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Astronomical masers

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1. Introduction

Molecules were first detected in the interstellar space in 1940. Absorption lines of three radicals CH, CH^+ and CN were observed in the spectra of hot stars. These molecules have spectral lines in the visible part of the electromagnetic spectrum, enabling their detection with optical telescopes. The next detection of an interstellar molecule could be possible in 1963 when 18-cm radio emission from the ground state of the OH radical was detected. Thus OH is the first molecule detected in interstellar space at radio frequencies. Since then radioastronomical observations have led to the discovery of a number of molecules in astronomical objects, and by now about 100 molecules (including molecular ions and radicals), ranging in size from two to thirteen atoms have been detected.

For the OH molecule, each rotational level is divided into four states, resulting in four allowed transitions. In the ground rotational level, the two transitions $\Delta F = 0$ at 1665 MHz and 1667 MHz are called main lines whereas the other two transitions $\Delta F = \pm 1$ at 1612 MHz and 1720 MHz are known as satellite lines. Wavelengths of these transitions are approximately 18 cm. Weaver *et al.* (1965) observed intense OH emission at 18 cm wavelength towards several H II regions. The line width of the radiation indicated a molecular kinetic temperature of about 100 K, whereas the intensity of the line was so high that the lower limit on the brightness temperature of the radiation was greater than 1000K. This situation was found in several astronomical objects. It pointed out strongly to NLTE conditions prevailing in these regions. Since the brightness temperature of the radiation was greater than the kinetic temperature, Litvak *et al.* (1966) and Perkins *et al.* (1966) suggested that the emission was due to maser amplification. Masers and lasers on the earth are quite artificial devices, therefore, the idea of natural masers appeared astonishing. However, the idea of natural masers was later on unanimously accepted. This article deals with the astronomical (natural) masers.

2. Very Long Baseline Interferometry (VLBI) experiments

Resolving power of a telescope varies as λ/D, where λ is wavelength of the radiation and D is diameter of the dish of the telescope. In the radio window, wavelengths are quite large, and therefore for a single dish antenna, spatial resolution is very poor. For example, for $\lambda = 18$ cm and D = 100m, the resolution is about 6 arc min. This is a very poor resolution. Obviously, to improve the resolution, the only factor that could be varied was the size of the dish. The novel idea of VLBI could help to increase the size of the dish. In VLBI, two telescopes separated by a large distance can be thought as the two outermost segments of a single telescope of a very large dish. The separation between the two telescopes is known as baseline and behaves as diameter of the dish of a single telescope. The maximum baseline (practically) on the earth may be of the order of the radius of the earth, which corresponds to a resolution of few milliarcsec for $\lambda = 18$ cm. It is a very good resolution, and is better than that of an optical telescope.

In 1967, VLBI experiments involving radio telescopes across the United States were performed by J.M. Moran and coworkers. In the first experiment, they used 140-feet antenna of the National Radio Astronomical Observatory (NRAO), Green Bank with the 120 - feet antenna of the Massachusetts Institute of Technology, Lincoln Observatory, Cambridge, situated at a distance of 845 km (resolving power about 0.044 arc sec). In the second experiment, the 140-feet antenna of the NRAO was used with the 85-feet antenna of the University of California situated at a distance of 3506 km (resolving power about 0.01 arc sec).

It was found that OH 18 cm emission originated from a number of spots which had angular sizes of about 0.01 arc sec and brightness temperature up to 10^{12} K. It was interesting to note that the line width was still narrow, which corresponded to kinetic temperatures of about 100K. Extremely high intensities observed in narrow lines suggest very strongly that there was a maser action. No other explanation seemed plausible.

3. Maser action in other molecules

The next molecule found with maser action is H_2O (Cheung *et al.*, 1969) through its transition $6_{16} \rightarrow 5_{23}$ at 22.2 GHz. H_2O lines are usually observed in the earth's atmosphere due to its high water vapour content. However, astronomical H_2O maser emission at 22.2 GHz involves the levels with rather high energies, which are relatively unpopulated in the earth's atmosphere. Thus, the earth's atmosphere is fairly transparent for the maser radiation. It is interesting to notice that wherever the transition $6_{16} \rightarrow 5_{23}$ is observed, it is always found with maser action.

Another molecule found with maser action is SiO (Snyder and Buhl, 1974) through its transition $J = 2 \rightarrow 1$ of the $v = 1$ vibrational state at 86 GHz. Many more maser lines were subsequently detected involving vibrational states up to $v = 3$ and rotational levels up to $J = 6$. Hence, the molecule was the first to exhibit such a rich spectral structure.

Besides the so-called "classical masers" of OH, H_2O and SiO, a number of other cosmic molecules have been found to exhibit maser action. The list of these molecules includes CH, HCN, CH_3OH, H_2CO and NH_3.

Maser emission has been discovered in a wide variety of galactic sources, including comets, molecular clouds, star formation regions and circumstellar envelopes of late-type (evolved) stars. Thus, the study of astronomical masers (as well as molecules in astronomical objects) provides valuable information about the physical conditions at the stage of the birth of stars (interstellar molecular clouds) as well as at the stage of the death of the stars (circumstellar envelopes of evolved stars). Powerful maser emissions have been discovered in the extra-galactic sources also. For example, the extra-galactic source IC 4553 is almost a million times more luminous than any OH source observed in the galaxy. Hence, they have been named "mega-masers".

3.1 Polarisation

OH has paramagnetic properties, and therefore, degeneracy of the energy levels is lifted by the introduction of a magnetic field. Electric fields of the lines generated in $\Delta m = 0$ transitions oscillate along the magnetic axis, whereas of the lines generated in $\Delta m = \pm 1$ transitions rotate in circles, in the clockwise and counter-clockwise directions in the plane perpendicular to the direction of the magnetic field.

H_2O and SiO are non-paramagnetic as they have closed electronic shells, and therefore these molecules have much weaker response to the magnetic field.

4. Theoretical approach

Observations show that astronomical masers are in a steady state. The fastest variation observed so far has time scales of at least few weeks, which is much longer than the typical time scales for pump and decay processes in the pertinent sources. Therefore, in the theoretical investigations, statistical equilibrium equation (SEE) coupled with the equations of radiative transfer is solved. In the investigation all possible sources and sinks are accounted for.

Maser action requires a population inversion in a certain transition. A two-level system will never produce population inversion. Population inversion can only occur as a result of cycling through a system of levels. Hence, the SEE should include a number of levels. There is no set rule about the number of levels to be accounted for. The model, in principle, should contain enough number of levels that the inclusion of additional levels would not affect the maser emission.

4.1 Pumping

A system can be excited into higher levels by either collisions or radiation from an external source. According to the nature of the process that dominates these excitations, pumping scheme is known as collisional or radiative. It was recognised quite early that chemical pumps cannot explain the emission from the astronomical masers.

4.2 *Saturation effect*

Optical depth for the maser transition is negative, and thus the intensity of the maser transition grows exponentially. This exponential growth of the intensity, of an unsaturated maser cannot continue indefinitely because it would eventually lead to infinite energy density for sufficiently large masers. Indeed the conversion efficiency of inversions to the maser photons approaches unity and the maser saturates. Saturation starts at the line centre, where the intensity is the highest, and then spreads to the wings with further increase in the intensity. Finally, the growth rate becomes uniform across the line and the flux assumes the shape of the Doppler profile. Thus, the line is broadened to its original profile.

5. Favourable situation for maser action in astronomical objects

Why are astronomical objects apparently capable of producing maser action with such ease whereas special efforts are required to produce lasers and masers in the terrestrial laboratories? The answer lies in the great difference in densities and geometrical dimensions between the two environments. In a molecule (atom) level populations begin to thermalise when the density becomes comparable to $N_{cr} = A/K$, where A is the Einstein A-coefficient for a transition and K is the collisional rate coefficient for the transition. For a diatomic molecule, for the transition $J = 1 \rightarrow 0$, A-coefficient is $\sim 10^{-6} s^{-1}$. As of the day, knowledge of collisional rate coefficients is very poor. Therefore, estimation of the collisional rate coefficients is very uncertain. If we take geometrical cross section $\sim 10^{-15} cm^2$, and thermal velocity ~1 km/s, then the collisional rate coefficient is $\sim 10^{-10} cm^{-3}/s$. Hence, the critical density for thermalisation is $\sim 10^4$ cm^{-3}.

This value of critical density is quite high by interstellar standards, but is extremely low for the terrestrial laboratories. Thus, line thermalisation is a rule in the terrestrial environment, but is an exception in the interstellar medium. However, N_{cr} involves typical parameters whose variations are quite large. The A-coefficient, in particular, varies as ν^3 and its range is quite substantial. For example, CO has relatively small A-coefficients for rotational transitions, and therefore this molecule thermalises quite easily. On the other hand, OH, H_2O and other molecules have large values for A-coefficients, Thus, these molecules can maintain non-thermal populations even at higher densities. Molecular vibrational and electronic transitions with typical A-values of ~ 1 s^{-1} and $\sim 10^7$ s^{-1}, require further higher densities for thermalisation.

This gain is given by

$$\tau = \frac{h\nu}{4\pi\Delta v_D^\nu} g_u B_{ul} \int (n_u - n_l) \, dl$$

where the indices u and l stand for the upper and lower levels of the maser transition and other symbols have their usual meanings. An appreciable maser effect requires substantial gain, which in turn requires large column densities. Since the volume densities are small, the only way to reconcile these conflicting simultaneous requirements of small volume densities and large column densities is with large dimensions. For a typical allowed transition, the required column density to produce $\tau = 1$ is more than 10^{14} cm^{-2}. For $n \approx 10^4$ cm^{-3}, linear dimension is more than 10^{10} cm. Hence, low densities and large dimensions provide favourable situations for maser action in astronomical objects.

In order to overcome the difficulties about the values of critical densities and dimensions, two approaches are employed in the construction of laboratory lasers. The first is to select the transitions with large A-coefficients, so that the corresponding critical densities are high. While the relatively long wavelength transitions of masers are always thermalised in the laboratory, critical density for a typical vibrational transition is ~ 10^{12} cm^{-3} for $v = 1 \rightarrow 0$, and it increases with v. Critical densities for electronic transitions are still higher. Thus, NLTE population distributions can be sustained at relatively high densities in the vibrational and electronic transitions employed for laboratory lasers. These lasers obviously require substantial amounts of excitation energies to populate higher levels, which are usually not available in most astronomical regions. This is one of the reasons for the non-existence of astronomical lasers.

Critical densities for the maser transitions are obviously smaller than the normal laboratory densities. Thus, in order to produce maser action in the laboratories, special techniques for creating low pressure in the medium are employed.

The second solution is to increase the radiation path-length by bouncing the laser photons between the two plane parallel mirrors. Thus, the linear dimensions of the systems are effectively increased by the many passes of the laser beam in a resonant cavity. This technique is possible only in those systems where high degree of mode selectivity can be maintained. The reason is that the phase coherence, which allows constructive interference in successive passes, occurs only within a limited band width such that $\Delta_9^{\nu} /\nu \sim Q^{-1}$. The Q value of a resonant cavity is ~ 10^8 - 10^9 for optical resonators. In the astronomical masers, where band width is ~ 10^{-5}, this technique is obviously inapplicable. However, it is unnecessary there because typical lengths in astronomical masers are at least ~ 10^{13} cm and the required gains are obtained in the course of plain photon propagation, as in a single-pass laser.

6. Applications

Astronomical masers were discovered shortly after the construction of the very first laboratory lasers. The maser radiation, being an intense and collimated beacon can serve as a probe for the source in which it was generated and for the medium through which it propagates. The masers can be use for

(i) Distance measurement

(ii) Measurement of galactic rotation and magnetic field

(iii) Interstellar scattering

(iv) Circumstellar disk structure

(v) Evolutionary schemes for late-type stars

(i) Distance measurement

Distance determination is the most difficult problem in astronomy. The only geometric methods, applicable outside the solar system, are based on the measurements of angular and linear dimensions. If an object subtends an angle θ in the plane of the sky and the corresponding linear dimension is1, then the distance of the object is given by $D = 1/\theta$ The most reliable astronomical distances are provided by parallax measurements. However, these measurements are unfortunately limited to distances of only ~ 30 pc.

One method to overcome this problem is to transform light-travel times to linear dimensions. This approach has been used in the determination of OH maser shell radii in late-type stars. It deals with the phase lag between the blue- and red-shifted components (front-back idea). Maser photons in the red-shifted peak originate from the far side of the object and have to cross the entire shell before reaching the point from where the blue-shifted photons start their journey towards the observer. Thus, the blue- and red-shifted components should be displaced in phase, with the red trailing the blue by the time in which the light crosses the object. The angular sizes of the objects can be measured accurately with the help of the VLBI technique. By using this technique, prospects for extra-galactic distance measurements appear promising.

In another method, on differentiating the relation between 1 and θ, we get

$$\text{Linear velocity} = D \times \text{angular velocity.}$$

The angular velocity, called proper motion, is determined from the apparent displacement of the source in the sky between the two epochs. But, the corresponding transverse linear velocity, cannot be measured directly. However, linear radial velocities can be determined with the help of the Doppler effect, and in a cluster of objects, various velocities along the line of sight and perpendicular to it can be statistically related to each other by making some assumptions about the geometry of the cluster's internal velocity field.

(ii) Measurement of galactic rotation and magnetic field

A survey of OH/IR stars within one degree of the galactic centre resulted in the first direct detection of galactic rotation in a stellar population near the centre. The results show that the average radial velocity of stars varies linearly with galactic longitude, as expected in a rotation. From a model fit to the velocity distribution, the mass distribution near the centre was derived. The results are in good agreement with those obtained from quite different methods and assumptions.

Of the classical maser molecules, OH is the only one that is paramagnetic. The Zeeman effect of a typical magnetic field in an OH/H II region, a few milli Gauss, splits its spectral lines by an amount exceeding the line width, producing pairs of right and left circularly polarised lines. The splitting is proportional to the magnitude of the magnetic field, whose value can thus be measured directly. Using this approach, magnetic field in a number of OH maser sources has been determined.

(iii) Interstellar scattering

Radio radiation propagating in the interstellar medium is subject to scattering by interstellar plasma. This scattering produces diffractive and refractive effects, induced by large-scale fluctuations in the density of free electrons in the intervening medium. Maser spots provide compact input sources that are particularly suitable for observations of scattering effects.

(iv) Circumstellar disk structure

Theoretical models for cloud collapse-the process which leads to star formation, suggest that a disk around the central star should always be produced. Identification of circumstellar disk around a newly formed star and probing its structure are major challenges for astronomical observations. Using the Hat Creek millimetre array, interferometric observations of the Orion SiO maser in the 86 GHz $v = 1$, $J = 2 - 1$ transition were performed and the evidence for the most detailed mapping of an expanding - rotating circumstellar disk is obtained.

(v) Evolutionary schemes for late-type stars

Maser emissions in late-type stars result from coincidences among certain properties of the circumstellar environment. Such coincidences are a direct consequence of the detailed structure of the stellar surroundings, which itself show the evolutionary stage reached by the star.

7. Conclusions

Observations as well as theoretical investigations of astronomical masers provide valuable information about the physical conditions in astronomical objects. There may be some additional molecules which may show maser action in some astronomical objects. Physical conditions in astronomical objects vary substantially. Theoretical investigations may help in selecting appropriate transitions of some molecules for making searches for new astronomical massers. However, poor knowledge of collisional rate coefficients constraints the theoretical investigations.

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