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ON BLACK WIDOW EVOLUTIONARY SCENARIOS FOR BINARY NEUTRON STARS

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ABSTRACT

The scenario whereby the pulsar 1957+20 ablates its companion by soft gamma-ray synchrotron emission is critically examined, with particular regard to how the outflowing material, beginning at photospheric temperatures, is heated through the cooling barrier to coronal temperatures. Assuming the conductivity to be at most the Spitzer value, this consideration is found to constrain the mass flux, more than two orders of magnitude more severely than merely considering cooling near the sonic point. This would imply that the ablation scenario fails by a large margin even if the emission from the pulsar is beamed along the orbital plane.

Subject headings: pulsars — stars: eclipsing binaries — stars: winds — stars: X-rays — X-rays: binaries

I. INTRODUCTION

There is now a body of evidence that neutron stars drive a wind off their companion, possibly accrete from this wind, and ultimately vaporize the companion in its entirety. The solitary millisecond pulsar 1937+21, if it was spun up by accretion from a hypothesized companion (Alpar *et al.* 1982), must have somehow disposed of it. Low-mass X-ray binaries appear, according to one interpretation, to turn off suddenly, there being none observed in the 10^{35-36} ergs s^{-1} range. This would imply some mechanism that can drive mass loss faster than braking mechanisms (Ruderman *et al.* 1988, hereafter RSTE). RSTE propose an evaporative mechanism, and, since braking by gravitational radiation is important down to companion masses of order 10^{-1} $M_\odot$, the evaporative mechanism should be capable of reducing the companion even further.

Most recently, the discovery of the eclipsing binary pulsar 1957+20 (Fruchter, Stinebring, and Taylor 1988) has given direct observational support for the ability of a neutron star to ablate its companion down to about 0.025 $M_\odot$. The wind that is apparently responsible for the eclipse, assuming the plasma frequency at eclipse exceeds 430 MHz, has a density of at least 10^9 cm^{-3} at a distance of 5×10^{10} cm from the companion, and estimating a velocity of at least several times 10^7 cm s^{-1} by equating the ram pressure of the wind with the kHz radiation pressure from the pulsar (Kluzniac *et al.* 1988), or taking it to be comparable to the escape velocity, one arrives at a mass-loss rate that is consistent with the hypothesis that the current pulsar has reduced the companion to its present state. The total luminosity of the pulsar is probably less than 10^{36} ergs s^{-1}, given the current lower limit to the spin-down time of 5×10^8 yr (D. R. Stinebring and J. H. Taylor, private communication). Scenarios whereby the pulsar could indirectly but efficiently generate soft gamma rays were promptly proposed (Kluzniak *et al.* 1988; Phinney *et al.* 1988) as part of an ablation scenario similar to that of RSTE. X-rays are also mentioned, but are harder to generate efficiently via synchrotron radiation over a path length of 10^{10} cm.

The question of whether a pulsar, or any compact object with the means for particle acceleration, could vaporize a noncompact companion was raised in the context of Cyg X-3 (Colgate 1986; Eichler and Ko 1988), where reportedly positive VHE gamma-ray observations imply a large, possibly super-Eddington flux of cosmic rays incident on the companion, and for which there is an observed period increase on a time scale of 10^6 yr and considerable obscuration of the X-ray source. Note that the effective Eddington flux can be considerably reduced by atomic resonant lines.

Wind excitation by sub-Eddington illumination is also possible in principle if radiative cooling does not reconvert the needed heat back to photons within the hydrodynamic time scale, and there is much literature on the subject, though not always in the context of evaporative evolution. The impinging radiation can be soft X-ray (Basko and Sunyaev 1973; Arons 1973; McCray and Hatchett 1975), or soft cosmic rays, $E < 100$ MeV, to take the least penetrating high energy quanta. For more penetrating radiation, such as MeV gamma radiation (RSTE), radiative losses are a crucial factor. For highly penetrating cosmic rays, radiative losses are generally prohibitive, unless the impinging radiation is locally super-Eddington, in which case the high penetration is advantageous to rapid mass loss (Eichler and Ko 1988).

In recent papers on the subject, e.g., RSTE, and briefly in Eichler and Ko (1988) and Phinney *et al.* (1988), the analysis of when radiative cooling is important has been done at the hydrodynamic scale, where the temperature is near its maximum. There remains the question of how the material is brought from photospheric temperatures to coronal temperatures, for in the range 10^5–10^6 K both the cooling function and density are much higher than in the corona. The most conservative way of estimating the maximum allowed mass flux is to equate the heating rate with the cooling rate at 10^5 K, and this would give a cooling constraint up to four orders of magnitude more severe than an analysis limited to the coronal cooling; here the density ratio and, assuming normal line cooling, the cooling function ratio each contribute about two orders of magnitude. This would also be incomplete, however, since heat conduction may play an important role in heating the material to coronal temperatures (e.g., McKee and Cowie 1977).

In this *Letter* we include electron heat conduction in our

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analysis and construct a model of stimulated outflow that considers the fluid quantities in the photospheric-coronal transition region.[1] We find that the limit on mass outflow for 1957+20 type parameters requires radiation with a higher interaction cross section than that of soft gamma radiation, and conclude that, within this general class of models, the pulsar must put out a less penetrating form of radiation in order to accomplish the evaporation rate suggested by the observations. Alternatively, a completely different type of model may be required.

II. MODELS WITH HEAT CONDUCTIVITY AND COOLING

The equations for a steady state one-dimensional outflow from a dense surface are

$$nu = C \,, \tag{1}$$

$$dP + mC\,du + mn\,d\Phi = 0 \,, \tag{2}$$

and

$$\frac{d}{dx}\kappa\frac{d}{dx}T = 5Ck\frac{d}{dx}T + n^2L(T) - n\sigma F(x) + mC\frac{d}{dx}(u^2/2) \,. \tag{3}$$

Here n is particle density, u is flow velocity, C is the proton flux and is constant, m is the proton mass, P is pressure, Φ is gravitational potential, $L(T)$ is the cooling function, σ is the absorption cross section, $F(x)$ is the flux of high-energy quanta that drives the wind, κ is the heat conductivity, and k is Boltzmann's constant. The factor of 5 in the enthalpy flux term assumes that the gas is basically ionized hydrogen.

The above equations, already a great geometric simplification, are further simplified by the following assumptions. Since the surface is irradiated only from one side at a time, the transition to super–escape velocities is assumed to be sudden enough that gravity is not too important; otherwise, any winds excited would merely blow horizontally across the stellar surface.

The sonic point occurs where $E/A^{3/4}$ is a maximum (Eichler and Ko 1988) for situations where gravity is negligible or for radially symmetric outflow. This generally occurs at a distance or the surface that is comparable to the scale of the companion star (unless the heating can be arranged to be highly localized). Much closer to the surface, therefore, we assume that the Mach number is small and neglect the inertial terms in equations (2) and (3). With both of these approximations, P is constant. Of the remaining terms in the energy equation, different ones are expected to dominate in different zones. We tentatively neglect the heating term at all but the largest temperatures, which we later justify. The cooling function $L(T)$ is taken to be $rT^{-1/2} = 10^{-19}T^{-1/2}$ ergs $K^{1/2}$ cm^3 s^{-1} between a reference temperature T_0, which we take to be 10^5 K, and $10^{7.5}$ K. McKee and Cowie (1977) have taken this function to be proportional to $T^{-0.6}$, where T is in degrees Kelvin, as an analytic representation of the results of Raymond, Cox, and Smith (1976). Choosing the exponent to be -0.5 instead of -0.6 proves to be extremely convenient analytically and should not affect the results significantly. Later it will be clear that the cooling function does not even enter the final expression for the maximum mass flux if the ablation is conduction-limited. The cooling function at $T < 10^5$ K is not important for our analysis, and for convenience we take it to vanish. At $T > 10^{7.5}$ K, the cooling function can be taken to be proportional to $T^{1/2}$ though this regime is also not too important here. Finally, we use the Spitzer conductivity for κ, which we express below as $qT^{5/2}$ and argue later that this leads to a liberal estimate of the mass flux. The quantity q is calculated using a Coulomb logarithm of 10 and is 1.8×10^{-6} ergs cm^{-1} s^{-1} K$^{-7/2}$. With all the above simplifications, the energy equation (3) is now

$$\frac{d}{dx}T^{5/2}\frac{d}{dx}T = a\frac{d}{dx}T + bT^{-5/2} \tag{4}$$

above T_0, where $a = 5Ck/q$ and $b = P^2r/qk^2$. Integrating the equation once, and assuming negligible heat flux into the photosphere ($T \times 0$), we obtain

$$T = \frac{z}{a} - \frac{b}{a^2}\ln\left(\frac{az + b}{az_0 + b}\right) , \tag{5}$$

where

$$z = T^{5/2}(dT/dx), \qquad z_0 = z(T_0) = aT_0 \,. \tag{6}$$

Note that the integral of dz^2/dT over T does not receive much contribution from low T so our results are insensitive to the particular assumptions made there and, for convenience, we set z_0 and T_0 to 0. It is useful to define a critical temperature T_c below which cooling dominates the divergence of the enthalpy flux, and above which the reverse holds. It is readily found to be

$$T_c = \frac{b}{a^2}(1 - \ln 2) \,, \tag{7}$$

and above T_c, if cooling is completely ignored there, the equation can be further integrated to yield

$$x = \int_{T_c}^{T}\frac{T^{5/2}\,dT}{a(T - T_c) + z_c} = \int_{T_c}^{T}\frac{T^{5/2}\,dT}{a[T + (b/a^2)\ln 2]} , \tag{8}$$

where T_c is chosen to be the origin of x. Assuming the sonic point to occur at a distance x_m, from the surface, where x is the size of the star, P/C is of order $(m_p kT_m)^{1/2}$, the thermal momentum at the maximum temperature, which is estimated below to be less than 10^8 K; hence, T_c is of order

$$T_c = 2.4 \times 10^{-3}\ T_m \,. \tag{9}$$

Accounting for the variation of P between low T and the sonic point raises the above estimate for T_c by a factor of 8/3, but it is in any case small compared to T_m. The heat flux at T_c, hence the constant of integration z_c, is also small, so at $T > T_c$ the temperature profile is given by

$$x = \frac{2}{5a}T^{5/2} \,. \tag{10}$$

Neglect of the heating term at all but the highest temperature is justified by noting that the time $\tau(T)$ spent by a fluid element at temperature T is x/u, and, as $u \propto 1/n \propto T$, $\tau(T) \propto T^{3/2}$. The divergence of the enthalpy flux, on the other hand, goes as $T^{-3/2}$; hence if the two terms are comparable at the highest T, the heating term is dwarfed by the enthalpy term at lower T.

The limit on the particle flux C is obtained by requiring that on the scale of the companion star x_m, T does not exceed the maximum allowed given the heating rate, i.e., the above condition that the heating term and the enthalpy term are comparable at the highest T. The latter is estimated by placing the

[1] A related question concerns the details of how the solar corona is replenished, e.g., whether the new material is lifted above the photosphere by heat conduction from above, or whether direct Alfvén wave pressure is required.

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sonic point at x_m and, assuming the heating time to be x/c_s, where c_s is the sound velocity, one finds that

$$kT_m = 1.5 \times 10^{-9} \left(\frac{BL_{36}\, x_{10}\, \sigma_{-24}}{D_{11}{}^2}\right)^{2/3} \text{ ergs} \quad (11)$$

and that the proton flux C is

$$C = 4 \times 10^{16} \left(\frac{BL_{36}\, \sigma_{-24}}{D_{11}{}^2}\right)^{5/3} (x_{10})^{2/3} \text{ cm}^{-2} \text{ s}^{-1} . \quad (12)$$

Here subscripts refer to the power of 10 that the quantity is to be raised to when expressed in cgs units; e.g., L_{36} is the primary luminosity in units of 10^{36} ergs s^{-1}, x_{10} is x_m in units of 10^{10} cm, etc. The quantity B is the beaming factor that could enhance the irradiation of the companion. D is the distance between the primary and the companion. Although this estimate is somewhat uncertain, it appears to fall short by some three orders of magnitude of what is required by the observations of PSR 1957+20. By comparison, the limit that is obtained by equating the heating and cooling rates at the sonic point is approximately $C = 1 \times 10^{19}$ $(BL_{36}\, \sigma_{-24}/D_{11}{}^2)^{5/3}$ $(x_{10})^{2/3}$ cm^{-2} s^{-1}, which is perhaps marginally consistent with the observations for σ_{-24} of order unity.

Moreover, it seems unlikely that the pulsar could significantly ablate the companion even during an earlier, more luminous stage, for it could sustain a given luminosity for at most 3×10^{16} $L_{36}{}^{-1}$ s. It follows from equation (12) that even for L_{36}, say, of order 10^2, with $\sigma_{-24} < \frac{1}{3}$, $D_{11} = 1.7$, $x_{10} = 0.6$, and B of order 3, only about 10^{-3} solar masses could be ablated.

Although we have restricted the problem by adopting the Spitzer conductivity, as opposed to one that is reduced by heat flux instabilities, it can be argued on physical grounds that this results in a liberal estimate of the allowed mass flux because it gives the most rapid heating of the material, and causes energy to be shared by the most particles. (Note that the cooling rate does not enter the final expression for the mass flux in the lowest approximation, the cooling merely necessitates heat conductivity, and it is the latter that enters the final expression. It might be therefore argued that one could play with the functional form of the heat conductivity in such a way as to optimize the mass flux. But the conductivity must be equal to or lower than the Spitzer value, and it is hard to see how lowering the conductivity at any point could enhance the mass flux.)

The estimated particle flux produces a column density of only about 10^{18} $\sigma_{-24}{}^{5/3}$ cm^{-2} for PSR 1957+20 parameters; hence a soft gamma-ray wind is not the most efficient for generating a wind. Choosing σ_{-24} to be $10^{9/4}$ (i.e., penetration to $\sim 10^{-2}$ g cm^{-2}) maximizes C without entering the self-shielding regime.

It is conceivable that quanta with such shallow penetration, e.g., soft X-rays, are efficiently generated, directly or indirectly, by the pulsar, but we do not know of any natural scenario that guarantees such high efficiency. Moreover, it is not clear that the requirements of high flux and low penetration can be met simultaneously, because a large soft X-ray flux photoionizes the heavy elements that would otherwise absorb them efficiently: For example, according to Figure 1 of Buff and McCray (1974), heating to 10^7 K is possible only when $L/D^2 n > 10^4$ ergs cm s^{-1}. For PSR 1957+20 parameters, this implies $n < 10^9$ cm^{-3} at the companion surface, whereas the observations imply $n > 10^9$ cm^{-3} at the much larger eclipse radius.

III. POSSIBLE ALTERNATIVES AND SUMMARY

Below we briefly discuss several more elaborate possibilities that could work in favor of wind excitation. The total collecting area of the companion can be enhanced if it is nondegenerate and there is also the possibility of convection giving rise to some internal coronal mass-feeding mechanism such as spicules from the surface. If the surface of the companion is at a temperature of 2700 K, the blackbody luminosity is then 4×10^{30} R_{10}^2 ergs s^{-1}. We estimate that at least 10^{29} ergs s^{-1} would be required for sufficient mass ejection into the corona so the surface activity would have to be extremely efficient. An even more serious problem is that the effective Kelvin-Helmholtz time is only about 10^7 M_{32}^2 R_{10}^{-3} yr, smaller than the apparent evolutionary time scale, and it is hard to see how the star could be nondegenerate. Inflation of the companion by ultra–high-energy neutrinos (Gaisser *et al.* 1986) is plausible from the point of view of total energy budget, as the power input is of the order of 10^{32} $f_{\rm he}$ $R_{10}{}^2$ ergs s^{-1} in the thick target limit (and somewhat more in the thin target limit). However, this implies that fraction $f_{\rm he}$ of the pulsar's power output that emerges in the form of high-energy baryons must be of order unity, and this would be in marked contrast to conventional pulsar theory, which favors e^+e^- pairs.

We have considered the possibility that the steady state solution is unstable, but this seems unlikely in view of the fact that the feedback in the system is negative, i.e., higher particle flux implies more rapid cooling and less diffusivity, which both work against particle flux.

It is possible that, if the cooling is mainly due to atomic lines, the wind is due to the radiation pressure of the line photons interacting resonantly with the heavier atoms. A thorough examination of the possibility is beyond the scope of this *Letter*. However, the observations currently imply a surface temperature no more than that of the Sun, where the particle flux is negligible in the present context. Even if the star is pure carbon, we do not find a strong case for a radiatively driven wind, though sufficiently detailed calculations remain to be done.

Similarly, radiative transfer could conceivably be invoked as a heat conduction mechanism (Königl 1984). Given that the line emissivity decreases with temperature, however, it is not clear that hotter material could heat cooler material via transfer of atomic line radiation.

To conclude, we have attempted a complete model of wind excitation of the companion to PSR 1957+20, including coronal mass injection, which is a particularly important issue if the companion is degenerate. The model, however, yields a maximum mass flux that is too low unless the impinging radiation has a penetration of only 10^{-2} g cm^{-2} or less, and we have mentioned several difficulties with the hypothesis of such shallow penetration. While the interpretation of the observations (Fruchter, Stinebring, and Taylor 1988) offered by these authors is extremely compelling, the details of the wind excitation remain an open theoretical question. Unless some solution is found to the coronal injection problem, recently proposed ablation scenarios fail.

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