Pulsar Glitch Behaviour and AXPs, SGRs and DTNs

M. Ali Alpar
Sabancı University, Orhanlı, Tuzla 81474, Istanbul, Turkey

Abstract. Large pulsar glitches seem to be common to all radio pulsars and to exhibit a universal behaviour connecting the rate of occurrence, event size and interglitch relaxation that can be explained if the glitches are due to angular momentum exchange in the neutron star. This has implications for the energy dissipation rate. The large timing excursions observed in SGRs are not similar to the pulsar glitches. The one glitch observed in an AXP is very similar to pulsar glitches and demonstrates that typical neutron star glitch response occurs when the external torque is constant for an extended period of time. In the long run the timing variations of both the AXPs and the SGRs are much stronger than the timing noise of radio pulsars but comparable with the behaviour of accreting sources. For the DTNs, the thermal luminosities do not seem compatible with cooling ages and statistics if these sources are magnetars. The energy dissipation rates implied by the dynamical behaviour of glitching pulsars will provide the luminosities of the DTNs under propeller spindown torques supplied by fossil disks on neutron stars with conventional $10^{12}$ G dipole magnetic fields.

1. The Signature of Large Pulsar Glitches

A simple model detailed first for the Vela pulsar’s glitches pictures the glitches as the discrete component of angular momentum exchange between the observed crust and other components of the neutron star (Alpar et al. 1993 and references therein). There is also a continuous part of the angular momentum exchange between the components. It is believed that the interior of the neutron star is superfluid, which means that the angular momentum is transported by discrete carriers, the quantized vortices of the superfluid. There is a simple analogy with an electronic circuit that contains resistive as well as capacitive elements. The parts of the superfluid where there is a continuous vortex current that allows the superfluid to take part in the spindown are the resistive elements, where continuous energy dissipation accompanies the angular momentum transport. Say these resistive parts have total moment of inertia $I_A$. The resistive parts may be disjoint regions within which there is a vortex density and vortex current. Some of these vortices may be trapped by pinning centers. The resistive parts collectively are the analogues of capacitor 'plates' and the wires connecting them in an electronic circuit. These resistive regions are separated by vortex free regions, analogues of the space between capacitor plates. The glitches are...
capacitive discharges of vortices through vortex free regions, say of moment of inertia $I_B$, which do not sustain a continuous vortex current.

In a glitch a certain number of vortices get unpinned throughout the resistive trap regions A, move through the regions A and B rapidly and repin in other parts of the resistive trap regions A. This sudden motion of vortices reduces the superfluid rotation rate by an amount $\delta \Omega$ throughout the vortex free regions B. Under the simple assumption that the area density of the unpinned vortices is uniform throughout the resistive regions A, the average decrease in superfluid rotation rate throughout the regions A is $\delta \Omega/2$. The angular momentum lost by the superfluid through this sudden discharge of vortices is gained by the neutron star crust, leading to the observed increase in the crust’s rotation rate, $\Delta \Omega$, which is the glitch:

$$I_c \Delta \Omega = (1/2 I_A + I_B) \delta \Omega.$$  (1)

Here $I_c$ denotes the effective moment of inertia of the crust, including all components of the star that are already rigidly coupled to the crust on timescales short compared to the rise time of the glitch. Application of the model to pulsar glitches shows that $I_c$ contains almost the entire moment of inertia of the star, with $I_A$ and $I_B$ making up a few per cent (Alpar et al. 1993). The physical reason is that the superfluid core of the neutron star, which makes up the bulk of the moment of inertia, is coupled to the crust strongly, on short time scales (Alpar, Langer, & Sauls 1984). The superfluid regions A and B responsible for the glitches make up the superfluid in the inner crust of the neutron star, which indeed constitutes a few percent of the star’s moment of inertia.

The spindown rate of the superfluid, and hence the observed spindown rate of the crust, depend on the vortex current that achieves the continuous angular momentum transport (the internal torque). This vortex current is driven by a lag in rotation rate between the superfluid and the crust. The lag is offset by the changes in the rotation rates of both the crust ($\Delta \Omega$) and the superfluid ($\delta \Omega$) at the glitch. There is, therefore, a glitch induced change $\Delta \hat{\Omega}$ in the observed spindown rate of the crust. Part of this glitch induced change in the spindown rate relaxes promptly, as an exponential decay with relaxation times less than a month in the Vela pulsar. What is of interest for the long term behaviour of the pulsar is a change in the spindown rate that does not heal in a prompt exponential decay but instead is observed to relax gradually, as a linear function of time, completing its recovery at the time of the next glitch:

$$\Delta \hat{\Omega}(t) = \Delta \hat{\Omega}(0)(1 - t/t_g)$$  (2)

where $t_g$, the parameter describing the slope of the relaxation in spindown (the 'anomalous' second derivative) is found to be

$$t_g = \delta \Omega/|\dot{\Omega}|$$  (3)

and

$$\Delta \hat{\Omega}(0)/|\dot{\Omega}| = I_A/I_c.$$  (4)

Eqs. (1)-(4) relate the three model parameters, $I_A/I_c$, $I_B/I_c$ and $\delta \Omega$, to the observed parameters $\Delta \Omega$, $\Delta \hat{\Omega}(0)$ and $t_g$. The interpretation of the model is that
the glitch induced change in spindown rate reflects the complete stopping of vortex current in all resistive regions A, because the current is a very sensitive function of the driving lag and stops when the lag is offset by the glitch. (This is called ‘nonlinear response’ in the jargon of the model.) The particular form of the recovery given in Eqs. (2) and (3) reflects the uniform density of unpinned vortices, as does the factor 1/2 in Eq.(1). For the Vela pulsar the timescale \( t_g \) extracted from the observed second derivative agrees with the time to the next glitch within 20 %. The recovery means that the unpinned vortex density is re-pinned by time \( t_g \) - so the traps are ready to go unstable again on that timescale. Using Eqs. (1)-(4), the long term second derivative of \( \Omega \) is:

\[
\ddot{\Omega} = \frac{I_A}{I} \frac{\dot{\Omega}^2}{\delta \Omega} = (\beta + 1/2) \left[ ((\Delta \dot{\Omega} / \dot{\Omega})_{-3})^2 / ((\Delta \Omega / \Omega)_{-6}) \right] (\dot{\Omega}^2 / \Omega) \tag{5}
\]

where \( \beta = I_B / I_A \). This is equivalent to the positive anomalous braking index

\[
n \equiv \Omega \dot{\Omega} / \dot{\Omega}^2 = (\beta + 1/2) \left( (\Delta \dot{\Omega} / \dot{\Omega})_{-3} \right)^2 / (\Delta \Omega / \Omega)_{-6}. \tag{6}
\]

The time to the next glitch can be expressed as

\[
t_g = 2 \times 10^{-3} (\beta + 1/2)^{-1} \tau_{sd} \left( (\Delta \Omega / \Omega)_{-6} / (\Delta \dot{\Omega} / \dot{\Omega})_{-3} \right) \tag{7}
\]

where \( \tau_{sd} = \Omega / (2|\dot{\Omega}|) \) is the characteristic dipole spindown time.

The implications of this simple pattern in the Vela pulsar’s interglitch behaviour are: (i) The neutron star is in a nonlinear response regime, highly sensitive to perturbations of the lag. In such a nonlinear response situation the energy dissipation rate can be shown to be quite large,

\[
\dot{E}_{\text{diss}} \sim I_A \omega |\dot{\Omega}| > I_A \delta \Omega |\dot{\Omega}| \sim 10^{41} |\dot{\Omega}| \text{ergs s}^{-1}. \tag{8}
\]

Here \( \omega \) is the lag between the rotation rates of the crust and the pinned superfluid. \( \dot{E}_{\text{diss}} \) determines the thermal luminosities of older neutron stars. (ii) The result, from the fits to the data, that \( I_A/I_c, I_B/I_c \) are \( \leq 10^{-2} \) means the core superfluid is strongly coupled to the outer crust on short timescales, which in turn implies that precession would be strongly damped. The applicability of this simple model to all pulsar glitches and interglitch behaviour will imply that points (i) and (ii) are relevant to all neutron stars.

2. Evidence for the ‘Universality’ of Glitch Behaviour ?

An important caveat in comparing observed glitch parameters with the model is the distinction between the total \( \Delta \dot{\Omega}(0) \), which may include contributions from transients, and the component of \( \Delta \dot{\Omega}(0) \) associated with the long term recovery (Eq.(2)). The observations typically do not resolve this point. In some of the glitch observations a single exponentially decaying transient fit to postglitch data is presented, sometimes along with a long term second derivative value. There may be more than one transient, the relaxation times are expected to be different in different pulsars, the data is not uniform and do not cover similar timespans in all the different pulsars. From the detailed fits to the Vela pulsar
postglitch behaviour, it is known that the $\Delta \dot{\Omega}(0)$ values associated with various transients are comparable with that associated with the long term interglitch recovery. We adopt the total value of $\Delta \dot{\Omega}(0)$ as the long term offset in $\dot{\Omega}$ to be used in the model, without subtracting the part associated with transient exponential decay that was fitted by the observers to the data for some glitches. If the other glitching pulsars indeed behave like the Vela pulsar then values of $\beta$ of order one, within an order of magnitude, should be obtained.

Lyne, Shemar, & Graham-Smith (2000) measured second derivatives of the rotation rate from 7 out of 16 glitching pulsars they had observed (excluding the Crab and Vela pulsars). Out of these 7 pulsars, those with quoted relative errors of $>20\%$ in the second derivative, as well as PSR B2224+65 for which the error in $\Delta \dot{\Omega}/\dot{\Omega}$ exceeds the nominal value, and PSR B1823-13, for which there is a postglitch second derivative measurement, but an observed $\Delta \dot{\Omega}/\dot{\Omega}$ was not reported, were excluded from the comparison with the model. The data for the remaining 3 pulsars (PSR B1727-33, PSR B1737-30 following the first and fifth glitches and PSR B1500-21) were compared with the model, Eqs. (5), (6) and (7). Out of 10 glitching southern pulsars (excluding the Vela pulsar) studied by Wang et al. (2000), 7 have yielded second derivative measurements, with $<20\%$ quoted errors, after an observed glitch. Out of these 7, one pulsar, PSR J1614-5047, is in conflict with the model. This pulsar has a negative second derivative measurement with quoted errors of only 1.5$\%$ in a timing fit covering a 563 d part of its postglitch epoch, after first displaying a positive second derivative over 325 d. The quoted second derivative value, however, differs strongly from the plot of $\dot{\Omega}$ data (Wang et al. 2000, Fig.8). For the remaining 6 pulsars (PSR J1048-5832 following the second and third glitches, PSR J1341-6220 following the third and ninth glitches, PSR J1709-4428, PSR J1731-4744, PSR J1801-2451 and PSR J1803-2157) the results of Wang et al. (2000) were compared with the model.

The 12 glitches from these 9 pulsars form the complete sample, published to date, of large glitches with changes in spindown rate at the glitch and with relatively accurate post glitch second derivative measurements. Using Eq. (6) values of $\beta$ can be derived for each of these glitches. For 10 of the 12 glitches, $\beta$ values of 0.3-16 are obtained. These are, within an order of magnitude, similar to the values obtained for the Vela pulsar glitches. For the third glitch of PSR J1341-6220 $\beta = 43$ while for the glitch observed from PSR J1709-4428 $\beta = 1120$, clearly in conflict with the other $\beta$ values. Eq. (7) gives $t_g$, the expected time to the next large glitch for each pulsar. Values of $t_g$ of the order of several years are typical. For the pulsars with repeated large glitches, $\Delta \Omega/\dot{\Omega} > 10^{-7}$, we can compare the expected and observed intervals $t_g$ between these large glitches. The ratio $(t_{g,\text{obs}}/t_g) = 1.6$ (PSR B1737-30, glitch 1 to glitch 5), 0.96 (PSR J1048-5832, glitch 2 to glitch 3), 2.5 and 0.7 (PSR J1341, glitch 3 to glitch 5 and glitch 9 to glitch 12). It can be concluded, with caution, that the model developed for the Vela pulsar may be applicable to most large glitches, and that there may be common dynamical behaviour for all neutron stars.

Johnston & Galloway (1999) have obtained braking indices for 20 pulsars from which glitches have not been observed. Anomalous braking indices were found for all 20 pulsars, with negative values in 6 pulsars (in 5 of them with relative errors $<20\%$) and positive values in the rest (with relative errors $<
Johnston & Galloway (1999) interpreted the positive anomalous braking indices as due to interglitch recovery, without evoking a specific model. For these pulsars, no glitch has occurred during the timespan of the observations. The values of the parameter $\beta$ obtained from Eq. (6) with the measured braking indices and with nominal glitch values $\Delta \Omega/\Omega = 10^{-7}$ and $\Delta \dot{\Omega}/\dot{\Omega} = 10^{-3}$ are of order $\beta \sim 0.36 - 4.5$, consistent with all these pulsars having similar glitches with similar ratios of the vortex trap (capacitive) and vortex creep (resistive) moments of inertia. The negative braking indices were interpreted by Johnston & Galloway (1999) as reflecting an unresolved glitch during their observation time spans. Since all glitches involve a negative step (an increase in the absolute value) of the rate of spindown, and since the pulsars were not monitored continuously, a glitch occurring between two timing observations would lead to a negative $\ddot{\Omega}$ estimate, equivalent to a negative braking index. The fractional changes in the spindown rate in the four unobserved glitches are inferred from the negative braking indices of Johnston & Galloway (1999) according to:

$$\Delta \dot{\Omega}_i = \ddot{\Omega}_i t_i.$$  

These values of $\Delta \dot{\Omega}/\dot{\Omega} \sim 5 \times 10^{-4} - 4 \times 10^{-3}$ are typical for glitching pulsars. The probability that 4 out of the 20 pulsars in the Johnston & Galloway (1999) sample have had unresolved glitches within the observation timespans, so that they have negative anomalous second derivatives, can be evaluated using the observation timespans devoted to each pulsar and model estimates for the interglitch time intervals $t_g$ of each pulsar, using Eq. (7). This probability turns out to be as large as 0.16 for one particular scaling of $t_g$ with pulsar rotation frequency. Thus positive and negative braking index measurements from pulsars that have not been observed to glitch are also consistent with the model, on the account of $\beta$ and $\Delta \dot{\Omega}$ values inferred and also statistically.

3. SGR and AXP Timing Behaviour: Comparison with Isolated Pulsars

The timing behaviour of AXPs and SGRs could provide a clue as to whether these objects are magnetars or accreting sources. If magnetars are not qualitatively different from the radio pulsars, they should have very steady spindown rates, with a low level of timing noise, like the radio pulsars. All radio pulsars show steady spindown rates for as long as they have been observed, with timing noise levels (Arzoumanian et al. 1994, Alpar, Nandkumar, & Pines 1986) that are significantly lower than those of the accreting sources (Bildsten et al. 1997). Kaspi, Chakrabarty & Steinberger (1999) reported such quiet spindown in RXTE timing observations of the AXPs 1RXS J170849.0-400910 (for a period of 1.4 yr) and 1E 2259+586 (for 2.6 yr). In earlier observations the latter source, and a third AXP, 1E 1048.1-5937, had been observed to display noisy spindown behaviour, similar to torque noise typical of accreting sources (Mereghetti 1995, Baykal & Swank 1996, Corbet & Mihara 1997). Baykal et al. (2000) showed from later archival RXTE observations that 1E 1048.1-5937 continued to display noisy torque behaviour while 1E 2259+586 had a stable luminosity behaviour, a luminosity time series with a particularly low level of fluctuations, during the
same epoch when Kaspi et al. (1999) had observed quiet spindown. Not all AXPs have been observed in epochs of quiet spindown; those that do have extended quiet spindown episodes have been observed to have strong timing noise at other epochs; and quiet spindown (low torque noise) coincides with low luminosity noise. Thus the observed timing behaviour of AXPs is consistent with an accretion scenario. Furthermore, Baykal et al (2001) show, by adding recent RXTE pulse period measurements to earlier timing results, that a well known accreting source, the high mass X-ray binary 4U 1907+09, has been spinning down at an almost constant rate, with very low level timing noise, for almost 15 years, clinching the case that quiet spindown does not necessarily imply a non-accreting source. To conclude that a source is like a radio pulsar in spindown behaviour, it would have to be spinning down with low noise all the time.

The extended quiet spindown of the AXP 1RXS J170849.0-400910, continuing for more than two years in frequently monitored RXTE timing, was interrupted by a sudden glitch (Kaspi, Lackey, & Chakrabarty 2000). This glitch seems to be a typical example of the universal large pulsar glitches described above in both the fractional change in frequency, $\Delta \Omega/\Omega \approx 6.2 \times 10^{-7}$, and in the fractional change in spindown rate, $\Delta \dot{\Omega}/\dot{\Omega} \approx 3.8 \times 10^{-3}$. This is the first instance of the 'universal' glitch occurring in a neutron star other than a radio pulsar and shows that the same neutron star dynamics shows up in response to spindown under an external torque provided the spindown proceeds at a constant rate. Data is not yet available for checking the second derivative characteristic of the interglitch behaviour observed in radio pulsars. The glitch model, Eq.(7), can be used to infer that $t_g \approx 1$ yr, so that there is an appreciable probability of observing such a glitch within the two year timespan of the observed quiet spindown. Indeed if the quiet spindown continues, repeated glitches should be expected.

The possibility that the observed timing residuals of AXPs during noisy periods arise from a series of unresolved glitches can be explored with various combinations of model glitches that fall in gaps in the observations (Heyl & Hernquist 1999). The required event sizes are $\Delta \Omega/\Omega \sim 10^{-4}$ for the AXP 1E 1048.1-5937 (much larger than the values for the radio pulsar glitches) and $\Delta \Omega/\Omega \sim 10^{-6}$ for the AXP 1E 2259+586. Taking $\Delta \dot{\Omega}/\dot{\Omega} \sim 10^{-3}$, and $\beta$ as large as 10, Eq. (7) predicts average event intervals $t_g \sim 10^2$ yrs or longer for both AXPs while the interval required to explain the timing excursions in the AXPs is a few years in some fits. Thus both the size and the rate of the hypothesized unresolved glitches in SGRs are large compared to the pulsars.

Woods et al. (2001) have recently reported all timing observations, through January 2001, of the two SGRs with $\dot{\Omega}$ measurements, SGR 1900+14 and SGR 1806-20. No events resembling pulsar glitches, i.e. discrete and sudden spin-up events against the background of spindown, were either resolved or implied by mismatches in extrapolations of timing solutions into gaps between observations. In both sources the most prominent characteristic of the timing behaviour is changes in the spindown rate by factors of as much as 3-4 extending over periods of several months. These variations were followed through frequently sampled RXTE-PCA observations in 2000. Such large variations cannot be due to changes in moment of inertia of the crust through quakes or gradual plastic deformation. If the universal behaviour of radio pulsar glitches is taken as
a guide to the internal torques, and the distribution of moment of inertia in various components of the neutron star, then the limitation on the crust core coupling time, $\tau < 450$ P(s), obtained by extrapolating the limit $\tau < 40$ s for the Vela pulsar glitches (Dodson, Lewis, & McCulloch 2001) through the theoretical explanation of the tight crust-core coupling (Alpar et al. 1984), implies that during the large changes of $\dot{\Omega}$ the entire star is rotating rigidly with the observed crust. Thus a change by a factor of 3-4 in the spindown rate, if due to a structural change, would imply a corresponding change in the moment of inertia of the entire neutron star. The variations in spindown rate therefore are likely to reflect variations in the external torque on the star. Such changes are easy to understand if the external torque is an accretion torque. Changes in spindown (or spinup) rate by such factors of 3-4 is common in accreting sources. The overall power in timing noise is reported by Woods et al. (2001) to be compatible with the range of noise strengths in accreting sources and much stronger than the timing noise in radio pulsars. If the external torque is a dipole spindown torque with a magnetar field then the strength of the variations in the spindown rate (timing noise) being so much larger than timing noise strength in the radio pulsars must be ascribed to a qualitative change in the external torque when the magnetic field is in the $10^{14}$ G magnetar range rather than the $10^{12}$ G range of the radio pulsars. Such a qualitative change in torque behaviour must occur at surface magnetic fields larger than $B_0 = 1.1 \times 10^{14}$ G at the neutron star’s magnetic pole, since the radio pulsar with the largest inferred field value, PSR J1814-1744 (Camilo et al. 2000) with $B_0 = 1.1 \times 10^{14}$ G, does not exhibit the large torque variations observed from the SGRs. But then neither do the highest magnetic field radio pulsars exhibit soft gamma ray bursts. In the magnetar model, the gamma ray burst behaviour and the torque behaviour of neutron stars as isolated rotating dipoles must go through a transition at $B_0 > 1.1 \times 10^{14}$ G.

Are the SGRs similar to the AXPs in their overall timing behaviour? It may well be that the SGRs also go through extended quiet spindown phases that have been observed from some AXPs and from the known accreting source 4U 1907+09 but that for the SGRs the quiet spindown phases have not yet occurred during the era covered by observations. In any case the SGRs do have the noisy timing behaviour characteristic of the accreting sources. It is the occurrence of the repeated soft gamma ray bursts, the defining characteristic of the SGRs, and not the timing behaviour during the quiescent X-ray phases, that sets the SGRs apart from their potential relatives the AXPs, and from the accreting X-ray sources. The recent observations of Woods et al. (2001) most significantly make the point that no soft gamma ray bursts took place in either SGR 1900+14 or SGR 1806-20 during the changes in spindown rate that were followed through the RXTE PCA observations in 2000, which, as argued above, probably reflect changes in the external torque. During burst active epochs, in 1998-1999 for SGR 1900+14 and late 1996-early 2000 for SGR 1806-20, sparsely sampled timing data imply a steady long term spindown rate. In any case, models for the bursts must confront why the largest observed variations in external torque are separated from any burst activity, by many years in SGR 1900+14 and by about 10 months in SGR 1806-20, as Woods et al. (2001) find.
4. Thermal Luminosities of DTNs: Cooling Magnetars or Energy Dissipation?

The dim thermal neutron stars discovered in ROSAT surveys (Treves et al. 2000) have similarities with the AXPs and SGRs. In particular the three dim thermal neutron stars with measured periods all have periods similar to the AXP and SGR periods (P = 8.37 s, 5.16 s and 22.7 s, respectively, for RXJ 0720.4-3125, RBS 1223 and RXJ 0420.0-5022). Distance estimates for the DTNs are typically in the range of 100 pc, with large uncertainties. With n=6 detected nearby examples, the DTNs must form a very abundant population in the galactic plane where they all lie. Scaling to the entire galactic plane with a radius of 10 kpc, and assuming a galactic birthrate R = R_{-2} \times 10^{-2} \text{ yr}^{-1} gives the relation

\[ \tau_6 = n(R_{-2})^{-1}(d/100\text{pc})^{-2} \]

between the lifetime \( \tau_6 \) (in 10^6 yrs) of the population with \( n \) objects detected out to distance \( d \).

Like the AXPs and SGRs the DTNs have been proposed as examples of magnetars. This is based on the interpretation of their X-ray luminosity as cooling luminosity, which implies that the neutron star is young. The slow rotation rate in conjunction with young age then implies efficient braking, i.e., that a magnetic field of magnetar strength must have spun down the neutron star through magnetic dipole radiation. According to the whole range of standard cooling calculations, the luminosity of a young neutron star, of age 10^{2} \text{ yrs} < \tau < 10^{5} \text{ yrs}, is in the range \( L_x \sim 10^{33} \text{ erg s}^{-1} - 10^{34} \text{ erg s}^{-1} \) (see, for example, Fig.5 of Ögelman (1995)). The cooling luminosity is about \( 10^{32} \text{ erg s}^{-1} \) at \( \tau = 10^{6} \text{ yrs} \) and drops to about \( 10^{26} \text{ erg s}^{-1} \) by \( \tau = 3 \times 10^{6} \text{ yrs} \).

For RBS 1223, comparison of periods determined from recent Chandra observations and earlier ROSAT HRI observations lead to an estimate of the spin-down rate, \( \dot{\Omega} = -(1.7 - 4.7) \times 10^{-12} \) (Hambaryan et al. 2001), similar to the spin-down rates of AXPs and SGRs. The uncertainty in the spin-down rate reflects the uncertainties in the two period determinations and is not a measurement of timing excursions. If the source is a rotating dipole, the magnetic moment in units of \( 10^{30} \text{ G} \) is \( \mu_{30} \cong (I_{45}P_{-15})^{1/2} = 190-320 \), implying dipole fields in the magnetar range. For this source the dipole spindown time \( \tau = P/2\dot{P} \) is found to be 4000-12000 yrs. Distance estimates give \( d = 100-200 \text{ pc} \) or \( d = 700-1500 \text{ pc} \). Only for the latter case, at the largest distance \( d = 1500 \text{ pc} \), the luminosity \( L_x \sim 10^{33} \text{ erg s}^{-1} \) of RBS 1223 is barely consistent with the lowest luminosities allowed by standard cooling models at the estimated age of \( \sim 10^{4} \text{ yrs} \).

For another DTN, RXJ 1856.6-3754, there is a kinematic age determination of \( 10^{6} \text{ yrs} \) based on proper motion measurements and on an inferred birthplace in the Upper Sco OB association (Walter 2001). Differences in parallax measurements with HST are likely to be resolved with new HST data. If this source has a period in the range 5 s - 23 s of the other DTNs, and is spinning down by magnetic dipole radiation, the magnetic moment implied by taking the kinematic age as the dipole spindown time is

\[ \mu_{30} \cong 4P(\tau_6/I_{45})^{-1/2} \]
giving $\mu_{30} = 20-92$. Adopting the distance value of $140 \pm 40$ pc (Kaplan, van Kerkwijk & Anderson 2001) gives a thermal X-ray luminosity $L_x \sim 10^{32}$ erg/s, which is consistent with standard cooling at the estimated magnetar age.

The two other DTNs with measured periods, RXJ 0720.4-3125 ($P=8.37$s) and RXJ 0420.0-5022 ($P=22.7$s) have spindown ages of $1.1 \times 10^5$ yrs and $8.2 \times 10^5$ yrs respectively, if they are magnetars with $\mu_{30} = 100$. With their observed thermal X-ray fluxes, both sources must be at distances of 500-1000 pc if the luminosities are standard cooling luminosities. If these are the distances to which the observed sample of DTNs extends, then from Eq.(10), the lifetime of DTNs is $\tau = (6-25) \times 10^4 (R_\odot)^{-1}$ yrs. Of the four DTNs with measured periods and age determinations or estimates (within the magnetar model, except for RXJ 1856.6-3754 which has a kinematic age estimate), only one, RXJ 0720.4-3125, has an age estimate within this range of the statistically determined lifetimes. More and better distance and age determinations will resolve whether this difficulty for the magnetar model is real.

The evidence, from pulsar glitches, of a common dynamical behaviour for all pulsars, implies a different origin for the X-ray luminosity, energy dissipation in the exchange of angular momentum between the components of the neutron star rotating at different rates. The observed postglitch and interglitch behaviour indicate strong, nonlinear coupling between the components. This implies that the energy dissipation rate, which is proportional to the lag $\omega$ between the crust and the pinned superfluid components is large. The lag must be greater than the reduction $\delta \Omega$ in the rotation rate of the pinned superfluid at a glitch. With the value of $\delta \Omega \sim 10^{-2}$ rad s$^{-1}$ and of neutron star crust moments of inertia commonly inferred from glitches, a lower bound on the energy dissipation rate, given in Eq.(8) is obtained. Using this together with an upper bound obtained from thermal X-ray observations of radio pulsars (Alpar et al. 1987, Yancopoulos, Hamilton, & Helfand 1994), the observed luminosities of the DTNs, interpreted as due to energy dissipation in the neutron star yield bounds on the spindown rate (Alpar 2001):

$$L_x/10^{43} < |\dot{\Omega}| < L_x/10^{41}. \quad (12)$$

The range of spindown rates inferred from DTN fluxes, at the more likely distances of the order of 100 pc, are $|\dot{\Omega}| \sim 10^{-13} - 10^{-10}$ rad s$^{-2}$. This range includes the observed spindown rate of RBS 1223 and overlaps with the range of spindown rates of the AXPs and SGRs. The DTN spindown can be understood as due to propeller torques from a fossil accretion disk on a neutron star with conventional magnetic moment, $\mu \sim 10^{30}$ G (Alpar 2001). In the propeller epoch, the lifetime of a neutron star is not bounded by the duration of initial cooling, as it is in the case of the cooling magnetar model. Lifetimes of a few $10^6$ yrs statistically inferred from the likely distances of the order of 100 pc are quite acceptable. The requirement of thermal luminosities for old neutron stars, arising from large energy dissipation rates is a strong consequence of the observed glitch behaviour if it prevails universally among all neutron stars.

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