GMSW as a detector of gravitational waves

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Abstract

The effect of an excitation of a gravitational wave (GW) on shock waves in a highly magnetized plasma [H]. GMSW, is studied as an effective means for the detection of GW radiated by neutron stars. It is shown that there is every reason to identify the giant impulses of the pulsar NP 0532 with GMSW.

1 Introduction

In the History of the century Physics, I suppose there is not such a grave experimental problem (with the exception of the controlled thermonuclear responses problem) that has been investigated for more than thirty years by different research groups as the gravitational waves detection problem (GWDP). Though much means are used to solve it, the GWDP has got not enough convincing positive result.

The reason for such an unsatisfactory condition in the GWDP, as the author supposes consists in the mistake of the originally chosen direction of its solving - in the program of the creation of the gravitational radiation detectors. The direct detection of GW can be realized by the tidal GW effect on a nonrelativistic detector (solid) or due to the relativistic GW effect on a detector which has a relativistic component (laser ray). In the both cases the GW effect on the detector (the experimental body displacement or the laser ray deviation) is proportional to the GW magnitude. And the expected GW amplitude values of astrophysics sources are extremely small (see, for example, [9] and [11]). The existing programs of gravitational radiation detection are calculated generally for astrophysics sources of two types: 1. Supernova; 2. close double systems. In the first case a GW amplitude which is of the order of $10^{-17} - 10^{-18}$ with the radiation in a broad frequency spectral range with the characteristic frequency of the order of $10^3$ sec$^{-1}$ may be expected; in the second case - an amplitude of the order of $10^{-20} - 10^{-21}$ with constant frequency in the interval of 0,1 - 10 sec$^{-1}$. Due to the expecting of the very small amplitude of the gravitational radiation, the experimental programs, oriented on direct gravitational radiation detection, run into the problem of noise of shot and quantum character. This contradiction has continued for 30 years and demands the creation of high-precision deeply cooled detectors.

On the other hand it is well-known that, even such weak by amplitude GW consist of rather high energy - for the above examples this energy is of the order of w/cm$^2$ for the first case and it is of...
the order of $10^{-13} - 10^{-11}$ w/cm$^2$ for the second case. The registration of the electromagnetic signal of that strength gives no problems. Therefore the problem of the gravitational radiation detection should be studied differently - to look for the specific electromagnetic signals as a result of the GW effect on the matter of those regions of Galaxy where the gravitational radiation intensity is large.

Setting the problem this way we, first of all, study the effect of gravitational waves on plasmalike media. The corresponding investigations were fulfilled in the 80s years generally in the Kazan school of Gravitation, and a number of specific electromagnetic reflections of a plasma for plane gravitational waves (PGW) was revealed. In [2] - [5] the effect of PGW on plasmalike media was investigated by the methods of relativistic kinetic theory in the approximation when the back response of matter on the PGW is negligible:

$$8\pi \varepsilon \ll \omega^2,$$

(1)

where $\omega$ is the characteristic PGW frequency, $\varepsilon$ is the matter energy density ($G = \hbar = c = 1$). These papers have revealed a number of phenomena of interest, consisting in the induction of longitudinal electric oscillations in the plasma by PGW. In spite of the strictness of the results obtained in [2-5], the effects discovered in these papers have very little to do with the real problem of GW detection. Moreover, the above calculations show lack of any prospect for GW detectors based on dynamic excitation of electric oscillations by gravitational radiation. There are two reasons for that: the smallness of the ratio $(m^2G/\varepsilon^2) = 10^{-43}$ and the small relativistic factor $\langle v^2 \rangle / c^2$ of standard plasmalike systems. The GW energy transformation coefficient to plasma oscillations is directly proportional to a product of these factors.

However, the situation may change radically, if strong electric or magnetic fields are present in the plasma. In [6] where the induction of surface currents on the metal-vacuum interface by a PGW was studied, it was shown that the values of currents thus induced can be of experimental interest. In [7] on the basis of relativistic kinetic equations, a set of magnetohydrodynamics (MHD) equations was obtained, which described the motion of collisionless magnetactive plasma on the background of a PGW of an arbitrary magnitude and it was shown that, provided the propagation of the PGW is transversal, there arises a plasma drift in the PGW propagation direction.

## 2 GMSW

In Ref.[1] the exact solution of relativistic MHD on the PGW background of an arbitrary magnitude was obtained. On the basis of this a new class, that is of the sufficiently nonlinear threshold effects, named GMSW - gravitational magnetic shock waves, was discovered.

PGW metrics of polarisation $e_+$ are described by the expression [9]:

$$ds^2 = 2 dudv - L^2 [e^{2\beta}(dx^2)^2 + e^{-2\beta}(dx^3)^2],$$

(2)

where $\beta(u)$ is an arbitrary function (the PGW amplitude); the function $L(u)$ (the PGW background factor ) obeys an ordinary second order differential equation ; $u = \frac{1}{\sqrt{2}}(t - x^1)$ is the retarded time and $v = \frac{1}{\sqrt{2}}(t + x^1)$ is the advanced time. Let there be no PGW at $(u \leq 0)$:

$$\beta(u)|_{u \leq 0} = 0; \quad L(u)|_{u \leq 0} = 1,$$

(3)

the plasma is homogeneous and at rest:

$$v^v_{|u \leq 0} = v^u_{|u \leq 0} = \frac{1}{\sqrt{2}}, \quad v^2 = v^3 = 0;$$

$$2$$
\[ \varepsilon|_{u \leq 0} = \varepsilon_0; \quad p|_{u \leq 0} = p_0. \]  
(\(p = p(\varepsilon)\) is the pressure of the plasma, \(v_k\) is the vector of its dynamic velocity), and a homogeneous magnetic field belongs to the plane \(\{x^1, x^2\}\):

\[ H_1|_{u \leq 0} = H_0 \cos \Omega; \quad H_2|_{u \leq 0} = H_0 \sin \Omega; \]
\[ H_3|_{u \leq 0} = 0; \quad E_4|_{u \leq 0} = 0, \]  
(5)

where \(\Omega\) is the angle between the axis \(0x^1\) (the PGW propagation direction) and the direction of the magnetic field \(\mathbf{H}\). The conditions (5) agree with the vector potential

\[ A_v = A_u = A_2 = 0; \]
\[ A_3 = H_0(x^1 \sin \Omega - x^2 \cos \Omega); \quad (u \leq 0). \]  
(6)

The exact solution of the relativistic MHD equations on the metrics background (2) obtained in [1] satisfies the initial conditions (3) - (5) and is determined by the governing function:

\[ \Delta(u) = 1 - \alpha^2 \left[ e^{2\beta} - 1 \right], \]  
(7)

where \(\alpha\) is dimensionless parameter:

\[ \alpha^2 = \frac{H_0^2 \sin^2 \Omega}{4\pi(\varepsilon_0 + p_0)}. \]  
(8)

This solution consists of a physical singularity on the hypersurface \(\Sigma_* : u = u_*\):

\[ \Delta(u_*) = 1 - \alpha^2 \left[ e^{2\beta(u_*)} - 1 \right] = 0, \]  
(9)

on which the densities of the plasma energy and of the magnetic field tend to infinity, the dynamic velocity of the plasma as a whole tends to the velocity of light in the PGW propagation direction. In this case the relation of the magnetic field energy density to the plasma energy tends to infinity. The above singularity is the GMSW spreading in the PGW propagation direction at a subluminal velocity. In [1] it is shown that, in the frame of reference of an external observer, the particles are reaching the singular surface (9) for infinitely long time. According to Eq.(9) the conditions of the singularity arising are

\[ \beta(u) > 0; \]  
\[ \alpha^2 > 1. \]  
(10)

The extremely important fact is that, the singular condition is even possible in a weak PGW (\(|\beta| \ll 1\)) on the condition of a highly magnetized plasma (\(\alpha^2 \gg 1\)). In this case the singular condition, according to (9), arises on the hypersurfaces \(u = u_*\):

\[ \beta(u_*) = \frac{1}{2\alpha^2}. \]  
(12)

In particular, in case of a barotropic equation of state (\(p = k\varepsilon, 0 \leq k < 1\)):

\[ \varepsilon = \varepsilon_0 \Lambda^{-1-\nu}; \]  
(13)
\[ v_v = \frac{1}{\sqrt{2}} L^\nu \Delta^{1+\nu/2}; \]  

\[ \frac{v_u}{v_v} = \Delta^{-2} \left[ \Lambda^{-\nu} + \alpha \Delta - 1 \right] L^{-2} e^{-2 \beta \cot^2 \Omega} ; \]  

\[ H^2 = \frac{H_0^2}{\Lambda^2} = \left( \cos^2 \Omega + L^2 \Lambda^{-\nu} e^{3 \beta \sin^2 \Omega} \right) , \]  

where \( \Lambda = L^2(u) \Delta(u) \), \( \nu = 2k/(1-k) \geq 0 \), \( H^2 = 1/2F_{ik}F^{ik} \) is an invariant of the electromagnetic field, (strength square of the magnetic field in the frame of reference comoving with the plasma).

It follows from (13) - (16) that, for \( \beta > 0 \) the plasma moves in the GW propagation direction \((v^1 = \frac{1}{\sqrt{2}}(v_u - v_v) > 0)\), by \( \beta < 0 \) - in the opposite direction. The effect is a maximum in the PGW propagation direction, that is perpendicular to the intensity of the original magnetic field, and vanishes in the direction parallel to the magnetic field intensity.

The singular character of the solution (13) - (16) is the consequence of the approach, in which the magnetactive plasma has been described on the background of vacuum PGW. In this case the gravitational wave plays the role of an infinite reservoir of energy. At the surface (9) the condition of the vacuum approximation (1) is broken. Therefore for correct describing the plasma motion at the surface (9) it is necessary to take into account the back plasma influence on the PGW metrics. It is noted (??) that, this leads to a strong (almost 100 % ) absorbing of the GW the acceleratred up to sublight velocity by plasma.

The energy of the shock wave is taken from the GW energy, thus the GMSW is being an effective mechanism transforming the GW energy into other types of energy (generally into electromagnetic energy). In [11] on the basis of the plasma energy and PGW balance a self-consistent model is suggested. It turned out that this process consists of a number of common regularities [11], [19]:

1. Calculation of the plasma back influence on the GW removes the singularity pointed above.

2. GMSW is completely described by three nonnegative dimensionless parameters: by the equation of plasma condition (parameter \( k \)), by the first (\( \xi^2 \)):

\[ \xi^2 = \frac{\pi G \varepsilon_0 (1 + \alpha^2)}{c^2 \beta_0^2 \omega^2} \]  

and the second (\( \Upsilon \)) parameters of GMSW:

\[ \Upsilon = 2 \alpha^2 \beta_0 , \]  

where \( \beta_0 \) is the maximum amplitude of vacuum PGW;

3. The necessary condition of GMSW exitation is (10) and (11):

\[ \Upsilon \geq 1 ; \]  

\[ ^1 \text{And as far as the author knows, it is the only of all today-known mechanisms.} \]
4. The only criterion of the GW strong damping is the large value of the second parameter of GMSW, $\Upsilon$:

\[ \Upsilon \gg 1; \quad \text{(20)} \]

5. In this case the plasma maximum response to GW is achieved when the value of the first parameter of GMSW is small:

\[ \xi^2 \ll 1, \quad \text{(21)} \]

6. The plasma response to GW is like a single impulse. Moreover the shock wave stage is always changed by the reverse stage, when the plasma turns back. Simultaneously its density pressure and the magnetic field strength damp;

7. The plasma response, with the ultrarelativistic equation of state ($k = 1/3$), is much larger than the plasma response with the nonrelativistic equation of state ($k = 0$), and in this case in an ultrarelativistic plasma the impulse duration is a little bit larger;

8. The GMSW impulse duration, $\tau$, does not exceed one forth of the GW period:

\[ \tau \leq \frac{T}{4} = \frac{\pi}{2\omega}. \quad \text{(22)} \]

9. At a maximum of the GMSW impulse the density of the magnetic energy reaches the value:

\[ \left( \frac{H^2}{8\pi} \right)_{\text{max}} = \frac{H_0^2}{8\pi} \sqrt{1 + \xi^2}. \quad \text{(23)} \]

10. The local flash of the magnetic field intensity in the GMSW leads to the power flash of the plasma magnetobremsstrahlung radiation, which is proportional to the magnetic field intensity square [10].

\section{GMSW in the magnetospheres of neutron stars}

The only possible source of a GMSW can apparently be neutron stars magnetospheres on the stage of the quadrupole oscillations of a neutron star or on the stage of a Supernova [1].

On the Fig.1. the relation of the GMSW first and second parameters in the magnetosphere of the neutron star which is of the mass of $M = 1.67M_\odot$ (pulsar NP 0532) to the distance to the star center is shown.

\footnote{Here and further speaking about the maximum response of plasma we mean its energetic characteristics: the density of the plasma energy current and the density of the magnetic field energy.}
Figure: 1. GMSW parameters in a NP 0532 magnetosphere for a dipole radial dependence of the magnetic field strength $H \sim 1/r$. Solid line: $\log \xi^2$; dotted line: $\log \Upsilon$. We supposed $R = 1.2 \times 10^6\text{cm}$ in the neutron star radius, $H(R) = 10^{12}\text{G}$, $\beta_0(R) = 10^{-8}$.

In this case the electrons density in the magnetosphere was calculated according to the estimate suggested in [13]:

$$n_e(R) \sim \frac{H}{4\pi\epsilon R}.$$  \hspace{1cm} (24)

As we can see on this drawing in the region of $0.8 \leq \log(r/R) \leq 1.2$, i.e., $7.6 \cdot 10^7 \leq r \leq 1.9 \cdot 10^8\text{cm}$ the conditions of the GMSW excitation are realized. If the magnetic field of a neutron star is described as that of a dipole, then the geographic angle $\Theta$ (counted relative to the magnetic equator) will be connected with the above angle $\Omega$ by the relation $\Omega = \pi/2 - \Theta$. Therefore the GMSW excitation condition depends on the angle $\Theta$:

$$\sin^2 \Theta < 1 - \frac{1}{2\alpha_0^2|\beta|}.$$  

Thus, in the magnetosphere of a neutron star (or a Supernova) a GMSW can be excited in the region of the magnetic equator, similarly to pulsars with a knife-like radiation pattern. In this region, as was demonstrated by the above examples, the gravitational radiation can be absorbed practically completely by the excitation of shock waves. A neutron star of such type should radiate gravitational waves only from its magnetic poles, similarly to pulsars with a pencil-like radiation pattern. In this case the probability of observing gravitational sources directly detecting a GW can be sharply dropped.

However the GMSW open another way of observing gravitational waves. The excited GMSW first of all carries with itself strong magnetic fields. These magnetic fields go from a neutron star in the magnetic equator plane and therefore they have to encrease the intensity of the brake radiation of the pulsar at the instant when the GMSW front is passing by. Thus, at the moment of the quadrupole oscillations exciting the anomalous intensity splashes in the pulsar radiation must be observed. According to (22) duration of these flashes is to be shorter or of the order of the GW period quarter and hence - of the quarter of the neutron star own oscillations period.

According to [9] the frequency of neutron stars own oscillations of neutron stars as a function of the mass of the latter variates in the bounds of $5 \cdot 10^3 \div 2 \cdot 10^4\text{sec}^{-1}$ mass. Therefore according to
the duration of the GMSW impulses and at the same time of the radiation flashes must satisfy the condition:

\[
\tau < 3 \cdot 10^{-4} \div 4 \cdot 10^{-5} \text{sec.}
\] (25)

Naturally the question about the nature of the pulsars quadrupole oscillations arises. The nuclear responses of an explosion character with heavy hyperons like \(n + n \leftrightarrow p + \Sigma^-\), that proceed in the nucleus of neutron stars at densities more than \(10^{15} \text{g/cm}^3\) may be the energy source for those oscillations. The presence of the strong magnetic field is to reduce to the asymmetry of the explosions, i.e., to the quadrupole moment excitation. A neutron star has to be rather young for such processes to happen in it. The calculations show \[15\], that after the Supernova explosion the neutron star temperature falls approximately in an order during \(10^4\) years. Consequently, the GMSW is to be looked for in the radiation of the rather young pulsars excited not earlier than 10,000 years ago.

4 Pulsar in Crabe NP 0532

The pulsar with the required parameters exists - it is the famous pulsar in the Crabe nebula, NP 0532; its life-time is less than 1000 years (Supernova, 1054 year). This pulsar is the youngest of all known ones (and, consequently, it is the hottest); it has the shortest period: \(T = 0,033\) sec. But the most surprising fact is that, in the radio-radiation of this pulsar one observes anomalies, that can be, in a great degree of assurance, identified with the GMSW. That is: in the radioradiation NP 0532 one observes single non-regular, so-called giant impulses (in the average 1 impulse an every 5 - 10 minutes) \[12\]. The intensity of the radiation by the giant impulses is larger in tens times (approximately in 60 times), than in common impulses. But the most interesting fact is that, the duration of the giant impulses is not more than \(9 \cdot 10^{-5}\) sec, i.e., almost in 2(!) orders shorter than that of the usual pulsars NP 0532 (\(\tau \sim 6 \cdot 10^{-3}\) sec). The duration of the usual impulses, as it is not difficult to see, is of the order of 1/5 of the rotation period. Thus, the common pulsars are clearly geometrically explained by the pulsar rotation. The duration of the giant impulses is 300 times shorter than the rotation NP 0532 period, in consequence of this fact there is still no satisfying theoretical model for the excitation of the giant impulses.

However, the giant impulses can be easily explained as the GMSW, while the duration of the giant impulses is related not to the period of rotation of the pulsar and the angle of the knife-like pattern of the radiation direction, but to the period of its own oscillations. The comparing of the durations of the giant NP 0532 impulses with the duration of the GMSW impulse \[22\] shows a striking coincidence of these values. Really, in case of the NP 0532 pulsar by the annihilation line shift in the spectrum of \(\gamma\)-radiation (400 keV instead of 511) the gravitational red displacement is known \[17\] and \[18\]: \(\Delta E/E = MG/Rc^2 = 0.217\). The extrapolation of the neutron star calculations \[9\] gives the NP 0532 pulsar mass: \(M = 1.67M_\odot\) and the radius of the corresponding neutron star: \(R = 12\) km. According to the estimates \[12\] the magnetic field strength of the NP 0532 pulsar surface is of \(10^{12}\) G. Then according to \(22\) the GMSW impulse duration for the NP 0532 pulsar is to be approximately 87 microseconds. The observed duration of the giant NP 0532 impulse is approximately 90 microseconds \[12\] (!). For the explanation of the observed radiation the amplitude maximum GW values on the stellar surface of the order of \(10^{-5}\) are requied. Such an amplitude corresponds to the gravitational radiation power of the order of \(4 \cdot 10^{42}\) erg/sec and the neutron star oscillations energy of the order of \(E_m \approx 4 \cdot 10^{41}\) erg. Taking into account that for the lifetime the NP 0532 pulsar of (1000 years) approximately \(7 \cdot 10^7\) giant impulses have been radiated, we get the estimate of the energy which was brought from the
neutron star by the gravitational waves $E = 2.8 \cdot 10^{49}$ erg. It is $10^{-5}$ of the rest energy of the given neutron star. This is completely connected with the suggestion about the constant rebuilding of its nucleus.

Note that, only the PSR 0833 of all known pulsars, apparently can radiate (but more seldom) the giant impulses. The other known pulsars are too old to do that. Therefore it is necessary to focus on the observing of these pulsars. It is worth to especially emphasize that, there are no other mechanisms which can accelerate the shock wave till the sublight velocities. Therefore it is very important to study the spectrum of the giant impulses in the X-ray range with the aim of discovering the violet shift of the radiation spectrum. Detailed studying of the giant impulses (their forms and moment spectrum) will allow not only to verify the existence of gravitational radiation, but also to give additional information about neutron star structure and about the processes taking place in their interior. In turn it is necessary to research the GMSW-impulses formation in detail theoretically. We intend to study this problem in future papers.

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