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Does mass accretion lead to field decay in neutron stars ?

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The recent discovery[1,2] of cyclotron lines from gamma-ray bursts indicates that the strong magnetic fields of isolated neutron stars might not decay. The possible inverse correlation[3] between the strength of the magnetic field and the mass accreted by the neutron star suggests that mass accretion itself may lead to the decay of the magnetic field. We calculated the spin and magnetic field evolution of the neutron star under the hypothesis of the accretion-induced field decay. We show that the calculated results are consistent with the observations of binary and millisecond radio pulsars.

Whether neutron stellar magnetic fields decay or not is at present a controversial issue. Statistical analyses[4,5] of $\sim$ 400 radio pulsars and the study[3] of the origin and evolution of magnetized neutron stars in binary systems indicate that neutron stars are born with magnetic fields of 10^{12}G which then decay with a time constant of $(5-10)\times 10^{6}$yr. Estimates of age and magnetic field strength of binary millisecond radio pulsars, however, require[6] that the field decay, if it occurs, should stop or proceed much more slowly on time scales of $\gtrsim 10^{9}$yr, at field strenghts $\lesssim 10^{10}$G. Pulsar models in which magnetic fields do not decay but align with the rotation axis are shown to also be consistent with the observed properties of radio pulsars[7,8,9].

Ohmic dissipation of electrical currents in the crust has been thought to be the physical cause for field decay[10]. However, recent calculations[11] of the ohmic decay of dipolar magnetic fields have shown that the field does not decay exponentially as has been assumed in most statistical analyses of radio pulsars and that, if the field occupies the entire crust, it decays by only less than a factor of 100 in a Hubble time.

If the strong magnetic fields of neutron stars do not decay, then the origin of the weak magnetic fields of less than 10^{10}G, found in binary and millisecond radio pulsars[12], remains to be explained. Neutron stars in binary and millisecond radio pulsars are thought to be formed by the iron core collapse of massive stars or by the accretion-induced collapse of massive white dwarfs (for reviews see refs. 13 and 14). In one scenario for the weak field and rapid rotation of millisecond radio pulsars it is argued that, quite simply, white dwarfs[15,16,17] or iron cores of massive stars[18] with the appropriate field strength and angular momentum give birth to the observed millisecond radio pulsars after a collapse. In another scenario, mass accretion in low mass X-ray binaries, which are assumed to be progenitors of millisecond radio pulsars, is proposed to cause both the field decay[19] and the spin-up[20]. In fact, Taam and van den Heuvel[3] found a possible inverse correlation between the magnetic field strength and the estimated total mass of accreted matter for binary X-ray sources and for binary and millisecond radio pulsars. This inverse correlation supports the latter scenario. A study of the evolution of magnetic fields in the crust of a neutron star[21] showed further that the inward heat flux caused by mass accretion powers thermomagnetic effects that could remove the strong magnetic field of a neutron star.

In the present paper we examine further the possibility that magnetic fields of neutron stars indeed decay only when neutron stars undergo mass accretion. We do that by considering gamma-ray bursts and the periods and field strengths of binary and millisecond radio pulsars.

The recent discovery[1,2] of cyclotron absorption lines with energies 20 keV and 40 keV from gamma-ray bursts revealed that the central objects of gamma-ray bursters are indeed strongly magnetized neutron stars with magnetic fields of 10^{12}G as has already been suggested in some theoretical works[22,23]. The statistical arguments suggest $\sim 10^7$yr (refs. 24 and 25) or $\gg 10^7$yr (ref. 26) for the age of neutron stars in gamma-ray bursters depending on the assumed distance. When combined with the high field strength, the latter age estimate contradicts the field decay hypothesis whereas the former does not.

We note that the absorption lines were seen only in a limited portion of the burst[1]. This observed fact can also be used to test the field decay hypothesis, if the cyclotron absorption lines appear and disappear due to the rotation of the star, since the presence of the cyclotron lines depends sensitively on the configuration of the magnetic field relative to the line of sight[27]. If this is the case, the 5–10s duration of the cyclotron absorption feature indicates the rotation period of $\gtrsim 10 - 20$s. This rotation period and the field strength put the gamma-ray burst sources into the category of the "turned-off" pulsars[5]. If the spin-down of the neutron star is caused by the magnetic field, which decays exponentially on a time scale of τ_B, the variation of the rotation period P with time t is represented by

$$P^2 = AB_0^2\tau_B[1 - \exp(-2t/\tau_B)] + P_0^2, \quad (1)$$

where B_0 and P_0 are the initial field strength and rotation period, respectively, and the constant $A = 9.8 \times 10^{-40}\text{sG}^{-2}$ for a stellar moment inertia of 10^{45} g cm^2 and radius of 10^6 cm. In order to attain the rotation period of $\gtrsim 10 - 20$ s from the initial value of maybe less than 1 s, magnetic braking requires the initial field strength of the neutron star to be larger than $\sim 2 \times 10^{13}$G if $\tau_B \sim 10^7$yr. This value of the initial field is on the high side, compared to the average values of $\sim 10^{12}$G indicated from the statistical analyses of radio pulsars. In view of that we would like to pursue here the other possibility, namely, that the magnetic fields of gamma-ray burst sources, which might be isolated neutron stars, do not decay.

As already mentioned, the weak magnetic fields of less than 10^{10}G are found in binary and millisecond radio pulsars[12], whose magnetic fields are plotted against rotation periods in Fig. 1. In the resurrected pulsar scenario[20] the progenitors of millisecond radio pulsars are the low mass X-ray binaries and their rapid rotations are the consequence of the spin-up due to mass accretion in binary systems. Let us consider the weak magnetic field and the rapid rotation of these radio pulsars in terms of the hypothesis that mass accretion leads to both spin-up and field decay. We assume that the magnetic field decays with accretion as

$$B = \frac{B_0}{1 + \Delta M / m_B} = \frac{B_0}{1 + \dot{M} t / m_B}, \tag{2}$$

where B is the field strength at time t, ΔM the accreted mass, m_B the mass constant for the field decay and $\dot{M}$ the accretion rate. Equation (2) fits well the inverse correlation between the magnetic field strength and the estimated mass of the total accreted matter for binary X-ray sources and binary and millisecond radio pulsars[3]. As already noted by Taam and van den Heuvel[3], this inverse correlation is also consistent with the simple field decay hypothesis if the larger amount of accreted matter is interpreted simply to reflect the greater age of the neutron star. Here, however, although we do not advocate any physical model leading to equation (2), we do assume that a direct relatin between field loss and accreted mass exists. Note that equation (2) represents a change in the whole field, not just the component perpendicular to the rotation axis. Using the formula given by Ghosh and Lamb[28] for the accretion torque, the variation of rotation period is described by

$$\dot{P} = -0.11 I^{-1} (\mathrm{G} M)^{3/7} (B R^3)^{2/7} n \dot{M}^{6/7} P^2, \tag{3}$$

where n is the dimensionless accretion torque (for details see ref. 28), R the radius, I the moment of inertia and G the gravitational constant. The calculated evolutionary tracks in the magnetic field versus rotation period diagram are illustrated by solid lines in Fig. 1. Rotation periods and magnetic fields become smaller with increasing time. The calculations were terminated when the inner edge of the accretion disk reached the surface of the neutron star. When the mass constant for the field decay is $m_B \gtrsim 10^{-3} M_\odot$, the evolution proceeds along the equilibrium rotation line[28] (dash-dotted line in Fig. 1), where the spin-up torque due to accreting matter and the spin-down torque due to magnetic field are balanced. This is because the time scale of the field decay is longer than the spin-up time scale. After mass accretion stops, stars move horizontally rightwards in Fig. 1. If $m_B \gtrsim 10^{-4} M_{\odot}$, the calculated evolutionary tracks are consistent with B and P of binary and millisecond radio pulsars. These evolutionary tracks are also approximately consistent with B and P of low mass binary X-ray sources such as suggested from the beat frequency model[29] for the quasi-periodic X-ray oscillations (see ref. 30 for a review). Note that the possible inverse correlation[3] between B and ΔM is represented well by equation (2) with $m_B \sim 10^{-4} M_{\odot}$. Hence, if we adopt $m_B \sim 10^{-4} M_{\odot}$, the accretion-induced field decay hypothesis represented by equation (2) is consistent with B, P, and ΔM as observed or estimated for binary and millisecond radio pulsars and binary X-ray sources.

The magnetic fields of single radio pulsars are in the range of $10^{11} - 10^{13}$G with a distribution peak around 10^{12}G. The accreted mass of interstellar matter onto a single radio pulsar is negligible compared to $m_B \sim 10^{-4} M_{\odot}$. Hence, the accretion-induced field decay hypothesis argues that the present field strengths of single radio pulsars should be equal to their initial values. This assertion, however, conflicts with the results of the statistical analyses[4,5] of radio pulsars, which suggest that surface fields decay on a time scale of $(5 - 10) \times 10^6$yr. Pulsar statistics depends, however, on the assumptions made for the radio luminosity law, the braking index, the magnetic field evolution, the distribution of initial field strength and so on. In order to resolve the above conflict, the statistical analysis under the assumption of no field decay should be conducted, examining especially the dependence on the assumptions for the above properties.

Mass accretion of neutron stars is likely to give rise to the inward heat flow through the crust. The thermomagnetic effects in the crust due to this inward heat flux, such as suggested by Blondin and Freese[21], have been invoked as a possible mechanism of the accretion- induced field decay. The formula of Blondin and Freese predicts, in its simplest form, a stronger dependence of the field decay on time compared to equation (2). The field decay formula due to the thermomagnetic effects, however, may depend on the structure of the crust, the accretion process, and the history of the heat flux. More detailed study on the thermomegnetic effects in the crust is important in order to resolve the controversial issue of the field decay in neutron stars. Other possible mechanisms for the accretion-induced field decay should also be explored.

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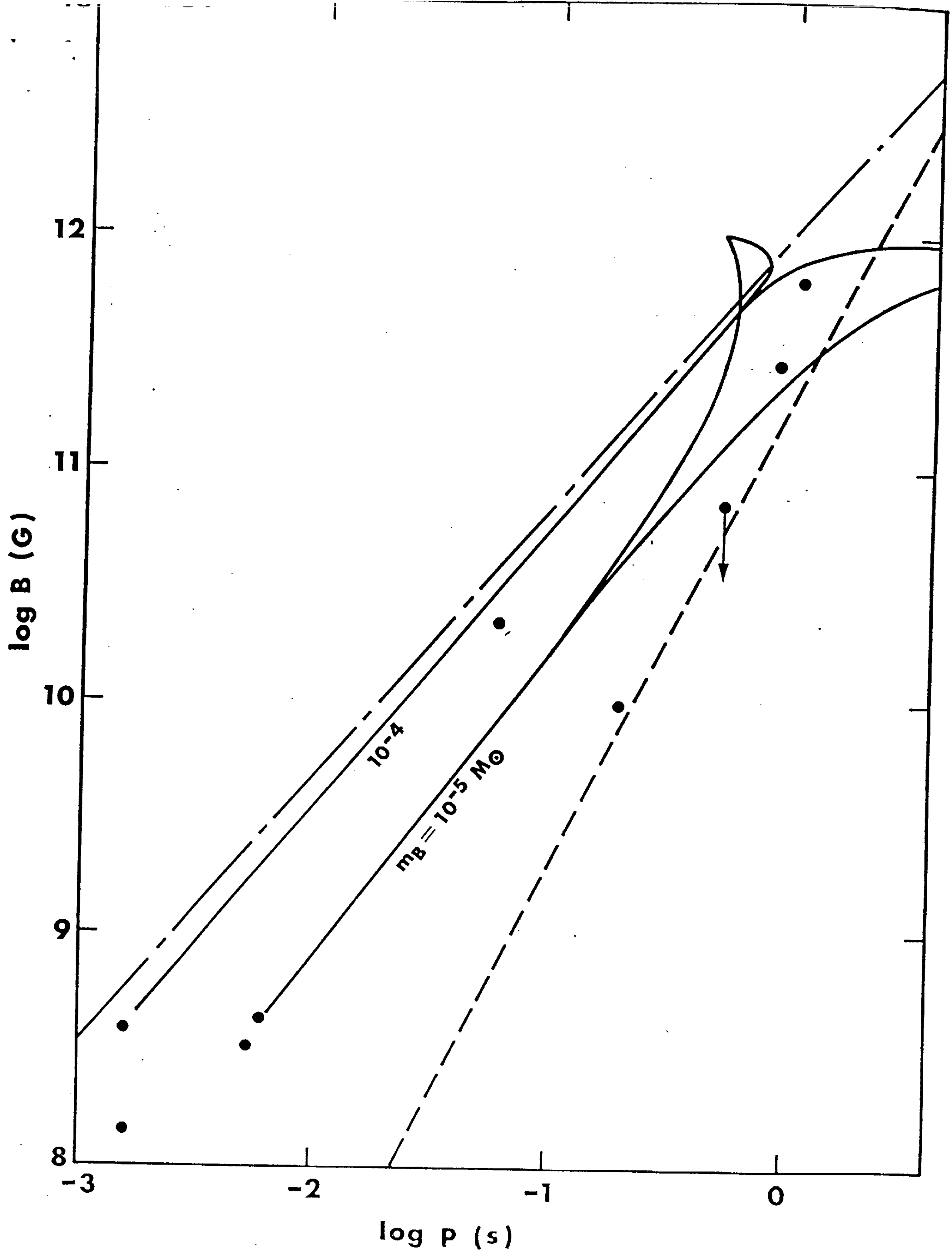
Figure Captions

Fig. 1. Evolutionary tracks (solid lines) of neutron stars in the magnetic field versus rotation period diagram. Rotation periods and magnetic fields become smaller with accreted mass and hence with increasing time. After mass accretion stops, stars move horizontally rightwards. The initial magnetic field is taken as $B_0 = 10^{12}$G, the initial rotation period is chosen as $P_0 = 0.5$ or 100 s, and the mass accretion rate is fixed at $\dot{M} = 1.1 \times 10^{18}$gm/s. The mass, radius, and moment of inertia of the neutron star are taken as $1.4M_\odot$, 106 cm, and 10^{45}gm cm^2, respectively. The dash-dotted and dashed lines denote the equilibrium rotation[28] and pulsar death lines[5], respectively. The filled circles represent the positions of binary and millisecond radio pulsars in this diagram.



12
11
10
9
8
log B (G)
-3
-2
-1
0
log P (s)
10-4
mB = 10-5 M⊙