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ANTI-GLITCH INDUCED BY COLLISION OF A SOLID BODY WITH THE MAGNETAR 1E 2259+586

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ABSTRACT

Glitches have been frequently observed in neutron stars. Previously, these glitches have unexceptionally manifested as sudden spin-ups that can be explained as being due to impulsive transfer of angular momentum from the interior superfluid component to the outer solid crust. Alternatively, they may also be due to large-scale crust-cracking events. However, an unprecedented anti-glitch was recently reported for the magnetar 1E 2259+586, which clearly exhibited a sudden spin-down, strongly challenging previous glitch theories. Here we show that the anti-glitch can be well explained by the collision of a small solid body with the magnetar. The intruder has a mass of about 1.1×10^{21} g. Its orbital angular momentum is assumed to be antiparallel to that of the spinning magnetar, so that the sudden spin-down can be naturally accounted for. The observed hard X-ray burst and decaying softer X-ray emission associated with the anti-glitch can also be reasonably explained. Our study indicates that a completely different type of glitch due to collisions between small bodies and neutron stars should exist and may have already been observed previously. It also hints at a new way of studying capture events by neutron stars: through accurate timing observations of pulsars.

Key words: planet–star interactions – pulsars: general – pulsars: individual (1E 2259+586) – stars: magnetars – stars: neutron

1. INTRODUCTION

Neutron stars are compact objects with typical mass $M_{\rm ns} \sim 1.4\ M_\odot$ and radius $R_{\rm ns} \sim 10^6$ cm. They usually appear as radio pulsars, with surface magnetic field $B_0 \sim 10^{11}$–10^{12} G. A small number of magnetars with B_0 significantly larger than 4.4×10^{13} G (Thompson & Duncan 1995; Mereghetti 2008; Olausen & Kaspi 2013) also exist. Glitches have been observed in both normal pulsars (Wang et al. 2000; Espinoza et al. 2011; Yu et al. 2013) and magnetars (Kaspi et al. 2000, 2003; Dib et al. 2008; Livingstone et al. 2010; Eichler & Shaisultanov 2010; Gavriil et al. 2011). Previously, these glitches have unexceptionally manifested as sudden spin-ups that may be due to impulsive transfer of angular momentum from the interior superfluid component to the outer solid crust (Anderson & Itoh 1975; Pines & Alpar 1985; Pizzochero 2011), or caused by large-scale crust-cracking events. However, recently, an unprecedented anti-glitch from the magnetar 1E 2259+586 was reported (Archibald et al. 2013), which clearly exhibited a strange sudden spin-down.

Anti-glitches could be due to either an internal or an external mechanism. For example, an impulsive angular momentum transfer between regions of more slowly spinning superfluid and the crust can produce the anti-glitch (Thompson et al. 2000). An external model such as strong outflows (Tong 2014), or a sudden twisting of the magnetic field lines (Lyutikov 2013), or accretion of retrograde matter (Katz 2013; Ouyed et al. 2013) can also cause the spin-down. However, most of these models involve gradual deceleration processes. They cannot generate a sudden spin-down and cannot account for the associated hard X-ray burst. Also, they can hardly explain the extreme rarity of anti-glitches.

In this study, we propose a completely different external mechanism for the anti-glitch. We suggest that the sudden spin-down could be due to the collision of a solid body with the magnetar. Our model can reasonably explain the associated hard X-ray burst and the decaying softer X-ray emission.

2. ANTI-GLITCH AS OBSERVED

The anomalous X-ray pulsar (AXP) 1E 2259+586 is a magnetar ($B_0 = 5.9 \times 10^{13}$ G) with a rotation period of about 7 s (rotation frequency $\nu \sim 0.143$ Hz) and frequency derivative of $\dot{\nu} = -9.8 \times 10^{-15}$ Hz s^{-1}, lying at a distance $d = 4 \pm 0.8$ kpc (Tian et al. 2010). Historically, two major spin-up glitches were observed in this AXP in 2002 (Woods et al. 2004) and 2007 (İçdem et al. 2012). In 2012 April, the pulse time of arrival (TOA) of 1E 2259+586 experienced a strange anomaly that is most prominently characterized by a clear sudden spin-down. The overall behavior can be described by two possible timing scenarios (Archibald et al. 2013). In the first, there is an instantaneous change in frequency $\Delta\nu = -4.5(6) \times 10^{-8}$ Hz on about April 18. This spin-down glitch was then followed by a spin-up glitch of amplitude $\Delta\nu = 3.6(7) \times 10^{-8}$ Hz that occurred about 90 days later. In the second scenario, an anti-glitch of $\Delta\nu = -9(1) \times 10^{-8}$ Hz occurred on April 21. Another anti-glitch of amplitude $\Delta\nu = -6.8(8) \times 10^{-8}$ Hz happened about 51 days later. Note that in this scenario, the amplitudes of the two anti-glitches are comparable.

The two scenarios fit the TOA data almost equally well (Archibald et al. 2013; however, see Hu et al. 2013 for a slightly different data analysis). It seems somewhat surprising that two very different scenarios could be consistent with the same data. The difference is actually due to the action of the persistent spin frequency derivative. In the first scenario, the fitted derivative is $\dot{\nu} \sim -3.7 \times 10^{-14}$ Hz s^{-1}. This enhanced spin-down episode lasts for a long period of about 90 days, leading to too much spin-down. So, it needs a normal spin-up glitch to compensate for the excess. In the second scenario, the fitted derivative is $\dot{\nu} \sim -2.3 \times 10^{-14}$ Hz s^{-1}, and this spin-down episode lasts only for about 51 days, which is clearly insufficient. So, it further needs another spin-down anti-glitch to be in line with the latest TOA data.

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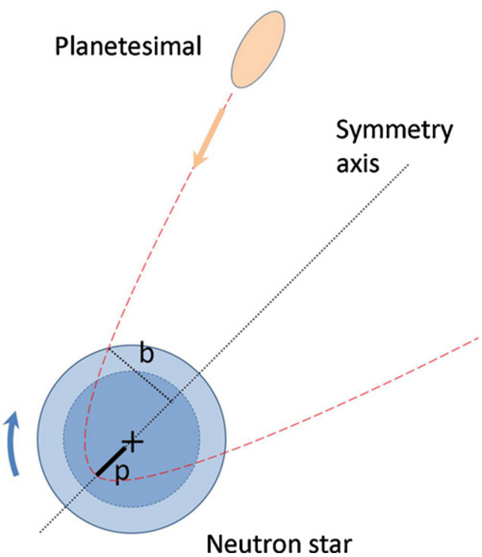

Figure 1. Schematic illustration of the collision process. The deep blue circle is the core of the neutron star, and the light blue ring represents the crust (not to scale). The planetesimal heads for the neutron star along a retrograde parabolic orbit (red dashed curve) with a periastron distance of p. For 1E 2259+586, p is $\sim 1.7 \times 10^4$ cm, and the impact parameter at the star surface is $b \sim 2.6 \times 10^5$ cm.

For the above two scenarios, additional observational facts may help us decide which one supports the truth better. Note that a hard X-ray burst with a duration of about 36 ms was detected by *Fermi*/GBM on 2012 April 21 (Foley et al. 2012), consistent with the epoch of the preceding anti-glitch. The observed fluence of $\sim 6 \times 10^{-8}$ erg cm^{-2} in the 10–1000 keV range corresponds to an energy release of $E_{\rm xb} \sim 1.1 \times 10^{38}$ erg. An increase in the 2–10 keV flux by a factor of two was also observed to be closely related to the anti-glitch (Archibald et al. 2013). It decayed continuously as a power-law function of time in $\sim$260 days. A simple integration then gives an extra energy release of $E_{\rm x} \sim 2.1 \times 10^{41}$ erg during this epoch. The flux increase was accompanied by a moderate change in the pulse profile (Archibald et al. 2013). On the contrary, as for the succeeding glitch/anti-glitch event, no associated radiative or profile changes were recorded. It strongly indicates that the preceding event and the succeeding event should be very different in nature. We thus believe that the first scenario, i.e., an anti-glitch plus a normal glitch, is more reasonable. We will carry out our study based on this description.

3. MODEL

3.1. *Small Body–Neutron Star Collision*

We propose that the sudden spin-down could be due to the collision of a small solid body with the magnetar. The planetesimal has a mass of $m_{\rm pl}$. It headed for the magnetar along a retrograde parabolic orbit, with a periastron distance of p (see Figure 1). Arriving at periastron, its velocity will be $V_{\rm pl} = (2GM_{\rm ns}/p)^{1/2}$, where G is the gravitational constant. The orbital angular momentum is $-m_{\rm pl} \cdot V_{\rm pl} \cdot p$. We assume that the planetesimal was captured by the magnetar. Conservation of angular momentum then gives

$$I_{\rm c} \cdot 2\pi\nu - m_{\rm pl} V_{\rm pl} p = I_{\rm c} \cdot 2\pi(\nu - \Delta\nu), \qquad (1)$$

where $I_{\rm c}$ is the moment of inertia of the neutron star crust and all stellar components that are rigidly coupled to it. Here we will first take $I_{\rm c} \sim 0.01 I_{\rm tot} \sim 10^{43}$ g cm^2 as a typical value (Pizzochero 2011; Hooker et al. 2013), with $I_{\rm tot}$ being the moment of inertia of the whole star. However, in Section 5, we will discuss the other extreme wherein the superfluid in the core strongly couples to the crust as a whole. Equation (1) can be further simplified as

$$m_{\rm pl}\sqrt{2GM_{\rm ns}p} = 2\pi I_{\rm c} \cdot \Delta\nu. \qquad (2)$$

The collision is a very complicated process. Tidal heating and Ohmic dissipation heating may happen. Part of the planetesimal will be evaporated, ionized, and lost. The pulsar may even be temporarily quenched (Cordes & Shannon 2008; Mottez et al. 2013a, 2013b). Here in our analysis, we omit many of the subtle effects for simplicity. Falling of the solid body onto the compact star can lead to the release of binding energy of $GM_{\rm ns}m_{\rm pl}/R_{\rm ns}$. The efficiency of transferring this energy into *prompt* high temperature radiation (i.e., a burst) is very small for a neutron star without a magnetic field. However, the strong magnetic field of 1E 2259+586 can help increase the efficiency significantly (Colgate & Petschek 1981). Also, although the impact process may manifest as a series of falling-backs and re-expansions, the majority of the binding energy should finally be deposited as thermal energy onto the star crust, leading to an enhanced and much prolonged X-ray afterglow (Harwit & Salpeter 1973). This may correspond to the decaying X-ray emission associated with the anti-glitch of 1E 2259+586. As mentioned before, the observed extra energy release connected to the anti-glitch is $E_{\rm xb} + E_{\rm x} \sim E_{\rm x}$. Taking $E_{\rm x} \sim GM_{\rm ns}m_{\rm pl}/R_{\rm ns}$, we obtain the required mass of the planetesimal to be $m_{\rm pl} \sim 1.1 \times 10^{21}$ g. Substituting $m_{\rm pl}$ into Equation (2), we further obtain the periastron distance to be $p = 1.7 \times 10^4$ cm. Of course, in this case, the solid body will collide with the neutron star before arriving at the periastron (see Figure 1). The off-axis distance of the impact point on the neutron star surface (i.e., the impact parameter) is $b \sim 2.6 \times 10^5$ cm.

We now give a more detailed description of the collision. For simplicity, we assume that the planetesimal is a homogeneous iron–nickel body with density $\rho_{\rm pl} = 8$ g cm^{-3} (Colgate & Petschek 1981). Its radius is then $r_{\rm pl} = 3.2 \times 10^6$ cm. Originally, the planetesimal is a sphere. When approaching the neutron star, it will elongate due to strong tidal force. The likely maximum shear strength of the Fe–Ni body is $S = 10^{10}$ dyn cm^{-2}. So, it will break up at the distance of $\sim 1.2 \times 10^{10}$ cm given by (Colgate & Petschek 1981)

$$R_{\rm b} = \left(\rho_{\rm pl} r_{\rm pl}^2 M_{\rm ns} G/S\right)^{1/3}. \qquad (3)$$

When the material finally pushes through the strong magnetic field, it will be compressed to a thin sheet with the thickness of only a few millimeters and density up to 10^6 g cm^{-3}. It also stretches significantly in length. As a result, the time difference of arrival at the neutron star surface becomes (Colgate & Petschek 1981)

$$\Delta t_{\rm a} = \frac{2r_{\rm pl}}{3} \cdot \left(\frac{2GM_{\rm ns}}{R_{\rm b}}\right)^{-1/2}. \qquad (4)$$

Taking $m_{\rm pl} = 1.1 \times 10^{21}$ g, a binding energy of 2.1×10^{41} erg will be released during the fierce impact. Most of the energy will be reconverted into kinetic energy due to plume development excited by the collision. However, even a small portion of $\sim 5 \times 10^{-4}$ being radiated in the 10–1000 keV range will be enough to account for the observed hard X-ray burst

($E_{xb} \sim 1.1 \times 10^{38}$ erg) connected to the anti-glitch. The calculated duration of $\Delta t_a = 12$ ms from Equation (4) is slightly less than that of the burst (36 ms). But it is acceptable since Δt_a may mainly correspond to the rising phase of the hard X-ray burst. Other portions of the binding energy will finally be deposited as thermal energy onto the crust after complicated processes. Heat diffusion can lead to a power-law decay of softer X-ray emission on a relatively long timescale (Lyubarsky et al. 2002), which may correspond to the power-law decay of the 2–10 keV flux after the anti-glitch.

3.2. Origin of the Small Body

Since a neutron star can retain its planetary system during the violent supernova explosion that gives birth to it (Wolszczan 1994), we speculate that there are various possibilities for the solid body. First, asteroids could be gravitationally disturbed by other planets and be scattered toward the central star (van Buren 1981; Guillochon et al. 2011). Second, as in our solar system, circumstellar Oort-like clouds might also exist around the neutron star. Comets in these regions can also fall toward the central star due to the disturbance caused by nearby stars (Tremaine & Zytkow 1986; Downs et al. 2013). Third, in a system with multiple planets, the planets may have chances to collide with each other and produce some clumps with a negative angular momentum (Katz et al. 1994; Ford & Rasio 2008). Fourth, even if the neutron star escapes the planetary system due to a large kick velocity, it will take the runner ∼2400 yr to pass through the planetary system and the Oort-like clouds. During this period, the probability of capturing small bodies will be considerable (Zhang et al. 2000). Finally, a neutron star, due to its proper motion in space, may occasionally encounter other stars that possess a comet cloud, and may experience an episode of copious collisions (Pineault & Poisson 1989; Shull & Stern 1995).

When modeling 1E 2259+586, we derived a relatively small periastron distance of $p = 1.7 \times 10^4$ cm. But actually, the capture radius can be much larger. When a solid body is passing through the magnetosphere of a pulsar, strong Alfvén waves will be excited which can carry away angular momentum very quickly. As a result, the material falls onto the neutron star if (Tremaine & Zytkow 1986)

$$p \leqslant \left(\frac{9}{32\pi^2 G c^2} \cdot \frac{B_0^4 R_{ns}^{12}}{r_{pl}^2 \rho_{pl}^2 M_{ns}} \right)^{1/9}. \tag{5}$$

For a magnetar, the capture distance can be $\sim 20 R_{ns}$. Also note that small bodies with p up to $\sim 80 R_{ns}$ (or possibly even larger) will be disrupted on their first passage and then accreted on their second or subsequent passages (Tremaine & Zytkow 1986; Livio & Taam 1987). Additionally, if the solid body was of icy composition with $\rho_{pl} \sim 1$ g cm^{-3}, the allowed distance will further increase by about 1.5 times.

Recently, the interaction between a relativistic pulsar wind and the orbiting small body was studied in great detail by Mottez & Heyvaerts (2011a, 2011b). It was found that Alfvén wing structures will form when the planet moves in the centrifugally driven wind. As a result, the orbit will drift at a rate of (Mottez & Heyvaerts 2011b)

$$\left| \frac{da}{dt} \right| \sim \frac{16\pi r_{pl}^2 R_{ns}^4 B_0^2 \nu}{\mu_0 c m_{pl} \sqrt{G M_{ns} a^3}}, \tag{6}$$

where a is the semi-major axis and μ_0 is the magnetic permeability of vacuum. Note that Equation (6) needs a correction when the eccentricity is not zero. For a prograde orbit, a increases and the orbit becomes more distant, but for a retrograde orbit, a decreases. The effect is very significant for a planetesimal with a diameter ⩽100 km. For example, for a retrograde small body with $r_{pl} = 30$ km, $m_{pl} = 10^{21}$ g, and $a = 10^{12}$ cm, we have $da/dt \sim -2.8 \times 10^9$ cm yr^{-1}. A retrograde planetesimal could thus be captured in less than ∼1000 yr even if it is initially at a distance of ∼0.1 AU. This effect can markedly increase the capture rate.

However, the exact event rate is very difficult to calculate due to many uncertainties concerning the planetary system of pulsars. For example, a preliminary estimate by Mitrofanov & Sagdeev (1990) gives a wide range of one event every 5000–3×10^7 yr for a single neutron star, depending on various assumptions of the capture radius, the relative velocity at infinity, and the number density of small bodies. In some special cases such as during comet showers, the event rate can even be as high as ∼1 yr^{-1} (Tremaine & Zytkow 1986; Zhang et al. 2000; Livio & Taam 1987). For the whole Milky Way, Wasserman & Salpeter (1994) argued that of order 0.1–1 collisions may happen daily in the halo if the mass function extends continuously from brown dwarfs to asteroids.

4. EXPLANATION OF THE SUBSEQUENT NORMAL GLITCH

For the subsequent normal spin-up glitch of amplitude $\Delta\nu = 3.6(7) \times 10^{-8}$ Hz that occurred about 90 days later, we suggest that it can be explained by usual glitch mechanisms, such as the mechanism involving co-rotation of unpinned vortices under weak drag forces (Pizzochero 2011). According to this mechanism, vortices in the superfluid star core are only weakly pinned to the lattice of a normal nuclear component. As the neutron star slows down, vortices are continuously depinned and then rapidly repinned. This dynamical creep can effectively shift the excess vorticity outward on short timescales. The transferred core vorticity will be repinned in the neutron star crust, where the pinning force increases rapidly by orders of magnitude. When the accumulated spin frequency lag exceeds the maximum value ($\Delta\nu_{max}$) that can be endured by the crust, a sudden spin-up glitch will happen. Major normal glitches were observed in 1E 2259+586 in 2002, 2007, and 2012. They show an obvious periodicity, which means that the typical interval between glitches is $\Delta t_{gl} \sim 5$ yr. The maximum frequency lag can then be calculated as $\Delta\nu_{max} = \Delta t_{gl} \cdot |\dot{\nu}| = 1.5 \times 10^{-6}$ Hz (Pizzochero 2011).

In the crust, the maximum pinning force is obtained when the density is $\rho_m \sim 0.2\rho_0$, with ρ_0 the nuclear saturation density. Define a dimensionless radius $x = R/R_{ns}$, then ρ_m corresponds to $x_m = 1$–$4\rho_m R_{ns}^3/(\pi M_{ns}) \approx 0.97$. The angular momentum stored for Δt_{gl} and released at the glitch is $\Delta L_{gl} = I_\nu(x_m) \cdot \Delta\nu_{max}$, where $I_\nu(x_m)$ is the effective moment of inertia. Then, the amplitude of the glitch is (Pizzochero 2011)

$$\Delta\nu = \frac{\Delta L_{gl}}{I_{tot}[1 - Q(1 - Y_{gl})]}, \tag{7}$$

where Q is the standard superfluid fraction, and Y_{gl} is a parameter that globally describes the fraction of vorticity coupled to the normal crust on timescales of the glitch rise time.

In Equation (7), taking typical parameters to be $Q = 0.95$ and $Y_{gl} = 0.05$ (Pizzochero 2011), we can then obtain a predicted glitch amplitude of $\Delta\nu = 3.1 \times 10^{-8}$ Hz for 1E 2259+586. It is in good agreement with the observed value of $3.6(7) \times 10^{-8}$ Hz.

5. DISCUSSION

Collisions between small bodies and neutron stars are basically possible. This mechanism has been widely engaged to account for various transient X-ray/γ-ray events (Colgate & Petschek 1981; van Buren 1981; Tremaine & Zytkow 1986; Livio & Taam 1987; Pineault & Poisson 1989; Mitrofanov & Sagdeev 1990; Katz et al. 1994; Wasserman & Salpeter 1994; Shull & Stern 1995; Zhang et al. 2000; Cordes & Shannon 2008; Campana et al. 2011). In previous studies, most of the attention has been paid to the associated radiative activities. Here we suggest that they potentially can also be diagnosed through accurate timing observations of pulsars. This might be a more realistic way, since many pulsars are routinely monitored and the pulse TOA data are of extremely high accuracy.

In our calculations, for the moment of inertia, we have taken $I_c \sim 0.01 I_{tot}$. Although this is a reasonable assumption for 1E 2259+586 (Kaspi et al. 2003; İçdem et al. 2012), there are also indications that in some pulsars, the superfluid in the core may become strongly coupled to the crust over a very short timescale (Pines & Alpar 1985; Wang et al. 2000; Yu et al. 2013). So, we now discuss another choice for $I_c \sim I_{tot}$. Since the mass of the small body is determined from the observed X-ray fluence, m_{pl} in Equation (2) will remain unchanged. We can then derive the periastron distance as $p \approx 1.7 \times 10^8$ cm $\sim 170 R_{ns}$. According to the discussion in Section 3.2, the planetesimal may not be directly captured in this case, but it could be disrupted on its first passage and then accreted on its second or subsequent passages. Specifically, the magnetic thrust action due to Alfvén wings (Mottez & Heyvaerts 2011a, 2011b) may play a key role in the process because the orbit drift rate could be as large as $da/dt \sim -1.2 \times 10^{15}$ cm yr^{-1} according to Equation (6). So, an anti-glitch of similar amplitude will still occur.

The collisions between small bodies and neutron stars can also lead to normal spin-up glitches, which is a completely different external mechanism. In fact, considering the coplanarity of almost all planetary systems observed so far, the chance of producing spin-up glitches should be much larger than that for anti-glitches. We speculate that among the several hundred normal glitches observed so far, some might actually be collision events.

A basic feature of collision-induced glitches is that they are unlikely to show any periodicity for a single neutron star. Also, they are more likely to happen in young pulsars than in old pulsars, since the orbital motion of small bodies might be more unstable soon after the supernova explosion. Note that a collision-induced glitch can be either radiatively active or silent. In Equation (2), if we take $p = 40 R_{ns}$, then a mass of $m_{pl} = 2.3 \times 10^{19}$ g will be enough to produce a glitch with amplitude similar to that of the anti-glitch observed in 1E 2259+586. In this case, since m_{pl} is lower by a factor of $\sim$50, it is expected that the associated X-ray burst will be very weak and hard to detect.

Finally, it is interesting to note that observational evidence for asteroids at a close distance to PSR B1931+24 was recently reported (Mottez et al. 2013a, 2013b). For PSR J0738−4042, evidence of an asteroid interacting with the pulsar was also declared very recently (Brook et al. 2014). In the future, more observations would be available and should be helpful for probing such collision events.

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