“Anti-glitches” in the Quark-Nova model for AXPs I

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Abstract

In the Quark-Nova model, Anomalous X-ray Pul-
sars (AXPs) are quark stars surrounded by a degenerate iron-rich Keplerian ring (a few stellar radii away). AXP bursts are caused by accretion of chunks from the inner edge of the ring following magnetic field penetration. For bright bursts, the inner disk is prone to radiation induced warping which can tilt it into counter-rotation (i.e. retrograde). For AXP 1E2259+586, the 2002 burst satisfies the condition for the formation of a retrograde inner ring. We hypothesize the 2002 burst reversed the inner ring setting the scene for the 2012 outburst and “anti-glitch” when the retrograde inner ring was suddenly accreted leading to the basic observed properties of the 2012 event.

Keywords dense matter accretion, accretion disks stars: neutron – stars: individual(1E 2259+586) – X-rays: bursts

1 Introduction

Archibald et al. (2013) recently reported the first observation of a sudden spin-down in an AXP (1E 2259+586). This spin-down was associated with an X-ray burst with peak luminosity of the order of $10^{38}$ erg s$^{-1}$ that lasted for about 36 ms. This puzzling “anti-
glitch” begs for an explanation (e.g. Lyutikov 2013; Tong 2014; Katz 2014).

In the Quark-Nova model (Ouyed et al. 2002; Keränen et al. 2005; Ouyed&Leahy 2009; Niebergal et al. 2010; Ouyed et al. 2013), Soft Gamma-ray Repeaters (SGRs) and AXPs undergo outbursts from accretion. For SGRs, accretion is from a co-rotating shell (see Ouyed et al. 2007a; hereafter OLNI) whereas AXPs accrete from a Keplerian ring (see Ouyed et al. 2007b; hereafter OLNII). In both cases, the shell/ring is located a few stellar radii away from the quark star and consist of degenerate iron-rich material from the ejected neutron star crust. In our model, anti-glitches are expected in SGRs (see section 6.2 in OLNI). Here we focus on AXPs and refer the interested reader to OL-NII, Ouyed et al. (2010; hereafter OLNIV) and Ouyed et al. (2011; hereafter OLNV) for more details on the AXPs in our model.

The Quark-Nova model for AXPs normally leads to sudden spin-up during bursts, caused by accretion from the inner Keplerian ring. However, as we show below it also allows for sudden spin-down during bursts if a preceding burst is bright enough to reverse the inner ring. Here we show that the warping instability (Pringle 1992&1996) could develop following a bright burst which leads to a retrograde inner ring. The possibility of spin-down torques induced by a retrograde Keplerian accretion disk has previously been explored (e.g. Nelson et al. 1997). Such torques could also occur if warping leads to an inner disk tilted by more than 90 degrees (e.g. van Kerkwijk et al. 1998).

1 Other fall-back accretion models of SGRs/AXPs have been proposed, and may account for the anti-glitch as in the Quark-Nova model (e.g. Katz 1994; Alpar 2001; Trümper et al. 2010). However, the Keplerian ring in our model is unlike a fall-back disk around a neutron star. The ring is rich in heavy elements, is very close to the quark star (a few stellar radii away) and is degenerate. Similar ring formation when a neutron star is born appears implausible since the proto-neutron star is too large. In addition there is a strong outflow of energy during or immediately following the SN which may also prohibited the formation of a degenerate Keplerian ring.
2 Our model

2.1 Ring properties

The general properties of the Keplerian ring (and other general features of our model) can be found in §2 in OLNII and §2 in OLNIV. We define the ring’s inner radius as $R_{\text{in}}$ and the outer radius as $R_{\text{out}}$ (see Fig. 1 in OLNIV for an illustration of the ring’s structure, geometry and the star-ring configuration; see also figure Fig. 2 in OLNIV). Viscosity causes the ring’s outer radius to spread radially outwards at a rate given by (see Appendix A in OLNII) $R_{\text{out}} \sim 105 \text{ km} \left( \frac{\tau_{\text{keV,0.2}}^{\text{eq}}}{10^{4} \text{ yr}} \right)^{\frac{1}{2}}$ with $\tau_{\text{yr}}$, being the age of the system in units of $10^{4}$ years while the ring’s temperature during quiescence (superscript “q”) is given in units of 0.2 keV. For AXP 1E2259+586 with an estimated age of $\sim 2.5 \times 10^{4}$ years (see Tendulkar et al. 2013) this gives $R_{\text{out}} \sim 166$ km; we thus use 200 km as our fiducial value for $R_{\text{out}}$. Since the source spends most of its life in quiescence, $R_{\text{out}}$ spreading is mainly determined by the ring’s temperature during this phase: $T_{\text{ring}}^{\text{q}}$ is in the sub-keV range while the temperature during burst, $T_{\text{ring}}^{b}$, is in the keV range.

The ring’s average density is found from equation $\rho_{\text{ring}} \sim m_{\text{ring}}/(2H_{\text{out}} R_{\text{out}}^{2})$. Here, $H_{\text{out}} \sim 54$ km $\rho_{\text{ring,3}} R_{\text{out,200}}^{3}$ is the ring’s vertical scale-height at $R_{\text{out}}$ with the ring’s average density $\rho_{\text{ring,3}}$, given in units of $10^{3}$ g cm$^{-3}$ and the ring’s outer radius $R_{\text{out,200}}$ given in units of 200 km (in old sources $R_{\text{out}} \gg R_{\text{in}}$). This gives $\rho_{\text{ring}} \sim 1.1 \times 10^{3}$ g cm$^{-3} \times m_{\text{ring,8}}^{6/7} R_{\text{out,200}}^{3}$ with $m_{\text{ring,8}}$ being the mass of the ring in units of $10^{-8} M_{\odot}$. We chose $m_{\text{ring}} = 10^{-8} M_{\odot}$ as our fiducial value to ensure that for a QS with a period exceeding $5$ ms the fall-back material has enough angular momentum to form a Keplerian ring (see eq. 8 in OLNII and §2 in OLNII for more details). A value $m_{\text{ring}} = 10^{-8} M_{\odot}$ also offers the advantage that the ring is easier to reverse for typical burst energies in the QN model.

The iron-rich ring is made of ions in the strong-coupling regime which solidifies when the Coulomb parameter is $\Gamma \sim 175$ (Nagara et al. 1987). The solidification temperature is estimated at $T_{\text{s}} \sim 9.5$ keV $\times \left( \frac{g}{10^{9} \text{ g cm}^{-2}} \right)^{1/3}$ (De Blasio 1995; Baiko & Yakovlev 1995; Pothekin 1999), so that here with $\rho_{\text{ring}} \sim 10^{3}$ g cm$^{-3}$, we get $T_{\text{s}} \sim 0.2$ keV, i.e the ring is solid except perhaps during bursts. The ring made of cold (sub-keV) solid matter is thus prone to tidal shearing. As shown in §2.1 in OLNII, the ring fractures into hundreds of cylinders (which we dubbed walls) each of thickness $\Delta_{\text{wall}} \sim 862.5$ cm $f_{\text{Pr}} R_{\text{in,25}}^{1/2}$; here the ring’s inner radius, $R_{\text{in}}$ is given in units of 25 km and $f_{\text{Pr}}$, a dimensionless tensile strength of the ring’s material. The walls are stacked against each other but separated by a degenerate fluid; effectively each wall in high pressure contact with the next through a melted (nocrystalline) material. The typical mass of a wall is of the order of $M_{\text{wall}} \sim 10^{-11} M_{\odot}$ in our model.

2.2 Ring warping and tilting conditions: the 2002 burst

The condition for warping was presented in Pringle (1992 and 1996) for a geometrically thin and optically thick accretion disk. Numerical simulations by van Kerkwijk et al (1998; their Fig. 1) show the tilt oscillating between 90 and 180 degrees. Wijers & Pringle (1999) simulations, in a different regime, can reproduce the observed tilt of Her X-1 of about 25 degrees; the inner disc in such systems was shown to tilt through more than 90 degrees at high luminosities. This suggest that radiation warping is a real phenomena.

There are two relevant timescales: the radiation torque timescale ($t_{\Gamma}$) and viscous timescale ($t_{\nu}$)

$$t_{\Gamma} = \frac{12\pi \Sigma R_{3}^{3} \Omega}{L_{*}} \quad \text{and} \quad t_{\nu} = \frac{2R^{2}}{\nu},$$

where $L_{*}$ is the luminosity of the source; $R$, $\Sigma$, $\Omega$, and $\nu$, the radius, the surface density, the Keplerian angular velocity and the viscosity of the disk, respectively.

For the inner ring, the ring’s surface density is $\Sigma \sim \rho_{\text{ring}}(2H_{\text{in}})$ which gives

$$t_{\Gamma} \sim 7.0 \text{ years} \frac{m_{\text{ring,8}} R_{\text{in,25}}^{3} M_{\odot}^{1/2}}{R_{\text{out,200}}^{7/2} L_{\text{acc,35}}},$$

where the luminosity is given in units of $10^{35}$ erg s$^{-1}$. The quark star mass, $M_{\text{QS}}$, is given in units of $1.5 M_{\odot}$.

To estimate the viscosity we consider the physical state of the ring. The ring is made up of solid degenerate walls (a few meters thick) separated by thin layers of normal fluid. The shear from the Keplerian angular velocity is concentrated in the thin fluid layers. Because of the inhibition of radial fluid motions (i.e. perpendicular to the fluid layers) and thus inhibition of turbulence, we do not expect the magneto-rotational instability to develop in the thin fluid (this remains to be confirmed). The thin fluid layers become the main contributor to the effective (overall) viscosity of the system.
As a result, we adopt the standard Spitzer viscosity as an order of magnitude estimate. The viscous timescale (see Appendix A in OLNII) is

$$t_v \sim 21.9 \text{ years} \times \frac{R_{\text{in,25}}^2}{(T_{\text{ring,keV}}^{\text{b}})^{5/2}},$$

where the ring’s temperature during the bursting phase (superscript “b”) is in keV.

The $t_\Gamma < t_v$ condition (Eq. 4.1 in Pringle 1996) allows the instability to develop and sets the conditions for retrograde motion. Thus, ring warping occurs in our model when $L_{\text{acc}} > L_{\text{cr}}$ with

$$L_{\text{cr}} \sim 3.2 \times 10^{34} \text{ erg s}^{-1} \times \frac{m_{\text{ring}}}{R_{\text{in,25}}} \frac{M_{\text{QS,1.5}}^{1/2}(T_{\text{ring,keV}}^{\text{b}})^{5/2}}{R_{\text{out,200}}^{1/2}}. $$

The 2002 outburst of AXP 1E2259+586 was above $3 \times 10^{34} \text{ erg s}^{-1}$ for hundreds of days (see Fig. 13 in Woods 2004 and Fig. 2 in OLNII). For the instability to develop ($t_\Gamma < 1$ year; the length of time of $L > L_{\text{cr}}$), we require a reduction in $t_\Gamma$ by a factor of 10 or so for our fiducial values. Pringle (1996) notes in §5 that a disk wind induced by the radiation would increase the effectiveness of momentum transfer thus reducing $t_\Gamma$ by a factor of $v_{K,\text{in}}/c \sim 0.1$ where $v_{K,\text{in}}$ is the Keplerian velocity at $R_{\text{in}}$. Furthermore, it is important to note that the early part of the burst was significantly brighter which also shortens the effective $t_\Gamma$ by a factor of a few. Effectively a net reduction of $t_\Gamma$ to $t_\Gamma_{\text{eff}} < t_\Gamma/10$ is not unreasonable. The required outburst energy to reverse the inner ring is thus $E_{\text{burst}} \sim t_\Gamma_{\text{eff}} L_{\text{cr}} < 3 \times 10^{41}$ ergs. In our model, this is provided by accretion from the ring’s atmosphere as it settles back to its sub-keV, equilibrium, temperature (see §4.4 and Fig. 2 in OLNII).

3 The 2012 “anti-glitch”

After the 2002 burst the ring cools back down to sub-keV temperatures ($\sim 0.2 \text{ keV}$) which results in $t_v \sim 1.2 \times 10^3$ years (see eq. 9). During this period, the retrograde inner ring is penetrated by the magnetic field on timescales $\tau_B \sim 881 \text{ yrs} \times f_{\text{Fe,25}} R_{\text{in,25}}^3 / R_{\text{ring,3}}^{1/6}$ (eq. 17 in OLNII). The magnetic field penetration forces the innermost retrograde wall of the ring to co-rotate with the star. This leads to the accretion of the retrograde wall and transfer of its angular momentum to the star inducing a sudden spin-down (i.e. “anti-glitch”). To account for the 10 year interval between the 2002 glitch and the 2012 anti-glitch (i.e. $\tau_B \sim 10$ years) requires a dimensionless tensile strength $f_{\text{Fe}} \sim 0.1$ in our model which is not unreasonable (see §2.1 in OLNII).

The induced change in the star’s frequency is $\Delta \nu/\nu = -(M_{\text{wall}} R_{\text{in}}^2 \Omega_{K,\text{in}})/(2(5/M_{\text{QS}} R_{\text{QS}}^2 \Omega_{\text{QS}}))$ (see eq. 29 in OLNII; equation below gives the corrected version of eq. 30 in OLNII) which gives

$$\frac{\Delta \nu}{\nu} \sim -6.1 \times 10^{-7} \frac{P_{\text{QS,10}} R_{\text{in,25}}^{1/2} M_{\text{wall},11}}{M_{\text{QS,1.5}}^{1/2} R_{\text{QS,10}}^2},$$

where $P_{\text{QS,10}}$, $R_{\text{QS,10}}$ are the period ($P_{\text{QS}} = 2\pi/\Omega_{\text{QS}}$; in units of 10 s) and radius (in units of 10 km) of the quark star, respectively. The wall’s mass is in units of $10^{-11}M_\odot$. The above value is an upper limit: if the inner ring is not completely reversed, the angular momentum transfer is reduced by a factor $\alpha = \cos \theta$ where $\theta$ is the tilt (i.e. the angle between the orbit normal and the equatorial plane normal). Archibald et al. (2013) give $\Delta \nu/\nu \sim 3.1 \times 10^{-7}$ to $\sim 6.3 \times 10^{-7}$ using two different models which is consistent with our model estimates. Archibald et al (2013) observed a period of increased spin-down following the “anti-glitch” which can be explained in our model as described in §5.2 in OLNII.

3.1 The associated 2012 burst

The accretion of the innermost wall occurs on timescales exceeding the free-fall time of a few milliseconds. The resulting burst energy is $\sim \eta M_{\text{wall}} c^2 = 0.1 M_{\text{wall}} c^2 \sim 10^{42}$ ergs. Archibald et al. (2013) give a luminosity of about $10^{38} \text{ erg s}^{-1}$ in the 10-1000 keV band over a time of 36 ms. The discrepancy between the observed and predicted burst energy is not yet understood but may be a consequence of a lower mass-to-radiation energy conversion efficiency $\eta (< 0.1)$. In the QN model, the QS is bare and crustless since it is in the Color-Flavor Locked phase which is rigorously electrically neutral (Rajagopal & Wilczek 2001); we assume that the surface depletion of strange quarks is negligible (see discussion in Usov 2004). Hadronic matter falling onto the QS will convert into strange quark matter releasing mostly neutrinos. This implies a reduced mass-to-radiation energy conversion efficiency factor ($\eta$) during accretion events. Combined with the fact that the wall is accreted as chunks (rather than fluid as in standard accretion) this may significantly reduce heating and subsequent radiation during infall. Thus a reduction of $\eta$ by a few orders of magnitudes is plausible which may help resolve the discrepancy in burst energy in our model and the observed value.

This is the reason for the featureless spectrum emanating from the QS in our model.
4 Model Limitations and Predictions

In summary, in this picture a bright burst (∼ $10^{41}$ ergs) is required to reverse the inner ring. After several years, the reversed innermost wall is accreted to cause the anti-glitch. Our model relies heavily on the assumption that radiation-induced warping can occur in the degenerate ring surrounding the quark star and that it would lead to the formation of a retrograde inner ring. Only detailed numerical simulations (beyond the scope of this paper) can prove or disprove this assumption. The simulations could also include a more robust treatment of the viscosity of the ring. Such simulations could track the evolution of the retrograde ring and test if it could effectively remain stable for a few years before it is accreted, as seem to be the case in AXP 1E2259+586. In addition, the burst energy in our model is a few orders of magnitude higher than the observed value. Unless the mass-to-radiation energy conversion efficiency $\eta$ is drastically reduced due to surface properties of the QS, this would be a major challenge to our model.

Our model has the following features and predictions:

- If the first outburst (in this case the 2002 event) is bright enough to reverse more than one wall, then we expect different outcomes. For example, more than one reversed wall can be accreted in an episode and also reversed and normal walls can be accreted in the same episode. Interestingly, Archibald et al. (2013) mention two possibilities, an anti-glitch-anti-glitch pair or an anti-glitch-glitch pair fits their data.
- If the anti-glitch is bright enough, it can also lead to a reversal of the next inner ring. In this case an “anti-glitch” would be associated with the subsequent outburst (roughly 10 years later).
- We expect a possible outburst within the next decade (around year ∼ 2022), since the time it takes the magnetic field to penetrate the counter-rotating innermost wall and accrete it is $\tau_B \sim 8.81$ yrs $\times f_{Fe,0.1}^{2} R_{in,25}^{1/6}/\rho_{ring,3}$. 
- The fall-back material is representative of the QN ejecta and is thus rich in heavy elements (Jaikumar et al. 2007). If heated to keV temperatures we expect atomic lines to be detected (e.g. Koning et al. 2013).

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