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Letter to the Editor

Eclipse mechanisms for binary pulsars

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Abstract. The parameters of the new eclipsing millisecond pulsar PSR 1744-24A in Terzan 5 are sufficiently different from those of PSR 1957+20 that one can now put very severe constraints on the theoretical models and formation scenarios of such systems. Most importantly, the eclipses cannot be caused by refractive effects (either total reflection or bending of the radio signal paths). Instead, they very likely are produced by an absorption mechanism, possibly combined with pulse-smearing effects. A model based on free-free absorption by the gas evaporated from the companion remains viable in spite of difficulties. Independent of the particular eclipse mechanism, we discuss the results of some preliminary dynamical calculations of the evaporative flow.

Key words: pulsars – stars: binaries

Lyne *et al.* (1990) have recently announced the discovery of a new eclipsing millisecond binary pulsar, PSR 1744-24A, located in the globular cluster Terzan 5. This comes only two years after the first such extraordinary object, PSR 1957+20, was discovered (Fruchter, Stinebring and Taylor 1988). The new 11.6-millisecond pulsar is in a low eccentricity 1.8-hour orbit around an unseen companion. The eclipse duration is very variable, but usually represents about one half of the orbital period. The mass function $f = 3.2 \times 10^{-4} M_\odot$ indicates a companion mass $m_c \approx 0.09 M_\odot$, assuming a neutron star mass $m_p \approx 1.4 M_\odot$, and an inclination angle i such that $\sin i \approx 1$. Given the long eclipse duration, the typical size r_E of the eclipsing region must be comparable to the binary separation $a \approx 0.85 R_\odot$. The Roche lobe of the companion has a radius $r_{RL} \approx 0.15 R_\odot << r_E$. As in PSR 1957+20, the eclipsing region must therefore be a gas outflow emanating from the companion, and resulting probably from the heating of the companion by a high energy component of the pulsar radiation.

If the rate of evaporation is large enough, the companion could eventually be destroyed, leaving behind an isolated millisecond pulsar such as PSR 1937+21. This formation scenario, proposed by Ruderman *et al.* (1989 a, b), appeared to have been confirmed by the discovery of PSR 1957+20, despite some residual theoretical difficulties (Eichler and Levinson 1988).

Along with this scenario has come the idea (Phinney *et al.* 1988, Kluźniak *et al.* 1988, Emmering and London 1990) that refractive effects (either total reflection or bending of the radio signal paths) are responsible for producing the eclipses. This would require that the plasma frequency inside the eclipsing region be comparable to the observing frequency $\nu_{obs} \approx 1400\,\mathrm{MHz}$. If the gas has mean molecular weight per electron μ_e and ionization fraction η at $r \approx r_E$, the characteristic density inside the eclipsing region would then be

$$\rho(r_E) \approx \rho^{(refr)} \equiv \left(\frac{\pi m_e}{e^2}\right) \mu_e \eta^{-1} \nu_{obs}^2 \sim 5 \times 10^{-14}\,\mathrm{g\,cm^{-3}} \eta^{-1} \mu_e \left(\frac{\nu_{obs}}{1400\,\mathrm{MHz}}\right)^2 . \quad (1)$$

Refractive models for PSR 1957+20 do have some attractive features. The rather high density of equation (1) implies an evaporation time scale $t_{evap} \sim 10^7\,\mathrm{yr}$ (cf. eqn. [5] below), much shorter that the pulsar spin-down time $T \equiv P/\dot{P} = 3 \times 10^9\,\mathrm{yr}$. This would explain nicely an eventual complete disappearance of the companion. However, an evaporation time scale as small as $10^7\,\mathrm{yr}$ is already ruled out almost certainly by the pulsar timing observations (Fruchter *et al.* 1990). The high density of equation (1) also agrees well, for PSR 1957+20, with that determined from *momentum balance* if one assumes that most of the pulsar radiation gets absorbed and exerts pressure at the boundary of the eclipsing region (Phinney *et al.* 1988; see also below). The principal difficulty of refractive models for PSR 1957+20 is that they cannot explain the observed frequency dependence of eclipse duration (Fruchter *et al.* 1990). Models based on total reflection of the radio signals at the sharp boundary of a high-density eclipsing region (Phinney *et al.* 1988, Kluźniak *et al.* 1988) predict no frequency dependence at all. Models based on refractive bending of the radio signal paths do predict a qualitatively correct effect, but cannot fit both the eclipse duration and its frequency dependence (Emmering and London 1990). An even stronger frequency dependence of the eclipse duration may be present in the Terzan 5 pulsar (Nice *et al.* 1990). Even if we ignore this difficulty, there are now two far more compelling arguments which can be used to rule out refractive eclipse mechanisms as well as their associated large densities and small evaporation time scales.

First, as noted by Lyne *et al.* (1990), the energy flux from the pulsar intercepted by its companion is at least two orders of magnitudes smaller for the Terzan 5 system than for PSR 1957+20. A strict upper limit on the density in the eclipsing region can be obtained from the fundamental requirement of energy conservation. Assume for simplicity that the outflow from the companion is spherically symmetric at least up to r_E. The constant mass flux is $\dot{m}_c = 4\pi r_E^2 \rho(r_E) v_f$. Here v_f, the flow velocity, must be larger than the escape velocity *from the system*, $v_{esc} = (2Gm_p/a)^{1/2} \approx 800\,\mathrm{km\,s^{-1}}$ for the gas to be able to leave. The rate at which energy is carried away from the companion, $\dot{E}_c \approx \dot{m}_c v_f^2/2 \approx 2\pi r_E^2 \rho(r_E) v_f^3$ must certainly be smaller than the fraction $\dot{E}_p(r_c/2a)^2$ of the pulsar spindown power intercepted by the companion, assumed to have a radius $r_c \leq r_{RL}$. This implies an *upper limit* for the density:

$$\rho(r_E) < \rho^{(max)} \equiv \frac{\dot{E}_p r_c^2}{8\pi a^2 v_f^3 r_E^2} \sim 10^{-16}\,\mathrm{g\,cm^{-3}} \left(\frac{\dot{E}_p}{10^{34}\,\mathrm{erg\,s^{-1}}}\right) \left(\frac{r_c}{0.15 R_\odot}\right)^2 \left(\frac{\beta}{3}\right)^{-3}, \quad (2)$$

where $\beta \equiv v_f/v_{esc}$. This is at least two orders of magnitudes below the density required for refractive effects (eqn. [1]), and the most likely value of $\rho^{(max)}$ is probably much smaller yet. Indeed, the value $\dot{E}_p = 10^{34}\mathrm{erg\,s^{-1}}$ is itself an upper limit, obtained by placing the pulsar on the spin-up line (Dewey *et al.* 1988). The preliminary determination by Lyne *et al.* (1990) of the period derivative gives $\dot{P} = (-5 \pm 9) \times 10^{-20}$, indicating that the actual value of $\dot{E}_p$ is probably at least an order of magnitude smaller. In addition, a large fraction of the available energy is probably radiated away and never gets converted into kinetic energy (cf. Fruchter *et al.* 1990). If, as in PSR 1957+20, the companion is degenerate, its radius decreases to $r_c \approx 0.09 R_\odot$ for a hydrogen dwarf and $r_c \approx 0.03 R_\odot$ for a helium dwarf (Shapiro and Teukolsky 1983). Finally, a value $\beta \geq 3$ is favored by all models, our own dynamical calculation indicating $\beta \approx 6$ (see below). Therefore, the value we quote in equation (2) appears to be a very conservative upper limit. It seems to us almost impossible that a peculiar geometry and/or abnormally large period derivative would conspire to bring this limit up to the level of equation (1).

Direct estimates of the density *near the boundary* of the eclipsing region in PSR 1957+20 come from the observed excess time delays near signal disappearance and reappearance (Fruchter *et al.* 1989). These estimates give densities many orders of magnitude smaller than that required for refractive effects (Rasio *et al.* 1989). However, one can always argue (as was done in most of the refractive models mentioned above) that the eclipsing region might be bounded by a sharp contact discontinuity where the density suddenly increases. Similar excess time delays just before and after eclipses are not always observed in the Terzan 5 pulsar, but there is preliminary evidence (Lyne *et al.* 1990) for short periods of phase-coherent signals sometimes *reappearing during eclipses*, and associated with excess time delays $\gtrsim$1 ms. These delays, if confirmed, allow us to directly estimate the density well inside the eclipsing region. For a time delay $\Delta t_a = (e^2/2\pi m_e c) DM/\nu_{obs}^2$, with the dispersion measure $DM \sim l n_e$, we find a corresponding density

$$\rho(r \leq r_E) \approx \rho^{(delays)} \equiv \left(\frac{2\pi m_e c}{e^2}\right) \mu_e \eta^{-1} \left(\frac{\nu_{obs}^2 \Delta t_a}{l}\right) \sim 10^{-17}\,\mathrm{g\,cm^{-3}} \left(\frac{\nu_{obs}}{1.4\,\mathrm{GHz}}\right)^2 \left(\frac{\Delta t_a}{1\,\mathrm{ms}}\right) \left(\frac{l}{1 R_\odot}\right)^{-1}. \quad (3)$$

This is more than three orders of magnitudes smaller than $\rho^{(refr)}$, confirming that refractive effects are completely ruled out. Again, only a very peculiar geometry, such as one where a very high density region is confined to a thin sheet surrounding the eclipsing region, could reconcile equations (3) and (1).

Eclipse mechanisms other than refraction by a dense plasma have been proposed (Fruchter *et al.* 1990, Michel 1989, Rasio *et al.* 1989, Wasserman and Cordes 1988) which do not suffer from the above considerations. As noted by Lyne *et al.* (1990), the gradual decay and rise of pulse amplitude observed in the Terzan 5 pulsar (recently confirmed by Nice *et al.* 1990) strongly suggest that an *absorption mechanism* is responsible for the eclipses. Recent Faraday rotation measurements of PSR 1957+20 indicate that the magnetic field strength $B \lesssim 1\,\mathrm{G}$ near eclipse, ruling out cyclotron absorption (cf. Fruchter *et al.* 1990). As noted by Cheng (1989), the observed color temperature $T \gtrsim 6000\,\mathrm{K}$ of the reprocessed radiation from the companion rules out the dust grain absorption model of Michel (1989). A model based on *free-free absorption*, as proposed by Wasserman and Cordes (1988) and Rasio *et al.* (1989), remains viable. Indeed, the optical observations of the companion in PSR 1957+20 have indicated that a large fraction, if not most, of the pulsar spindown power intercepted by the companion may be reradiated in the form of optical luminosity (Callanan *et al.* 1989, Djorgovski and Evans 1988, Fruchter *et al.* 1988, 1990, van Paradijs *et al.* 1988). If this is also the case in the Terzan 5 pulsar, the surface temperature of the heated side of the companion must be close to the maximum allowed by energy conservation, $T(r_c) = (\dot{E}_p/8\pi\sigma a^2)^{1/4} \approx 6000\,\mathrm{K}$. On the other hand, theoretical considerations (Emmering and London 1990, Michel 1989, Rasio *et al.* 1989) seem to indicate that the pulsar radiation couples very weakly to the eclipsing gas. It may then be reasonable to assume that the gas undergoes adiabatic cooling as it escapes from the companion's surface, implying a temperature $T(r_E) \approx T(r_c)(r_c/r_E)^{4/3} \approx 600\,\mathrm{K}$, and a highly supersonic flow. At such a low temperature, free-free absorption is likely to be causing the eclipses.

If free-free absorption is indeed causing the eclipses of the Terzan 5 pulsar, a calculation similar to the one we did for PSR 1957+20 (Rasio *et al.* 1989) gives then an expected electron number density $n_e(r_E) \approx 3 \times 10^6\,\mathrm{cm^{-3}}$, or $\rho(r_E) \approx \rho^{(ff)} \approx 5 \times 10^{-18}\,\mathrm{cm^{-3}}$. The corresponding excess time delays near eclipse are expected to be $\Delta t_a \approx 200\,\mu\mathrm{s}$ for an observing frequency $\nu \approx 1400\,\mathrm{MHz}$. Delays of this magnitude have indeed been detected during some observations of Terzan 5, though not all (Lyne *et al.* 1990, Nice *et al.* 1990). In addition, free-free absorption can easily explain the frequency dependence of eclipse duration observed for both pulsars. In fact, one calculation based on free-free absorption (Rasio *et al.* 1989) predicts almost exactly the $\sim \nu_{obs}^{-0.6}$ dependence reported by Nice *et al.* (1990) for Terzan 5. The principal theoretical difficulty of free-free absorption models is to determine how exactly such a low-temperature evaporative outflow from the companion star is created. Clearly, between some energy deposition layer and the stellar surface, gas must be accelerated to escape velocity, and then be allowed to expand and cool down as it leaves the system. At least we know that the gas can remain ionized as its temperature decreases, because it is probably out of ionization equilibrium everywhere outside the stellar surface (Wasserman and Cordes 1988). Unfortunately, a realistic calculation of the flow, even in a simplified geometry, seems rather difficult at present, given our almost complete lack of knowledge about the composition and energy spectrum of the pulsar radiation as well as about the structure and chemical composition of the companion star.

Recent observations at the VLA of the Terzan 5 pulsar as well as PSR 1957+20 show that, at the higher observing frequencies, the variation in time of the full mean flux density from the pulsar may not follow that of the pulsed flux (Fruchter and Goss 1990, Lyne *et al.* 1990). This suggests that *pulse smearing* (Fruchter 1989, see also Fruchter *et al.* 1990) might be partly responsible for the disappearance of the signal. A broadening of the signal comparable to the individual pulse width has indeed been reported for PSR 1957+20 (Fruchter *et al.* 1990), but not yet for Terzan 5 (Lyne *et al.* 1990, Nice *et al.* 1990). We can roughly estimate the typical wind density necessary for pulse smearing to become important by equating the pulse width t_p to the change $\delta\Delta t_a$ in time delay of the pulses over the instrumental integration time t_i. Typical values are $t_p \approx 0.05\,P$ and $t_i \approx$ a few minutes. The time delay of the pulses due to their passage through the ionized wind is $\Delta t_a = (e^2/2\pi m_e c) DM/\nu_{obs}^2$, where $DM \sim r n_e(r)$ is the dispersion measure for a line of sight passing at a distance r from the companion. Over the integration time t_i, the dispersion measure changes by a small amount $\delta DM \approx (\partial DM/\partial r)\delta r_i$, with $\delta r_i \sim 2\pi a t_i/P_{orb}$. For a density profile with $n_e(r) \propto r^{-2}$ (valid once the wind has reached terminal velocity), we then find a mass density

$$\rho(r_E) \approx \rho^{(smear)} \equiv \left(\frac{m_e c}{e^2}\right) \frac{\mu_e \nu_{obs}^2\, t_p\, P_{orb}}{\eta a t_i} \sim 10^{-16}\,\mathrm{g\,cm^{-3}}\,\eta^{-1}\mu_e \left(\frac{\nu_{obs}}{1400\,\mathrm{MHz}}\right)^2 \left(\frac{t_i}{2\,\mathrm{min}}\right)^{-1} \times \left(\frac{t_p}{500\,\mu\mathrm{s}}\right). \quad (4)$$

This density is just consistent with the upper limit (2), and only slightly larger than that estimated from the reported time delays occuring during eclipses (eqn. [3]). Pulse smearing may also be partly responsible for the frequency dependence of eclipse duration. For PSR 1957 +20, Fruchter *et al.* (1990) have noticed that pulse smearing alone, combined with the observed variation in the time delays of the pulses near eclipse would in fact predict exactly the measured frequency dependence of eclipse duration. For Terzan 5, it is easy to see, from the above derivation, that for the simple, spherically symmetric $\propto r^{-2}$ density profile, the frequency dependence predicted on the basis of pulse smearing alone is $\propto \nu_{obs}^{-1}$. This is not very far from the value $\sim \nu_{obs}^{-0.6}$ reported by Nice *et al.* (1990). Therefore, it does seem to us that one cannot at present rule out that pulse smearing plays a role in explaining the eclipses. *Simultaneous observations of both pulsed and mean fluxes, or simultaneous observations of the pulsed flux with different integration times would be particularly helpful at this point.*

Turn now to the characteristic evaporation timescale for the companion,

$$t_{evap} \equiv \frac{m_c}{\dot m_c} \approx \frac{m_c}{4\pi r_E^2 v_f \rho(r_E)} \sim 5\times 10^9\,\mathrm{yr} \left(\frac{m_c}{0.1 M_\odot}\right) \left(\frac{\beta}{3}\right) \left(\frac{\rho(r_E)}{10^{-16}\,\mathrm{g\,cm^{-3}}}\right)^{-1}. \quad (5)$$

It is reassuring to note that the energy constraint of equation (2) implies a lower limit on the evaporation time scale $t_{evap} > 5\times 10^9$ yr which is still smaller (though barely) than the pulsar spin-down time, $T \sim 10^{10}$ yr for Terzan 5. However, both equation (3) and the density estimated from free-free absorption give $t_{evap} > 10^{10}$ yr. Clearly then, t_{evap} must have been much shorter in the past for so much of the companion mass to have been evaporated. *Any formation scenario for the system will need to take into account these considerations.*

Much insight about the eclipses can be gained by performing simple dynamical calculations of the outflow of material from the companion. Figure 1 shows the result of such a calculation. The method we use is described in detail in Rasio *et al.* (1989). There are two free parameters in the calculation: a constant C_{rad} which measures the pressure exerted on the gas by the pulsar radiation (assumed isotropic), and the flow velocity v_f at $r = r_c$. Here the parameters were adjusted so that the leading edge of the flow be at orbital phase $\phi \approx 0$, as suggested from the observed position of eclipse onset. The smallest velocity which can bring the gas that far before it turns around is $v_f \approx 6 v_{esc}$. The corresponding low value of $C_{rad} \approx 30$ is consistent with the one we found for PSR 1957+20, if the new pulsar has a spindown power about 100 times smaller. This would imply a period derivative $\dot P \sim 10^{-19}$, in agreement with the preliminary determination by Lyne *et al.* (1990). Note that if the pulsar radiation could not penetrate the gas, as is assumed in our calculation, the density distribution *inside* the flow would be changed, but not the overall shape of its boundary. This is because the boundary is determined essentially by momentum balance, which our calculation always reproduces correctly (unless the flow is everywhere subsonic, a rather unlikely possibility). It is clear from Figure 1 that the shape of the boundary is very asymmetric. The symmetry of the eclipses (still observed here in spite of their variable duration, cf. Lyne *et al.* 1990)) is then further indication that they are caused by absorption, since the radio signals must be able to penetrate the gas, into a region closer to the companion where the flow is still almost spherically symmetric.

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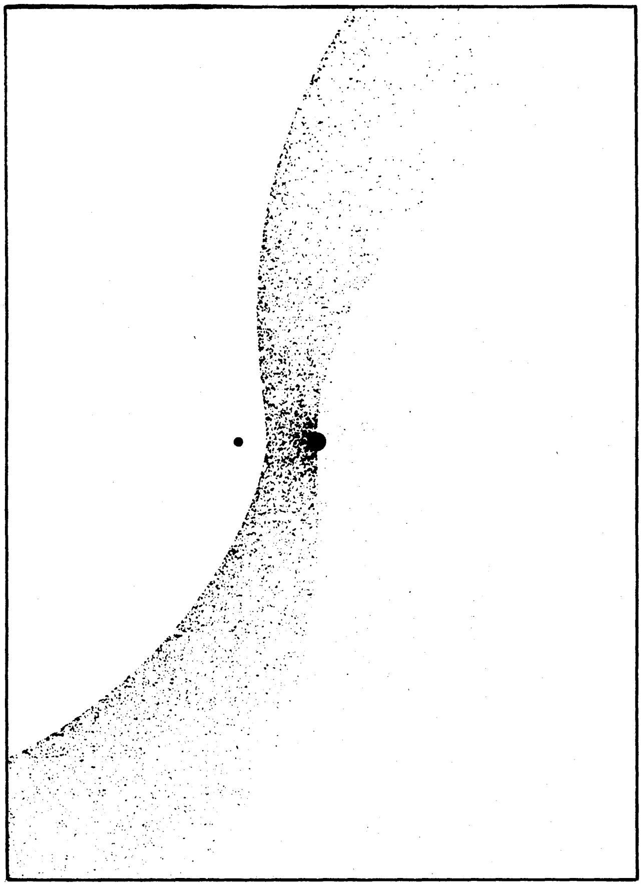

Fig. 1. Possible geometry of the Terzan 5 system. A projection onto the orbital plane of the system is shown, with orbital rotation in the counterclockwise direction. Gas is extracted from the side of the companion (large solid dot on the right) heated by the pulsar (smaller dot on the left, not drawn to scale). A delicate balance between gravity, Coriolis forces and the pressure exerted by the pulsar radiation determines the shape of the outflow.

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