THE ASTROPHYSICAL JOURNAL, 204:L115–L118, 1976 March 15

AN OPAQUE SHELL AROUND HERCULES X-1?

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Received 1975 September 25; revised 1975 December 10

ABSTRACT

We suggest that the observations of intense soft X-rays from Her X-1 imply the existence of a centrifugally supported gas shell of radius $\sim 2\text{–}7 \times 10^8$ cm partially surrounding the neutron star that absorbs a substantial fraction of the hard X-ray luminosity and reradiates it as soft X-rays.

Subject headings: X-rays: sources — stars: neutron

I. INTRODUCTION

The possible existence of a strong soft X-ray source associated with Her X-1 was suggested some time ago by Avni *et al.* (1973) and Pringle (1973). Recently, copious soft X-ray emission from Her X-1 in the energy range 0.1–1.0 keV has been observed by Shulman *et al.* (1975) and confirmed by Catura and Acton (1975). A blackbody fit to the observations of Shulman *et al.* at 0.23 keV has a temperature $T_s = 5.5 \times 10^5$ K and a total luminosity $L_s \approx 3.1 \times 10^{37}$ ergs s^{-1}, assuming a distance of 6 kpc to Her X-1 (cf. Bahcall 1973). This luminosity is comparable to that of the X-radiation observed in the energy range 1.0–60 keV, the spectrum of which can be fitted (above 7 keV) by a blackbody with a temperature $T_h = 6.2 \times 10^7$ K and a total luminosity $L_h \approx 2.7 \times 10^{37}$ ergs s^{-1} (Ulmer *et al.* 1973). In Table 1 we list the values of these parameters inferred from the observations.

The striking fact that the luminosity in soft X-rays is comparable to that in hard X-rays poses the following problem. Her X-1 is believed to be a rotating neutron star that is accreting matter from its binary companion (cf. Lamb 1975). The minimum size of the soft X-ray source can be estimated from the blackbody limit, as pointed out by McClintock *et al* (1974). The soft X-ray source cannot be the surface of the neutron star since, in order to radiate the observed luminosity L_s, the surface temperature would have to be greater than $\sim 6 \times 10^6$ K and the spectrum would then peak above 1.5 keV, contrary to observation. In fact, the minimum radius that a spherical surface must have to radiate the luminosity L_s at 5.5×10^5 K is $R_s = 7 \times 10^8$ cm. The energy source for this soft radiation cannot be gravitational infall to such a radius, because once accreting matter falls this deep into the neutron-star gravitational potential and releases so much energy, it must eventually fall the rest of the way to the stellar surface, releasing ~ 100 times the energy in harder X-rays—contrary to observation.

In this *Letter* we suggest that the observed soft X-rays are the result of an opaque shell of gas at a radius $\sim 10^8$ cm, that subtends a solid angle Ω_s which is a substantial fraction of 4π steradians and is located where centrifugal force and the magnetic field of the neutron star impede the gravitational infall of the gas (cf. Lamb 1975). The shell absorbs harder X-rays emanating from the neutron star surface and reradiates the absorbed luminosity as soft X-rays. If this hypothesis is correct, then future observations of the soft X-ray pulse shape, spectrum, and polarization may be invaluable in improving our understanding of the interaction of stellar magnetic fields with accreting matter, the resulting flow pattern, and the way matter enters the magnetosphere of a pulsating X-ray source.

TABLE 1

PROPERTIES OF HERCULES X-1 X-RAY EMISSION INFERRED FROM OBSERVATION

D (kpc)	6
L_s (10^{37} ergs s^{-1})	3.1
T_s (10^6 K)	0.55
R_s (10^8 cm)	7.0
L_h (10^{37} ergs s^{-1})	2.7
T_h (10^6 K)	62
$L = L_h + L_s$ (10^{37} ergs s^{-1})	5.8

II. AN OPAQUE SHELL

We have noted that if the soft X-ray source has a temperature $T \sim 5 \times 10^5$ K, the minimum radius it can have is $R \sim 7 \times 10^8$ cm. The soft source can have a somewhat smaller radius, $R \sim 1.3 \times 10^8$ cm, if its temperature is $T \sim 1.5 \times 10^6$ K and it is becoming transparent at X-ray energies greater than ~ 0.23 keV. These radii are comparable to earlier estimates by Pringle and Rees (1972), Davidson and Ostriker (1973),

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and Lamb, Pethick, and Pines (1973) of the so-called Alfvén radius, R_A, for a neutron-star X-ray source with a magnetic dipole moment $\mu \sim 10^{30}$–10^{32} gauss cm^3 (R_A is the characteristic radius of the magnetosphere). Therefore, let us consider the possibility that the soft X-ray source is an opaque shell of flowing gas at the Alfvén surface, where the neutron-star magnetic field first enforces corotation of the accreting matter.

How gas flows from a circumstellar accretion disk into the magnetosphere of a rapidly rotating neutron star and eventually to the neutron star surface is a complex and as yet unsolved problem. It has been suggested (Elsner and Lamb 1975; Arons and Lea 1975) that the gas enters the magnetosphere by means of hydromagnetic instabilities combined with turbulent diffusion onto magnetic field lines; presumably it then flows along these field lines towards the magnetic poles.

Our philosophy here is to consider a highly idealized model of an opaque shell in order to make simple dimensional estimates of its properties, and then to compare these properties with observations, bearing in mind the modifications which are likely to follow from more realistic assumptions. In particular, we neglect for the moment the dynamical effects of rotation. We shall return to a discussion of the probable importance of rotation in § III. Assume then that accreting matter is flowing inward with radial component of velocity $v_r \leq (2GM/r)^{1/2}$ toward a neutron star of mass M until it is deflected by the stellar magnetic field; there it enters a thin, hydrostatically supported shell. This occurs at the radius R_A where the magnetic pressure, $B^2/8\pi$ of the stellar dipole field $B \approx \mu/r^3$ balances the ram pressure of the infalling gas, ρv_r^2, plus the weight per unit area of a gas shell of surface density $\sigma_s = M_s/\Omega_s R_A^2$, where M_s is the mass of the shell and Ω_s is its solid angle. The radius R_A of the shell is then given by

$$\frac{1}{8\pi}\left(\frac{\mu}{R_A^3}\right)^2 = \rho v_r^2(R_A) + \frac{GM\sigma_s}{R_A^2} . \qquad (1)$$

We assume that the total luminosity of the X-ray source, $L = L_h + L_s$, is given by $L = GM\dot{M}/R_n$, where R_n is the neutron star radius and $\dot{M}$ is the mass accretion rate. This rate is related to the shell mass by a characteristic time t_d for matter in the shell to drop to the surface of the neutron star, $\dot{M} = M_s/t_d$, so that

$$M_s = t_d R_n L/GM . \qquad (2)$$

We construct models for the shell subject to the constraints that it must absorb hard X-rays and reradiate them with the observed soft X-ray luminosity and color temperature $T_s \approx 5.5 \times 10^5$ K. These constraints are sufficient to define a narrow range of acceptable shell parameters R_A, t_d, and shell temperature T. In Table 2 we list the properties of two models which roughly bracket the allowed range. For each model we have taken $L = 5.8 \times 10^{37}$ ergs s^{-1} and have assumed $M = 1.33\ M_\odot$, $\Omega_s = 2\pi$, and $R_n = 15$ km (cf. Pandharipande, Pines, and Smith 1975). Model 1 is sufficiently opaque to radiate as a blackbody, so $T = T_s$, and it has the largest acceptable radius, $R_A = 7 \times 10^8$ cm. Model 2 has a somewhat greater shell temperature and is partially transparent to soft X-rays. It has the smallest acceptable radius, $R_A = 1.3 \times 10^8$ cm.

Can gas in such a shell have an effective temperature as low as this? At low densities the electrons in the inflowing gas will be brought to a temperature $T_e \lesssim 10^7$ K by Compton interactions with the X-ray flux from the star and the shell. This will occur on a time scale (Buff and McCray 1974) $t_C \approx 10^{-2}\ (R_A/10^8\ \text{cm})^2\ (L_s/10^{37}\ \text{ergs s}^{-1})^{-1}$ s, which is comparable to the free-fall time scale $t_{ff} = (R_A^3/2GM)^{1/2} \approx 0.06\ (R_A/10^8\ \text{cm})^{3/2}\ (M/M_\odot)^{-1/2}$ s. At $T_e \lesssim 5 \times 10^7$ K the time scale for the electron and ion temperatures to equilibrate is shorter yet. As gas enters the shell, it will become more dense, and radiative cooling mechanisms in addition to Compton scattering will become important. On the inside of the shell the gas pressure is roughly comparable to the pressure of the stellar dipole field. Thus the quantity P/F, where F is the X-ray flux from the star, will be $\gtrsim 10^{-11}$ cgs. Therefore, according to Figure 1, curve b, of McCray and Hatchett (1975), the gas will continue to cool until it reaches an equilibrium temperature at which it can reradiate thermally the radiation it absorbs from the neutron star surface.

Now suppose that the shell is an isothermal atmosphere resting on top of the magnetosphere. Then we can estimate its scale height $\delta \approx kTR_A^2/(GMm_H)$ and find the energy dependence of its X-ray opacity. Note that in both models the Compton optical depth is in

TABLE 2

Opaque Shell Models of the Soft X-Ray Source in Hercules X-1

Shell Parameter	Model 1	Model 2
Radius R_A (10^8 cm)	7	1.3
Temperature T (10^6 K)	0.55	1.5
Drop time t_d (s)	86	0.76
Magnetic moment μ (10^{30} gauss cm^3)	120	2.1
Compton opacity τ_C	4.7	1.1
Scale height δ (10^4 cm)	20	2.0
Oxygen photoelectric opacity $\tau_0(\epsilon)$	$350\ \epsilon_{keV}^{-3}$	$1.6\ \epsilon_{keV}^{-3}$
Soft X-ray opacity $\tau_s(\epsilon)$	$8.5\times10^{-3}\ \epsilon_{keV}^{-3}$	$3.6\times10^{-3}\ \epsilon_{keV}^{-3}$
Effective opacity $\tau_{eff}(\epsilon)$	$0.35\ \epsilon_{keV}^{-3/2}$	$0.11\ \epsilon_{keV}^{-3/2}$
Free-fall time t_{ff} (s)	1	0.08
Sonic time t_s (s)	82	9.4

the range $1 < \tau_C < 10$, so that X-rays will be scattered by the shell but not much degraded in energy by Comptonization. However, we find from the Saha equation, which is applicable at the gas densities under consideration, that elements with $Z \geq 8$ have one or more K-shell electrons, and that the shell has significant photoelectric opacity $\tau_0(\epsilon)$ (mainly due to oxygen) above about 0.6 keV. For example, in model 1 the shell is opaque from 0.6 to 5 keV.

At X-ray energies $\epsilon < 0.6$ keV the dominant opacity mechanisms are bremsstrahlung and photoabsorption by He II, each of which depends on X-ray energy roughly as ϵ^{-3}. Their combined opacity $\tau_s(\epsilon)$ is given in Table 2, as well as the "effective opacity" $\tau_{\text{eff}} \approx (3\tau_s\tau_c)^{1/2}$, which determines whether a surface is opaque at soft X-ray energies (cf. Felten and Rees 1972). Model 2 has $\tau_{\text{eff}}(\epsilon) \approx 1$ at 0.23 keV, the shell becoming translucent above this energy. Therefore, the model is viable even though the shell gas temperature $T = 1.5 \times 10^6$ K, because the X-ray continuum from the shell at about 0.23 keV may be decreasing more rapidly than a blackbody with the same temperature.

III. DISCUSSION

These idealized models for an opaque shell around Her X-1 are not meant to be taken literally, because we have not attempted to construct a dynamical model for the interface between the infalling gas and the magnetosphere. Rather, the models are meant to illustrate that a gas shell with interesting spectral characteristics is likely to occur at a radius ~ 2–7×10^8 cm from the neutron star if the magnetic field delays the infall of the gas at this radius, and that such a shell is indicated by the soft X-ray observations.

It is of interest to compare the drop time t_d to two characteristic time scales that one may estimate for the shell on dimensional grounds. These times, the free-fall time t_{ff}, and the sonic time $t_s = R_A/c_s$ for gas to flow a distance R_A at the sound speed c_s corresponding to the shell temperature, are also listed in Table 2. In model 1, $t_d \approx t_s \approx 80 t_{\text{ff}}$. In model 2, on the other hand, $t_s \approx 12 t_d$ and $t_d \approx 9 t_{\text{ff}}$, so the mean flow velocity in the shell is mildly supersonic.

In reality, centrifugal force is likely to play an important role in determining the properties of the shell. Flowing gas entrained in the stellar magnetic field can probably form a dense shell only in the vicinity of the centrifugal radius, $R_c = (GM/\Omega^2)^{1/3}$, where centrifugal and gravitational forces will just balance if gas is corotating with the neutron star (Pringle and Rees 1972; Davidson and Ostriker 1973; Lamb, Pethick, and Pines 1973). The irregularity of the observed spin-up rate of Her X-1 (Giacconi 1975) lends further support to the hypothesis that $R_A \approx R_c$ (Lamb, Pines, and Shaham 1976). In Her X-1, $\Omega = 2\pi/1.24$ s and $R_c \approx 1.9 \times 10^8$ cm. Thus the actual shell radius probably lies between the shell radii of models 1 and 2, which we recall were chosen to fit the observed values of the quantities L_s and T_s, and roughly bracket the allowed range. These arguments therefore suggest that the shell is not completely opaque to soft X-rays, since R_c is significantly smaller than the smallest radius, 7×10^8 cm, which the observations permit for a completely opaque shell.

The observed absence of soft X-rays during that part of the 35$^{\text{d}}$ cycle when the hard X-rays are off (Fabian, Pringle, and Rees 1973; McClintock *et al.* 1974; Shulman *et al.* 1975) is not inconsistent with the present model if the hard X-ray OFF periods are caused by obscuration of our line of sight to the neutron star by accreting matter (Katz 1973; Roberts 1974; Gerend and Boynton 1975; Petterson 1975). The same matter could easily obscure the shell source of soft X-rays.

We cannot resist making a few speculations about the likely geometry of the shell that can be tested by future observations. It seems reasonable that the shell would be thickest at the magnetic equator, becoming thinner at higher magnetic latitudes as the gas accelerates along magnetic field lines toward the magnetic poles. (We assume that the shell corotates with the star.) Therefore, we might envisage the shell as a wide opaque ring at the magnetic equator which becomes transparent at high latitudes, finally becoming opaque again at the magnetic poles where the flow converges. A possible geometry is illustrated schematically in Figure 1.

In this example the line of sight to the observer

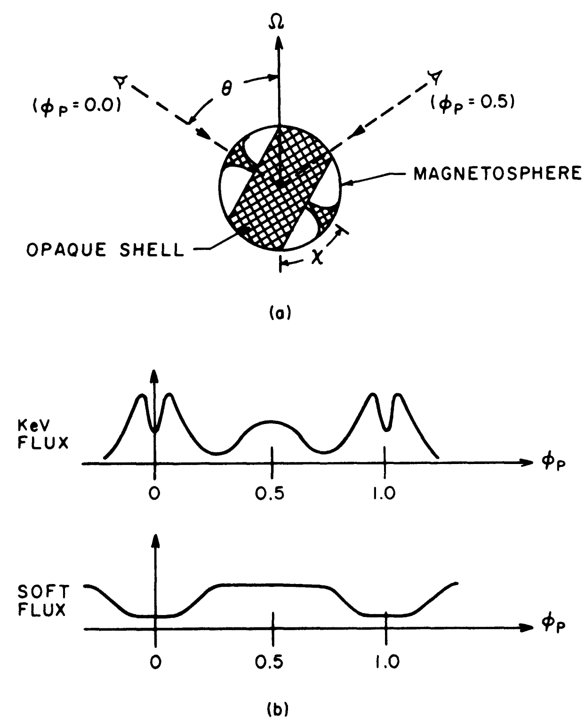

FIG. 1.—(*a*) A possible geometry for the opaque shell partially surrounding Her X-1. Here χ is the angle between the rotation axis and the magnetic dipole axis, and θ is the angle between the rotation axis and the sightline to the source, which passes closest to the magnetic poles at pulse phases $\phi_p = 0.0$ and 0.5. The gas shell, here assumed to lie around the magnetic equator, and the increased density of gas above the magnetic poles, are indicated schematically by cross-hatching. (*b*) The qualitative character of the keV and soft X-ray pulse wave forms which would be produced by this geometry.

makes an angle $\theta \sim 60°$ with the rotation axis of the neutron star, approximately the same as the angle χ between the dipole axis and the rotation axis, as indicated in Figure 1*a*. The soft X-ray pulse waveform has a broad maximum at pulse phase $\phi_p \sim 0.5$, and a sharper minimum at $\phi_p \sim 0$. On the other hand, the hard X-rays coming from the stellar surface would have maxima at $\phi_p \sim 0$ and 0.5, when the line of sight passes closest to the magnetic poles; in addition the hard X-ray peak near $\phi_p \sim 0$ might be to some extent double-peaked (Lamb, Pethick, and Pines 1973). The hard and soft X-ray pulse waveforms are indicated schematically in Figure 1*b*. Such waveforms agree qualitatively with those observed in Her X-1 (Giacconi *et al.* 1973; Doxsey *et al.* 1973; Holt *et al.* 1974; Joss and Fechner 1975; Shulman *et al.* 1975), although the soft X-ray data are not yet of high enough quality to provide a good test. This example suggests that one may want to consider the possibility that the observed beaming of the hard X-rays is primarily due to collimation by the shell, rather than due to anisotropic emission at the neutron-star surface. If the gas shell does play such a role, the geometry in Figure 1 further suggests that the observed variability of the hard X-ray interpulse (peak near $\phi_p \sim 0.5$) may be related to changes in the thickness of the gas shell.

We have also noticed that the optical luminosity of such a shell is roughly sufficient to account for the optical pulsations that are observed occasionally to come from the vicinity of the neutron star (Middleditch and Nelson 1973; Groth 1974).

In conclusion, if our conjecture that the soft X-ray source in Her X-1 is an opaque shell of gas surrounding the neutron star magnetosphere proves correct, future observations of the soft X-ray spectrum, pulse waveform, and polarization should prove invaluable in understanding the flow of matter in the vicinity of the neutron star. In particular, simultaneous observations of the soft and hard X-ray waveforms might reveal the extent to which the hard X-rays from the stellar surface interact with the soft X-ray source, while hard and soft X-ray polarization measurements might pin down the orientation of the stellar magnetic field with respect to the gas shell (Rees 1975).

This work was begun in June 1975 at a workshop on Compact X-Ray Sources at the Aspen Center for Physics. We have had the benefit of many stimulating discussions, particularly with J. Arons, S. Hatchett, F. Kahn, D. Q. Lamb, C. J. Pethick, and D. Pines. Support by NASA grant NSG-7128 at Colorado and by NSF grants GP 41560 and MPS75-08790 at Illinois is gratefully acknowledged.

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Note added in proof.—The possibility that obscuring matter at the Alfvén surface might be responsible for soft X-ray emission has also been mentioned by M. M. Basko and R. A. Sunyaev (1976, *M.N.R.A.S.*, in press).

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