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On the possibility of the OMPR signal observation in the space maser radiation

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The effect of optic-metrical parametric resonance (OMPR) can take place when the specific conditions on the space maser radiation intensity, on the period of a compact binary system and on the geometrical location of the involved astrophysical objects are fulfilled. In this case the periodical gravitational radiation emitted by the binary affects the electromagnetic radiation of the maser and the periodical change of the intensity of the maser signal takes place. Contrary to all of the known "first order in amplitude" effects theoretically suitable for the detection of gravitational waves (GW), this effect being resonant is a "zero order" one and does not demand super sensitivity of the instruments. If observed, the OMPR effect could be used for the construction of the GW-map of the sky.

Keywords: Gravitational wave; Space maser

1 Introduction

In spite of the efforts and impressive results on the way to the direct detection of GW, this goal is far from being reached. This is due to the extremely small amplitude of the signal which is supposed to be registered in all 18 known [1] physical effects theoretically suitable for the detection of GW. All these effects including the most promising interferometric and rigid bar antenna ones are the first order in amplitude of the GW effects, that is they demand the accuracy of about 10^{-24}. This is not only the cause of all the experimental problems but also the reason why the success in measurements (when happens) would be hardly possible to use. The evidence of the GW radiation existence is given in [2], and it provides an excellent coincidence with the theory. This means that we could try to search for the principally different types of the effects based on the specific characteristics of the phenomenon, for example, on the wave character of it. In this case there is a hope to use a zero order in amplitude effect such as some resonance. If found, this effect would have another privilege, since the sources of GW must now be stable periodic sources like double stars or even pulsars, and not the catastrophic events (with great amplitudes) for which we have to wait when using the known approaches.

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The possibility of the optic-metrical parametric resonance (OMPR) effect was analyzed in [3]. It is based on the following physical background. Put a two-level atom into a spectroscopically strong resonant electro-magnetic wave (EMW), make it vibrate mechanically along the wave vector of the EMW and provide certain conditions on the frequency and amplitude of vibrations and on the Rabi frequency of the "atom+field" system. Then the observable spectra of scattered radiation obtain the large nonstationary components [4]. "Spectroscopically strong field" means that the stimulated transitions dominate over the spontaneous decay. "Large nonstationary component" is a feature providing the large amplitude periodical change of the intensity of the detected signal at a frequency close to the resonance frequency. This is due to a periodical absorption-to-amplification change of the energy flow when an electro-magnetic wave (EMW) interacts with the atomic medium [5].

The two-level atoms can be found in nature in the space masers, the radiation of the saturated space masers is spectroscopically strong, the mechanical vibrations of the atoms can be provided by the periodical GW passing through the maser. It will be shown that the necessary conditions can be sources/found in a variety of the astrophysical systems. The amplitude of the OMPR signal is of the same order as the signal registered by radio telescopes during the observations of the radio sources.

2 Brief theory of the OMPR effect

Let us regard a two-level atom in a strong monochromatic quasi-resonant field. The system of Bloch's equations for the components of the density matrix components is

$$\begin{aligned} \frac{d}{dt}\rho_{22} &= -\gamma\rho_{22} + 2i\alpha_1\cos(\Omega t - ky)(\rho_{21} - \rho_{12}) \\ (\frac{\partial}{\partial t} + v\frac{\partial}{\partial y})\rho_{12} &= -(\gamma_{12} + i\omega)\rho_{12} - 2i\alpha_1\cos(\Omega t - ky)(\rho_{22} - \rho_{11}) \\ \rho_{22} + \rho_{11} &= 1. \end{aligned} \tag{1}$$

Here ρ_{22} and ρ_{11} are the populations of the levels, ρ_{12} and ρ_{21} are the polarization terms, γ and γ_{12} are the longitudinal and transversal decay rates of the atom (if level 1 is the ground level, $\gamma_{12} = \gamma/2$); $\alpha_1 = \frac{\mu E}{\hbar}$ is the Rabi parameter (Rabi frequency) proportional to the intensity of the electromagnetic wave (EMW), μ is the dipole momentum, E is the electric stress, k is the y-component of the wave vector of the EMW, v is the atom velocity along the Oy-axis pointing at the detector, $\gamma << \alpha_1$ is the condition of the strong field.

Let this atom belong to a saturated space maser in the field of the periodic gravitational wave (GW) emitted by a compact binary star or by a pulsar and propagating anti-parallel to the Ox-axis pointing at the GW-source. The GW acts on the atomic levels, on the maser radiation and on the geometrical location of the atom. In [3] it was shown that the first effect is much smaller than the other two effects. The action of the GW on the monochromatic EMW could be accounted for by the solution of the eikonal equation

$$g^{ik}\frac{\partial\psi}{\partial x^i}\frac{\partial\psi}{\partial x^k} = 0; \quad i,k = 1\text{–}4. \tag{2}$$

The atom velocity, v, could be obtained from the solution of the geodesic equation

$$\frac{d^2x^i}{ds^2} + \Gamma^i_{kl}\frac{dx^k}{ds}\frac{dx^l}{ds} = 0; \quad i,k,l = 1{-}4 \tag{3}$$

(and not from the solution of the geodesic declination equation as in the calculations of the displacements of the parts of the laboratory setups, designed for the detection of GW).

The equations (1–3) are basic for the theory of the OMPR effect. The weak gravitational field in the empty space (far from masses) is described by the linearized Einstein equations. Then the perturbation of the metric tensor suffices the wave equation, and the perturbed metric tensor can be written as

$$g^{ik} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 + h\cos\frac{D}{c}(x^1 - x^2) & 0 \\ 0 & 0 & 0 & -1 - h\cos\frac{D}{c}(x^1 - x^2) \end{pmatrix}, \tag{4}$$

where h is the dimensionless (small) amplitude of the GW, D is the frequency of the GW, $x^i, (i = 1{-}4)$ are the coordinates.

The solution of (2) with regard to (4) shows that the action of the GW causes a phase modulation of the EMW. Since h is very small, the phase modulated EMW can be presented (in Cartesian coordinates) as a superposition [6]

$$E(t) = E\cos(\Omega t - ky) + E\frac{\omega}{8D}h[\cos((\Omega - D)t - ky) - \cos((\Omega + D)t - ky)]. \tag{5}$$

The solution of (3) with regard to (4) gives [3]

$$y(t) \sim h\frac{c}{D}\sin(Dt + Kx), \tag{6}$$

where K is the GW wave vector. The expression (6) makes it possible to get the component of the atom velocity directed towards the Earth

$$\begin{aligned} v &= v_0 + v_1\cos Dt, \\ v_1 &= hc. \end{aligned} \tag{7}$$

Substituting (7) and (5) into (1), we get

$$\begin{aligned} \frac{d}{dt}\rho_{22} &= -\gamma\rho_{22} + 2i[\alpha_1\cos(\Omega t - ky) + \alpha_2\cos((\Omega - D)t - ky), & (8)\\ &\quad -\alpha_2\cos((\Omega + D)t - ky)](\rho_{21} - \rho_{12}), & (9)\\ \frac{d}{dt}\rho_{12} &= -(\gamma_{12} + i\omega)\rho_{12} - 2i[\alpha_1\cos(\Omega t - ky) + \alpha_2\cos((\Omega - D)t - ky), \\ &\quad -\alpha_2\cos((\Omega + D)t - ky)](\rho_{22} - \rho_{11}), & (10)\\ \rho_{22} + \rho_{11} &= 1. \end{aligned}$$

where $\alpha_2 = \frac{\omega h}{8D}\alpha_1$, and (7) was used in the expression for the full time derivative $\frac{d}{dt} = \frac{\partial}{\partial t} + kv$. The solution of the system (8) is performed by the asymptotic expansion method, the small parameter being $\varepsilon = \frac{\gamma}{\alpha_1}$ (notice that $\frac{\alpha_2}{\alpha_1} \sim \varepsilon$ too). The essential point is the OMPR conditions:

i) the EMW field must be spectroscopically strong

$$\frac{\gamma}{\alpha_1} = \Gamma\varepsilon; \Gamma = O(1); \varepsilon << 1; \tag{11}$$

ii) the intensity of the additional EMW

$$\frac{\alpha_2}{\alpha_1} = \frac{\omega h}{8D} = b\varepsilon; b = O(1); \varepsilon << 1; \tag{12}$$

iii) the amplitude of the atomic oscillations

$$\frac{kv_1}{\alpha_1} = \frac{\omega h}{\alpha_1} = \kappa\varepsilon; \kappa = O(1); \varepsilon << 1; \tag{13}$$

iv) the frequency condition

$$(\omega - \Omega + kv_0)^2 + 4\alpha_1^2 = D^2 + O(\varepsilon) \Rightarrow D \sim 2\alpha_1; \tag{14}$$

and ε is the same value everywhere. If they are fulfilled, then the principal term of the asymptotic expansion for $Im(\rho_{21})$ which characterizes the scattered radiation energy flow can be calculated explicitly. The effect of the OMPR is that at frequency shifted by D from the central peak of the EMW (that is from the signal of the space maser), the energy flow is proportional to ε^0, i.e. has zero order in the powers of the small parameter of the expansion, and has the form

$$Im(\rho_{21}) \sim \frac{\alpha_1}{D}\cos 2Dt + O(\varepsilon). \tag{15}$$

It means that the signal intensity at this frequency does not depend on the GW amplitude and changes with the (doubled) frequency of the GW. The OMPR signal can be registered with the help of the special statistical processing of the radio telescope signal.

3 Analysis of the astrophysical systems

The analysis of the astrophysical systems includes the characteristics of the EMW sources, i.e. space masers, the characteristics of the GW sources, i.e. compact binaries and pulsars and the geometrical configuration of maser, binary and Earth.

3.1 EMW sources

As it was shown in [7] the minimal brightness temperature of a maser needed to provide the OMPR and calculated with regard to

$$T_b = \frac{\sqrt{3\pi}}{8}\frac{\hbar^2 c^3}{k}\frac{D}{\omega^2\mu^2} \sim 10^{-7}\frac{D}{\omega^2\mu^2} \tag{16}$$

is equal to $T_b \sim 10^8$ K for the observations dealing with a binary ($D \sim 10^{-4}$ s^{-1}) and is equal to $T_b \sim 10^{14}$ K for the observations dealing with a pulsar ($D \sim 10^2$ s^{-1}). Here we considered $\omega \sim 10^9$ s^{-1} and $\mu \sim 3 \cdot 10^{-19}$ CGS$_q \cdot$ cm. The known brightness temperatures of the spots in the cosmic masers are 10^9K for methanol masers, 10^{12} K for OH-masers and 10^{15} K for H_2O-masers. Therefore, the existing masers could in principle provide the intensities of the EMW needed for the OMPR. If the intensity of a maser is higher than that needed for the OMPR, it means that in the depth of this maser there exists a region where the OMPR condition is satisfied.

3.2 GW sources

The suitable periodical GW source is a compact binary system with mass $M \sim 10^{33}$ g, characteristic radius $R \sim 10^{10}$ cm, and gravitational ellipticity $g_e \sim 10^0$. The comprehensive reviews of various binaries are presented in [8–10]. For example, there are such binaries as RX J1914.4+2456, V407 Vul [11] with the period of 9.5 min, KUV 01584-0939, ES Cet [12] with the period of 10.3 min and XTE J1807-294 [13] with the period of 40.1 min. The binary with the shortest period now known is RX J0806.3+1527 [14] and it has a period equal to 5.3 min and is only 100 pc away from the Earth. Thus, the binary stars provide the GW frequencies $D \sim 10^{-4}$–10^{-3} Hz.

Another possible candidate is a neutron star (pulsar) with mass $M \sim 10^{33}$ g, radius $R \sim 10^6$ cm and gravitational ellipticity, g_e, varying from $g_e = 10^{-3}$ [15] to $g_e = 10^{-6}$ [16]. There is a theoretical lower limit for the rotation period of a pulsar [17], which is equal to 0.5–2 ms depending on the equation of state.

3.3 Geometrical configuration

The optimal configuration is such that the Earth and the GW source are located in the ends of the diameter of a circumference while the maser is on this circumference. Then there is a right angle between the direction of the EMW falling on the Earth and the direction of the GW falling on the maser. The correlation between the distance between the maser and the GW source, r_S, the GW source parameters and the GW amplitude, h, is given by the expression [15]

$$h = \frac{GMR^2D^2g_e}{c^4 r_S}. \tag{17}$$

Using the definitions and the OMPR conditions it was found [7] that

$$r_S = \frac{16Gk^2}{\pi c^7 \hbar^3}(MR^2g_e)(\mu^2\omega^2T_b^2). \tag{18}$$

The first factor is the combination of constants, the second factor characterizes the GW source, the third factor characterizes the EMW source

$$r_S \sim 10^{-31}(MR^2g_e)(\mu^2\omega^2T_b^2) \text{ [cm]}. \tag{19}$$

Then for a binary we get $r_S \sim 10^3 T_b^2$ cm and for a pulsar $r_S \sim 10^{-10}T_b^2$ cm, that is for the minimal brightness temperatures given above $r_S \sim 10^{19}$ cm for a binary and $r_S \sim 10^{18}$ cm for a pulsar.

4 Observation possibilities

The supposed signal presents the periodic change of the intensity of the maser signal with the frequency proportional to the frequency of the GW source. The resonance character of the effect means that the amplitude of this change does not depend on the amplitude of the GW (see (15)) and is comparable with the height of the maser peak. It is clear that the regular observations cannot provide evidence for the signal due to pulsars because of latter's high frequency. As to the binaries, we have to follow the changes during the times proportional to their periods. The results of [18] where the swift fluctuations of the space masers radiation were investigated suggest searching for the periodic components in the existing data and perform the observations with regard to the suitable systems.

4.1 Examples

The examples of the astrophysical systems that could be suitable for the GW observations based on the OMPR method were searched for in [19], [20] and are given below. The mentioned masers are H_2O ones, the distances between the GW sources (pulsar and double star) and corresponding masers are tens of parsecs, d is the estimated distance from the Earth.

	Name	RaJ	DecJ	d(pc)	GW fr(Hz)
B	RXJ0806.3+1527	08:06.3	$+15^0 27$	100	0.0031153
M	RT Vir	13:00:06.1	$+05^0 27' 14''$	120	
P	B1133+16	11:36:03.2477	$+15^0 51' 04.48''$	360	0.841812
M	AF Leo	11:25:16.4	$+15^0 25' 22''$	270	
P	B0031-07	00:34:08.86	$-07^0 21' 53.4''$	720	1.06050049872
M	U CET	02:31:19.6	$-13^0 22' 02.0''$	660	

5 Discussion

The suggested theoretical and observational analysis shows that there are astrophysical systems that could produce an observable signal corresponding to the action of the GW on the space masers. Let us mention some important details. The amount of atoms taking part in the effect is proportional to the cube of the GW length (about one cubic a.u.) which is enough for observation. The atoms located on the line of the GW propagation at regions neighbor to the OMPR one and moving in counterphase could produce the compensating action. Therefore, the size of the maser and the length of the GW should be taken into account. Since $\Omega \simeq \omega$, not only the single frequency mentioned in the calculations will take part in the effect but the finite region of frequencies around it. This means that the effect (if any) will be easily observable. It can be shown [4] that Doppler effect does not bring atoms out from the resonance. Several GW sources acting on the same maser do not affect each other.

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