WHERE ARE ALL THE FALLOUT DISKS? CONSTRAINTS ON PROPELLER SYSTEMS

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ABSTRACT

Fallback disks are expected to form around newborn neutron stars following a supernova explosion. In almost all cases, the disk will pass through a propeller stage. If the neutron star is spinning rapidly (initial period \( \sim 10 \) ms) and has an ordinary magnetic moment (\( \sim 10^{30} \) G cm\(^3\)), the rotational power transferred to the disk by the magnetic field of the neutron star will exceed the Eddington limit by many orders of magnitude, and the disk will be rapidly disrupted. Fallback disks can thus survive only around slow-born neutron stars and around black holes, assuming the latter do not torque their surrounding disks as strongly as do neutron stars. This might explain the apparent rarity of fallback disks around young compact objects.

Subject headings: accretion, accretion disks — pulsars: individual (SN 1987A) — stars: neutron — X-rays: stars

1. INTRODUCTION

Following a supernova explosion, some of the ejected matter may remain bound to the remnant and fall back (Colgate 1971). A disk can form from this material if its specific angular momentum \( l \) exceeds the Keplerian value at the surface of a newly formed neutron star, \( l_\text{k} = (GM/R)^{1/2} \approx 1.4 \times 10^{16} \) cm\(^2\) s\(^{-1}\), where \( M \) is the mass of the star and \( R \) is its radius. Simulations of the presupernova evolution of rotating stars (Heger et al. 2000) suggest \( l \approx 10^{22} \rightarrow 10^{23} \) cm\(^2\) s\(^{-1}\), implying that disks can form (see also Mineshige et al. 1997).

Initially, the mass flow rate will be high (\( \gtrsim 1 \) \( M_\odot \) s\(^{-1}\)) and accretion will proceed by neutrino cooling (Narayan et al. 2001). This will continue until the mass flow rate drops below the critical value at which photon cooling dominates and the radiation pressure can prevent steady accretion. In the spherical case (Chevalier 1989), this critical mass flow rate is \( \sim 10^{22} \) g s\(^{-1}\) and Fryer et al. (1999) estimate the mass of the material that would remain following the neutrino cooling is \( \lesssim 10^{-9} M_\odot \).

If the gas has angular momentum, the critical mass flow rate and the mass remaining from the neutrino cooling epoch increase (Chevalier 1996). Later, the mass flow rate will still be super-Eddington, but depending on the magnetic moment, the system will most likely be in the propeller regime (Shvartsman 1970a; Illarionov & Sunyaev 1975; Davies & Pringle 1981; Romanova et al. 2004).

Michel & Dessler (1981) suggested that fallback disks are relevant to radio pulsars, unlike the conventional view of pulsars as isolated electromagnetic engines. Lin et al. (1991) associated the formation of planets around pulsars with fallback disks. Meyer-Hofmeister (1992) invoked a fallback disk around the remnant of SN 1987A to explain the deviation of the observed light curve from the theoretical one for pure radioactive decay (see also Mineshige et al. 1993).

Recently, fallback disks (Chatterjee et al. 2000; Alpar 2001; Marsden et al. 2001b; Ekşi & Alpar 2003) have been invoked to explain anomalous X-ray pulsars (AXPs; Woods & Thompson 2005) via accretion, rather than the competing magnetar model (Duncan & Thompson 1992). This rekindled interest in the consequences of fallback disks for radio pulsars. A fallback disk assisting magnetic dipole torque can explain the discrepancy between characteristic and supernova ages (Marsden et al. 2001a), braking indices of pulsars being less than 3 (Menou et al. 2001), and the distribution of radio pulsars in the \( P-\dot{P} \) diagram (Alpar et al. 2001). Qiao et al. (2003) proposed a fallback disk model for periodic timing variations of pulsars. Blackman & Perna (2004) suggested that the jets observed in the Crab and Vela pulsars are collimated by fallback disks. If fallback disks assist magnetic dipole torques, field strengths based on pure dipole radiation \( [B \approx 6 \times 10^{15} (PP)^{1/2}] \) would be overestimates. Note that the so-called high magnetic field pulsars (Camilo et al. 2000) have braking indices smaller than 3, indicating that they are not spinning down purely as magnetic dipoles.

A fallback disk (Xu et al. 2003; Shi & Xu 2003) has also been invoked for the central compact objects (Pavlov et al. 2004) in supernova remnants. These objects may be related to AXPs. One member of this group is the central X-ray point source in Cassiopeia A, which is just 320 yr old and hence likely to possess a fallback disk. A fallback disk model of soft gamma-ray repeaters (SGRs; Woods & Thompson 2005) was proposed by Ėrtan & Alpar (2003), who showed that the X-ray enhancement following the August 27 giant flare of SGR 1900+14 can be interpreted as the postburst relaxation of the inner region of a disk that had been pushed back by the flare energy.

While there is ample theoretical motivation for considering fallback disks around young compact objects, the existence of these disks has never been confirmed observationally. There are tight limits on the luminosities of young systems like SN 1987A (Park 2004) and Cas A (Chakrabarty et al. 2001), in which fallback disks are especially likely. For Cas A, Chakrabarty et al. (2001) showed that its optical properties are not similar to those of quiescent low-mass X-ray binaries. Infrared emission is predicted (Perna et al. 2000) by accretion models of AXPs, and possible infrared counterparts have even been identified (see Tam et al. 2004 and references therein) for five of the six known AXPs. However, the observations are not consistent with a standard thin disk model. Moreover, observations of bursts from AXPs (Gavriil et al. 2002) suggest that AXPs are related to SGRs, for which the magnetar model is favored.

In this Letter we address the lack of observed fallback disks. We argue that such disks will be short lived because they would likely be disrupted by the spin-down power of the neutron star in either the propeller phase or the radio pulsar phase. In the following section we calculate the spin-down power (Pried-
horsky 1986; Treves & Bocci 1987) transferred from the magnetoosphere of a neutron star to the disk in the propeller regime and show that for conventional initial periods \( P_0 \sim 10 \) ms and magnetic moments \( \mu \sim 10^{30} \text{ G cm}^3 \), as estimated for radio pulsars, the luminosity of the disk will be much larger than the Eddington limit for all mass flow rates. In this regime, accretion is highly unstable, and the disk is likely to evolve very quickly until the inner radius of the disk is outside the light cylinder (see § 2). Beyond this point, the neutron star becomes a radio pulsar and the star can no longer torque the disk (or vice versa).

In the context of wind-fed, mass-exchange binaries, Shvartsman (1970b) argued that a fast-rotating neutron star would first become an ejector (radio pulsar), in which the disk remains outside the light cylinder. Only after the star slows down can inflowing matter penetrate the light cylinder, allowing the propeller stage to commence. For fallback disks, a fixed amount of mass is available in the disk, rather than a continuous supply as in a mass-exchange binary. Therefore, once a rapidly rotating neutron star progresses through the initial unstable accretion and propeller stages to an ejector/radio pulsar stage, it is the end of the road for the disk; the system cannot switch back to a propeller or accretion phase. We elaborate on these points in the following sections.

2. CONSTRAINTS ON PROPELLERS

For a fallback disk to affect the spin evolution of a neutron star, the disk inner radius must be inside the light cylinder \( R_L = c / \Omega \), where \( \Omega \) is the stellar angular velocity. To within a factor of order unity, the disk inner radius \( R_{in} \) is approximated by the Alfvén radius \( R_{Alf} \equiv R_{Alf} = [\mu / (2GM)^{1/2} M^{1/2}]^{2/7} \) (Davidson & Ostriker 1973), where \( M \) is the mass flow rate and \( \mu \) is the stellar magnetic moment. When the disk is inside the light cylinder, it suppresses radio pulsar emission. If the inner radius of the disk is also inside the corotation radius \( R_c = (GM / \Omega^2)^{1/3} \), the inflowing matter will accrete and spin the star up.

Initially, a fallback disk is likely to form in the accretion phase. As the \( M \) in the disk declines (recall that fallback disks are not replenished), the inner radius moves out, and when it is beyond the corotation radius, the system will enter the propeller stage at which the inflowing matter, instead of being accreted, is expelled. Here the neutron star spins down through the interaction of its magnetosphere with the disk. If the torque (angular momentum flux) acting on the star by the disk is \( \Omega \), the power transferred to the disk by the neutron star will in turn be \(- \Omega N \). This power will add to the gravitational potential of the inflowing matter, viz., \( GMM/R_{in} \), enhancing the energy budget of the disk. Some of the energy will be used to drive matter from the system, provided the velocity of the expelled matter \( v_{out} \) is greater than the escape velocity \( v_{esc} = (2GM/R_{in})^{1/2} \). The outflowing matter will carry away kinetic energy at the rate \( \frac{1}{2} Mv_{out}^2 \). Hence, the net radiative luminosity of the disk in the propeller phase is given by

\[
L_{disk} = \frac{GMM/R_{in} - \Omega N - \dot{M}v_{out}/2 \text{ if } v_{out} > v_{esc}}{GMM/R_{in} - \Omega N \text{ if } v_{out} < v_{esc}}
\]  

The velocity of the expelled matter depends on the coupling of the disk to the magnetosphere; i.e., the torque, which can be written \( N = nR_{in}^5 \Omega_n(R_{in}) M \). Here \( n \) is the dimensionless torque and depends only on the dimensionless fastness parameter \( \omega_n = \Omega / \Omega_n(R_{in}) \). Conservation of angular momentum requires that \( v_{out} = R_n \Omega_n(R_{in}) (1 - n) \), and using this in equation (1), the disk luminosity in the propeller regime is

\[
L_{disk} = \frac{GMM}{R_{in}} \frac{|1 - \omega_n n - (1 - n)^2/2| \text{ if } v_{out} > v_{esc}}{1 - \omega_n n \text{ if } v_{out} < v_{esc}}
\]  

For \( v_{out} < v_{esc} \), the matter expelled by the magnetosphere can return to the disk at some radius larger than the inner radius. As shown by Spruit & Taam (1993), the matter will then accumulate near the inner boundary and accrete sporadically.

Many prescriptions have been proposed for propeller torques. We estimate \( n \) by assuming that the magnetosphere and the inflowing matter are “particles” colliding and transferring angular momentum. If the collisions are elastic and the moment of inertia of the star is much larger than that of the inflowing matter, one finds \( n = 2(1 - \omega_n) \), whereas completely inelastic collisions would give \( n = 1 - \omega_n \). In both cases we assume that the mass of the particle representing the magnetosphere is much greater than that of the particle representing the accreting fluid. Let us thus define an “elasticity parameter” \( \beta \) and write

\[
n(\omega_n) = (1 + \beta)(1 - \omega_n),
\]  

where \( \beta \) varies between zero and unity and measures how efficiently the kinetic energy of the neutron star is converted into kinetic energy of expelled matter through the interaction of the magnetosphere with the disk. The limiting case of \( \beta = 0 \) corresponds to a “completely inelastic” interaction in which the fraction converted to heat is maximized, while \( \beta = 1 \) corresponds to an “elastic” interaction in which the rotational energy of the neutron star is completely converted into kinetic energy of expelled matter without heating the disk. This can be seen more clearly when we substitute the torque prescription of equation (3) into equation (2):

\[
L_{disk} = \frac{GMM}{2R_{in}} \frac{[1 + (1 - \beta^2)(\omega - 1)]^2 \text{ if } v_{out} > v_{esc}}{2 - 2(1 + \beta)(1 - \omega_n) \omega_n \text{ if } v_{out} < v_{esc}}.
\]  

For \( \beta = 1 \), \( L_{disk} = GMM/2R_{in} \), which is precisely the luminosity of a Keplerian disk with no torque applied at the inner boundary. Since any fluid process that strips matter from the disk would be dissipative, the \( \beta = 1 \) limit will never be realized in practice. In the accretion regime, the tangential velocity of the flow will adjust to the velocity of the magnetosphere, which corresponds to \( \beta = 0 \). For the torque to be continuous across the transition from accretion to propeller regimes, we must assume \( \beta = 0 \) at least for \( \omega_n \approx 1 \). Since the dependence of the expressions in equation (4) on \( \beta \) is weak (as long as \( \beta \) is not close to unity), choosing \( \beta \) in the range 0–0.5 produces little difference in the results. Note that early propeller torques employed in the literature are less efficient than our estimate, but the recent detailed simulations of Romanova et al. (2004) suggest even stronger torques than we employ.

From equation (4), we can solve for the minimum period \( P_{\text{min}} \), below which the luminosity of a propeller disk will exceed the Eddington limit \( L_E = 4\pi GMC/M \), where we take \( k_{\text{esc}} = 0.2 \) for the electron-scattering opacity as appropriate.
for the high metal content of the fallback matter. Taking \( \beta = 0 \) and defining \( \theta = L_c R_m/GMM \), we obtain

\[
P_{\text{min}} = \frac{2 \pi R_m^{3/2}}{\sqrt{GM}} \left( \frac{\sqrt{2} - 1}{4} + \frac{1}{4} \right) \text{ if } v_{\text{out}} > v_{\text{esc}},
\]

(5)

Another limiting period \( P_{\text{min}} \) is obtained if the inner radius of the disk is inside the light cylinder. This gives

\[
P_{\text{min}} = \frac{2 \pi}{c} R_m.
\]

(6)

Finally, if the disk is in the accretion phase, then the maximum \( P \) is given by the Eddington limit: \( GMM_{\text{max}} R = L_c \). Figure 1 shows all these limits in the \( P-M \) plane. We see that only a limited area of the plane is consistent with the various constraints we have discussed. Note that for a given stellar magnetic moment, there is a global minimum period \( P_{\text{min}} \), below which no stable disk is permitted for any \( M \). A neutron star that is born with a shorter period cannot have a stable fallback disk. For \( M = 10^{30} \text{ g cm}^{-3} \), the global minimum period is \( P_{\text{min}} = 35.2 \text{ ms} \). For a general \( M \) and \( R_c \), the minimum period can be approximated as

\[
P_{\text{min}} \approx 0.036 \mu_3^{1/3} \text{ s},
\]

(7)

where \( \mu_3 = \mu/10^{30} \).

The propeller regime with supercritical mass flow rates has been studied by Mineshige et al. (1991), who argued that the inner radius of the disk will adjust so that the luminosity does not exceed the Eddington limit. Our work shows that for a conventional neutron star (\( \mu = 10^{30} \text{ g cm}^{-3}, P = 10 \text{ ms} \)), the disk cannot penetrate the light cylinder and yet have its luminosity be less than the Eddington limit. In such a system, the accretion and propeller phases will progress very rapidly, on a much shorter timescale than the viscous time of the disk, as the accretion and spin-down power cause the inner regions of the disk to evaporate. Once the disk moves outside the light cylinder, it will likely be disrupted by the radiative pressure of the neutron star (Shvartsman 1970b), which now acts like a radio pulsar. Recently, Eksi & Alpar (2005) argued that the transition from the inner-zone dipole field to the radiative-zone field can be broad, which would imply that the disk may be able to find a stable inner boundary outside the light cylinder. If true, the pulsar would evaporate the disk slowly through the interaction of the pulsar wind with the disk. Whether the pulsar will be slowed down to periods at which the disk inner radius can repenetrate the light cylinder depends on the complex physics of this interaction.

3. DISCUSSION

We have shown that fallback disks around newly born neutron stars with conventional periods and magnetic moments will be disrupted by a combination of the transfer of accretion power and rotational power of the neutron star to the disk. Therefore, while fallback disks may form, they would not be able to survive, for standard initial neutron star parameters.

Our results are general, in the sense that for all propeller systems outside the shaded region in Figure 1, the disk is either outside the light cylinder or will be pushed there rapidly. Thus, not all combinations of the magnetic moment and period are allowed. In particular, for a given magnetic moment, there is a minimum allowed neutron star period \( P_{\text{min}} \), given by equation (7). If a neutron star is born with a shorter period, only a short-lived fallback disk is possible. This may explain the lack of direct observational evidence for fallback disks around young neutron stars even though one expects a fair amount of fallback material with angular momentum to accumulate during and soon after the supernova.

An advantage of the fallback disk model for AXPs is that the neutron stars in these systems would be drawn from the same population as radio pulsars, except for one new parameter describing the initial mass of the disk (Chatterjee & Hernquist 2000). However, our results indicate that if fallback disks are
to be present around AXPs, these neutron stars must have been born with long periods and/or small magnetic dipole fields that are not typical of radio pulsars. It is interesting that recent studies (Vranesic et al. 2004) based on the Parkes multibeam survey imply that 40% of pulsars are “injected,” with initial periods in the range 0.1–0.5 s (as first suggested by Vivekanand & Narayan 1981, using a smaller sample of pulsars). For the fallback model to be relevant, AXPs must be drawn from this subpopulation of slow pulsars.

For SN 1987A, Ögelman & Alpar (2004) assumed that the star was born spinning rapidly and that its present luminosity owes to pure magnetic dipole spin-down. They concluded that the observed upper limit on the luminosity of the star requires the magnetic field of the putative pulsar to be either very small (almost in the millisecond pulsar range) or very large (in the magnetar range). In the latter case, the pulsar has spun down rapidly after the supernova, and so the present luminosity is low. The magnetar solution of Ögelman & Alpar (2004) falls rapidly after the supernova, and so the present luminosity is low. The magnetar solution of Ögelman & Alpar (2004) falls in the region of Figure 1 in which a fallback disk is not allowed. Therefore, this solution is viable; even if the system had fallback material, it would have been ejected early on. However, the other solution of Ögelman & Alpar (2004) corresponds to a small magnetic dipole moment ($\mu_{30} \sim 0.01$) for the neutron star, so a fallback disk is very likely to survive. The luminosity from the disk in the propeller phase would then be much larger than the magnetic dipole luminosity assumed by Ögelman & Alpar (2004). Hence, the upper limit on the magnetic field must be much lower in order to satisfy the observational constraint on the luminosity.

Another explanation for the lack of fallback disks is given by Fryer et al. (1999), who argue that accretion flows with heavy elements will be dynamically unstable when heavy elements recombine, producing a line-driven wind that eventually expels all the initially bound material.

Finally, supernovae may sometimes produce black holes. The formation of fallback disks around black holes was investigated by Mineshige et al. (1997), and a fallback disk model for ultraluminous X-ray sources (ULXs; Fabbiano & White 2005) was suggested by Li (2003). Rotating black holes can transfer energy to their surrounding disks (e.g., Li 2002), just like neutron stars, in which case such disks would again reach super-Eddington luminosities and be disrupted. However, if the energy transfer is significantly less than for neutron stars, the disk may survive more easily. It would be interesting to search for fallback disks around young black hole systems. Li (2003) mentions two ULXs associated with supernova remnants that may be accreting black holes.

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