THE EVOLUTION OF A NEWBORN MILLISECOND MAGNETAR WITH A PROPELLER-RECYCLING DISK

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ABSTRACT

A rapidly rotating and highly magnetized neutron star (NS) could be formed from the explosive phenomena such as superluminous supernovae and gamma-ray bursts. This newborn NS can substantially influence the emission of these explosive transients through its spin-down. The spin-down evolution of the NS can sometimes be affected by fallback accretion, although it is usually regulated by the magnetic dipole radiation and gravitational wave radiation of the NS. Under appropriate conditions, the accreting material can be firstly ejected and subsequently recycled back, so that the accretion disk can keep in a quasi-steady state for a long time. Here we describe the interaction of the NS with such a propeller-recycling disk and their co-evolution. Our result shows that, the spin-down of the NS can be initially dominated by the propeller, which prevents the disk material from falling onto the NS until hundreds or thousands of seconds later. It is suggested that the abrupt fall of the disk material onto the NS could significantly suppress the magnetic dipole radiation and then convert the NS from a normal magnetar to a low-field magnetar. This evolution behavior of the newborn NS can help to understand the very different influence of the NS on the early GRB afterglows and the late supernova/kilonova emission.

\textit{Subject headings:} stars: neutron - accretion - gamma-ray burst: general

1. INTRODUCTION

It is widely considered that a rapidly rotating and highly magnetized neutron star (NS) could be formed from the core-collapse of some massive stars, which can be characterized by a long-duration gamma-ray burst (GRB) or a superluminous supernova (SLSN). The existence of such a millisecond magnetar is beneficial for explaining the long-lasting energy engine of these phenomena for the first few hours or days (Dai & Lu 1998a,b; Zhang & Mészáros 2001; Kasen & Bildsten 2010; Yu et al. 2017). It was also suggested that a millisecond magnetar can be formed from some mergers of double NSs which produce the short-duration GRBs (Dai et al. 2006; Rowlinson et al. 2013; Zhang 2013; Yu et al. 2013; Metzger & Piro 2014). This hypothesis, if true, can provide a robust constraint on the equation of state of NS matter, since the remnant NS of mergers must have very high masses. Therefore, in order to confront this model with observations in more details in the future, it is necessary to investigate the energy release process of these millisecond magnetars more carefully. In addition, such an investigation can also help to discover the theoretically predicted accretion-induced collapse events (AICs) of white dwarfs in future transient surveys (Dessart et al. 2006; Piro & Thompson 2014; Yu et al. 2019a,b).

The influence of a newborn NS on the accompanied transient emission is highly dependent on the spin-down behavior of the NS. The spin-down is usually determined by the magnetic dipole (MD) radiation and, sometimes, also by the gravitational wave (GW) radiation if the ellipticity of the NS is high enough. Meanwhile, it is natural to consider that a fraction of the material in supernova ejecta or merger ejecta could not escape from the central NS and finally fall back onto the NS. In this case, the early evolution of the newborn NS and consequently the transient emission would be influenced by this fallback accretion (Dai & Liu 2012; Kumar et al. 2008a,b), despite the majority of the material falls only on a very short timescale. However, it should still be noticed that the accretion can sometimes enter a propeller state, if the NS is highly magnetized and rapidly rotating, as expected for the NSs in GRBs and SLSNe. In this case, the material could be ejected away by the centrifugal force rather than be accreted onto the NS (Illarionov & Syunyaev 1975; Alpar & Shaham 1985; Lovelace et al. 1999). This propeller effect has been widely discussed in the literature and supported by the observations of some accreting millisecond pulsars (van der Klis et al. 2000; Patruno et al. 2009; Patruno & D’Angelo 2013; Bult & van der Klis 2014). Piro & Ott (2011) suggested that some unusual supernovae could be powered by a propeller outflow, in addition to the traditional radioactive power. Gompertz et al. (2014) used the propeller outflow to explain the extended emission and the X-ray afterglow plateau of some short GRBs. The combining effects of fallback accretion and propeller on GRBs and SLSNe have been investigated by Metzger et al. (2018).

However, alternatively, it is still worth considering that the propeller, even though operating, may not be strong enough to eject the material to infinity. Instead, the propeller-ejected material could finally fall back to the disk at a certain radius. In other words, the material in the disk can be recycled for a long time and maintain a quasi-steady state, which is somewhat similar to a dead disk surrounding a pulsar in a binary (Syunyaev & Shakura 1977; Spruit & Taam 1993; D’Angelo & Spruit 2010, 2012; Romanova et al. 2018). Nevertheless, even though the disk is quasi-steady, the NS can still be spun...
down by the propeller and, finally, the disk material must fall onto the NS. When the material lands on the polar surface of the NS, it can in principle repel the magnetic field lines from the polar cap region or even bury some field lines. As a result of this delayed accretion, the effective dipolar magnetic field can be decreased and then the MD radiation is suppressed, which can undoubtedly influence the energy release from the NS and the accompanied transient emission. The purpose of this paper is to calculate the early evolution of a newborn millisecond magnetar under the influence of such a propeller-recycling accretion disk.

2. THE ACCRETION AND PROPELLER

The primary reason for the existence of a long-lived propeller-recycling disk is that the high magnetic field of the central NS can drag and accelerate the disk material and then prevent the material from falling onto the NS. Therefore, balancing the magnetic pressure and the ram pressure of the accretion flow, the inner boundary of the disk can be roughly determined by the Alfvén radius as

\[ R_m = \left(\frac{\mu^4}{GM_m M_{\text{disk}}^2}\right)\frac{1}{1/7} = 2.8 \times 10^6 M_{s,1.4}^{-1/7} P_{s,6}^{12/7} P_{s,14}^{3/7} M_{\text{disk},-5}^{-1/7} \text{ cm}, \]

(1)

where \( \mu = B_s R_s^4 \) is the magnetic moment of NS, \( G \) is the gravitational constant, \( M_{\text{disk}} \) is the mass rate of accretion flow in the disk, \( B_s \) and \( M_s \) are the strength of surface dipolar magnetic field, the radius, and the mass of NS, respectively. Hereafter the conventional notation \( Q_x = Q/10^x \) is adopted in the cgs units and, additionally, \( M_{s,1.4} = M_s/1.4 M_\odot \) and \( M_{\text{disk},-5} = M_{\text{disk}}/10^{-5} M_\odot \) s\(^{-1} \). Once the disk material enters the region inside \( R_m \), the high magnetic pressure can enforce the material to corotate with the NS. Then, we can judge whether the disk is in the accretion or the propeller state by comparing this Alfvén radius with the corotation radius. Here the corotation radius can be defined by

\[ R_c = \left(\frac{GM_s}{\Omega_s^2}\right)^{1/3} = 1.7 \times 10^6 M_{s,1.4}^{1/3} P_{s,6}^{2/3} \text{ cm}, \]

(2)

where \( \Omega_s \) is the spin frequency of NS and \( P_s = 2\pi/\Omega_s \) is the spin period. The disk material is rotating at the Keplerian frequency \( \Omega_K = \sqrt{GM_s/R_c^3} \) at each radius. Inside \( R_c \), the spin frequency of NS is slower than the Keplerian frequency.

If \( R_m < R_c \), the magnetic field would first slow down the disk material inside \( R_c \). Once the angular momentum of the material is lost, the disk material can no longer keep Keplerian rotation at the orbit and finally fall onto the surface of the NS along the magnetic field lines. Consequently, the angular momentum carried by the disk material can be gradually transferred to the NS and spin it up. The torque acting on the NS due to accretion can be expressed by

\[ T_{\text{acc}} = M_{\text{acc}} P_m^2 \Omega_{K,m} \approx M_{\text{acc}} \sqrt{GM_s R_m}, \]

(3)

Elaborated calculations show that the proportional coefficient between the inner disk radius and the Alfvén radius could range from 0.5 to 1 (Ghosh & Lamb 1979a,b; Arons 1986, 1993), which however essentially cannot affect the calculations in this paper.

where \( \Omega_{K,m} = \sqrt{GM_s/R_m^3} \) is the Keplerian frequency at the Alfvén radius and \( M_{\text{acc}} \) is the mass rate accreted onto the NS. On the contrary, if \( R_m > R_c \), the disk material would be accelerated by the magnetic field to approach corotation outside \( R_c \). As a result, the velocity of disk material exceeds the Keplerian velocity and the gravity becomes too small to support it. Then, the centrifugal force can strongly throw the material away from the disk to produce a propeller outflow. Meanwhile, the NS is spun down and the corresponding torque can be written as (Lai 2014)

\[ T_{\text{pro}} = -\dot{M}_{\text{pro}} R_m^2 \Omega_s, \]

(4)

where \( \dot{M}_{\text{pro}} \) is the mass rate of the propeller outflow.

In order to describe the continuous transition between the propeller and accretion phases, a fastness parameter is defined for the NS and disk system as

\[ \omega = \frac{\Omega_s}{\Omega_{K,m}} = \left(\frac{R_m}{R_c}\right)^{3/2} = 2.2 M_{s,1.4}^{-5/7} P_{s,6}^{18/7} B_{s,14}^6 M_{\text{disk},-5}^{-3/7} P_{s,3}^{-1}. \]

(5)

Obviously, the value of \( \omega \) reflects the proportional relationship between the two characteristic radii. By using this parameter, we can phenomenologically express the disk mass change rate in terms of accretion rate and propeller mass loss rate by

\[ \dot{M}_{\text{disk}} = \dot{M}_{\text{acc}} + \dot{M}_{\text{pro}} \]

(6)

with

\[ \dot{M}_{\text{acc}} = 1 + \omega^n \dot{M}_{\text{disk}} \]

(7)

and

\[ \dot{M}_{\text{pro}} = \frac{\omega^n}{1 + \omega^n} \dot{M}_{\text{disk}}, \]

(8)

where the artificial parameter \( n > 1 \) is introduced to represent the sharpness of the phase transition. The above expressions can naturally give \( \dot{M}_{\text{acc}} \approx \dot{M}_{\text{disk}} \) and \( \dot{M}_{\text{pro}} \approx 0 \) for \( \omega \ll 1 \), and \( \dot{M}_{\text{pro}} \approx \dot{M}_{\text{disk}} \) and \( \dot{M}_{\text{acc}} \approx 0 \) for \( \omega \gg 1 \). Substituting Equations (7) and (8) into Equations (3) and (4), the total torque acting on the NS by the disk can be written as

\[ T_{\text{disk}} = T_{\text{acc}} + T_{\text{pro}} = 1 - \omega^{n+1} \frac{\dot{M}_{\text{disk}}}{1 + \omega^n} \sqrt{GM_s R_m}. \]

(9)

When \( \omega = 1 \), the accretion and the propeller effects become comparable to each other and then the total torque vanishes.

The propeller outflow escaping from the Alfvén radius is usually supposed to be able to escape to infinity, as long as the centrifugal velocity of the material exceeds the escaping velocity at the radius, i.e., \( v_{\text{pro}} \approx \Omega_s R_m > v_{\text{esc}} = \sqrt{2GM_s/R_m} = \sqrt{2\Omega_K R_m} \). However, this assumption is actually challenged by the following considerations. Firstly, the propeller acceleration could be inefficient, because the material can in principle be thrown out much before it completely achieves corotation at the Alfvén radius (Syunyaev & Shakura 1977). Secondly, the kinetic energy of the propeller material can
be substantially consumed by some internal dissipations in the outflow. Finally, the propeller velocity is probably dominated by the azimuthal component and the component perpendicular to the disk could be relatively small. So, the propeller material is in principle easy to collide with the successive falling material. The viscous friction between the outward and inward flows can significantly decelerate the propeller outflow. In an extreme case, the propeller outflow can even be completely obstructed and absorbed by the accretion disk. Due to this material recycling, the disk can basically keep in a quasi-steady state. The net consequence of the propeller effect is just to transfer angular momentum from the NS to the disk (Matt et al. 2010; D’Angelo & Spruit 2010, 2012). Therefore, the necessary condition for the existence of a quasi-steady disk is that the disk should initially be in a propeller state for \( \omega > 1 \). According to equation (5), the corresponding requirement on the initial mass flow rate of the disk can be written as

\[
\dot{M}_{\text{disk,i}} < 6.0 \times 10^{-5} M_{\odot}^{-5/3} R_s^{6/5} T_{\text{disk}}^{-7/3} \approx 10^{-7} M_{\odot}^{-1} \text{s}^{-1} \quad (10)
\]

As shown, for given NS parameters, a relatively small mass flow rate is helpful for the appearance of a long-lived quasi-steady disk. Therefore, qualitatively, such a disk tends to exist in the events of double NS mergers and white dwarf AICs, in contrast to the normal core-collapse supernovae (Macfadyen et al. 2001; Rosswog 2007).

3. THE NS AND DISK EVOLUTIONS

In the presence of a quasi-steady propeller-receding disk, the spin evolution of the central NS should be determined by

\[
\frac{dJ_s}{dt} = T_{\text{md}} + T_{\text{gw}} + T_{\text{disk}}, \quad (11)
\]

where \( J_s = L_s \Omega_s \) is the angular momentum of the NS, \( L_s \approx (2/5)M_s R_s^2 \) is the inertial moment of the NS, \( T_{\text{md}} \) and \( T_{\text{gw}} \) are the torques due to MD radiation and GW radiation, respectively. Since the inner boundary of the disk can extend into the light cylinder of the NS, some closed magnetic field lines of the NS can be truncated in the disk and become open lines. In this case, the MD radiation of the NS can be enhanced by a factor of \((R_m/R_{lc})^{-2} \) (Parfrey et al. 2016). Therefore, the corresponding torque can be written as (Metzger et al. 2018)

\[
T_{\text{md}} = -\frac{\mu^2 \Omega_s^2}{6c^3} \left( \frac{R_m}{R_{lc}} \right)^2, \quad (12)
\]

where \( R_{lc} = c/\Omega_s \) is the light cylinder radius of the NS. For a magnetar, it is usually considered that the internal magnetic field can be much higher than the surface dipolar magnetic field (e.g. Duncan & Thompson 1992; Price & Rosswog 2006). Then, the NS could be deformed by the internal magnetic field to have an ellipticity of \( \varepsilon = 10^{-3}(B_{\text{int}}/10^{18} \text{G})^2 \) (Usov 1992; Fan et al. 2013; Gao et al. 2016). In this case, a secular GW radiation can be produced and the corresponding torque can be written as (Zhang & Meszáros 2001)

\[
T_{\text{gw}} = -\frac{32G\mu^2 \varepsilon^2 \Omega_s^5}{5c^4}, \quad (13)
\]

which is usually much smaller than the torque given by Equation (12) unless the surface dipolar magnetic field is much lower than \( \sim 10^{12} \text{G} \).

Besides the influence on the spin evolution of the NS, the disk can also lead to a change of the mass and the surface magnetic field of the NS, once the disk enters the accretion phase. On one hand, the baryonic mass of the NS can evolve as \( dM_{\text{acc}}/dt = M_{\text{acc}} \) and subsequently the gravitational mass can be determined by \( M_{\text{b,NS}} = M_{\text{b,NS}}(1 + 3GM_{\text{b,NS}}/5R_{\odot}c^2)^{-1} \) (Dai & Liu 2012). The corresponding changes in the radius and inertial moment of the NS depend on the specific equation of state. For simplicity, we use a constant NS radius in our calculation, in view that the total mass of the accretion disk is relatively small. On the other hand, in principle, the material fallen onto the NS surface could repel some open field lines into the closed region and even bury some lines. Then, the surface dipolar magnetic field can be reduced, which may be assumed to follow an empirical behavior as (Taam & van den Heuvel 1986; Shibazaki et al. 1989; Fu & Li 2013)

\[
B_s(t) = \frac{B_{s,i}}{1 + M_{\text{acc}}(t)/M_c}, \quad (14)
\]

where \( B_{s,i} \) is the initial strength of the surface dipolar field, \( M_{\text{acc}}(t) = \int_0^t M_{\text{acc}}(\tau) d\tau \) is the total mass of the accreted material, and the critical mass \( M_c \) is considered to be on the order of \( (10^{-5} - 10^{-3})M_{\odot} \) although it is very uncertain (Shibazaki 1989; Cheng & Zhang 1998; Zhang & Kojima 2006). Tentatively, a relatively high value of \( M_c = 0.001M_{\odot} \) is adopted in our calculation. After the surface dipolar field is suppressed, the NS would exhibit as a normal pulsar rather than a magnetar, from the perspective of its MD radiation. Here it should be mentioned that the surface multi-polar magnetic fields as well as the magnetic fields internal to the neutron star should not be significantly affected by accretion and should remain strong as before. In any case, through Ohmic diffusion and Hall drift, the repelled/buried field lines could finally return to their original positions (Gepper et al. 1999) and then the NS can become a magnetar again. However, since these diffusions are usually very slow, the corresponding timescales could be as long as a few hundred years (Fu & Li 2013), which is much longer than the time of interest here.

Accompanying with the evolution of the NS, the mass and the angular momentum of the accretion disk evolves as

\[
\frac{dM_{\text{disk}}}{dt} = -\dot{M}_{\text{disk}} + \dot{M}_{\text{rec}}, \quad (15)
\]

\[
\frac{dJ_{\text{disk}}}{dt} = -T_{\text{disk}} + T_{\text{rec}}. \quad (16)
\]

Here the mass flow rate of the disk can be determined by \( \dot{M}_{\text{disk}} = M_{\text{disk}}/\tau_v \), where \( M_{\text{disk}} \) is the total mass of the disk and \( \tau_v \) is the viscosity timescale. This viscosity timescale can be given as \( \tau_v = R_{\text{out}}^2/\nu \approx 2/\alpha \Omega_{K_{\text{out}}} \), where \( R_{\text{out}} \) is the outer radius of the disk and \( \alpha \) is the dimensionless viscosity parameter (Shakura & Syunyaev 1973). Following Kumar et al. (2008a, b), Metzger et al. (2008), and Lei et al. (2017), we assume that the disk has a simple ring shape and its mass is concentrated at the
outer radius. Then, the angular momentum of the disk can be expressed by $J_{\text{disk}} \approx \sqrt{GM_sR_{\text{out}}M_{\text{disk}}}$. Finally, we can simply take $M_{\text{rec}} = M_{\text{pro}}$ and $T_{\text{rec}} = T_{\text{pro}}$ for the propeller-recycling state.

By solving Equations (11), (15) and (19), we present the temporal evolutions of the fundamental parameters of the NS and the disk in Figure 1 where the initial values of the parameters are taken to ensure that the propeller condition given in Equation (10) can be satisfied at the beginning. Specifically, as the NS spins down initially due to the propeller, the stellar angular momentum can be effectively transferred to the disk, although it could still be insignificant compared with the original angular momentum of the disk. Meanwhile, the mass of the disk also keeps invariant, because the propeller material is assumed to be totally recycled back to the disk. Nevertheless, as the NS continuously spins down, the disk would finally enter the accretion phase. The accretion onto the NS surface suppresses the surface magnetic field and thus the Alfvén radius is decreased, which reduces the value of $\omega$. Then, the decrease of $\omega$ can further make the accretion more efficient. As a result, the disk evolves from the propeller phase to the accretion phase very quickly. Simultaneously, due to the sharp decay of the magnetic field, the MD radiation of the NS can be suppressed significantly. This feature can be used to explain the sharp decay following the so-called internal-plateau GRB afterglow, which was usually explained by the collapse of the NS (e.g., Troja et al. 2007; Lyons et al. 2010; Zhang 2014; Lü & Zhang 2014; Liu et al. 2015). After this sharp decay, the spin-down of the NS can be sometimes dominated by the GW radiation, if the NS is deformed significantly by its internal magnetic field (e.g., Gao et al. 2016; Yu et al. 2018). As the accretion continues, the mass of the disk decreases substantially, which leads to the increase of the outer radius and as well as the viscosity timescale. Consequently, the accretion rate can be reduced following an usual temporal behavior of $t^{-5/3}$ (Michel 1988; Chevalier 1989). As the decrease of the accretion rate, the value of $\omega$ can finally rebound to increase and then, for $\omega \approx 1$, a general balance appears between the accretion and the propeller. At this stage, the decrease of the accretion rate would become somewhat slower than $t^{-5/3}$.

In Figure 2 we present the influence of the variation of the model parameters $B_{s,i}$, $P_{s,i}$, and $M_{\text{disk},i}$ on the evolution of the crucial parameter $\omega$, which delineates the evolutionary behavior of the NS and the disk. Obviously, as usually known, the propeller is more likely to happen for more rapid rotation and higher magnetic fields. For a sufficiently small disk mass to satisfy $\omega_i > 1$, the duration of the propeller phase and the lifetime of the quasi-steady propeller-recycling disk can be calculated by

$$t_{\text{disk}} \approx \frac{(\omega_i - 1)I_{s,i}\Omega_{s,i}M_{s,i}}{T_{\text{pro},i}} = \frac{(\omega_i - 1)GM_{s,i}I_{s,i}}{\Omega_{s,i}I_s^{1/2}}$$

$$= 3.3 \times 10^3(\omega_i - 1)M_{s,i,14}^2R_{s,i,14}^{-2}B_{s,i,14}^{-2}P_{s,i,-3}$$

(17)
Nevertheless, if the magnetic field is extremely high, the MD radiation of the NS could initially exceed the energy release due to the propeller effect. In this case, the lifetime of the propeller-recycling disk should be determined by the MD spin-down timescale that is shorter than the estimate given in Equation \(17\). The value of \(t_{\text{disk}}\) can further be shortened if the NS can collapse into a black hole before the propeller ends. The collapse could be due to the spin-down of the NS, if the mass of the NS is higher than the maximum mass of non-rotating NSs. Additionally, the collapse can also happen in the accretion phase, if accretion makes the NS’s mass exceed its maximum value. No matter whether the collapse happens or not, the eventual accretion onto the compact object can always take place, as long as the fallback accretion disk exists.

4. SUMMARY AND DISCUSSION

For a newborn NS, its early evolution could be influenced by fallback accretion. It is found that, for a millisecond magnetar, the accretion disk could be initially in a propeller-recycling state for about hundreds or thousands of seconds. Nevertheless, as a result of the NS’s spin-down due to the propeller effect, the disk can eventually enter the accretion phase. During this stage, the decrease of the accretion rate can be firstly well described by the usual temporal behavior of \(t^{-5/3}\) and subsequently become somewhat slower. In any case, due to the accretion, the surface dipolar magnetic field of the NS could be effectively reduced and then the NS will appear as a low-field magnetar at later time.

Such an evolutional behavior of the newborn NS is consistent with the evidence of a possible long-lived neutron star engine in some short GRBs (Yu et al. 2018; Li et al. 2018). On one hand, the post-GRB NSs are strongly inferred to be magnetars with a surface dipolar magnetic field of \(<10^{14} – 10^{15}\) G, in order to account for the early afterglow emission of GRBs including the plateau or flare features (Yu et al. 2010; Zhang 2013; Rowlinson et al. 2013). On the other hand, however, the luminosity of the optical transient emission (i.e., AT2017gfo) in the GW170817/GRB 170817A event stringently constrained the surface dipolar magnetic field of the remnant NS to be lower than \(<10^{12}\) G (Ai et al. 2018; Yu et al. 2018; Li et al. 2018). It is indicated that the MD radiation of this remnant NS had probably been suppressed at a time of several hours after the birth of the NS. The calculation results presented in this paper suggest that this suppression of the MD radiation could be caused by the delayed accretion from a propeller-recycling disk. The total mass of the accretion disk is required to be not higher than several hundredths of solar mass, which is roughly consistent with the order of magnitude of the ejecta mass of double NS mergers and white dwarf AICs.

Finally, in principle, the disk accretion could sometimes lead to an accretion feedback outflow, which can provide extra energy injection to the transient emission. However, in observations, such a sharp energy pulse at hundreds or thousands of seconds seems not ubiquitous in the GRB afterglow emission. So, it may suggest that the efficiency of this direct energy release due to the delayed accretion could not be very high, e.g., lower than \(<10^{-4}\). The effect of the fallback accretion is primarily reflected by its important influence on the early evolution of the newborn NS.

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