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SOME OBSERVATIONAL TESTS OF X-RAY PULSAR EMISSION MODELS+

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Abstract

Our understanding of neutron star physics relies heavily on knowing values of their mass, radius and magnetic field strength, and our only information about these comes from the surface radiation. There are however still major uncertainties about how this arises, concerning the nature of the mass exchange and the accretion flow, the magnetopause structure, the infall deceleration, the actual pulsation mechanism and the atmosphere geometry. We discuss the alternatives, and point out several possible observational tests.

I. Some Outstanding Crucial Ambiguities

Out of the many unsolved questions about X-ray pulsars, there are three, connected with the actual emission mechanism, which are particularly irksome to the theoretician, but which appear to be within reasonable reach of observational solution. These are a) Is the mass exchange mechanism due to Roche lobe overflow, or due to (X-ray induced or spontaneous) wind transfer, and if the latter, will a disk form or not? ([1], [2], [3]). b) Is the pulsation mechanism due to intrinsic beaming at the polar caps ([4]), or to occultation at the Alfvén surface ([5], [6]), and if due to both, in what proportions? c) Is the deceleration of the infalling matter due to a collisionless shock ([7,8]), or to binary coulomb encounters ([7,9]) (besides radiation pressure contributions), that is, does the emitting polar cap atmosphere stick out significantly, emitting both across the field as well as along it, or is it mostly along it?

These questions, it is seen, tie into each other rather closely, and the reason why they are important is that their answer can have a significant effect on the determination of at least two crucial neutron star parameters, namely, the surface gravitational redshift and the magnetic field strength. The observed flux at earth F_x leads of course to a different estimate of the accretion efficiency $GM_xR_x^{-1}c^{-2}$, depending on the degree of beaming, that is even if we know M_x from doppler delay curves and eclipses, the value of R_x deduced depends crucially on the pulsation mechanism. This is of interest also for our understanding of the dynamics of the neutron star interior, via its effect on the calculation of the moment of inertia ([10]). The magnetic field strength, for its part, is either deduced from its effects on the rate of change of the pulsation period, $-\dot{p}/p$, for which the Alfvén geometry and the mass exchange mode is important, or is directly measured via cyclotron lines, the frequency of which is gravitationally redshifted and therefore affected by whether there is a shock which stands off above R_x or not. Spectroscopic observations with a resolution $E/\Delta E \gtrsim 100$, as well as studies of the correlation of pulse shapes with the X-ray luminosity in different bands, may resolve these questions.

II. Mass Exchange Mechanism and Disk Question

In the X-ray domain, this boils down to resolving the dynamics of the flow at the Alfvén surface, located typically at

$$R_A(\mathrm{sph}) = \tag{1}$$

$$10^8 (B/10^{12}G)^{4/7} (R_{ns}/10^6 cm)^{12/7} (M/M_o)^{-8/7} (\dot{M}/1.3\ 10^{18} gs^{-1})^{-2/7}\ cm,$$

for spherical infall, and at

$$R_A\ (\mathrm{disk}) = \tag{2}$$

$$3\mathrm{x}10^7 (B/10^{12}G)^{40/69} (R_{ns}/10^6 cm)^{120/69} (M/M_o)^{-13/69} (\dot{M}/1.3\ 10^{18} gs^{-1})^{-16/69} \alpha^{18/69}\ cm$$

for disk accretion, where α is the viscosity parameter of the disk ($\alpha < 1$). The Keplerian (~ free fall) and thermal velocities are

$$V_{kep}/c \simeq V_{ff}/c = 6\ 10^{-2} (M/M_o)^{1/2} (r/10^8 cm)^{-1/2}$$

$$V_{th}/c \simeq 2\ 10^{-2}\ (T/10^6 K)^{1/2} \tag{3}$$

The Fe line observed in many X-ray pulsars very probably arises from this region ([11], [12]), and it could be used to trace the temperature and flow structure at the interface between the inflowing gas and the magnetic field, somewhat as the galactic structure is studied in radio astronomy. If one could resolve the blue and red rotation components of the Fe line, this would confirm the existence of a magnetopause. Analysis of the outer shoulders of the pulse profiles could reveal whether most of the emitting matter is at a particular distance from the axis of rotation, which would argue for a disk, or whether it is spread out over a range of axial distances smaller than the maximum, which might indicate either a very well covered Alfven surface, fed from a disk, if the minimum velocity component is relatively very strong, or a more or less symetrical infall from all directions, if the emission strength at different velocities changes only very gradually. The strength and thermal width of the line might also give some clues as to the width of the Alfvén shell, providing valuable information about the viscosity at the field-plasma interface, and possible instabilities which might cause penetration of plasma into the magnetic cavity. The presence of several discrete velocity components might indicate either penetration of diamagnetic blobs, or strong non-dipole field components. Spectroscopic observations with $E/\Delta E \gtrsim 300$ would be the best for this, but $E/\Delta E \gtrsim 50$ would already be extremely useful.

III. Pulsation Mechanism

In order to test the possible contribution of the Alfvén shell as an occulting screen, one would want to know first the geometry and dynamics of the magnetopause flow, as described in II. This should be complemented by long term studies of the correlation of the X-ray luminosity with pulse shape in at least four bands,

$$E_s \lesssim 0.5 \;,\; E_{ph} \sim 2\text{-}6 \;,\; E_T \sim 8\text{-}12 \;,\; E_T' \sim 15\text{-}25 \text{ keV} \qquad (4)$$

Here E_s is characteristic of screen reprocessing, E_{ph} is the band where photoabsorbtion may dominate; and E_T, E_T' are bands where scattering dominates. At least two of the latter are helpful, because the scattering opacity above 8 keV should be frequency independent at the Alfvén shell and the pure screen mechanism would predict similar shapes at different energies. (The intensity $I\nu$, originating at the surface of the star, could of course be different). If the screen mechanism dominates pulse formation, one would expect that a decrease in L_x (i.e. $\dot{M}$) would decrease screen opacity and therefore decrease the modulation factor (pulse throughs should fill in), while with increasing L_x, the pulse throughs should go down towards zero, i.e.

$$\text{Screen modulation} = \text{increasing function of } (L_x) \qquad (5)$$

On the other hand if the intrinsic beaming dominates pulse formation, very little change of the modulation with L_x is expected for either pencil or fan beams. For intrinsic fan beams, a change of the duty cycle or pulse width is expected to be correlated with L_x, while for intrinsic pencil beams the pulse multiplicity is expected to vary in a definite fashion with frequency, but not with luminosity, as discussed in the next section.

IV. Matter Deceleration and Geometry of the Emission Region

For luminosities $L_x \gtrsim 10^{37}$ erg s^{-1} radiation pressure plays a major role in the deceleration of the infalling matter at the polar caps, creating a smoothed-out radiation shock ([13]). In this case, the shock standoff distance varies from about $d_s \lesssim 0.1\ R_*$ to many times R_*, increasing approximately as $d_s \sim L_x^m$, with $m \sim 2/3$. The emitting atmosphere is the accretion funnel below the shock, sticking out above the stellar surface. The intrinsic beaming will be preferentially fan type, especially at the higher L , when the side surface largely exceeds the top surface of the column. The fan beam pulse width will be influenced by the amount of curvature of the side surface being sampled, this increasing with d_s and L_x. If a flat surface emits a narrow intrinsic beam, one can roughly estimate the angular width of the actual beam from a curved surface as $\Delta\phi \sim$ channel width/height $\sim d_s^{3/2} d_s^{-1} \sim d_s^{1/2}$, where we used $a = a_0 [(R_\star + d_s)/R_\star]^{3/2}$ for the width of a dipole channel and took $d_s >> R_\star$. For $d_s \lesssim R_\star$ the dependence is not as strong, though still noticeable. Since in a radiation shock $d_s \sim L_x^{2/3}$, we expect

$$\Delta\phi \text{ (intrinsic pulse)} \sim L_x^{1/3}, \quad (6)$$

for $L_x \gtrsim 10^{37}$ erg s^{-1}. Thus, if the luminosity of the pulsar varies in time, so should the pulse width. Another quantity that may vary with L_x is the frequency of the cyclotron line feature, observed in some objects, if this arises near the shock. If the field is a dipole one would expect

$$\omega_H \sim (R^* + d_s)^{-3} \sim (1 + \text{const } L_x^{2/3})^{-3}, \quad (7)$$

For luminosities $L_x \lesssim 10^{37}$ erg s^{-1}, radiation pressure loses its importance, and one of the key uncertainties in deducing an atmosphere structure is whether a collisionless shock occurs, or whether the infalling protons are decelerated in the denser part of the stationary atmosphere by binary (coulomb or nuclear) encounters. In the absence of radiation pressure, the collisionless shock height (if present) would go as $d_s \sim n_e^{-1} \sim L_x^{-1}$, being given by the cooling or the coulomb exchange length. The collisionless shock would thus lead ([14]), by a reasoning similar to the high L_x case, to

$$\Delta\phi \text{ (intrinsic pulse)} \sim d_s^{1/2} \sim L_x^{-1/2}, \quad (8)$$

for $L_x << 10^{37}$ erg s^{-1}. This differs from the high L_x case treated before in equation (6). Similarly if the cyclotron feature arises near the shock, one would get

$$\omega_H \sim (R^* + d_s)^{-3} \sim (1 + \text{const } L_x^{-1})^{-3}, \tag{9}$$

for $L_x << 10^{37}$ erg s^{-1}.

If no collisionless shock occurs (and theoretically, the physics of these shocks is largely unknown, so this is a distinct possibility) the stopping by binary encounters requires $y_0 \sim 5 - 50$ gm/cm^2, occurring in the dense part of the atmosphere. In this case the emitting region does not stick out significantly above the surface, and the beaming is essentially in a pencil pattern. In a magnetic field $B \sim 10^{12}$ gauss pointing perpendicular to the surface, the strong angular and frequency dependence of the cross sections leads to a very distinctive frequency behaviour of the pulse shapes. Detailed calculations ([15]) for homogeneous atmospheres indicate a rough rule of thumb for the pulse multiplicity in different frequency ranges (ω_H = cylcotron frequency), namely

$$\begin{aligned} &\text{single pulse:} \quad 10^{-1} \lesssim \omega/\omega_H \lesssim 1 \\ &\text{triple pulse:} \quad \text{few} \times 10^{-2} \lesssim \omega/\omega_H \lesssim 10^{-1} \\ &\text{double pulse:} \quad \omega/\omega_H \lesssim \text{few} \times 10^{-2}, \end{aligned} \tag{10}$$

for pencil beam systems in which the magnetic axis is not too close to 90^0 away from the line of sight. These calculations also indicate that the spectrum is harder at midpulse, which observationally has been known to occur in some objects. Unlike in the shock cases, very detailed theoretical pulse profiles have been calculated for the pencil beam models ([15]), which would arise from binary particle deceleration. A refinement in progess now ([16]) consists in calculating the temperature and density profile of the coulomb decelerating atmosphere, which should provide more realistic spectra and pulse shapes to compare with observations.

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