ON YOUNG NEUTRON STARS AS PROPELLERS AND ACCRETORS WITH CONVENTIONAL MAGNETIC FIELDS

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ABSTRACT

The similarity of rotation periods of the anomalous X-ray pulsars (AXPs), the soft gamma-ray repeaters (SGRs), and the dim isolated thermal neutron stars (DTNs) suggests a common mechanism with an asymptotic spin-down phase, extending through the propeller and early accretion stages. The DTNs are interpreted as sources in the propeller stage. Their luminosities arise from frictional heating in the neutron star. If the 8.4 s rotation period of the DTN RX J0720.4−3125 is close to its rotational equilibrium period, the estimated propeller torque indicates a magnetic field in the 10^{12} G range. The mass inflow rate onto the propeller is on the order of the accretion rates of the AXPs. The limited range of rotation periods, taken to be close to equilibrium periods, and conventional magnetic fields in the range 5 \times 10^{11} to 5 \times 10^{12} G correspond to a range of mass inflow rates \(3.2 \times 10^{14} \text{ g s}^{-1} < M < 4.2 \times 10^{17} \text{ g s}^{-1}\). Observed spin-down rates of the AXPs and SGRs also fit in with estimates for these magnetic fields and equilibrium periods. The source of the mass inflow is a remnant accretion disk formed as part of the fallback during the supernova explosion. These classes of sources thus represent the alternative pathways for those neutron stars that do not become radio pulsars. For the highest mass inflow rates the propeller action may support enough circumstellar material so that the optical thickness to electron scattering destroys the X-ray beaming, and the rotation period is not observable. These are the radio-quiet neutron stars at the centers of supernova remnants Cas A, Puppis A, RCW 103, and 296.5±10. The statistics and ages of DTNs suggest that sources in the propeller phase are quite common, maybe accounting for the majority of neutron stars formed in supernovae. AXPs are the rare cases whose \(M\) history has allowed them to evolve rapidly to the post–propeller accretion phase. The different classes represent alternative pathways rather than consecutive phases of evolution. Thus, for example, the AXPs are not descendants of the DTNs. This model obviates the need to postulate magnetars for AXPs and DTNs. Frequently sampled timing observations of AXPs, SGRs, and DTNs can distinguish between this explanation and the magnetar model.

Subject headings: accretion, accretion disks — stars: magnetic fields — stars: neutron — supernovae: general

1. INTRODUCTION

Anomalous X-ray pulsars (AXPs) are characterized by periods in the range 6–12 s (see Mereghetti 2001a for a review and an extensive list of references therein for properties of specific AXPs). RX J0720.4−3125, one of the dim nearby ROSAT point sources thought to be thermally emitting neutron stars (Walter, Wolk, & Neuhauser 1996; Walter & Matthews 1997), has a measured period (Haberl et al. 1997) of 8.4 s, while a recently discovered member of this class, RX J0420.0−5022, is reported to have a period of 22.7 s (Haberl, Pietsch, & Motch 1999). Among the four confirmed soft gamma-ray repeaters (SGRs; Mazets et al. 1979, 1981; Cline et al. 1980; Woods et al. 1999) with quiescent X-ray sources, there are two with measured pulse periods. Both periods are in the AXP period range, with \(P = 7.47\) s for SGR 1806−20 (Kouveliotou et al. 1998) and \(P = 5.16\) s for SGR 1900+14 (Hurley et al. 1999; Kouveliotou et al. 1999). For the AXPs it was pointed out (Koyama, Hoshi, & Nagase 1987; van Paradijs, Taam, & van den Heuvel 1995; Corbet et al. 1995; Ghosh, Angelini, & White 1997) that these periods would obtain as equilibrium periods for the accretion rates \(M \sim 10^{15} \text{ g s}^{-1}\) corresponding to the observed luminosities and for \(10^{11}−10^{12} \text{ G magnetic fields}\).

Values of \(\dot{P}\) measured from the AXPs and SGRs, together with the long rotation periods in the 5–12 s range, have led to the suggestion that these sources are magnetars (Kouveliotou et al. 1998, 1999; Duncan & Thompson 1992; Thompson & Duncan 1993, 1995), neutron stars with very strong magnetic fields \(B \sim 10^{14}−10^{15} \text{ G}\), spinning down through magnetic dipole radiation and/or a magnetically powered relativistic wind. These models account for SGR bursts and flares as magnetically induced instabilities. The short cooling age estimated for RX J0720.4−3125 has also been suggested (Heyl & Hernquist 1998) as evidence for a magnetar if the source is an isolated pulsar born with a short rotation period. We propose here an alternative explanation, extending the accretion hypothesis to include propeller phases and linking these classes of neutron stars as stars with conventional \(\sim 10^{12} \text{ G magnetic fields}\). Mass inflow from a disk (van Paradijs et al. 1995; Ghosh et al. 1997) around the neutron star will produce torques on the neutron star on the order of the spin-down torques observed. The AXPs and SGRs are accreting at least part of the incoming mass flow. The similarity of the periods simply reflects similar conditions. All these systems are asymptotically approaching equilibrium periods in a common range, defined by the common ranges of magnetic fields and mass transfer rates. As the approach to rotational equilibrium is asymptotic, \(P/\dot{P}\) is not the true age of these systems. Sources of different ages and different circumstances with similar conventional magnetic fields have similar periods in this asymptotic regime under a fairly large range of mass inflow rates.

Observed magnetic fields of radio pulsars now extend to

\[7.47 \text{ s}\]
... 5.5 \times 10^{13} \text{ G} \quad \text{(Gotthelf et al. 2000; Camilo et al. 2000). It is not yet known observationally whether the magnetic field distribution of neutron stars extends to the 10^{14} \text{--} 10^{15} \text{ G range. We take the} 10^{11} \text{--} 10^{13} \text{ G range of \text{"conventional\"} magnetic fields to follow what the accretion hypothesis with this conservative assumption requires.}

We propose that the dim isolated thermal neutron stars (DTNs), AXPs, SGRs, and radio-quiet neutron stars (RQNSs) constitute the alternative subclasses of young neutron stars produced by supernovae, complementary to the subclass of neutron stars that show up as radio pulsars (Kaspi 2000). In view of the plausible associations of several AXPs with supernova remnants (SNRs), tight upper limits on the mass of a binary companion (Mereghetti, Israel, & Stella 1998; Wilson et al. 1999), and statistics and age considerations, these sources are likely to be young neutron stars under mass inflow from a remnant disk formed by fallback material from the supernova explosion (Chevalier 1989; Lin, Woosley, & Bodenheimer 1991; Mineshige, Nomoto, & Shigeyama 1993).

Most ideas discussed in this paper and their links to related subjects were first presented in an earlier preprint (Alpar 1999). The DTNs are the propeller counterparts to the AXPs the scenario of accretion from a remnant disk, preceded with a propeller phase, has been explored also by Chatterjee, Hernquist, & Narayan (2000), who have presented the working hypothesis of the present work, that all supernovae are due to their different mass inflow environments and histories. At the highest mass inflow rates we have the RQNSs. These are propellers whose pulse periods are not observable owing to accumulated circumstellar material that is optically thick to electron scattering. The subclasses unified in this scenario represent the entire range of mass inflow rates, extending from $M \approx 0$ for the radio pulsars to near Eddington rates inferred for the RQNSs.

Table 1 displays observed parameters and model estimates for the AXPs, for the two SGRs with $\dot{P}$ measurements, for the two DTNs with measured periods, and for a typical RQNS. Section 2 discusses the energy dissipation in a neutron star under an external torque. Section 3 introduces propeller torques and applies these ideas to DTNs. Section 4 presents a simple model for asymptotic spin-down. Section 5 relates the different classes of neutron stars, including the RQNSs, as supernova products under mass inflow. Section 6 reviews the expected signature of a remnant disk around the neutron star, and § 7 presents the conclusions.

2. LUMINOSITY OF A NONACCRETING NEUTRON STAR FROM ENERGY DISSIPATION

The DTNs yield fits to blackbody spectra with temperatures of 57 eV for RX J185635 $\approx 3754$ and 79 eV for RX J0720.4 $\approx 3125$ and luminosities in the $L_x \approx 10^{31} \text{--} 10^{32}$ ergs s$^{-1}$ range (Walter et al. 1996; Walter & Matthews 1997;

\begin{table}[h]
\centering
\caption{Model Parameters for AXPs, ATNs, and RQNS}
\label{tab:1}
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Source & $P$ (s) & $\dot{P}$ (s s$^{-1}$) & $\Omega$ (rad s$^{-2}$) & $M_{1.5}$ ($10^{15}$ g s$^{-1}$) & $P_{eq}$ (s) & $\tau$ (yr) & $\mu_0$ ($10^{10}$ G cm$^{-3}$) & $t_{SNR}$ (yr) \\
\hline
AXPs & & & & & & & & \\
1E 1048.1 \& 5937 & 6.44 & $2 \times 10^{-11}$ & $\ldots$ & 0.2 & 64.4 & $9.3 \times 10^3$ & 2.14 & $\ldots$ \\
$\ldots$ & $\ldots$ & $\ldots$ & $\ldots$ & 1 & 23 & $7.4 \times 10^3$ & 1.45 & $\ldots$ \\
1E 2259 \& 586 & 6.98 & $6 \times 10^{-13}$ & $\ldots$ & 0.5 & 8.25 & $5.7 \times 10^4$ & 0.67 & $\ldots$ \\
$\ldots$ & $\ldots$ & $\ldots$ & $\ldots$ & 2 & 7.4 & $1.7 \times 10^4$ & 0.54 & $< 2 \times 10^4$ \\
4U 0142 \& 61 & 8.69 & $2.1 \times 10^{-12}$ & $\ldots$ & 1 & 10.5 & $2.1 \times 10^4$ & 0.57 & $\ldots$ \\
RX J170849.0 & 11 & $2 \times 10^{-11}$ & $\ldots$ & 12 & 12.1 & $1.5 \times 10^5$ & 2.36 & $\ldots$ \\
1E 1841 \& 045 & 11.8 & $4 \times 10^{-11}$ & $\ldots$ & 3.5 & 17.5 & $3.2 \times 10^5$ & 1.96 & $< 3 \times 10^5$ \\
AX J1845 \& 0258 & 6.97 & ($7.8 \times 10^{-12}$) & ($-10^{-12}$) & 1 & 16.8 & $1.2 \times 10^4$ & (1) & $< 8 \times 10^3$ \\
\hline
SGRs & & & & & & & & \\
SGR 1806 \& 20 & 7.47 & $8.3 \times 10^{-11}$ & $\ldots$ & 100 & 13.8 & 148 & 7.9 & $\ldots$ \\
SGR 1900 \& 14 & 5.16 & $1.1 \times 10^{-10}$ & $\ldots$ & 20 & 9.1 & $1.3 \times 10^3$ & 2.2 & $\ldots$ \\
\hline
DTNs & & & & & & & & \\
RX J0720.4 \& 3125 & 8.39 & ($2.9 \times 10^{-11}$) & ($-2.6 \times 10^{-12}$) & 1 & 10.8 & $2 \times 10^4$ & 0.59 & $\ldots$ \\
RX J0420.0 \& 5022 & 22.7 & ($8.2 \times 10^{-10}$) & ($-10^{-11}$) & 6.4 & 7.58 & $5.27 \times 10^3$ & 3.6 & $\ldots$ \\
RQNS in Cas A & & ($4.7 \times 10^{-11}$) & ($-3 \times 10^{-10}$) & 735 & 0.99 & 689 & (1) & 320 \\
\hline
\end{tabular}
\end{table}

Note.—Model parameters for all six AXPs, for the two SGRs with observed $P$ and $\dot{P}$, the two DTNs with observed periods, and the source in Cas A as a representative RQNS. For the AXPs and SGRs, mass inflow rates chosen are greater than the mass accretion rate inferred from the observed luminosity. For AX J1845 \& 0258, for which $\dot{P}$ has not been measured, we assume $\mu_0 = 1$. For the two DTNs and for the RQNS in Cas A, we infer $|\dot{\Omega}|$ from the luminosity. For the DTNs, we assume $P = P_{eq}$ and for the Cas A source $\mu_0 = 1$ is assumed. Parentheses mark input quantities that are not taken from observations.
Haberl et al. 1997; Motch & Haberl 1998; Kulkarni & van Kerkwijk 1998). Several further candidates for this class (Stocke et al. 1995; Haberl, Motch, & Pietsch 1998; Schwoppe et al. 1999; Motch et al. 1999; Haberl et al. 1999) also have similar blackbody temperatures, flux values, and limits on the ratio of X-ray flux to optical flux. Accretion from the ISM would require unlikely ambient ISM densities and low velocities (for a discussion of accretion from the ISM for the DTNs, see Treves et al. 2000 and references therein). The presence of several dim thermal neutron stars within a few 100 pc suggests that there are \( \sim 10^4 \) such sources in the Galaxy, requiring ages of \( \sim 10^6 \) yr or longer, if the birth rate is \( 10^{-2} \) yr\(^{-1} \) or less. A recent report (Walter 2001) of the parallax and proper motion of the DTN RX J185635-3754 indicates, by extrapolation of the proper motions, that the position of this neutron star coincides at the time of birth with the positions of the Sco-Cen OB association and the runaway star \( \zeta \) Oph. From this initial position and the proper motion, the age of this neutron star is derived to be \( 1.15 \times 10^6 \) yr.

The cooling of a young neutron star can typically yield the observed thermal luminosities at ages on the order of \( 10^5 - 10^6 \) yr (Ögelman 1995). For a neutron star born with a rotation period on the order of 10 ms (as typically inferred from the \( P_- \) and \( P_+ \)-values of young pulsars) to have spun down to the 8.4 s period of RX J0720.4 - 3125 in \( 10^5 \) yr or less as a rotating magnetic dipole would require a mean spin-down rate \( \dot{\Omega} \) on the order of \( 10^{-13} \) rad s\(^{-1} \), and a magnetic field on the order of \( 10^{14} \) G or more (Heyl & Hernquist 1998; Kulkarni & van Kerkwijk 1998).

There is an alternative source of the thermal luminosity that takes over at \( \sim 10^5 - 10^6 \) yr, after the initial cooling, and lasts longer than the cooling luminosity. There will be energy dissipation (frictional heating) in a neutron star being spun down by some external torque. The rate of energy dissipation is given by (Alpar et al. 1984; Alpar, Nandkumar, & Pines 1985)

\[
\dot{E}_{\text{diss}} = I_p \omega |\dot{\Omega}|, \tag{1}
\]

where \( I_p \) is the moment of inertia of some component of the neutron star whose rotation rate is faster than that of the observed crust by the amount \( \omega \). The thermal luminosity of a nonaccreting neutron star at ages greater than \( \sim 10^6 \) yr will be supplied by \( \dot{E}_{\text{diss}} \) (Umeda et al. 1993), as the cooling luminosity rapidly falls below \( \dot{E}_{\text{diss}} \) after the transition from neutrino cooling to surface photon cooling. Among the radio pulsars with X-ray emission (Ögelman 1995; Becker & Trumper 1997), observations (Alpar et al. 1987; Yanco-poulos, Hamilton, & Helfand 1994) of the pulsar PSR 1929+10, whose spin-down age is \( 3.1 \times 10^6 \) yr, provide an upper limit to the thermal luminosity that yields \( I_p \omega < 10^{43} \) g cm\(^2\) rad s\(^{-1} \) (Alpar 1998). Note that this is treated as an upper limit rather than a detection because it is not possible to ascribe the point sources resolved by the X-ray observations entirely to luminosity of the neutron star although this is likely to be the case.

A lower limit to \( \dot{E}_{\text{diss}} \) can be obtained from the parameters of large pulsar glitches (Alpar 1998). The consistency of the observed glitch parameters of all pulsars with large glitches (\( \Delta \dot{\Omega}/\dot{\Omega} \geq 10^{-5} \)) and measured second derivatives \( \ddot{\Omega} \) of the rotation rate (Shemar & Lyne 1996) as well as the statistics of the large glitches (Alpar & Baykal 1994) support the hypothesis that large glitches are a universal feature of pulsar dynamics. The current phenomenological description (Alpar et al. 1993; Alpar 1998) of large glitches entails angular momentum exchange between the crust and an interior component (a pinned superfluid in current models) that rotates faster than the crust by the lag \( \omega \). The typical glitch-related change in relative rotation rate of the crust and interior, \( \delta \omega \sim 10^{-2} \) rad s\(^{-2} \), inferred from the common behavior of all pulsars with large glitches, must be less than the lag \( \omega \). Using values of \( \dot{I}_p \sim 10^{42} \) cm\(^2\)s\(^{-1} \) inferred from the detailed postglitch timing measurements available for the Vela pulsar glitches (Alpar et al. 1993), we obtain the lower bound \( I_p \omega > \dot{I}_p \delta \omega = 10^{44} \) g cm\(^2\) rad s\(^{-1} \). This lower bound is independent of the details of the glitch models and rests only on the assumption that the large glitches involve angular momentum exchange within the neutron star. Furthermore, as the mode of angular momentum transfer inside the star depends only on neutron star structure, the same parameter \( I_p \omega \) would determine the energy dissipation rates in all neutron stars under external torques, also when the source of the external torque is not magnetic dipole radiation. The upper and lower bounds together imply

\[
\dot{E}_{\text{diss}} = \left| \dot{\Omega} \right| < 10^{-13} \text{ ergs s}^{-1} \leq \dot{E}_{\text{diss}} \leq 10^{-10} \text{ rad s}^{-2}. \tag{2}
\]

The measured spin-down rates of AXPs and SGRs all fall in this range, providing another similarity, in addition to the periods, between the DTNs, AXPs, and SGRs. If DTN spin-down rates actually coincide with AXP spin-down rates, that is, the similarity between the two classes is tighter than the range of DTN spin-down rates implied by energy dissipation constraints, the DTN spin-down rate would be closer to \( \dot{\Omega} \sim 10^{-12} \) rad s\(^{-2} \), which means that \( \dot{E}_{\text{diss}} \) is closer to the upper limit in equation (2). With the 8.4 s period of RX J0720.4 - 3125, these spin-down rates imply surface magnetic fields in excess of \( 10^{14} \) G if magnetic dipole spin-down is assumed. Are there other spin-down mechanisms that will give high spin-down rates, larger than \( 10^{-12} \) rad s\(^{-2} \), with \( 10^{12} \) G magnetic fields typical of the canonical radio pulsars and of the accreting neutron stars with observed cyclotron lines?

3. PROPELLER SPIN-DOWN

High spin-down rates, larger than \( 10^{-12} \) rad s\(^{-2} \), can indeed be expected for neutron stars with conventional \( 10^{12} \) G fields under the typical spin-down torques for certain phases of accreting sources. For the AXPs, accretion is a possibility that has already been explored (Mereghetti & Stella 1995; van Paradijs et al. 1995; Ghosh et al. 1997) and will be pursued below. In connection with the DTNs, we note that a neutron star subject to mass infall will experience high spin-down rates even when the inflowing mass is not accreted because of the star’s centrifugal barrier (the propeller effect; Illarionov & Sunyaev 1975). We propose that RX J0720.4 - 3125 and the other DTNs are neutron stars with magnetic fields on the order of \( 10^{12} \) G, spinning down under propeller torques. There is no accretion yet in the propeller phase. The luminosities of the DTNs are produced by energy dissipation in the neutron star. These luminosities are dimmer, by several orders of magnitude, than the accretion luminosities that would have been produced if the mass inflow were accreted. The propeller torques
depend on the magnetic moment of the neutron star and on the rate of mass inflow. Using the spin-down rates estimated from the energy dissipation luminosities together with order-of-magnitude expressions for propeller torques, we show that the neutron star has a dipole magnetic field on the order of $10^{12}$ G. The estimated range of mass inflow rates coincides with the range of mass accretion rates inferred from the X-ray luminosities of the accreting AXPs and SGRs, suggesting that the DTNs are in the propeller stage and the AXPs and SGRs in the accretion phase under similar mass inflow circumstances.

Occasional quiescent states of some X-ray transients are likely examples of the propeller phase (Cui et al. 1998; Zhang, Yu, & Zhang 1998; Campina et al. 1998; Menou et al. 1999). Sources that are persistently in the propeller phase have not been detected previously. This is understandable since they are not lit up with an accretion luminosity. Thus, these sources are the first observed examples of propellers, observed only through their dissipation luminosities, only as the nearest members of the DTN class, and only by ROSAT, in view of their surface temperatures in the soft X-ray band.

In the propeller phase there is a spin-down torque exerted on the neutron star, through the interaction of its magnetosphere with the ambient material. The order of magnitude of this spin-down torque is

$$N = I |\dot{\Omega}| = \mu^2 / r_A^3,$$  

(4)

where $\mu = BR^3$ is the magnetic moment of the neutron star with surface dipole magnetic field $B$ and radius $R$, and

$$r_A = 9.85 \times 10^8 \text{ cm} \mu_\text{30}^{\frac{2}{7}} M_{15}^{\frac{2}{7}} m^{-\frac{1}{7}},$$  

(5)

is the Alfvén radius (Lipunov 1992; Frank, King, & Raine 1992). Here $\mu_{30}$ denotes the magnetic moment in units of $10^{30}$ G cm$^3$, $M_{15}$ is the mass inflow rate in units of $10^{15}$ g s$^{-1}$, and $m$ is the neutron star mass in solar mass units. The propeller phase will last until accretion starts when a critical rotation period $P_{\text{acc}}$ is reached. This critical period is on the order of, but somewhat smaller than, the equilibrium rotation period

$$P_{eq} = 16.8 \, s \, \mu_{30}^{6/7} M_{15}^{-3/7} m^{-5/7},$$  

(6)

which obtains when the star’s rotation rate equals the Keplerian rotation rate of ambient matter at the Alfvén radius; that is, when the corotation radius $r_c = (GM)^{1/2} \Omega^{-2/3}$ becomes equal to $r_A$. In the propeller phase the source settles to an asymptotic spin-down toward the equilibrium. A source is most likely to be observed during its asymptotic phase. Since in the asymptotic regime $r_c$ is close to $r_A$, we can estimate the magnetic moment of a propeller from its spin-down rate and rotation rate, without knowing its mass inflow rate, simply by substituting $r_c$ in equation (4). This leads to

$$\mu = \frac{(I |\dot{\Omega}| GM)^{1/2}}{\Omega}.$$  

(7)

We take the DTN RX J0720.4 $-$ 3125, with $P = 8.4$ s, $L_X = 2.6 \times 10^{31}$ (D/100 pc)$^2$ ergs s$^{-1}$ as our typical example (Haberl et al. 1997). The other DTN with a reported rotation period, RX J0420.0 $-$ 5022, $P = 22.7$ s, $L_X = 2.7 \times 10^{30}$ (D/100 pc)$^2$ ergs s$^{-1}$ (Haberl et al. 1999), yields similar results. For RX J0720.4 $-$ 3125 we obtain $\mu_{30} \sim 0.79$ $-$ 7.9 using the bounds on the spin-down rate, equation (2), with the luminosity corresponding to a nominal distance of 100 pc. Thus, if RX J0720.4 $-$ 3125 is a propeller, it has a conventional magnetic field,

$$7.9 \times 10^{11} \, G < B < 7.9 \times 10^{12} \, G.$$  

(8)

Using equation (6) and setting the equilibrium period to be equal to the observed period, we can now obtain bounds on the mass inflow rates:

$$M_{15} = (16.8 \, s/P)^{7/3}(\mu_{30})^{2} m^{-5/3}.$$  

(9)

This yields $M_{15} \sim 3.15$ $-$ 315 for the mass inflow rate for RX J0720.4 $-$ 3125. These are rough order-of-magnitude estimates based on the approximation that the present periods of these sources can be taken to be equal to the equilibrium periods. The parameters given in Table 1 are based on the simple model of the asymptotic spin-down presented in § 4.

For most DTNs and for all RQNSs, which, as we propose below, are also propeller candidates, we do not have observed rotation periods. For these sources, setting the rotation period to be less than the equilibrium period,

$$M_{15} < \mu_{30}^{1/3} |\dot{\Omega}|^{1/6} m^{-1/2} I_{15}^{1/6},$$  

(10)

from equations (6) and (7). With the range of $|\dot{\Omega}|$ obtained from DTN luminosities (eq. [3]), $M_{15} \sim (0.1$ $-$ 200) is obtained for these DTNs for $\mu_{30} = 1$.

If the source of mass inflow is not depleted, the propeller phase is followed by an accretion phase starting at some critical period. The neutron star will continue to spin down, now as an accreting source, as its period evolves from the critical period toward the equilibrium period. Similarity of the rotation periods of the AXPs with the $8.4$ s period of the DTN RX J0720.4 $-$ 3125 suggests that the approach to rotational equilibrium is an asymptotic process extending through the propeller phase on to the accretion phase. These sources are asymptotically close to their individual equilibrium rotation periods, which lie in a narrow range determined by their magnetic moments and mass inflow histories.

The mass accretion rates inferred from the X-ray luminosities of the AXPs and SGRs all fall in the range $M_{15} \sim 1$ $-$ 100. The corresponding magnetic moments for accreting sources near rotational equilibrium are in the $10^{12}$ G range given the 5 $-$ 15 s rotation periods:

$$\mu_{30} = (P_{eq}/16.8 \, s)^{7/6} M_{15}^{1/2} m^{5/6}.$$  

(11)

To summarize: (a) The spin-down rates inferred for the DTN sources through the interpretation of their luminosities as due to energy dissipation (eqs. [1]$-$[3]) agree with the observed spin-down rates for the AXPs and SGRs to order of magnitude. (b) Estimates of the magnetic moment, from the spin-down rates for the DTNs as propellers close to rotational equilibrium, coincide in the same range as the magnetic moments inferred from the mass accretion rates implied by the X-ray luminosities of AXPs and SGRs as accretors asymptotically close to rotational equilibrium. This is the conventional $10^{12}$ G range of most young neutron stars observed as rotation-powered pulsars and in high-mass X-ray binaries. (c) Furthermore, the mass inflow rates inferred for the DTNs from the assumption that they are close to rotational equilibrium are similar to the accretion rates of the AXPs and SGRs.

These estimates are independent, as point a derives from the bounds in equation (2), point b from equations (4) and (7), and point c from equation (9). As estimates within the
simple model with constant $\dot{M}$, they strongly support the hypothesis that the sources are instances of asymptotic spin-down near similar equilibrium periods. Beyond the similarities, differences between the classes should naturally be present, most likely reflecting different initial conditions and time histories regarding $\dot{M}(t)$.

4. THE ASYMPTOTIC SPIN-DOWN REGIME

We now turn to a simple model for the asymptotic spin-down. A neutron star in the presence of inflowing matter experiences both spin-down and spin-up torques. The long-term evolution is determined by the balance between these, described by a function (Ghosh & Lamb 1991) that goes through zero when $\Omega$ where is described by a function (Ghosh & Lamb 1991) that goes through zero when $\Omega = \omega_c/\Omega_{eq}$, where $\omega_c$ is of order 1, and $\Omega_{eq} = 2\pi/P_{eq}$. In accretion from a disk, the relative specific angular momentum brought in by the accreting material to spin the neutron star up is $[(GM_r)^{1/2} - \Omega r_s^2]$. Since the dimensional torque is $\mu^2/r_s^2 \sim M(GM_r)^{1/2}$, spin-down near equilibrium can be modeled as

$$\dot{\Omega} = \left(\mu^2/r_s^2\right)(1 - \Omega/\Omega_{eq}) = \left(\Omega_{eq} - \Omega/\tau\right), \quad (12)$$

where $\tau = \Omega_{eq} r_s/\mu^2$. Here the zero of the torque (the end of the spin-down era) is taken to be at $\Omega = \Omega_{eq}$ rather than $\omega_c/\Omega_{eq}$, for simplicity.

The existence of an equilibrium period and asymptotic evolution toward the equilibrium period is supported broadly by the properties of X-ray binaries. Sources with periods $P > P_{eq}$ can accrete from disks and spin-up (in a time-averaged sense) during accretion. The opposite regime of fast rotating sources in the propeller phase has not been invoked except for quiet episodes of transient sources, whose periods are consistent with being close to equilibrium periods. At periods much shorter than $P_{eq}$, accretion is not possible and the source is spun down by “propeller” torques from the disk. The prevalence of a common range of periods in both the DTNs, which are in the propeller phase, and in the AXPs, which are accreting sources, suggests that this period range is typical of an extended asymptotic spin-down regime encompassing both the propeller and the accretion phases. Thus, accretion starts at a transition period somewhat shorter than but close to the equilibrium period $P_{acc} < P_{eq}$ ($\Omega_{acc} > \Omega_{eq}$). The torques are continuous functions of the neutron star period at this transition to accretion, and the same spin-down equation, the simple model of equation (12), applies as the source starts to accrete. The luminosity of the AXPs, an accretion luminosity, is much larger than the dissipation luminosities of the DTNs, which are propellers, but both kinds of sources follow the same asymptotic spin-down.

This simple model has certain limitations. Accreting sources exhibit strong fluctuations in torque. Furthermore, if the accretion luminosity is proportional to the mass accretion rate, then the dimensional torque in equation (12) together with equation (5) predict that $|\dot{\Omega}| \sim L_s^{5/2}$, which is not observed to be the case in general. Electromagnetic torques between the disk and the neutron star play an important role. All significant torques are of comparable magnitudes near equilibrium, given by the magnitude of the dimensional accretion torque $\mu^2/r_s^2 \sim M(GM_r)^{1/2}$. The real torques could lead to initial power-law decays of $\Omega$ as a function of time. Whatever the form of the initial spin-down may be, once the rotation rate is close to the equilibrium value, the factor $(\Omega_{eq} - \Omega)$ dominates the asymptotic evolution, which becomes an exponential decay. The simple qualitative model of equation (12) describes the linearized secular dynamics in the asymptotic regime, close enough to equilibrium, provided that the total torque is some analytic function of the star’s rotation rate. We employ equation (12) to make simple estimates as detailed below. The relaxation times $\tau$ given in Table 1 are on the order of the age estimates of the SNRs likely to be associated with AXPs, but the estimates are much smaller than the ages of $\sim 10^6$ yr we estimate for the DTNs on the basis of their statistics. The relaxation time $\tau$ is not an indicator of age but only a parameter of the simple model. The different classes of neutron stars like the DTNs and AXPs may have very different ages, as we discuss in the next section.

While the simple model assumes that the mass inflow rate is a constant for each source, fluctuations or secular changes in $M$ will constantly reset the value of the equilibrium period and prolong the asymptotic spin-down regime, as long as the fluctuating $P_{eq}$ remains greater than $P$. When $P$ eventually falls within the range of fluctuations of both signs in $P_{eq}$, this would lead to spin-up as well as spin-down episodes. The AXPs and SGRs are observed to be constantly spinning down. A decaying $M$ leads to a natural explanation for the prevalence of spin-down in an accreting source: the equilibrium period increases as $M$ decreases, and the source will be spinning down as its period tracks the equilibrium period (Ghosh et al. 1997; Chatterjee et al. 2000), answering the criticism of accretion models raised by Li (1999). Chatterjee et al. (2000) have employed an $M$ decaying as a power law in time, corresponding to the viscous evolution of a thin disk ( Mineshige et al. 1993; Canizzo, Lee, & Goodman 1990). Such decay is expected in the case of a remnant disk around the neutron star, left over from the core collapse of the supernova. The duration of the asymptotic phase is then determined by the finite lifetime of the disk. The actual situation warrants taking into account propeller boundary conditions. The propeller activity could support a thick disk or corona. It would also lead to a different characteristic time dependence of $\dot{M}$.

Let us now employ the simple asymptotic model of equation (12) with these caveats in mind. The mass inflow history of each source is represented by a constant mass inflow rate. We use this approach to make a simple comparison and classification of the possible outcomes for young neutron stars under mass inflow from the finite reservoir of a remnant disk. The disk mass and mass inflow rate actually decay as a function of time. If the representative constant mass inflow rate we employ is high, this corresponds to younger systems and/or higher initial mass inflow conditions. The results are given in Table 1 and Figure 1. With constant $\mu$ and $r_s$, the spin-down leads $\Omega$ toward $\Omega_{eq}$:

$$\Omega(t) = [\Omega(0) - \Omega_{eq}] \exp (-t/\tau) + \Omega_{eq}, \quad (13)$$

This solution is to describe the spin-down through both the propeller and the accretion phases in the asymptotic regime, with mass accretion starting at some $\Omega_{acc} > \Omega_{eq}$. Here $\Omega(0)$ denotes the rotation rate at the beginning of the asymptotic phase, and $t$ is the time spent in the asymptotic phase. Without assumptions on the initial conditions and evolution before the asymptotic regime is reached, it is not possible to derive the true age from the asymptotic model, or the duration of the asymptotic phase itself, since $\dot{M}$ is not a constant in reality. We use this simple model to make esti-
mates of $\Omega_{\text{eq}}$ and the magnetic moment $\mu$. From equations (5), (6), and (12) we obtain

$$\tau = 1.3 \times 10^{12} \ s I_{45}^2 M_{15}^{-1} m^{-2/3} \Omega_{\text{eq}}^{4/3}. \quad (14)$$

Substituting the expression for $\tau$ in the spin-down equation (12), $\Omega_{\text{eq}}$ can be obtained for each source with known $\Omega$ and $\Omega$ by solving

$$\Omega_{\text{eq}} = \Omega + 1.3 \times 10^{12} \ s I_{45}^2 M_{15}^{-1} m^{-2/3} \Omega_{\text{eq}}^{4/3}. \quad (15)$$

Once the equilibrium rotation rate is estimated, the magnetic moment $\mu$ can be obtained from equation (11).

Sample solutions are given in Table 1 for the AXPs, the SGRs with measured $P$ and $P$, and for the DTNs with measured periods. The AXPs show changes in spin-down rate, by up to an order of magnitude, on timescales of several years. Long-term average values of the spin-down rate are used, as appropriate for the model to describe the long-term average trend. Mass inflow rates are inferred from the observed luminosities taken as accretion luminosities onto neutron stars, $M_{\text{acc}} = RL/GM$. The luminosity has been observed to change by as much as a factor of 15 in AXPs (Torii et al. 1998). Furthermore, since the mass inflow rate from a remnant disk will be decreasing as a function of time, the constant representative $M$ appropriate for our simple model should be larger than the present time $M_{\text{acc}}$ inferred from the accretion luminosity. For 1E 1048.1$-$5937, the current $M_{\text{acc}}$ leads to $P_{\text{eq}} = 64$ s, while for 1E 2259$+$586 the current $M_{\text{acc}}$ gives a relaxation time $\tau$ that may be larger than the age of the associated SNR. For these two sources, taking examples of mass inflow rates $P > M_{\text{acc}}$, one can obtain solutions in agreement with the asymptotic model.

Three out of six AXPs provide direct evidence of youth through their likely supernova associations. These AXPs are situated close to the centers of the SNRs. The associations with SNRs are not as certain for the SGRs. The SGRs are at edges of the SNRs, requiring velocities $\sim 1000$ km s$^{-1}$ if they were born at the center (for a recent discussion of the SNR associations of the AXPs and SGRs, and references to the individual associations, see Gaensler 2000).

5. THE FALLBACK MASS INFLOW AND THE SIGNATURE OF THE NEUTRON STAR BORN IN A SUPERNOVA

Does the narrow range of observed rotation periods indicate a very restricted range of $M$? The range of estimates for the sources in Table 1 extends from $10^{13}$ to $10^{15}$ g s$^{-1}$. To estimate the parameter range corresponding to the narrow range of equilibrium periods, we note that the magnetic moment and mass inflow rate are independent parameters. Using equation (9) for magnetic moments in the range from $5 \times 10^{11}$ to $5 \times 10^{12}$ G, the range of mass inflow or accretion rates that would lead to equilibrium periods of 5--15 s extends over 3 orders of magnitude, up to about half the Eddington rate:

$$3.2 \times 10^{14} \text{ g s}^{-1} < \dot{M} < 4.2 \times 10^{17} \text{ g s}^{-1}. \quad (16)$$

This is not a very restricted range. Figure 1 shows the mass inflow rate as a function of the equilibrium period for $0.5 < \mu_{\text{eq}} < 5$. Also shown are the model solutions for equilibrium periods and mass inflow rates for all the sources presented in Table 1. The narrow range of observed periods lies between the vertical lines. We note that the narrow range of observed and equilibrium periods corresponds to a rather wide range of $M$, extending over more than 2 orders of magnitude. Sample solutions for different sources are scattered in $M$ and $\mu$, as they should be, since the magnetic moments of neutron stars are probably not correlated with the mass inflow from their environments. This scatter suggests that the model does not require an artificial correlation between these parameters. The values of $\mu$ and $M$ can be checked for the likelihood of such imposed correlations. Since the combination $B^2 / M$ determines $P_{\text{eq}}$, we look for correlations between the values of $B^2$ and $M$ in Table 1 by performing t-tests on correlation coefficients of $B^2$ versus $M$. The AXP AX J1845$-$0258 is excluded, as in the absence of a measured $P$ we have arbitrarily assumed $B = 10^{13}$ G for this source (its inclusion does not effect the conclusions). For the five AXPs the likelihood that the tabulated $B^2$- and $M$-values are drawn from an uncorrelated random population is more than 5%. For the five AXPs together with the two DTNs in Table 1 there is more than 10% likelihood that the sample is drawn from a population with randomly associated $B^2$- and $M$-values. For both these cases the hypothesis that the underlying neutron star populations have randomly associated $B^2$- and $M$-values (within the ranges quoted above) can be sustained. When the two SGRs are added to the AXPs and DTNs, much larger correlation coefficients are obtained. The likelihood that the AXP, DTN, and SGR sample in Table 1 comes from a random population is very small. The correlations appear to be real. But this is an artifact arising because the SGR 1806$-$20 has $M_{15} = 100$ in the model solution. On the scale of a scatter plot that includes the point $(M_{15} = 100, B_{12} = 7.9)$, the points for all the AXPs and DTNs appear clustered together, as a result of their small $M_{15}$-values. This cluster is effectively a point; together with the point for SGR 1806$-$20, we have effectively a two-point graph, which, of course, yields a very high spurious correlation coefficient. When the RQNS in Cas A is also included in the sample, with its even larger $M_{15}$ scale, the scatter plot effectively contains three points, one point representing the cluster of points for AXPs and DTNs, one point for SGR 1806$-$20,
and one point for the Cas A source. This case also appears to reflect a random population, but coming from an effectively three-point scatter plot, this conclusion is not reliable.

In short, the AXPs and DTNs appear to be compatible with a random association of \( B^2 \)- and \( M \)-values, while to decide on the compatibility of the whole sample with the hypothesis of random \( B^2 \)- and \( M \)-values, more examples of SGRs and RQNSs are needed.

The mass inflow rates we obtain are all above \( \sim 10^{14} \) g s\(^{-1} \). This may mean that for lower average \( M \) the propeller phase never starts, and the neutron star continues life as a radio pulsar. At the other extreme, extended exposure to the highest mass inflow rates may lead to accumulation of enough circumstellar material such that the optical thickness to electron scattering washes away any beaming of the X-rays from the neutron star, and the rotation period is not detected (Lamb et al. 1985; Ghosh et al. 1997).

If all supernovae left neutron stars that went through an AXP phase under mass inflow from the debris, then we would expect at least 100 such objects for a lifetime of greater than \( 10^4 \) yr and galactic supernova rate of \( 10^{-2} \), since the AXPs would be observable from all galactic distances. That we observe only a few indicates that such sources rarely reach the accretion phase.

The number of DTNs must be much larger since we see several within a distance on the order of 100 pc. In the Galaxy we would expect about \( 10^4 \) DTNs, and a lifetime on the order of \( 10^6 \) yr or longer, for a birthrate of \( 10^{-2} \) \( \) yr\(^{-1} \) or lower. The much smaller number of the AXPs may be due to the depletion of the supply of mass inflow in most sources by the end of the propeller phase. If the mass inflow is depleted before the end of the propeller phase, subsequent accretion phases never occur. This may be the reason why the numbers of AXPs and SGRs are much less than the number of DTNs. The rare AXPs and SGRs are thus the young objects born with conventional magnetic fields but in circumstances of large enough mass inflow toward the neutron star so that the timescales of the asymptotic spin-down, which scale with \( M^{-1} \), are short compared to the lifetime of the mass supply. These are the rare sources that have gone through the propeller phase rapidly, to start accretion before the matter supply is depleted. The more common source is the DTN, in a propeller phase of duration \( 10^4 \) yr, surviving the disappearance of the SNR. While it is reasonable to expect that the lifetime of the mass supply increases at the lower mass inflow rates, one needs a model of the disk evolution to make a quantitative comparison with the propeller spin-down. If DTNs are born at a rate comparable to the total supernova rate, then a significant fraction of SNRs must leave the neutron star under conditions of low enough \( M \).

Are the AXPs descendants of DTNs? The SNR associations of some AXPs rule this out since the statistics of the DTNs imply ages on the order of \( 10^8 \) yr, and the total age after consecutive DTN and AXP phases would then far exceed the SNR age. The conclusion is that DTNs and AXPs result from mutually exclusive initial conditions and mass inflow histories. AXPs probably started with initial \( M \) much larger than the current \( M \) and evolved promptly through the propeller into the accretor phase, while DTNs never had large \( M \) and have experienced a prolonged propeller phase.

The SGRs are like the AXPs in their X-ray properties. Both classes of sources are detectable throughout the Galaxy, and their comparable numbers suggest the SGRs are also in the same rare or relatively short beginning accretor phase as the AXPs.

For the SGRs the magnetar hypothesis is on a strong footing, in that it provides the energy store and a detailed dynamical model for the soft gamma-ray bursts (Thompson & Duncan 1995). While the present work does not address the mechanisms of the gamma-ray burst phenomenon, it is nevertheless intriguing that, as Wang & Robertson (1985) have noted, propellers (and probably their descendants, the early accretors) can support relativistic particle luminosities and gamma-ray production in the surrounding accumulated matter. The energy source could be sporadic accretion of accumulated circumstellar mass released through instabilities. The remnant disk scenarios were first recalled in connection with the problem of planet formation around pulsars (Lin et al. 1991), and disk instabilities involving planet-like masses (Mineshige et al. 1993) or colliding planet scenarios (Katz, Toole, & Unruh 1994) are consistent with the luminosities of the SGRs. It may not be unreasonable to speculate that SGRs are also a class of neutron stars surrounded with mass inflow, with disk and magnetic field instabilities, and to ask whether magnetar fields can be accommodated in a variant of this scenario. While accretion/propeller scenarios attempting to cover DTNs, AXPs, and SGRs face the question why only the SGRs show gamma-ray bursts, the proposal that DTNs, AXPs, and SGRs are all magnetars must face the question why the AXPs and DTNs do not show gamma-ray bursts.

Why is it that the AXPs are observed as pulsars while the low-mass X-ray binaries (LMXBs) are not? The important exceptions are 4U 1626−67 and the millisecond X-ray pulsar XTE J1808−369. The explanation for the rarity of LMXB pulsars has been that Comptonization by circumstellar material will destroy pulses by washing out the beams emerging from the neutron star if the material is optically thick to electron scattering (Lamb et al. 1985). This was noted in connection with the AXPs by Ghosh et al. (1997). The present picture is consistent with this: the AXPs are observed as pulsars because they are in the beginning stages of accretion, and the corona around them does not have significant optical thickness \( \tau_{es} > 1 \) to destroy the beaming. Work in progress to test this hypothesis by modeling the AXP spectra as unsaturated Comptonization and estimating the optical thicknesses will be reported separately.

The RQNSs found in centers of the SNRs Cas A, Puppis A, RCW 103, and 296.5+10 (Chakrabarty et al. 2001; McLaughlin et al. 2001; Gaensler, Bock, & Stappers 2000; Petre, Becker, & Winkler 1996; Gotthelf, Petre, & Hwang 1997; Gotthelf, Petre, & Vasish 1999; Merheghetti, Bignami, & Caraveo 1996; Vasish et al. 1997) may be the propeller sources for which the cumulative effect of the mass inflow has indeed set up a corona of \( \tau_{es} > 1 \) around the neutron star. The source properties are very similar. Variability of the flux (Gotthelf et al. 1999) favors accretion or propeller-driven energy dissipation rather than the cooling luminosity of an isolated neutron star. The low luminosities, \( L_X \sim 10^{32}−10^{34} \) ergs s\(^{-1} \), suggest that these sources are in the propeller phase. Accretion would imply \( M \sim 10^{13}−10^{14} \) g s\(^{-1} \), which can accrete onto the neutron star only if the rotation period is longer than 50 s (eq. [6]) for \( B \sim 10^{12} \) G. But then at these low accretion rates we should see pulses at the rotation period. Blackbody effective areas of 1 km\(^2\) also...
enhance the expectation of coherent pulsations at the rotation period from these sources, while upper limits to the pulsed fraction of 13% and 35% have been obtained for the RQNSs in RCW103 and Cas A, respectively (Gotthelf et al. 1999; Chakrabarty et al. 2001). Taking the RQNSs to be propeller sources with $L_X = \dot{E}_{\text{diss}}$, as we did for the DTNs, leads to $|\Omega| \sim 10^{-10}$ to $10^{-8}$ rad s$^{-2}$. Since the rotation periods of the RQNSs are not known, we use equation (10) as an equality with $B \sim 10^{12}$ G and obtain

$$M > 2 \times 10^{17} \text{ g s}^{-1}. \quad (17)$$

For the RQNSs the mass inflow rates are indeed higher than those inferred for the DTNs and AXPs, consistent with the proposal that the RQNSs are the high-$M$ end of our spectrum of neutron stars under mass inflow from remnant disks. Model parameters for the RQNSs in Cas A are displayed in Table 1. The luminosity is typical of the RQNSs. For a propeller with luminosity arising from energy dissipation, taking $|\Omega| > 3 \times 10^{-10}$ rad s$^{-2}$ with $\mu_{30} = 1$, and one obtains $M > 7.4 \times 10^{-17}$ g s$^{-1}$, in agreement with the interpretation here; $P_{\text{eq}} < 1$ s, corresponding to the high-mass inflow rate. The unobserved periods of the RQNSs are smaller than the observed range of periods of the AXPs and DTNs. The RQNSs are the youngest sources in our classification except for the young radio pulsars. They may be the predecessors of AXPs. The RQNS in PKS 1209–52 has a pulse period of 0.4 s (Zavlin et al. 2000), similar to the equilibrium period of 1 s that we have inferred for the RQNS in Cas A. With the pulsed fraction upper limit of 35%, the Cas A source may yet prove to be an X-ray pulsar. Alternatively, the high $M$ may have already accumulated a circumstellar corona of enough optical thickness to electron scattering to destroy the pulsar’s beaming.

6. LUMINOSITY OF THE DISK

For both the DTNs and the AXPs there will be another source of energy dissipation in the disk or circumstellar material, owing to accretion down to $r_A$:

$$L(r_A) = (3/2)GM \dot{M}/r_A \sim 3/(2GM)^{2/3} \Omega^{2/3} \dot{M} \sim 1.3 \times 10^{33} \text{ erg s}^{-1} \dot{M}_{15} \dot{m}^{2/3} P^{-2/3}. \quad (18)$$

Near rotational equilibrium, $L(r_A) = I \Omega \dot{\Omega}$, the power expended on the star by the spin-down torque. For the AXPs this luminosity is smaller than the accretion luminosity by a factor

$$L(r_A)/L \sim 3/2R/r_A(M/M_{\text{acc}}) \sim 10^{-2}(M/M_{\text{acc}}) m^{-1/3} P^{-2/3}, \quad (19)$$

noting that the mass inflow may not be all accreted even in the AXPs. For the DTNs $L(r_A)$ is actually larger than the observed luminosity $\dot{E}_{\text{diss}}$ by a factor

$$L(r_A)/\dot{E}_{\text{diss}} \sim (\Omega/|\Omega|)^{2}(I_0 \omega/|\Omega|) \sim 10^{-2} \Omega^{-4} \Omega. \quad (20)$$

If this luminosity is dissipated entirely at the boundary region, $r \sim r_A$, the effective temperature is

$$T(r_A) = [L(r_A)/4\pi r_A^2 \sigma]^{1/4} \sim 9.5 \times 10^4 \text{ K} \dot{M}_{15}^{1/4} P^{-1/2}. \quad (21)$$

If the disk temperature lies in the extreme ultraviolet range, this would be extremely difficult to detect, but being nearby sources, DTNs with low neutral hydrogen column density might provide a chance of looking for a disk luminosity as a test of the present model.

For the thin-disk model employed by Chatterjee et al. (2000), calculations of the expected disk spectrum and luminosity extending to the optical, infrared (IR), and submillimeter are reported by Perna, Hernquist, & Narayan (2000). Radiation in the optical and IR is contributed by inner parts of the disk. These authors noted that observational upper limits in the IR and optical for the AXP 1E 2259+58.6 (Coe & Pfighting 1998; Hulleman et al. 2000b) pose a problem for thin-disk models but that these upper limits can be satisfied if the disk inner radius is large enough, $\sim 10 r_A$, as in advection-dominated accretion flow models. In that case there would still be an excess in the longer wavelengths that are contributed by the outer disk. Recent observations (Hulleman, van Kerkwijk, & Kulkarni 2000a) on another AXP, 4U 0142+61, actually detected the source in the $I, R,$ and $V$ bands. The reddened flux values were found to be lower than the thin-disk prediction incorporating irradiation (Vrtilek et al. 1990; Perna & Hernquist 2000) as well as viscous dissipation. Reducing the disk luminosity by increasing the inner radius does not work because the resulting “red” excess at longer wavelengths is incompatible with the data for 4U 0142+61 (Hulleman et al. 2000a). An alternative means of reducing disk luminosity that would be in agreement with the 4U 0142+61 data would be to reduce the outer radius; Hulleman et al. (2000a) note that such a disk would fit in a tight binary like 4U 1820–30 (Stella, White, & Priedhorsky 1987), but neither the spectrum of 4U 0142+61, nor its association with an SNR agree with the spectrum or age of an LMXB like 4U 1820–30. For remnant thin disks to satisfy even the upper limits of Hulleman et al. (2000b) for 1E 2259+58.6, thin disks with disk outer radii less than $10^{10}$ cm are required. Such a limited extent indicates a very young age, $t < 100$ yr, in terms of the viscous evolution of the isolated thin disks employed by Chatterjee et al. (2000), as can be seen by using the time-dependent self-similar solutions of Mineshige et al. (1993).

Also recently, Kaplan, Kulkarni, & Murray (2001) have set 3σ upper limits in the near-IR for a counterpart to the RQNS in Cas A. They point out that scaling from the observed X-ray flux of this source with the assumption that the ratio of X-ray-to-R-band fluxes is the same as in 4U 0142+61, the expected values of $R$ and other optical and IR fluxes lie well below their observational upper limits for the RQNSs in Cas A. Applying the same scaling to the disk curve employed for 4U 0142+61 by Hulleman et al. (2000a) in their Figure 3, I find fluxes in the $(1-4) \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ range at optical and IR frequencies for the Cas A source, which are just compatible with the upper limits except for the K band.

Taking all the evidence together, thin-disk models fail to explain current observational results in terms of remnant disks. However, it is not necessarily true that the remnant disks are such thin disks. Several considerations suggest that remnant disks may have a quite different structure. The propeller effect might well lead to boundary conditions that alter the disk evolution. The work done on the inflowing material by the propeller, at the rate $\Omega \dot{\Omega}$, may lift and sustain the material at distances much larger than $r_A$. The emerging radiation may have a lower effective temperature from a larger effective area. The remnant disk may be a thick disk, or it may be enshrouded in a Comptonizing
corona, as we invoked above. As concluded by Mereghetti (2001b) in a recent review, “Unfortunately, detailed estimates of the expected optical brightness from disks around isolated neutron stars are very uncertain and depend on several factors, like the disk inclination, dimensions, amount of X-ray reprocessing, etc...” (Perna et al. 2000). It seems therefore premature to draw firm conclusions on the basis of the single case of 4U 0142+61. The search for the optical counterparts of other AXPs is complicated by the large reddening and by the fact that their error boxes are not small enough to search for counterparts at such faint magnitude levels (see, e.g., the case of 1E 1841−045; Mereghetti et al. 2001). In this respect, more accurate positions for the AXPs are expected from the ongoing program of observations with the Chandra and XMM-Newton satellites, which will also provide high-quality spectral information, possibly allowing to discriminate between different X-ray emission mechanisms.”

There is a comparable uncertainty and a lack of detailed models concerning the predictions of magnetar models for the optical emission to be explained in terms of the magnetospherical activity of a magnetar, as Hullemann et al. (2000a) remark when they turn to the magnetar model by elimination of disk accretion models. Modeling of remnant disks and circumstellar material with propeller boundary conditions, and of the magnetospheric emission from magnetars, to be compared with current and future observations on the spectra of DTNs, AXPs, and RQNSs will help to resolve these issues.

Finally, we note that a fallback disk applying propeller torques has been proposed as the explanation for the discrepancy between characteristic and actual ages of the radio pulsar B1757-24 (Marsden, Lingenfelter, & Rothschild 2001a).

7. DISCUSSION AND CONCLUSIONS

A unified picture is proposed to account for all neutron stars formed in supernovae and to include RQNSs, DTNs, and AXPs, and perhaps SGRs. The salient features of this picture are as follows:

1. The signature of a young neutron star depends on the presence and nature of the mass inflow of fallback material from the supernova explosion. The related classes of sources represent different pathways under different mass inflow rates and histories.

2. Neutron stars are born with ~ 10^{12} G fields. We take the currently observed distribution of dipole fields of young neutron stars and posit that all new classes of neutron stars, except possibly the SGRs, can be explained by the same range of fields.

3. Radio pulsars are formed if there is no mass inflow or not enough to protrude the light cylinder. Higher mass inflow rates do not allow radio pulsar activity, leading instead to DTNs, AXPs, and RQNSs.

4. The similarity in the rotation periods of these sources is not a coincidence but rather a consequence of the asymptotic approach to rotational equilibrium under a wide range of mass inflow rates.

5. With low M the spin-down is too slow for the source to go through the propeller stage and reach the accretion stage before the circumstellar mass is depleted. These sources, observed as DTNs, are propellers for as long as 10^{5}–10^{6} yr and make up the most numerous class.

6. The DTNs are the first observed examples of neutron stars in the propeller phase.

7. A nonaccreting neutron star under propeller spin-down has a luminosity provided by energy dissipation inside the star.

8. The observability of the rotation period in the AXPs but not in the LMXBs can be explained qualitatively in terms of Comptonization as supported by an interpretation of their spectra. The RQNSs are the young neutron stars for which Comptonization washes out beaming so that the rotation period is not observable.

Arguments that AXPs and DTNs are magnetars are based on the grounds that isolated neutron stars with ordinary 10^{12} G fields cannot have spun down to ~ 10 s periods within the estimated ages. The present model obviates the need to postulate magnetars for AXPs and DTNs. For the SGRs the required energy budgets and dynamical arguments make a strong case for the magnetar hypothesis. Whether the large spin-down rates observed are due to spin-down by interaction with ambient matter, as proposed here as well as by Chatterjee et al. (2000), or to spin-down by a magnetar can be decided by detailed analysis of the fluctuations (noise) in the spin-down process, as the timing noise characteristic of accretion-powered neutron stars is quite distinguishable from the timing noise in the typically much quieter isolated rotation-powered pulsars. (The SNR-ISM connection suggested by Marsden et al. 2001b does not point at a dynamical signature of the neutron star.)

The timing analysis will require frequently sampled observations of the AXPs and SGRs. The recently reported extended quiet spin-down phases in 1E 2259+586 and 1RXS J170849.0−400910 (Kaspi, Chakrabarty, & Steinberger 1999) is not sufficient to conclude that these sources are undergoing spin-down under magnetic dipole radiation since the quiet spin-down phase was preceded by episodes of higher spin-down rates with large timing noise strengths (Baykal & Swank 1996; Baykal et al. 2000). Whether such changes in the torque repeat periodically as foreseen for a precessing magnetar (Melatos 1999) remains to be checked in future timing observations. A well-known accreting source, the LMXB 4U 1626−67, has exhibited similar quiet episodes as well as intervals of strong timing fluctuations that are typical of accreting sources (Chakrabarty et al. 1997). It is encouraging from the unified point of view of this work that during the quiet spin-down epoch that would allow the detection of glitches, 1RXS J170849.0−400910 has indeed exhibited a glitch that is very similar to the glitches of the Vela pulsar and other radio pulsars (Kaspi, Lackey, & Chakrabarty 2000). If the AXPs are confirmed as accreting sources, the glitch from 1RXS J170849.0−400910 will constitute strong support for our starting hypothesis that all neutron stars have the same internal dynamics and the associated energy dissipation rates. Observation of a spin-down rate in the expected range from RX J0720.4−3125 or periods and spin-down rates from other DTNs would constitute strong evidence for the propeller hypothesis.

The framework proposed here categorizes all young neutron stars in terms of the mass inflow from a remnant disk with neutron star magnetic fields in the conventional 10^{12} G range. Here we have presented the framework in broad outlines with a simplified asymptotic model, together
with interpretations of the various classes of neutron star on the basis of our hypothesis. This leads to a program of related issues to be followed up. These include models of the disk and circumstellar material, the emerging spectrum and pulse content, the time evolution of the mass inflow, and the resulting spin-down.

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