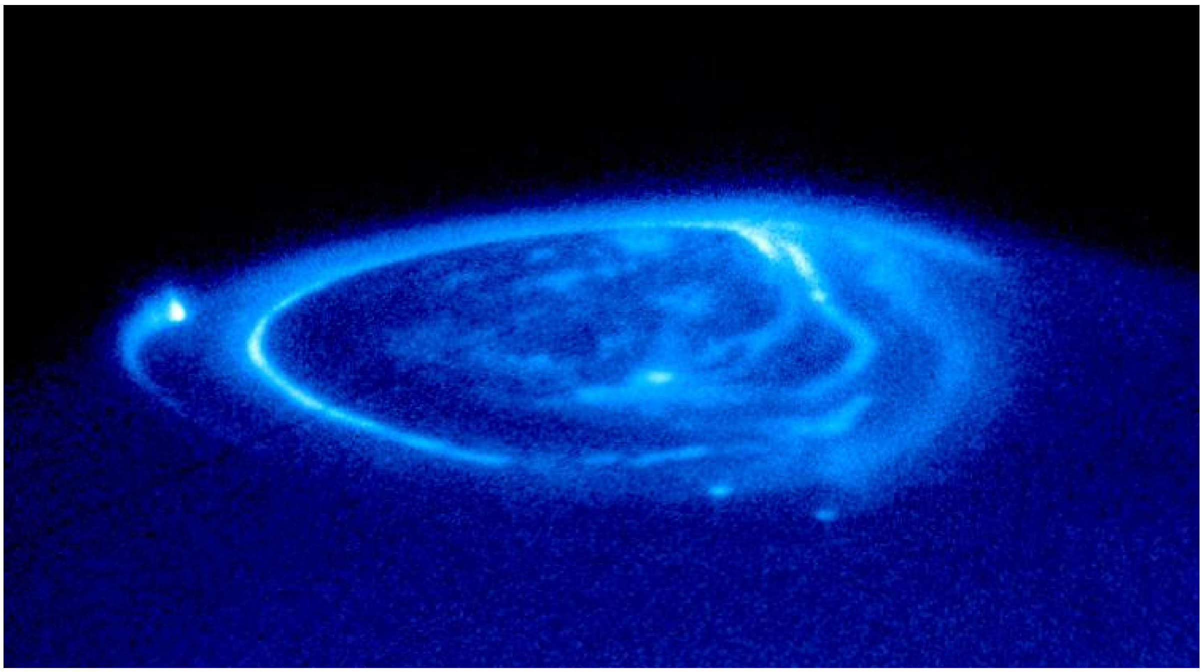
Lecture 33 : Celestial MASERs

In a historic paper published in 1917, Einstein introduced the concept of stimulated emission of radiation by atoms and molecules. The first MASER (Microwave Amplification by Stimulated Emission of Radiation) based on this idea was made in 1953, and the first LASER was made in 1960. After the advent of millimetre wave astronomy, astronomers have discovered a wide variety of MASERS in celestial bodies. In this lecture, the concepts of two-level systems and stimulated emission from them in quantum mechanics is systematically developed. Afterwards, the Ammonia MASER and Hydrogen MASER are discussed in terms of two-level quantum systems.



This close-up view of an electric-blue aurora, caused by the electron-synchrotron maser, glowing on Jupiter was taken by the Hubble Space Telescope in 2010. The Credit : NASA

Resource Material : *Text Books & Popular / Technical Articles*

1. A. Einstein, 1917, Physikalische Zeitschrift 18, 121
   The Quantum Theory of Radiation

2. M. Bertolotti, 1988, ***Masers and Lasers : A Historical Approach***, CRC Press

3. R. P. Feynman, 2012, ***The Feynman Lectures On Physics - Vol.3***, Pearson Eduction
   Caltech Online Resource

4. M. Elitzur, 1992, ***Astronomical Masers***, Springer

5. M. Gray, 2012, ***Maser Sources in Astrophysics***, Cambridge University Press

6. M. J. Reid & J. M. Moran, 1988, ***Astronomical Masers***
   in ***Galactic and Extragalactic Radio Astronomy***, ed.s G. L. Verschuur & K. I. Kellerman, Springer

16 December 2022

Suggested Problems

For the following problems, use the approximation that the angle averaged specific intensity of radiation in a maser, J_ν, is $I_\nu \Omega_b/4pi$, where Ω_b is the solid angle into which maser emission is beamed. Recall that radiative transfer of maser radiation operates in the Rayleigh-Jeans limit. For simplicity, consider the characteristics of water, where $\tau = 1s^{-1}$ and $A = 2 \times 10^9\ S^{-1}$. Consider a filamentary maser of length l, diameter d, at a distance D from the Earth. The observed flux density of the maser is F_ν.

1. Write an expression for the brightness temperature of the maser, and a condition for whether or not it is saturated, in terms of F_ν.
2. Now consider two cases in which a maser 'cloudlet' amplifies a background source but the cloud is sufficiently far from us that by itself the maser is too weak to see. The diameter of the cloudlet on the sky is d_m and the diameter of the background source is d_n. The cloudlet and background are separated by a distance $D_{nm} >> d_n, d_m$ and $D_{nm} << D$.

   For dm > dn, what can you say about the perceived diameter of the detected maser emission with respect to d_m and d_n? The solid angle of the maser emission is no longer set by l and d, as it was before. Give an approximate expression for Ω_b.

   For $d_m < d_n$, what is the diameter of the detected maser emission? Is Ω_b larger or smaller than in the previous case?
3. Consider a maser filament of length l in isolation. If l is not large enough then the maser will be unsaturated. Otherwise the maser naturally generates enough specific intensity (I_ν) that it saturates toward its two ends. Symmetry arguments lead one to hypothesize the presence of an unsaturated core at the middle of the filament's length. Now a background source is placed along the axis of the maser and its flux ramps up from zero. (Assume it has the same diameter as the maser.) What happens to the location of the unsaturated core? Eventually the un-saturated core disappears. At this point how much greater has I_ν increased due to the background source? (Hint: Think about how radiation grows in a saturated maser.)
4. Arihanta needs help with his thesis! As he writes that the NGC4258 masers are saturated he has second thoughts. But could they be too bright to be saturated as he assumes? (This problem applies to disks around protostars as well as those around blackholes.)

   For an edge-on thin disk strong maser emission is visible in projection along the diameter perpendicular to the line of sight. (Call this diameter the 'midline' of the disk). Consider a central mass M and a mass-less disk of outer radius R_0, at which the rotation velocity $v(R_0)$ is v_0. The maser linewidth is δv. What is the line-of-sight path length of the maser emission as a function of projected radius along the midline? Divide the maser emission along the midline among many parallel filaments whose lengths you just computed. What is the filament diameter as a function of projected radius? (Hint: Consider the effects of velocity shear in the disk, with respect to δv.)

   Now address Arihanta's worry. What is the expression for the maximum flux density of saturated maser filaments expressed as a function of projected radius along the midline? The observed maser lines are 0.1-0.6 Jy. Evaluate the order of magnitude of this limit using the following assumptions: a distance of 7Mpc, a central mass of 4×10^7 $M_\odot$, $\delta v = 1$ km/s, $n_{H_2} = 10^{10}$ cm^{-3} uniformly throughout the disk, $n_{H_2O}/n_{H_2} = 3 \times 10^{-5}$, pump efficiency of 1%, and that 1% of the water molecules are in the upper and lower maser levels together. (This is appropriate for typical temperatures of about 400 K.)