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HARD X-RAY SPECTRA FROM GAP ACCRETION ONTO NEUTRON STARS

WLODZIMIERZ KLUŹNIAK
Physics Department, Stanford University; and Astrophysics Laboratory, Physics Department, Columbia University, New York, NY 10027[1]
AND
JAMES R. WILSON
University of California, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
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ABSTRACT

Weakly magnetized neutron stars undergoing disk accretion are found to emit copious hard X-rays if the marginally stable orbit lies outside the stellar surface. In this general relativistic picture (impossible in Newtonian gravity) the accretion disk terminates well outside the stellar surface. Accreting matter crosses the "gap" between the disk and the star in free fall; it then strikes the neutron star surface at a shallow angle, creating a hot equatorial accretion belt with a temperature inversion. For accretion rates that are not too high, the fluid flowing through the gap is optically thin to X-rays escaping from the equatorial belt. The structure of the surface boundary layer in such stars may then be largely decoupled from that of the disk. We exhibit a typical emergent spectrum, which was obtained in a self-consistent manner by a one-plus-one–dimensional radiative transfer and hydro code; power-law emission extends up to $\sim$200 keV.

Subject headings: accretion — relativity — stars: neutron — X-rays: spectra

1. INTRODUCTION

At present, the issue of whether accreting neutron stars emit hard X-rays (or even γ-rays) is open both observationally and theoretically. In this *Letter* we show that if an accreting, weakly magnetized neutron star is sufficiently compact, thermal processes can yield spectra extending above 100 keV. This occurs in the new regime of accretion, proposed by Kluźniak & Wagoner (1985), where because of the effects of general relativity the accretion disk does not extend to the stellar surface. In this case the atmospheric structure and emission can be computed following the approach of Alme & Wilson (1973), with nonradial flow included.

With the exception of brief X-ray bursts in some sources, bright X-ray emission from neutron stars in binary systems is powered by the release of gravitational binding energy of infalling matter which takes place both in the accretion disk and at (or near) the surface of the neutron star (Pringle & Rees 1972; Shakura & Sunyaev 1973). Most accreting neutron stars, and especially low-mass X-ray binaries and X-ray bursters, do not exhibit coherent pulsations at currently detectable levels or any other direct evidence of strong magnetic fields; in such sources the accreting fluid is thought to be striking a large part of the stellar surface (e.g., Mitsuda et al. 1984). Successful fits to some observed spectra have been carried out under the assumption that the disk extends right down to the equatorial zone of the neutron star (Czerny, Czerny, & Grindlay 1986). The blackbody peak at near-Eddington luminosities occurs at 1 or 2 keV, but frequently harder power-law emission is also seen, especially at lower luminosities. Such power laws were usually interpreted in terms of Comptonization in a postulated $\sim$5 keV spherical corona around the neutron star (White, Stella, & Parmar 1988), but this may no longer be tenable.

Several sources in the *HEAO 1* catalog (Levine et al. 1984) were reported to have emission in the highest energy bin, i.e., for photon energies $E > 80$ keV. Power laws extending that far have also been reported in balloon observations, e.g., for Cyg X-2 (Maurer et al. 1982) and to even higher energies for Cyg X-3 (Meegan, Fishman, & Haynes 1979). The Galactic bulge transients are well known to exhibit fairly hard emission (Knight et al. 1985). More recently, *Ginga* observations have shown that several sources show no evidence of spectral cutoff at the highest energy observed (30 keV); in some cases, e.g., for GS 2000+25 (Tanaka 1989), the temporal behavior of the spectrum is inconsistent with the usual model of Comptonized thermal emission. Although we are not trying to model any particular source, we point out those developments in the hope that our results may be of relevance.

Throughout this work we neglect magnetic effects. This is fully justified for the accretion rates considered here if the field strength is $<10^7$ G everywhere. Note that our results cannot apply for neutron stars with surface strength of the magnetic dipole field exceeding 10^8 G, because in that case the radius at which the disk terminates would be determined by magnetohydrodynamic effects (Ghosh & Lamb 1979a, b), as would be the flow between the disk and the neutron star. Those neutron stars may also be powerful emitters of hard X-rays, but through a quite different mechanism involving certain postulated magnetospheric effects (Kluźniak et al. 1988).

2. MODEL

Smooth matching of a disk solution to the stellar surface has not yet been achieved in the "Newtonian" case, i.e., when the accretion disk extends to the surface of the star[2] (see Kluźniak 1987 for a review of the problem). However, in general relativity another possibility is open. It is known that accretion disks around black holes terminate at some radius close to r_{ms}, the radius of the marginally stable orbit (i.e., the innermost stable circular orbit of a test particle) predicted by general relativity. Heuristically speaking, this occurs because within r_{ms} the gravitational pull of the star is so strong that it overcomes

[1] Postal address.

[2] For white dwarfs a solution has recently been found by Kley (1989).

the "centrifugal barrier." In fact, matter is accelerated so rapidly in the inward radial direction that flow becomes supersonic at a radius r_s only slightly smaller than r_{ms} (Muchotrzeb & Paczyński 1982). At radii $r < r_s$ the fluid spirals in, supersonically and without dissipation, onto the black hole along essentially free-fall trajectories (see also Shakura & Sunyaev 1973; Novikov & Thorne 1973; Czerny et al. 1986; Matsumoto et al. 1984). It has been pointed out (Kluźniak & Wagoner 1985) that if radiative and other stresses within r_s are neglected, the same behavior will hold for a disk around a neutron star. Naturally, this requires (assumes) that the radius of the neutron star is smaller than that of the marginally stable orbit: $R < r_s < r_{ms}$. The neglect of mechanical stresses is justified (except when R is very close to r_s) because the scale height of the neutron star atmosphere does not exceed $\sim 10^2$ cm, and farther out the flow is supersonic. Fluid stresses cannot then be transmitted from the stellar atmosphere to the disk, and the matching of the boundary-layer solution to the disk is trivial: outside a stand-off shock above the neutron star surface the solution is nearly the same as that for an accretion disk around a black hole (if the effects of illumination of the inner region of the disk are neglected).

The precise values of neutron star radii are not known, but it is not unreasonable to assume that $R < r_{ms}$, at least for some accreting neutron stars. For nonrotating stars $r_{ms} = 6M(G/c^2)$. Many nonrotating models satisfy $R < 6M(G/c^2)$: all models from the Arnett & Bowers (1977) collection (based on a wide range of equations of state [EOSs]) satisfy this inequality for stellar masses close to the maximum values allowed, while for models based on soft EOSs the inequality holds also for masses close to the value 1.4 $M_\odot$ (Kluźniak & Wagoner 1985). Some models of rapidly rotating neutron stars also exhibit the property that $R < r_{ms}$. Friedman, Ipser, & Parker (1986) explicitly discuss the stability of orbits for neutron stars spinning at the maximum theoretically possible rotation rate, $\Omega = \Omega_K$, at which equatorial mass shedding occurs. They find that $R < r_{ms}$ at $\Omega = \Omega_K$ for all stars with $\beta < 0.40$, where β is the injection energy related to the polar redshift z_p through $\beta = (z_p + 1)^{-2}$. Note that all the maximum-mass models listed in their Table 2 do in fact satisfy $\beta < 0.40$. In that table, β ranges from 0.28 to 0.39, Ω from 0.76×10^4 to 1.54×10^4 s^{-1}, angular momentum j from 0.47 to 0.68, and the equatorial velocity v_{eq} from 0.43 to 0.53 times the speed of light. Friedman et al. also find that for the softest equations of state $R < r_{ms}$ holds at $\Omega = \Omega_K$ even for reasonably small masses $M < 2$ $M_\odot$. In general, for a star with a fixed baryon mass, the quantity $r_{ms} - R$ increases with decreasing spin rate Ω of the star. From the existence of maximally rotating ($\Omega = \Omega_K$) models with $R < r_{ms}$ reported by Friedman et al., one can deduce that the same inequality will be satisfied by an even wider margin for corresponding models with lower Ω. The values of $r_{ms} - R$ correct through first order in stellar angular momentum have been computed for a few models based on various EOSs by Kluźniak & Wagoner (1985).

In summary, for the most massive neutron stars, rotating and nonrotating alike, apparently all the conventional equations of state predict $R < r_{ms}$. For moderate masses, $M < 2$ $M_\odot$, only the softer EOSs allow $R < r_{ms}$. Observational evidence that neutron stars are compact (R/M is small) has recently been summarized by Mészáros & Riffert (1987).

We therefore consider a neutron star separated from its accretion disk by a region, which we call "an accretion gap." In the gap the velocity field is independent (to first approximation) of the mass accretion rate, and the fluid follows free-fall trajectories which terminate at the stellar surface (or rather in the atmosphere). Note the contrast with the disk, where the radial velocity of the fluid is controlled by viscous torques and vanishes in the limit of zero viscosity or zero $\dot{M}$.

Azimuthal symmetry is assumed. For a given star the surface density of fluid at any fixed point in the gap depends only on $\dot{M}$. The radial velocity of the fluid in the gap between the disk and the star is large enough that the scattering optical depth in the poloidal direction is less than unity[3] for $\dot{M}$ typically less than $\sim 10^{-9}$ $M_\odot$ yr^{-1}. This means that much of the radiation generated near the stellar surface can escape the system without further interactions with the accreting fluid. The disk will be illuminated to some extent nonetheless, and this may influence its structure (in particular the value of r_s). However, we believe that specifying r_s, the fluid composition, and the mass accretion rate $\dot{M}$ (and the rate per unit area), as well as the metric (or, equivalently, stellar parameters such as the radius R, the mass M, the dimensionless angular momentum j, etc.), allows one to construct a unique steady solution for the structure of the equatorial boundary layer. In this sense, the boundary layer (which we also call the equatorial accretion belt or the atmosphere) is decoupled from the disk.

For $\dot{M}$ higher than $\dot{M} \sim 10^{-9}$ $M_\odot$ yr^{-1} the spectrum emergent from the atmosphere will be reprocessed, mainly through scattering in the gap. The same will be true, at any accretion rate, of photons emitted at large inclination angles to the axis of symmetry (i.e., nearly radially). The spectrum presented below is therefore not the spectrum which would actually be observed for high inclination angles or at a high accretion rate. Nevertheless, even then the results presented here are not without interest; indeed, to compute the spectrum of photons reprocessed in the optically thick accretion stream one needs to know the input spectrum of X-ray photons entering the base of the accretion column (the term "accretion wall" would be more appropriate in this axially symmetric geometry of equatorial accretion). For extremely high ($> 10^{-8}$ $M_\odot$ yr^{-1}) accretion rates, our basic assumptions may fail because of the influence of radiation on the accretion flow.

3. CALCULATION AND RESULTS

To simulate conditions in the equatorial belt of a neutron star accreting through the "gap" between the marginally stable orbit and the stellar surface, we let a stream of plasma of given initial velocity (u^ϕ, u^r) and density traverse the stellar atmosphere. The system is evolved in time until a steady state is reached. The resulting solution yields the vertical structure of the atmosphere (as a function of height above the neutron star surface, $h = r - R$) as well as the emergent (local) spectrum of radiation. The numerical calculations are performed in one spatial dimension, i.e., in plane-parallel geometry. The atmosphere is not static; it rotates differentially within the stellar equator in response to the deposition of momentum by the incoming stream. As the inner boundary conditions at the

[3] This is seen from the equation for surface density, $\Sigma = -\dot{M}/(2\pi r u^r)$. The expression for radial velocity can be found, for example, in Kluźniak & Wagoner (1985) or Czerny et al. (1986). Note that Czerny et al. made an arithmetic error in the discussion following their eq. (2): they state that for $\dot{M} = 10^{-10}$ $M_\odot$ yr^{-1} and for $r = 2.4r_g$ the surface density is 20 g cm^{-2}, whereas in reality it is slightly less than 1 g cm^{-2}. Thus their claim of high optical thickness is greatly exaggerated in this situation.

stellar surface, $r = R$, we impose zero fluid velocity in the frame of the star and zero radiative flux.

The actual parameters used were chosen to be approximately representative of a neutron star with $R < r_{ms}$ (actually, $R = 0.87 r_{ms}$) and rotating with a period $P \sim 1$ ms ($cJ/GM^2 \equiv j = 0.5$). As discussed above in § 2, these values are not untypical of some rotating models. However, the results presented do not rely in their qualitative features on the high rotation rate assumed. The velocity of matter freely falling from a Keplerian orbit at r_{ms} has been computed (as a function of radius) through first order in j by Kluźniak & Wagoner (1985); this velocity has to be boosted to the rest frame of the stellar surface. The input parameters for the numerical computation were: the infall velocity at the top of the atmosphere, $u^{\hat{r}} = -7.0 \times 10^8$ cm s^{-1} (vertical component) and $u^{\hat{\Phi}} = 1.3 \times 10^{10}$ cm s^{-1} (horizontal component), and the acceleration of gravity, $g = 1.6 \times 10^{14}$ cm s^{-2}. The density of the infalling plasma was adjusted to yield luminosity per unit area $L/4\pi R^2 \equiv \int F(E)dE = 1.7 \times 10^{24}$ ergs s^{-1} cm^{-2}. The total luminosity will depend on the width of the accretion stream or, equivalently, on the total mass accretion rate. Note that for the value of u^r chosen, the incoming beam is optically thin (to electron scattering) in the poloidal direction for $\dot{M} < 2 \times 10^{-10}\ M_\odot$ yr^{-1}. As discussed in § 2, the spectrum obtained will be locally valid also for somewhat higher accretion rates, but in that case the spectrum of photons actually emerging after their passage through the incoming beam will be modified by scattering in that relatively cool fluid.

We stress that the following computation has been performed in the rest frame of the star, and, therefore, the single computation presented here can represent to some extent a wide variety of situations. Performing the calculation for a variety of parameters, we found that the results are most sensitive to the infall angle of the incoming beam. The same ratio of $u^{\hat{\Phi}}/u^{\hat{r}}$ as for the rotating model actually used would also obtain for a nonrotating ($\Omega = 0$) star with $R = 0.82 r_{ms}$, and even though $u^{\hat{\Phi}}$ for such a star would differ by some 30% from the value given above, the qualitative features of the solution presented below will doubtless hold also for a nonrotating star with $R \approx 0.8 r_{ms}$.

The infalling particles deposit their energy and momentum in the atmosphere through Coulomb collisions. The relevant formulae can be found in Alme & Wilson (1973). We closely follow their method of solution. The main new feature in our calculation is that matter has two components of velocity; most of the motion occurs in the azimuthal direction. The fluid atmosphere is coupled to radiation and evolves in time according to the equations of viscous hydrodynamics which control the redistribution of momentum. The coefficient of viscosity is rescaled to mock up turbulent viscosity: $\eta_r = \eta(1 + \mathscr{R}/\mathscr{R}_c)$, where η is given by Spitzer 1962, $\mathscr{R}$ is the Reynolds number, and $\mathscr{R}_c = 10^3$. The actual method of solution is to determine the profile of energy and momentum deposition and then to use the radiative transfer code, in Lund's one-dimensional version (Lund 1985), to solve for the vertical structure (profiles of azimuthal velocity, pressure, density ρ, and temperature T of the atmosphere; radiative flux F, etc.). This method of radiative transfer calculation uses multienergy representation of the spectrum in the diffusion approximation. The Fokker-Planck approximation is used to represent energy exchange in Compton scattering. The solution is then iterated in time until a steady state is reached. This method of solution is very similar to the one used by Alme & Wilson (1973). Neither

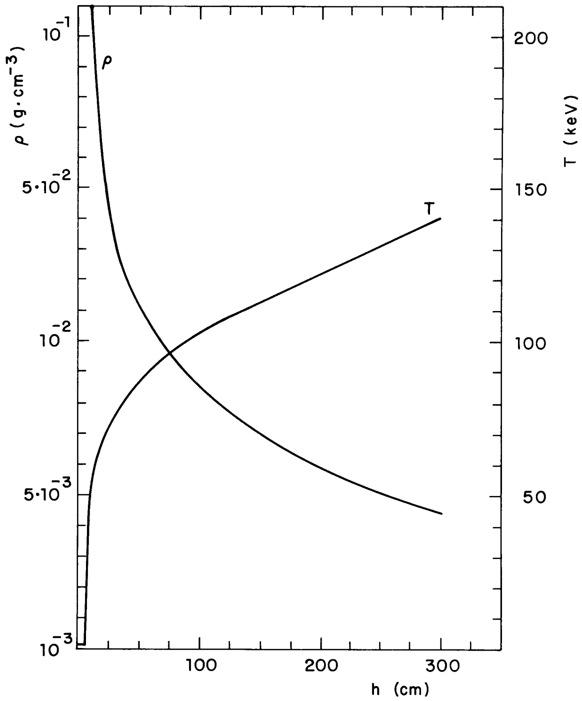

FIG. 1.—Vertical structure of a neutron star equatorial accretion belt. Density and temperature of the differentially rotating atmosphere are shown as a function of height above the neutron star surface. Note the sharp temperature inversion. Incoming plasma (not shown) penetrates the optically thin outer layers of the atmosphere at a shallow angle, heating these layers to $T \sim 100$ keV.

horizontal transfer of momentum by radiation nor pair creation was included.

The resulting structure of the atmosphere is plotted in Figure 1 as a function of vertical height above the surface, h. Note that the bottom layers of the atmosphere are dense and relatively cool: $T \approx 1$ keV. The precipitous drop in density to $\rho \sim 10^{-2}$ g cm^{-3} and the jump in temperature to $T \sim 10^2$ keV occurs roughly at optical depth unity, i.e., the hot, tenuous upper layers of the atmosphere are optically thin. The upper atmosphere rotates about the equator with a speed of $\sim 2 \times 10^8$ cm s^{-1} in the frame of the star.

The emergent angle-averaged local spectrum is given in Figure 2. The plot shows the energy intensity carried away by photons at the top of the atmosphere. Comparison with the results of Alme & Wilson (1973), where the accretion was assumed to be spherical, reveals that in our case the spectrum is much harder. Clearly, this is the result of the rather shallow angle of incidence of the infalling matter. In Figure 2 note the power law of energy index $\alpha = -1.2$ extending nearly up to 200 keV. This hard component of the X-ray spectrum can be understood in terms of unsaturated Comptonization of soft photon input, where the relation between the spectral index and the Compton y-parameter is $\alpha = 3/2 - (9/4 + 4/y)^{1/2}$ (e.g., Rybicki & Lightman 1979). The obtained index $\alpha = -1.2$ implies $y = 0.8$, yielding, at optical depth $\tau \approx 1$, a characteristic temperature of $T \approx 100$ keV, in good agreement with the profile of Figure 1.

For completeness, we also exhibit (in Fig. 3) the radial variation of the velocity of the infalling beam as it penetrates the atmosphere. The net radial radiative energy flux is also shown in units of the flux value reached at the outer boundary

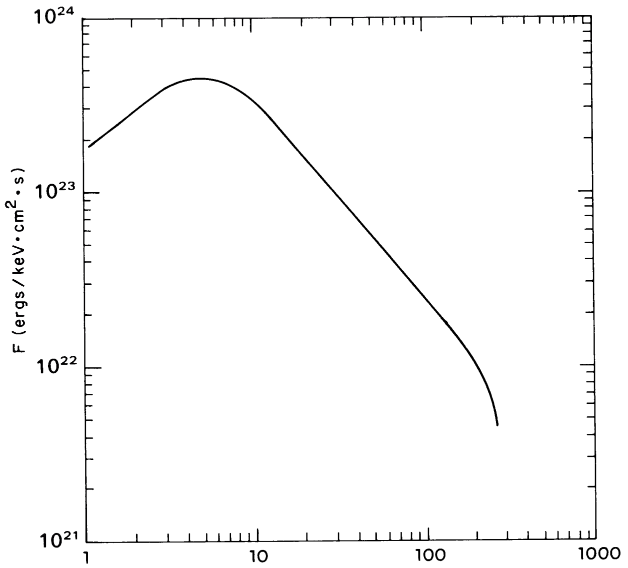

FIG. 2.—Spectrum of radiation emergent from the top of the atmosphere of Fig. 1. The plot shows the angle-integrated energy flux of photons crossing a horizontal plane at a height of $h = 299$ cm above the neutron star surface. The normalization is $\int F(E)dE = 1.7 \times 10^{24}$ ergs cm^{-2} s^{-1}, corresponding to about one-fifth of Eddington flux. This spectrum and the atmospheric structure of Fig. 1 were computed self-consistently.

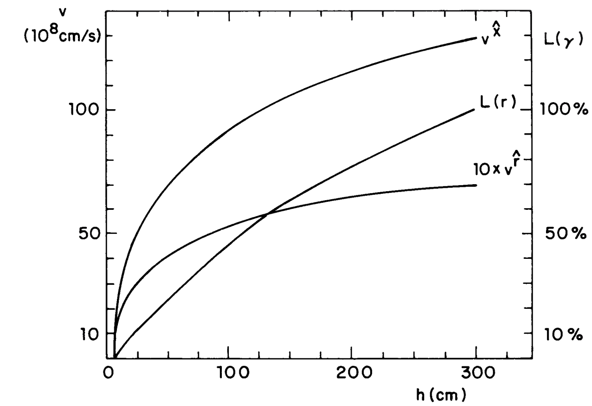

FIG. 3.—Velocity of the incoming beam and the outgoing total radiative flux as functions of height above the neutron star surface. The flux (scale at right) is shown as a fraction of the flux at the outer boundary, which is placed at the height $h \equiv r - R = 299$ cm. The scale for the velocity curves is shown at the left; the horizontal component (parallel to the equator) of the velocity, $v^{\hat{x}}$, and 10 times the magnitude of the vertical component, $10 \times |v^{\hat{r}}|$, are plotted. See text for discussion.

($h \approx 3 \times 10^2$ cm). At the outer boundary the velocity ($v^{\hat{x}}$, $v^{\hat{r}}$) of the beam attains the input values ($u^{\hat{\phi}}$, $u^{\hat{r}}$) given in the text at the beginning of this section. The nearly linear increase of $L(r)$ in Figure 3 and that of T in Figure 2 near the outer boundary are numerical artifacts. Another calculation showed flat velocity and temperature profiles at heights between 3 and 7 m.

Up to this point the latitudinal (poloidal) structure of the boundary layer was ignored. Hydrostatic equilibrium implies that the latitudinal length scale of the atmosphere obtained is on the order of 100 m. The actual width of the accretion belt depends, naturally on the cross-sectional area of the fluid accreting through the "gap" between the disk and the star. This is unknown at present.

Radiation from the neutron star will have appreciable effects on the inside of the accretion disk. Surface L is about one-fifth of Eddington, so that the radial force on the disk will be some fraction of $g/5$. Also, heating of the inside of the disk will cause matter to fall in. The system is probably unstable. We expect our results to be some sort of time-averaged solution. The radiation will be reprocessed to a certain extent in the accretion flow. Emission from the accretion disk itself will also contribute to the spectrum actually observed. If the results are interpreted within the context of the rapidly rotating neutron star model (see text above), the spectrum observed at infinity cannot be obtained from the local one reported here by a simple redshift; information on the angular distribution of emission is needed to perform the necessary integration.

The general conclusion of our paper is not affected by neutron star rotation. The hot spectrum is due to the low angle of accretion. We have performed other calculations with different parameters (rotation rates, composition, zoning). The qualitative features of all results were similar. It is clear that the main result, i.e., the presence of hard ($\sim 10^2$ keV) emission in accretion onto stars of radius smaller than that of the marginally stable orbit, will persist for a range of system parameters.

Our model predicts that the hard spectrum becomes less prominent as the mass accretion rate (and hence the luminosity) increases. For highest accretion rates the gap between the disk and the stellar surface becomes optically thick to scattering, the hard spectrum becomes thermalized, and the effective inner radius of the disk shrinks to the radius of the neutron star.

The computation was part of a larger project of looking for X-ray signatures of neutron stars which have undergone a non-axisymmetric deformation through the Chandrasekhar-Friedman-Schütz instability (Wagoner 1984). The authors thank Bob Wagoner for suggesting their collaboration and for numerous conversations and suggestions. W. K. thanks him also for encouragement, and thanks Fred Lamb for helpful conversations on accretion. This work was prepared under contract DOE W-7405-ENG-48. W. K.'s research supported in part by NSF grants PHY-86-03273 and AST-86-02831.

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