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The timing behavior of magnetar Swift J1822.3−1606: timing noise or a decreasing period derivative? *

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Abstract The different timing results of the magnetar Swift J1822.3−1606 are analyzed and understood theoretically. It is noted that different timing solutions are caused not only by timing noise, but also because the period derivative is decreasing after the outburst. Both the decreasing period derivative and the large timing noise may originate from wind braking associated with the magnetar. Future timing of Swift J1822.3−1606 will help clarify whether or not its period derivative is decreasing with time.

Key words: pulsars: individual (Swift J1822.3−1606) — stars: magnetar — stars: neutron

1 INTRODUCTION

Magnetars are peculiar pulsar-like objects. They are assumed to be neutron stars powered by decay of a strong magnetic field (Duncan & Thompson 1992). A neutron star is often confirmed as a magnetar if the dipole magnetic field at its surface is higher than the quantum critical field ($B_{\rm QED} = 4.4 \times 10^{13}$ G). The dipole magnetic field at its surface is calculated from the period and period derivative (assuming magnetic dipole braking, Kouveliotou et al. 1998). However, the assumption of magnetic dipole braking also challenges the magnetar model. One example is the existence of a low magnetic field magnetar (Rea et al. 2010; Tong & Xu 2012). Alternatively, it is possible that magnetars are wind braking (Tong et al. 2013 and references therein). Wind braking would help to explain the controversial timing results found in magnetar Swift J1822.3−1606.

Swift J1822.3−1606 is a magnetar candidate, discovered by *Swift*/BAT on 2011 July 14 (Cummings et al. 2011). Up to now, different timing results have been obtained for this source (Livingstone et al. 2011; Rea et al. 2012; Scholz et al. 2012). The reported period derivative differs by a factor of about three. The corresponding characteristic magnetic field can be larger or smaller than the quantum critical field. This is directly related to whether or not this source is another low magnetic field magnetar.

In papers describing their observations, Rea et al. (2012) and Scholz et al. (2012) mainly discuss the effect of timing noise. In their opinion, it is the large timing noise that results in different period derivative measurements in Swift J1822.3−1606. In this paper, we explore another effect: The period

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derivative of Swift J1822.3−1606 may be decreasing with time. Therefore, it is natural that different period derivatives are obtained using different data sets. The physical reason may be that magnetars are wind braking (Tong et al. 2013). A decaying particle wind after the outburst will result in a decreasing period derivative.

Description of the model and quantitative calculations are presented in Section 2. Discussion and conclusions are presented in Section 3.

2 MODELING THE SPIN DOWN RATE OF SWIFT J1822.3−1606

2.1 Description of Observations and Theory

Rea et al. (2012) reported two period derivatives of Swift J1822.3−1606 (in sect. 3.2). Using observations from the first 90 d, a period derivative of $\dot{P} = 1.6(4) \times 10^{-13}$ was obtained (uncertainties in the last digit are at the 1σ confidence level). Considering data from all the 275 d, the corresponding period derivative is $\dot{P} = 0.83(2) \times 10^{-13}$. These two values provide some hints that the period derivative is decreasing with time. The large uncertainty in the data set covering a short time may be caused by timing noise. Similar behavior can also be seen in Livingstone et al. (2011) and Scholz et al. (2012). In Livingstone et al. (2011), using observations covering 84 d, a period derivative of $\dot{P} = 2.55(22) \times 10^{-13}$ is reported. Using observations spanning 402 d, Scholz et al. (2012) reported three solutions for period derivatives: $\dot{P} = 0.683(21) \times 10^{-13}$ (fitting with period and one period derivative), $\dot{P} = 1.71(7) \times 10^{-13}$ (fitting with period and two period derivatives) and $\dot{P} = 3.06(21) \times 10^{-13}$ (fitting with period and three period derivatives).

Similar behaviors are also seen in other magnetars. Since the beginning of magnetar timing studies, it has been found that magnetars have a higher level of timing noise than do normal pulsars (Gavriil & Kaspi 2002; Woods et al. 2002). Large variations in period derivative are seen in AXP 1E 2259+586 (Kaspi et al. 2003), AXP 1E 1048.1−5937 (Gavriil & Kaspi 2004), SGR 1806−20 (Woods et al. 2007) and AXP 1E 1547.0−5408 (Camilo et al. 2008). Two clear examples are AXP XTE J1810−197 (Camilo et al. 2007) and the radio loud magnetar PSR J1622−4950 (Levin et al. 2012). In these two sources, a decreasing period derivative is observed while the star's X-ray luminosity is decreasing after the outburst. Therefore, from previous observations, there may also be large timing noise in Swift J1822.3−1606. At the same time, its period derivative may also decrease with time (a decreasing X-ray luminosity is also observed). This may explain why a lower period derivative is obtained when using a longer time span of observations.

The physics that explains a varying period derivative may be that magnetars are wind braking (Tong et al. 2013). The decay of a strong magnetic field will power the star's X-ray luminosity. At the same time, a (magnetism-powered) particle wind is also generated. The rotational energy of magnetars is mainly carried away by this particle wind. A varying particle wind naturally results in a varying period derivative. The fluctuations of this particle wind may account for the large timing noise in magnetars. Since both the X-ray luminosity and the particle wind luminosity are from magnetic field decay, an estimate of the particle wind luminosity that is model independent is $L_{\rm p} \sim L_{\rm x}$, where $L_{\rm p}$ and $L_{\rm x}$ are the particle wind luminosity and the X-ray luminosity, respectively. The origin of this particle wind may be either internal (e.g., low amplitude seismic activities, Thompson & Duncan 1996), or magnetospheric (e.g., coronal particles, Beloborodov & Thompson 2007). For details of wind braking in magnetars and discussion of other models, see Tong et al. (2013) and references therein.

2.2 Calculations for Swift J1822.3−1606

X-ray observations of Swift J1822.3−1606 have given its flux evolution with time. Using the flux evolution function and its extrapolations, we can calculate the theoretical period derivative as a function of time. The longest time span of X-ray observations of Swift J1822.3−1606 has been done by Scholz et al. (2012, with 400 d of observations). According to Scholz et al. (2012), a double exponential flux decay model is preferred.

$$F(t) = F_1 \exp[-t/\tau_1] + F_2 \exp[-t/\tau_2] + F_{\rm q}\,, \tag{1}$$

where $F(t)$ is the $1{-}10$ keV source flux as a function of time, t is in units of days after the BAT trigger time (MJD 55756.5), $\tau_1 = 15.5\,\rm d$ and $\tau_2 = 177\,\rm d$ are the two decay time scales, $F_1 = 20.9 \times 10^{-11}\,\rm erg\,cm^{-2}\,s^{-1}$ and $F_2 = 1.74 \times 10^{-11}\,\rm erg\,cm^{-2}\,s^{-1}$ are the two flux normalizations and $F_{\rm q} = 3 \times 10^{-3} \times 10^{-11}\,\rm erg\,cm^{-2}\,s^{-1}$ is the fixed quiescent flux (constrained by *ROSAT*). See Scholz et al. (2012, sect. 3.3 there) for details.

The rotational energy loss rate due to an isotropic particle wind is proportional to $L_{\rm p}^{1/2}$ (sect. 3 in Tong et al. 2013). Therefore, the period derivative will evolve with time as $\dot{P}(t) \propto L_{\rm p}^{1/2} \propto L_{\rm x}^{1/2} \propto F(t)^{1/2}$ (short term evolution, e.g. several years). Including a constant factor

$$\dot{P}(t) = N_0\, F(t)^{1/2}\,, \tag{2}$$

where N_0 is the normalization constant. The observed period derivative is the average value over a certain time span. Expanding the period at epoch t_1,

$$P(t) = P(t_1) + \dot{P}(t_1)(t - t_1)\,, \tag{3}$$

where $P(t)$ and $P(t_1)$ are the rotation period at times t and t_1, respectively, and $\dot{P}(t_1)$ is the period derivative at t_1. Therefore, the observed period derivative for time span $t - t_1$ is (t is the end time, t_1 is the start time)

$$\dot{P}_{\rm obs}(t - t_1) = \dot{P}(t_1) = \frac{1}{t - t_1}(P(t) - P(t_1))\,. \tag{4}$$

Rewriting the above equation,

$$\begin{aligned} \dot{P}_{\rm obs}(t - t_1) &= \frac{1}{t - t_1}\int_{t_1}^{t} \dot{P}(t'){\rm d}t' \\ &= N_0 \frac{1}{t - t_1}\int_{t_1}^{t} F(t')^{1/2}{\rm d}t' \\ &= N_0 g(t, t_1), \end{aligned} \tag{5}$$

where $g(t, t_1) = \int_{t_1}^{t} F(t')^{1/2}{\rm d}t'/(t - t_1)$ and $F(t)$ is obtained by fitting the observed flux decay (Eq. (1)).

The timing of Livingstone et al. (2011) is done for a time span of $85.5 - 1.5$ d after the BAT trigger time, but the timing of Scholz et al. (2012) is for a time span of $404.5 - 2.5$ d after the BAT trigger time. According to Equation (5), the ratio of period derivative between Scholz et al. (2012) and Livingstone et al. (2011) should be $g(404.5, 2.5)/g(85.5, 1.5) = 0.48$. The observed value is $0.683(21)/2.55(22)$, for solution 1 (The cases of solution 2 and solution 3 will be discussed in the next section). The observation and theory are consistent within uncertainties. The same can also be done for the timing of Rea et al. (2012). Using the observed flux decay there, the theoretical value of period derivative ratio between observations spanning 275 d and 90 d is 0.60 and the observed value is $0.83(2)/1.6(4)$. This shows the observation and theory are consistent with each other.

We can also plot the theoretical period derivative as a function of time span. Employing the period derivative of solution 1 in Scholz et al. (2012) as the normalization, the predicted period derivative as a function of time is

$$\dot{P}_{\rm obs}(t - t_1) = \dot{P}_{\rm obs}(404.5 - 2.5)\frac{g(t, t_1)}{g(404.5, 2.5)}\,. \tag{6}$$

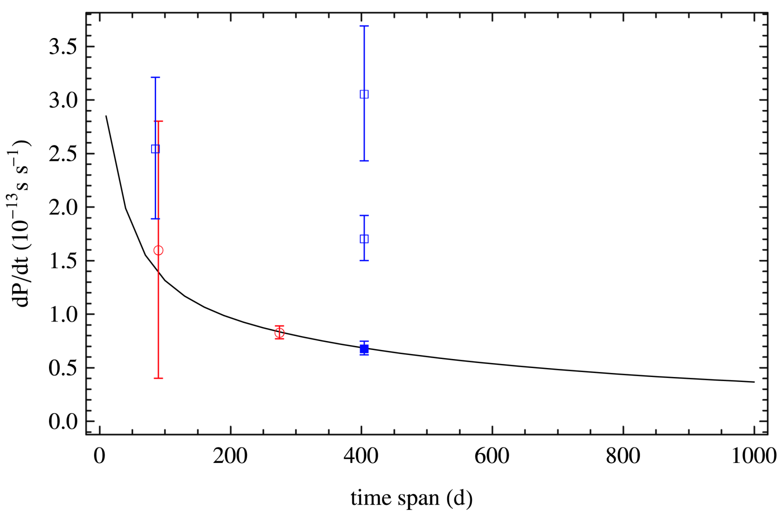

Fig. 1 Theoretical period derivative as a function of observed time span. The continuous line is the theoretical period derivative. Circles are timing data from Rea et al. (2012). Squares are timing data from Livingstone et al. (2011) and Scholz et al. (2012). The filled square is taken as normalization of the theoretical curve. The error bars are 3σ.

The timing solutions in Livingstone et al. (2011), Rea et al. (2012) and Scholz et al. (2012) are taken at different epochs (i.e., different t_1). However, the differences are only one or two days. Therefore, this difference is negligible. $t_1 = 2.5$ is assumed in the following calculations (the value of t_1 in Scholz et al. 2012).

Figure 1 shows the theoretical period derivative and the current observed data. The theoretical curve (using solution 1 in Scholz et al. (2012) as normalization) is consistent with the timing of Rea et al. (2012). The large uncertainties in the timing of Livingstone et al. (2011) and the result of timing over 90 d from Rea et al. (2012) may be due to timing noise.

In the future, when longer time spans for observations are available, a smaller period derivative is expected. For example, 800 d of timing observations will result in a period derivative of $\dot{P} = 0.44 \times 10^{-13}$. This is the theoretical period derivative averaged over 800 d. If separate timings can be done for the first 400 d and the last 400 d, a smaller period derivative is expected. Currently, timings of 400 d give a period derivative of $\dot{P} = 0.683 \times 10^{-13}$. A period derivative of $\dot{P} = 0.19 \times 10^{-13}$ is expected for only the last 400 d timing, which is about three times smaller. Future timing observations of Swift J1822.3−1606 will help clarify whether or not its period derivative is decreasing with time.

3 DISCUSSION AND CONCLUSIONS

The above calculations are mainly based on Equation (3). In Equation (3), only the first period derivative is included in the expansion. The observed $\dot{P}$ is the average value of period derivative over the observed time span. During timing studies, higher order period derivatives may also be included (e.g., solution 2 and solution 3 in Scholz et al. 2012). When higher order period derivatives are considered, the corresponding $\dot{P}$ will approach its instantaneous value at the expansion epoch. Therefore, the reported $\dot{P}$ represents an earlier value when higher order period derivatives are included. If the physical spin down rate is decreasing with time, we should see a larger $\dot{P}$ when higher order period derivatives are included. This is just the three timing solutions in Scholz et al.

(2012). Therefore, the three timing solutions of Scholz et al. (2012) provide us with another piece of evidence that the period derivative of Swift J1822.3−1606 is decreasing with time.

When calculating the theoretical spin down rate, the particle wind luminosity is assumed to be equal to the soft X-ray luminosity. The actual wind luminosity may have a slightly different value. After the outburst, the star's X-ray luminosity decreases with time. Since the particle wind is also from magnetic field decay, then it is natural that the wind luminosity also decreases with time. Therefore, a decreasing period derivative is always expected irrespective of the details of particle wind luminosity. In the long term, the X-ray luminosity will return to its quiescent value. The particle wind will also relax to its quiescent state. The long-term predicted period derivative is very sensitive to the condition of the quiescent state. When assuming $L_{\rm p} = L_{\rm x}$, the period derivative at late time will be $\dot{P} \propto F_{\rm q}^{1/2}$, where $F_{\rm q}$ is the quiescent flux. For a quiescent flux ten times higher, the late time period derivative will be three times larger.

The surface dipole field obtained by assuming magnetic dipole braking is only the effective field strength. In the presence of strong particle wind, the rotational energy loss rate is amplified. For a given period derivative, the resulting dipole field will be much lower (Tong et al. 2013). In the actual case, the geometry (e.g., the magnetic inclination angle) will also affect the spin down history of the neutron star (Tong & Xu 2012). In the case of normal pulsars, the assumption of magnetic dipole braking is a reasonable lowest order approximation (Xu & Qiao 2001). However, in the case of magnetars, the assumption of magnetic dipole braking will be too simple even at the lowest order approximation. An alternative is that magnetars are wind braking (Tong et al. 2013; Tong, Yuan, & Liu 2013). A decaying particle wind can result in a decreasing period derivative for Swift J1822.3−1606.

Another explanation for the decreasing period derivative is the twisted magnetosphere model (Thompson et al. 2002; Beloborodov 2009). After the outburst, the magnetar's magnetosphere gradually untwists. Therefore, the effect of the dipole magnetic field will decrease. This will cause a decreasing period derivative. However, the twisted magnetosphere model may have difficulties in explaining the variations in the period derivative that happen on a short timescale (Camilo et al. 2007; Levin et al. 2012). In the above wind braking of magnetars, the wind luminosity can vary dramatically on short timescales. Such difficulties no longer exist in the wind braking model.

In conclusion, the different timing results of Swift J1822.3−1606 are caused not only by its timing noise, but also by its decreasing period derivative. The decreasing period derivative and large timing noise may have both originated from wind braking. Future timing observations of Swift J1822.3−1606 will help to clarify whether or not its period derivative is decreasing with time. This would also help us to answer whether or not wind braking is important in this source.

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