Isolated thermal neutron stars, soft gamma-ray repeaters and anomalous X-ray pulsars: propellers and early accretors with conventional magnetic fields?

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The similarity of rotation periods from three interesting classes of neutron stars, 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 spindown phase, extending through the propeller and early accretion stages. The DTNs are interpreted as sources in the propeller stage. Their low luminosities arise from frictional heating in the neutron star. SGRs and AXPs are accreting at $\dot{M} \sim 10^{15} \text{gm/s}$. The limited range of near equilibrium periods corresponds to a limited range of mass inflow rates $\dot{M}$. For lower rates the source of mass inflow may be depleted before the asymptotic stage is reached, while sources with higher $\dot{M}$ or later ages possess circumstellar material that is optically thick to electron scattering, destroying the X-ray
beaming and the modulation at the rotation period. The model works with conventional magnetic fields of $10^{11}-10^{12}$ G, obviating the need to postulate magnetars. Frequently sampled timing observations of AXPs, SGRs and DTNs can distinguish between this explanation and the magnetar model.
Anomalous x-ray pulsars (AXPs)\(^1\)–\(^{16}\) are characterized by periods in the range 6-12 secs. RXJ0720.4-3125, one of the two (or a few) dim nearby ROSAT point sources thought to be thermally emitting neutron stars\(^{17}–^{23}\), has a measured period\(^{19}\) of 8.4 s, while two of the four confirmed soft gamma ray repeaters (SGRs) also have periods in the AXP period range, with \(P = 7.47\)s for SGR 1806-20 and \(P = 5.16\) s for SGR 1900+14\(^{24}–^{29}\). For the AXPs it was pointed out\(^1,2\) that the similar periods would obtain as equilibrium periods for accretion rates \(\dot{M} \sim 10^{15}\)gm/s corresponding to the luminosities and \(10^{11}\)–\(10^{12}\) G magnetic fields. The limited range of \(\dot{M}\) then needs to be explained\(^3\). \(\dot{P}\) values 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\(^{29}–^{33}\), neutron stars with very strong magnetic fields \(B \sim 10^{14}\) G spinning down through magnetic dipole radiation. The short cooling age estimated for RXJ0720.4-3125 has also been suggested\(^{34}\) as evidence for a magnetar if the source is an isolated pulsar born with a short rotation period. We propose here an explanation for all three classes of neutron stars with conventional \(10^{12}\) G magnetic fields and rotation periods of the order of 10 ms at birth. Presence of mass transfer at rates \(\dot{M} = 10^{15} – 10^{16}\) gm/s either from a very low mass companion\(^1\) or a remnant disk\(^2,3\) around the neutron star will produce torques on the neutron star of the order of the spindown torques observed. The SGRs and AXPs would be accreting at least part of the incoming mass flow. The similarity of the periods would simply reflect that 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 have similar periods in the asymptotic regime if they have similar magnetic fields and are subject to spindown under similar mass inflow rates.

All AXPs, SGRs and DTNs are listed in Table 1 together with measured pulse periods and \(\dot{P}\) values. The two DTNs yield fits to blackbody spectra
with temperatures of 57 eV for RXJ185635-3754 and 79 eV for RXJ0720.4-3125 and luminosities in the $L_x \sim 10^{31-32}$ erg s$^{-1}$ range$^{17-21}$. A few further candidates for this class, which recently emerged from ROSAT surveys, also have similar blackbody temperatures, flux values and limits on the ratio of X-ray flux to optical flux$^{22,23}$. Accretion from the interstellar medium would require unlikely ambient interstellar medium densities and low velocities.

The cooling of a young neutron star can typically yield the observed thermal luminosities at ages of the order of $10^5$-$10^6$ yrs$^{35-37}$. For a neutron star born with a rotation period of the order of 10 ms, (as typically inferred from the P and $\dot{P}$ values of young pulsars), to have spun down to the 8.4 s period of RXJ0720.4-3125 in $10^6$ yrs as a rotating magnetic dipole would require a mean spindown rate $\dot{\Omega}$ of the order of $10^{-14}$ rad s$^{-2}$, and a magnetic field of the order of $3 \times 10^{13}$ G or more$^{34}$. The presence of two dim thermal neutron stars within $\sim 100$ pc suggests that there are $\sim 10^4$ such sources in the galaxy, requiring ages of $\sim 10^6$ years or longer, if the birth rate is $10^{-2}$ yr$^{-1}$ or less.

**Luminosity of a non-accreting neutron star from energy dissipation**

There is an alternative source of the thermal luminosity which takes over at $\sim 10^5$-$10^6$ yrs, 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$^{38,39}$

$$\dot{E}_{diss} = I_p \omega |\dot{\Omega}|$$

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 $\omega$. $\dot{E}_{diss}$ will supply the thermal luminosity of a non-accreting neutron star at ages greater than $\sim 10^6$ years$^{40-42}$, as the cooling luminosity rapidly falls below $\dot{E}_{diss}$ after the transition from neutrino cooling to surface photon cooling. Among the radio pulsars with X-ray emission$^{35,42}$, observations$^{43,44}$ of the pulsar PSR 1929+10, whose spin-down age is $3.1 \times 10^6$ yrs, provide an
upper limit to the thermal luminosity which yields\(^{45}\) \(I_p \omega < 10^{43}\) gm cm\(^2\) rad s\(^{-1}\).

A lower limit to \(\dot{E}_{\text{diss}}\) can be obtained from the parameters of large pulsar glitches\(^{45}\). The consistency of the observed glitch parameters of all pulsars with large glitches and measured second derivatives \(\ddot{\Omega}\) of the rotation rate\(^{46}\) as well as the statistics of the large glitches\(^{47}\) support the hypothesis that large glitches are a universal feature of pulsar dynamics. The current phenomenological description\(^{45,48}\) of large glitches entails angular momentum exchange between the crust and an interior component (a pinned superfluid in current models) which 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 behaviour of all pulsars with large glitches, must be less than the lag \(\omega\). Using values of \(I_p \sim 10^{43}\) gm cm\(^2\) inferred from the detailed postglitch timing measurements available for the Vela pulsar glitches\(^{48}\) we obtain the lower bound \(I_p \omega > I_p \delta \omega = 10^{41}\) gm 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. Further, 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

\[
10^{41} |\dot{\Omega}| \text{erg s}^{-1} < L = \dot{E}_{\text{diss}} < 10^{43} |\dot{\Omega}| \text{erg s}^{-1}. \tag{2}
\]

The luminosities of RXJ0720.4-3125 and RXJ185635-3754 give

\[
|\dot{\Omega}| \sim 10^{-12} - 10^{-10}\text{rads}^{-2}. \tag{3}
\]

With the 8.4s period of RXJ0720.4-3125 these spindown rates would imply surface magnetic fields in excess of \(10^{14}\) G if magnetic dipole spindown is assumed. While there is no direct observational evidence for \(10^{14}\) G magnetic...
fields, $10^{12}$ G fields are typical of the canonical radio pulsars and of the accreting neutron stars with observed cyclotron lines.

**Propeller spindown rates**

Can high spindown rates, larger than $10^{-12}$ rad s$^{-2}$, obtain for neutron stars with conventional $10^{12}$ G fields? This can indeed be expected under the spindown torques in certain phases of accreting sources. For the AXPs this is a possibility that has already been explored$^{1-3}$ and will be pursued below. In connection with the DTNs, we note that a neutron star subject to mass inflow will experience high spindown rates even when the inflowing mass is not accreted, because of the star’s centrifugal barrier (the propeller effect)$^{49}$ and propose that RXJ 0720.4-3125 and RXJ185635-3754 are neutron stars with magnetic fields of the order of $10^{12}$ G, spinning down under propeller torques. The luminosities are produced by energy dissipation in the neutron star, for just the range of propeller spindown torques expected for the mass inflow rates indicated by the luminosities of the accreting AXPs and SGRs as mass accretion rates. A neutron star interacting with a mass inflow onto its magnetosphere will not accrete if its rotation rate is fast enough to set up an efficient centrifugal barrier to the incoming mass$^{49}$. For neutron stars born with rapid rotation rates in an ambience with mass inflow, a phase of propeller spindown should precede the start of accretion. Let us explore the possibility that the DTNs are in the propeller stage and the AXPs and SGRs in the subsequent accretion phase. Sources in the propeller phase have not been detected previously. This is understandable since they are not lit up with an accretion luminosity. RXJ 0720.4-3125 and RXJ185635-3754, if they are the first observed examples of propellers, are observed 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 spindown torque exerted on the neutron star, through the interaction of its magnetosphere with the ambient material. The order of magnitude of this spindown torque is

$$N \sim \mu^2/r_A^3$$  \hspace{1cm} (4)
where $\mu = BR^3$ is the magnetic moment of the neutron star with surface dipole magnetic field $B$ and radius $R$, and

$$r_A = 9.85 \times 10^8 cm \mu_{30}^{4/7} \dot{M}_{15}^{-2/7} m^{-1/7}$$

is the Alfvén radius$^{50,51}$. Here $\mu_{30}$ denotes the magnetic moment in units of $10^{30}$ G cm$^3$, $\dot{M}_{15}$ is the mass inflow rate in units of $10^{15}$ gm 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 is reached. This critical period is of the order of, but somewhat smaller than the equilibrium rotation period

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

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 $r_c = (GM)^{1/3} \Omega^{-2/3}$ becomes equal to $r_A$. The neutron star will continue to spin down, now as an accreting source, as its period evolves from the critical period towards the equilibrium period. Similarity of the rotation periods of the AXPs is taken to indicate their proximity to rotational equilibrium at similar equilibrium periods. The approach to rotational equilibrium is likely to be an asymptotic process extending through the propeller phase on to the accretion stage. This provides a natural explanation of the similarity of the rotation periods of all AXPs and of the rotation period of RXJ0720.4-3125. All these neutron stars could have been born with short periods, and similar magnetic moments and encounter similar ranges of mass inflow rates. Surrounding the neutron star initially there may be material from the debris of the core collapse in a supernova explosion or of a Thorne-Zytkow object already within the gravitational capture radius of the neutron star, possibly in the form of a disk$^{2,3}$. The propeller phase can also occur in the evolution of a neutron star in a binary, preceding the accretion phase. In the propeller phase the source settles to an asymptotic spindown towards the equilibrium. Accretion starts during the asymptotic spindown phase. A source is most likely to be observed during its asymptotic phase.
From Eq. (6) we obtain
\[
\mu_{30} \sim 0.45(P_{eq}/8.4 s)^{7/6} \dot{M}_{15}^{1/2} m_{15}^{5/6}
\] by normalizing \(P_{eq}\) to the 8.4 s rotation period of RXJ0720.4-3125. This estimate of the magnetic moment also applies to the DTNs as propellers and to AXPs and SGRs as accretors asymptotically close to rotational equilibrium. The similarity in periods ascribed to the asymptotic range then translates, for magnetic fields in the conventional \(10^{12}\) G range \((\mu_{30} \sim 1)\), into a restricted range of \(\dot{M} \sim 10^{15}\) gm s\(^{-1}\), so the task is to understand why a restricted range of \(\dot{M}\) prevails in the observed sources\(^3\). As accreting neutron stars the luminosities of the SGRs and AXPs indicate accretion rates in the \(10^{15}\) gm s\(^{-1}\) range. For the non-accreting DTNs \(\dot{M} \sim 10^{15}\) gm s\(^{-1}\) is the rate of mass inflow onto the propeller. This mass inflow, while not accreting, causes the neutron star to spin down. The propeller torques estimated with Eqs.(4) and (5) for conventional magnetic moments and with \(\dot{M} \sim 10^{15}\) gm s\(^{-1}\) produce the spindown rates inferred for the DTN sources through the interpretation of their luminosities as due to energy dissipation (Eqs.(1)-(3)). Observed spindown rates for the AXPs and SGRs also agree with the rough estimates using Eq.(4) to order of magnitude.

**Asymptotic spindown**

We now turn to a simple model for the asymptotic spindown. A neutron star in the presence of inflowing matter experiences both spindown and spin-up torques. The long term evolution is determined by the balance between these, described by a function \(n(\Omega/\Omega_{eq} - \omega_c)^{52,53}\) which goes through zero when \(\Omega = \omega_c \Omega_{eq}\) where \(\omega_c\) is of order one, 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 \([(GMr_A)^{1/2} - \Omega r_A]\). Since the dimensional torque is \(\mu^2/r_A^3 \sim \dot{M}(GMr_A)^{1/2}\), spindown near equilibrium can be modelled as
\[
\dot{\Omega} = (\mu^2/I r_A^3)(1 - \Omega/\Omega_{eq}) = (\Omega_{eq} - \Omega)/t_0
\] where \(t_0 = \Omega_{eq}I r_A^3/\mu^2\). 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 full torque expression throughout the neutron star’s history is probably more complicated. For example, the torque may contain a factor $(r_c/r_A)^\beta$ to describe a reduction in the early, rapid propeller phases when the star is rotating much faster than the disk and $r_c << r_A$; $\beta = 3/2$ is proposed for a supersonic propeller\textsuperscript{50}; or the magnetic moment could decay at a rate proportional to the spindown rate\textsuperscript{54}. These effects lead to initial power law decays of $\Omega$ as a function of time, but the final evolution is asymptotic. Whatever the form of the initial spindown 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 in time. Here we employ the simple asymptotic model of Eq.(11) assuming that the magnetic moment is constant, and that the mass inflow rate is also a constant representing the long term average $\dot{M}$.

With constant $\mu$ and $r_A$, the spindown leads $\Omega$ towards $\Omega_{eq}$:

$$\Omega(t) = [\Omega(0) - \Omega_{eq}]\exp(-t/t_0) + \Omega_{eq}. \quad (9)$$

This solution is to describe the spindown through both the propeller and the accretion phases, with mass accretion starting at some $\Omega_{acc} < \Omega_{eq}$. From Eqs.(5),(6) and (12) we obtain

$$t_0 = 1.3 \times 10^{12}s I_{45} \dot{M}^{-1} m^{-2/3} \Omega_{eq}^{4/3}. \quad (10)$$

Substituting this expression in the spindown equation, Eq.(12), $\Omega_{eq}$ can be obtained for each source with known $\Omega$ and $\dot{\Omega}$ by solving

$$\Omega_{eq} = \Omega + 1.3 \times 10^{12}s \dot{\Omega} I_{45} \dot{M}^{-1} m^{-2/3} \Omega_{eq}^{4/3}. \quad (11)$$

For the AXPs the mass inflow rate can be equal to or somewhat larger than the mass accretion rate inferred from the luminosity, as the propeller mechanism may still be partially effective. The typical value $\dot{M} \sim 10^{15}$ gm/s of the mass inflow rate inferred from the accretion luminosities as the AXPs will be adopted here for non-accreting sources like RXJ0720.4-3125. Once the equilibrium rotation rate is estimated, the magnetic moment $\mu$ can be
obtained from Eq.(6),

$$\mu_{30} = 0.32 \dot{M}_{15}^{1/2} m^{5/6} \Omega_{eq}^{-7/6}. \tag{12}$$

The time since the beginning of the propeller phase can be obtained from Eq.(12) for a given initial rotation period, which we take to be $P(0) = 0.01$ s for a newborn neutron star subjected to propeller spindown. The time $t_{\text{min}}$ estimated from Eq.(12) is:

$$t_{\text{min}} = t_{0} \log[(\Omega(0) - \Omega_{eq})/(\Omega - \Omega_{eq})]. \tag{13}$$

This estimated time $t_{\text{min}}$ is actually a lower bound for the time spent in the propeller and accretion phases. Fluctuations in $\dot{M}$ will erratically offset the asymptotic relaxation by inducing changes in the "target" $\Omega_{eq}$. Then the asymptotic spindown will extend under relatively small short term changes in $\dot{M}$ as long as $\Omega$ remains larger than $\Omega_{eq}(\dot{M})$. Each change in $\dot{M}$ would reset the asymptotic spindown, towards the new $\Omega_{eq}(\dot{M})$. Thus the asymptotic spindown phase could last much longer than $t_{\text{min}}$, which is a valid estimate for a single uninterrupted value of $\dot{M}$. The actual duration of the asymptotic phase is likely to be determined by the timescale on which $\dot{M}$ becomes large enough to attain $\Omega_{eq}(\dot{M}) > \Omega$, on the average, so that the system enters a sustained spin-up phase.

**Evolution: sources with low $\dot{M}$ may not survive the propeller phase**

Sample solutions for $t_0$ and $t_{\text{min}}$ are given in Table 1 for the AXPs and SGRs with measured $P$ and $\dot{P}$ and for the dim source RXJ0720.4-3125. The AXPs show changes in spindown rate, by up to an order of magnitude, on timescales of several years. Long term average values of the spindown 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. In the case of 1E2259+586 a mass inflow rate $\dot{M} \sim 10^{17}$ gm/s, rather than the accretion rate $\dot{M} \sim 2 \times 10^{15}$ gm/s must be taken to obtain an age estimate $t_{\text{min}}$ in agreement with the
age estimate for the possibly associated supernova remnant CTB 109. For RXJ0720.43125, a mass inflow rate of $10^{15}$ gm/s typical of the AXPs was adopted since this source is presumably a non accreting, propeller source. Along with its observed $P = 8.47s$, $\dot{\Omega} = 2.6 \times 10^{-12}$ ($\dot{P} = 2.9 \times 10^{-11}$ s s$^{-1}$, comparable to the AXP values) was inferred from Eq.(1), taking its luminosity as due to energy dissipation in the neutron star, $L = \dot{E}_{diss}$. The inferred magnetic fields are all in the $10^{11} - 10^{12}$ G range. The solutions show that ages can be much larger than the timescale $t_0$ which would give an estimate close to the real age if the spindown followed a power law in time rather than an asymptotic relaxation. At constant $\dot{M}$, the asymptotic regime would extend indefinitely. In practice the duration of the spindown phase is determined by the evolution of $\dot{M}$. If all neutron stars are born with similar magnetic fields, it is the mass inflow rate that determines the equilibrium period towards which the spindown leads. Two alternatives have been suggested for the supply of the mass inflow$^1, 2$. (i) If $\dot{M}$ is supplied by a remnant disk, formed from the debris of the supernova explosion or the progenitor evolution of a Thorne-Zytkow object$^2$, the spindown phase would be terminated by the depletion of the supply of $\dot{M}$. Two out of six AXPs provide direct evidence of youth through their likely supernova associations. Here we venture the suggestion that a remnant disk around the neutron star might also be formed from the debris of the core regions in a supernova explosion. 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 $> 10^4$ yrs and galactic supernova rate of $10^{-2}$, since the AXPs would be observable from all galactic distances. That we only observe a few indicates that mass inflow at the required rates from remnant disks or debris is rare, or that such sources rarely reach the accretion phase. The number of DTNs in the galaxy must be much larger, since we see two within a distance of the order of 100pc, limited by the low luminosity of these sources. In the galaxy we would expect about $10^4$ DTNs, and a lifetime of the order of $10^6$ yrs or longer, for a birth rate 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. This waiting time effect will be enhanced if the propeller phase is preceded with an isolated pulsar (ejector) phase during which pulsar radiation prohibits gravitational capture and mass inflow. In this phase the pulsar spins down rapidly through magnetic dipole radiation. The propeller phase starts when gravitational capture of matter is permitted, that is, when the Shvartsman radius at which the pulsar luminosity would stop mass inflow becomes smaller than the Bondi-Hoyle gravitational capture radius. This gives

$$\dot{M} = \frac{2}{3} \mu^2 \Omega^4 / C_s c^4 = 2 \times 10^{10} \mu_{30}^2 \Omega^4 / (kT(\text{keV}))^{1/2}$$  \hspace{1cm} (14)$$

where $c$ is the speed of light, $C_s$ and $T$ are the sound speed and temperature in the ambient medium. The initial phase of dipole spindown would last until the critical period given by Eq.(14)

$$P = 0.47 \mu_{30}^{1/2} (kT(\text{keV}))^{-1/8} \dot{M}_{15}^{-1/4}$$  \hspace{1cm} (15)$$

is reached, at the time

$$t_1 = 3.5 \times 10^6 \text{yr} I_{45} (kT(\text{keV}))^{-1/4} \dot{M}_{15}^{-1/2} \mu_{30}^{-1}.$$  \hspace{1cm} (16)$$

Values of $t_1$ are given in Table 1. If the mass inflow is depleted before a time of the order of $t_1$, if relevant, plus the duration of the propeller phase, which is of the order of $t_{\text{min}}$, the 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. Further, one can understand, by the same token, why mass inflow rates $< 10^{15}$ gm s$^{-1}$ are not inferred: at lower mass inflow rates the waiting times $t_1$ before the propeller phase, and $t_{\text{min}}$ or longer during the propeller phase exceed the lifetime of the mass inflow source. The rare AXPs and SGRs are thus the young objects born with conventional magnetic fields but in circumstances of large enough mass inflow towards the neutron star, so that the timescales $t_1$ and $t_{\text{0}}$, which scale with $\dot{M}^{-1/2}$ and $\dot{M}^{-1}$ respectively, are short compared to the lifetime of the mass supply: These are
the rare sources which have evaded the ejector phase and/or gone through
the propeller phase in time to start accretion before the matter supply is
depleted. The more common source is the DTN, outliving an ejector phase
and now in a propeller phase of duration $10^6$ yrs. If DTNs are born at
rates comparable to that of radio pulsars in supernova explosions, then a
significant fraction of SNRs must leave the neutron star under mass inflow
conditions of $\dot{M} = 10^{15}$ gm/s. For most DTNs the propeller stage must be
long enough that the source of mass inflow is depleted before the start of
accretion. (ii) Alternatively, the spindown could be taking place from a very
low mass binary companion. At present the timing observations give $a_x \sin i$
values which limit the companion mass to be less than a few tenths of a
solar mass.$^{16,29}$ There are serious constraints on this scenario: If all AXPs
are to be descendants of DTNs, either the propeller phase lasts 1000 times
longer than the AXP accretion phase, or only $10^{-3}$ of DTNs turn into AXPs,
according to the comparison of total numbers of these two types of sources
in the Galaxy. The DTN-propeller phase should start when the low mass
companion evolves, to start mass inflow towards the neutron star. This will
take longer than $10^8$ yrs, followed by $10^6$ yrs for the DTN-propeller phase,
and then a much shorter time, $10^3$ yrs, for the AXP accretion phase. This
is difficult to explain if the timescale of the mass inflow is the evolutionary
timescale of the low mass binary. A comparison with the population of
LMXBs with the assumption that a fraction $f$ of LMXBs go through the
AXP phase gives $f \ t_{AXP} = (N_{AXP}/N_{LMXB})t_{LMXB} \leq 0.1t_{LMXB} \sim 10^7 - 10^8$
 yrs, contradicting the estimate of $t_{AXP} = 10^3$ yrs from the comparison with
DTNs. A way out of these difficulties within the LMXB scenario would be for
the AXPs to represent a rare path in LMXB evolution and a low probability
to evolve out of the propeller (DTN) stage. Taking into account also the
evidence for possible association with supernova remnants for two AXPs,
mass supply from a debris disk around a single neutron star seems to be the
more likely scenario.

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. The associations of most SGRs with SNRs and plerions, and their gamma-ray bursting activity suggest that the SGRs are younger than the AXPs. While the present work does not address the mechanisms of the gamma ray burst phenomenon, it is intriguing that as Wang and Robertson\textsuperscript{71} 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.

**Comptonized spectra: higher $\dot{M}$ sources may not allow pulsar beams**

Why is it that the AXPs are observed as pulsars while the LMXBs are not (with the one important recently discovered exception XTE J1808-369\textsuperscript{55})? The proposal that millisecond radio pulsars have been spun-up through accretion in LMXBs\textsuperscript{56,57} and the beat frequency model\textsuperscript{58} which implied millisecond rotation periods for the neutron star in connection with the first discovered\textsuperscript{59} quasi-periodic oscillations in LMXBs, were followed by extensive searches for millisecond pulsars in LMXBs all with null results\textsuperscript{60–63}. The explanation\textsuperscript{64} for the rarity of LMXB pulsars has been that comptonization by material around the neutron star will destroy pulses by washing out the beams emerging from the neutron star if the material is optically thick to electron scattering\textsuperscript{65–68}. 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 is yet to build up significant optical thickness to destroy the beaming.

The power law photon energy spectra of AXPs are characterized by large photon indices (soft and steep spectra). The values of the photon index $\Gamma$ for AXPs range between 3 and 4, with only one source having an index of 2.5, while high mass x-ray binaries typically have power law indices of 1-2; among
LMXBs with power law spectral fits, most have indices less than 2, with the highest value of 2.8\textsuperscript{69}. According to the extensive simulations of unsaturated comptonization by Pozdnyakov, Sobol and Sunyaev\textsuperscript{70}, the photon index is related to the compton $\gamma$ parameter or to a related parameter $\gamma$ through the expression:

$$\Gamma = -1/2 + [9/4 + \gamma]^{1/2}$$ (17)

where fits to Monte Carlo simulations give:

$$\gamma = (\pi^2/4)(m_e c^2/kT)(\tau + 1/2)^{-2}$$ (18)

for a comptonizing medium of optical thickness $\tau$ and spherical symmetry. In the spectra of the AXPs there is no evidence for a high energy cut-off indicating the electron temperature. Taking the electron temperature to be at higher energies than the observational band, that is, taking $kT > 10$ keV, limits on the optical thickness can be obtained. The models of Wang and Robertson\textsuperscript{71} for the propeller stage give a temperature 35 keV in the plasma accumulated above the boundary of the magnetosphere, for $P = 8$ s, $\dot{M} = 10^{15}$ gm/s, and allowed values of the dimensionless parameters $\eta = 0.5$, $\beta = 0.01$, and $\zeta = 1$. With $kT = 35$ keV, the photon indices give optical thickness values of the order of one. These values are given in Table 2. One can use the estimates of Wang and Robertson for the density, of the order of $10^{-9}$ gm/s accumulated at the boundary of the propeller magnetosphere, which gives an optical thickness to electron scattering $\tau \sim 1$ for scattering medium dimensions of the order of $r_A \sim r_c \sim 10^9$ cm in the systems of interest. The intrinsic luminosity can be estimated to be 0.2-0.3 of the luminosity emerging from the comptonized cloud using the feedback model of comptonized spectra\textsuperscript{72}. The intrinsic thermal Bremsstrahlung luminosity that Wang and Robertson have adopted for the plasma envelope can indeed amount to 0.2-0.3 of the observed luminosities. Whether there is an evolutionary connection or not, what distinguishes SGRs and AXPs from LMXBs is that as young accretors their circumstellar material is not optically thick to electron scattering yet. Thus the unsaturated comptonization spectra are soft and the beaming of the neutron star luminosity is not washed out by comptonization.
On the unique millisecond x-ray pulsar SAX J1808.4-3658

The recently discovered source SAX J1808.4-3658 with a 2.5 ms period is likely to be an old LMXB if millisecond rotation powered pulsars evolve through spin up by accretion in old LMXBs that have weak magnetic fields. This is the only LMXB whose rotation period has been observed. SAX J1808.4-3658 can be explained qualitatively again by the properties of the comptonizing medium, this time in the opposite limit of very large relative contribution of intrinsic luminosity from the medium coupled with efficient feedback from the medium to the neutron star’s surface luminosity. A first report of the spectrum noted a power law spectrum extending without break to energies above 120 keV, suggesting an electron temperature > 120 keV for the comptonizing medium. Heindl and Smith have examined the 2.5-250 keV spectrum with the PCA and HEXTE detectors on RXTE. They find a soft excess for which there is an ambiguity among fits with various spectral models, with a Comptonized model for the spectrum below 20 keV yielding kT = 22 keV and optical thickness τ = 4. When the broad band spectrum was fitted with an iron line + disk blackbody to cover the soft excess below 20 kev, plus a power law with exponential cut-off above 34 keV, with an e-folding energy (equivalent kT) of 127 keV, the power law index defining the spectrum at 20-150 keV was found to be 1.86. Gilfanov et al. have also analyzed the RXTE spectra in terms of Comptonized models, finding power law indices between 1.86 and 2.29 for different observations. They find that a cut-off energy must be at least 100 keV, and the e-folding energy is at least 270 keV, and consider comptonization by the bulk motion of plasma surrounding this burster. Assuming the properties of the Comptonizing material determine the spectrum at the higher energies, above 20 keV, while the soft excess below 20 keV is dominated by the input source spectrum, we adopt a photon index Γ = 2, and an equivalent kT= 120 keV to describe the thermal and kinetic energy of bulk motion. This yields an optical thickness of 1.1 to electron scattering (Table 2), consistent with the explanation that this unique source of X-ray pulsations has an observ-
able rotation period because unsaturated Comptonization ($\tau \sim 1$) allows the beamed radiation to emerge without smearing. Gilfanov et al.\textsuperscript{75} have also noted that the luminosity decayed abruptly by a factor of about 30 within 5 days but the spectral characteristics, in particular the broad band power law photon index of $\Gamma \sim 2$ did not change through this transition. They interpret the drop in luminosity as a transition from the accretion regime to the propeller regime. The implied constancy of comptonizing material around the star through transitions between accretion and propeller phases is in line with the assumption of the present model that the dynamical interaction with the circumstellar material (the torques) are continuous through the accretor-propeller transition. Transitions between propeller and accretion stages have been discussed recently also in connection with the X-ray transients Aquila X-1\textsuperscript{76,77}.

**Predictions and summary of the model**

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

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

with the corresponding effective temperature

$$T(r_A) = \left(\frac{L(r_A)}{4\pi r_A^2\sigma}\right)^{1/4} \sim 9.5 \times 10^4K\dot{M}_{15}^{1/4}P^{-1/2}$$

For the AXPs this luminosity is smaller than the accretion luminosity by a factor

$$L(r_A)/L \sim 3/2R/r_A(\dot{M}/\dot{M}_{acc}) \sim 10^{-2}(\dot{M}/\dot{M}_{acc})m^{-1/3}P^{-2/3}$$

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 $\dot{E}_{diss}$ by a factor

$$L(r_A)/\dot{E}_{diss} \sim (J\Omega|\vec{\Omega}|)/(I_p\omega|\vec{\Omega}|) \sim (10^2 - 10^4)\Omega.$$
For both AXPs and DTNs the temperature in Eq.(20) applies, indicating the
euv range for the radiation from the disk. 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.

Thus a unified picture to include SGRs, DTNs and AXPs can be pro-
posed. The salient features of this picture are: (i) The similarity in the
rotation periods of these three classes of sources is not a coincidence but
rather a consequence of the asymptotic approach to rotational equilibrium
under similar circumstances. (ii) 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. (iii)
The circumstances are similar for the sources with observed rotation periods
because of selection effects for $\dot{M}$. Larger $\dot{M}$ give optically thick comptoniz-
ing matter which suppresses the beaming of the radiation and renders the
pulses at the rotation period of the star unobservable, while with low $\dot{M}$ the
spindown is too slow for the source to go through the propeller stage and
reach the accretion stage before the circumstellar mass is depleted. (iv) The
DTNs are the first observed examples of neutron stars in the propeller phase.
(v) A non-accreting neutron star under propeller spindown has a luminosity
provided by energy dissipation inside the star. (vi) The SGRs are neutron
stars accreting from the debris of their supernova remnants, from a leftover
or protoplanetary disk. (vi) The AXPs are also likely to be in an early stage
of accretion, following the SGR stage. The source of the accreted mass is
likely to be a finite store of debris around the neutron star, like a remnant
disk. Alternatively there is a small chance that they might represent the
beginning stages of a rare path in LMXB evolution. (vii) All these sources
have conventional $10^{12}$ G magnetic fields, supporting the viewpoint that neu-
tron stars are born with $10^{12}$ G fields and the weak fields of the millisecond
and binary pulsars and of the LMXBs that exhibit QPOs result from field
decay on evolutionary timescales of the LMXBs (induced by spindown of the
neutron star and/or by accretion).

This picture obviates the need to postulate magnetars on the grounds that isolated neutron stars with ordinary $10^{12}$ G fields cannot have spun down to $\sim 10$ s periods within the estimated ages. Whether the large spindown rates observed are due to spindown by interaction with ambient matter, as proposed here, or to spindown by a magnetar can be decided by detailed analysis of the fluctuations (noise) in the spindown 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. This analysis will require frequently sampled timing observations of the AXPs and SGRs. Observation of a spindown rate in the expected range from RXJ0720.4-3125 would constitute strong evidence for the propeller hypothesis. The expected euv radiation from the disk is another prediction that could be checked in the nearby DTNs, though absorption in the euv band makes this difficult.

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| Source               | P (s)   | $\dot{P}$ (s s$^{-1}$) | $M_{15}$ | $P_{eq}$ (s) | $t_0$ (yrs) | $\mu_{30}$ | $t_{min}$ (yrs) | $t_1$ (yrs) |
|---------------------|---------|------------------------|---------|--------------|-------------|------------|-----------------|-------------|
| 1E1048.1-5937       | 6.44    | $2 \times 10^{-11}$    | 1       | 23           | 7.4 x 10$^3$ | 1.45       | 5 x 10$^4$     | 2.4 x 10$^6$ |
|                     |         |                        | 5       | 10.8         | 4.1 x 10$^3$ | 1.33       | 3 x 10$^4$     | 1.2 x 10$^6$ |
| 1E2259+586          | 6.98    | $6 \times 10^{-13}$    | 2       | 7.4          | 1.7 x 10$^4$ | 0.54       | 1.6 x 10$^5$   | 4.6 x 10$^6$ |
|                     |         |                        | 100     | 6.99         | 367         | 3.57       | 4.9 x 10$^3$   | 9.8 x 10$^4$ |
| 4U0142+61           | 8.69    | $2.1 \times 10^{-12}$  | 1       | 10.5         | 2.1 x 10$^4$ | 0.57       | 1.8 x 10$^5$   | 6.1 x 10$^6$ |
| SGR1806-20          | 7.47    | $8.3 \times 10^{-11}$  | 100     | 13.8         | 148         | 7.9        | 1.1 x 10$^3$   | 4.4 x 10$^4$ |
| SGR1900+14          | 5.16    | $1.1 \times 10^{-10}$  | 20      | 9.1          | 1.3 x 10$^3$ | 2.2        | 9.1 x 10$^3$   | 3.6 x 10$^5$ |
| RXJ0720.4-3125      | 8.39    | $(2.9 \times 10^{-11})$ | 1       | 10.8         | $2 \times 10^4$ | 0.59     | $1.7 \times 10^9$ | $5.9 \times 10^6$ |

For RXJ0720.4-3125 the $\dot{P}$ value is inferred from the luminosity according to Eq.(1).

| Source               | Γ       | $\tau(kT=10\text{keV})$ | $\tau(kT=35\text{keV})$ |
|---------------------|---------|--------------------------|--------------------------|
| 4U0142+61           | 3.67    | 2.4                      | 1.04                     |
| 1E1048.1-5937       | 2.5     | 3.8                      | 1.8                      |
| 1E1841-045          | 3       | 3.4                      | 1.4                      |
| RXJ170849.0-400910  | 2.9     | 3.6                      | 1.47                     |
| eg                  | 2       | 5.1                      | 2.5                      |
| eg                  | 1.5     | 8                        | 4                        |
| SAX J1808.4-3658    | 2.02    | $\tau(kT=120\text{keV})$ | =1.1                     |

The rows labeled "eg" give examples for typical power law spectra for x-ray binaries. For SAX J1808.4-3658 $\tau$ is quoted for an equivalent temperature of 120 keV.