ON DISKS AND MAGNETARS: AFTER THE DISCOVERY OF A FALLBACK DISK

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ABSTRACT

After the recent discovery of a fallback disk around the anomalous X-ray pulsar 4U 0142+61, we briefly review the assumptions of fallback disk models and magnetar models. Old data in different optical and near IR bands combined with new Spitzer data in the mid-IR range are compatible with a *gas* disk. Magnetar strength fields in the higher multipoles 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 presence or absence, and properties of a fallback disk after the supernova explosion is a likely initial condition on neutron star evolution.

1. EVIDENCE FOR FALLBACK DISKS

It was proposed some years ago that the different properties of all categories of young neutron stars can be explained by the presence or absence, and initial mass of a fallback disk [1] and that anomalous X-ray pulsars (AXPs) have their special properties as a result of evolution with a fallback disk around them [2]. This proposal brings in the possibility of bound matter, necessarily with angular momentum, left from the supernova, as a third initial condition for newly formed neutron stars, in addition to the initial magnetic dipole moment and initial rotation rate.

A search for fallback disks was on, especially around AXPs, in particular 4U 0142+61. Data were compared with available thin disk models. The conclusions drawn in earlier work, on the basis of optical and near infrared data, were that there were no disk [3,4], or that the inner disk was advection dominated [5]. 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 X-rays from the neutron star and reprocessing of the X-rays in the disk.

Spitzer observations of 4U 0142+61 [6] yielded its detection in the mid-IR band. The authors found that the mid-IR detections can be fitted well with a disk model. Adopting the earlier evaluation of optical and near IR data and the suggestion that the strongly pulsed nature of the optical radiation [7] 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 found [8, 9] that all available data, from the earlier observations in the optical and near infrared bands and the recent Spitzer Observatory data in the mid-IR can be fitted by a conventional gaseous disk model with viscous energy dissipation and mass inflow together with irradiation reprocessing. When we first reported these results [8], we found out that the best fitting A_V value from our fits, $A_V = 3.5$, agreed well with the value $A_V = 3.6 \pm 0.2$ found in a detailed study, reported at the same conference, of reddening in the directions of 4U 0142+61 and other AXPs [10].

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 & Çalışkan [11] 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.

The 27% pulsed optical flux observed from the AXP 4U 0142+61 seems to provide a strong indication that a disk is not present or at least that it does not protrude the light cylinder. This is based on the impression that pulsar magnetospheres will not function with a disk in them. Disk-magnetosphere models were proposed for pulsar emission from the early days [12], and are not restricted to the specific early models. Actually, as proposed more recently by Cheng & Ruderman [13], a magnetosphere with a disk in it works; it can generate optical and higher energy radiation with high pulse amplitude at the pulsar rotation frequency. Ertan & Cheng [14] showed that such a disk-magnetosphere model can produce the optical pulses of 4U 0142+61.

2. ON MAGNETAR MODELS

Magnetar models [15,16] successfully employ strong magnetic fields to explain the source of the bursts in Soft Gamma Repeaters (SGRs) and in AXPs. Strong magnetic fields in the neutron star crust and near the star's surface provide the energy and trigger and sustain the mechanisms of the bursts. In these models magnetic field decay in the neutron star crust is the

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source of X-ray luminosity. Surface magnetic field strengths required by magnetar models are of the order of 10^{14}-10^{15} G, above the quantum critical field B_{crit} = 4.7 × 10^{13} G. These strong fields are built up, dissipated and "released" in the crust of the neutron star by *local* processes.

Strength of the long range *dipole* component of the magnetic field perpendicular to the rotation axis determines the spindown rate of an isolated pulsar:

$$I \Omega\, d\Omega/dt = 2/3\, B(\text{dipole, perp})^2 R^6 \Omega^4 / c^3 \qquad (1)$$

Now, AXPs, SGRs and dim isolated thermally emitting neutron stars (DINs), which resemble AXPs and SGRs in some properties, all have rotation periods in the same narrow range P = 3-12 s, giving rotation rates $\Omega \sim O(1)$. All of the sources with measured period derivatives exhibit spindown with spindown rates in the $\sim 10^{-12}$ rad s^{-2} range. *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 [17]. For some of the sources measurement of a spindown rate is not available, but association with supernova remnants (SNR) indicates a young age. Assuming that the neutron star had a sub-second rotation period, as must be the case for the familiar radio pulsars, again indicates magnetar range dipole fields in order for the source to have spun down to the presently observed rotation period in the 10 s range within such a young age. These are the arguments, in the framework of dipole spindown of an isolated neutron star, for a magnetar strength field specifically in the *dipole* component.

3. ON FALLBACK DISK MODELS

Why are the periods of all these sources in the same narrow range?

Psaltis & Miller [18] showed that dipole (braking index n = 3) or any other power law spindown, with n = 2-4, will produce the observed period clustering only if the observed periods are very close to final periods. But the AXPs and SGRs are not close to the isolated rotation powered pulsars' "death valley"in the P-dP/dt plane. The only way out is that their magnetic moments decay on a timescale shorter than the spindown timescale.

Colpi et al. [19] showed that among present models for magnetar field decay in the neutron star crust only Hall cascade models give the observed X-ray luminosity by magnetic energy dissipation *as well as* the period clustering. Models in this class work if the field decay timescale is restricted to be less than 10^4 yrs. Thus the period clustering of all sources in the 3-12 s period range is difficult to explain with magnetar models.

This is where an angular momentum store interacting with the neutron star can provide a natural explanation. A disk around the neutron star acts as a "gyrostat"- the equilibrium period is:

$$P_{eq} = \mu^{6/7} (dM/dt)^{-3/7} (GM)^{-3/14} \qquad (2)$$

where dM/dt 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.

Current spindown epochs of the sources correspond to an extended mild propeller phase near rotational equilibrium. Some part of the mass inflow through the viscous disk is accreted onto the neutron star, accounting for the X-ray luminosity [1].

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 [20].

The spindown epoch is extended as a "tracking phase" [2]. This is because the mass of the isolated fallback disk and the mass inflow rate in the disk decrease with time, so that the inner radius of the disk recedes, and the equilibrium period constantly gets longer. The spindown of the neutron star can follow this under certain torque models [2].

An order of magnitude estimate for disk torques can be made, 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. For *dipole* magnetic fields B of the order of a few 10^{12} to a few 10^{13} G on the neutron star surface these estimated torques yield the observed range of large spindown rates. Thus 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 corresponding to a wider range of dM/dt [1].

A more 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 [2,9,21,22].

4. MAGNETARS AND FALLBACK DISKS

An isolated neutron star's evolutionary fate is determined by the initial conditions at formation. To the conventional initial conditions of rotation rate and magnetic moment, one must add the presence or absence of bound matter with angular momentum. A fallback disk, and its properties (initial disk mass) constitute a potential third initial condition, in addition to the dipole moment and initial rotation rate of the neutron star. This may be a key to explaining different categories of isolated neutron stars, the isolated radio pulsars (now possibly extending to rotating radio transients, RRATS [23]), AXPs, SGRs, DINs and the radio-quiet neutron stars, RQNS - now called compact central objects, CCOs.

The timing and evolutionary properties of the neutron star are determined by the long range dipole component of its magnetic field. In their magnetic field requirements fallback disk models differ from magnetar models *in the dipole component*. For example, the best fit to combined optical, near-IR and mid-IR data from 4U 0142+61 with an irradiated gas disk model, and with $A_V = 3.5$, implies, within uncertainties, a surface dipole magnetic field strength of 10^{12} G on the equator; 2×10^{12} G on the poles [9]. The maximum field values obtained in our fits, with $A_V = 2.6$, were 2×10^{13} G on the equator; 4×10^{13} G on the poles. This dipole field stops the disk at the right inner radius inferred from the optical observations. If the disk emission extends into the UV range, the disk inner radius and the dipole field is smaller. *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 [24,25].

So what is the nature of the magnetar fields? The magnetar models require extra strength fields on the neutron star surface and crust. 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.

INTEGRAL observations of AXPs, detecting strongly pulsed hard X-rays [26], 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 from the SGR 1806-20 [27] and the SGR 1900+14 [28] add to this new prospect.

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