Radio and X-ray Signatures of Merging Neutron Stars

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ABSTRACT

We describe the possible electromagnetic signals expected from the magnetospheric interactions of a neutron star binary prior to merger. We find that both radio and X-ray signals of detectable strength are possible. We discuss possible links with the phenomenon of gamma-ray bursts and describe the prospects for direct detection of these signals in searches for radio and X-ray transients.

Key words: gravitation – stars: magnetic fields – stars: neutron – pulsars: general – gamma-rays: bursts – X-rays: bursts

1 INTRODUCTION

The gravitational wave-induced merger of binary neutron stars has evoked considerable interest in recent years due to their importance as a source of gravitational radiation (Thorne 1987 and references therein) and potentially also gamma-ray bursts (Blinnikov et al 1984; Paczynski 1986; Eichler et al 1989; Paczynski 1991). The goal of identifying electromagnetic signatures of the merger events is an important one, even if such manifestations are not gamma-ray bursts. Given the considerable information processing required to infer the presence of a gravitational wave burst (Cutler et al 1993), the presence of another signature will be invaluable.

In this paper we examine the magnetospheric interactions in merging neutron star binary systems and describe their pre- and post-merger signatures. In particular, we consider systems containing one low field \( B_e \sim 10^{9–11} \text{G} \), rapidly spinning \((P \sim 1–100 \text{ms})\) recycled pulsar and one high field \( (B_m \sim 10^{12–15} \text{G}) \), slowly spinning \((P \sim 10–1000 \text{s})\) non-recycled pulsar, as expected on both empirical and evolutionary grounds. We shall examine how energy is extracted from the spin and orbital motion of the pulsar and in what manner it is radiated. Aspects of this calculation have been considered before by Vietri (1996), who considered magnetospherically induced gamma-ray bursts, and Lipunov & Panchenko (1996), who considered the the far-field dipolar and quadrupolar configurations of a dipole merging with a superconducting sphere. Our default estimates will be for systems in which the high field pulsar has a field \( \sim 10^{15} \text{G} \) (sometimes called a magnetar), which has the potential for the strongest signal. Recent work suggests that such pulsars may constitute \( \sim 10\% \) of the young pulsar population (Kulkarni & Thompson 1998).

In section 2 we will describe the magnetospheric interactions that remove energy from the orbit and which allow it to emerge in electromagnetic form. This section will draw heavily on concepts from pulsar electrodynamics and also the field of satellite-magnetosphere electrodynamics, such as in the Io-Jupiter system. One of the primary results is that much of the energy is released as a pair plasma into the magnetosphere. Section 3 describes the physical state and evolution of this plasma, drawing on concepts developed to describe Soft Gamma Repeaters and section 4 reviews the state of the observations appropriate to this phenomenon.

2 THE EXTRACTION OF SPIN AND ORBITAL ENERGY

High magnetic field pulsars spin down rapidly, so that we consider the high field pulsar to be essentially non-rotating. A corollary to this is that the light cylinder radius for the magnetar magnetosphere (or ‘magnetarsphere’!) is \( \sim c/\Omega \sim 5 \times 10^{11} \text{cm}(P/100 \text{s}) \), so that all of our subsequent discussion concerns processes occurring deep within the closed region of this magnetosphere. This will hold true right up to the point of merger as tidal interactions cannot enforce synchronisation in a coalescing neutron star binary (Bildsten & Cutler 1992).

The extraction of energy from the pulsar spin and orbital motion is driven by how the strongly conducting neutron star interacts with the external magnetic field of the magnetar. As a model problem we consider perfectly conducting sphere moving through an externally imposed uniform magnetic field \( \mathbf{B}_0 \) with velocity \( \mathbf{v} \) and rotating with angular velocity \( \Omega \). Motion of a conducting sphere through magnetic field is possible only if the resistivity of the sphere (neutron star) is nonzero. But the neutron star crust is vir-
tually a perfect conductor: the magnetic diffusion times for neutron stars are very long - in fact comparable to the age of the universe. We argue that the required resistivity is due to the dissipation of the induced magnetospheric currents far from the neutron star surface. This is analogous to the case of isolated pulsars, where currents are dissipated in the pulsar wind-ISM shocks more than $10^9$ light cylinder radii away.

The electrodynamics of the low-field pulsar interaction with the magnetar magnetic field is considered in appendix A. Qualitatively, this interaction has several important ingredients. The conducting neutron star excludes the external field from its interior. The induced magnetic field has a dipole structure with the magnetic dipole directed against the external field. The resultant magnetic field is

$$B_{\text{tot}} = B_0 + \frac{R^3}{2r^3}B_0 - \frac{3R^3}{2r^3}(B_0 \cdot r)r$$

(1)

At the surface the total magnetic field has only a tangential component, inside the star the magnetic field is zero. The orbital motion of the neutron star with respect to the external field will induce surface charges with a dipole structure and surface charge density

$$\sigma_{\text{orb}} = \frac{1}{4\pi\varepsilon_0 R_0} \left( B_0 \cdot [R_0 \times \mathbf{v}] \right)$$

(2)

where $R_0$ is the radius of the neutron star. These surface charges will also produce electric fields which will have a component along the total magnetic field. If the neutron star orbits in a vacuum, this electric field will accelerate charges from the surface or surrounding region to relativistic energies. If the internal magnetic field of the neutron star is exactly zero, the resulting structure of the electric field will be of the “outer gap type” (Chen, Ho & Ruderman 1986) - a region in the magnetosphere with $E_\parallel$ which does not intersect the surface of the neutron star. However, there is likely to be some small component of radial magnetic field at the surface. This could result either from whatever intrinsic field the recycled neutron star possesses or from a second-order induced field resulting from rotation of the star (see below and appendix A). In this case the electric field will draw charges from the surface.

Similarly to orbital motion, the rotation of the neutron star will produce a surface charge density

$$\sigma_{\text{rot}} = \frac{3R_0\Omega B_0 \sin \psi \sin \theta}{8\pi c}$$

(3)

where $\psi = \cos \beta \cos \theta \sin \alpha - \sin \theta \cos \alpha$ and $\Omega = \Omega(\sin \alpha, 0, \cos \alpha)$, i.e. $\psi$ is the polar angle in the frame aligned with $\mathbf{B}$ and rotating with the neutron star. This charge density is stationary in the frame of the neutron star while in the laboratory frame it yields an additional surface current $\mathbf{j} = \sigma_{\text{rot}} \mathbf{r} \times \mathbf{B}$. The magnetic field due to this current is of order $(R\Omega/c)^2$ smaller than the external field $B_0$, but has a radial component at the surface.

Similarly to the case of the aligned rotator studied by Goldreich & Julian (1969), the strong electric field produced by surface charges will accelerate charges in an attempt to short out the component of the electric field that lies parallel to the magnetic field. The typical densities of the primary beam will be $n_{\text{ej}} \sim n_{\text{ej}}B_0/2\pi\varepsilon_0 c$ for acceleration by $\sigma_{\text{rot}}$ and $\sim vB_0/2\pi\varepsilon_0 c$ for acceleration by $\sigma_{\text{orb}}$. After being accelerated to sufficient energies ($\gamma \sim 10^6$) the initial primaries produce curvature photons and a dense population of secondary electron-positron pairs that will screen the induced electric field. This mechanism of energy extraction is essentially the same as in the classical pulsar case with a couple of small but important differences. The first is that, unlike the case of the pulsar, the near field energy density is dominated by the plasma, rather than Poynting flux (see appendix A). Secondly, the field configuration defined by $\mathbf{B}$ contains no closed magnetosphere. In the traditional pulsar case, the ‘working surface’ of the energy extraction is limited to the polar cap, a fraction $\sim (r\Omega/c)^2$ of the the total surface area, which is linked to the open field lines. In the case under discussion here, the polar cap effectively encompasses the entire star.

The energy extracted by accelerating primary particles is limited by the maximum energy that primary particles can reach:

$$L \sim 4\pi R^2 n_{\text{ej}}\gamma_{\text{max}} m_\text{e} c^3 \sim 3.1 \times 10^{36} \text{ergs s}^{-1}. \quad (4)$$

However, the energy extraction from the orbital motion is likely to be significantly more efficient than implied by (4). Once the pair production cascade has loaded the external field lines with plasma, the spiraling neutron star emits Alfvén waves along the external magnetic field (Drell, Foley & Ruderman 1965; Barnett & Olbert 1986; Wright & Southwood 1987), in much same way as Io interacting with Jupiter or various artificial satellites in the earth’s magnetosphere. In this case, the pair production front acts as a surface of finite resistivity, allowing the neutron star to ‘cross field lines’. We assume that these waves are dissipated in the magnetar magnetosphere by non-linear damping mechanisms similar to those invoked by Soft Gamma Repeater models (e.g. Thompson & Duncan 1995). Thus we shall assume that the bulk of the energy extracted from the orbit is deposited into the magnetospheric pair plasma, and is of order (Drell et al 1965)

$$L_{\text{orb}} \sim 4\pi R^2 B_0^2 \left( \frac{R}{a} \right)^6 \frac{v^2}{c} \sim 7.4 \times 10^{35} \text{ergs s}^{-1} \left( \frac{B_0}{10^{12}\text{G}} \right)^2 \left( \frac{a}{10^{-8}\text{cm}} \right)^7. \quad (5)$$

Additional sources of energy are the Poynting losses due to the motion of the induced dipole (Lipunov & Panchenko 1996) and the time varying component of the induced magnetic fields (see appendix A), though the corresponding luminosities are much smaller than that given by Eq. (5). Poynting fluxes will be in a form of low frequency electromagnetic waves. Unlike the equivalent situation for pulsars, where the density of the secondary plasma is low, these low frequency electromagnetic waves may not be able to propagate through the dense secondary plasma present in the “magnetarsphere” - they will convert their energy into plasma (Asseo et al. 1978). Thus, most of the energy lost by the neutron star will be converted into plasma in the near

\footnote{Even if the resistivity were considerably lower, a similar level of energy extraction would occur via the screw-instability of strongly wound magnetic field configurations (Low 1986; Aly 1991; Volker, van Oss & Kuijper 1993; Gruzinov 1999), given only the assumption of sufficient ambient plasma to justify the force-free approximation.}
zone and later radiated - this is in contrast to normal pulsars where most of the losses within the light cylinder are due to the Poynting flux.

Our situation also differs somewhat from that considered by Vietri (1996), who addressed the problem of the merger of two high-field pulsars. The consequently large radii of field line curvature implied screening was ineffective and allowed efficient acceleration of particles and high energy emission. The fundamental difference in our case is that plasma screening occurs close to the low field neutron star, where the radius of curvature is smaller. The result is efficient generation of pair plasma and effective screening of parallel electric fields. The pair plasma will then mediate the dominant energy extraction by Alfvén wave emission.

2.1 Radio Emission

In normal pulsars, the acceleration of particles by electric fields at the surface yields coherent radiation observed as radio emission. Thus, we might hope for similar signals in this instance. The lack of a complete theory of pulsar radio emission forces us to adopt a simple parameterisation based on what we know about pulsars. We expect the radio emission to be associated with the primary beam only, whose luminosity is given by Eq. (3). We shall adopt an efficiency of $\epsilon \sim 0.1$ for the conversion of primary beam energy to radio luminosity, based on the radio efficiencies of pulsars (see Taylor, Manchester & Lyne 1993), assuming the pulsar beam luminosity is $\sim 10^{-3}$ of the spin-down luminosity (Kennel & Coroniti 1984). Then an optimistic estimate for the radio flux at 400 MHz (chosen because it is at this frequency that the pulsar fluxes are best estimated) is

$$F_{\nu} \sim 2.1 \text{ mJy} \ rac{\epsilon}{0.1} \left(\frac{D}{100 \text{ Mpc}}\right)^{-2} B_{15}^{3/2} a_{-7}^{-5/2}. \quad (6)$$

This is within the range of the larger radio telescopes operating today, although somewhat less than the sensitivities of current radio transient searches.

There are several complications that may preclude generation of radio emission. If the neutron star is moving through a pre-existing plasma generated by the previous orbital cycles the electric gaps may be quenched, there will be no need to accelerate further particles and the beam luminosity may drop to zero. In addition, the formation of positronium in the magnetic fields exceeding $\sim 4 \times 10^{12} \text{ G}$ (Uslov & Melrose 1996, Arons 1998) may also quench the radio emission.

Furthermore, the generated radio emission may be absorbed in the magnetosphere. We expect that nonresonant Thomson scattering of the low frequency ($\nu << \nu_{B}$) radio emission will not be important due to the strong suppression ($\sigma = \sigma_{T}(\nu/\nu_{B})^2$) of the scattering cross-section by the magnetic field at low frequencies. Resonant cyclotron absorption may be important in the outer regions of the magnetosphere where the cyclotron frequency becomes comparable to the radio wave frequency ($a \sim 10^{10} \text{ cm}$). Nevertheless, such absorption does not occur in the pulsar case, so we may reasonably expect the radio emission to escape the magnetosphere.

Thus, the first electromagnetic signature we anticipate from a realistic merging neutron star binary is a coherent radio burst, emitted $\sim$ seconds before the gravitational wave burst. However, the effects of interstellar dispersion can cause delays of hours, possibly allowing for radio follow-up observations at low frequencies (Palmer 1993; Lipunova, Punchenko & Lipunov 1997).

3 EVOLUTION OF THE MAGNETOSPHERIC PAIR PLASMA

Most of the energy liberated by the strong electric fields of section 2 is not radiated, but is rather released into the magnetosphere of the slowly-rotating magnetor in the form of Alfvén waves and a dense pair plasma. The energy release is a significant fraction of the local magnetic energy density. In such a case, a wind, driven either by hydro-magnetic or plasma pressure, is likely to result (Paczynski 1986, 1990, Melia & Fatuzzo 1995; Katz 1996) while some will remain trapped, in a fashion similar to that of the Soft Gamma Repeater picture of a magnetically confined pair plasma (Thompson & Duncan 1995). We envisage that the plasma released into regions of decreasing field strength powers the wind while plasma released into regions of increasing field strength will be trapped. Figure 2 shows a schematic version of our scenario.

Let us consider first the case of the wind. A release of energy at the rate given by equation (3) results in a compactness parameter $\eta = L/ac \sim 10^{-2} B_{15} a_{-7}$. Thus, this is the same situation envisaged in cosmological models for gamma-ray bursts (Paczynski 1986; Goodman 1986), wherein the release of a large quantity of pure energy within a small volume leads to a relativistically expanding fireball. The energy release during the neutron star inspiral will drive a relativistically expanding wind of pairs and photons. Thermal and statistical equilibrium between photons and pair plasma is maintained during the expansion by pair production and comptonization (Cavallo & Rees 1978) until the conoving temperature drops to $T \sim 3 \times 10^{9} \text{ K}$ and pair production can no longer maintain the necessary electron scattering optical depth. At this point the radiation escapes, with an approximately thermal spectrum. However, the relativistic boost increases the observed temperature by a factor $\gamma$, the original Lorentz factor of the fireball and reduces the observed burst time by the same factor. Thus, the observed energetic and temporal properties of the wind emission may be approximately described by thermal emission at the appropriate initial temperatures and timescales, despite the fact that the true photosphere is on scales much larger than the original volume. Hence, we shall estimate the observed flux in this case as

$$F_{\text{wind}} \sim \frac{\alpha L}{4\pi a^{2}} \sim 3 \times 10^{30} \text{ergs cm}^{-2} \text{s}^{-1} B_{15}^{2} a_{-7}^{-9}, \quad (7)$$

($\alpha$ is the fraction of the energy release lost in the wind) yielding effective temperatures just before merger $\sim 1.5 \text{MeV} B_{15}^{1/2}$. The case of the trapped plasma is somewhat more subtle. This plasma is very optically thick (Svensson 1987; Thompson & Duncan 1995) and the inspiral time $\sim 0.4 \text{ s} a_{-7}^{1/3}$ is short. Hence, very little of the total energy contained in the magnetosphere is radiated in this time. The emission that does occur is dominated by the region just above the
surface of the magnetar, where the strong magnetic field decreases the electron scattering cross-section and thereby decreases the electron scattering cross-section and thereby promotes a larger photon flux. At late times, the plasma temperature is high enough that ablation of material from the surface of the star is likely to provide an Eddington limit $F_{\text{edd}} \sim 4.14 \times 10^{26} \text{ergs cm}^{-2} \text{s}^{-1} B_{15}^{-2}$. 

(8)

In the case of Eddington limited cooling, we see that the emission actually gets softer as the inspiral proceeds (the opposite of the contribution from the relativistic wind) because the plasma temperature increases and acts to negate the magnetic suppression of the electron scattering cross-section.

Thus, our strongest prediction is the presence of an X-ray precursor to the neutron star merger. This precursor should be dominated by approximately thermal emission from the wind component, which progressively hardens as the binary approaches merger. For magnetars ($B_{15} \sim 1$), this can approach energies $\sim 1.5 \text{ MeV}$ while binaries containing a normal pulsar ($B_{15} \sim 10^{-3}$) will only get as hard as $\sim 50 \text{ keV}$. In some cases these objects may be accompanied by softer ($\sim 1 \text{ keV}$) components associated with the cooling of the trapped plasma. The observed flux will be dominated by the harder wind component, with flux levels $\sim 3 \times 10^{-6} \text{ergs cm}^{-2} \text{s}^{-1} B_{15}^{-2} a_{\ast}^{-7}$ for a source at 100 Mpc (the distance scale for which we expect a few neutron star mergers per year).

### 3.1 The Ultimate Fate of the Pair Plasma

Much of the energy released by the processes in section 3 is retained in the magnetospheric plasma for timescales longer than the inspiral time, i.e. the merger event will occur surrounded by a significant magnetospheric plasma. This energy totals about $E_{\text{plasma}} \sim 2 \times 10^{57} \text{ergs} B_{15}^{2}$. Vietri (1996) proposed that this energy, most of which is released on the last few orbits, could power a Gamma-Ray Burst as it escapes its magnetic confinement. Our estimate of the energy release is somewhat smaller than his (strictly speaking he calculated the maximum energy a magnetosphere could contain, rather than the energy release itself). Recent determinations of the distances (Metzger et al 1997; Kulkarni et al 1998; Djorgovski et al 1998) to burst events suggest that much larger energy releases are required to explain many gamma-ray bursts (modulo beaming considerations).

A more intriguing possibility occurs if it is the magnetar which is disrupted to form a rapidly rotating disk around the compact merger remnant (as might be expected from the non-recycled and thus presumably lighter object). If the magnetic field footpoints remain tied to the disrupted material the magnetosphere is forced to co-rotate with the disk and the corotation radius must move rapidly inwards, converting closed field lines to open ones and ejecting the magnetospheric plasma. This would allow the plasma to tap the much larger reservoir of disk rotational energy to power the gamma-ray burst (as in many other gamma ray burst models. See Hartmann 1996 for a review) and could also account for significant collimation of the outflow. Furthermore, the approximate equipartition between plasma energy density and magnetic field energy is appropriate for the formation of an episodic jet (Ouyed & Pudritz 1997), which may contribute to burst temporal variability. Finally, the magnetospheric origin of the pair plasma would also avoid the baryonic loading problem encountered by mechanisms which propose to generate the pairs by neutrino annihilation close to the merger product (Janka & Ruffert 1996; Ruffert & Janka 1998).

### 4 DISCUSSION

#### 4.1 Observations

Our results predict the appearance of X-ray and Radio transients as precursors to gravitational wave bursts and possibly also Gamma-Ray Bursts.

Motivated by the search for X-ray counterparts to GRB, Gotthelf, Hamilton & Helfand (1996) and Greiner (1999) have searched the Einstein & ROSAT databases, respectively, for brief X-ray transients. The energy ranges searched are somewhat softer ($\sim 0.1 - 4 \text{ keV}$) than we would predict for the peak of the energy distribution. Nevertheless, both searches found classes of transients of possible astronomical origin in sufficient abundance to encompass any reasonable estimate of the event rate (Phinney 1991; Narayan, Piran & Shemi 1991; Lipunov et al 1995, Arzoumanian, Cordes & Wasserman 1999). Searches for untriggered bursts in the BATSE catalogue (Kommers et al 1997) proved even more interesting, revealing a class of bursts restricted to the 25-50 keV channel. Most of these events are consistent with being intensity fluctuations in Cygnus X-1, but the remaining 10% are consistent with the expectations of our model.

If some neutron star mergers do yield GRB, then our results may provide an explanation for the subset of GRB discovered to show X-ray precursors (Murakami et al 1992; Castro-Tirado et al 1993; in 'T Zand et al 1999). These events show the characteristic soft-to-hard spectral evolution we anticipate, although the spectrum in well-studied cases such as GB900126 (Murakami et al 1991), appears somewhat softer ($\sim 1.5 \text{ keV}$) than we would expect. The flux ($\sim 2 \times 10^{-6} \text{ergs cm}^{-2} \text{s}^{-1}$), however, is appropriate, suggesting perhaps that an analysis more sophisticated than the black-body assumption is required.

Perhaps the best candidate for our model is the unusual transient GB900129 observed by Ginga (Strohmayer et al 1995), which yielded a thermal bremsstrahlung temperature $\sim 20 \text{ keV}$ and duration 5-10 s. Strohmayer et al note the similarity to the SGR spectral characteristics, which agrees with the magnetospheric origins in our model as well. Figure 2 shows the comparison of the energetics of various observed transients with our models.

Radio transients associated with GRB are a subject of growing interest and several searches (e.g. FLIRT and STARE) are ongoing. However, radio searches for brief transients are particularly bedevilled by terrestrial interference. Most limits lie in the 10-100 kJy range at 76 MHz (FLIRT; Balsamo 1999) and 611 MHz (STARE; Katz et al 1998). These don’t particularly constrain our model, which anticipates signals $\sim \text{mJy-Jy}$. One radio transient uncovered by FLIRT does deserve mention. FLIRT (Balsamo 1999) located a radio transient apparently associated with GRB 980329. The transient is unique in the database and occurred within 50 s of the burst. The transient showed evidence for dispersion, with a DM $\sim 66 \text{pc cm}^{-3}$. All these argue that the
association is real. However, the signal was very narrow band, indicative of terrestrial interference. If one does choose to interpret this ambiguous transient as a real association, the dispersion measure would rule out a truly cosmological burst. Furthermore, the \( \sim 1 \) kJy flux would suggest distances \( \sim 1 \) Mpc based on our luminosity estimates. All these would argue against the suggestion that the event occurred at very high redshift (Fruchter 1999) and the red optical transient would most likely arise from extinction (Reichart et al 1999).

4.2 Binaries with Black Holes

We have not yet discussed the signatures of mergers associated with binaries in which one of the components is a black hole rather than a neutron star, although such binaries may outnumber the double neutron star binaries (e.g. Bethe & Brown 1998). If the black hole is formed from a strongly magnetized object, then only open field lines remain. Thus, the inspiral of a neutron star through this magnetosphere will still generate the relativistic wind and it’s associated X-ray signature but there will be no trapped magnetospheric plasma. We would then expect to see the same X-ray and radio precursor to the event, but no soft X-ray component to the precursor or any post merger signature associated with the magnetospheric pair plasma. For binaries in which the low field component is a black hole, the effective resistivity of the event horizon (Thorne, Price & Macdonald 1986) is considerably larger than that for a neutron star crust. Consequently the distortion of the magnetic field due to the orbital motion is much smaller and the energy extraction in observable energy is similarly reduced. Furthermore, one cannot extract charged particles from the event horizon, although ‘outer gap’ acceleration is still feasible. We expect such mergers to be (electromagnetically) much quieter.

5 CONCLUSION

If neutron star mergers are not associated with GRB, then any additional electromagnetic signatures will be invisible when the search begins in earnest for the gravitational wave signal. Li & Paczynski (1999) have suggested one such signature; namely a post-merger mini-supernova powered by radioactive decay of disrupted neutron star material. We have demonstrated the possibility of additional precursor signals in the radio and X-ray regimes, driven by the magnetospheric interactions of the neutron star and their magnetic fields. Our results differ somewhat from those of Vietri (1996) who considered a related model. We ascribe this to the much more localized interaction in our scenario, the result of a more realistic choice of parameters, and to our more complete description of the electrodynamics of the accelerated plasma.

To conclude we re-iterate the properties of what we would consider a prime candidate for an electromagnetic counterpart to a neutron star merger. Estimates of the merger rate suggest that the events typically observed would be at distances \( \sim 100 \) Mpc, suggesting X-ray fluxes \( \sim 3 \times 10^{-9} \text{ergs cm}^{-2} \text{s}^{-1} \) with effective temperatures progressing upwards through the 10–100 keV range preceding the gamma-ray event on timescales of order seconds or less. Associated radio fluxes could be as much as \( \sim 5 \) Jy at this distance, although the ability of the radio waves to propagate in the late-time plasma shroud is rather uncertain. The coincidence of the radio signal could be influenced by dispersion in both the host galaxy and ours. Dispersion in the inter-Galactic medium will be of the order of \( \sim 1 \) cm\(^{-3}\)pc\((D/100\text{Mpc}) \) for an ionized IGM mass fraction \( \sim 10^{-2} \) of the critical density and thus is unlikely to contribute significantly for any detectable events.

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APPENDIX A: ELECTROMAGNETIC INTERACTION OF A NEUTRON STAR WITH EXTERNAL MAGNETIC FIELD

Our problem concerns the electrodynamics of a low field neutron star orbiting in the field of a high field neutron star. Although the intrinsic field of the neutron star will be important, let us begin with the model problem of a spinning, conducting sphere in a uniform, externally imposed field.

Consider an unmagnetized conducting sphere in an external homogeneous magnetic field $B_0$. The external field will induce surface currents

$$ g = \frac{c}{4\pi} B_0 \sin \theta e_\phi $$

(A1)

flowing in the azimuthal direction $e_\phi$ about the $B_0$ axis. These currents will induce magnetic field with a dipole structure $\mu = -B_0 R_0^2/2$ so that the total field is

$$ B_{\text{tot}} = B_0 + \frac{R_0^3 B_0}{2r^3} - \frac{3 R_0^3 (B_0 \cdot r) r}{2 r^5} $$

(A2)

At the surface the radial component of the total magnetic field is zero. Consider now the same sphere, moving with velocity $v$ and rotating with angular velocity $\Omega$. The relativistic correction of the order $v^2/c^2$ in the magnetic field is the same in the star’s rest frame (which is moving and rotating with respect to the laboratory frame). In the star’s rest frame the electric field is a sum of electric fields due to the uniform motion and rotation. The electric field due to the rectilinear motion is uniform, given by $E_{\text{orb}} = \frac{1}{c} [v \times B_0]$, while the electric field due to the rotation is $E_{\text{rot}} = \frac{1}{c} [\Omega \times r] \times B_{\text{tot}}$. $E_{\text{rot}}$ has radial and meridional components:

$$ E_{\text{rot},r} = \frac{(2 r^3 + R_0^3)}{2 c r^4} \left( r^2 (B_{\text{tot}} \cdot \Omega) - (B_{\text{tot}} \cdot r) (\Omega \cdot r) \right) $$

$$ E_{\text{rot},\psi} = \frac{(r^3 - R_0^3)}{c r^4} (B_{\text{tot}} \cdot r) \left( -r^2 + (\Omega \cdot r) r \right) $$

(A3)

where $\sin \psi = (\cos \phi \cos \theta \sin \alpha - \cos \alpha \sin \theta)$ is the polar angle in the frame aligned with $\Omega$ and we assumed that $B$ is antiparallel to $z$ and $\Omega = \Omega \sin \alpha, 0, \cos \alpha$. There is also a non-inertial, spatially distributed charge density associated with this electric field (the Goldreich-Julian density)

$$ \rho = \frac{1}{4\pi} \text{div} E = \frac{\Omega \cdot B_{\text{tot}}}{2\pi e c}. $$

(A4)

The ample supply of charges inside the star will short out the total electric field inside the star by producing surface charge density $\sigma = \frac{1}{4\pi} E_r$:

$$ \sigma_{\text{orb}} = \frac{1}{4\pi e R_0} (B_0 \cdot [R_0 \times v]) $$

$$ \sigma_{\text{rot}} = \frac{3 B_{\text{rot}} \Omega R_0 \sin(\psi) \sin \theta}{8 \pi e c} $$

(A5)

The surface charge distribution $\sigma_{\text{orb}}$ has dipole structure with $b = \frac{R_0^2}{8\pi e} [v \times B_0]$, while $\sigma_{\text{rot}}$ has monopole (total charge $Q_{\text{rot}} = -B_0 \Omega R_0^3 \cos \alpha/c$) and quadrupole contributions. Both types of surface charges will produce electric fields outside of the star with nonzero component along the magnetic field line of the order

$$ E_{\parallel,\text{orb}} \approx -\frac{R_0^3}{c r^4} (B_0 \cdot [r \times v]) \cos \theta $$

$$ E_{\parallel,\text{rot}} \approx -\frac{B_0 \Omega R_0^3 \cos \alpha \cos \theta}{c r^2} $$

(A6)

These electric fields will accelerate the primary charges to relativistic energies.

The surface charge distribution $\sigma_{\text{orb}}$ is stationary in the moving but non-rotating frame, while surface charges $\sigma_{\text{rot}}$ are stationary in the neutron star frame (which is moving and rotating with respect to the lab frame). An observer in the neutron star frame will detect three types of electric currents; due to rotation of $\sigma_{\text{orb}}$ and inertial currents due to electric fields of the surface charges $j_\text{in} = [(E_{\sigma_{\text{orb}}} + E_{\sigma_{\text{rot}}}) \times \Omega]/(4\pi)$. Inertial current due to $E_{\sigma_{\text{rot}}}$ will generate magnetic field of the order $B_{\text{rot}} \approx B_0 (\Omega R_0/c)^2$ with a component perpendicular to the surface of the millisecond pulsar. Equivalently, in the laboratory frame the charges $\sigma_{\text{rot}}$ rotating with the star will produce surface currents along the $\psi$ direction $g_{\text{rot}} = \sigma_{\text{rot}} [\Omega \times r]$ that will generate magnetic field $B_{\text{rot}}$.

The Poynting losses due to rotating dipole will be proportional to the time varying component of the induced magnetic field $\propto B_0 (\Omega R_0/c)^2 \sin \alpha \cos(\Omega t)$, so that the resulting Poynting flux would be $P \propto B^2(\Omega R_0/c)^4 \sin^2 \alpha$. It is suppressed by a small factor $(\Omega R_0/c)^2 \ll 1$ if compared with the rotating dipole with the strength equal to the external magnetic field.
Figure 1. Schematic version of the energy extraction process. The motion of the companion through the magnetar field induces a plasma flow from the companion into the magnetosphere. The pressure of this flow will drive a relativistic wind in those regions where the flow moves into a regime of weaker field, while the plasma remains trapped in the case when it flows into a stronger field regime. The hot pair plasma will ablate some baryons off the surface of the neutron star, providing a baryon-loaded sheath which regulates the cooling of the trapped plasma.

Figure 2. Here we show the expected evolution of the X-ray precursor signal for binaries containing a recycled pulsar with either a normal field neutron star or a magnetar. The solid lines indicate the wind emission (the solid vertical line at the right indicates the luminosity) while the dotted lines indicate the cooling emission of the trapped magnetospheric plasma (also with appropriate luminosity scale). The dashed part of the $10^{15}$ G curve indicates the region where bound positronium production may alter the plasma injection mechanisms, possibly resulting in more nonthermal, high-energy emission. The points show the various transients discussed in the text (solid symbols are associated with GRB, open symbols are not). The time error bars are determined from the quoted time resolution and rise times of the signals. We see that the detected temperatures and time delays are broadly consistent with the expected theoretical values.
Trapped Pair Plasma
X-Ray Signature
Cooling Region
Acceleration Region
Alfven Wave Damping and Plasma Production
Relativistic Wind
Radio Signature
X-Ray Signature
Pair Production Front
