978-1-107-03284-2 — Cosmic Masers – from OH to H0 (IAU S287)
Edited by R. S. Booth , W. H. T. Vlemmings , E. M. L. Humphreys
Excerpt
More Information

T1:

Advances in Maser Theory *Chair: Roy Booth*

Cosmic Masers - from OH to H_0
Proceedings IAU Symposium No. 287, 2012
R.S. Booth, E.M.L. Humphreys & W.H.T. Vlemmings, eds.

doi:10.1017/S1743921312006576

Advances in Maser Theory

Vladimir Strelnitski

Maria Mitchell Observatory, 4 Vestal Street, Nantucket, MA 02554
email: vladimir@mmo.org

Abstract. The groundwork of the cosmic maser theory was laid four decades ago. The elapsed time, including the few years after the last IAU symposium dedicated to masers, did not add much to the fundamentals. In this review, I will summarize some cornerstones of the theory, with an emphasis on issues that don't seem to have received due attention in the past. I will also comment on some new developments.

1. Introduction

Before discussing the theory of astrophysical masers, I would like for us to remember a person who was especially knowledgeable and productive in this field during the past three decades, Professor Bill Watson. Unfortunately, Bill passed away between this and the previous maser symposium. He worked actively in the field up until his premature death in 2009.

The foundations of the theory of maser amplification in astrophysical environments were developed soon after the discovery of the first cosmic masers – in the late 1960s and early 1970s. Seminal papers were published by Marvin Litvak and by Peter Goldreich with colleagues. Later, the theory was elaborated upon and concretized by other authors, but qualitatively new ideas appeared rarer and rarer. When I started preparing this review, I realized that *advances* in cosmic maser theory during the four years passed after the Australia symposium have been modest at best. This explains my decision to dedicate most of the presentation to revisiting the basics of the theory. By doing so, I will emphasize the points that, in my opinion, have not been given enough attention in the past and yet have a good potential to provide deeper insight into the physics of masers. I will also comment on some new developments, especially those that can illustrate the application of the classical aspects of the theory.

I hope that this approach will help us create a common theoretical context for further discussions. I also hope that this review will help practitioners in this field, especially the young researchers, to make fast order-of-magnitude estimates of physical parameters of the maser environment while planning or interpreting observations and that it will help them to avoid some typical mistakes.

2. Population Inversion and Masing as non-LTE Phenomena

Masing in a spectral line requires the fulfillment of two conditions: (1) population inversion, and (2) the absolute value of the optical depth in the line (the 'gain' of the maser) to be > 1. Maser radiation is an extreme case of non-LTE radiation. What is its place among other observable non-LTE phenomena? There are two useful approaches to answer this question.

The first approach (e.g. Strelnitski, Ponomarev & Smith (1996)) is based on the notion of excitation temperature:

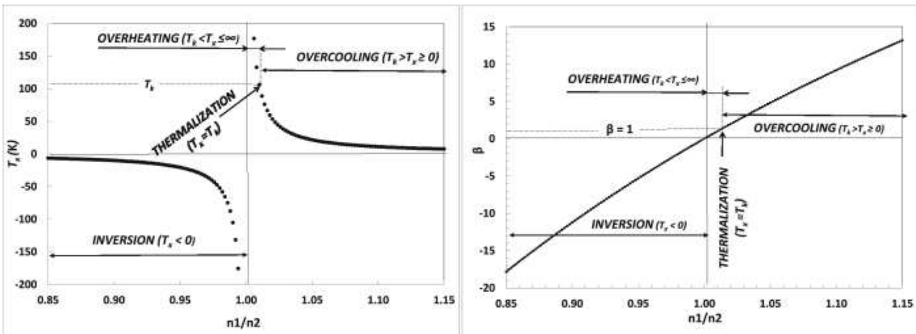

Figure 1. (left) Excitation states of a transition described by the T_x parameter. (right) Excitation states of a transition described by the β parameter.

$$T_x = \frac{h\nu}{k} \, [\ln(\frac{n_1}{n_2})]^{-1} \, , \qquad (2.1)$$

where $n_1 = N_1/g_1$ and $n_2 = N_2/g_2$ are the populations, per a degenerate sublevel, of the lower and upper levels of the transition, g_1 and g_2 are the statistical weights, and the other symbols have their usual meaning. Fig. 1(left) shows T_x as a function of n_1/n_2 for a transition with an arbitrary frequency ($\nu = 22.2$ GHz). The function has a singular point at $n_1 = n_2$, jumping from $+\infty$ to $-\infty$ when n_1/n_2 changes from > 1 to < 1.

While T_x is only a useful parameter, the kinetic temperature of the gas, T_k, describing the energetic state of the translational degrees of freedom, has a meaningful thermodynamical sense, because translational motions are 'maxwellized' in most astrophysical environments. If collisions control the populations of levels 1 and 2, T_x approaches T_k, and the transition 1-2 is said to be 'thermalized' (see more in section 4). T_k is just a point on the graph of T_x (its value in Fig. 1(left) was arbitrarily set to 106 K). It is natural to call the state of the transition with $+\infty \geqslant T_x \geqslant T_k$ 'overheating' and the state with $T_k \geqslant T_x \geqslant 0$ – 'overcooling.' The former causes an enhanced emission and the latter – an enhanced absorption in the line.

The other way to describe the excitation states of a transition is via the parameter

$$\beta_{12} \equiv \frac{1 - \frac{b_2}{b_1}\exp(-\frac{h\nu}{kT_k})}{1 - \exp(-\frac{h\nu}{kT_k})} = \frac{1 - \exp(-\frac{h\nu}{kT_x})}{1 - \exp(-\frac{h\nu}{kT_k})} \, , \qquad (2.2)$$

first introduced by Brocklehurst & Siton (1972). The coefficients b_1, b_2 are Menzel's coefficients of departure from LTE populations (Menzel (1937)). The graph of β as a function of n_1/n_2 is shown in Fig. 1(right). This function has no singularities, it goes smoothly through 0 when n_1/n_2 passes from > 1 to < 1 and it equals $+1$ at the point of thermalization ($T_x = T_k$). Like T_x, the β function is positive for ($n_1/n_2 \geqslant 1$) and negative for the population inversion. However, unlike T_x, which is a single function for each transition, there is an infinite number of β functions for each transition, corresponding to different values of T_k. The plot in Fig. 1(right) is for the same $\nu = 22.2$ GHz and $T_k = 106$ K as in Fig. 1(left).

An important methodological conclusion from this analysis is that overcooling of a transition ($T_x < T_k$; $\beta > 1$) is not 'anti-inversion' and the enhanced absorption caused by overcooling is not an 'anti-maser' effect, as they are frequently called. Inversion and maser are *absolute* phenomena, whereas the occurrence of overcooling and the ensuing enhanced absorption depend on the value of kinetic temperature. The opposite to overcooling of a transition is its overheating, not inversion. Unlike the 'relative' non-LTE phenomena, masing can, in principle, be accompanied by specific modifications of the radiation field and its interaction with matter. These effects include the line and beam narrowing; competition between spatial modes for pumping (which may make the apparent geometry of maser spots different from the actual geometry of the active region); the exertion of a 'negative' radiation pressure upon the medium; and the transition of the maser to the regime of 'oscillations'(as distinguished from the one-pass, travelling-wave amplification).

3. Maser as a Quantum Heat Engine

It is easily shown that a steady-state inversion of populations is impossible in a *two-level* quantum system. Whatever the number and temperatures of the energy reservoirs interacting with such a system, its excitation temperature will always be between the temperatures of the reservoirs – kinetic temperature, T_k, for collisional reservoirs and brightness temperature, T_b [see equation (4.4) below], for radiative reservoirs. Since both T_k and T_b are essentially positive, T_x of a two-level system will always be positive.

At least one extra level is needed in order to create the 'pumping' – a net population transfer from the lower to the upper maser level, which can cause and sustain population inversion. From the point of view of thermodynamics, any steady-state pumping mechanism is a cyclic quantum 'heat engine,' with some transition(s) of the cycle taking energy from high-temperature reservoirs ('sources') and some other transitions giving energy to low-temperature reservoirs ('sinks'). The source and sink are equally important for pumping. A correct description of a pumping mechanism should therefore refer to the types of *both* of them, not just to the type of the source, as it is frequently presented. Considering the elementary processes responsible for pumping – collisional (C), radiative (R), or chemical (X), there are nine possible source-sink combinations:

RR	RC	RX
CR	CC	CX
XR	XC	XX

The pumping is, respectively, 'radiative-radiative,' 'radiative-collisional,' etc.

The thermodynamical approach to maser physics is a helpful tool. A few examples of its application include: the idea of the (counter-intuitive) collisional-collisional (CC) pumping (Strelnitski (1984), Kylafis & Norman (1987), Elitzur & Fuqua (1989)); the account for the rates of *both* the source and the sink processes in a correct evaluation of the upper limit of maser luminosity (e.g. Strelnitski (1984)); the idea of the photon sink on the cold dust as a boost of the CR pumping rate and as a possible cause of variability of masers due to variations of the dust temperature (Strelnitski (1981)).

4. Thermalization

When the collisional transition probability, in a *two-level* system surpasses the Einstein coefficient of spontaneous emission,

$$C_{21} \equiv q_{21} N_c \gtrsim A_{21}, \tag{4.1}$$

T_x approaches T_k – the transition is 'thermalized' (see section 1). Here $q_{21} = \langle v\sigma \rangle$, v is the relative velocity of the target and collider, $\sigma(v)$ is the collision cross-section, and the angle brackets signify averaging over the velocity distribution. The condition (4.1) translates into a condition for the collider's number density: $N_c \gtrsim A_{21}/q_{21}$.

One may expect that sufficiently frequent collisions between the maser levels would do the same – bring the (negative) excitation temperature of the transition to the (positive) kinetic temperature, i.e. destroy the population inversion. However, as argued in section 2, a maser is, by necessity, a system of *more than two* levels. The use of the naïve two-level thermalization condition (4.1) to evaluate the upper limit of an allowable gas density in a maser may lead to large mistakes.

Actually, the frequently used condition (4.1) requires some elaboration even in its application to a two-level system. This condition follows from the obvious equation for the ratio of the level populations in a steady-state two-level system:

$$\frac{N_2}{N_1} = \frac{C_{12} + B_{12}J_{12}}{A_{21} + C_{21} + B_{21}J_{12}}\ , \tag{4.2}$$

where B_{12} and B_{21} are the Einstein coefficients for stimulated absorption and emission, respectively, and J_{12} is the radiation intensity averaged over directions and frequencies within the line. When $C_{21} >> A_{21}$ *and* $B_{21}J_{21}$, it follows from equation (4.2) and the well-known relation between C_{12} and C_{21}:

$$\frac{N_2}{N_1} = \frac{g_2}{g_1}\mathrm{e}^{-\frac{h\nu}{kT_k}} \tag{4.3}$$

– the Boltzmann population ratio with $T_x = T_k$, which means thermalization by collisions.

However, the additional condition $C_{21} >> B_{21}J_{21}$ can be unquestionably fulfilled only when $J_{12} \to 0$ – in an optically thin medium without external radiation. If $C_{21} << A_{21}$ in an optically thin system, and the external radiation is strong enough to also make $C_{21} << B_{21}J_{21}$, then, using the well-known relation $g_1B_{12} = g_2B_{21}$ and the definition of the brightness temperature (based on the Planck equation),

$$T_r = \frac{h\nu}{k}\ \left[\ln\left(\frac{2h\nu^3}{c^2J_{12}} + 1\right)\right]^{-1}, \tag{4.4}$$

we get from equation (4.2):

$$\frac{N_2}{N_1} = \frac{g_2}{g_1}\mathrm{e}^{-\frac{h\nu}{kT_r}}\,, \tag{4.5}$$

i.e. the Boltzmann distribution with $T_x = T_r$. One can consider this case as 'thermalization' of the transition by external radiation.

In an optically thick medium (the smallest optical depth $\tau_{min} >> 1$), the trapped line photons and the collisions work in concert toward thermalization, and T_x (and T_r) approach T_k at lower densities than predicted by condition (4.1), namely, at $N_c \sim A_{21}/(q_{21} \cdot \tau_{min})$ [see e.g. Avrett & Hummer (1965)).

In a maser, the rate of thermalizing collisions should be compared not with the spontaneous emission rate A_{21} but with the rate of pumping. It is customary to describe the rate of pumping by four phenomenological coefficients: Λ_1, Λ_2 ($\mathrm{cm^{-3}s^{-1}}$) – the coefficients of population supply to the maser levels from other levels, and Γ_1, Γ_2 ($\mathrm{s^{-1}}$) – the population decay rates. Assuming, for simplicity, that $\Gamma_1 = \Gamma_2 \equiv \Gamma$ and $C_{12} = C_{21} \equiv C$, one can present the (unsaturated) population *difference* (the quantity that determines the maser gain) as

$$\Delta N_0(\mathrm{cm^{-3}}) \equiv (N_2 - N_1)_0 \approx \frac{\Lambda_2 - \Lambda_1}{\Gamma + C}. \tag{4.6}$$

By formal analogy with the two-level system, it may appear that 'thermalizaiton' of the maser occurs when C exceeds Γ. However, equation (4.6) is not analogous to equation (4.2). If pumping involves collisions, the quenching of the maser can be postponed to a much higher density than determined by $C \sim \Gamma$. For example, if the population supply involves collisions, then Λ_2 and Λ_1, and thus the whole numerator in equation (4.6) will grow with N_c, which would prevent the decrease of ΔN_0 after C becomes $\sim \Gamma$. A good example of this case is presented by the H masers (section 6).

The extreme case is the CC pumping in which the source and the sink are due to collisions with two kinds of particles with different kinetic temperatures (section 3). In this case, all the terms in the right-hand side of equation (4.6) are proportional to the gas density, and, as long as the relative abundances of the two kinds of colliders and their temperature difference are sustained, there is *no* limiting ('thermalizing') density at all.

5. Saturation

When the rate of radiative transitions stimulated by the growing maser radiation becomes comparable with the pumping rate, the equation for the population difference can be presented in the form:

$$\Delta N \approx \frac{\Delta N_0}{1 + \frac{B_{21}}{\Gamma + C}} \approx \frac{\Delta N_0}{1 + \frac{J_{12}}{J_s}}, \tag{5.1}$$

where ΔN_0 is the unsaturated population difference given by equation (4.6), and

$$J_s \equiv \frac{\Gamma + C}{B_{21}} \tag{5.2}$$

is the 'saturation intensity.'

In a maser, $\mathrm{d}I \propto \Delta N \cdot I \cdot \mathrm{d}s$, where $\mathrm{d}s$ is the differential of the path length. In an unsaturated maser, $\Delta N \equiv \Delta N_0$ does not depend on I, which results in $dI/I = \mathrm{const} \cdot ds$ and thus an exponential growth of I. Under strong saturation, when $J_{12} >> J_s$, we can ignore unity in the denominator of equation (5.1); ΔN becomes inversely proportional to J_{12}, and thus to the central intensity of the line, I. The dependence of $\mathrm{d}I$ on I cancels. Combining equations (4.7), (5.1) and (5.2), we get: $dI = \mathrm{const} \cdot (\Lambda_2 - \Lambda_1) \cdot ds$ – a linear amplification proportional to the pump rate.

The fully saturation regime is the one of maximum usage of available pumping, with the release of a maser photon for each pumping cycle (in an unsaturated regime, most of the pumping cycles are closed by a collisional relaxation of transition 2-1). This fact is used to estimate the capability of a theoretical pumping mechanism to secure the observed flux density, S, in the masing line. A useful relation is (Strelnitski (1984)):

$$\left(\frac{N_1 \Delta\Gamma}{\mathrm{cm}^{-3}\,\mathrm{s}^{-1}}\right) \gtrsim 10^1 \left(\frac{l}{\mathrm{A.U.}}\right)^{-3} \left(\frac{D}{\mathrm{kpc}}\right)^2 \left(\frac{S}{\mathrm{Jy}}\right) \left(\frac{\Delta\nu/\nu}{10^{-6}}\right), \tag{5.3}$$

where $N_1 \Delta\Gamma \approx \Delta\Lambda$ is the pump rate; l is the amplification length along the line of sight; D is the distance to the source; and $\Delta\nu$, ν are the line's width and central frequency. Note that equation (5.3) contains only one geometrical parameter of the maser – its length along the line of sight, whose probable upper limit can often be estimated from the interferometrical map of the source (e.g. Strelnitski (1984)). This equation is valid, within an order of magnitude, for any geometry elongated along the line of sight. In the extreme (and improbable) case of purely spherical geometry, the coefficient 10^1 should be replaced by 10^2.

6. Hydrogen Masers and Lasers

The first mm and submm masers on hydrogen recombination lines were discovered at the end of the 1980s in the emission-line star MWC 349 (Martín-Pintado *et al.* (1989)). Later, the proof of masing (formally, already 'lasing') in this star was extended to the

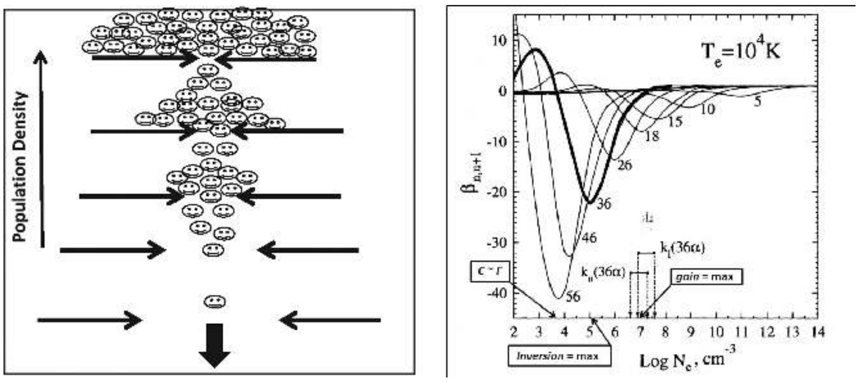

Figure 2. (left) To the formation of population inversion in recombining H atoms. (right) $\beta(N_e)$ for hydrogen recombination lines. The three arrows indicate the values of $\log N_e$ for which the H36α line has (1) $C \sim \Gamma$; (2) maximum inversion; and (3) maximum maser gain. Based on Storey & Hummer (1995) and Strelnitski, Ponomarev & Smith (1996).

IR domain (Strelnitski *et al.* (1996); Thum *et al.* (1998)). The observational aspects of hydrogen masers and lasers were reviewed by Martín-Pintado (2002). Here I will comment on some theoretical moments.

D. Menzel, the person who, apparently, was the first to understand the very possibility of radiation amplification in an inverted quantum system (Menzel (1937)), was also one of the first to create and... overlook a numerical model of hydrogen recombination line masers, discovered a half-century later. Use the above equation (2.2) to check that in Table 6 of his paper with Baker (Baker & Menzel (1938)), dedicated to the calculations of the theoretical Balmer decrements in gaseous nebulae, all the populations on levels $n > 5$ are *inverted* at $T_e = 10000$ K.

At low densities, typical for large HII regions, the inversion of populations across a wide group of Rydberg levels naturally arises as a result of spontaneous cascade after recombination to high-n levels. The rate of spontaneous decay steeply increases with decreasing n (approximately as n^{-5}). The analogy with a crowd rushing out from a building through a sequence of ever broadening doors (Fig. 2, left) may help understand why this leads to population inversion.

At higher densities, collisions with electrons and ions take part in the pumping. They redistribute the populations so that, depending on the density, the inversion for some group of levels increases, as compared with the purely radiative case, and for another group it decreases and can even be replaced by overcooling. Fig. 2(right) reproduces the results of calculations of the β parameter, as a function of electron density, for hydrogen α-lines with n from 5 to 56, for $T_e = 10^4$ K. At $N_e \approx 10^4$ cm^{-3}, for example, the lines around H55α attain maximum inversion (maximum absolute value of $\beta < 0$), whereas the lines around H25α are subject to maximum overcooling ($\beta > 1$). The shift of maser 'thermalization' to higher densities (see section 4) is illustrated with the H36α line. The 'two-level' condition of thermalization ($C \sim \Gamma$) is attained at $N_e \sim 5 \times 10^3$ cm^{-3}, but the inversion and the maser gain reach their maxima at much higher densities, $\sim 10^5$ and 10^7 cm^{-3}, respectuvely.

The possibility of maser amplification in high-n hydrogen recombination lines during the cosmological epochs of recombination and reionization was first considered by Spaans & Norman (1997). More recent investigation showed that observable effects from the epoch of recombination are improbable, but masing of the giant ionized clouds of the first galaxies, at $z \sim 10$, in the hydrogen lines whose frequencies, after red shift, fall into mm

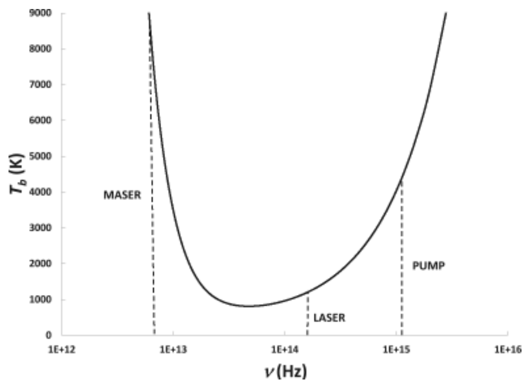

Figure 3. Lasers *vs.* masers

and short-cm domains may make them detectable with the modern radio-astronomical facilities (Loeb & Strelnitski, in preparation).

7. Astrophysical Lasers *versus* Masers

The broad inventory of masing and lasing hydrogen lines in MWC 349 helped understand why astrophysical masers are so common as compared with lasers. One of the possible reasons is connected with saturation (Strelnitski, Smith & Ponomarev (1996)).

Another way to understand the rareness of lasers (Messenger & Strelnitski (2010)) is based on the plausible assumption that the pumping cycles in most astrophysical environments contain at least one radiative step. The condition of maximum one maser photon per one pumping cycle (section 5) leads then to the conclusion that the *intensity* of the masing/lasing line must always be less or, at best, equal to the intensity of the pumping (source or sink) radiation. The dependence of brightness temperature on frequency for radiation of *fixed intensity* is shown in Fig. 3. The two branches of the curve correspond, asymptotically, to the Wien (laser) and Rayleigh-Jeans (maser) domains. Considering that the frequency of pumping is always higher than that of the maser or laser, Fig. 3 shows that, with the same pumping frequency, masers can achieve very high brightness temperatures, while the brightness temperature of lasers should, typically, be *lower* than that of pumping, which, observationally, creates a vicious circle. The probability of detecting high-gain astrophysical lasers is therefore low. This was recently pointed out also by Salzmann & Takabe (2011) in connection with the putative astrophysical X-ray lasers.

8. Polarization

Polarization of maser radiation, with its potential of extracting important information about the magnetic field in the maser's environment, remains one of the most controversial and 'polarizing' topics of cosmic maser theory.

The 'magnetic' interpretation of observed polarization was first addressed in the seminal paper of Goldreich, Keeley & Kwan (1973; hereafter 'GKK'). They considered the simplest case of 1-dimensional maser permeated by a homogeneous magnetic field B; the lowest angular momentum, $J = 1 - 0$, transition; and an isotropic pumping. Using an analytic, semi-classical approach, they obtained results for various combinations of four key parameters: the bandwidth of radiation, $\Delta\omega$; the Zeeman splitting $g\Omega$ (where g is the Landé g value for the upper state and $\Omega = eB/mc$ is the girofrequency); the population decay rate, Γ; and the stimulated emission rate, $R \equiv BJ$.

For paramagnetic molecules, such as OH, the Zeeman splitting $g\Omega$ in the magnetic fields of the expected strength is greater than the maser line width, which leads to the well anticipated result of a Zeeman pattern. The strength of the magnetic field can be directly determined from the observed separation of the circularly polarized σ components.

More complicated are the results for non-paramagnetic molecules, such as SiO, H_2O or CH_3OH , for which $g\Omega < \Delta\omega$ for any plausible values of the magnetic field strength. Analytical solutions were obtained by GKK only for linear polarization. One of the most cited results is that in a completely saturated maser ($R >> \Gamma$) and strong enough field [$g\Omega > (R\Gamma)^{1/2}$] the fractional linear polarization – the ratio of the Stokes parameters $Q = I_x - I_y$ and $I = I_x + I_y$, is

$$\frac{Q}{I} = \frac{3\sin^2\theta - 2}{3\sin^2\theta} \quad \text{for } \sin^2\theta \geqslant 1/3\ (\theta \geqslant 35^\circ);$$
$$\frac{Q}{I} = -1 \quad \text{for } \sin^2\theta \leqslant 1/3\ (\theta \leqslant 35^\circ),$$

where θ is the angle between the direction of the magnetic field and the propagation direction. Two important conclusions follow from this result: (1) linear polarization indicates the direction of the projection of the magnetic field onto the plane of the sky: it is either parallel or perpendicular to this projection; the change of the sign occurs at $\sin^2\theta = 2/3$ ($\theta = 54.7^\circ$, the so called 'van Vleck angle'); and (2) when the direction of the magnetic field is close to the direction of the line of sight ($\theta \leqslant 35^\circ$), the linear polarization reaches 100%.

Watson and co-authors revisited the problem in several papers (e.g. Watson & Western 1984; Watson & Wyld 2001) using the same formalism as GKK but obtaining solutions numerically. They showed, in particular, that the expected degree of linear polarization decreases with the decreasing degree of maser saturation and with the increasing angular momentum of the maser levels.

Detection of circular polarization in the maser radiation of non-paramagnetic molecules (SiO, H_2O) by the end of 1980s (Barvainis, McIntosh & Predmore (1987); Fiebig & Güsten (1989)) required a theory which would allow for an assessment of the magnetic field strength from the observed Stokes V parameter. The first interpretation was based on the theory for non-masing lines, which seems to be adequate for an unsaturated maser. According to this theory, V is proportional to $B\cos\theta$, and to the derivative of the intensity over frequency within the line:

$$V = \text{const} \cdot B\cos\theta \cdot \frac{dI}{d\nu}, \tag{8.1}$$

where the constant depends on the quantum-mechanical properties of the transition.

Nedoluha & Watson (1992) were the first to extend this classical theory to the case of a maser – a partially saturated H_2O maser. They came to the conclusion that, as long as $g\Omega >> R$, the error in the strength of the magnetic field obtained with the non-maser theory is less than a factor of 2, but it may be much greater if this condition is not fulfilled. Another important difference from the non-maser theory is the dependence of V on θ. The deviation from the classical $\cos\theta$ dependence increases with the intensity of the maser (Watson & Wyld 2001). For high intensities and saturation, the maximum V is achieved at $\cos\theta << 1$, closer to the perpendicular orientation of the field to the line of sight.

A persistent problem with the purely magnetic explanations of maser polarization is that, in some cases, the assessed magnetic field is implausibly strong. For example, Deguchi & Watson (1986) showed that the high degree of linear polarization in some strong H_2O masers (such as the famous 'super-maser' in Orion) requires magnetic fields of up to $\sim 1G$, whereas the subsequently measured circular polarization of H_2O emission led to the fields $\sim 10\,\mathrm{mG}$ (Fiebig & Güsten (1989); Nedoluha & Watson (1992)). Unlikely strong magnetic fields, $B \sim 10-100\,\mathrm{G}$, were indicated by the circular polarization of SiO maser in several late-type stars (Barvainis, McIntosh & Predmore (1987)). More recently, the magnetic interpretation of circular polarization observed in several 6.7 GHz and other methanol masers with the use of the Landé factors extrapolated from the only known laboratory measurements by Jen (1951)) for the 25 GHz transitions, with the correction for the old, recently revealed order-of-magnitude arithmetical error in the extrapolation, led to implausibly high values of the magnetic fields (e.g. Vlemmings, Torres & Dodson (2011); Fish *et al.* (2011)).

These cases urge the researchers to address the studies of non-magnetic or non-Zeeman mechanisms for polarization. I will briefly comment on a few of them.

The capability of *anisotropic pumping* to produce linear polarization has been discussed in many papers, starting in 1960s. For a recent application to unsaturated masers, see, for example, Asensio Ramos, Landi Degl'Innocenti & Trujillo Bueno (2005). Western & Watson (1983) showed that linear polarization can be produced by the competition between intersecting rays of a saturated maser in a non-spherical medium or a medium with velocity gradients, if, in addition, there is a lack of axial symmetry along the line of sight.

Variations of the orientation of a (relatively weak) magnetic field along the line of sight can cause circular polarization of the output radiation, if the input radiation is linearly polarized (Wiebe & Watson (1998)). In a maser with $R \sim g\Omega$, circular polarization can appear because of the change of the quantization axis from the direction of the magnetic field to the direction of propagation (Nedoluha & Watson (1994)).

Problems with the theories of maser polarization were strongly emphasized by Elitzur, including the acknowledgment of 'incompleteness' of his own, alternative analytical approach that he developed in a series of papers in the 1990s. The references and the summary of his views can be found in Elitzur (2002) and Elitzur (2007). In particular, he put into question the validity of the results obtained by numerical simulations based on GKK theory. References, including the papers with counter-arguments by Watson and co-authors can be found in Dinh-V-Trung (2009). The latter author performed a computer modeling of maser amplification in the presence of a strong magnetic field, proceeding from random realizations of broadband seed radiation for the maser. Averaging over the ensemble of emerging maser radiation led to the polarization parameters that are in general agreement with the old numerical simulations based on GKK theory, which the author considers to be a confirmation of the validity of the old numerical modeling. The summary of Watson's views on the problem of polarization is presented in his last review (Watson (2009)).

The best remedy from the uncertainties of the current theories of cosmic maser polarization is, probably, a complex approach, when each significant conclusion (such as the strength and structure of the magnetic field) is verified by more than one independent method.

9. Concluding Remarks:

- 'Anti-inversion' and 'anti-maser' don't have physical meaning.
- Pumping mechanisms must be identified by *both* their source *and* sink.
- Be careful while assessing when a maser 'thermalizes'!

- Saturation is the key to most maser problems.
- First numerical models of H masers were created a half-century before their discovery (without computers and without understanding the result).
- Beware of land mines while entering the field of maser polarization!

Acknowledgments: The preparation of this review and the participation of the author in the Symposium were supported by the IAU and the Maria Mitchell Association, which is gratefully acknowledged.

References

Asensio Ramos, A., Landi Degl'Innocenti, E., & Trujillo Bueno, J. 2005, *ApJ* 625, 985
Avrett, E. H. & Hummer, D. G. 1965, *MNRAS* 130, 295
Baker, J. G. & Menzel, D. H. 1938, *ApJ* 88, 52
Barvainis, R., McIntosh, G., & Predmore, C. R. 1987, *Nature* 329, 613
Brocklehurst, M. & Siton, M. J. 1972, *MNRAS* 157, 179
Deguchi, S. & Watson, W. D. 1986, *ApJ* 302, 750
Elitzur, M. 2002, in: V. Migenes & M. Reid, (eds.), *Cosmic Masers: From Protostars to Blackholes*, Proc. IAU Symposium No.206 (San Francisco: ASP), p. 452
Elitzur, M. 2007, in: J. Chapman & W. Baan (eds.), *Astrophysical Masers and their Environments*, Proc. IAU Symposium No.242 (San Francisco: ASP), p. 7
Elitzur, M. & Fuqua 1989, *ApJ* (Letters) 347, L35
Fiebig & Güsten 1989, *AA* 214, 333
Fish, V., Muehlbrad, T. C., Pratap, P., Sjouwerman, L. O., Strelnitski, V., Pihlström, Y. M., & Bourke, T. M. 2011, *ApJ* 729, 14
Goldreich, P., Keeley, D. A., & Kwan, J. Y. 1973, *ApJ* 179, 111
Jen, C. K. 1951, *Phys. Rev.* 81, 197
Kylafis, N. D. & Norman, C. 1987, *ApJ* 323, 346
Litvak, M. M. 1970, *Phys. Rev. A* 2, 2107
Martín-Pintado, J. 2002, in: V. Migenes & M. Reid (eds.), *Cosmic Masers: From Protostars to Blackholes*, Proc. IAU Symposium No.206 (San Francisco: ASP), p. 226
Martín-Pintado, J., Bachiller, R., Thum, C., & Walmsley, M. 1989, *AA* 215, L13
Menzel, D. H. 1937, *ApJ* 85, 33
Messenger, S. J. & Strelnitski, V. 2010, *MNRAS* 404, 1545
Nedoluha, G. E. & Watson, W. D. 1992, *ApJ* 384, 185
Nedoluha, G. E. & Watson, W. D. 1994, *ApJ* 423, 394
Salzmann, D. & Takabe, H. 2011, *PASJ* 63, 727
Spaans, M. & Norman, C. A. 1997, *ApJ* 488, 27
Storey, P. J. & Hummer, D. G. 1995, *MNRAS* 272, 41
Strelnitski, V. 1981, *Soviet Astron.* (Letters) 7, 223
Strelnitski, V. 1984, *MNRAS* 207, 339
Strelnitski, V., Ponomarev, V., & Smith, H. 1996, *ApJ* 470, 1118
Strelnitski, V., Haas, M. R., Smith, H. A., Erickson, E. F., Colgan, S. W. J., & Hollenbach, D. J. 1996, *Science* 272, 1459
Strelnitski, V., Smith, H., & Ponomarev, V. 1996, *ApJ* 470, 1134
Thum, C., Martin-Pintado, J., Quirrenbach, A., & Matthews, H. E. 1998, *AA* 333, L63
Vlemmings, W. H. T., Torres, R. M., & Dodson, R., 2011 *AA* 529, 95
Watson, W. D. 2002, in: V. Migenes & M. Reid (eds.), *Cosmic Masers: From Protostars to Blackholes*, Proc. IAU Symposium No. 206 (San Francisco: ASP), p. 464
Watson, W. D. 2009, *Rev.Mexicana AyA* (Serie de Conferencias) 36, 113
Watson & Wyld 2001, *ApJ* (Letters) 558, L55
Western & Watson, W. D. 1983, *ApJ* 275, 195
Wiebe & Watson, W. D. 1998, *ApJ* (Letters) 503, L71