An Accretion Model for Anomalous X-Ray Pulsars

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ABSTRACT

We present a model for the anomalous X-ray pulsars (AXPs) in which the emission is powered by accretion from a fossil disk, established from matter falling back onto the neutron star following its birth. The time-dependent accretion drives the neutron star towards a “tracking” solution in which the rotation period of the star increases slowly, in tandem with the declining accretion rate. For appropriate choices of disk mass, neutron star magnetic field strength and initial spin period, we demonstrate that a rapidly rotating neutron star can be spun down to periods characteristic of AXPs on timescales comparable to the estimated ages of these sources. In other cases, accretion onto the neutron star switches off after a short time, and the star becomes an ordinary radio pulsar. Thus, in our picture, radio pulsars and AXPs are drawn from the same underlying population, in contrast to models involving neutron stars with ultrastrong magnetic fields, which require a new population of stars with very different properties.

Subject headings: stars: neutron – pulsars: general – accretion, accretion disks – X-rays: stars

1. Introduction

Anomalous X-ray pulsars (AXPs) are a subclass of X-ray pulsars comprising approximately half a dozen members with certain well-determined properties (e.g. Mereghetti & Stella 1995; van Paradijs, Taam & van den Heuvel 1995). AXPs are sources of pulsed X-ray emission with steadily increasing periods lying in a narrow range, $P \sim 6 - 12$

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seconds, and having characteristic ages $P/2\dot{P} \sim 10^3 - 10^5$ years. While it is generally believed that AXPs are neutron stars, they differ significantly from other manifestations of these objects. AXPs have periods more than an order of magnitude larger than those of typical radio pulsars. Compared with high-mass X-ray binary pulsars, AXPs have relatively low luminosities, $L_x \sim 10^{35} - 10^{36}$ erg/sec, and soft spectra. Generally, AXP spectra are well-fitted by a combination of blackbody and power-law contributions, with effective temperatures and photon indices in the range $T_e \sim 0.3 - 0.4$ keV and $\Gamma \sim 3 - 4$, respectively. In addition, AXPs have no detectable binary companions and at least two have been associated with young supernova remnants.

A particularly uncertain aspect of AXPs is the energy source that supports their X-ray emission. From timing measurements, it is clear that they cannot be rotation-powered. For values characteristic of AXPs, the rate of loss of rotational energy is $|\dot{E}| \equiv 4\pi^2 I \dot{P}/P^3 \approx 10^{32.5}$ erg/sec, orders of magnitude smaller than their X-ray luminosities. Motivated by this discrepancy, two competing theories for AXPs have emerged. In one, the energy source for the X-rays is internal and the AXPs are modeled as isolated, ultramagnetized neutron stars (“magnetars”; Duncan & Thompson 1992), powered either by residual thermal energy (Heyl & Hernquist 1997a) or by magnetic field decay (Thompson & Duncan 1996). The observed X-ray luminosities place severe limitations on both possibilities. If residual thermal energy drives the emission, then the envelope of the neutron star must consist primarily of light elements (Heyl & Hernquist 1997b). If magnetic field decay supplies the energy, then non-standard decay processes may be required unless the field is $B > 10^{16}$ G (Heyl & Kulkarni 1998). In either case, the measured periods and estimated period derivatives and ages are consistent with field strengths $B > 10^{14} - 10^{15}$ G. These values are similar to those inferred for soft gamma repeaters (SGRs) from timing data (e.g. Kouveliotou et al. 1998, 1999; but see, however, Marsden, Rothschild & Lingenfelter 1999).

The second class of theories for AXPs invokes accretion to power the X-ray emission. Several variants of this hypothesis have been put forward. Mereghetti & Stella (1995) suggested that AXPs are neutron stars with magnetic fields similar to those of radio pulsars, accreting from binary companions of very low mass. Wang (1997) proposed that the AXP candidate RX J0720.4-3125 is an old neutron star accreting from the interstellar medium. (For an interpretation of this object as an ultramagnetized star, see Heyl & Hernquist 1998a.) In another model, AXPs are descendants of high-mass X-ray binaries and are accreting from the debris of a disrupted binary companion, following a period of common-envelope evolution (van Paradijs et al. 1995; Ghosh, Angelini & White 1997). In all these analyses, the magnetic fields inferred from the observed luminosities and spin periods is $B < 10^{12}$ G, if the neutron star is accreting near its equilibrium spin period.
A potential advantage of accretion-powered models for AXPs over those based on ultrastrong magnetic fields is that these neutron stars then have intrinsic properties similar to those of ordinary radio pulsars and luminous X-ray pulsars. However, efforts to detect binary companions of AXPs have been unsuccessful and have placed severe limits on companion masses (e.g. Mereghetti, Israel & Stella 1998; Wilson et al. 1998). Moreover, it is clear that if AXPs are accreting, then they cannot be in equilibrium with their accretion disks, since all these objects are observed to spin down. Ghosh et al. (1997) suggest that this deficiency can be overcome by time-dependent accretion, but do not demonstrate if a young, rapidly spinning neutron star can be spun down to periods $P \sim 10$ seconds on timescales consistent with, e.g., age estimates based on associations with supernova remnants (e.g. Vasisht & Gotthelf 1997).

In this paper, we propose that AXPs are indeed accreting, but that the accretion disk was established as part of the process which formed the neutron star, through fallback of material from the progenitor following the supernova explosion. After an initial phase of transient evolution, the accretion rate in this scenario declines steadily as the material in the disk is depleted. At late times, the accretion rate evolves self-similarly, and the torques on the star spin it down in a regular manner. We demonstrate that for plausible choices of the parameters, this time-dependent accretion yields periods, ages, and luminosities consistent with the observed properties of AXPs.

2. Accretion from a Debris Disk

Following the formation of a neutron star through the core collapse of a massive progenitor, it is plausible that mass ejection during the explosion will not be perfectly efficient and that a small amount of mass, $M_{fb}$, can fall back. The amount of this fallback is uncertain, but various lines of argument suggest that $M_{fb} \lesssim 0.1M_\odot$ is not unreasonable (Lin, Woosley & Bodenheimer 1991; Chevalier 1989). Much of this material will be directly accreted by the neutron star, and some may be expelled when the accretion rate exceeds the Eddington limit, depending on the relative contribution of neutrino emission to the energy loss rate. However, some of the fallback is likely to carry sufficient angular momentum that it will settle into an accretion disk of mass $M_d$ around the neutron star. The relationship between $M_{fb}$ and $M_d$ depends on the detailed properties of the progenitor, but our model for AXP formation does not require large disk masses and can, in principle, operate even if $M_d \ll M_{fb}$.

The fate of the material settling into the disk is uncertain, but the problem we are describing is similar to tidal disruption of stars by massive black holes. Numerical
simulations show that material captured by the black hole in such an event will circularize into an accretion disk on roughly the local dynamical time and that the subsequent evolution of the disk through viscous processes can be characterized in a simple manner (Cannizzo, Lee & Goodman 1990). In our analysis, we assume that fall back will establish a thin accretion disk on a timescale $T \approx 1$ msec. Detailed calculations show that the long-term behavior of the system is insensitive to the numerical value of $T$.

The accretion disk will exist for radii only beyond the magnetospheric radius $R_m \approx 0.5 r_A = 6.6 \times 10^7 B_{12}^{4/7} m^{-2/7} \text{ cm}$ (Frank, King & Raine 1992), where the Alfvén radius, $r_A$, indicates the transition point at which the flow becomes dominated by the magnetic field, and $B_{12}$ is the surface magnetic field strength of the star in units of $10^{12}$ G. We parameterize the mass accretion rate through the disk, $\dot{M}$, in ratio to the Eddington rate, $\dot{M}_E = 9.75 \times 10^{17} \text{ g/s}$, by $\dot{m} \equiv \dot{M}/\dot{M}_E$. (In numerical estimates, we always take the neutron star mass and radius to be $M_* = 1.4 M_\odot$ and $R_* = 10^6 \text{ cm}$, respectively.) Note, however, that we allow for the possibility that the mass accretion rate onto the surface of the star, $\dot{M}_X$, will be different from $\dot{M}$, if some of the material is driven from the system prior to reaching the neutron star surface. Thus, the X-ray luminosity will be set by $\dot{M}_X$ rather than by $\dot{M}$, but we will generally take the location of $R_m$ and the torque applied to the neutron star to be determined by $\dot{M}$.

Whether or not the disk will influence the spindown of the neutron star or lead to accretion-induced X-ray emission will depend on the location of $R_m$ relative to the light cylinder radius, $R_{lc} = c/\Omega$, and the corotation radius $R_c$ defined by $\Omega = \Omega_K(R_c)$, where $\Omega$ is the angular rotation frequency of the star and $\Omega_K(R)$ is the Keplerian rotation rate at radius $R$ (e.g. Shapiro & Teukolsky 1983). If at any time $R_m > R_{lc}$, we assume that the disk will effectively evolve independently and will not affect the neutron star. Thus, we anticipate that even if all neutron stars acquire debris disks through fallback, most will live as ordinary radio pulsars, for appropriate choices of $M_d$, $B$, and initial spin period, $P_0$. In other cases, accretion will be permitted and the neutron star will behave as an accreting X-ray source. As we shall see, according to this model it is possible for a given neutron star to spend a portion of its life either as a radio pulsar or as an accreting source.

During accretion, the interaction between the disk and the star can lead to several distinct phases of evolution. If $R_m \gg R_c$, which corresponds to $\Omega \gg \Omega_K(R_m)$, the “propeller” effect will operate, so that accretion onto the surface of the star will be inefficient owing to centrifugal forces acting on the matter (Illarionov & Sunyaev 1975). The details of this process are uncertain. During the propeller phase, we assume that $\dot{M}_X \ll \dot{M}$ but that spindown will nevertheless be efficient. In other words, matter will be driven to $R_m$ by viscous processes where it can torque the star, but mass ejection occurs
subsequently before the material reaches the star’s surface. Thus, such an object will spin down rapidly but will be X-ray faint. Later, as $\Omega$ approaches $\Omega_K(R_m)$, the system enters a quasi-equilibrium “tracking” phase, in which the spin of the star roughly matches the rotation period of the disk at $R_m$. However, because the mass accretion rate declines steadily, a true equilibrium is never attained, unlike in the case of accreting neutron stars in binaries. In this phase, we assume $\dot{M}_X \sim \dot{M}$ and that the star will be X-ray bright. We parameterize the time of transition from the propeller phase to the tracking phase by $t_{\text{trans}}$.

Analyses of accretion onto black holes suggests that the infall will eventually become an advection-dominated accretion flow (an ADAF; Narayan & Yi 1994, 1995; Abramowicz et al. 1995; Narayan, Mahadevan & Quataert 1998; Kato, Fukue, & Mineshige 1998) and that much of the mass will be ejected prior to reaching the surface of the star (e.g. Blandford & Begelman 1999, Menou et al. 1999, Quataert & Narayan 1999). The ADAF transition will occur at a characteristic time $t \sim t_{\text{ADAF}}$, when the associated accretion luminosity falls to $\approx 0.01L_E$ (this is a rough estimate, cf. Narayan & Yi 1995), where the Eddington luminosity is $L_E = 1.8 \times 10^{38}$ ergs/s. At the beginning of the ADAF phase, we expect the star to be X-ray bright, but the X-ray luminosity will decline rapidly with time as $\dot{M}_X$ becomes much smaller than $\dot{M}$. Thus we expect to observe bright sources only between $t_{\text{trans}}$ and $\sim 2t_{\text{ADAF}}$. We identify this phase of evolution with the AXPs. For the parameters of interest (§4), the AXP phase corresponds to no more than an order of magnitude in time, say from $t \sim 5000$ yr to $t \sim 40000$ yr. It is this slender range that we hope to exploit to explain the surprisingly narrow distribution of AXP periods.

If, on the other hand, the neutron star enters the ADAF phase before reaching the efficiently accreting tracking phase, then it remains a dim “propeller system” for most of its lifetime, and is never seen as a bright AXP.

3. Details of the Model

Cannizzo et al. (1990) have shown that once the accretion disk is established and evolves under the influence of viscous processes, the accretion rate declines self-similarly according to $\dot{m} \propto t^{-\alpha}$. Motivated by these results, we choose to parameterize the accretion rate in our model by

$$\dot{m} = \dot{m}_0, \quad 0 < t < T$$
$$\dot{m} = \dot{m}_0 \left( \frac{t}{T} \right)^{-\alpha}, \quad t \geq T,$$

where $T$ is of order the dynamical time in the inner parts of the disk early on, and $\dot{m}_0$ is a constant, which we normalize to the total mass of the disk, $M_d = \int_0^\infty \dot{M}_d dt$, by
\[ \dot{m}_0 = \frac{(\alpha - 1)M_d}{[\alpha \dot{M}_E T]}, \] assuming \( \alpha > 1 \). Cannizzo et al. (1990) find \( \alpha = 19/16 \) for a disk in which the opacity is dominated by electron scattering and \( \alpha = 1.25 \) for a Kramers opacity. The evolution at early times during the initial settling of the disk is uncertain, and will probably need to be studied numerically. It is possible that \( \alpha \) could differ from order unity during an early phase when the accretion is highly super-Eddington, thereby compromising the relationship between \( M_d \) and \( \dot{m}_0 \). However, our results at late times are insensitive to this initial transient behavior and the form for the accretion rate given in equation (1) should be appropriate.

Given the accretion history from equation (1), the time-dependence of the stellar spin can be computed from

\[ I \ddot{\Omega} = \dot{J}, \]

where \( I \) is the moment of inertia of the star and \( \dot{J} \) is the torque acting on the star from the accretion disk. Throughout, we assume that torque will be applied only when \( R_m < R_{lc} \).

For the range of parameters chosen below, \( R_m < R_* \) at \( t = 0 \), and hence the accretion disk extends down to the surface of the star. Thus, the torque exerted on the star is

\[ \dot{J} = \dot{M}_E R_m^2 \Omega_K(R_m) \]

(see, e.g., Popham & Narayan 1991); note that we have assumed that the accretion rate at the very surface of the star can be at most at the Eddington rate, with any excess material being blown away before it can reach the star’s surface by the pressure of radiation from the star. If \( t_{R_*} \) is the time at which \( R_m \) equals \( R_* \), we take the subsequent torque to be given by the following simple heuristic formula (see Menou et. al. 1999):

\[ \dot{J} = 2\dot{M}R_m^2 \Omega_K(R_m) \left( 1 - \frac{\Omega}{\Omega_K(R_m)} \right). \]

When \( \Omega \) is very large compared to the “equilibrium” angular velocity \( \Omega_K(R_m) \), we have the propeller phase in which the spin-down torque is large as a result of the large angular momentum transferred to the ejected material. The torque approaches zero as \( \Omega \) approaches \( \Omega_K(R_m) \), and becomes a spin-up torque for \( \Omega < \Omega_K(R_m) \) (this never happens in our scenario, except for a brief period of a month or so very early in the history of the neutron star, before it enters the propeller phase).

Equation (2) coupled with equation (3) for the torque can be integrated to yield an analytic solution for \( \Omega(t) \) in terms of incomplete gamma functions for arbitrary \( \alpha \). A particularly simple form results from the choice \( \alpha = 7/6 \). Since this value is very nearly that found by Cannizzo et al. (1990) for disks dominated by either electron scattering or Kramers opacities, we will adopt \( \alpha = 7/6 \) in what follows. The solution of equation (3) for \( t > t_{R_*} \) is then

\[ \Omega(t) = \frac{\Omega(t_{R_*}) e^{2c_1(t_{R_*}^{1/2} - t^{1/2})} + 2c_2 [Ei(2c_1 t^{1/2}) - Ei(2c_1 t_{R_*}^{1/2})]}{e^{-2c_1 t^{1/2}}}, \]

where \( c_1 = 1.25 \), \( c_2 = 0.5 \), and \( Ei(z) \) is the exponential integral.
where $Ei(x) = \int_{-\infty}^{x}(e^{y}/y)dy$ is an exponential integral, $c_1 = 2\dot{m}_0\dot{M}_E R_{m,0}^2 T^{1/2}/I$, and $c_2 = 2\dot{m}_0\dot{M}_E R_{m,0}^2 \Omega_K(R_{m,0})T/I$. Quantities subscripted by zero refer to their values at $t = 0$.

For arbitrary $\alpha$, the solution to equation (3) in the limit $t \gg t_{R*}$ can be obtained using an asymptotic expansion, yielding $\Omega(t) \sim \Omega_K(R_{m,0})(t/T)^{-3\alpha/7}$. The corresponding characteristic age, $t_c \equiv -\Omega/2\dot{\Omega}$ and braking index $n \equiv \Omega\ddot{\Omega}/\dot{\Omega}^2$ then become $t_c \sim 7t/6\alpha$ and $n \sim (7 + 3\alpha)/3\alpha$. Note that for $\alpha = 7/6$, $t_c \sim t$ and $n \sim 3$, which are identical to those for a radio pulsar spinning down by magnetic dipole radiation. Thus, remarkably, the steady timing behavior of a star being spun down by a fossil accretion disk with $\alpha = 7/6$ will be indistinguishable from that of a radio pulsar spinning down by emitting magnetic dipole radiation.

The evolutionary phases described in Section 2 can be identified from equation (4). When the first term in equation (4) dominates, $\dot{\Omega} \propto e^{-2c_1 t^{1/2}}$ and spin-down is rapid; this is the propeller phase. When the second term dominates, $\dot{\Omega} \propto t^{-1/2}$ and the spin period of the star nearly equals the evolving equilibrium period; this is the tracking phase. Note that the spin-down torque is applied by the full $\dot{m}$, which can be vastly super-Eddington at early times (for the choice of parameters below), although presumably the X-ray luminosity would never exceed the Eddington limit.

4. Representative Results

For the examples shown here we choose an initial disk mass of $M_d = 0.006 M_\odot$, an initial dynamical time of $T = 1$ ms, an initial neutron star spin period of $P_0 = 15$ ms, and $\alpha = 7/6$. Although arbitrary, these are plausible values; for instance, $M_d$ is a very small fraction of the likely fallback mass $M_{fb}$, and $P_0$ is comparable to the estimated initial spin period of the Crab pulsar. We assume that neutron stars are born with magnetic field strengths in the range $\log(B_{12}) \sim 1 - 10$ (Narayan & Ostriker 1990). Figure 1 shows the spin histories of 10 neutron stars with field strengths spanning this range.

For the assumed values of $M_d$, $T$, $P_0$, and $\alpha$, a neutron star with a field strength $B_{12} \sim 5 - 10$ becomes an AXP (Fig. 1). Early on, for a period ranging from a few days to up to a year, depending on the magnetic field strength, the star accretes at the Eddington rate and is very bright. This phase is not visible since it is lost in the emission from the supernova explosion. As $\dot{M}$ decreases with time, $R_m$ increases, and the system switches to a much dimmer propeller phase which lasts for about $10^4$ yr. In this phase, the star spins too rapidly to accrete much mass; it spins down rapidly, however, as a result of the large
decelerating torque due to the material that is flung out by centrifugal forces. Ultimately, at \( t = t_{\text{trans}} \sim 10^4 \) yr, the star achieves quasi-equilibrium with the accretion disk and enters the tracking phase where it becomes bright in X-rays. For the examples shown, the luminosity is initially \( L_x \sim 10^{36.5} \) erg s\(^{-1}\), with \( L_x \) decreasing as \( t^{-\alpha} \). The bright phase lasts for only a short time. When \( t = t_{\text{ADAF}} \sim 19000 \) yr (i.e., when \( \dot{m} \sim 0.01 \)), the accretion flow switches from a thin disk to an ADAF. Thereafter, the mass accretion rate onto the neutron star falls rapidly as a result of heavy mass loss in a wind. By \( t \sim 2 \times t_{\text{ADAF}} \sim 10^{4.6} \) yr, the mass accretion rate is likely to be quite low and the system will be dim once again.

A neutron star with an intermediate magnetic field strength, such as \( B_{12} = 4 \) (Fig. 1), enters the efficiently accreting tracking phase at a time \( t_{\text{trans}} \) which is greater than \( 2 \times t_{\text{ADAF}} \), the cutoff for visibility assumed in this model. Such a “propeller system” would thus remain in the dim propeller phase for almost the whole of its lifetime before directly entering the ADAF phase.

For smaller field strengths, \( B_{12} \sim 1 - 3 \), the behavior is quite different (Fig. 1). Like their strong field counterparts, these stars have an initial brief Eddington-bright accretion phase, followed by a propeller phase. However, because of their smaller \( R_m \) (a consequence of their smaller \( B_{12} \)), the spindown due to accretion is less effective and \( R_{lc} \) remains small. Therefore, with time, as \( \dot{M} \) is reduced, a stage is reached when \( R_m \) becomes greater than \( R_{lc} \). At this point, accretion ceases completely and the neutron star becomes a radio pulsar. The pulsar phase then proceeds in the normal fashion, lasting for millions of years until the star crosses the “death line” (e.g. Bhattacharya & van den Heuvel 1991). By this time, the fossil disk would most likely have dissipated completely, so it is very unlikely that the dead pulsar would be resurrected in a late phase of accretion.

Figure 2 exhibits the different phases discussed above in a \( B_{12} - P \) diagram. Note the clean division between radio pulsars and AXPs. Let \( B_{12,RP} \) be the critical field below which neutron stars become radio pulsars, and let \( B_{12,AXP} \) be the critical field above which neutron stars go through a bright AXP phase. Then, for a choice of \( M_d = 0.006M_\odot \) and \( P_0 = 15 \) ms, \( B_{12,RP} = 3.9 \), and \( B_{12,AXP} = 4.2 \). The “propeller” systems occur for intermediate values of field strength. For the above choice of parameters, note also the narrow range of resulting AXP spin periods.

The precise values of \( B_{12} \) that result in radio pulsars and AXPs, and the period range over which AXPs are seen, both depend on the parameters of the model, notably \( M_d \) and \( P_0 \). In the above example, we have chosen values for these parameters that seem best to produce results in agreement with observations. While we defer to a future paper the question of how these conclusions would change were the parameters to be drawn from broad distributions instead of from delta functions, we give below the results for a few other
choices of parameter values.

As mentioned above, for $M_d = 0.006 M_\odot$ and $P_0 = 15$ ms, $B_{12,RP} = 3.9$ and $B_{12,AXP} = 4.2$; a neutron star with the critical field $B_{12} = 4.2$ would just enter the tracking phase at the cutoff time $2 \times t_{ADAF} = 38000$ yr with a period of 7.1 s; neutron stars with higher fields would enter the tracking phase before this cutoff time, and thus one would have a distribution of periods on both sides of 7.1 s.

For $M_d = 0.006 M_\odot$ and $P_0 = 20$ ms, $B_{12,RP} = 0.8$ and $B_{12,AXP} = 4.1$; at the cutoff time $2 \times t_{ADAF} = 38000$ yr, a neutron star with $B_{12} = 4.1$ would have a period of 6.9 s. For $M_d = 0.012 M_\odot$ and $P_0 = 15$ ms, $B_{12,RP} = 0.5$ and $B_{12,AXP} = 2.4$; at the cutoff time $2 \times t_{ADAF} = 70000$ yr, a neutron star with $B_{12} = 2.4$ would have a period of 4.3 s.

For $M_d = 0.006 M_\odot$ and $P_0 = 10$ ms, $B_{12,RP} = 36.0$ and $B_{12,AXP} = 4.4$; since $B_{12,RP} > B_{12,AXP}$, any system that does not become a radio pulsar goes through a bright AXP phase, and there are no “propeller systems” that directly enter the ADAF phase without going through a brightly accreting phase; a neutron star with the critical field strength $B_{12} = 36.0$ enters the tracking phase at $t_{\text{trans}} = 266$ yr with a period of 3.7 s and at the cutoff time $2 \times t_{ADAF} = 38000$ yr has a period of 53.9 s. Similarly, for $M_d = 0.003 M_\odot$ and $P_0 = 15$ ms, $B_{12,RP} = 31.1$ and $B_{12,AXP} = 7.4$; a neutron star with $B_{12} = 31.1$ enters the tracking phase at $t_{\text{trans}} = 713$ yr with a period of 7.3 s and at the cutoff time $2 \times t_{ADAF} = 21000$ yr has a period of 47.0 s.

Thus, it is clear that not all choices of parameter values produce a narrow range of periods; it remains to be seen whether this narrow range would persist if the parameters were drawn from distributions centered at or near the “best case” values used in the figures.

5. Conclusions

We have described a model in which a newly-born neutron star can experience accretion at a time-varying rate from a disk formed as a result of fallback following a supernova explosion. As shown above, for plausible values of the magnetic field strength, initial spin period, and disk mass ($B_{12} \gtrsim 5$, $P_0 = 0.015$ s, $M_d = 0.006 M_\odot$), a neutron star will be spun down to periods similar to those of observed anomalous X-ray pulsars, $P \sim 10$ seconds, on timescales characteristic of the estimated ages of AXPs, $\sim 10,000 - 40,000$ years. These conditions are met if the object is seen as an AXP during the tracking phase of evolution discussed previously up to roughly twice the age at which the accretion flow evolves into an ADAF, $t_{ADAF}$. Early during this period, the X-ray luminosity of the source is high compared with observed AXPs; however, the luminosity is expected to fall quickly after
about $t_{ADAF}$, and so it could mean, for example, that the known AXPs are seen some time after $t_{ADAF}$. For the above parameter values, this model thus matches the properties of observed AXPs. Different choices of parameters (for example, lowering the field strength to $B_{12} = 3$) yields a radio pulsar for an extended period of time. Yet other values of the surface magnetic field strength (for example, $B_{12} = 4$) produce systems that remain in the X-ray faint propeller phase right until the time they make the transition into the dim ADAF phase. In this paper, we have merely pointed out the existence of a region in parameter space that produces objects with properties resembling AXPs. Whether or not this model is capable of accounting for the observed relative birthrates of radio pulsars and AXPs will require a more thorough analysis.

Our model has a number of advantages over previous theories for AXPs as accreting sources. The accretion flow is time-varying, and thereby provides a natural explanation for the increasing periods of AXPs. Accretion from a fossil disk evades limits on companion masses associated with AXPs from timing measurements. Thompson et al. (1999) have recently pointed out that large recoil velocities severely limit the radial extents of disks that would remain bound to a neutron star. This is not a difficulty for our model, as the disk is tightly bound initially, before spreading radially as it enters a period of self-similar evolution.

The other leading model for AXPs invokes ultramagnetized neutron stars ($B \sim 10^{14} - 10^{15}$ G) to account for their timing behavior (e.g. Thompson & Duncan 1996) and their X-ray emission (e.g. Heyl & Hernquist 1997b, Heyl & Kulkarni 1998). An advantage of our scenario is that it relies on a standard population of isolated neutron stars having magnetic fields similar to those inferred for radio pulsars and binary X-ray pulsars and does not require the existence of a separate class of neutron stars.

How can we discriminate between these two models? By chance, the steady spindown caused by accretion from a fossil disk is indistinguishable from that describing the evolution of ordinary radio pulsars. Thus, it appears unlikely that this aspect of AXPs will unambiguously distinguish these two models. However, these theories differ significantly in detail, and many observational tests can, in principle, separate them.

Torque fluctuations are commonly seen in X-ray binaries (e.g. Bildsten et al. 1997). Whether or not the torque fluctuations seen in AXPs can be explained by our model (or, indeed any of the proposed accretion scenarios) remains to be seen, but it is at least plausible that an accretion flow can produce torque noise. The origin of this behavior according to the ultramagnetized neutron star model is uncertain. Proposals include fluctuations induced by glitches (Heyl & Hernquist 1999) or “radiative precession” (Melatos 1999).
The narrow distribution of AXP periods (a factor $\sim 2$) is puzzling, and lacks a definitive explanation. In our model, neutron stars accreting from a debris disk would be visible as AXPs for only a relatively brief period of time, and hence would be seen in similar evolutionary states. Whether or not this is sufficient to reproduce the observed population of AXPs will depend principally on the distribution of neutron star-disk systems in the parameter space defined by magnetic field strength ($B_{12}$), initial spin period ($P_0$), and disk mass ($M_d$), and how or if these parameters are correlated. The other two relevant parameters are $\alpha$ and $T$, which define the mass accretion rate in equation (1); our long-term results are quite insensitive to the precise value of $T$, and the value of $\alpha$ is rather closely fixed by the results of Cannizzo et al. (1990).

An interesting question concerns the relationship of AXPs to SGRs. These sources appear similar in most respects, except that SGRs are subject to occasional, energetic outbursts. Previously, it has been suggested that bursts of gamma-ray emission could be produced by interchange instabilities in the crusts of slowly accreting neutron stars (Blaes et al. 1990) or by solid bodies impacting neutron stars (Harwitt & Salpeter 1973; Tremaine & Zytkow 1986). Conceivably, these processes could play a role in our model, but at present we have no specific, testable proposal that would distinguish AXPs from SGRs in this context.

Certainly, the most unambiguous discriminant between the accretion and ultramagnetized neutron star models would be a direct measurement of the magnetic field strength (i.e., not derived from timing data). We predict that AXPs should have magnetic fields $B \sim 10^{13}$ G, above average compared with those of radio pulsars, but lying within the same observed range. According to the magnetar hypothesis, however, AXPs have much larger magnetic fields, $B \sim 10^{14} - 10^{15}$ G. Like some binary X-ray pulsars, it is possible that AXPs will contain information in their spectra that would provide a determination of the magnetic field strength.

Existing AXP spectra are well-fitted by thermal profiles with power-law tails at high energies (e.g. Corbet et al. 1995, Oosterbroek et al. 1998, Israel et al. 1999), but lack the resolution to exhibit discrete spectral features. Power-law tails at high energy are characteristic of accreting neutron stars at low luminosities (e.g. Asai et al. 1996, Zhang, Yu & Zhang 1998, Campana et al. 1998), though the high energy tails are typically harder than in the AXPs. In the ultramagnetized neutron star model, the tails presumably arise as a result of departures from blackbody emission (e.g. Heyl & Hernquist 1998b). At present, therefore, the spectral information is ambiguous. However, the recently deployed Chandra X-ray satellite and the forthcoming XMM mission promise to revolutionize the field of high-precision X-ray spectroscopy, and we are thus optimistic that the true nature of AXPs
will be revealed in the near future.

Several arguments against an accretion model of AXPs have been presented in the literature. Some of these arguments apply to our model as well. Tight limits on optical and especially infrared counterparts of AXPs (e.g. Coe & Pighetli 1998) severely constrain the amount of emission that can come from the disk. For reasonable parameters, the disks in our model expand to about an AU during the AXP phase, and it might be difficult to make the disk as dim as the observations require. Kaspi, Chakrabarty & Steinberger (1999) have shown that the AXP 1E 2259+586 has an extraordinarily low level of timing noise. This is hard to explain in an accretion-based model because the disk, by virtue of its turbulent nature, is likely to produce a noisy torque. Note, however, that the fossil disks are likely to differ from conventional disks in accreting binary systems by virtue of, e.g., their composition, so the implications of the observations for our model are uncertain.

Li (1999) has argued that AXPs cannot respond quickly enough to a changing $\dot{M}$ to track the equilibrium spin period of a time-dependent disk. This is clearly not a problem for our model. As Fig. 1 shows, the systems that become AXPs ($B_{12} \gtrsim 5$) spin down rapidly enough in the propeller phase to be able to attain periods close to their (evolving) equilibrium spin periods in $\sim 10^3 - 10^4$ years.

We would like to thank Deepto Chakrabarty, Jeremy Heyl, and Vicki Kaspi for useful discussion. This work was supported in part by NSF grant AST 9820686.

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Fig. 1.— The period evolution of a neutron star of initial spin period $P_0 = 0.015$ seconds and total mass of the surrounding accretion disk $M_d = 0.006M_\odot$. The values of $B_{12}$ are 1, 2, ..., 10, with $B_{12} = 1$ for the lowermost curve and $B_{12} = 10$ for the uppermost. Neutron stars with $B_{12} \lesssim 3.9$ go into a long phase as radio pulsars, in which the magnetospheric radius $R_m$ is larger than the light cylinder radius $R_{lc}$. Neutron stars with $B_{12} \gtrsim 4.2$ go through a propeller phase of rapid spin-down, eventually reaching the more slowly evolving tracking phase. The AXP phase, as explained in the text, is roughly between $t_{\text{trans}}$, the time of transition between the propeller and tracking phases, and $\sim 2t_{\text{ADAF}}$; where $t_{\text{ADAF}}$ is the time at which the accretion flow becomes advection-dominated. Stars with intermediate values of $B_{12}$ (shown is the case with $B_{12} = 4$) remain in the propeller stage until they become too dim to be seen at $t \sim 2t_{\text{ADAF}}$. Although the diagram shows the period evolution for $t > 2t_{\text{ADAF}}$ to continue on the tracking phase, the exact evolution at these times is uncertain, as it is not clear how the mass outflows during the ADAF phase will affect the torque applied by the disk.

Fig. 2.— The different possible phases of evolution of a neutron star of initial spin period $P_0 = 0.015$ seconds and total mass of the surrounding accretion disk $M_d = 0.006M_\odot$. All the stars go through an initial brief stage of Eddington-bright accretion, during which the star is spun up to the extent of the width of the bold long-and-short-dashed line on the left. Subsequently, stars with $B_{12} \lesssim 3.9$ go through a short stage of accretion in the propeller phase before becoming radio pulsars during which time the magnetospheric radius $R_m$ is larger than the light cylinder radius $R_{lc}$; they continue in this stage until they reach the pulsar death line, given by $B_{12} \approx 0.2P^2$ (Bhattacharya & van den Heuvel 1991). On the other hand, stars with $B_{12} \gtrsim 4.2$ go through a dim propeller phase for $\sim 10^4$ years, eventually reaching the bright AXP phase which, as marked, lasts between $t_{\text{trans}}$ and $2t_{\text{ADAF}}$; after $t = 2t_{\text{ADAF}}$, we assume that the AXPs will be too dim to be seen; this region is marked as “Dead AXPs”; note that there is no possibility that these latter neutron stars will be seen as radio pulsars after the AXP phase, since they will be beyond the pulsar death line. Stars with intermediate values of $B_{12}$ are “propeller systems”, which pass directly from the propeller phase into the dim ADAF phase. The area hatched with solid lines denotes the region in which the neutron star is X-ray bright; the area hatched with broken lines denotes the region in which the neutron star acts as a radio pulsar.
The graph shows the variations in magnetic field strength ($B_{12}$) with time ($t$) in years, for different phases of a magnetar, namely the Bright AXP phase, Dim AXP phase, Dim propeller phase, and Radio pulsar phase. The graph illustrates how these phases evolve over time, with $B_{12}$ increasing as $t$ increases.
Brightly accreting early phase

Dim propeller phase

Bright AXPs

Dead AXPs

Start of pulsar phase

Pulsar death-line

Radio pulsars

B_{12}

P (seconds)