MILLISECOND PULSARS

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ABSTRACT. Millisecond pulsars are intrinsically interesting because they illustrate some of the most extreme physical conditions to be found anywhere in the Universe, and because their evolution exhibits several stages of great drama. It had been widely believed for several years that spin-up of an old neutron star by accretion from a close stellar companion explained their fast rotation, but the absence of companions in several cases cast doubt on that picture. This spring a millisecond pulsar in a close binary was discovered in which the companion appears to be evaporating, thus reconciling the existence of lone millisecond pulsars with the standard picture. Ongoing observations of this new system, and complementary calculations, promise to answer many of the questions remaining about this dramatic phase in stellar evolution.

1. Why Study Millisecond Pulsars?

At first blush, it might seem odd to give such close attention to a sub-class of a sub-class. Radio pulsars are a small fraction of all neutron stars, and the known population of millisecond pulsars is a tiny minority ($\sim 10^{-2}$) of radio pulsars. Yet, once described, the attractive properties of millisecond pulsars become immediately clear, for they exhibit some of the most extreme physical conditions, and one of the most dramatic evolutionary histories, of any class of astronomical objects.

To begin, they are among the most stable clocks anywhere. Whereas normal pulsars change period at a long-term average rate $\dot{P} \sim 10^{-15}$, for millisecond pulsars the typical $\dot{P} \sim 10^{-19}$ (Backer 1987). Such extreme long-term stability pushes even the best laboratory clocks to their limits. On shorter timescales, *i.e.*, days, they are also extremely regular: typical timing excursions over a single day are generally smaller than 500 ns.

At the same time, their extremely fast rotation rate pushes them into very exotic physical conditions. Like other neutron stars, their gravitational potential is mildly relativistic: $GM/(rc^2) \sim 10^{-1}$. However, in contrast to ordinary neutron stars, millisecond pulsars rotate near break-up: $\Omega/\Omega_{break-up} \simeq 0.1 - 0.6$, rather than $\sim 10^{-3}$. In fact, they rotate so rapidly that they exceed the stability limit for the axisymmetric Maclaurin spheroids, and become triaxial. The resulting gravitational radiation enforces a lower bound on the period of 1 – 1.3 ms.

Finally, in order to spin down at all, they must couple electromagnetically to the outside world, and so possess a fairly strong magnetic field: $\dot{P} \sim 10^{-19}$ implies $B \sim 10^9$ G for a moment of inertia $\sim 10^{45}$ gm cm^2. Because, as I will discuss later, the age of these neutron stars is

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probably $\gtrsim 10^9$ yr, in contrast to the typical age of ordinary radio pulsars $\sim 10^6$ yr, mechanisms as yet unknown must exist to preserve the field against Ohmic decay.

2. Best Bet Evolutionary History

There is a general consensus that the most likely progenitor systems for millisecond pulsars are low-mass X-ray binaries (Alpar, *et al.* 1982). A number of arguments support this conclusion, but perhaps the strongest is that one expects the neutron star in these X-ray binaries to ultimately be spun up to millisecond periods. When material is accreted from a disk onto a magnetized collapsed star, it brings along the angular momentum it had in its Keplerian orbit just outside the magnetospheric boundary. In principle, the resulting change in neutron star spin could have either sign. Balance is achieved only when:

$$P \simeq 2L_{38}^{-3/7}B_9^{6/7}\text{ms},$$

where L_{38}, the luminosity in units of 10^{38} erg s^{-1}, is typically order unity in low-mass X-ray binaries. If the spin rate initially is slower, continued accretion decreases P until enough mass has been transferred to achieve equilibrium. Because the specific angular momentum at the magnetospheric boundary is roughly twice the specific angular momentum of a neutron star rotating at break-up, the star must accrete only $\sim 0.05\times$ its initial mass in order to achieve a millisecond period. At the accretion rate that would produce 10^{38} erg s^{-1}, that takes only $\sim 10^7$ yr.

Other arguments are consistent with this story. The relatively weak magnetic field found in the millisecond pulsars is consistent with the observed absence of pulses from low-mass X-ray binaries. Likewise, the comparatively large number of millisecond pulsars in globular clusters (about a third of all those known: Kulkarni 1988) comports well with the relatively large number of low-mass X-ray binaries in globulars.

However, prior to this spring several large gaps remained in this picture. Most importantly, there was no plausible explanation for what happened to the companion in the solitary millisecond pulsars. In addition, if the accretion rate diminished gradually, then the same mechanics which spun up the neutron star during the period of high accretion rate would spin it down as the accretion rate fell.

A possible answer to these questions was provided in a pair of papers written last winter (Ruderman, Shaham, and Tavani 1988; Ruderman, Shaham, Tavani, and Eichler 1988). They suggested that the increasing spin rate of the accreting neutron star in a low-mass X-ray binary could, through a variety of possible mechanisms, produce a substantial luminosity in high energy photons. Those energetic photons striking the companion would then heat its surface above the escape temperature, ultimately evaporating the entire companion in a relatively short time. Thus, accretion would stop quickly, avoiding the spin-down problem, and the companion star would be eliminated, explaining the observed solitary millisecond pulsars within the context of the low-mass X-ray binary model.

3. PSR 1957+20

3. 1. Observations and Immediate Inferences

Remarkably enough, within a few months of the submission of these papers, an example of just this sort of process was discovered (Fruchter, Stinebring, and Taylor 1988: FST). PSR 1957+20 has the second-fastest known period—1.6 ms—but more importantly, it is in a close binary with a period of 9.2 hr and a projected semi-major axis (of the neuton star's orbit) of 2.7×10^9 cm. The orbit is very nearly circular, for the eccentricity is no more than 10^{-4}

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(Fruchter 1988). From these numbers (and an assumed neutron star mass of $1.4M_\odot$), we may infer that:

$$M_c \simeq 0.024/\sin i M_\odot \qquad a_c \simeq 1.6 \times 10^{11} \text{ cm} \qquad R_L \simeq 2 \times 10^{10} \text{ cm}$$

where M_c is the companion mass, a_c is its semimajor axis, and R_L is the radius of its Roche lobe, assuming synchronous rotation (as seems quite likely, considering the very small eccentricity). It is particularly instructive to compare R_L to the radius of a cold degenerate H-rich star of this mass: $R_d \simeq 8 \times 10^9 \sin^{1/3} i$ cm. Other than the very small companion mass, these numbers taken by themselves are not so remarkable.

What makes this pulsar truly special is that it *eclipses*. At an observing frequency of 430 MHz, the eclipse lasts for 0.83 hr, almost a tenth of the orbital period. Thus, the radius of the optically thick (to radio photons) region of the companion is $\simeq 5 \times 10^{10}$ cm, or $\simeq 2.5 \times R_L$!

We are immediately forced to the conclusion that the companion is losing mass at a substantial rate. Matter outside the companion's Roche lobe cannot stay near it, and yet the densest part of this material orbits the neutron star in association with the companion because the eclipse is quite well-defined. Therefore, the eclipsing material must be continually replenished by mass-loss from the companion. From the magnitude of fluctuations in pulse time delays just outside eclipse, FST estimated that the electron density $n_e > 10^6$ cm^{-3}(interestingly, these fluctuations are much stronger during egress than ingress); if the plasma moves with a velocity comparable to the orbital velocity (this is certainly a lower limit), then the mass loss rate $\dot{M}_c > 10^{-14} M_\odot$ yr^{-1}. Although this is an interesting rate, it is far too small to affect even such a low mass companion in a Hubble time. It is likely, however (see §3.2) that $\dot{M}_c$ is considerably greater than this lower limit.

If this mass loss is being driven by heating of the companion's surface, the visible light from the system should be modulated at the orbital period (again assuming synchronism). In fact, this is just what is seen (Fruchter, Gunn, Lauer, and Dressler 1988: FGLD; Kulkarni, Djorgovski, and Fruchter 1988; Djorgovski and Evans 1988; van Paradijs, *et al.* 1988). At maximum light, $m_V = 20.3$ mag, while minimum light is at least 0.85 mag, and possibly as much as 3 mag, fainter. Moreover, maximum and minimum occur at the correct phases relative to the pulsar eclipse, giving an absolute confirmation to the optical identification.

From the optical data, even more may be learned about the system (Djorgovski and Evans 1988; FGLD; van Paradijs, *et al.* 1988). Although the extinction is a bit uncertain, it may be bounded between 1 and 2 mag, so that the colors at maximum light correspond to a color temperature of $\simeq 5800$ K. Combining the extinction correction and the distance estimated from the dispersion measure ($\simeq 0.9$ kpc), the radius of the optical photosphere is found to be between 4.9×10^9 cm and 1.4×10^{10} cm, with the most likely value of 1.1×10^{10} cm. This number is in very good agreement with the *a priori* supposition that the companion should be just slightly larger than a cold degenerate star of that mass.

Furthermore, if the color temperature is a good approximation to the effective temperature, and we have an estimate of the stellar radius, we know its absolute luminosity. It is $\simeq 5 \times 10^{31}$ erg s^{-1}. As of yet there is only an upper limit on the pulsar spin-down rate: $\dot{P} < 3 \times 10^{-20}$ (Fruchter 1988), but we may use it, along with theoretical predictions of the neutron star's moment of inertia to estimate what fraction of the strong dipole wave radiated by the pulsar directed at the companion (assuming isotropic radiation) is converted to heat at the surface of the companion. Uncomfortably for theorists, $L_c/L_{pulsar} > 0.1$, using the best estimate of the stellar radius and the upper limit on $\dot{P}$ (FGLD; van Paradijs, *et al.* 1988). If the measured $\dot{P}$ proves to be much smaller than 3×10^{-20}, we may be driven to consider nuclear matter equations of state which allow larger moments of inertia than had hitherto been considered.

3. 2. Theory and Future Work

It will come as no surprise when I remark that there are already almost twice as many theoretical as observational papers on this object (Cheng 1988; Eichler and Levinson 1988;

Kluźniak, *et al.* 1988; Michel 1988; Phinney, *et al.* 1988; Rasio, *et al.* 1988; van den Heuvel and van Paradijs 1988), with more certain to appear in the near future. The main problems under consideration so far have been: What is the density of the eclipsing matter outside the companion's Roche lobe? And, how is the power in the low frequency wave from the pulsar transformed so that it can penetrate to the surface of the companion and drive the mass loss?

The answer to both of these questions remains controversial. A plausible answer to the former is given by Phinney, *et al.* (1988). They argue that the strong wave from the pulsar can be treated as a relativistic fluid so that the boundary between the radio-opaque matter escaping the companion and the transparent relativistic fluid can be determined simply by momentum balance. Because we know the answer (from the eclipse geometry), it is possible to work backwards to find the momentum flux in mass loss from the companion. Given a typical velocity of order the orbital speed, one then finds that the density is six orders of magnitude greater than in the region producing the timing fluctuations just outside eclipse. The corresponding $\dot{M}_c$ is then $\sim 10^{-8} M_\odot$ yr^{-1}, which will destroy the companion in a mere 2×10^6 yr.

Not all models suppose that the low frequency wave and the stellar mass loss interact hydrodynamically (*e.g.*, Rasio, *et al.* 1988 and Michel 1988). Fortunately, there is a clear observational test: the hydrodynamic picture predicts a contact discontinuity between the relativistic and ordinary fluids which defines the boundary between transparent and radio-opaque regions, while the others predict a more gradual transition. If the eclipse duration at other radio frequencies is the same as at 430 MHz, then the density gradient is sharp; if the duration decreases at higher frequencies, then the gradient is more gradual. VLA measurements will soon provide an answer.

The situation is even vaguer with respect to how the low frequency power penetrates to the companion's surface. If the mass loss takes place as a plasma, then the low frequency wave cannot possibly reach the companion. Somehow its power must be "up-converted" into higher frequency photons with greater penetrating power. Various authors have suggested mechanisms for producing photons ranging from the ionizing ultraviolet to MeV γ-rays, but all the mechanisms are little more than guesses. It is possible, if the photons are more energetic than a few keV, and if a large enough fraction is directed away from the companion, that they might be directly observable. Whether or not that is the case, more detailed calculations of the thermal and hydrodynamic conditions in the base of the stellar wind can also constrain the energy of the penetrating photons because heat deposited deep inside the stellar atmosphere will be wasted in thermal radiation, while if the photons are absorbed at too high an altitude the wind's sonic point will occur in a region of such low density that the mass loss rate will be too small (Cheng 1988; Eichler and Levinson 1988).

Beyond these questions, work is also likely to soon begin on simulating the dynamics of the wind from the companion in order to understand the duration and asymmetry of the eclipse, as well as on modeling the detailed shape of the optical light curve.

In a final *coup de theâtre*, it is also possible to see the effects of the low frequency wave in the interstellar medium far outside the binary. Kulkarni and Hester (1988) have obtained an Hα image of the pulsar region which shows a nebula with a distinct cometary shape several arcseconds across. They interpret the line emission as due to a bow shock supported by the pressure of the relativistic wind driven by the low frequency wave. To order of magnitude, the separation between the head of the cometary nebula and the pulsar agrees with the prediction made assuming a spin-down luminosity corresponding to $\dot{P} \sim 3 \times 10^{-20}$, an external density of ~ 1 cm^{-3}, and a pulsar space velocity ~ 100 km s^{-1}.

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