POSSIBLE CONTRACTION OF THE MEMBERS OF THE BINARY PULSAR PSR 1913+16 AND ITS ASTROPHYSICAL CONSEQUENCES

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ABSTRACT. It is proposed that the small difference between the observed and the theoretically predicted decrease of the orbital period of the Binary Pulsar PSR 1913+16 is not due to the insufficiency of the quadrupole formula and can be attributed to a mass-energy loss due to the contraction of the binary's members. Assuming that the pair's primary is a typical, noncontracting pulsar, is in favour of a slowly contracting, neutron-star companion, thus limiting the member's radii to at most 25 km and 28 km, respectively. The primary's computed total absolute luminosity is in excellent agreement with the observed upper limit of its X-ray and optical luminosities. Moreover, the companion's slow contraction rate implies that its present total absolute luminosity presents a maximum at wavelengths characteristic of X-rays. Finally, it suggests that if the energy-loss remains constant, the duration of the contraction phase will be of the order of 10^8 y and the final radius about 25 km.

Perhaps the most interesting feature of the Binary Pulsar PSR 1913+16 is the observed decrease of the orbital period P_b of the pulsar, the system's visible primary, by a well-determined amount:

$$(-\dot{P}_b/P_b)_{obs.} = (1.1 \pm 0.2) \times 10^{-16} \ s^{-1}$$

where a dot denotes total time-derivative (Taylor et al. 1979). This decrease is explained as a decay of the binary due to the emission of orbital energy and angular momentum in the form of gravitational radiation. The corresponding result predicted theoretically via the quadrupole formula (Peters and Mathews 1963) is:

$$(-\dot{P}_b/P_b)_{pred.} = 0.8 \times 10^{-16} \ s^{-1}$$

differing from the observationally determined value by an extra amount:

$$(-\dot{P}_b/P_b)_{ext.} = 0.3 \times 10^{-16} \ s^{-1}$$

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approximately equal to its 24% and about 1.5 times larger than the quoted uncertainty of the observational data.

The above discrepancy is very close to the uncertainty of the observations, and so it is probable that more accurate, future observations will confirm the validity of the quadrupole formula in this case in spite of the expressed skepticism concerning this validity in general (Ehlers et al. 1976). On the other hand, the quadrupole formula has not been generalized in the case of a realistic binary so that to include the internal characteristics of the members and moreover post-Newtonian corrections to the Keplerian orbits, always assumed for the member's motion (see, however, Epstein and Wagoner 1975).

Here we present the motivation and the main results of an independent method for explaining the above discrepancy, which proved to be in favour of an active neutron-star companion, provided that the primary is treated as a typical noncontracting pulsar. Details and proofs will be given elsewhere (Spyrou, to be published). Thus, we consider that the discrepancy is not due to the insufficiency of the quadrupole formula. Instead, treating the members as realistic, extended bodies, and not simply as idealized point masses, we attribute the discrepancy in the value of $-\dot{P}_b/P_b$ to a change of the internal characteristics of the members.

It is obvious that we have to relate, somehow, the members' internal characteristics with their orbital motion. These characteristics, however, do not enter the dynamical laws of the orbital motions of the members provided by the Newtonian theory of gravity, usually applied. As the required generalization of these dynamical laws, we use the results of the recently developed post-Newtonian celestial mechanics for realistic binaries (Spyrou 1981 a,b; Caporali and Spyrou 1981). In this context each member is treated as a perfect-fluid body and the basic parameter describing it is its total mass-energy or inertial mass, m, defined as:

$$m = \overline{m} + c^{-2} E$$

where $\overline{m}$ and E are the body's rest mass and Newtonian total self energy and c is the velocity of light in vacuum. This theory has already been applied in the case of the Binary Pulsar (Spyrou 1981b) for determining the inertial masses, as well as the invariant rest masses under different assumptions, according to which both members do not contract, but rather they are in stable hydrodynamical equilibrium (constant and negative self energies). Moreover, most of this theory's dynamical laws, like, e.g., the orbital energy and orbital angular momentum per unit reduced mass, h and ℓ, as well as the generalized laws of Kepler and mass-function, have functional forms similar to their Newtonian counterparts.

In applying these results for explaining the extra decay of the Binary Pulsar, we shall let the inertial masses change due to the change of the self energies. (After all, we know that the Binary Pulsar has a nonvanishing luminosity.) Moreover, we shall demand that the purely orbital parts, h and ℓ, of the total energy and angular momentum, do not change, so that orbital energy and angular momentum losses in the form of gravitational waves be excluded. Then it can be shown that any change $\dot{M}$ of the total mass-energy will induce the following extra changes in the semimajor axis, a, eccentricity, e, and orbital period, P_b, of the relative orbit:

$$\dot{P}_b/P_b = \dot{a}/a = (e^{-2} - 1)^{-1}\,(\dot{e}/e) = \dot{M}/M\ .$$

In the case of the Binary Pulsar, these relations reduce to:

$$\dot{M}/M = -0.3 \times 10^{-16}\ s^{-1} = \dot{a}/a,\ \dot{e}/e = -0.4 \times 10^{-16}\ s^{-1}\ ,$$

showing that the extra decay ($\dot{a} < 0$, $\dot{e} < 0$) can be attributed to a certain decrease of the total mass-energy ($\dot{M} < 0$) due to both members.

For the evaluation of the quantity $\dot{m}/m$ for a member, we assume that this member is a homogeneous, spherically symmetric and uniformly rotating collapsed object whose interior is described by the Fermi-Dirac statistics for noninteracting particles of degenerate matter. Under these assumptions, it can be show that:

$$\frac{\dot{m}}{m} = C_R\,\frac{\dot{R}}{R} - \frac{2E_{kin}}{\bar{m}c^2}\,\frac{\dot{P}}{P}$$

where R, P and E_{kin} are the member's radius, period of axial rotation and kinetic energy of rotation, respectively, and the coefficient C_R, which is a known function of the member's internal characteristics, for a contracting star must be positive.

The coefficient C_R is always negative for typical white dwarfs, showing that isolated (as far as changes of their interior are concerned) white dwarfs cannot contract (and according to current theories of stellar evolution they, as well as isolated neutron stars, cannot expand). So if the companion is a white dwarf, the mass-energy loss is due solely to the visible pulsar's contraction. The same is true for a dead pulsar or a black hole companion. The coefficient C_R, however, for isolated neutron stars, can be either negative or positive, and so in the case of an active neutron-star companion, the mass-energy loss, in general, is due to both members' contraction.

In the case of the Binary Pulsar PSR 1913+16, the white dwarf and dead pulsar companions are ruled out on evolutionary grounds concerning the system itself (Srinivasan and van den Heuvel 1982), and so the companion can be either a neutron star or a black hole. In speculating about the unseen companion's nature, we recall that the visible pulsar, on the basis of its short pulse period (Smarr and Blandford 1976) and its weak dipole, magnetic field strength (Srinivasan and van den Heuvel 1982), is believed to be the older member of the binary. So it seems very probable that the major part of the mass-energy loss is due to the companion's contraction, and this rules out the possibility of a black hole companion, because, obviously, a black hole cannot emit energy, at least classically. Since, moreover, the companion is believed to be the younger member of the binary, it, most probably, is a rotating neutron star. This, along with the close proximity of the inertial masses of the members, implies that the slow-down rate of the companion cannot differ drastically from typical values, as is the primary's slow-down rate (Manchester and Taylor 1977). This slow-down rate solely, however, is not enough for explaining the mass-energy loss. So finally we are left with a rotating slowing-down and contracting neutron-star companion, which is responsible for almost all of the proposed mass-energy loss.

In view of the above, we adopt here the point of view according to which the visible pulsar does not contract and that the mass-energy loss is entirely due to the contraction of the companion neutron star. Moreover, we shall assume that the mass-energy densities of both members are in the range of the currently accepted densities of stable pulsars, namely, between $10^{13.40}$ gr.cm^{-3} and $10^{15.80}$ gr.cm^{-3} (Misner, Thorne and Wheeler 1972). This assumption simply means that the proposed contraction rate, if any, must be very small. In this way it is proved that the condition $C_R = 0$ for the noncontracting primary pulsar, along with the constancy of its rest mass, limit the pulsar's present radius and mass-energy density to about 25 km and $10^{13.44}$ gr.cm^{-3}, respectively. (The corresponding radius for the lowest possible density $10^{13.40}$ gr.cm^{-3} is about 30 km.) Moreover, it can be shown that the positivity of the coefficient C_R, necessary for a contracting pulsar, implies that its self-energy is negative, $E < 0$. This again is in favour of a slow contraction and shows that the proposed contraction is to be considered as a relic of the supernova explosion, from which the pulsar was formed. In other words, the major part of the contraction occurred during the supernova explosion, and after that the contraction continues in a very slow rate, the pulsar passing through various stages of stable (quasistationary) hydrodynamical equilibrium ($E < 0$) until it reaches the final stage of no contraction ($C_R < 0$). From a physical point of view, this slow appraoch to the final stable state is more preferable than its instantaneous settlement after the supernova explosion, and shows that the gravitational collapse could continue even after the formation of the neutron star.

In the case of the quasistationary, companion pulsar, we arbitrarily assume that its mass-energy is equal to the lowest possible density of stable pulsars, $10^{13.40}$ gr.cm^{-3}. Then the positivity of the coefficient C_R and the constancy of the companion's rest mass limit its present radius to about 28 km, while its radius and density at the final stable state of no contraction are found to be 25 km and $10^{13.55}$ gr.cm^{-3}, respectively. We notice that the difference of 5 km between the two radii is more pronounced that the corresponding difference of 3 km in the case of the companion pulsar. This could mean that in the case of the primary and little more massive pulsar the contraction has proceeded in the past in a faster way, and has decelerated to an almost zero value. This conclusion is again in favour of an older pulsar primary.

From the estimated radius and the observationally known slowdown rate of the primary pulsar, we find that its total absolute luminosity, interpreted as (minus) the rate of change of its total self-energy, is:

$$L_1 = 4.96 \times 10^{35} \text{ erg s}^{-1}$$

This result is in excellent agreement with the observed upper limits of the primary's X-ray and optical luminosities (Davidsen et al. 1975):

$$L_{1x} < 3 \times 10^{35} \text{ erg s}^{-1} \qquad L_{1v} < 0.17 \times 10^{35} \text{ erg s}^{-1}$$

and shows that its energy emission is practically all in the X-ray range. The corresponding absolute temperature is $T_1 = 2.9 \times 10^6$°K, showing that the emitted radiation presents a maximum at a wavelength about 10 Å, characteristic of the X-rays of energy of approximately 1.2 KeV.

In the case of the companion pulsar from the known values of the inertial masses, the radius and the coefficient C_R and assuming a slow-down rate $\dot{P}_2/P_2$ of the same order of magnitude as the primary's one, the contraction rate is estimated equal to:

$$\frac{\dot{R}_2}{R_2} = -\ 0.06 \times 10^{-16}\ \text{s}^{-1}$$

Moreover, the companion's absolute luminosity consists of two parts, the first of which, L_{2P}, depends only on the slow-down rate, while the second, L_{2R}, depends only on the contraction rate. These two parts are estimated equal to:

$$L_{2P} = 6.27 \times 10^{35} \text{ erg s}^{-1} \qquad L_{2R} = 1.42 \times 10^{38} \text{ erg s}^{-1}$$

The corresponding absolute temperatures are 3.04×10^6°K and 1.22×10^7°K showing that the emitted energies present their maxima at wavelengths 9.5 Å and 2.4 Å, respectively, characteristic of X-rays. The total luminosity, 1.43×10^{38} erg s^{-1}, corresponds to an absolute temperature 1.23×10^7°K and presents its maximum at a wavelength 2.4 Å (X-rays of energy 5.24 KeV).

Finally, some further consequences of the companion pulsar's contraction hypothesis are the following: i) Provided that the mass-energy-loss rate remains constant, the duration of the contraction phase will be about 4×10^8 y; ii) The primary's spin-down time is 2.1×10^8 y and it is equal to its slow-down time and to twice its cooling rate; iii) The companion's inertial mass at the final stable state will be 0.49 $m_\odot$, approximately 40% of its present value; iv) Although the companion's final rest-mass density will increase (by about 38%) due to the continuous squeezing of the baryons, the final inertial-mass density will reduce (by about 37%), due to the continuous loss of the star's self-energy; v) The companion's number of baryons is about 6×10^{58} (that of one solar mass pulsar being of the order 10^{57}).

In conclusion, the physically reasonable pulsar contraction hypothesis explains in an independent and very satisfactory way the visible pulsar's X-ray emission and other observed properties, and along with the presently accepted evolutionary data on the Binary Pulsar is in favour of an active neutron-star companion.

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Discussion

Rees: Bertoth, Carr and I have recently been considering what pulsar timing data may tell us about an important cosmological phenomenon: the possible presence of a stochastic background of long-wavelength gravitational waves, produced either in the initial instants of the big bang, or by (for instance) Population III massive objects at large redshifts. These waves would generate a very small time-varying redshift (i.e., change in ratio of clock rates) between a pulsar and the Earth. Limits on the "timing noise" or ordinary pulsars set interesting limits on waves with periods of 1 - 100 years. However, the best limits on periods 10 - 10^4 years are potentially offered by the orbital behavior of the binary pulsar. If we assume that the intrinsic secular behavior is given by the Landau-Lifshitz formula, this can be predicted with an accuracy which is already ~ 10^{-11} parts per year, and which can be improved at least to 10^{-12}. The absence of any discrepancy between observed and predicted orbital decay would then imply that gravitational waves with periods in the band 10 - 10^4 years constitute less than 10^{-4} to the density parameter Ω.

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