Methanol MASERS in Astrophysics

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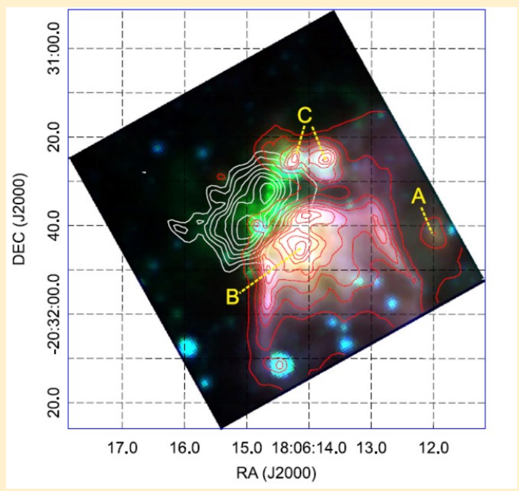
M.A.S.E.R:
Microwave Amplification by Stimulated Emission of Radiation

Abstract

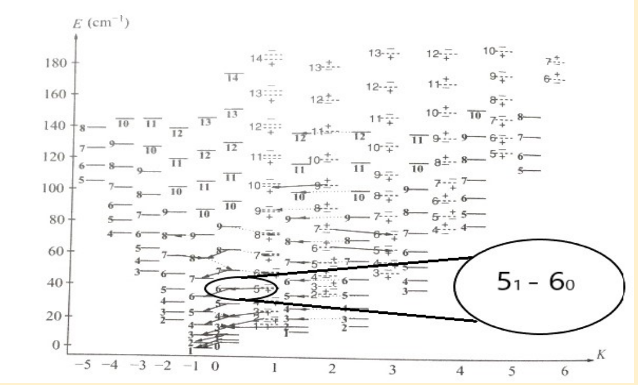
This project involved the processing of observations taken of Methanol maser G9.62+0.19E on the Warkworth IRASR 30m radio telescope. The data sets of observed intensities and velocities of the radiation coming from the maser were correlated and plotted in Matlab. From there, eight Gaussians were fitted to the multiple spectral lines of methanol. Using the parameters of the approximated Gaussians, the corresponding kinetic temperatures of the characteristic spectral features were calculated. These different characteristics represent the various sources that contribute to the maser radiation from this galactic object. By fitting Gaussians to the spectra, the appropriateness of the model can be explored and important properties of the maser medium can be determined.



Introduction

As indicated by the nomenclature, an astrophysical maser is a natural galactic source of intense microwave radiation produced via stimulated emission. The intensity of the maser radiation comes from the amplification of the gain medium through the mechanism of 'pumping'. Molecular clouds formed in the environments of young stellar objects serve as the optical cavity through which radiation can be amplified. Energy is pumped into the molecular clouds (via internal collisions or external astrophysical sources), which induces population inversion whereby stimulated emission is the dominant radiative process. Stimulated emission is the only mechanism responsible for the production of identical, coherent photons. Each stimulated transition results in the emission of two 'twin' photons that can then induce stimulated emission in other excited molecules in the cloud. This is the 'masing' process. Methanol maser G9.62+0.19E is the brightest methanol maser source catalogued to date. This maser was first detected by astronomer Karl Menten in 1991.

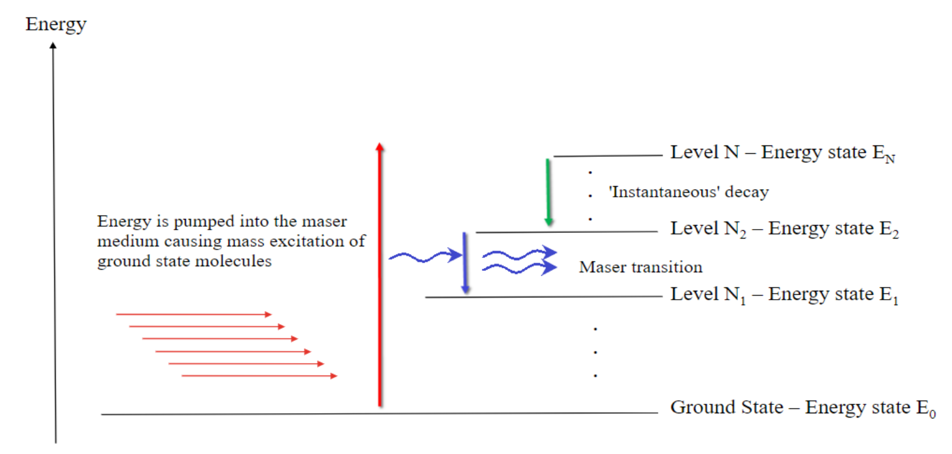
Energy Levels



Methanol molecules have many radiatively allowed transitional states, each associated with a unique quantized energy level. Stimulated emission involves an incident photon of a particular energy (frequency) interacting with a molecule in an excited (non-ground level) state of the same energy. The interaction results in the molecule undergoing a downwards transition to a lower energy state, whereby the incident photon then continues to propagate alongside an identical photon emitted from the transition. The transition associated with the most intense methanol maser radiation (corresponding to a 6.7GHz signal) is from the energy levels 5_1-6_0.

Cultivating the Maser Medium

In order to sustain an active maser medium, population inversion must be upheld. Population inversion refers to the state of an environment not in thermodynamic equilibrium, in which the number of molecules in an excited state is greater than in the ground state. The mechanism responsible for driving the maser environment away from equilibrium is pumping. By introducing external energy to the system, molecules can be pumped to higher energy levels creating more opportunities for stimulated emission to occur.
The energy pumped into the methanol cloud is absorbed by the molecules, causing mass excitation. From there, an almost instantaneous decay occurs from a short-lived higher state to a metastable state of excitation. Large populations of molecules will remain in this metastable state until incident photons come and induce stimulated emission. Once stimulated emission has taken place, the molecule will transition to a lower energy state where it can be pumped to a higher state, starting the process again.



Chain Reaction

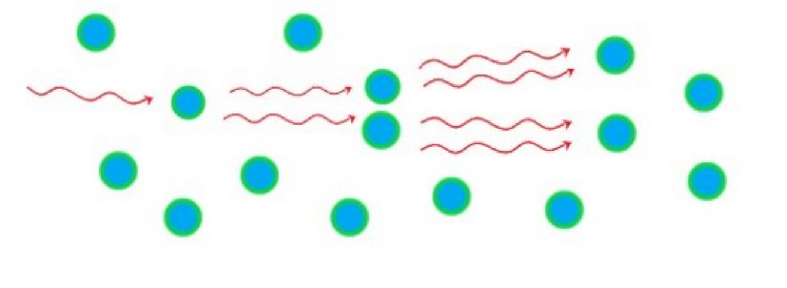
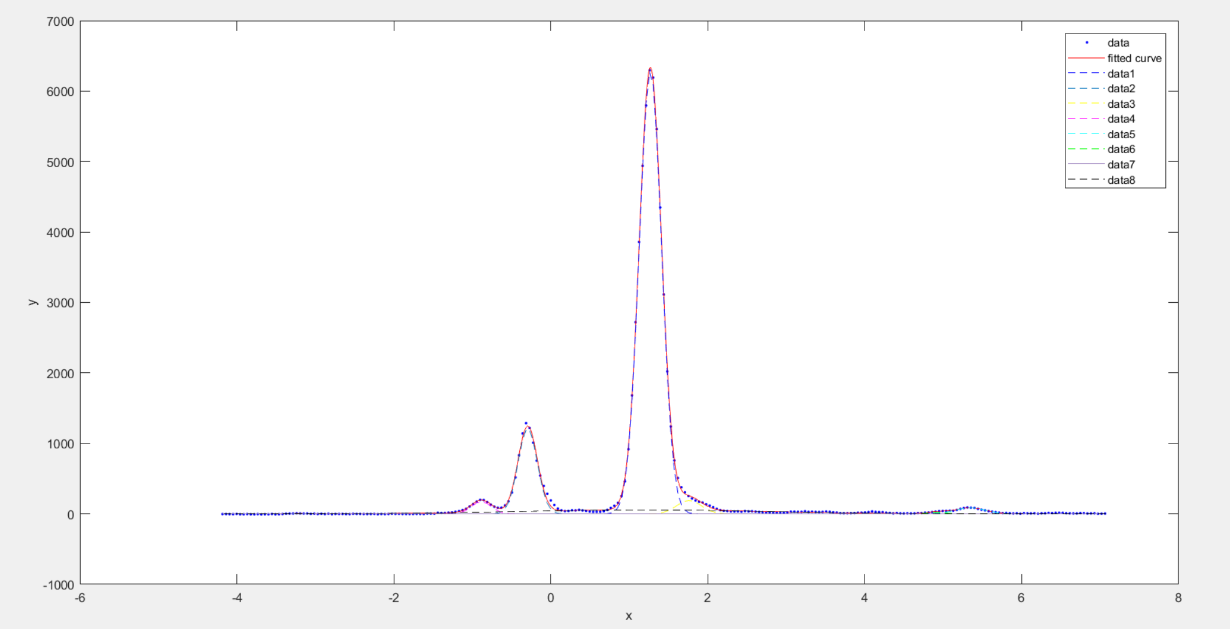


Illustration of the chain effect of stimulated emission within a population of quantum mechanical systems.

Each time stimulated emission takes place, the number of coherent photons (same phase, direction, frequency and polarization) increases by two. So, for every molecule in a metastable state, when stimulated emission occurs the result is two photons with the potential to induce stimulated emission in two other molecules. This chain reaction is exponential and is the source of amplification of the maser radiation.

Fitting Gaussians



The above plot was made using Matlab's 'fit' function and it features eight Gaussians that have been formulated to approximate the spectral lines of the methanol maser source. The main spectral feature is represented by the sharpest peak, which corresponds to methanol.

$$T = \frac{Mv^2}{2k}$$

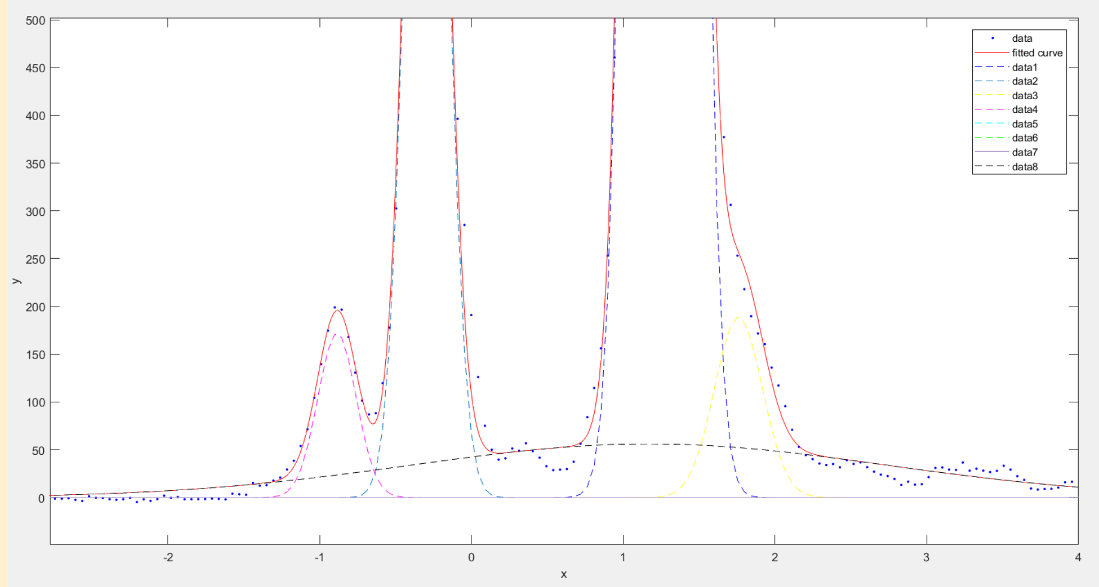
M is the mass of $CH_3OH = 32 \times m_{proton}$
v is the line width of the spectral feature
$k = 1.3806 \times 10^{-23}$ is the Boltzmann constant

Using the previous formula and the Gaussian coefficients (estimated from the observed data parameters) shown in the table below, the kinetic temperatures of the spectral features were determined.

Plot Number	Amplitude (Jy)	Radial Velocity (km/s)	Line Width (km/s)	Kinetic Temperature (K)
1	7000	1.3	0.2	77.53
2	1300	-0.3	0.2	77.53
3	240	1.8	0.2	77.53
4	200	-0.9	0.2	77.53
5	90	5.4	0.2	77.53
6	30	5	0.15	43.61
7	12	-3.2	0.25	121.15
8	25	4.1	0.2	77.53

Main Conclusions

Upon close examination of the spectral plot fit with the Gaussians (see zoomed in image below), it becomes apparent that the Gaussian approximation is not exact. There is a level of inaccuracy that indicates the need for additional parameters to be considered when modelling the features.



We solve the radiative transfer equation by taking the absorption coefficient α and writing it in terms of a Gaussian function.

$$\alpha_\nu \propto \varphi(\Delta\nu) \times (N_1 B_{12} - N_2 B_{21})$$

Where $\varphi(\Delta\nu)$ represents a Gaussian function.
N_1 and N_2 are the populations of molecules at the ground state and excited states, respectively.
B_{12} and B_{21} are Einstein's coefficients corresponding to the probability of stimulated absorption and stimulated emission, respectively.

By population inversion, the population of excited states must be greater than that of the ground state. Therefore, $N_2 >> N_1$, which means that the absorption coefficient will be negative ($\alpha<0$). From here, we solve the radiative transfer equation to get the following result.

$$I_\nu = I_\nu^0 e^{-\tau_\nu} \quad \textit{where} \quad \tau_\nu = \alpha_\nu R \quad \textit{in a homogeneous media}$$

τ_ν is optical depth and R is the distance of propagation through the active media.

$$\tau_\nu = \alpha_\nu R \quad \textit{and} \quad \alpha_\nu \propto \varphi(\Delta\nu) \quad \textit{then} \quad \tau_\nu = aR\varphi(\Delta\nu) \quad \textit{where } a \textit{ is some negative constant.}$$

From the above we see that τ_ν will be a negative value, which means that if we substitute it back into the radiative transfer equation (which already has a negative exponential), the two negatives will cancel and result in a positive exponential function. By comparison, a Gaussian curve has a negative exponential. Thus, by inputting a Gaussian into the radiative transfer equation, we get an output which is not Gaussian. This shows that modelling the intensity of maser radiation requires an equation that deviates from that of a Gaussian.

Key References

Gray, M. (2012). *Maser Sources in Astrophysics. New York: Cambridge University Press.*

Einstein, A. (1917). On the Quantum Theory of Radiation. In *Physikalische Zeitschrift 18, 121 (pp. 167-183). Leipzig, Germany: S, Hirzel.*

Acknowledgements

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