Registration of gravitational waves emitted by periodic astrophysical sources: prospects for GW-astronomy and stellar navigation

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Abstract. All the efforts to directly detect the gravitational waves (GW), including the recent successes of the LIGO and VIRGO teams, are focused on registering the catastrophic events in deep space. The two main features of this activity are the unpredictability of these events and the extreme sensitivity of the necessary equipment. The principally new method of the GW detection is based on the effect of optic-metrical parametric resonance (OMPR) and does not require catastrophic events and supersensitive equipment. The corresponding theory shows that the periodic GW, emitted by a short-period binary star, acts on a distant astrophysical maser and produces a specific signal that can be registered by a regular radio telescope. The main feature of such signal is the periodic change of the intensity of the only one detail in a maser’s spectrum. The observations of 49 such masers were performed with the RT-22 radio telescope at Pushchino Observatory of RAS. The program of signal processing included the identification of periodic components in a spectrum, the elimination of artifacts associated with the observation procedure, and the determination of the frequencies of periodic components. After that the corresponding binary stellar systems were identified. Thus, close binaries become a kind of GW-beacons in the Milky Way. This gives rise to the GW-astronomy, provides obvious applications for stellar navigation and gives a clue to the study of the geometric structure of our galaxy.

1. Introduction
The theory of the OMPR effect that became the basis of the new method of the GW detection was developed in [1] by extending the effect suggested in [2] and later discussed in [3-4]. A two-level atom (TLA) is a well known model of an atom convenient for theoretical research. TLA is put into the monochromatic resonant field, and the stimulated radiation dominates over the spontaneous one (strong field). The intensity of the field is characterized by Rabi frequency, \( \alpha_1 = \frac{\mu E}{\hbar} \), (\( \mu \) is induced dipole momentum; \( E \) is electric stress), which is the frequency of population oscillation between the atomic levels. In case of small periodic perturbation like small mechanical oscillations of an atom or of its velocity in the direction of the radiation wave vector, a parametric resonance (PR) is possible [2]. It results in the appearance of a non-stationary periodic component in the registered spectrum of the scattered radiation; ‘non-stationary’ here means that its amplitude periodically varies with time with the period defined by the frequency of the atomic mechanical oscillations. Since the effect has a resonance nature, the amplitude of non-stationary component does not depend on the (small) amplitude of periodic perturbation and has the same order with the amplitude of the main signal. Thus, the effect has zero-order...
in amplitude. The dynamics of the effect can be described by the system of Bloch’s equations for the density matrix components [5].

The TLA is a model, which is hard to realize in laboratory but which is perfect for the description of transitions in the molecules of astrophysical masers. The electromagnetic wave (EMW) acting on a TLA in a saturated maser is strong. The small periodic perturbation of a TLA’s velocity can be delivered by a periodic GW emitted by a distant short-period binary star system. The GW acts i) on the atomic levels’ positions, ii) on the EMW produced by maser, and iii) on the location of a TLA belonging to this maser. It can be shown [1] that the first effect is negligibly small in comparison with two others. The action of the GW on the monochromatic EMW is found from the solution of the eikonal equation, in which the metric tensor describes the GW. The action of the GW on the atom’s geometrical location is found from the solution of the geodesic equation (and not of the equation of geodesic declination which is common for the usual theory). Then the component of atom’s velocity, orthogonal to the GW wave vector

\[ v = v_0 + \frac{hc}{2} \cos Dt \]  

(h is the dimensionless amplitude of the GW, c is the speed of light, D is the GW frequency). Provided certain OMPR conditions are fulfilled [1,2, 4], the asymptotic expansion method can be used to find the solution of the Bloch’s equations modified with regard to the mentioned above:

\[ \frac{d}{dt} \rho_{22} = -\gamma \rho_{22} + \frac{2i}{\hbar} [\alpha_1 \cos(\Omega t - ky) + \alpha_2 \cos((\Omega - D)t - ky) - \alpha_2 \cos((\Omega + D)t - ky)] \left(\rho_{21} - \rho_{12}\right) \]

\[ \frac{d}{dt} \rho_{12} = -(\gamma_1 + i\omega) \rho_{12} - \frac{2i}{\hbar} [\alpha_1 \cos(\Omega t - k_1y) + \alpha_2 \cos((\Omega - D)t - ky) - \alpha_2 \cos((\Omega + D)t - ky)] \left(\rho_{22} - \rho_{11}\right) \]  

\[ \rho_{22} + \rho_{11} = 1 \]

Here \( \rho_{ii} \) are populations, \( \rho_{12} \) is the polarization term, \( \gamma \) is the decay rate of the excited state, \( \Omega \) and \( k \) are the frequency and the wave vector of maser radiation, \( \alpha_2 \equiv \frac{\omega h}{\hbar D} \alpha_1 \) (\( \omega \) is the frequency of the atomic transition), \( \gamma/\alpha_1 = \epsilon \) is the small parameter. The oscillating velocity of an atom appears in the expression for the full time derivative \( \frac{d}{dt} = \frac{\partial}{\partial t} + kv \).

The detailed analysis of the needed parameters of astrophysical objects can be found in [1,3,4]. It was shown that the OMPR conditions can be sufficed in natural environment. Then the principal term of the asymptotic expansion for \( \text{Im}(\rho_{21}) \) which characterizes the scattered radiation energy flow (the observable flux) can be calculated explicitly and it appears to be oscillating and proportional to

\[ \text{Im}(\rho_{21}) \frac{\alpha_1}{D} \cos 2Dt + O(\epsilon). \]  

The physical meaning of this result is that under the action of a periodical GW in conditions of the OMPR, the EMW energy of a maser is redistributed, and the flux coming to the telescope and corresponding to a certain spectrum detail is periodically amplified and attenuated with the (doubled) frequency of the GW. The OMPR signal has two specific features distinguishing it from other signals. First, it presents the periodical change of the only one detail in a maser spectrum. Second, contrary to all the signals suggested to use for the GW registration, it has zero order in powers of the small parameter of expansion. The last means that no special ultra-sensitive instrumentation is needed to register the corresponding peak and, therefore, no big signal/noise problem appears.

The observations were carried out on RT-22 (the 22-meter radio telescope at Pushchino Radio Astronomy Observatory, Lebedev Physical Institute, Russian Academy of Sciences). The registration of the OMPR signal produced by the GW was first reported in [6]. An example of
an OMPR signal (non-stationary detail) can be seen on the set of the subsequent spectra of the registered astrophysical maser radiation given on Figure 1. Both specific features mentioned above can be clearly seen. The total number of investigated masers was 49, but some of them appeared obviously useless for our goals. The signal processing was performed for 136 observational sessions for 28 masers. The periodic behavior of a single component of the spectrum was registered in more than 60 sessions dealing with 9 masers. All the details of the observational procedure, instrument calibration and signal processing can be found in [7].

On Figure 2 there is an example of signal processing result free from the artifacts due to the total time of the session, to the period of antenna calibration, to the number of measurements between calibrations etc. High peak on Figure 2 presents a period of 68 minutes corresponding to the non-stationary component like that shown on Figure 1 for the radio source W3(OH) (RA 2h23m18s, Dec +61°38’58”) obtained by RT-22 on June 30, 2009, Puschino RAO RAS.

![Figure 1. Time dependence of the W49N radio source spectrum. Obtained by RT-22 telescope, February 07, 2008, PRAO RAS, Puschino.](image1)

![Figure 2. Lomb-Scargle periodogram with window function filter.](image2)

The observational session is limited by the duration of night. The smallest registered period was equal to 14 min 58 sec and the largest one – to 146 min [8]. The results of observations of the periodic spectra components are given in Tables 1 and 2. Six and more periods are usually considered as a proof of true periodicity, but it was also shown that the phase shift between the two sessions of W3OH observations marked with a in Table 2 perfectly fitted the 68 min calculated period.

Positions and epochs, corresponding to masers mentioned in Tables 1 and 2, are given in Table 3. Notice that the distances’ estimations are rather rough.
Table 1. Observations of details with periodic variability (6 and more periods per session).

| Period (min) | Maser   | Date (dd.mm.yyyy) | N – number of periods, V – detail’s location |
|--------------|---------|-------------------|---------------------------------------------|
| 14.58 ± 0.02 | W 3 OH  | 13.11.2009        | N = 9; V = -52 km/s                          |
| 21.61 ± 0.13 | Cep A   | 17.04.2009        | N = 7; V = -51 km/s                          |
| 23.14 ± 0.05 | Cep A   | 17.04.2009        | N = 6; V = -52 km/s                          |
| 46.06 ± 0.36 | Cep A   | 16.03.2010        | N = 9; V = -60 km/s                          |
| 50.64 ± 0.24 | RT Vir  | 19.10.2010        | N = 9; V = -49 km/s                          |
| 62.91 ± 0.32 | RT Vir  | 17.10.2010        | N = 7; V = -45 km/s                          |
| 67.63 ± 0.84 | RT Vir  | 18.10.2010        | N = 6; V = -52 km/s                          |
| 81.64 ± 1.39 | RT Vir  | 19.10.2010        | N = 6; V = -49 km/s                          |

Table 2. Observations of details with periodic variability (2-6 periods per session).

| Period range (min) | Period (min) | Maser   | Date (dd.mm.yyyy) | N – number of periods, V – maser feature, km/s |
|--------------------|--------------|---------|-------------------|-----------------------------------------------|
| 44                 | 43.8 ± 0.68  | NML Cyg | 22.04.2009        | N = 3; V = -48                                |
|                    | 43.81 ± 0.41 | Cep A   | 21.04.2009        | N = 3; V = -58                                |
| 46                 | 45.98 ± 0.57 | NML Cyg | 21.04.2009        | N = 3; V = -35                                |
|                    | 46.14 ± 0.52 | Cep A   | 24.04.2009        | N = 5; V = -52                                |
| 62-63              | 62.54 ± 1.31 | NML Cyg | 22.04.2009        | N = 2; V = -51                                |
|                    | 63.07 ± 0.37 | Cep A   | 14.10.2010        | N = 3; V = -51                                |
| 68                 | 67.55 ± 1.37 | W 51 N  | 20.12.2009        | N = 2.5; V = -60                              |
|                    | 68.08 ± 0.65 | W 3 OH  | 26.06.2009        | N = 2; V = -61                                |
|                    | 68.34 ± 0.71 | W 3 OH  | 30.06.2009        | N = 2; V = -61                                |
|                    | 68.08 ± 0.68 | NML Cyg | 16.04.2009        | N = 2.5; V = -51                              |
|                    | 68.33 ± 0.90 | Cep A   | 21.04.2009        | N = 3; V = -69                                |
|                    | 68.35 ± 0.94 | Cep A   | 31.07.2009        | N = 3; V = -65                                |
|                    | 67.77 ± 0.5  | Cep A   | 28.01.2010        | N = 4; V = -38                                |
|                    | 68.54 ± 1.67 | RT Vir  | 06.11.2010        | N = 3.5; V = -45                              |
| 83-84              | 83.03 ± 1.01 | W 3 OH  | 27.08.2009        | N = 2; V = -61                                |
|                    | 83.06 ± 0.76 | Cep A   | 16.03.2010        | N = 5; V = -46                                |
|                    | 84.59 ± 1.67 | RT Vir  | 06.11.2010        | N = 2; V = -50                                |
| 93-94              | 93.05 ± 0.81 | RT Vir  | 14.11.2009        | N = 3; V = -48                                |
|                    | 94.11 ± 1.52 | RT Vir  | 18.10.2010        | N = 5; V = -49                                |
|                    | 94.14 ± 1.12 | Cep A   | 17.03.2010        | N = 2; V = -59                                |
| 110                | 110.39 ± 0.15 | RT Vir  | 15.10.2010        | N = 3; V = -53                                |
|                    | 110.59 ± 3.33 | RT Vir  | 17.03.2010        | N = 2; V = -55                                |
|                    | 110.15 ± 0.76 | RT Vir  | 09.10.2009        | N = 4; V = -51                                |
| 144                | 143.72 ± 1.66 | Cep A   | 16.03.2010        | N = 3; V = -37                                |
|                    | 144.19 ± 1.9 | RT Vir  | 19.10.2010        | N = 3; V = -53                                |
|                    | 143.86 ± 3.22 | RT Vir  | 12.11.2009        | N = 3; V = -53                                |

\(^a\) - result reported in [7].
Table 3. Positions and epochs of the observed masers.

| Maser   | α (1950) | δ (1950) | Distance (pc) | V_{LSR} | Type |
|---------|----------|----------|---------------|---------|------|
| Cep A   | 22 54 19 | 61 45 44 | 700           | -8      | SFR  |
| RT Vir  | 13 00 06 | 05 27 12 | 220           | 14      | STAR |
| W 3 OH  | 02 23 18 | 61 38 58 | 1950          | -48.81  | SFR  |
| NML Cyg | 20 44 34 | 39 55 57 | 1610          | -19.6   | STAR |
| W 51 N  | 19 21 22.4 | 14 25 13.0 | 7000      | 63.0    | SFR  |

Turning to the interpretation of the obtained results, the following should be mentioned. If
an active star near the maser demonstrates periodic behavior, the pumping mechanism follows
it, and this could reasonably explain the periodic change in radiation intensity of maser cloud
as a whole. Then the observed periods must have the same time scale with the star processes
(regularly, months or even years). But we observe tens of minutes’ periodic changes in the
radiation intensity, and besides, the changes take place with only a single detail corresponding
to a single condensation belonging to the maser cloud. This means that it is not the neighbor star
that causes the effect. Also, the turbulence processes inside a 10^6 a.u. diameter gas condensation
cannot explain the results for the similar reason. Thus, there should be another cause, which
is external. Obtained results obviously cannot be the effect of the instrumental, weather or
interstellar medium instability influence, because it is only a single feature of the spectrum that
periodically changes and not the whole set of them.

In order to suggest the appropriate GW sources, notice the following. The wave vector of
the GW falling upon a maser must be perpendicular to the line of sight connecting maser and
the Earth. It means that the possible locations of short-period binaries that could affect the
observed maser belong to the base plane of the cone with the Earth at its top, as shown on
Figure 3.

Figure 3. Geometrical configuration of an astrophysical system.

We suspect a certain star to be binary, observing the change of intensity in its luminosity.
This means, that the Earth location is close to the rotation plane of this binary. The GW
emitted by this binary will affect a maser in a strongest way if this maser is also located close
to the plane of rotation of this binary. These remarks give a clue for the search of candidates to
take part in the described effect. Table 4 contains the examples of the binaries with due periods,
sufficing geometrical conditions mentioned above. Notice, that eq. (2) means that the period
of a due binary should be twice the period of the maser spectral component’s oscillation. For
various interior conditions, one and the same maser condensation can be a receiver for various
GW sources and can produce several non-stationary features on the spectrum (because of the
conditions’ change with time, their appearance may be not simultaneous). On the other hand,
one and the same GW-source can act on several masers.
Table 4. Examples of the possible GW sources acting on the observed masers.

| Period (min) | Maser  | Binary             | Period (min) | Ra (HH MM SS) | Dec (dd mm ss) |
|-------------|--------|--------------------|--------------|---------------|----------------|
| 44          | Cep A  | SBC9 050AB         | 86.3136      | 09 58 54.94   | -66 53 10.2    |
|             | NML Cyg|                    |              |               |                |
| 46          | NML Cyg| SBC9 2431AB        | 91.6704      | 09 47 11.94   | 51 54 8.9      |
|             | Cep A  |                    |              |               |                |
| 62-63       | NML Cyg| SDSS J073817+285520 AB | 126.0 | 07 38 17.74 | 28 55 19.7 |
|             | Cep A  |                    |              |               |                |
| 68          | W 51 N | KID 08912468       | 136.5624     | 20 00 27.74   | 45 10 04.4     |
|             | W 3 OH |                    |              |               |                |
|             | NML Cyg|                    |              |               |                |
|             | Cep A  | V0524 And          | 136.0699     | 01 05 47.15   | 44 35 03.7     |
|             | RT Vir | V2214 Cyg          | 136.9598     | 19 32 14.81   | 27 58 35.5     |
| 83          | W 3 OH | V592 Cas           | 165.6907     | 00 20 52.24   | 55 42 16.2     |
|             | Cep A  |                    |              |               |                |
| 93-94       | RT Vir | BOKS-35105         | 187.2        | 19 38 31.37   | 46 41 19.2     |
|             | Cep A  |                    |              |               |                |
| 110         | RT Vir | BP Lyn AB          | 220.05       | 09 03 8.89    | 41 17 47.6     |
|             | Cep A  |                    |              |               |                |
| 144         | RT Vir | V963 Ori AB        | 288.0        | 06 19 16.9    | 20 34 48.0     |
|             | Cep A  |                    |              |               |                |

Thus, short-period binaries become a kind of GW-beacons, distributed in the sky. This gives rise to the GW-astronomy, provides obvious applications for stellar navigation and gives a clue to the study of the geometric structure of our galaxy Milky Way as was discussed in [3-4].

References
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