ON THE SLOW-DOWN OF THE MILLISECOND PULSAR PSR 1937 + 214

(Letter to the Editor)

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Abstract. There are indications that less than 10^{-3} of the spin-down energy of the millisecond pulsar PSR 1937 + 214 emerges as electromagnetic radiation. The implications of this result are discussed. The surface magnetic field would then be $\sim 10^7$ G, making the pulsar optically undetectable, and casting aspersions on the accretion disc spin-up neutron star models for the pulsar. The pulsar should have an equatorial ellipticity $\varepsilon \sim 10^{-9}$, which can be accounted for if the equatorial magnetic field departs from axisymmetry by one part in 10^3.

The 1.56 ms pulsar PSR 1937 + 214 with a $\dot{P} = 1.2 \times 10^{-19}$ s^{-1} is losing energy at a rate of 2×10^{36} erg s^{-1} (Backer *et al.*, 1982). If all this energy loss were due to electromagnetic radiation, then the pulsar should have a surface magnetic field $B \sim 5 \times 10^8$ G, four orders of magnitude smaller than the canonical value. If the optical and the X-ray emission from a pulsar come from close to the velocity-of-light cylinder, then the emission scales as $B^4 P^{-10}$ (Pacini, 1970). A comparison with the Crab pulsar reveals that the millisecond pulsar should have an optical magnitude $m_v \approx 22$ and an X-ray flux of 0.1 HRI counts s^{-1} (1 HRI count s$^{-1} \approx 10^{-10}$ erg cm^{-2} s^{-1}).

Whereas the optical identification of the pulsar with a 20th magnitude star has since been discounted (Lebofsky and Rieke, 1983) the observed X-ray flux is $< 10^{-3}$ HRI counts s^{-1}, which is ~ 100 times smaller than the predicted flux. This suggests that electromagnetism is only partially responsible for the spin down. Indeed, all available radio, infrared, optical, and X-ray upper limits show that, below 10^{19} Hz, $< 10^{-3}$ of the spin-down energy emerges as electromagnetic radiation (Becker and Helfand, 1983). The rest presumably is radiated away gravitationally.

For a pulsar losing energy by both gravitational and electromagnetic radiation, we have

$$\dot{P}/P = \alpha\Omega^4 + \beta\Omega^2 \tag{1}$$

and

$$\ddot{P}/P = -(\dot{P}/P)(\dot{P}/P + 2\alpha\Omega^4) + 2(\dot{\varepsilon}/\varepsilon)\alpha\Omega^4 + 2(\dot{B}/B)\beta\Omega^2\,, \tag{2}$$

where

$$\alpha = 32GI\varepsilon^2/5c^5 \quad \text{and} \quad \beta = R^6 \sin^2\theta\, B^2/6c^3 I \tag{3}$$

(cf. Ferrari and Ruffini, 1969).

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If the electromagnetic radiation takes away only 10^{-3} of the total spin-down energy, then $B \approx 2 \times 10^7$ G (for mass $M = 1 M_\odot$, radius $R = 10^6$ cm). This is more than an order of magnitude lower than the field needed to account for whole of the spin-down. With this weaker magnetic field, and according to the Pacini model, the pulsar should have $m_v \approx 38$ and an X-ray flux of 6×10^{28} erg s^{-1}, i.e. 10^{-5} HRI counts. Thus the pulsar would be optically undetectable. This X-ray flux is less than the upper limits of 10^{-3} HRI counts imposed by the Einstein Observatory results.

The weak magnetic field has interesting implications if the millisecond pulsar were an old neutron star spun up by accretion from a surrounding Keplerian disc. For accretion to take place, the Alfvén radius should not be smaller than the corotation radius (Davidson and Ostriker, 1973). The Alfvén radius for a given neutron star goes as $B^{4/7} \dot{m}^{-2/9}$ where $\dot{m}$ is the accretion rate, so that weaker fields require lower accretion rates. The critical mass accretion rate is given by

$$\dot{m}_{17}^{2/9} = 0.222 B_7^{4/7} R_6^{12/7} (M/M_\odot)^{-10/21} P_{ms}^{-2/3} . \tag{4}$$

If $B_7 \sim 1$, mass accretion rates are $\sim 10^{14}$ g s^{-1}, requiring time scales $\sim 10^{10}$ yr, which are very long. Thus, if the pulsar magnetic field is $\sim 10^7$ G, then accretion disc spin-up models for the millisecond pulsar are unlikely to be valid.

If $\dot{P}$ is predominantly due to gravitational radiation, then $\dot{P}/P = \alpha\Omega^4$ and the millisecond pulsar should have an equatorial ellipticity $\varepsilon = 3.7 \times 10^{-9}$. If we treat ε and B as constants, then from Equation (2) $\ddot{P}/P = -3(\dot{P}/P)^2$. (This should be compared with the value $\ddot{P}/P = -(\dot{P}/P)^2$ which would obtain if $\dot{P}$ were entirely due to electromagnetic radiation). The energy being radiated away as gravitational waves is $\approx 4 \times 10^{36}$ erg s^{-1} and corresponds to a flux at earth of $\approx 6 \times 10^{-9}$ erg s^{-1} cm^{-2}. The radiation frequency is 1280 Hz, which incidentally is very close to the frequency of Webers' detectors.

The equatorial ellipticity responsible for the gravitational radiation can be due to rotation or magnetic stresses. If it is due to rotation, then the neutron star should be a Jacobi ellipsoid just beyond the bifurcation point, which is possible only if its mass is $0.7 M_\odot$ (Datta and Ray, 1983). For all larger masses, it will be much below the bifurcation point. We have the equilibrium condition for a magnetic Maclaurin spheroid:

$$\varepsilon I(\Omega^2 - 2B_{12}) = 2(\mathfrak{M}_{11} - \mathfrak{M}_{22}) , \tag{5}$$

where B_{12} is defined in Chandrasekhar (1969) and $\mathfrak{M}_{11}$, $\mathfrak{M}_{22}$ are the equatorial components of the magnetic energy. Since the magnetic energy is a small fraction of the rotation energy, the equilibrium configuration will be determined by rotation alone. We can then substitute for Ω^2 and B_{12} values appropriate for a Maclaurin spheroid. An ellipticity $\varepsilon = 3.7 \times 10^{-9}$ corresponds to a departure, from axisymmetry, of the magnetic field by only one part in 10^3.

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