On Fallback Disks and Magnetars

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Abstract

The discovery of a disk around the anomalous X-ray pulsar 4U 0142+61, has rekindled the interest in fallback disks around magnetars. We briefly review the assumptions of fallback disk models and magnetar models. Earlier data in optical and near IR bands combined with new Spitzer data in the mid-IR range are compatible with a *gas* disk. Higher multipole fields with magnetar strengths together with a dipole field of 10^{12}-10^{13} G on the neutron star surface are compatible with the presence of a disk around the neutron star. The possible presence and properties of a fallback disk after the supernova explosion is a likely initial condition to complement the initial rotation period and initial dipole field in determining the evolutionary paths and different types of isolated neutron stars.

1 Spindown Rates and Periods of Isolated Pulsars

The spindown rate of an isolated pulsar is determined by the strength of the *dipole* component of the magnetic field:

$$I\Omega\dot{\Omega} = \frac{2}{3}\frac{B_{dip,\perp}^{2} R^{6}\Omega^{4}}{c^{3}}, \tag{1}$$

where $B_{dip,\perp}$ denotes the component of the surface dipole field perpendicular to the rotation axis. All magnetars with measured period derivatives exhibit spindown at rates in the $\sim 10^{-12}$ rad s^{-2} range, and have periods in the 3−12 s range corresponding to rotation rates Ω (rad / s) ~ $O(1)$. If the spindown mechanism is the dipole radiation of an isolated magnetized neutron star then the combination of such slow rotation rates with such large spindown rates implies a dipole magnetic field with magnetar range values on the neutron star surface (Kouveliotou et al., 1998). For some of the sources we have evidence for association with supernova remnants (SNR) indicating a young age, of some 10^4 yrs. If the neutron star's initial rotation period was in the sub-second range, as inferred for the isolated radio pulsars, a magnetar range dipole field is implied for the source to have spun down to the present rotation period within such a short time. These arguments for a magnetar strength *dipole* field apply *if the neutron star is spinning down under the dipole radiation torque.*

Why do all magnetar candidates, anomalous X-ray pulsars (AXPs), soft gamma-ray repeaters (SGRs) and dim isolated thermally emitting neutron stars (DINs) have rotation periods all in the same narrow range P = 3−12 s, giving rotation rates $\Omega \sim O(1)$?

As Psaltis and Miller (2002) have shown, dipole spindown (braking index $n = 3$) or spindown with any other power law index in the range n = 2−4, can produce the observed period clustering only if the observed periods are very close to final periods. Isolated rotation powered pulsars cease their activity when they reach final periods and spindown rates in the ranges corresponding to the "death valley"in the $P - \dot{P}$ plane. But the periods and spindown rates of AXPs and SGRs are not in the "death valley" neighbourhood. The possible way out for magnetar dipole spindown is that the neutron star's magnetic moment decays on a timescale shorter than the spindown timescale. Colpi, Geppert and Page (2000) showed that only Hall cascade models, among available models for magnetar field decay, yield the X-ray luminosity by magnetic energy dissipation *as well as* the period clustering. These models work if the field decay timescale is less than 10^4 yrs. The period clustering of all sources in the 3−12 s period range is difficult to explain with magnetar models.

2 The Fallback Disk Model

The period clustering provided the hint for fallback disk models. A disk around the neutron star is an angular momentum store that can act as a "gyrostat". The disk interacting with the neutron star can provide a natural explanation for period clustering, as representing the range of equilibrium periods that the neutron star approaches asymptotically. The equilibrium period is the Kepler period at the inner disk radius, roughly the Alfven radius,

$$r_A \approx \mu^{4/7} \dot{M}^{-2/7} (GM)^{-1/7} \tag{2}$$

$$P_{eq} = 2\pi r_A^{3/2} (GM)^{-1/2} \tag{3}$$

where $\dot{M}$ is the mass inflow rate in the disk, μ is the dipole magnetic moment of the neutron star and M is the star's mass. Since AXPs, SGRs and DINs are not in binaries the disk must be a *fallback disk* from the core collapse in the supernova that formed the neutron star. Such fallback disks may be formed in some supernovae (e.g. Heger et al. 2003).

Spindown rates provided by disk torques can be estimated with

$$I\left|\dot{\Omega}\right| \sim \mu^2 r_A^{-3} \sim \mu^{2/7} \dot{M}^{6/7} (GM)^{3/7} \tag{4}$$

The observed spindown rates can be obtained using equilibrium periods in the range of observed periods and mass inflow - mass accretion rates of the order of the rates implied by the X-ray luminosity, with *dipole* magnetic fields B of the order of a few 10^{12} to a few 10^{13} G on the neutron star surface ($\mu \sim 10^{30}$ G cm^3). Disk torques can yield the observed spindown rates, *without invoking magnetar values for the dipole component* of the neutron star magnetic field, with the bonus of explaining the narrow range of observed periods from AXPs, DINs and SGRs.

Chatterjee, Hernquist and Narayan (2000) proposed the presence of a fallback disk to explain the period clustering of AXPs. Detailed comparison of fallback disks against the ages and present properties of AXPs depends on the joint mass and angular momentum evolution of the fallback disk and produces model dependent results (Chatterjee, Hernquist and Narayan 2000; Ekşi and Alpar 2003; Ekşi, Hernquist and Narayan 2005; Ertan et al. 2006).

Alpar (2001) independently proposed fallback disks, not only for AXPs, but as a third initial condition, in addition to the traditional initial conditions of the dipole magnetic moment and rotation rate, to explain different categories of isolated neutron stars. These classes of young neutron stars include the isolated radio pulsars (now possibly extending to the rotating radio transients - RRATS), AXPs, SGRs, DINs and the radio-quiet neutron stars (RQNS - called compact central objects, CCOs now).

3 The Search for Fallback Disks

The search for fallback disks around AXPs, in particular 4U 0142+61, in the optical and near infrared bands yielded data that were compared with available thin disk models. The conclusions drawn in earlier work were that there was no disk (Hulleman, van Kerkwijk and Kulkarni 2000, 2004), or that the inner disk was advection dominated (Perna, Hernquist and Narayan 2000). These conclusions were based on fitting the data with A_V from a wide range of plausible values, in conjunction with a particular model for disk irradiation by, and reprocessing of, X-rays from the neutron star.

Observation of 27% pulsed optical flux from 4U 0142+61 (Kern and Martin 2002) supported the inference that there was no disk because of the prevailing view that a pulsar magnetosphere cannot operate in the presence of a disk protruding inside the light cylinder. Disk-magnetosphere models were proposed for pulsar emission from the early days (Michel and Dessler 1981) and are not restricted to the specific early models. A magnetosphere with a disk in it can generate optical and higher energy radiation with high pulse amplitude at the pulsar rotation frequency (Cheng and Ruderman 1991). Ertan and Cheng (2004) showed that such a disk-magnetosphere model can produce the optical pulses of 4U 0142+61.

4 The Fallback Disk of 4U 0142+61: a Gas Disk

Wang, Chakrabarty and Kaplan (2006) detected 4U 0142+61 in the mid-IR band with Spitzer observations. These authors found that the mid-IR detections can be fit well with a disk model. Adopting the interpretation of the earlier optical and near IR data, that these were not compatible with disk models, and the suggestion that the strongly pulsed nature of the optical radiation rules out a disk intruding deep within the light cylinder, they concluded that the disk indicated by the mid-IR data is a passive dust disk situated beyond the light cylinder.

We have evaluated all available data, from the earlier observations in the optical and near infrared bands, and from the recent Spitzer observations in the mid-IR with gas disk models (Ertan et al. 2006). We find that the combined data set can be fit by a conventional gaseous disk model with viscous energy dissipation and mass inflow together with irradiation reprocessing. The best fitting A_V value from our fits, $A_V = 3.5$, agrees well with the value $A_V = 3.5 \pm 0.4$ found in a detailed study of reddening in the directions of 4U 0142+61 and other AXPs (Durant and van Kerkwijk 2006).

With $A_V = 3.5$, dereddened optical data yield a disk inner radius $r_A = 10^9$ cm. Assuming the mass inflow through the disk is fully accreted, to give the observed X-ray luminosity, we obtain a surface dipole field $B = 2 \times 10^{12}$ G (on the poles). With torque models appropriate for the age estimate, about 85% of the mass inflow in the disk must be accreting, giving similar estimates for the surface fields. The corotation radius for AXP 4U 0142+61 is 7×10^8 cm. The disk inner radius is close to the corotation radius but somewhat larger. The star is a weak propeller, accreting while spinning down. Taking the unlikely extreme value of $A_V = 2.6$ leads to $B = 4 \times 10^{13}$ G (on the poles). We infer the value of the inner radius of the disk around 4U 0142+61 from the optical observations. If the disk emission extends into the UV range, the disk inner radius and the dipole field are actually smaller than the current estimates of Ertan et al. (2006).

While 4U 0142+61 is the AXP with the most extensive data set, there are observations of other AXPs in some bands. Using all available data, Ertan and Çalışkan (2006) found that gas disk models are compatible with the data from all AXPs. Interestingly, irradiation parameters derived from independent fits to data from all the individual sources agree, to order of magnitude, with the irradiation model we employed for 4U 0142+61. These fits all yield $r_A \sim 10^9$ cm for the disk inner radius and the irradiation parameter $C \sim 10^{-4}$ found in all sources. This is the same range of C as found from fits to the 4U 0142+61 data.

5 Magnetars and Fallback Disks

The bursts in Soft Gamma-Ray burst sources (SGRs) and in AXPs are explained by magnetar models (Thompson and Duncan 1995, Woods and Thompson 2006). These models employ strong magnetic fields in the neutron star crust and near the star's surface to trigger and sustain the bursts. Magnetic field decay in the neutron star crust is the source of the X-ray luminosity. Surface magnetic field strengths of the order of 10^{14}–10^{15} G, above the quantum critical field $B_{crit} = 4.4 \times 10^{13}$ G are required. These strong fields are built up, dissipated and "released" in the crust of the neutron star by *local* processes.

The timing and evolutionary properties of the neutron star are determined by the long range dipole component of the magnetic field. If there is a disk around the neutron star, the dipole field stops the disk at an inner radius where magnetic stresses balance the material stresses in the disk. The Kepler rotation period at the inner edge of the disk sets the equilibrium period towards which the neutron star evolves asymptotically. Dipole magnetic fields of strength 10^{12}–10^{13} G on the neutron star surface, and mass inflow rates commensurate with the accretion rates can give the observed *period clustering as equilibrium periods of the star with the disk*.

Fallback disk models do not explain the bursts of the SGRs and AXPs. However, the post burst X-ray and IR luminosity enhancements observed from some sources can be explained well as due to the effect of the burst on the fallback disk and the subsequent relaxation of the disk (Ertan and Alpar 2003, Ertan, Göğüş and Alpar 2006).

The presence of a gas disk indicates a surface dipole field of 10^{12}–10^{13} G. The magnetar models require extra strength fields on the neutron star surface and crust. So what is the nature of the surface magnetar fields?

The mechanisms of winding up the field and breaking the crust by magnetic stresses are all *local* processes. There is no reason to expect that production of magnetar strength fields should take place on the global scale of the surface dipole field. Thus the bursts could be triggered by surface fields with magnetar strengths in the *higher multipoles*, while disks like the one observed in 4U 0142+61 provide the spindown torques on the neutron star, in interaction with its dipole magnetic field. The possibility of such a hybrid situation, with higher multipole fields present on the neutron star surface, bears on several issues.

The suppression of radio emission in magnetars by shorting the inner gap can be achieved by the presence of higher multipole fields near the surface, having super-quantum-critical values in the near range of the multipole fields, prevailing through the inner gap. Radio pulsars with $> 10^{13}$ G dipole fields (Camilo et al. 2006) do function as radio pulsars in spite of the strength of the surface dipole field. The transient AXP XTE J 1810−197, a magnetar candidate, also shows up as a radio pulsar (Camilo et al. 2006). All this suggest that the complex, smaller scale structure of a many multipole magnetar field has the possibilities of allowing or suppressing radio pulsar emission, depending on the options of evolutionary and/or geometrical non-interference or overlap of the magnetar strength multipoles with the inner gap. A similar discussion of the role of multipole components may be relevant also for the RRATS (McLaughlin et al. 2006), some of which have positions in the $P-\dot{P}$ diagram not far from the positions of the magnetar candidates.

INTEGRAL observations of AXPs, detecting strongly pulsed hard X-rays (Kuiper et al. 2006) provide a new prospect for magnetar, fallback disk and hybrid models to explore, as such behaviour is not expected with either standard isolated pulsar/magnetar magnetospheric models, or with magnetospheric models with disks. INTEGRAL observations of persistent unpulsed hard X-rays from the SGR 1900+14 add to this new prospect (Götz et al. 2006).

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