Cosmic MASERs: From Protostars to Blackholes
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The puzzle of natural lasers

Vladimir Strelnitski
Maria Mitchell Observatory, 3 Vestal St., Nantucket, MA 02554, USA; vladimir@mmo.org

Abstract. Hundreds of strong astrophysical masers have been detected since the first, serendipitous detection of such a maser in 1965. Surprisingly, no high-gain natural lasers in the optical domain and only one in the infrared domain have been detected during these decades. What does inhibit natural lasing? An answer is proposed in this presentation.

1. Introduction

There is an interesting parallel in the history of ideas and implications concerning the laboratory and natural (= cosmic, celestial, astrophysical) masers and lasers. It seems that the principal possibility of light amplification by the stimulated emission of radiation was first put forward by an astrophysicist, as a natural possibility in non-equilibrium astrophysical media (Menzel 1937). Whatever the reason, the first laboratory realization of the idea was not in the optical, but in the microwave domain: the first masers were created in 1954, and the first laser only six years later. The first natural masers were discovered serendipitously in 1965 (Weaver et al 1965). The first (and still the only one reliably known) high-gain natural laser was detected only thirty years later (Strelnitski et al. 1996).

Why are natural masers so widespread (we now know hundreds of them, both in our own and other galaxies), but natural lasers are not? This presentation is an attempt to answer the question.

2. Two Conditions of Strong Amplifications

In order for a maser or laser to be strong and detectable, two conditions should be fulfilled: (1) an inversion of populations should be created on the quantum transition in question by some pumping process; and (2) the pumping should be strong enough and the medium large enough to sustain an efficient amplification regardless of the effect of saturation — the tendency of the amplified radiation to decrease the population inversion. We now show that each of these conditions favors natural masers, but not lasers.

3. Population Inversion

By differentiating Boltzman's formula, regarded as the definition of the excitation temperature T_{12} of the transition 1 → 2, one obtains:

$$\left|\frac{\delta T_{12}}{T_{12}}\right| = \frac{kT_{12}}{h\nu_{12}}\left(\left|\frac{\delta n_1}{n_1}\right| + \left|\frac{\delta n_2}{n_2}\right|\right) , \tag{1}$$

where n_1, n_2 are the populations of the levels 1 and 2, ν_{12} is the frequency of the transition, and the constants k, h have their usual meaning. This equation shows that the variation in excitation temperature, caused by a given variation in level populations, increases with the decreasing frequency of the transition. Natural pumping processes produce, on the average, comparable variations of level populations for all transitions. Thus, on the average, they disturb the excitation temperature (in particular, invert the populations) of longer wavelength transitions with more strength. This is the first reason why masers are more frequent in nature than lasers.

4. Saturation

The decrease of the unsaturated population inversion due to saturation is given by the well-known equation (e.g. Elitzur 1992):

$$\Delta n = \frac{\Delta n_0}{1 + \frac{J}{J_s}} , \tag{2}$$

where Δn is the actual population difference, Δn_0 is the population difference before saturation, J is the intensity of the amplified radiation averaged over directions and over frequencies within the line, and J_s is the "saturation intensity" — the intensity that equalizes the rate of the transitions induced by the maser photons and the pumping rate. An order-of-magnitude estimate of J_s is given by

$$J_s \sim \frac{\Gamma}{B} , \tag{3}$$

where Γ is the characteristic rate of the sink in the pumping cycle, and B is the Einstein coefficient. Since B has the same order of magnitude for all the electric-dipole transitions and Γ does not depend on the frequency of the transition either, J_s should be, by the order of magnitude, the same for both the maser and the laser wavelength domains. On the other hand, J has a general tendency of increasing with the decreasing wavelength. In particular, the intensity of spontaneous emission, which in most cases plays the role of a seed emission for amplification, increases with frequency as ν^3. As a result, even if some pumping process is capable to create population inversion at an optical or infrared transition, the starting amplification, at these frequences, will saturate the pumping very quickly, which will reduce the amplification from exponential to linear and prevent the creation of a strong, detectable laser source.

This mechanism of inhibiting strong lasing was discussed in more detail in Strelnitski, Ponomarev, & Smith (1996), as an explanation of the high frequency cut-off of hydrogen recombination line masers and lasers in MWC349 — the only known source where strong amplification extends as deep into the laser wavelength domain as down to about 50 microns. This apparently young star is surrounded by a large neutral disk whose surface is ionized by the UV radiation of the star and represents an ideal, optically thick environment for maser and laser amplification in hydrogen recombination lines. The lucky orientation of the disk (almost exactly edge-on) favors the detectability of these masers and lasers, which have relatively high directivity of radiation in the plane of the disk. Both the apparent shortness of this phase in the star's evolution and the fortunate, edge-on orientation of the disk make it doubtful that many objects of this type will be discovered in the future.

5. Conclusions

There is no principal difference in the physical nature of masers and lasers, and it is puzzling why so many natural masers, but almost no lasers have been observed so far. We indicate two possible reasons making the detectable astrophysical lasers rare: (1) difficulty of creating population inversion on high frequency transitions by the naturally occurring pumping mechanisms, and (2) fast saturation of such transitions, preventing efficient, exponential amplification.

References

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