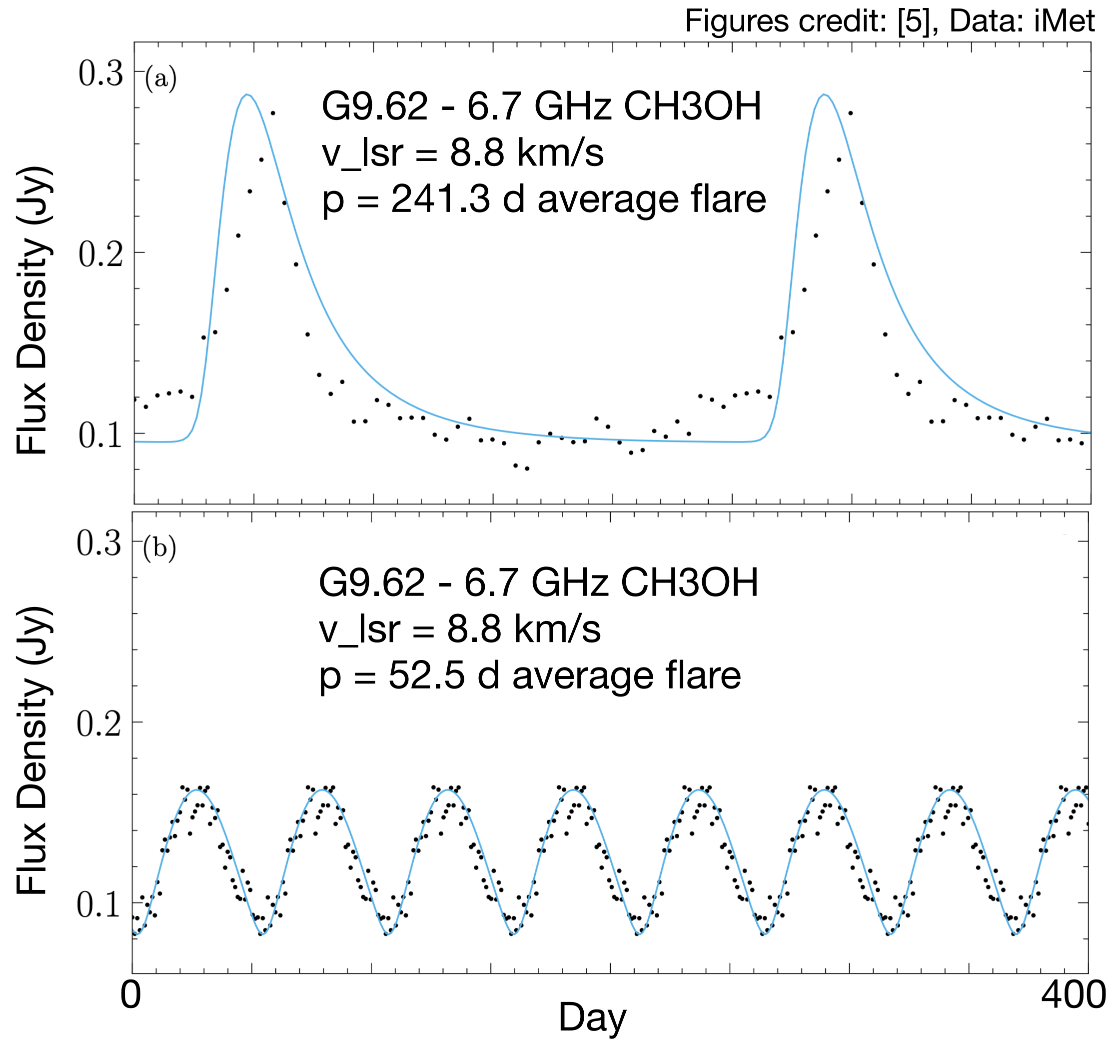
$$\Lambda_n(z,\tau) = \Lambda_0 + \Lambda_1 \sum_{m=1}^{\infty} \frac{1}{\cosh^2[(\tau - mp)/T_p]}$$

Λ_0: constant pump amplitude
Λ_1: pump pulse amplitude
p: pump period
T_p: pump pulse width

Figure credit: [4], Data: McLeod et al. (2022)



Figures credit: [5], Data: iMet



(The time axis is not in terms of JD because average flare shapes are used for modelling.)

Future Work

We are working towards establishing a database of sources that exhibit superradiant emission. These sources will include not only class II methanol and main line hydroxyl lines, but also 22 GHz water and SiO lines.

References
[1] Rajabi & Houde 2020, *MNRAS*, 494, 5194
[2] Dicke, R.H. 1954, *Phys. Rev.*, 93, 99
[3] Rajabi et al. 2019, *MNRAS*, 484, 1590
[4] Rajabi et al. 2023, *MNRAS*, 526, 443
[5] Rashidi et al. 2026, *MNRAS*, 545, staf2200

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