Phase Transitions in Evolving Millisecond Pulsars and in Accreting X-ray Neutron stars in Binaries[1]

Norman K. Glendenning & Fridolin Weber

One of the great fascinations of neutron stars is the deep interior where the density is a few times larger than the density of normal nuclei. There, in matter inaccessible to us other than fleetingly in relativistic collisions, unfamiliar states may exist. The most exotic of these is, of course, quark matter—the deconfined phase of hadronic matter. It is quite plausible that ordinary canonical pulsars—those like the Crab, and more slowly rotating ones—have a quark matter core, or at least a mixed phase of quark and confined hadronic matter in the high-density interior. However, this will not alter appreciably the static properties of the star, and will go unnoticed in canonical pulsars.

By comparison, millisecond (ms) pulsars are centrifugally flattened in the equatorial plane and the density is diluted in the interior. We shall suppose that the critical phase transition density lies between the diluted density of millisecond pulsars and the high density at the center of canonical pulsars. Then as a millisecond neutron star spins down because it is radiating angular momentum in a broad band of electromagnetic frequencies as well as in a wind of particle-antiparticle pairs, a change in phase of matter in the inner part of the star will occur. The relativley incompressible nuclear matter in the core progressively changes phase to compressible quark matter. Self-gravity and the weight of the exterior neutron star envelope will shrink the star and decrease its moment of inertia. The spin rate will be altered so as to conserve angular momentum. The star can spinup for a lengthy era.

The converse of this may occur in another class of neutron stars. Some neutron stars have non-degenerate companions. Such stars are radio silent because a wind from the hot surface of the companion disperses the pulsed radio signal which a rotating magnetized neutron star would otherise radiate into space. Late in the life of the neutron star, when the slowly evolving companion begins to overflow the Roche lobe, mass transfer onto the neutron star commences. The drag of the magnetic dipole torque will be eclipsed by the transfer of mass and angular momentum onto the neutron star. It has begun its evolution from an old slowly rotating neutron star with long period and high magnetic field, to a ms pulsar with low field (sometimes referred to as a "recycled pulsar"). During the long intermediate stage, when the surface and accretion ring are heated to high temperature, the star radiates x-rays.

At an accretion rate of $10^{-9} M_{\odot}/\mathrm{y}$ it would take only 10^8 y to spin up the neutron star to a period of 2 ms (500 Hz). Consequently, any asymmetry in the mass accretion pattern will cause millisecond variability in the x-ray luminosity, which is observed. As these accreters attain the critical density at the center, and then in an expanding region, the already present quark matter will transform to confined hadronic matter. The moment of inertia will increase, causing the star to stall in the region of critical spins for a few tens of millions of years. There will be an anomalous number of accreters that appear at or near the same frequency. This is what was found recently in data obtained with the Rossi X-ray Timing Explorer (RXTE) [3].

[1] N. K. Glendenning & F. Weber, in *Physics of Neutron Star Interiors*, eds. Blascke, Glendenning and Sedrakian, Springer-Verlag, 2001

[2] Bhattacharya, D. & van den Heuvel, E.P.J. 1991, Phys. Rep., 203, 1

[3] M. van der Klis, Ann. Rev. Astron. Astrophys., (2000)