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ON THE MAGNETIC FIELD EVOLUTION IN ISOLATED NEUTRON STARS

MARIO LIVIO,[1] CHUN XU,[2] AND JUHAN FRANK[3]
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
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ABSTRACT

We examine the discrepancy between the theoretically expected number of detectable isolated old neutron stars (10^2–10^3), and the actually detected number of candidates (2–3). We argue that this discrepancy is explicable in terms of the suppression of accretion from the interstellar medium onto the old neutron stars. We show that for such a suppression to occur, a specific pattern for the magnetic field evolution in neutron stars is required. Strong magnetic fields ($B \gtrsim 10^{12}$ G) are required to decay rapidly, while fields of the order of 10^{10} G are required to remain constant in the absence of accretion. The required pattern agrees with recent theoretical models for magnetic field decay in neutron stars.

Subject headings: accretion, accretion disks — stars: magnetic fields — stars: neutron — stars: statistics

1. INTRODUCTION

Currently old neutron stars are observed essentially as either members of low-mass X-ray binaries or as millisecond pulsars. However, nearly three decades ago, Ostriker, Rees, & Silk (1970) and Shvartsman (1970) suggested that isolated old neutron stars (IONs) might be observable through the thermal emission resulting from the accretion of interstellar medium (ISM). This suggestion has been revisited by Treves & Colpi (1991), Blaes & Madau (1993), and Madau & Blaes (1994). These authors predicted that a few hundred to a few thousand IONs would be detected by the soft X-ray Position Sensitive Proportional Counter (PSPC) on board the *ROSAT*. Similarly, a few tens of detectable IONs have been predicted for the Wide-Field Camera (WFC) survey (Madau & Blaes 1994; Manning, Jeffries, & Willmore 1996). In contrast to these optimistic predictions, only three candidate IONs have actually been detected (Stocke et al. 1995; Walter, Wolk, & Neuhäuser 1996; Haberl et al. 1996), and, of these, the identification of the Stocke et al. (1995) object is ambiguous (it could be an Eddington-limited X-ray binary in NGC 1313). Furthermore, it has been suggested that these objects may not be powered by accretion at all (Caraveo, Bignami, & Trümper 1996). Essentially, no plausible candidates were found (Manning et al. 1996) in the all-sky survey bright source catalog (BSC; Pounds et al. 1993). This puzzling discrepancy between the predictions and the observations has been discussed by Manning et al. (1996), who suggested several possible solutions.

The huge discrepancy between the number of predicted IONs and the number of detected candidates can in principle arise from a number of causes (see also Manning et al. 1996).

1. *The number of IONs in the Galaxy could be lower than estimated* (10^9) *by Madau & Blaes* (*1994*).—While it is certainly the case that pulsar birthrate estimates (e.g., Narayan & Ostriker 1990) and nucleosynthesis constraints (e.g., Arnett, Schramm, & Truran 1989) seem to give somewhat ambiguous results, we feel that the above discrepancy is too large to be explained by this effect alone.

2. *The emission* (*for a given accretion rate*) *of the accreting IONs has been overestimated.*—While departures from blackbody, especially at high magnetic fields (e.g., Nelson et al. 1995), and at very low magnetic fields and low accretion rates (e.g., Zampieri et al. 1995), certainly exist, they are not likely to affect the estimates by more than a factor of a few.

3. *There is a significantly smaller number of low-speed IONs than estimated.*—The mean speed of pulsars at birth (Lyne & Lorimer 1994) is considerably higher than that assumed by Madau & Blaes (1994). Since the accretion rate is roughly proportional to v^{-3} (see eq. [1] below), it may certainly be the case that the number of detectable IONs would be reduced as compared to the estimates. It is unclear, however, whether the velocity distribution at birth gives an adequate representation for the velocity distribution of IONs. Furthermore, IONs with speeds of the order of 50 km s^{-1} can certainly be detected (e.g., Madau & Blaes 1994). Consequently, it is unlikely that the velocity distribution alone can account for the discrepancy between the estimates and the observations.

The large discrepancy between the observed and predicted numbers of IONs may not be fully explained by the reasons listed above. We raise the possibility that a more dramatic reduction in the predicted accretion rates may be necessary to explain the near nondetection of IONs. In the present paper, we concentrate on the possibility that accretion onto IONs is prevented by the action of dipole emission and magnetic propellers. We show that this has important consequences for the question of magnetic field decay in IONs. The latter problem has received immense attention in recent years, both in the form of theoretical studies (e.g., Sang & Chanmugam 1987; Urpin, Chanmugam, & Sang 1994; Romani 1990; Sengupta 1997, and references therein) and in the form of statistical studies (e.g., Narayan & Ostriker 1990; Lamb 1992; Verbunt 1994, and references therein). We propose that the paucity of observed IONs indicates that very high magnetic fields decay relatively fast to values of the order of 10^{10} G, but essentially no subsequent decay occurs in the absence of accretion.

Our numerical calculations and the results are presented in § 2, and a discussion and conclusions follow in § 3.

[1] mlivio@stsci.edu.
[2] Also Astronomy Department, University of Maryland, College Park, MD 20742; chunxu@stsci.edu.
[3] Permanent address: Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803; frank@rouge.phys.lsu.edu.

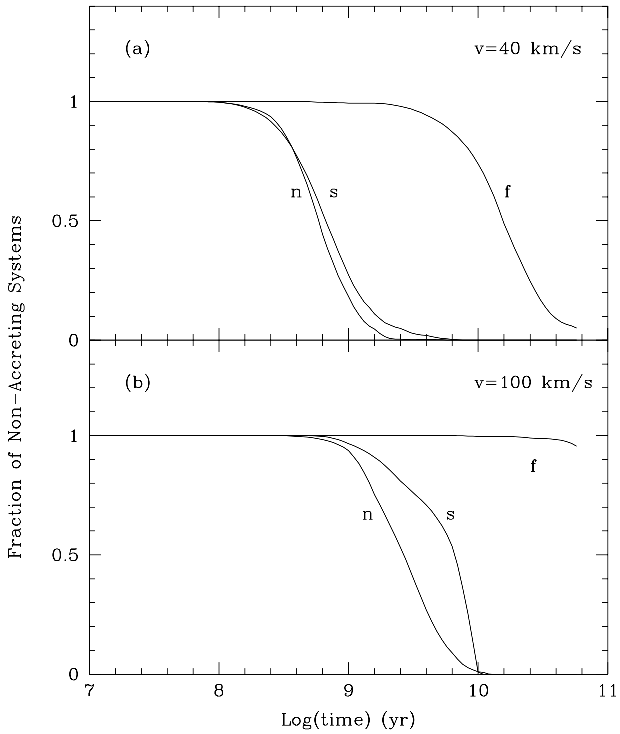

FIG. 1.—(*a*) Fraction of nonaccreting systems as a function of time for an assumed typical density of the ISM of $n = 1$ cm^{-3} and a fiducial velocity of $v = 40$ km s^{-1} is shown for three illustrative examples of magnetic field decay (see text): the label "n" stands for no decay ($\tau = 10^{11}$ yr, $B_m = 10^{10}$ G), "s" means slow decay ($\tau = 10^9$ yr, $B_m = 10^8$ G), and "f" means fast decay ($\tau = 10^7$ yr, $B_m = 5 \times 10^9$ G). (*b*) Same as (*a*), but for an assumed $v = 100$ km s^{-1}for the entire population.

2. THE SPIN AND MAGNETIC FIELD EVOLUTION OF ACCRETING NEUTRON STARS

The accretion rate onto a nonmagnetized neutron star moving through the ISM is given by the Bondi-Hoyle (Bondi & Hoyle 1944; Bondi 1952) formula,

$$\dot{M}_{\rm acc} = \frac{4\pi\xi G^2 M^2 \rho}{(v^2 + c_s^2)^{3/2}} , \quad (1)$$

where M is the mass of the neutron star, v is its velocity relative to the ISM, ρ is the ISM density, and c_s is the speed of sound. Three-dimensional numerical simulations have verified the validity of this expression with $\xi \sim 0.25-1$, depending on the specific heat ratio in the gas (e.g., Matsuda et al. 1991). For material to actually be accreted onto a spinning, magnetized neutron star, the centrifugal barrier must be overcome. The theoretical expectation of "propeller" ejection of material in the case of a rapidly spinning, magnetized object (e.g., Illarionov & Sunyaev 1975) has recently been confirmed observationally for the magnetized white dwarf AE Aqr (Eracleous & Horne 1996; Wynn, King, & Horne 1997).

In order to determine what fraction of the IONs are expected not to accrete due to the "propeller" mechanism, we have to follow the spin and magnetic field evolution of a population of neutron stars. Generally, the spin evolution progresses along the following phases (e.g., Blaes & Madau 1993; Wang 1997). At first, the neutron star spins down by the emission of dipole radiation during the pulsar active phase. At some point, the pulsar encounters the observed "death line," where the period and period derivative satisfy (e.g., Manchester & Taylor 1981) $\dot{P} \simeq 3 \times 10^{-17} P^3$. Once the ram pressure of the medium becomes larger than the pressure associated with the Poynting flux, material can reach the Alfvén radius, $r_{\rm A}$. However, the matter still cannot be accreted, as long as $r_{\rm A} > r_{\rm co}$ (where $r_{\rm co}$ is the corotation radius). During this second phase, the neutron star spins down mainly due to the propeller effect, with the expelled material removing the specific angular momentum (corresponding to the escape velocity) at $r_{\rm A}$. The evolution of the spin during these phases is governed in general by the equation (e.g., Goldreich & Julian 1969; Gunn & Ostriker 1970; Wang & Robertson 1985),

$$\dot{P} = \begin{cases} \dfrac{2\pi^3}{c^3} \dfrac{B^2 R^6}{I} \dfrac{1}{P} & p_{\rm ram} \lesssim p_{\rm Poynting} \\ \dfrac{1}{2\pi} \dfrac{(GMr_{\rm A})^{1/2} \dot{M}_{\rm acc}}{I} P^2 & p_{\rm ram} > p_{\rm Poynting};\ r_{\rm A} > r_{\rm co} , \end{cases} \quad (2)$$

where B is the magnetic field strength, c is the speed of light, R and I are the radius and moment of inertia of the neutron star, respectively, and P is the spin period. The first term on the right-hand side of equation (2) represents the effect of the dipole radiation, and the second is the spin-down due to the propeller effect.

In addition to the equation for the spin, we need to specify the magnetic field decay law. Because of the uncertainty concerning field decay in neutron stars (see, e.g., Verbunt 1994 for a review), and since this is exactly the property we would like to explore, we express the field decay in the form,

$$B(t) = B_0 \exp(-t/\tau) + B_m . \quad (3)$$

Here, B_0 is the initial field value for which a distribution has been assumed (see below), and we treat B_m and the decay timescale τ as free parameters.

We solved equation (2), together with equations (1) and (3), for a population of pulsars having an initial distribution of magnetic fields that is a Gaussian centered on $\log B_0 = 12.46$, with a dispersion of $\sigma_{\log B_0} = 0.31$ (cf. Lorimer et al. 1993). For the initial spins, we assumed a Gaussian distribution, centered on $\log P_0 = -1.65$, with a dispersion of $\sigma_{\log P_0} = 0.2$. The masses of all the neutron stars were assumed to be 1.4 $M_\odot$, and the radius was taken to be 10 km.

We performed several sets of calculations, selecting three representative examples of field decay to illustrate our point. In the "no decay" case, we took $\tau = 10^{11}$ yr, $B_m = 10^{10}$ G. In the "slow decay" case, we assumed that the field decays, but not too rapidly; therefore, we took $\tau = 10^9$ yr, $B_m = 10^8$ G. Finally, in our favored scenario of "fast decay," we assumed that high fields decay rapidly, but intermediate fields do not decay; hence, we took $\tau = 10^7$ yr, $B_m = 5 \times 10^9$ G.

It is now known that the velocity distribution of pulsars at birth extends to (and is centered around) much higher velocities than those assumed by Madau & Blaes 1994 and Manning et al. 1996 (see Lyne & Lorimer 1994). Even without a detailed analysis of how the velocity distribution evolves, it is clear that the present fraction of low-velocity IONs, which are likely to be detected, is significantly smaller than estimated previously. Therefore, we regard the fiducial value of 40 km s^{-1} in the calculations described below as representative of the potentially best detectable population.

In Figure 1, we show the fraction (of the total) of the systems in which *accretion is suppressed* as a function of time, for a typical ISM density $n = 1\ \mathrm{cm}^{-3}$, for two assumed relative velocities between the IONs and the ISM, and for the three field decay modes defined above. As can be seen in Figure 1, the fraction of nonaccretors generally decreases with time, and this fraction is greater for larger velocities at any given time. In our preferred case of "fast decay," we can see that (for $n = 1\ \mathrm{g\ cm}^{-3}$, $v = 40\ \mathrm{km\ s}^{-1}$) more than 70% of the systems do not accrete at $t = 10^{10}$ yr. The large fraction of nonaccretors, in this case, is due to the fact that the duration of the propeller phase decreases with the magnetic field strength as $B^{-2/7}$ (see eq. [2]). Thus, for high fields, this phase is relatively short. The rapid decay of the high fields (but the constancy of intermediate fields) thus ensures that a large fraction of the systems remains as propellers.

3. DISCUSSION AND CONCLUSIONS

In spite of predictions for the existence of hundreds of observable IONs, at most three candidates have been detected. An examination of possible reasons for this enormous discrepancy led us to speculate that accretion from the ISM onto IONs is significantly suppressed. We found that in order to suppress the accretion in a large fraction of the IONs, a specific pattern for the magnetic field evolution in neutron stars is required. Specifically, high values ($B \gtrsim 10^{12}$ G) of the magnetic field are required to decay rapidly (with an exponential timescale of about 10^7 yr), but fields of $\sim 10^{10}$ G are required to remain constant.

The magnetic field evolution in neutron stars has been discussed extensively over the years (see, e.g., reviews by Lamb 1991; Chanmugam 1992; Phinney & Kulkarni 1994). An important recent result (Sengupta 1997) shows that general relativistic effects reduce the decay rate, and that in particular, at late times in the evolution, *the decay rate is decreased by several orders of magnitude* (compared to the nonrelativistic case). At the same time, as the temperature of the crust decreases, the electrical conductivity increases, which also acts to decrease the decay rate (e.g., Urpin & Muslimov 1992). These two effects act exactly in the direction that, according to our calculations, is required for the suppression of accretion, namely, a relatively fast decay of the high fields in the early stages, followed by an essentially nondecay phase. The above considerations suggest a plausible self-consistent picture in which the magnetic field at birth decays initially, because the crust is still hot, to $B \sim 10^{10}$ G. Since this field is strong enough to prevent accretion despite the inevitable spin down, essentially no further field decay occurs because of the absence of accretion, and the IONs remain in the propeller stage for timescales comparable to the age of the universe.

Thus, the near-nondetection of IONs provides valuable information on the evolution of the magnetic field in neutron stars. We should note that the existence of a few accreting ION candidates (e.g., J0720.4−3125; Haberl et al. 1996; Wang 1997) is fully consistent with the general picture we presented, since the prediction is that some small fraction of the IONs will be accreting.

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