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THE DYNAMICAL INFLUENCE OF RADIATION IN TYPE 1 X-RAY BURSTS

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ABSTRACT

We consider the dynamical effects upon an accretion disk of incident radiation generated by thermonuclear burning on the surface of a nonrotating, nonmagnetic neutron star—as exemplified in type 1 X-ray burst sources. Under these conditions, we find that the torque applied by the radiation field leads to enhanced mass transfer, and the associated accretion power contributes substantially to the total luminosity of the burst. However, this accretion will provide a smaller fraction of the total burst energy if the neutron star possesses a magnetosphere or is in rapid rotation.

Subject headings: radiation mechanisms — stars: accretion — stars: neutron — X-rays: bursts

I. INTRODUCTION

The standard model for type 1 X-ray bursts is that of unstable thermonuclear burning on the surface of a neutron star (for a review, see Lewin and Joss 1983). Strong magnetic fields suppress the instability by funneling the accreting material onto small polar caps, where, under the increased effective accretion rate, continuous burning can take place. Consequently it is commonly assumed (although not actually required) that the accretion flow, which supplies the fuel for burning, is nonmagnetospheric. Surface conditions are not profoundly influenced by the stellar rotation rate, so this parameter does not feature significantly in models of the type 1 burst phenomenon. Such spherically symmetric models allow, in principle, the determination of luminosities, temperatures, distances, and mass-to-radius ratios of bursters (e.g., London, Taam, and Howard 1986; Tanaka 1986; van Paradijs and Lewin 1987). An additional complication is provided by the interaction between the bursting stellar surface and the accretion disk (Lapidus and Sunyaev 1985; Czerny, Czerny, and Grindlay 1986), which can affect the spectrum and the directionality of the outgoing radiation. In what follows, we point out that the star-disk interaction has also a significant influence upon the total burst energy, through an entirely different physical effect. We show that a nonrotating, nonmagnetospheric neutron star is inconsistent with the asumption that all of the observed burst energy is derived from thermonuclear burning, since in this situation the implied radiation torque requires that there be a significant contribution to the luminosity from accretion.

II. RADIATION PRESSURE EFFECTS

Consider a neutron star whose surface is radiant, thereby illuminating a surrounding accretion disk. The accretion disk will be assumed to be geometrically thin, while the accreting matter will be treated as a single fluid, thus ignoring the possiblity (Walker 1988) that the interaction between radiation and disk could drive electrical currents in the latter. Of the radiation forces acting, the component perpendicular to the plane of the disk leads only to changes in the local disk structure and has no direct influence on the mass transfer rate. We shall not concern ourselves with the local disk properties, and this force component will therefore be ignored. The radial force, however, can lead to bulk motion of material at the disk surface and is more interesting. The consequent surface motions differ according to the magnitude of the viscosity within the disk: if the time scale for communicating vertical shear is less than the time scale for radiation-driven outflow, then the surface remains in Keplerian rotation—we shall refer to this as "good" or "strong" coupling. In terms of the α viscosity prescription (Shakura and Sunyaev 1973; Pringle 1981), the viscous coupling will be good if $\alpha^2 > l$, where l is the luminosity of the star in units of the Eddington luminosity. The reverse condition ($\alpha^2 < l$) implies a loose coupling, so that the surface material can then rotate at sub-Keplerian speeds. We note that radiation which diffuses into the interior of the disk will contribute to the viscosity. This modifies the criterion for strong/weak coupling, but does not alter the behavior of the disk in a given regime.

Of particular interest is the response of the disk to a luminous event: some type of burst of duration t_B. In the loose coupling approximation, angular momentum is preserved, while the pressure of radiation forces surface material out from equilibrium radii R (at $l \simeq 0$) to a new equilibrium at $\sim R/(1 - l)$. For a Keplerian frequency Ω, this shift is accomplished in a time $\sim l^{-1/2}\Omega^{-1}$, and at $R \sim R_*$, this is much smaller than observed values of t_B, for all types of bursts. However, at the outer edge of the disk the time scale for driving off material is much larger. Indeed, since the radius of the Roche lobe is comparable with the binary separation (low-mass companion), mass loss from the system, during a burst, would require t_B to be comparable with the orbital period of the system. This circumstance is never observed, so the disk will not lose material, and, when the burst subsides, the surface layers will return (infall) to their equilibrium radii R.

If the viscous coupling is good, then the disk behaves rather differently. In this case there is no equilibrium radius, under the influence of radiation pressure, since the surface material can acquire angular momentum from the interior, leading to a persistent surface outflow. However, the surface material can only gain as much angular momentum as the interior loses, so that the interior inflow rate increases, giving zero net change in the accretion rate.

III. RADIATION TORQUE

At first sight the normal and radial components appear to be the ony forces present. However, there must also be a torque acting on the disk surface, since absorption of radiation will increase the total inertia (mass), at constant angular momentum, and therefore decrease the specific angular momentum of the disk. This is the Poynting-Robertson (PR) effect (Robertson 1937; Blumenthal 1974). Consider an optically thick disk element of area A, mass ΣA, absorbing a photon of energy $E_{\rm ph}$ emitted from a central point source (i.e., the stellar surface). The fractional change in specific angular momentum, resulting from this absorption, is $\Delta j/j \simeq -E_{\rm ph}/\Sigma A c^2$ (for Lorentz factor $\gamma \simeq 1$); see Rybicki and Lightman (1979). Upon reemission of this energy (assumed isotropic in the rest frame of the emitter) there is no change in specific angular momentum, but corresponding to the loss of inertia there is a fractional change in angular momentum $\Delta J/J \simeq -E_{\rm ph}/\Sigma A c^2$. Multiplying by the rate of absorption of such photons, we find the time scale for loss of angular momentum by the PR effect, $t_{\rm PR}$:

$$t_{\rm PR}{}^{-1} = -\frac{\partial \ln J}{\partial t} \simeq \frac{FA}{E_{\rm ph}} \frac{E_{\rm ph}}{\Sigma A c^2} = \frac{F}{\Sigma c^2}\,, \tag{1}$$

for radiant flux F across the disk surface, and disk surface density Σ. Here we have assumed the strong coupling limit, so that the torque is communicated to the interior of the disk. The appropriate time scale for the loose coupling regime is obtained with the replacement $\Sigma \to \kappa^{-1}$, κ being the opacity of the disk material. The deduced increase in mass transfer rate is, of course, independent of the coupling strength, since the torque applied by the radiation field is the same in each case. (The infall speeds differ by a factor τ, the line-of-sight optical half-depth of the disk, while the quantities of matter infalling at this speed differ by a factor τ^{-1}.)

For an instantaneous luminosity L we have $F = \xi L/4\pi R^2$, where the geometric factor $\xi \sim \max\,(R_*/R,\, dH/dR)$, for radius R, stellar radius R_* and disk thickness H. We will consider $R \sim R_*$, i.e., $\xi \sim 1$. This choice violates the point source asssumption, under which $t_{\rm PR}$ was formulated, but $t_{\rm PR}$ will still be correct to order of magnitude providing the star is nonrotating (see later). For quasi-Keplerian rotation the infall speed is just $2R/t_{\rm PR}$, so in the region $R \sim R_*$ the mass transfer rate implied by the PR torque is just

$$\dot{M}_{\rm PR} = 2\pi {\rm R}\, \frac{2{\rm R}}{t_{\rm PR}}\, \Sigma \simeq \frac{L}{c^2}\,. \tag{2}$$

The associated accretion luminosity is $L_{\rm PR} = \eta \dot{M}_{\rm PR} c^2$, where $\eta \simeq GM_*/R_* c^2$ (M_* is the stellar mass), and $\eta \simeq 0.2$ for a "standard" neutron star, giving $L_{\rm PR} \sim 0.2L$. More careful calculations, which account for the finite size of the source (see e.g., Guess 1962), reveal that $L_{\rm PR} \sim 8\eta L/3(1-\eta)$, so with $\eta \simeq 0.2$, $L_{\rm PR} \sim 0.6L$ is a better estimate. Furthermore, if the neutron star has a radius as small as 1.6 times the Schwarzschild radius, as suggested by Waki *et al.* (1984), then $\eta \simeq 0.3$ and $L_{\rm PR} \sim 1.2\,L$. In words: whatever the luminosity generated by thermonuclear burning, the resulting radiation torque ensures a comparable luminosity from accretion—*Irrespective of the quiescent accretion rate.* (Note that for thermonuclear burning on the surface of a white dwarf, $\dot{M}_{\rm PR} \sim Lc^{-2}$, but $L_{\rm PR} \ll L$, since $\eta \sim 10^{-3}$ in this case.)

IV. BURST ENERGETICS

Bursts are, of course, characterized by a large transient increase in luminosity, so that $M_{\rm PR}$, the increase in the accretion rate during a burst, is much larger than $\dot{M}_Q$, the quiescent accretion rate. It is interesting to investigate what effect this enhanced accretion rate has on the energetics of the bursting behavior. Suppose that the burst duration is t_B, and that of the quiescent phase t_Q, then the ratio of total mass accreted during each phase is

$$\frac{\dot{M}_{\rm PR}\, t_B}{\dot{M}_Q\, t_Q} \sim \frac{L t_B}{\dot{M}_Q c^2 t_Q}$$

$$\sim \frac{\text{total burst energy}}{\text{rest energy accreted during quiescence}}\,. \tag{3}$$

The ratio of accreted masses should then be $\sim \chi$, the rest mass conversion efficiency of nuclear fusion. We know $\chi \ll 1$, and the amount of nuclear fuel accreted during a burst is therefore negligible in this circumstance. In the standard model, however, the "apparent" value of χ (i.e., based on the assumption that all of the burst energy is derived from nuclear burning), which we shall denote χ_a, will, of course, vary by an amount $\Delta\chi_a \sim \chi$, because of the contribution of $L_{\rm PR} \sim L$. This is actually the minimum value expected for $\Delta\chi_a$, since our analysis is linear—see later discussion. These variations will always be in the sense of increasing the value of χ_a, because $L_{\rm PR}$ is positive. (Variations in the opposite sense could result from, say, continuous burning of accreting material.)

V. DISCUSSION

An important parameter which we have neglected thus far is the rotation frequency of the star, Ω_*: we have assumed $\Omega_* = 0$. If the star is rotating, then the disk will absorb angular momentum, as well as inertia, from the radiation field, and our calculation will then overestimate the torque. Since material orbits at the Keplerian frequency, the results we have obtained will be valid for $\Omega_* \ll \Omega_{\rm K} = (GM_*/R_*{}^3)^{1/2}$. Neutron stars can be spun-up to rapid rotation rates, during accretion episodes (Smarr and Blandford 1976), although gravitational radiation instabilities limit the accessible spin periods to greater than 1 ms or so. The two fastest known "recycled" pulsars, PSR 1937+21 and PSR 1957+20, have periods of 1.5 and 1.6 ms, respectively, while the Keplerian period at the surface of a neutron star ($M_* = 1.4\, M_\odot$, $R_* = 10$ km) is a factor of 3 smaller than this. Evidently there are stars which do not satisfy the condition $\Omega_* \ll \Omega_{\rm K}$, and a quantitative investigation of the influence of Ω_* is clearly important. We are currently undertaking a study of time-dependent radiation torques in type 1 bursters, including a full treatment of the effects of stellar rotation (Walker and Mészáros 1989).

In addition to the energy of the thermonuclear flash, radiation from the boundary layer (between disk and star) will also impinge upon the disk surface. However, boundary layer material is itself in rapid (although not Keplerian) rotation, and the torque applied by the boundary layer radiation is therefore smaller than that arising from nuclear burning on the stellar surface. Consequently, the PR effect probably does not, of itself, imply an unstable accretion mode. However, we note that our calculation gives a lower limit on the increase in accretion power, since our linear analysis completely neglects those additional torques which arise from the enhanced accretion luminosity. One may speculate that the nonlinear evolution of real systems permits much larger burst enhancements; conceivably this could be large enough to explain bursts with $\chi_a \sim 1$ (see Lewin and Joss 1983, for examples).

In our calculations we have assumed that the accreting neutron star does not have a magnetosphere. While there is good evidence that type 1 bursters do not possess large magnetospheres (Lewin and Joss 1983), the presence of a small magnetosphere is not excluded. In this case the influence of the PR torque would be reduced. Magnetospheric plasma corotates at angular frequency Ω_*, and there can be no radiation torques acting within this region. It is therefore valid (in an approximate treatment) to ignore effects of the magnetic field excepting the increase of the inner radius of the accretion disk. That is, in the case of a magnetospheric accretor, the quantity ξ (which we set to unity in the nonmagnetospheric case) is reduced to, at most, $\xi \sim R_*/R_A$, where R_A is the Alfvén radius.

In conclusion, we have described the dynamical influence, on an accretion disk, of irradiation by thermonuclear burning on the surface of the accreting star. The Poynting-Robertson "formalism" offers a particularly simple description of radiation torques in nonmagnetospheric accretion onto a nonrotating star. Using this description we estimate that a significant fraction of the energy of a type 1 X-ray burst may be due to accretion. This accretion will constitute a smaller fraction of the burst energy if there is a magnetosphere or if the stellar rotation is rapid. However, in the absence of conclusive evidence regarding these factors, we must expect that the additional energy release discussed here will play a significant rôle in determining burst luminosities and spectra.

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