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TIDAL PRESSURE INDUCED NEUTRINO EMISSION AS AN ENERGY DISSIPATION MECHANISM IN BINARY PULSAR SYSTEMS

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The discovery of binary pulsar systems and the subsequent tests of the General Theory of Relativity (GR) through precise timing measurements of the pulsar signals is truly one of the great scientific achievements of our age. Observation of these systems are being used to test GR in the strong field range with unprecedented precision; the results have been interpreted as providing the first evidence for the existence of gravitational radiation (see Ref. 1 and references therein.)

We review here the accuracy with which GR can be tested in such a system, and propose a new energy dissipation due to tidal pressure variation driven neutrino and antineutrino production. Although much work concerning possible systematic corrections to the interpretation of relativistic effects in the binary pulsar system has been done, the mention of such has gone missing in the current physics literature.

Estimation of the effects on orbital dynamics due to structure of the neutron star and its companion has received some attention. Deviations from a $1/r$ potential due to either tidal or rotationally induced mass quadrupoles of the system constituents are expected to be too small to affect the rate of periastron precession as predicted by GR (similar effects were considered by Dicke in regard to the precession of the perihelion of Mercury).[2,3,4]

Of particular interest here are mechanisms which can affect the rate at which the orbital period changes. So far, the best-studied binary pulsar system is PSR 1913 + 16 with orbital period P_b =27 906.98... s which is changing at a rate $\dot{P}_b = -2.425(10) \times 10^{-12}$s/s. The best-fit to a full GR description of the system gives masses for the pulsar $m_1 \approx 1.42$ and its companion $m_2 \approx 1.40$ in units of the Solar mass, each with relative precision of 1.5%. The semimajor axis is approximately 3 light seconds, and the orbital eccentricity is approximately 0.6. It is expected that the radius of the pulsar is of order 15 km, while little is known about the companion star. Since there is no eclipsing of the pulsar signal, the companion must be of white-dwarf size or smaller; because of the low mass of the companion, it is concluded that the companion is a neutron star or black hole.[5]

The observed rate of change is in agreement with the prediction due to the emission of gravitational radiation (we point out that effects due to the finite sizes of the system constituents are too small to affect the derivation using point masses). A number of possible systematic corrections have been considered. Given that the tidal bulge is of order 0.5 nm, direct viscous dissipation of orbital energy seems unlikely.[3,6] However, one worrisome possible correction concerns the relative acceleration between the earth-sun and binary pulsar systems. The fractional rate of change in orbital period

$$\alpha = \frac{\dot{P}_b}{P_b} = -8.77 \times 10^{-17}\mathrm{s}^{-1} \tag{1}$$

could in principle be due to a relative acceleration of the two systems toward each other of $a = \alpha c = 2.6 \times 10^{-8}\mathrm{m/s}^2$ which is on the order of 1/300 of the acceleration of Pluto in its orbit around the sun. An analysis of the dynamics based on observation of objects in the neighborhood of the binary pulsar is presented in Ref. 6. It is concluded that, due to a relative acceleration between the binary pulsar system and the solar system, there is a correction to the rate of the orbital period change of $\Delta\dot{P}_b = (-0.017 \pm 0.005) \times 10^{-12}$s/s, a 0.7% effect.

Other possible systematics corrections to GR tests have been considered. These include propagation effects, mass loss by the system constituents, and the possibility that the companion is itself a binary.[2,3,6]

We now propose a new tidal dissipation effect which can contribute to the orbital energy loss in the binary pulsar system. To an observer on the pulsar surface, a tidal bulge induced by the companion star would rise and fall at the pulsar frequency $\Omega = 100$rad/s; because this frequency is much lower than the typical normal mode oscillation frequencies for a neutron star,[7]

$$\omega_{osc} \approx (Gm_1/r_1^3)^{1/2} = 10^4\mathrm{rad/s} \tag{2}$$

we can assume that the bulge in the surface is given simply by the static equilibrium deformation:

$$\left\langle \frac{\delta r_1}{r_1} \right\rangle \approx \frac{m_2}{m_1} \frac{r_1^3}{< R^3 >} \approx 5 \times 10^{-15} \tag{3}$$

where $< R^3 >$ represents the average of the cube of the separation between m_1 and m_2. The deformation amounts to 0.1 nm.

The primary energy loss mechanism will be due to beta decay and its inverse when the pressure changes as the tidal bulge moves across the surface; the respective antineutrinos and neutrinos which are emitted in these processes escape, carrying away energy from the system. Under static conditions, the neutrons and protons comprising a neutron star are in equilibrium. When the pressure (and density) change, a new equilibrium must be established, which occurs through the mechanism outlined above.

Other effects due to a tidal pressure change, such as gravitational radiation and shock phenomena, are exceedingly small. Neutrino energy dissipation as a damping mechanism for radial oscillations of a neutron star is discussed in Ref. 7, and references therein.

To zero order, we consider the pulsar to be an incompressible sphere of constant density. Of course, this is a very crude approximation, but will illustrate the level at which dissipation effects can enter. Tidal effects enter through pressure changes induced in the volume of the pulsar : the pressure p becomes a function of r and θ which specify a location within the pulsar,

$$p(r,\theta) = \int_r^{r_1} \left[\frac{m(r')}{r'^2} - \frac{m_2 \cos\theta}{(r' - R\cos\theta)^2 + (R\sin\theta)^2} \right] G\rho dr' \tag{4}$$

and $m(r')$ is the (pulsar) mass contained in a sphere of radius r'. We are interested in the change in p from the equilibrium value

$$\Delta p(r,\theta) = Gm_2\rho \frac{r_1^2 - r^2}{R^3} \cos^2\theta. \tag{5}$$

We now let the sphere expand, and use the relativistic equation for an ideal gas to get the change in density within the pulsar:

$$3p(r,\theta) = c^2\rho(r,\theta) \tag{6}$$

where $c^2\rho$ represents the energy density.

Since the pulsar is rotating in the gravitational field gradient of the companion, the density will be a function of time. When the density increases, protons and electrons combine to neutrons, and neutrinos escape from the system; when the density decreases, neutrons decay to protons and electrons, with antineutrinos escaping from the system. We consider this process to be adiabatic with the exception of the neutrinos and antineutrinos which represent an energy dissipation from the system, since each produced carries away energy E_ν.

Letting n be the nucleon number density, $n = \eta\rho/m_n$, where η represents the fraction of the energy density in the form of nucleons. We can parameterize the ratio of proton to neutron number density as $n_p = \beta n_n$, and $n = n_p + n_n$, with $\beta = \beta(n)$. Using a simple model for the neutron star,[8] for low densities near the 5×10^{14}g/cm^3 as expected for the neutron star under consideration, $\beta \approx 0.01$ and $n_n \approx n$. When a change in density occurs, the ratio β changes, reflecting a change in the equilibrium number densities:

$$dn = dn_p + dn_n = (\beta + 1)dn_n + \beta' n_n dn_n \tag{7}$$

and it is the last part of the right hand side which describes the change to the new equilibrium density (if it could be established immediately) and emission of neutrinos. This term can be represented by $dn_p = \alpha dn_n$ and this should be integrated over the entire pulsar to give the total energy dissipation through neutrino emission. For the assumed parameters, using Ref. 8, we find $|\alpha| \approx 7 \times 10^{-3}$.

The volume integral change in the total number of protons averaged over one period is thus

$$\Delta|N_p| \approx 6\pi \int_0^{r_1} \int_0^{\pi} \alpha G \eta m_2 \frac{\rho}{m_n c^2} \frac{r_1^2 - r^2}{R^3} r^2 dr |\sin^2\theta \cos\theta| d\theta =$$

$$= \frac{8\pi}{15} \alpha G \frac{r_1^5}{R^3} m_2 \frac{\eta\rho}{m_n c^2} \tag{8}$$

We must further take into account that the rate of conversion from neutrons to protons is slow; if the rotation frequency f is much faster than τ_β, the fraction which convert is $1/f\tau_\beta$. Furthermore, to get the energy loss rate, $\Delta|N_p|$ must be multiplied by f and E_ν to get the power loss rate, and we find

$$P_{diss} = \frac{8\pi}{15} \frac{1}{\tau_\beta} \alpha G \eta \rho \left\langle \frac{r_1^5}{R^3} \right\rangle m_2 \frac{E_\nu}{m_n c^2} \tag{9}$$

which on substituting $\rho = 4 \times 10^{14} g/cm^3$, $E_\nu \approx$1MeV, $\alpha \approx 7 \times 10^{-3}$, $\eta \approx 0.9$, and taking $\tau_\beta = 880$ s, the free space neutron lifetime, we find

$$P_{diss} \approx 2 \times 10^{25} \mathrm{J/s}$$

which, as described below, is of greater magnitude than the energy loss rate in the binary pulsar system.

However, we still must account for the fact that the β decay rate is suppressed within the neutron star because the electron Fermi sea is filled; our result represents an upper limit. The suppression of the β conversion rate can be easily estimated. The electron Fermi momentum, since the electron density must equal the proton density to ensure charge neutrality, is[8]

$$n_e = n_p = \frac{p_F^3}{3\pi^2\hbar^3} \tag{10}$$

which gives $p_F \approx$ 100MeV/c for the system under consideration. Since the electrons are relativistic, $p_F = E_F/c$, and we can assume that the temperature $T <$ 1MeV, the approximate Coulomb potential between protons and electrons at the given density. We thus immediately see that the system is nearly degenerate, as expected, in which case the chemical potential is to good approximation simply the Fermi energy associated with the density.[9] The reduction in the β rate is given by the reduction in allowed free electron states:

$$\frac{\tau_{\beta,free}}{\tau_\beta} = 1 - \frac{1}{1 + e^{(E_e - E_F)/T}} \approx e^{-E_F/T} \tag{11}$$

since the electron energy E_e in the decay is always much less than E_F. Since Eq. (11) approaches unity at $T \to \infty$, suppression of the fraction of energy dissipation due to the neutrino emission to the observational fractional accuracy of the total energy dissipation (5×10^{-3}) requires a temperature of nearly 15 MeV, which is certainly much higher than expected neutron star interior temperatures which are of order 10 keV.[7]

It is also possible for the final electron state in β decay to be bound to the proton; in this case, the fact that the Fermi sea is filled is irrelevant to the decay channel. Of course, the lifetime of the hydrogen atom formed is likely very short and the energy levels perturbed, but nonetheless, the final state is orthogonal to the electron plane wave states the Fermi sea comprises. We can estimate the fraction of neutron decays (in free space) which result in a hydrogen atom. The electron must be in an S-state in order to have a nuclear overlap, and the density at the nucleus is $|\psi_n(0)|^2 = 1/\pi a_0^3 n^3$ where n is the principle quantum number and a_0 is the Bohr radius. Furthermore, the normalized electron kinetic energy spectrum, in the low energy limit, becomes $dN(E)/dE = 3.2\sqrt{E}$, for electron kinetic energies $E << 1$, where E is measured in units of $m_e c^2$. Thus, the probability that a decay results in a hydrogen atom is given by the ratio of the number and coupling to atomic S states to the free space density of plane wave states, in a energy range of 0 to R_∞ =13.6 eV:

$$\frac{\sum_{n=1}^{\infty}(\pi a_0^3 n^3)^{-1}}{\frac{4}{3}\pi(2m_e R_\infty)^{3/2}(2\pi\hbar)^{-3}}\int_0^x \sqrt{E}dE = 7\times 10^{-6}, \qquad x=\frac{R_\infty}{m_e c^2}, \tag{12}$$

and we see the β decay rate is never reduced by more than this factor. This estimate is very close to the value 4×10^{-6} obtained by L.Nemenov[10] in the framework of usual V-A weak interaction, and we accept as the final result the last number being a more reliable.

Given that the total orbital energy is related to the period through

$$P_b = \pi G m_1 m_2 \sqrt{\frac{m_1+m_2}{4|E|^3}} \tag{13}$$

we find $|E| = 1.7\times 10^{41}$ J, and that

$$\left|\frac{\dot{P}_b}{P_b}\right| = \alpha = \frac{3}{2}\left|\frac{\dot{E}}{E}\right| \tag{14}$$

which gives

$$|\dot{E}| = 10^{25}\ \text{Watt}$$

Thus, from Eq. (8), the dissipation due to neutrino loss through tidal pressure changes amounts to a fraction

$$\frac{2\times 10^{25}\times 4\times 10^{-6}}{10^{25}} = 8\times 10^{-6}$$

of the total orbital energy loss rate which is attributed to gravitational radiation; this is about 1/900 of the fractional observational accuracy on the rate of slowing. We note also that our simple model predicts a steady state (non-tidally driven) energy loss rate due to neutrino and antineutrino emission of less than 1% of the total luminous energy emission.

In conclusion, we have demonstrated a possible orbital energy dissipation which can lead to a finite systematic correction and eventually limit the degree at which General Relativity can be tested in a binary pulsar system. Our models are extremely simple and might not be a reasonable approximation to the system, but nonetheless show that additional attention to such effects might be required.

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