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CAN NEUTRON STARS ABLATE THEIR COMPANIONS?

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ABSTRACT

Ablation of stars by energetic photons from a compact companion is considered for general parameters. It is concluded that pulsars with conventional parameters cannot ablate their companions with gamma rays at orbital separation of 3×10^{10} cm or more. It is estimated that in the absence of heat conductivity, line cooling is important when the incident radiation flux is less than 10^{15} ergs s^{-1} cm^{-2}.

It is proposed that millisecond pulsars may be able to ablate their companions more readily than in previous scenarios if even a small fraction of the kilohertz radiation is absorbed by the atmosphere/wind of the companion and the heat conducted to the surface.

It is noted that there are several scenarios in which low-mass companions can evolve from $m > 0.1\ M_\odot$ to $m < 0.05\ M_\odot$ provided the companion nearly fills its Roche lobe. If contact with the Roche lobe is not constantly maintained by angular momentum loss, and if self-sustained accretion cannot occur without this contact, then the lack of fading LMXBs can be attributed to accretion nulling, punctuated by periods of vigorous accretion.

Subject headings: stars: mass loss — Sun: corona — Sun: solar wind — X-rays: binaries

1. INTRODUCTION

The evaporation of matter from stellar surfaces occurs in a variety of astrophysical contexts. Stellar coronae may replenish themselves by evaporating matter off the photosphere. Accreting X-ray sources may drive their own accretion flow by heating the atmosphere of their companion. This problem has been studied for some time in the context of binary X-ray sources and has an extensive literature (e.g., Arons 1973; Basko & Sunyaev 1973; Alme & Wilson 1974; McCray & Hatchett 1975; Basko et al. 1977; London, McCray, & Auer 1981, hereafter LMA). Similar physics applies to evaporation of matter from an accretion disk (Begelman, McKee & Shields 1983, Begelman & McKee 1983). It has also been proposed that red giants sufficiently close to quasars may be ablated by the quasar emission enough to feed the quasar (Shull 1983; Voit & Shull 1988). Eichler & Ko (1988) considered the shroud of matter that, according to some interpretations, envelops Cyg X-3 could be a wind excited off the companion by energetic particles, and concluded it would need to be driven by the radiation pressure of processed energy. Ruderman et al. (1989b, hereafter RSTE) considered a gas pressure driven wind with soft γ-rays and X-rays, say from an accreting companion, and suggested that low-mass companions would be ablated down to $0.03\ M_\odot$ in this manner, after which time the neutron star becomes a millisecond pulsar. Ruderman, Shaham, & Tavani (1989a, hereafter RST) in a companion paper, suggested that high-energy emission from the pulsar itself would finish off the companion that remained from the previous stage via ablation induced by high-energy quanta (of which several possibilities were discussed) that were powered, ultimately, by the pulsar.

The discovery of PSR 1957+20 (Fruchter, Stinebring, & Taylor 1988), which appears to be driving a wind off its companion, stimulated further interest in using soft radiation (Kluzniak et al. 1988; Phinney et al. 1988) to account for this wind. Eichler & Levinson (1988) argued that, even if produced with high efficiency, such radiation could not account for a plasma cutoff eclipse or for significant ablation of the companion, which would require $n > 10^9$ cm^{-3}. They assumed that there would be line cooling for PSR 1957+20 parameters. This assumption is not universally accepted at present, but it will be justified in more detail in § 3 of the present paper. Even if the density at the eclipse radius is only 10^7 cm^{-3}, as suggested by the posteclipse pulse delay, ablation by hard photons appears to be inadequate if line cooling is important.

The question remains whether the X- and/or soft γ-rays could have ablated the companion at an earlier stage—either when the pulsar was more luminous or if and when it was in an accreting X-ray emitting stage. The rapid period change of Cyg X-3 ($\dot{P}/P = 2 \times 10^{-6}$ yr^{-1}) is evidence, if only on empirical grounds, for rapid evolution of neutron star companions (Eichler & Ko 1988), and if this system is not terribly anomalous statistically, then the general class of such objects should spawn some 10^4 objects in the Galaxy. The paper of RSTE, which invoked gas pressure (as opposed to radiation pressure) to drive the evaporation, proposed a detailed evolutionary scenario in which ablation played a major role.

In this paper we consider the issue of line cooling; in particular, we compute numerically the escape parameter of a line and the column density of the flow in a manner that is mutually self-consistent. We find that line cooling is important for parameters that would reasonably be attributed to an immediate precursor to PSR 1957+20 or some similar system: e.g., (1) a pulsar with γ-ray luminosity $L_\gamma \ll 10^{38}$ ergs s^{-1}; or (2) an accreting neutron star with soft X-ray luminosity $L_x < 10^{38}$ ergs s^{-1}, a spectrum resembling that of Her X-1, and orbital separation $D > 10^{11}$ cm. Line cooling is at least marginally important for Cyg X-3 parameters ($L_x \sim 3 \times 10^{37}$ ergs s^{-1},

$D \sim 1 \times 10^{11}$ cm) even if all of the incident radiation were to penetrate the wind to the surface, and this becomes even more probable if much of the radiation is blocked by the wind. This point is discussed in § 3 following a basic review of the by now familiar calculations of a heat-nonconducting, stimulated spherical outflow (§ 2).

In § 4 we examine heat conductivity and suggest that millisecond pulsars can generate a significant mass loss off their companion even if only a small fraction of their kilohertz radiation is absorbed by the companion's atmosphere/wind, provided that the heat can be conducted to the surface. The viability of this scenario depends strongly on the efficiency with which such radiation is absorbed, but it works even if it is small.

(We also find that, though possibly important for some choice of parameters, heat conduction is unlikely to save a gamma-ray ablation scenario that otherwise fails.)

In § 5 several qualitative remarks are made concerning the various possibilities for ablation of accreting neutron star companions.

2. WINDS INDUCED WITHOUT HEAT CONDUCTIVITY

The mass-loss rate from a stellar surface illuminated by an external source of radiation has been calculated by several authors. Basko et al. (1977) estimated the mass flux by treating the transition zone as a discontinuity and assuming that the flow in the corona is isothermal. London & Flannery (1982) calculated the mass flux by solving the hydrodynamic equations in a plane-parallel geometry, including X-ray heating by photoionization of the heavy elements, C, N, O, etc., and assuming that the cooling is due to recombination of hydrogen.

The mass flux depends on $p_{\min}$, the characteristic pressure for transition from the photospheric or radiation temperature T_R to the temperature T_x. It is calculated at the minimum T beyond which cooling, in the presence of reionizing photospheric radiation, can no longer balance the heating by the external radiation.

Under the assumption that cooling is dominated by recombination with a $T^{1/2}$ dependence, LMA found the transition temperature T_t to be $3T_R$. The key physical point in their reasoning is that reionization by the photosphere balances recombinative cooling at T_R so that there is no net recombinative cooling. If free-free emission is significant T_t is somewhat lower, since photospheric heating, which is one-sided, does not balance free-free cooling of plasma at the photospheric temperature. Note that the assumption that recombination dominates free-free emission requires that it be reckoned at $T = T_t$, the simultaneous use of a purely free-free cooling rate and a transition temperature of $3T_R$ is inconsistent.

The value of T_x depends on the X-ray spectrum and on the atomic physics of the plasma at the transition region and is of order 10^6 K (LMA).

The pressure $p_{\min}$ can be written in the form

$$p_{\min} = 1.6 \times 10^3 \xi^{-1} \sigma_{-24} F_{13} T_5^{1/2} \text{ dyn cm}^{-2} , \quad (2.1)$$

where F_{13} is the X-ray flux in units of 10^{13} ergs cm^{-2} s^{-1}, ξ is the ratio of the total cooling rate to the free-free rate ($2 \times 10^{-27} T^{1/2}$ ergs cm^6 s^{-1}) at $T = 3T_R$, and σ_{-24} is the X-ray absorption cross section in units of 10^{-24} cm^{-2}. For a 20 keV exponential X-ray spectrum, and assuming cosmic abundances, LMA derive an effective value for σ_{-24} of at most 10.

In terms of a dimensionless parameter λ, the proton flux, can be written in the form (London & Flannery 1982),

$$C = 1.2 \times 10^{16} T_6^{-1/2} \lambda p_{\min} \text{ cm}^{-2} \text{ s}^{-1} . \quad (2.2)$$

Here T_6 is the value of T_x in units of 10^6 K. The value of λ depends on the details of the solution (see below).

In the present context, the heating time is considerably less than the characteristic flow time. In this limit the heating is sufficiently fast that the transition from T_R to T_x takes place in a very thin zone above which the temperature remains at the value T_x throughout the corona, λ then can be estimated with an isothermal wind model. If the escape temperature $T_\phi = GMm_p/kR$, where R is the radius of the star, is less than T_x the material is free to escape above the discontinuity and $\lambda \approx 1.8$ (Basko et al. 1977). Otherwise if $T_\phi > T_x$, the gas at the lower corona cannot escape, and therefore we have a hydrostatic corona in which the pressure drops exponentially. Only high enough above the stellar surface is the thermal energy of the gas sufficient to escape the star, and λ drops exponentially as $\lambda \approx 3^{3/2} \exp(-T_\phi/2T_x)$ (London & Flannery 1982).

RSTE argued that if a flux of soft γ-rays is part of the incident radiation such that the equilibrium temperature under γ-ray illumination is much higher than T_x, then at a pressure p_γ, below which the cooling cannot balance the γ-ray heating, the temperature of the gas will jump above the escape temperature, and no hydrostatic equilibrium is possible. One gains a factor in the mass flux of about $(T_x/T_R)^{1/2}$ over pure γ-ray heating by invoking X-ray preheating together with it.

The conditions for bootstrap accretion stimulated by γ-ray heating, with X-ray preheating to T_x, but unassisted by Roche lobe proximity, are marginally met, if at all, only under ideal assumptions. If the dimensionless number $Q = (T_x/3T_R)^{1/2}(\epsilon\zeta\chi\Phi\xi^{-1})(\alpha\sigma/\sigma_T)$ is more than about 0.5 (see Table 1 of RSTE), then bootstrap accretion is possible, but only for orbital radii well within 10^{11} cm, in any case close to Roche lobe contact. For example, it is marginal, for Q still unity, for a degenerate companion of mass 0.1 $M_\odot$, at the Roche lobe, and submarginal at greater distances (see also Tavani, Ruderman, & Shaham 1989). Here χ is the fraction of incident radiation that penetrates to the surface, Φ is the ratio of escape velocity to wind velocity, $\alpha\sigma/\sigma_T$ is the ratio of γ-ray inelastic interaction cross section to Thomson cross section, ξ is the ratio of true cooling to pure free-free cooling, ζ is the effective fraction of the evaporated mass that is captured by the neutron star, and ϵ is the production efficiency of soft γ-rays. All of the dimensionless numbers that multiply $(T_x/3T_R)^{1/2}$ must be less than unity. Our numerical solutions confirm that Φ is typically $\frac{1}{3}$ when $L(\alpha\sigma/\sigma_T)$ is of the order of 10^{38} ergs s^{-1} though it can be closer to unity with lower luminosity. Even the ideal gamma-ray spectrum gives $\alpha\sigma/\sigma_T$ of order $\frac{1}{3}$. χ must always be less than unity, and in the case of Cyg X-3, is probably much less than unity if the X-ray modulation is attributed to a thick wind. We will argue in the next section that ξ starts to become greater than unity for $L = 10^{38}$ ergs s^{-1} at distances of 1×10^{11} cm due to line cooling. If the companion has receded from its Roche lobe, ζ must be equal to or less than unity as well. It should also be noted that additional optimistic assumptions are typically made, including the neglect of horizontal pressure gradients resulting from the one-sidedness of the illumination, which should become an important consideration as Φ approaches unity. Perhaps the most optimistic assumption in RST and RSTE is that ϵ is close to unity. Soft γ-ray production requires first particle acceleration then radiation. Even a 30% efficiency at each stage would be optimistic in our view but would be small enough to ruin the scenario.

Altogether, it could be argued, even without line cooling and even with X-ray preheating, the dimensionless number Q is probably less than unity for most systems, and that self-sustaining accretion is dubious in the companion mass range $0.05 < m < 0.1\ M_\odot$, unless the companion nearly fills its Roche lobe. Soft γ-radiation does not assist the self-excited mass transfer scenario unless the parameters and spectrum are extremely fine-tuned, and is even then marginal.

Pure X-ray heating, with a reasonable X-ray spectrum, could carry an effective absorption cross section σ that is perhaps larger by an order of magnitude or more than the Thomson cross section, and this could give rise to an interesting wind if the companion is already down to $10^{-2}\ M_\odot$ in mass (Tavani et al. 1989) such that the escape temperature is not much larger than the temperature attainable by X-ray heating. However, this scenario encounters serious problems in the context of Cyg X-3, leaving aside the question of how the companion passed through a higher mass range. In this system, if the modulation is due to scattering by a hot wind (see Kouba & Molnar 1991 for a very detailed model for the X-ray light curve), it follows that the column density of the wind from infinity to the companion must be of order a Thomson scattering depth. The column density down to the surface of a small degenerate companion must be many scattering depths, and it is hard to see the X-ray emission needed for $\sigma \gg \sigma_T$ could penetrate efficiently to the surface.

Since a liberal estimate (Eichler & Levinson 1988) of the effect of classical heat conductivity suggests that it might enhance the mass flux for parameters that give Q less than but close to unity, we solved the hydrodynamic equations including heat conductivity, in three-dimensional spherical geometry, for transonic winds. We find that for a luminosity of 10^{38} ergs s^{-1} in soft gamma radiation at a distance of 2×10^{10} cm, it falls short by about a factor of 3 or so of making a significant effect when line cooling is ignored. If line cooling should happen to be important, classical heat conductivity makes a significant difference and restores the mass flux to a value that is within a factor of 3 of the values of RSTE. Further details are provided in the Appendix. We conclude, however, that heat conductivity does not help the RSTE scenario very much.

Finally, we note that the criterion for a millisecond pulsar to significantly ablate a 0.1 $M_\odot$ star is roughly the same as that for self-sustaining accretion since the maximum energy that the pulsar can store is about the energy released when this mass falls onto a neutron star. For a pulsar emitting 10^{37} ergs s^{-1} at a distance of 1.7×10^{11} cm, the orbital separation of the PSR 1957+20 system, the photospheric temperature is about $T_R = 2 \times 10^4$ K. As the pulsar is probably unsupported by X-ray preheating, it loses the factor $(T_x/3T_R)^{1/2} \sim 3$ in the value of Q. Using Table 1 of RSTE, and adjusting for the different orbital separation and photospheric temperature, we estimate that such a pulsar would excite a mass flux of

$$\dot{m} = 6(\sigma/\sigma_T)^{2/3}\epsilon\xi^{-1}(T_R/8 \times 10^4\ \mathrm{K})^{1/2} \times 10^{15}\ \mathrm{g\ s^{-1}} < 2\xi^{-1} \times 10^{15}\ \mathrm{g\ s^{-1}}$$

off a 0.03 $M_\odot$ companion. Since the pulsar can sustain such a luminosity for only 3×10^{15} s, it follows that at most $\sim 10^{-3}$ $M_\odot$ could be ablated. In the following section it will be argued that $\xi^{-1} \ll 1$ due to line cooling, and this would in any case render the other issues academic.

3. CRITERION FOR THE IMPORTANCE OF LINE COOLING

The issue of whether line cooling is important, or whether the lines are mostly thermalized by collisional deexcitation, has been discussed by several authors. London, McCray, & Auer (1981) used a simplified model based on a single two-state atom (meant to represent the He 304 Å line or some other line of comparable strength) and argued that, for Her X-1 parameters, collisional deexcitation would lower the contribution of line cooling well below that obtained for an optically thin plasma. Voit & Schull (1988) consider the contribution of $2s$–$2p$ transition of lithium-like ionization states of C, N, and O. Assuming that free-free emission is the primary cooling mechanism, they calculated that the C IV, N V, and O VI lines would suffer collisional deexcitation (the escape parameter $\gamma \sim 1$) when the X-ray flux is about 10^{12} ergs cm^{-2} s^{-1}, corresponding to a heating rate of about 10^{-11} ergs s^{-1}. Since line cooling is about 10^3 times the free-free cooling rate, it follows that the latter can be appropriate for a steady state solution only if the heating rate is 10^{-8} ergs s^{-1}. We have repeated these calculations in detail, taking into account all of the thermalized lines, integrating the column densities of self-consistent, steady state solutions numerically over temperature strata and recover more or less the same results.

However, as argued by LMA, the evaporative solution is not likely to be steady state. Rather, the hard photons are likely to heat up thick blobs of material in an unsteady fashion. The thickness of the blob is roughly determined by the depth at which continuum cooling is unable to balance heating. The thickness of a given temperature zone can be much larger than it would be in the steady state solution, in which material flows through a spatially fixed temperature profile as it heats up. The line photons are less likely to escape the blobs, and to the extent that the important ones fail to do so, it would justify their neglect in estimating the blob's thickness. This picture appears to be basically correct. However, we find below, by considering the contributions of all the thermalized lines (there are of order 30 thermalized lines at any given temperature), that if the incident radiation flux is less than 10^{15} ergs s^{-1} cm^{-2} the star can reemit all of the energy incident upon it at temperatures less than 10^6 K from the photospheres of the thermalized lines, giving rise to a hydrostatic or convective atmosphere. Thus, although the lines are suppressed, they are not negligible if the gas is indeed to be heated to coronal temperatures and beyond.

Let us define p_c to be the pressure above which heating by the external illumination is suppressed by bremsstrahlung (i.e., p_c is given by eq. [2.1] with $\xi = 1$, $\sigma = 10^{-23}$ cm^2). Then assuming that the star's atmosphere is indeed hydrostatic and isothermal down to a pressure p_L, below which line cooling no longer balances the heating, such that $p_L \ll p_c$, the column density of the layer from p_c to p_L is

$$N = \frac{p_c R^2}{GMm} = 7 \times 10^{20}\sigma_{-24}F_{13}T_5^{1/2}R_{10}^2(M_\odot/M)\ \mathrm{cm^{-2}}\ , \quad (3.1)$$

and the optical depth at line center is

$$\tau_L = 2.7 \times 10^3 X_4\theta_L f_L \lambda_{1000}\mu^{1/2}\sigma_{-24}F_{13}R_{10}^2(M_\odot/M)\ . \quad (3.2)$$

Here $10^{-4}X_4$ is the fractional abundance of the element, θ_L is the fractional abundance of the ion, f_L is the line oscillator strength, λ_{1000} is the wavelength at line center in units of 1000 Å, and μ is the atomic mass.

Following LMA the line cooling rate per particle can be written as

$$q_L = \frac{n_L E_L c_L \exp(-E_L/kT)}{1 + \gamma_L}, \quad (3.3)$$

where $n_L = 10^{-4} n_e X_4 \theta_L$, E_L is the line energy, c_L is the collisional deexcitation rate of the line, and $\gamma_L = 2n_e c_L(1 + \tau_L)/(A_L)$ is the escape parameter, such that $\gamma_L \gg 1$ for a thermalized line, where A_L is the radiative decay rate. The energy flux due to a single thermalized line, $f_L = Nq_L$, can now be found by using equations (3.1)–(3.3) and is given by

$$f_L = 1.8 \times 10^{12} \lambda_{1000}^{-4} \mu^{-1/2} T_5^{1/2} \exp(-1.4/T_5 \lambda_{1000}) \times \text{ergs s}^{-1}\ \text{cm}^{-2}. \quad (3.4)$$

Note that f_L is independent of column density and abundances provided that the line is thermalized. However, for sufficiently low column density, $\gamma_L < 1$, and the line is not thermalized, in which case one cannot use equation (3.4). The total flux f, at any given temperature, can then be found by adding up the contributions of all the thermalized lines.

By considering about 200 different lines of the elements He, C, N, O, Ne, Mg, Si, and Fe (Gaetz & Salpeter 1983), we calculate f at different temperatures. We first calculate γ_L for each line, by using equation (3.2), and find all the thermalized lines at a given temperature. Then we calculate f_L for each of the thermalized lines, using equation (3.4). Finally we sum up all the contributions and find f. In calculating γ_L we assume cosmic abundances. The collision strengths where taken from Gaetz & Salpeter (1983), and ionization fractions where taken from Shull & Van Steenberg (1982). Photoionization may decrease the ionization fractions somewhat but we do not expect the final answer to be affected critically.

From our calculations we find that line cooling is important at temperatures below 10^6 K when the incident radiation flux $< 10^{15}$ ergs cm^{-2} s^{-1}. In Table 1 we list a liberal equilibrium temperature, i.e., the temperature above which f exceeds the entire incident radiation flux, for several systems. It is emphasized that if we consider only the He 304 line for Her X-1, we find that line cooling is unimportant, in agreement with LMA. The importance of line cooling is raised by the presence of many more thermalized lines, and their presence at temperatures ranging up to 10^6 K. For γ-ray heating, only a small fraction of the radiation is absorbed above the photosphere and the maximum temperature should be well below that listed in the table. Similarly, if much of the X-radiation is modulated by the wind and cannot reach the companion's surface, the maximum temperature is reduced.

We conclude that the total neglect of line cooling in ablation scenarios is unjustified for $L/(4\pi D^2) < 10^{15}$ ergs s^{-1} cm^{-2}. Even at higher L/D^2, the effect of self-shielding would reduce the heating rate at the bottom of the slab, so line cooling could still be important. Convection, sudden changes in the ionization state of the gas, and the additional thermalized lines from the excitation of already excited atoms are all effects that work in the direction of making line cooling even more important, so our conclusion is in some sense conservative. The heating may result in a wind due to the radiation pressure of the trapped lines (e.g., Voit & Shull 1988), but this is properly considered a different mechanism.

4. ABLATION BY KILOHERTZ RADIATION FROM MILLISECOND PULSARS

We now calculate the mass loss rate from a companion assuming that a fraction of the kilohertz radiation from the pulsar is absorbed in the companion's atmosphere and conducted down to the base of the wind by classical heat conduction. In practice, we suspect that a magnetosphere could play an important role in extracting Poynting flux from the wind and conveying it to the atmosphere, much the way Earth's magnetosphere extracts energy from the solar wind. However, we restrict ourselves to a very simple geometric model.

We assume that the energy is deposited in a very thin layer, i.e., in the form of a δ function at $r = r_0$, and also that the heat flux vanishes at $r = r_0$ and at the photosphere, $r = R$. We invoke spherical symmetry, which is a gross approximation, since in reality the flowlines have must bend sharply away from the heating layer. The energy and momentum equation are then

$$\frac{d}{dr}\left(qr^2 T^{5/2} \frac{dT}{dr}\right) = C \frac{d}{dr}\left(5kT + \frac{mu^2}{2} - \frac{GMm}{r}\right) + n^2 r^2 L(T) - r^2 \eta F \delta(r - r_0), \quad (4.1)$$

$$dp/dr + mnu\, du/dr + GMmn/r^2 = 0, \quad (4.2)$$

where $C = nur^2$ is the particle flux, per steradian, $L(T)$ is the cooling function, F is the radiation flux, and η is the fraction of radiation that is absorbed.

Integrating the energy equation from R to r_0 and neglecting

TABLE 1

EQUILIBRIUM TEMPERATURE FOR VARIOUS BINARY SYSTEMS

Source	$M/M_\odot$ [a]	R [b] (10^{10} cm)	L [c] (10^{38} ergs s^{-1})	D [d] (10^{11} cm)	T [e] (10^5 K)
1957+20	0.025	1	10^{-3}	1.7	0.7
Cyg X-3	?	?	$\lesssim$0.5	1	8
Her X-1	2.2	10	0.2	6.3	1
Millisecond-pulsar [f]	Any	Any	0.2	1.7	2

[a] Companion's mass.
[b] Companion's radius.
[c] Total neutron star luminosity.
[d] Binary separation.
[e] Maximum equilibrium temperature, calculated by equating the total incident radiation flux ($L/4\pi D^2$) with the energy flux due to thermalized lines.
[f] Binary millisecond pulsar system resembling PSR 1957+20 in orbital parameters, but with a higher luminosity.

cooling gives

$$\eta F r_0^2 = C(5kT_0 + mu_0^2/2 - GMm/r_0) . \qquad (4.3)$$

If the heating rate of the kHz radiation is high enough, the thermal energy of a particle at r_0 is much greater than the gravitational energy and gravity can be neglected. Assuming that the kinetic energy at r_0 is of order kT_0, we can estimate the temperature at the heating layer, T_0, to be

$$kT_0 = \eta F r_0^2/6C . \qquad (4.4)$$

The temperature profile can be found approximately by equating the thermal flux with the enthalpy flux and neglecting all the other terms (Eichler & Levinson 1988).[1] One then finds

$$T^{5/2} = \frac{25kC}{2q}(R^{-1} - r^{-1}) , \qquad (4.5)$$

where we have assumed a heat conductivity of $qT^{5/2}$. On substituting equation (4.4) into equation (4.5) we obtain

$$C = 2.2 \times 10^{13}\left(\frac{R}{1 - R/r_0}\right)^{2/7}(\eta F r_0^2)^{5/7}\left(\frac{q}{q_S}\right)^{2/7} \text{ s}^{-1} \text{ (c.g.s.)} , \qquad (4.6)$$

where q_S, the Spitzer valve, is 1.8×10^{-6} ergs cm^{-1} s^{-1} $\text{K}^{-7/2}$. In laboratory plasmas, q/q_S may be as low as 0.03 due to saturation and/or instabilities. The radius of the heating layer, r_0, is determined by equating the ram pressure of the wind with the kHz radiation pressure. Assuming that the wind velocity at r_0 is of order of the sound velocity, one finds that

$$r_0(1 - R/r_0)^{1/2} = 2.1 \times 10^{14}(q/q_S)^{1/2}R_{10}^{1/2}\eta^3 F_{15}^{-1/2} \text{ cm} . \qquad (4.7)$$

If the R/r_0 term can be neglected, the mass loss rate is

$$dM/dt = 4\pi mC = 4.7 \times 10^{24}(q/q_S)R_{10}\eta^5 \text{ g s}^{-1} , \qquad (4.8)$$

independent of the radiation flux, provided that the basic geometry remains intact. The radius of the eclipse for PSR 1957+20 is $\sim 5 \times 10^{10}$ cm if $(q/q_S)^{1/6}\eta = 0.016$. Given the strong dependence on η, it is difficult to estimate the evaporation rate with certainty, but for $q/q_S \sim 0.1$, $\eta = 0.023(L_{35})^{1/6}$ with equations (4.7) and (4.8), this implies an evaporation rate of order $3 \times 10^{15}(L_{35})^{5/6}$ g s^{-1}. This is marginally consistent even with the original supposition (Fruchter et al. 1988) of eclipse by a plasma frequency cutoff and implies significant ablation over the spin-down time of the pulsar. [Given $r_0 = 2 \times 10^{10}$ cm, $(q/q_S) = 0.1$, a 3×10^{-2} $M_\odot$ companion would be evaporated in $\sim 3 \times 10^{15}(L_{37})^{-5/6}$ s.) Given the large geometric uncertainties and the strong dependence on η, there is clearly much uncertainty in our estimate of $\dot{M}$.

5. REMARKS

In this section we make several qualitative points relating to both the physics of outflow and the implications for LMXBs.

The physical significance of heat conduction is that it delivers heat efficiently to where it is needed most: the thin layer near $T = 10^5$ K that constitutes a cooling barrier to the flow. It can in this way counteract the effects of line cooling.

Conduction also allows heating by nonpenetrating forms of radiation, e.g., partial absorption of the kHz radiation from a millisecond pulsar as discussed in the previous section. Although such radiation is formally reflected from a solid surface, magnetic reconnection, instabilities at the fluid surface, and/or dissipation by anomalous resistivity within the skin depth could conceivably create partial absorption of kHz radiation. The sinusoidal nature of the kHz radiation pressure on the plasmapause probably assures that at least $\sim v_s/c$ of the kHz radiation is deposited as acoustic waves. Here we emphasize that even a small amount of absorption could be far more significant than heating by soft gamma rays, as proposed by Phinney et al. (1988), Kluzniak et al. (1988), and Ruderman et al. (1989a), for in the latter case, at most $\sim 10^{-4}n_9$ (where n_9 is the number density at the eclipse radius in units of 10^9 cm^{-3}) of the incident radiation is absorbed by the outflow. We may also note that the solar wind deposits more than $\sim 10^{-2}$ of its incident energy to Earth via perturbations of its magnetosphere. A similar efficiency might obtain for the pulsar wind impinging on the companion's magnetosphere.

It is not clear that heat flow proceeds according to the classical rate, since heat flux instabilities may interfere. It is shown elsewhere (Levinson & Eichler 1990) that a sufficiently strong magnetic field can suppress heat flux instabilities and allow classical conduction parallel to the field.

It is not clear that the eclipse requires a plasma frequency cutoff (or free-free absorption) as mechanisms at lower densities may be possible if the plasma is turbulent (Eichler 1991).

The arguments presented in § 2 against effective ablation do not apply to an object that nearly fills its Roche lobe since only a small disturbance (e.g., radiation pressure or coronal spillover) is necessary to stimulate overflow. Material that has already overflowed can get nearer to the neutron star, cover more of the sky, and possibly get evaporated from the accretion disk (Begelman & McKee 1983) to beyond the companion radius, possibly forming an excretion disk. We also note that for a large enough mass-loss rate nondegenerate evolution is possible (Phinney et al. 1988). Here contact with the Roche lobe can be maintained dynamically during the mass transfer and only afterward does the companion shrink within the Roche lobe. The rapid period change of Cyg X-3 may be suggestive of nondegenerate evolution. The main-sequence precursor to PSR 1957+20 deduced by Phinney et al. of ~ 0.5 $M_\odot$ and a period of ~ 5 hr is very similar in parameters to Cyg X-3.

If braking does not keep the companion in steady contact with the Roche lobe, the basic point of RSTE can easily be generalized to a relaxation oscillation scenario: the accretion shuts off after the mass-shedding companion becomes sufficiently recessed from the accretion disk and turns on again after angular momentum loss, say, by gravitational radiation, restores contact with the Roche lobe. Thus LMXBs, as they age, may spend a decreasing fraction of their time in the "on" stage, but nevertheless remain very luminous whenever they are in this stage. This would explain the apparent lack of fading LMXBs, i.e., those with $L < 10^{36}$ ergs s^{-1}. In terms of "on-time," all LMXBs may be young.

6. CONCLUSIONS

We have suggested that surface heating by the kHz radiation from millisecond pulsars combined with heat conduction to the surface may be an effective ablation scenario. The viability of the scenario depends sensitively on the geometry and effi-

[1] It is straightforward to show that the saturation parameter $\lambda d/dx$, where λ is now the electron mean free path, is of order $10u/v_{\text{eth}}$, where v_{eth} is the characteristic electron velocity, when the inward heat flux is equated with the outward enthalpy flux. This is less than unity for subsonic flow, independent of temperature. The contribution due to energetic electrons in the thermal tail may saturate.

ciency with which it is absorbed, and this should be the subject of future work.

We have argued that the ablation scenario proposed by Ruderman et al. (1989a) and others, in which pulsars rapidly evaporate their companions by soft gamma rays (or other quanta with similar interaction cross section) fails for general pulsar parameters, even if the radiation is produced with 100% efficiency and with the optimal spectrum, at orbital radii exceeding 3×10^{10} cm.

The companion scenario of Ruderman et al. (1989b) in which the neutron star in an earlier evolutionary phase accretes and yields much soft X-ray emission may work as long as the companion is close enough to the Roche lobe that a variety of mechanisms (e.g., radiation pressure, X-ray heated corona spillover) can generate Roche lobe overflow, even while recessed by a finite amount. This will suffice to explain the absence of fading LMXBs.

If the companion's surface is obscured by many scattering depths of outflowing material, as may be the case for Cyg X-3, the obscuration of the surface threatens self-excited, gas pressure–driven wind scenarios because the attenuation of incident radiation is enough to allow line cooling to set in. However, radiation pressure–driven winds are not affected by the amount of cooling.

The recent discovery of a second eclipsing millisecond pulsar 1744−24A (Lyne et al. 1990a, b; Nice et al. 1990)—with a 0.1 $M_\odot$ companion and a 1.8 hr period—does not obviously add to the observational constraints on wind excitation by pulsars since the incident flux on the companion is probably about the same, at present, as for PSR 1957+20.

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Note added in manuscript.—Recent observations indicate a rapid period change of PSR 1957+20 ($\dot{P}/P = 3 \times 10^{-8}$ yr^{-1}) (Ryba & Taylor 1991). This would appear to suggest a mass-loss rate of order 10^{16} g s^{-1}, which would further strengthen the case against gamma-ray heating even as the present-day evaporation mechanism.

APPENDIX

STIMULATED WIND WITH HARD PHOTONS AND HEAT CONDUCTION

Heat conduction, if not inhibited by heat flux instabilities, may boost $p_{\rm min}$ considerably by conducting heat into the thin layer of intense cooling.

Eichler & Levinson (1988) solved a simplified one-dimensional form of the mass, momentum, and energy equations, using the thermal conductivity of a fully ionized plasma which we expressed as $qT^{5/2}$, where q is 1.8×10^{-6} ergs cm^{-1} s^{-1} K$^{-7/2}$ (Spitzer 1962). It was found that cooling becomes unimportant, for parameters relevant to the present context, at temperatures well above 10^5 K. The evaporation mechanism and amount of outflow is then basically that discussed by Cowie & McKee (1977) in the context of interstellar clouds. The temperature profile is

$$T^{5/2} = (25kC_H/2q)x \,, \tag{A1}$$

where C_H is the proton flux in the presence of heat conduction and k is Boltzmann's constant. For pulsar PSR 1957+20 parameters, the proton flux was found to be less than 10^{15} cm^{-2} s^{-1}. This result was obtained by using a liberal estimate of the sonic temperature. More careful calculations, outlined below, give a sonic temperature which is less by a factor of about 3; hence, they provide an even stronger upper limit to the mass flux.

Since heat flux cannot flow into the system from infinity, it has to vanish at some distance from the companion which we denote by x_1. We also assume negligible heat flux into the photosphere which we choose to be at $x = 0$. Integrating the energy equation from $x = 0$ to $x = x_1$ gives

$$\int_0^{x_1} \frac{\Lambda}{u}\, dx = 5kT_1 + \frac{mu_1^2}{2} + mgx_1 \,, \tag{A2}$$

assuming that $T_0 < T_1$ and $u_0 < u_1$. Λ is the net heating rate per particle.

Neglecting gravity and assuming that u_1 is of order of the sound velocity the right-hand side of equation (A1) is of order $6kT_1$. The left-hand side is estimated by noting that $u \propto 1/n \propto T$, and $dx \propto T^{3/2}\, dT$, so that the contribution to the integral comes mainly from temperatures near T_1. Since at T_1 the cooling is negligible we get, $\Lambda \approx \sigma F$, and the integral is of order $\sigma F x_1/u_s$. One finds that

$$kT_1 = 2 \times 10^{-10}(\sigma_{-24} F_{13} x_{10})^{2/3} \text{ ergs} \,. \tag{A3}$$

The proton flux can be found by substituting equation (A3) into equation (A1).

Numerical integration of the energy momentum and mass flow equations in a spherical geometry gives a proton flux which is greater by a factor of 2, and even this modest factor is cancelled by retaining only 2π of the spherical geometry as is appropriate for one-sided illumination. We finally write our result as

$$C_H = 2 \times 10^{15}(\sigma_{-24} F_{13})^{5/3}(x_{10})^{2/3} \text{ cm}^{-2} \text{ s}^{-1} \,. \tag{A4}$$

The numerical integration also shows that of the limiting expressions (2.1) and (A4), the appropriate one is whichever gives the higher mass flux. We therefore conclude that heat conduction, if classical, becomes important for soft gamma-ray heating with X-ray preheating only if

$$(\sigma_{-24} F_{13})^{5/3}(x_{10})^{2/3} > 1.6\lambda\xi^{-1} T_{x6}^{-12} P_{\rm min} \,, \tag{A5}$$

where here we also use equation (2.1). This result implies that heat conduction is not very important for the types of parameters in RSTE, as stated at the end of § 2, as long as line cooling is unimportant. There is a window in which line cooling and conduction are both important in the presence of X-ray and/or soft γ-ray heating, but we do not feel that there is a promising ablation scenario associated with it.

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