Accretion Models for Young Neutron Stars

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ABSTRACT. Interaction with possible fallback material, along with the magnetic fields and rotation rates at birth should determine the fates and categories of young neutron stars. This paper addresses some issues related to pure or hybrid accretion models for explaining the properties of young neutron stars.

1. AXP as single neutron stars

Accretion from a fossil disk was first proposed by Van Paradijs, Taam & Van den Heuvel (1995) to explain the X-ray luminosity in the apparent absence of a binary companion: a neutron star with a fossil disk would result from the final spiral-in destruction of the binary. The ages of such systems however is in conflict with the apparent youth of AXP indicated by the SNR associations of some of them (Gaensler 2001, Tagieva & Ankay 2003). Accretion from a fallback disk left from the core collapse was proposed as a model for AXP by Chatterjee, Hernquist & Narayan (2000). In a simultaneous and independent paper (Alpar, 2001) I proposed fallback disks as an option for all young neutron stars, indeed as a factor that must be one of the determinants of the fates of all young neutron stars. Marsden et al (2001) argued that the presence and effectiveness of fallback disks is correlated with SNR morphology and SNR/ISM environment, but the AXP-SGR and SNR correlations they claimed are not supported (Gaensler 2001, Tagieva & Ankay 2003).

The fallback disk idea goes back to earlier work on supernovae which suggested that matter, with angular momentum, can remain bound on the neutron star after the supernova explosion (Chevalier 1989, Mineshige et al 1993). If so, the amount (or absence) of mass inflow \( \dot{M}(t) \) towards/onto the neutron star, accretion, the propeller effect and the associated torques constitute one set of determinants, along with the magnetic dipole (and other multipole) moments as the other set of parameters, in setting the life path of the neutron star. Thus, independently of its relevance to AXP and SGR, the possibilities of fallback disks and their effects on the evolution and dynamics of young neutron stars has emerged as a basic problem of general interest.

One basic motivation for accretion/propeller models is that the narrow range of rotation periods, common to AXP and SGR, and also to the Dim Thermal Neutron Stars, has a natural explanation in terms of rotational equilibrium between neutron star and disk. Transitions between accreting and propeller states (transients- Cui et al 1998, Campana et al 1998), and between spinup and spindown (eg Lovelace, Romanova & Bisnovatyi-Kogan 1999) occur near the equilibrium regime. As the rotational equilibrium is approached asymptotically, systems would tend to spend a long part of their lives near equilibrium and hence tend to be observed at their equilibrium periods. AXP are spinning down while accreting because the fallback disk is evolving, with the inner disk radius receding from the neutron star, and the equilibrium period, which the star tracks, increasing as the mass inflow rate decreases (Chatterjee, Hernquist & Narayan 2000). The narrow range of observed periods correspond to equilibrium periods with dipole surface magnetic fields in the \( 10^{12} \) G range and a not very restrictive range of mass inflow rates (Alpar 2001): AXP, SGR and DTN periods, with \( 10^{12} \) G fields, imply an \( \dot{M}(t) \) range restricted to two orders of magnitude. There is a selection based on \( \dot{M}(t) \). According to the suggested classification AXP and SGR are the sources that get to equilibrium accretion before the disk depletes. DTNs are also close to equilibrium
but still in the propeller phase. With lower $\dot{M}(t)$, longer lives and slower evolution the DTNs are much more numerous than the younger AXPs and SGRs. Lowest or zero $\dot{M}(t)$ give the radio pulsars, higher mass inflow rates all the way to Eddington give the ‘radio quite’ neutron stars (Alpar 2001).

2. Magnetars and Accretion

Magnetar models provide a physical model for SGR bursts, energy output and super-Eddington fluxes. With the AXPs now being observed to experience bursts also (Gavriil, Kaspi & Woods 2002) the magnetar models have gained in general applicability. In these models catastrophic release of energy from an intense magnetic field anchored in the neutron star provides the source of the bursts. Continuous energy dissipation as the magnetic field decays, rather than accretion, provides the source of X-ray luminosity of AXPs and SGRs in their quiescent phases. The detection of optical pulsations at a relatively large pulsed fraction from the AXP 4U 0142+61 (Kern & Martin 2002) also supports the magnetar models.

Neutron star spindown with magnetic dipole radiation at constant dipole moment cannot explain the narrow range of periods (Psaltis & Miller 2002). Magnetar models with field decay can explain the period clustering of AXPs and SGRs only under one particular class among the models for magnetic field decay inside the neutron star (Colpi, Geppert & Page 2000). The existence of some large magnetic field radio pulsars in the same region of the P-$\dot{P}$ diagram as the AXPs and SGRs poses a number of questions as to the critical value of the surface dipole field at which the radio pulsar mechanism is quenched, and why, at field values that are quite close, the magnetic decay mechanism producing the X-ray luminosity of AXPs and SGRs is not operative for the high field radio pulsars. If field decay turns out to be the actual operating mechanism, the X-ray luminosity of AXPs and SGRs will be recognized as restrictive and dependent on the range of field strengths, as a nonlinear process would. In magnetar models the selection, demanded by the rarity of the AXPs and SGRs, is provided by the selection of initial magnetic moments. In accretion models, the narrow range of periods finds an explanation in very general terms, of angular momentum equilibrium, while the selection of the observed classes of objects is provided by the range of mass inflow histories. Perhaps the AXPs and SGRs do have magnetar fields that provide the bursts, but the narrow range of periods is indeed due to rotational equilibrium with a fallback disk? This may be supported by the observation that AXPs and SGRs are closer to accreting sources than to isolated radio pulsars in their timing properties (Alpar & Baykal 2003).

Let us consider SGRs and AXPs in a hybrid model, with magnetar fields and fallback disks. Pulsar magnetic fields show a distribution peaking strongly in the $10^{12}$ G range with a tail extending well into the $10^{13}$ G range; There are radio pulsars with inferred surface dipole fields, at the pole, that exceed the quantum critical field, $B_{cr} = 4.4 \times 10^{13}$ G (Camilo et al 2000). Magnetars are in the tail end of this distribution as there is no indication that the B distribution is bi-modal. To retain the explanation of the observed range of rotation periods with magnetar fields, one must ask whether the observed torques (spindown rates), luminosities of the neutron star and luminosities expected from the disk and the equilibrium periods can all be understood with a consistent and reasonable $\dot{M}(t)$ range. Torques exerted by the disk on the neutron star were estimated as:

$$|\dot{\Omega}| = \mu^2/r_A^2(1 - \Omega/\Omega_K(r_A)) \sim \mu^{2/7}\dot{M}(t)^{6/7}[1 - \Omega/\Omega_K(r_A)]$$

(1)
(Alpar 2001, Chatterjee, Hernquist & Narayan 2000). The inner radius of the disk depends on the rotation rate of the neutron star, $R_A(\Omega) > r_A$ (e.g. Lovelace, Romanova & Bisnovatyi-Kogan 1995, Psaltis 2001). We adopt the estimates (Psaltis 2001)

$$R_A(\Omega) \sim r_A[1 - \Omega/\Omega_K(r_A)]^{-2/7} > r_A \quad \text{(accretion)}$$

$$R_A(\Omega) \sim r_A[1 - \Omega_K(r_A)/\Omega]^{-1/5} > r_A \quad \text{(propeller)}.$$  

(2)

For the accretion regime the dimensional torques are:

$$I[\dot{\Omega}] = \mu^2/r_A^3[1 - \Omega/\Omega_K(r_A)]^{6/7} \sim \mu^2/\dot{M}(t)^{6/7}[1 - \Omega/\Omega_K(r_A)]^{6/7}$$  

(3)

The observed AXP and SGR spindown rates, with the $\dot{M}(t)$ inferred from the quiescent $L_X$ and with magnetar values of the magnetic dipole moment, $\mu \sim 10^{32}$ G cm$^3$ require $[1 - \Omega/\Omega_K(r_A)]$ to be some $10^{1/3} \sim 2$ times smaller than the value needed with a conventional $\mu \sim 10^{30}$ G cm$^3$. This is feasible, with $\Omega/\Omega_K(r_A) \sim 0.4$, consistent with the system being in an asymptotic regime.

Upper limits and detected luminosities in the optical and IR (Hulleman et al 2001, Kaplan et al 2001) restrict thin disk models. While these are the only available models, usefully applied by Chatterjee, Hernquist & Narayan (2000) to calculate AXP evolution scenarios with the fallback disk model, they are not necessarily realistic descriptions of a fallback disk, going through propeller phase, possibly with outflows, a corona, mass returning to disk, irradiation. These effects are likely to alter the spectrum of the disk significantly from the standard thin disk spectrum. Nevertheless, disk luminosities are not likely to differ much from the estimates of energy dissipation rates at the inner disk. Taking into account the dependence of the inner radius of the disk on $\Omega$, one arrives at

$$L_{\text{disk}} = (GM\dot{M}(t)/r_A)\left(1/2 \left[1 - \Omega/\Omega_K(r_A)\right]^{2/7} - \Omega/\Omega_K(r_A)[1 - \Omega/\Omega_K(r_A)]^{6/7}\right)$$  

(4)

during accretion. Near equilibrium in the accretion regime, $\Omega/\Omega_K(r_A) \sim 1$, the disk luminosity is reduced in ratio to $(GM\dot{M}(t)/r_A)$. In the magnetar case, the expected disk luminosity scale $(GM\dot{M}(t)/r_A)$ is lower, by a factor of 10 or more, than it is for conventional $\mu \sim 10^{30}$ G cm$^3$ since $r_A \sim \mu^{4/7}\dot{M}(t)^{-2/7}$ is larger.

In the propeller regime the balance of the power expended by disk torques, after accounting for the neutron star spindown, goes into energy dissipation in the disk as well as powering any outflows. One finds

$$(L_{\text{disk}} + L_{\text{outflow}}) = (GM\dot{M}(t)/r_A)\left(1/2 \left[1 - \Omega_K(r_A)/\Omega\right]^{1/5} + \Omega/\Omega_K(r_A)[1 - \Omega_K(r_A)/\Omega]^{3/5}\right)$$  

(5)

Thus in the propeller regime also the disk luminosity is reduced, both through the reduction in the luminosity scale $(GM\dot{M}(t)/r_A)$ for the magnetar case, and further if the system is near equilibrium, $\Omega/\Omega_K(r_A) \sim 1$. (There is, however, an enhanced luminosity in the extreme propeller regime, when $\Omega \gg \Omega_K(r_A)$.)

While extending the accretion model to a neutron star with magnetar fields is thus compatible with the observed torques and disk luminosities, the starting point of the accretion models, that the observed period clustering reflects the range of equilibrium periods cannot be retained for dipole fields in the magnetar range: $\Omega_{eq} = (GM/r_A)^{1/2} \sim \mu^{-6/7}\dot{M}(t)^{3/7}$, so that the agreement with observed rotation rates using $\dot{M}(t)$ indicated
by the luminosities together with \( \mu \sim 10^{30} \) G cm\(^3\) is lost for magnetars. For the same luminosities, magnetars would have equilibrium periods that are about 100 times larger than the observed range. A hybrid model will be possible only if the dipole magnetic moment is still \( \mu \sim 10^{30} \) G cm\(^3\) while the magnetar field \( B \sim 10^{14} \) G on the neutron star surface has only higher multipoles.

3. AXPs and Thin Disk Models

Thin disk models are the only available models for the evolution of an isolated disk. Self similar solutions with a power law time evolution of the disk mass and mass inflow rate were employed for isolated disks (Canizzo et al 1990, Mineshige et al 1993) and were used by Chatterjee, Hernquist & Narayan (2000) to model AXP evolution. The observations and upper limits in the optical and IR ranges (Hulleman et al 2001, Kaplan et al 2001) are in conflict with the disk luminosities predicted by the standard thin disk models, which are nevertheless usefully employed to provide a calculable model. Real fallback disks may not be thin disks at all, especially after a propeller phase, or they may have comptonizing coronae. At present there are no realistic models for comparison with the observations. Even within thin disk models the dependence of the disk inner radius on rotation rate will reduce the disk luminosity for systems near rotational equilibrium as we noted above.

Francischelli & Wijers (2002) have argued that a thin disk cannot spin the ns down to AXP periods within the AXP ages inferred from supernova remnant associations unless the magnetic field \( B \) is larger than \( 3.7 \times 10^{13} \) G. Thin disk evolution with \( \dot{M}(t) \propto t^{-\alpha} \) depends sensitively on opacity through the power law index \( \alpha \). Francischelli & Wijers note that Kramers opacities should prevail in the disk, and have followed the disk evolution with the corresponding power law index \( \alpha = 1.25 \). However, they keep the same initial mass for the disk in their calculations with different power laws. For a given \( \alpha \) the evolution may be insensitive to the initial mass in a certain range, but for different \( \alpha \) there are different choices of the initial disk mass which can lead to AXP formation. Furthermore the disk material is likely to be iron rich (Fryer, Colgate & Pinto 1999), in which case the opacities are not well known and will not lead to a generally valid power law index, so that the evolution must be solved numerically.

A self similar solution with power law time dependence holds for a disk that extends all the way to \( r = 0 \). There are two varieties of such self similar solutions of the thin disk diffusion equation. The type of solution discussed above involves power law evolution of the disk mass while the disk angular momentum \( J_{\text{disk}} \) remains constant. The other type of self similar solution has constant disk mass while the disk angular momentum decays with a power law. The latter type of solution may be the appropriate way to use a thin disk model to describe the propeller regime, (mass outflow returns to disk). In either case a real disk does not extend down to \( r = 0 \), but is cutoff at a finite inner radius \( r_{in}(t) \). Starting off with power law evolution and using it at all times is not realistic. Numerical calculations for thin disk evolution with finite \( r_{in} \) are found to settle to self-similar solutions with power law decay of both types, but only for appropriate intervals of the evolution. With all these considerations it is likely that a thin disk model may give spindown to AXP periods even with \( 10^{12} \) G fields (Ekş 2003).

4. On Dim Thermal Neutron Stars

DTNs are nearby, and therefore abundant objects, with ages \( \sim 10^6 \) yrs. The classification in terms of fallback disk environments (Alpar 2001) interprets DTNs as slowly evolving objects, in the propeller phase in interaction with fallback disk of low mass and low mass inflow rate. The low luminosity is supplied by energy dissipation in the neutron star, in response to propeller spindown torques (unless the neutron star still has a cooling luminosity larger than the dissipation luminosity).
Measured $\dot{\Omega}$ agrees with the dissipation luminosity due to dipole spindown in the case of RBS 1223 (Hambaryan et al 2002). For RXJ 0720.4-3125 the measured $\dot{\Omega}$ cannot supply the observed luminosity (Kaplan et al 2002, Zane et al 2002). In this case the luminosity must be due to cooling. This is reasonable as standard cooling luminosities are high until about $10^6$ yrs.

If DTNs are magnetars the energy dissipation driven by the magnetic dipole torque is much less than the cooling luminosity: $L_{\text{diss}} \sim 10^{28} \text{erg/s} 10^{-3/2} \mu_{32}^{-1}$. In magnetar models the luminosity of DTNs would be due to cooling with a possible contribution supplied by field decay. For RXJ 0720.4-3125 bounds on the spindown rate rules out a magnetar (Kaplan et al 2002). In evaluating magnetar models for the period clustering of AXPs Colpi, Geppert & Page (2000) found that only one class of magnetar field decay models, Hall cascade in the crust of the neutron star, is consistent with the observed period clustering, luminosities and inferred ages of the AXPs, if the initial magnetic field strength is $10^{15}$ G. But this scenario extrapolates to luminosities of $10^{33}$ erg/s at the $10^6$ yr ages of the DTNs (Geppert et al 1999), higher than the observed DTN luminosities by an order of magnitude at least!

Could all the DTN luminosities be just due to the cooling of an isolated neutron star with a conventional magnetic field? DTNs seem to cluster in luminosity at about $10^{32}$ ergs / s. If this is borne out by more statistics, and the luminosity is due to cooling, then they cluster in age at about $10^9$ yrs! Why are there no older ones then? This is difficult to explain in terms of cooling luminosity.

If the luminosity is supplied by energy dissipation for most DTNs (those stars that are past the neutrino cooling luminosity era) its value will indeed stay roughly constant at $L_{\text{diss}} = 10^{32}$ erg/s for the duration of the propeller phase close to rotational equilibrium. Thus the age and luminosity (distance) determinations of the DTNs hold the clue as to whether they are propellers or cooling neutron stars under dipole spindown.

Acknowledgements

References

Alpar, M.A. 2001, Astrophys. J. 554, 1245.
Alpar, M.A. & Baykal, A. 2003, to be submitted.
Camilo, F. et al 2000, Astrophys. J. 541, 367.
Campana, S. et al 1998, Astrophys. J. Lett. 499, LL45
Canizzo, J.K., Lee, H.M. & Goodman, J. 1990, Astrophys. J. 351, 38.
Chatterjee, P., Hernquist, L., and Narayan, R. 2000, Astrophys. J. 534, 373.
Chevalier, R.A. 1989, Astrophys. J. 346, 847.
Colpi, M., Geppert, U. & Page, D. 2000, Astrophys. J. Lett. 529, LL29.
Cui, W. et al 1998 Astrophys. J. Lett. 502, LL49.
Ekşi, Y. 2003, to be submitted.
Francischelli, G.J. & Wijers, R.A.M.J. 2002,astro-ph 0205212.
Fryer, C.L., Colgate, S.A. & Pinto, P.A. 1999, Astrophys. J. 511, 885.
Gaensler, B.M. et al 2001, Astrophys. J. 559, 963.
Gavriil, F.P., Kaspi, V.M. & Woods, P.M. 2002, Nature 419, 142.
Geppert, U. et al 1999, in IAU Colloq. 177, Pulsar Astronomy - 2000 and Beyond, ed.
M. Kramer, N. Wex & R. Wielebinski (San Francisco: ASP)
Hambaryan, V. et al 2002, Astron. Astrophys. 381, 98.
Hulleman, F. et al 2001, Astrophys. J. Lett. 563, LL49.
Kaplan, D.L. et al 2001, Astrophys. J. 556, 339.
Kaplan, D.L. et al 2002, Astrophys. J. Lett. 570, LL79.
Kern, B. & Martin, C. 2002, Nature 417, 527.
Lovelace, R.V.E., Romanova, M.M. & Bisnovaty-Kogan, G.S. 1995, Mon. Not. R. Astr. Soc. 275, 244.
Lovelace, R.V.E., Romanova, M.M. & Bisnovatyi-Kogan, G.S. 1999, Astrophys. J. 514, 368.
Marsden, D. et al 2001, Astrophys. J. 550, 397.
Mineshige, S., Nomoto, K. & Shigeyama, T. 1993, Astron. Astrophys. 267, 95.
Psaltis, D. 2001, Lectures on Accretion, Feza Gürsey Institute, Istanbul.
Psaltis, D. & Miller, M.C. 2002 Astrophys. J. 578, 325.
Tagieva, S. and Ankay, A. 2003, Astronomical and Astrophysical Transactions 20.
Van Paradijs, J., Taam, R.E. and Van den Heuvel, E.P.J. 1995 Astron. Astrophys. Lett. 299, LL41.
Zane, S. et al 2002, Mon. Not. R. Astr. Soc. 334, 345.