1992ApJ...395..575U

THE ASTROPHYSICAL JOURNAL, 395:575–581, 1992 August 20

X-RAY EMISSION FROM SINGLE MAGNETIC EARLY-TYPE STARS

V. V. USOV
Physics Department, Weizmann Institute, Rehovot 76100, Israel

AND

D. B. MELROSE
Research Centre for Theoretical Astrophysics, School of Physics, University of Sydney, NSW 2006, Australia
Received 1991 December 9; accepted 1992 February 27

ABSTRACT

A new model for the X-ray emission from single early-type stars is presented. X-rays observed from these stars can be produced by the hot gas near the current sheet via the bremsstrahlung mechanism. Gas heating in the current sheet is considered and the X-ray luminosity of single magnetic early-type stars is estimated. Theoretical predictions of the model about the properties of X-rays are discussed.

Subject headings: radiation mechanisms: bremsstrahlung — stars: early-type — stars: magnetic fields — X-rays: stars

1. INTRODUCTION

Early-type stars, specifically OB and Wolf-Rayet (W-R) stars, are strong sources of X-ray emission (Seward et al. 1979; Moffat et al. 1982; Pollock 1987; Chlebowski 1989), and the X-ray luminosity of early-type stars is dependent on whether they belong to a binary system or not. Massive binaries of early-type stars are on average much brighter in X-rays than single stars (Pollock 1987; Chlebowski 1989). It is likely that the additional X-ray component of massive binaries results from stellar wind collision in these systems (Prilutskii & Usov 1975, 1976; Cooke, Fabian, & Pringle 1978; Moffatt et al. 1982; Pollock 1987; Chlebowski 1989; Galeev, Pilyugin, & Usov 1989; Williams et al. 1990; Usov 1992). The X-ray emission of such bright binaries as HD 93163 and HD 193793 is enhanced more than a few factors of 10 over the typical X-ray emission of the same single stars by bremsstrahlung radiation of the gas heated in the region where the stellar winds collide.

It has been suggested that the observed X-ray emission of single OB stars is due to the formation of a large number of quasi-periodic strong shocks in the outflowing gas (Lucy & White 1980; Lucy 1982a, b). These shocks are formed because of the development of instabilities in the radiation-driven stellar winds (Lucy & Solomon 1970; Mestel, Moore, & Perry 1976; MacGregor, Hartmann, & Raymond 1979; Carlberg 1980; Owocki & Rybicki 1984). In the model of Lucy & White (1980), X-ray emission of single early-type stars is generated in the stellar wind inside a few stellar radii due to heating of the outflowing gas to temperatures of about a few million kelvin by strong shocks. However, there are several possible points of conflict between the observational data on X-ray emission of early-type stars and the predictions of the model developed by Lucy & White (1980) and Lucy (1982a, b). Simulations of the formation of shocks in the radiation-driven wind (Owocki & Rybicki 1984; Owocki et al. 1988) show that the number of shocks and their Mach numbers differ substantially from those predicted in the simple model of Lucy (1982a, b), and this difference is unfavorable for X-ray generation. The most striking discrepancy is the observation of X-ray emission from W-R stars. Indeed, Pollock (1987) has estimated that unit optical depth sphere for X-ray emission of W-R stars is at ~ 100 stellar radius. At this distance from the star there are no shocks (Owocki & Rybicki 1984; Owocki, Castor, & Rybicki 1988) and hence there are practically no X-rays generated by the Lucy & White mechanism. It is desirable that alternative models for the X-ray emission of single early-type stars be formulated and explored.

In the model of Lucy & White (1980) for X-ray emission of early-type stars, the magnetic field of the stars is ignored. However, from the observations of nonthermal radio emission (Abbott et al. 1986; Bieging, Abbott, & Churchwell 1989) it follows that the early-type stars possess a magnetic field. The value of the surface magnetic field of the OB star, B_s, may be as high as a few hundred Gauss (Barker 1986). The values of B_s for the W-R stars may be more than an order higher than the highest values observed for the OB stars (Mullan 1983; Nerney & Suess 1987). Below we assume that the magnetic field of early-type stars is close to the highest values consistent with observations and consider an alternative mechanism for the generation of X-ray emission in the magnetospheres of early-type stars.

The paper is organized along the following line: § 2 discusses the structure of the magnetosphere of an early-type star and the current sheet formation. Section 3 considers the gas heating in the current sheet. Section 4 gives the expected parameters of X-ray emission from magnetic early-type stars. Section 5 formulates briefly the theoretical predictions about the properties of X-rays from magnetic early-type stars.

2. GAS OUTFLOW AND MAGNETIC FIELD GEOMETRY

The magnetosphere of an early-type star from whose surface there is a strong outflow may be divided into two regions (Mestel 1968; Mestel & Spruit 1987): (1) a wind zone in which gas flows outward drawing the magnetic field out into an open structure; and (2) a so-called dead zone in which gas is trapped and corotates with the star. The structure of the magnetosphere of an early-type

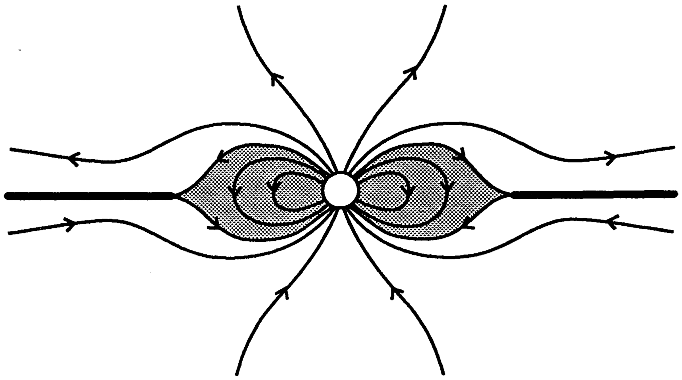

FIG. 1.—The model for a magnetized star with a wind. At large distances the wind drags the magnetic field lines toward the radial direction. A current sheet, indicated by the solid line, forms in the equatorial plane. In the "dead zone," shown shaded, the magnetic field lines are closed and confine the plasma.

star with a dipole magnetic field is shown schematically in Figure 1. In practice a dead zone is not completely quiescent. Active processes, such as particle acceleration and plasma ejection, may occur in this zone (Havnes & Goertz 1984). Here we restrict our consideration to physical processes in the wind zone.

The radius of the dead zone r_A (see Fig. 1) may be estimated by setting the ram pressure of the stellar wind ρv^2 equal to the characteristic value of the magnetic stress components $B^2/4\pi$. With ρ the gas density and v the flow speed, this gives

$$\rho v^2 = B^2/4\pi \,. \tag{1}$$

The flow speed is assumed to vary with radial distance r as (Castor & Lamers 1979; Lucy 1982a, b; Castor & Simon 1983)

$$v(r) = v_\infty(1 - R/r) \,, \tag{2}$$

where R is the radius of the star and v_∞ is the terminal speed of the wind. This velocity law is implied by the analysis of observational data and gives reasonable agreement between infrared, radio, Hα, and UV data (Castor & Simon 1983). The velocity law (2) is also near the velocity law $v(r) = v_\infty(1 - R/r)^{0.8}$ predicted in the theory of radiatively driven stellar winds in which the rotation and the finite disk correction factor are taken into account (Friend & Abbott 1986). Then, assumng that the magnetic field has a dipolar structure at $r \le r_A$ and that the density of the outflowing gas in the wind zone at $r \ge r_A$ is

$$\rho = \frac{\dot{M}}{4\pi r^2 v(r)} \,, \tag{3}$$

equations (1) and (2) imply

$$(1 - R/r_A) = \xi(R/r_A)^4 \,, \tag{4}$$

with

$$\xi = \frac{B_s^2 R^2}{\dot{M} v_\infty} \approx 2.9\left(\frac{B_s}{10^2\ \mathrm{G}}\right)^2 \left(\frac{R}{20R_\odot}\right)^2 \left(\frac{\dot{M}}{10^{-6}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{-1} \left(\frac{v_\infty}{10^8\ \mathrm{cm\ s}^{-1}}\right)^{-1} \,, \tag{5}$$

where $\dot{M}$ is the mass-loss rate for the star.

From equation (4) the value r_A is

$$r_A \approx R \times \begin{cases} (1 + \xi) & \text{for } \xi \ll 1 \,, \\ \xi^{1/4} & \text{for } \xi \gg 1 \,. \end{cases} \tag{6}$$

For example, in the case of O stars ($\dot{M} \approx 10^{-7}$–10^{-5} $M_\odot$ yr^{-1}, $v_\infty \approx (1$–$3) \times 10^8$ cm s^{-1}, $R \approx 20\ R_\odot$) with surface magnetic field $B_s \approx 200$ G, we have $\xi \approx 0.4$–10^2 and $(r_A - R)/R$ is in the range 0.4 to ≈ 2. At $r > r_A$ the geometry of the magnetic field becomes nearly radial ($B \approx B_r \approx r^{-2}$).

The typical values of surface rotation velocity for OB stars are $v_{\mathrm{rot}} \approx (0.1$–$0.2)v_\infty$ (Conti & Ebbets 1977; Hutchings 1981; Uesugi & Fukuda 1982). Approximate corotation within the Alfvén surface would give a rotational velocity $v_{\mathrm{rot}} r_A/R$ near r_A, and since this is smaller than v_∞ by a factor of a few or more, the rotation of the star does not change the estimate of r_A. However, the rotation is essential for the structure of the magnetic field: the toroidal magnetic field,

$$B_\phi \approx B_r \frac{v_{\mathrm{rot}}}{v_\infty} \frac{r}{R} \,, \tag{7}$$

1992ApJ...395..575U

is generated in the outflowing gas due to rotation (Weber & Davis 1967). The strength of the magnetic field is

$$B \approx B_s \times \begin{cases} \left(\dfrac{R}{r}\right)^3 & \text{for } R \le r < r_A \text{ (dipole)}, \\ \dfrac{R^3}{r_A r^2} & \text{for } r_A < r < R\,\dfrac{v_\infty}{v_{\text{rot}}} \text{ (radial)}, \\ \dfrac{v_{\text{rot}}}{v_\infty}\,\dfrac{R^2}{r_A r} & \text{for } R\,\dfrac{v_\infty}{v_{\text{rot}}} < r \text{ (toroidal)}. \end{cases} \tag{8}$$

In the wind zone at $r \gtrsim r_A$, a current sheet is formed in the outflowing gas; see Figure 1. This sheet separates regions with opposite direction of the magnetic field. The structure of the magnetic field is similar to that in the Earth's magnetotail (Ness 1965; Hones 1979; Akasofu 1980) and above solar active regions (Priest 1984). In both cases a high level of activity is observed in the region of the current sheets. In the Earth's magnetotail, for example, electrons with energy higher than 200 keV were detected in energetic electron streaming events observed on IMP-8 (Baker & Stone 1977). Such electrons are probably accelerated during magnetic reconnection in the current sheet of the Earth's magnetotail (Bieber & Stone 1980; Bieber 1984).

Both observations and theory indicate (Sweet 1969; Švestka 1976; Priest 1984) that the stored magnetic energy in the upper chromosphere and corona is the source of energy for solar flares. Plasma in the region of solar flares is heated up to a temperature of 10^7–10^8 K and generates X-ray emission (Švestka 1976). Reconnection is a favored mechanism for the release of magnetic energy in solar flares (e.g., Priest 1984). The density and strength of the magnetic field in the region of solar flares ($n \approx 10^{10}$–10^{11} cm^{-3} and $B \approx 10^2$ G) are comparable with the respective parameters near the current sheets in the early-type stars with strong magnetic fields. As a consequence, it is reasonable to expect strong heating of gas and generation of X-ray emission near the current sheet in the wind zone of magnetic early-type stars. Since the linear scales of the current sheet in these stars are more than 10^2–10^3 times larger than the linear scales of solar flares, activity on magnetic early-type stars due to such reconnection should be much stronger ($\sim 10^4$–10^6 times or more) than on the Sun.

3. GAS HEATING IN CURRENT SHEETS

Magnetic field reconnection in current sheets proceeds either as a quasi-steady process (Petschek 1964), or as an explosive process as suggested for solar flares (Sturrock 1968; Coppi & Friedland 1971; Syrovatskii 1981). In both cases the main fraction of the energy that is released is transferred both into the thermal energy through direct Joule heating of the plasma and into the kinetic energy of macroscopic motions (Petchek 1964; Sturrock 1968; Heyvaerts, Priest, & Rust 1977; Milroy 1984). The speed of these motions is of the order of the Alfvén speed. In the case of early-type stars with strong magnetic field the Alfvén speed is greater than the sound speed in the outflowing gas. Hence, the macroscopic motions generated near the current sheet are supersonic, like the shocks formed in the radiation-driven wind (see § 1). The kinetic energy of these supersonic motions is transferred into thermal energy in the shocks. Below we assume that the main fraction of the magnetic energy released in the current sheet during reconnection is thermalized.

The Petschek (1964) model for the power released in the current sheet gives

$$W \approx \frac{\pi}{4 \ln R_m} v_A l b \frac{B^2}{8\pi}, \tag{9}$$

where R_m is the magnetic Reynolds number, $v_A = B/(4\pi\rho)^{1/2}$ is the Alfvén speed, with ρ the mass density, and where l and b are, respectively, the length and the width of the current sheet. In the case of an early-type star with $B_s \approx 10$–10^2 G in the outflowing gas, one has $R_m \approx 10^7$–10^{12} at $r \sim r_A$ and the numerical coefficient in equation (9) is $\pi/4 \ln R_m \approx 0.04$.

Magnetic reconnection has been investigated both theoretically (analytically and numerically) and experimentally, e.g., the reviews by Syrovatskii (1981) and Milroy (1984), and it is found that the rate of reconnection is consistent with the simple Petschek model. Using Petschek's model, the total power released in reconnection in the wind zone of a magnetic early-type star is

$$P \approx 0.04 \int_{r_A}^{r_*} dr r 2\pi v_A \frac{B^2}{8\pi} = 10^{-2} \int_{r_A}^{r_*} dr r \frac{B^3}{(4\pi\rho)^{1/2}}, \tag{10}$$

where r_* is the radius of the external boundary of the outflowing gas, ρ and B are given by equations (3) and (8), respectively. In writing down equation (10) it is envisaged that the inward transport of magnetic flux due to the diffusion of field lines into the current sheet is balanced by the outward sweeping of magnetic flux due to the wind motion; near r_A the reconnection is probably episodic, with the wind drawing out the magnetic field lines between episodes of reconnection, with the two effects in balance on average.

The main contribution to the integral (10) is from the region $r \sim r_A$ where the magnetic field is almost radial. Taking this into account, from equations (2), (3), (8), and (10) one has

$$P \approx 10^{-2} \frac{B_s^3 R^6}{r_A^3} \left(\frac{v_\infty}{\dot{M}}\right)^{1/2} \phi\left(\frac{r_A}{R}\right), \tag{11}$$

1992ApJ...395..575U

with

$$\phi(z) = \int_z^{\infty} dx\, x^{-4}(1 - x^{-1})^{1/2} = \tfrac{16}{105} - \tfrac{2}{3}(1 - z^{-1})^{3/2} + \tfrac{4}{5}(1 - z^{-1})^{5/2} - \tfrac{2}{7}(1 - z^{-1})^{7/2} . \tag{12}$$

The value of $r_{\rm A}$ is given by equation (4). In the case of weak magnetic field ($\xi \ll 1$), equations (6), (11), and (12) imply $r_{\rm A} \approx R$ and

$$P \approx 10^{-2}\phi(1)B_s^3\, R^3\left(\frac{v_\infty}{\dot{M}}\right)^{1/2} \approx 5.1 \times 10^{33}\left(\frac{\dot{M}}{10^{-6}\ M_\odot\ {\rm yr}^{-1}}\right)^{-1/2}\left(\frac{v_\infty}{10^8\ {\rm cm\ s}^{-1}}\right)^{1/2}\left(\frac{B_s}{10^2\ {\rm G}}\right)^3\left(\frac{R}{20\ R_\odot}\right)^3 {\rm ergs\ s}^{-1} . \tag{13}$$

In the case of strong magnetic field ($\xi \gg 1$), the dimensionless function $\phi(z)$ may be approximated by

$$\phi(z) \approx 1/3z^3 . \tag{14}$$

Using equations (5), (6), (11), and (14), the total power released near the current sheet in the case of an early-type star with a strong magnetic field may be written in the form

$$P \approx 10^{-2}\, \frac{B_s^3\, R^9}{3r_{\rm A}^6}\left(\frac{v_\infty}{\dot{M}}\right)^{1/2} \approx \frac{10^{-2}}{3}\, \dot{M}v_\infty^2 \approx 2 \times 10^{33}\left(\frac{\dot{M}}{10^{-6}\ M_\odot\ {\rm yr}^{-1}}\right)\left(\frac{v_\infty}{10^8\ {\rm cm\ s}^{-1}}\right)^2 {\rm ergs\ s}^{-1} . \tag{15}$$

In this case, nearly 1% of the kinetic energy of the stellar wind can be transformed into heat in the current sheet.

The temperature of the hot gas near the current sheet is of the order of

$$T \approx \frac{P}{k\dot{N}} , \tag{16}$$

where P is the total power released in the current sheet and $\dot{N}$ is the rate per unit time that particles flow through the heating region at $r \approx r_{\rm A}$ and κ is Boltzmann's constant. The rate of flow is $\dot{N} = nSv(r_{\rm A})$, where the number density $n = \rho/m_p\mu$, where m_p is the proton mass and μ is the mean molecular weight of outflowing gas, is determined by equation (3), and where the area through which the heated gas flows is $S = 2\pi r_{\rm A}\, \Delta r(r_{\rm A})$, with the thickness of the current sheet $\Delta r(r) = [2v_D/v(r)]r$ determined by twice the product of the inflow speed, v_D, and the characteristic time $r/v(r)$ for the outward flow of gas, as required to give no net flow of magnetic flux. Thus we have

$$\dot{N} \approx \frac{\dot{M}}{4\pi r_{\rm A}^2\, v(r_{\rm A})m_p\,\mu}\, 2\pi r_{\rm A}\, \Delta r(r_{\rm A})v(r_{\rm A}) \approx 2 \times 10^{-2}\, \frac{\dot{M}}{m_p\,\mu} , \tag{17}$$

where equation (9) is used to write

$$\Delta r(r) \approx 0.04\, \frac{v_{\rm A}(r)}{v(r)}\, r . \tag{18}$$

From equations (13) and (15)–(17), for a completely ionized hydrogen plasma ($\mu = \frac{1}{2}$), one has

$$T \approx 0.7 \times 10^7\left(\frac{\dot{M}}{10^{-6}\ M_\odot\ {\rm yr}^{-1}}\right)^{3/2}\left(\frac{v_\infty}{10^8\ {\rm cm\ s}^{-1}}\right)^{1/2}\left(\frac{B_s}{10^2\ {\rm G}}\right)^3\left(\frac{R}{20\ R_\odot}\right)^3 {\rm K} , \tag{19}$$

for $\xi \ll 1$, and

$$T \approx \frac{\sqrt{2}}{3}\, \frac{m_p v_\infty^2}{\kappa} \approx 6 \times 10^7\left(\frac{v_\infty}{10^8\ {\rm cm\ s}^{-1}}\right)^2 {\rm K} , \tag{20}$$

for $\xi \gg 1$. Equations (19) and (20) provide only rough estimates for the gas temperature near the current sheet. A more detailed calculation of the temperature distribution near the current sheet should include the details of the magnetic reconnection process and the energy losses of the heated gas due to its radiation. No attempt is made here to include such details. From equations (19) and (20) one can see that if the magnetic field on the surface of an early-type star is strong enough, then the outflowing gas is heated near the current sheet to temperatures of $\sim 10^7$ K, so that its thermal radiation is in the X-ray range.

4. GENERATION OF X-RAY EMISSION

The fraction of the thermal energy of the hot gas lost by emission is characterized by the following dimensionless parameter:

$$\eta = \frac{r_{\rm A}}{v(r_{\rm A})t_c(r_{\rm A})} , \tag{21}$$

where $t_c(r_{\rm A})$ is the characteristic cooling time of the hot gas near the current sheet at $r \approx r_{\rm A}$. This fraction is approximately equal to η for $\eta < 1$ and is approximately equal to unity for $\eta \gtrsim 1$.

The ionized gas with $T \simeq 10^7$ K emits mainly due to free-free transitions of electrons in the Coulomb fields of ions (Gaetz & Salpeter 1983). In this case the characteristic cooling time of the hot plasma is

$$t_c \approx 4.7 \times 10^2\left(\frac{n}{10^{12}\ {\rm cm}^{-3}}\right)^{-1}\left(\frac{T}{10^7\ {\rm K}}\right)^{1/2} {\rm s} , \tag{22}$$

where $n = \rho/m_p \mu$ is the number density of the plasma. From equations (5), (6), and (19)–(22), one has

$$\eta \approx \begin{cases} 0.32\left(\dfrac{\dot{M}}{10^{-6}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{15/4}\left(\dfrac{v_\infty}{10^8\ \mathrm{cm\ s}^{-1}}\right)^{-1/4}\left(\dfrac{B_s}{10^2\ \mathrm{G}}\right)^{-11/2}\left(\dfrac{R}{20\ R_\odot}\right)^{-13/2} & \text{for } \xi \ll 1\ , \\ 0.5\left(\dfrac{\dot{M}}{10^{-6}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{5/4}\left(\dfrac{v_\infty}{10^8\ \mathrm{cm\ s}^{-1}}\right)^{-11/4}\left(\dfrac{B_s}{10^2\ \mathrm{G}}\right)^{-1/2}\left(\dfrac{R}{20\ R_\odot}\right)^{-3/2} & \text{for } \xi \gg 1\ . \end{cases} \tag{23}$$

The luminosity of the heated gas near the current sheet is equal to P for $\eta \geq 1$ and to ηP for $\eta < 1$.

Finally, from equations (13), (15), and (23), the X-ray luminosity of a magnetic early-type star has the following limiting values.

1. *Weak magnetic field* ($\xi \ll 1$):

$$L_X \approx \begin{cases} 5.1 \times 10^{33}\left(\dfrac{\dot{M}}{10^{-6}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{-1/2}\left(\dfrac{v_\infty}{10^8\ \mathrm{cm\ s}^{-1}}\right)^{1/2}\left(\dfrac{B_s}{10^2\ \mathrm{G}}\right)^{3}\left(\dfrac{R}{20\ R_\odot}\right)^{3}\ \mathrm{ergs\ s}^{-1} & \text{for } \eta \geq 1\ , \\ 1.6 \times 10^{33}\left(\dfrac{\dot{M}}{10^{-6}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{13/4}\left(\dfrac{v_\infty}{10^8\ \mathrm{cm\ s}^{-1}}\right)^{1/4}\left(\dfrac{B_s}{10^2\ \mathrm{G}}\right)^{-5/2}\left(\dfrac{R}{20\ R_\odot}\right)^{-7/2}\ \mathrm{ergs\ s}^{-1} & \text{for } \eta < 1\ . \end{cases} \tag{24}$$

2. *Strong magnetic field* ($\xi \gg 1$):

$$L_X \approx \begin{cases} 2 \times 10^{33}\left(\dfrac{\dot{M}}{10^{-6}\ M_\odot\ \mathrm{yr}^{-1}}\right)\left(\dfrac{v_\infty}{10^8\ \mathrm{cm\ s}^{-1}}\right)^{2}\ \mathrm{ergs\ s}^{-1} & \text{for } n \geq 1\ , \\ 10^{33}\left(\dfrac{\dot{M}}{10^{-6}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{9/4}\left(\dfrac{v_\infty}{10^8\ \mathrm{cm\ s}^{-1}}\right)^{-3/4}\left(\dfrac{B_s}{10^2\ \mathrm{G}}\right)^{-1/2}\left(\dfrac{R}{20\ R_\odot}\right)^{-3/2}\ \mathrm{ergs\ s}^{-1} & \text{for } \eta < 1\ . \end{cases} \tag{25}$$

The observed X-ray luminosities of the early-type stars cover a range from $\sim 10^{31}$ ergs s^{-1} to a few 10^{34} ergs s^{-1} (Pollock 1987; Chlebowski 1989). From equations (24) and (25) we can see that the expected X-ray luminosities of stars with $\dot{M} \sim 10^{-7}$–$10^{-4}\ M_\odot$ yr^{-1}, $v_\infty \sim (1$–$3) \times 10^8$ cm s^{-1}, $R \sim 20\ R_\odot$ and $B_s \sim 10$–10^2 G are consistent with the observed values.

So far we have ignored the absorption of X-rays in the stellar wind. Let us estimate the value of $\dot{M}$ at which the X-ray absorption has to be taken into account.

The optical depth $\tau_{\mathrm{abs}}(R, E)$ through the wind to the surface of the star ($r = R$) for X-rays with photon energy E is $\tau_{\mathrm{abs}}(R, E) = \sigma_{\mathrm{ph}}(E) N_{\mathrm{H}}$, where $\sigma_{\mathrm{ph}}(E)$ is the total cross section of photoelectric absorption per hydrogen atom and

$$N_{\mathrm{H}} \approx 10^{22}\left(\frac{\dot{M}}{10^{-6}\ M_\odot\ \mathrm{yr}^{-1}}\right)\left(\frac{v_\infty}{10^8\ \mathrm{cm\ s}^{-1}}\right)^{-1}\left(\frac{R}{20\ R_\odot}\right)^{-1}\ \mathrm{cm}^{-2} \tag{26}$$

is the hydrogen column density along the line of sight through the stellar wind to the surface of the star. The value of $\sigma_{\mathrm{ph}}(E)$ depends on the chemical composition of gas. In the case of the solar abundance the total cross section of photoelectric absorption per hydrogen atom is (Brown & Gould 1970)

$$\sigma_{\mathrm{ph}}(E) \simeq \begin{cases} 0.6 \times 10^{-22} E^{-3}\ \mathrm{cm}^2 & \text{for } 0.1\ \mathrm{keV} \leq E \leq 0.53\ \mathrm{keV}\ , \\ 2.0 \times 10^{-22} E^{-2.5}\ \mathrm{cm}^2 & \text{for } 0.53\ \mathrm{keV} < E \leq 8\ \mathrm{keV}\ , \end{cases} \tag{27}$$

where E is the photon energy in keV.

The best-fitting temperatures kT for the observed X-ray spectra of OB and W-R stars are concentrated in the range from ~ 0.3 keV to a few keV, i.e., near $kT \simeq 1$ keV (Moffat et al. 1982; Pollock 1987; Chlebowski 1989). From equations (26) and (27) it follows that for X-ray photons with energy $E \sim kT \sim 1$ keV the value of $\tau_{\mathrm{ph}}(R, E)$ is greater than unity for

$$\dot{M} \gtrsim 0.5 \times 10^{-6}\left(\frac{v_\infty}{10^8\ \mathrm{cm\ s}^{-1}}\right)\left(\frac{R}{20\ R_\odot}\right) M_\odot\ \mathrm{yr}^{-1}\ . \tag{28}$$

This condition of X-ray absorption in the stellar wind of an early-type star is in agreement with numerical calculations (Cassinelli & Olson 1979) in which the atomic abundances given for early-type stars by Withbroe (1971) is used.

If the optical depth through the wind to the Alfvén surface ($r = r_{\mathrm{A}}$) for the X-rays with the photon energy $E \sim kT$ is more than unity [$\tau_{\mathrm{abs}}(r_{\mathrm{A}}, kT) > 1$], the observed X-ray emission of star originates mainly from a distance $r \simeq r_{\mathrm{abs}}$ defined by the optical depth for escaping X-rays being equal to unity [$\tau_{\mathrm{abs}}(r_{\mathrm{abs}}, kT) = 1$]:

$$r_{\mathrm{abs}} \approx 40\,\delta\left(\frac{\dot{M}}{10^{-6}\ M_\odot\ \mathrm{yr}^{-1}}\right)\left(\frac{v_\infty}{10^8\ \mathrm{cm\ s}^{-1}}\right)^{-1} R_\odot\ , \tag{29}$$

where the dimensionless parameter δ depends on the chemical composition of the stellar wind and the spectrum of X-ray emission of hot gas near the current sheet and is of the order of unity.

To estimate the X-ray luminosity for the case $\tau_{\mathrm{abs}}(r_{\mathrm{A}}, kT) > 1$, it is necessary to integrate in equation (10) from τ_{abs} instead of τ_{A}. Taking this into account, from equations (11), (12), (21), (22), and (29) one has

$$L_X \approx 10^{-2}\,\frac{B_s^3 R^9}{3 r_{\mathrm{A}}^3 r_{\mathrm{abs}}^3}\left(\frac{v_\infty}{\dot{M}}\right)^{1/2} \times \begin{cases} 1 & \text{for } \eta \geq 1\ , \\ \eta & \text{for } \eta < 1\ , \end{cases} \tag{30}$$

where

$$\eta = \frac{r_{\rm abs}}{v_\infty \tau_c} \approx \delta^{-1}\left(\frac{v_\infty}{10^8 \text{ cm s}^{-1}}\right)^{-1} . \tag{31}$$

It follows from the dependences

$$\tau_{\rm abs} \propto \dot{M} , \quad r_{\rm A} \propto \begin{cases} \text{const} & \text{for } \xi \ll 1 , \\ \dot{M}^{-1/4} & \text{for } \xi \gg 1 , \end{cases} \tag{32}$$

that the dependence of L_X on $\dot{M}$ for the case $\tau_{\rm abs}(r_{\rm A}, kT) > 1$ is as follows:

$$L_X \propto \begin{cases} \dot{M}^{-7/2} & \text{for } \xi \ll 1 , \\ \dot{M}^{-11/4} & \text{for } \xi \gg 1 . \end{cases} \tag{33}$$

In both cases the X-ray luminosity decreases rapidly with increasing $\dot{M}$. Equations (30) and (33) are valid for $r_{\rm abs} \lesssim R(v_\infty/v_{\rm rot})$. If $r_{\rm abs} > R(v_\infty/v_{\rm rot})$ the character of the magnetic field at a distance $r \simeq r_{\rm abs}$ changes from radial to toroidal, and from equations (8) and (10) the expected X-ray luminosity of star is

$$L_X \approx 10^{-2}\left(\frac{v_{\rm rot}}{v_\infty}\right)^3 \frac{B_s^3 R^6}{r_{\rm A}^3}\left(\frac{v_\infty}{\dot{M}}\right)^{1/2} \times \begin{cases} 1 & \text{for } \eta \geq 1 , \\ \eta & \text{for } \eta < 1 , \end{cases} \tag{34}$$

where the dimensionless parameter η is determined by equation (31). In this case the dependence of L_X on $\dot{M}$ is weak:

$$L_X \propto \begin{cases} \dot{M}^{-1/2} & \text{for } \xi \ll 1 , \\ \dot{M}^{1/4} & \text{for } \xi \gg 1 . \end{cases} \tag{35}$$

The mass-loss rates of the early-type stars cover a large range from less than $10^{-7}\ M_\odot$ yr^{-1} up to $\sim 10^{-4}\ M_\odot$ yr^{-1}. From equations (5), (24), (25), and (30)–(35) the expected X-ray luminosity of an early-type star with typical parameters [$R \simeq 20\ R_\odot$, $v_\infty \simeq 2 \times 10^8$ cm s^{-1}, $v_{\rm rot} \simeq (0.1–0.2)v_\infty$] and with a surface magnetic field $B_s \simeq 10^2$ G increases with increasing $\dot{M}$ when $\dot{M}$ is small, reaching a maximum $L_X \simeq 10^{33}$–10^{34} ergs s^{-1} when the value of $\dot{M}$ is of the order of $10^{-6}\ M_\odot$ yr^{-1}. Beyond the maximum, L_X decreases sharply with increasing $\dot{M}$. When $\dot{M} \gtrsim 10^{-5}\ M_\odot$ yr^{-1} the value of L_X is practically constant and equals 10^{31}–10^{32} ergs s^{-1} (see eqs. [33] and [34]). This behavior of the X-ray luminosity can explain the fact that single OB stars are on the average essentially brighter in X-rays than single W-R stars (Pollock 1987; Chlebowski 1989).

5. DISCUSSION

We have considered, in this paper, the gas heating and X-ray generation near the current sheet in the magnetosphere of an early-type star. The X-ray emission observed from both OB and W-R stars can be explained in the frame of the model developed above. In the case of OB stars, besides the X-ray emission of hot gas heated in the current sheet, the X-ray emission suggested by Lucy & White (1980) may be important.

Let us discuss briefly the theoretical predictions of our model about the properties of X-ray emission from magnetic early-type stars. One of them, namely, the dependence of the X-ray luminosity L_X on the mass-loss rate $\dot{M}$, was discussed in the previous section. From this prediction it follows that the X-ray luminosity of OB stars depends very strongly on $\dot{M}$. On the contrary, the value of L_X for the W-R stars is practically independent of $\dot{M}$ (see eq. [34]). From equation (33) we can see that the expected X-ray luminosity of the W-R stars is very sensitive to the ratio $v_{\rm rot}/v_\infty$. The important differences between the OB and W-R stars arises from the larger $\dot{M}$ for the W-R stars.

The observations of time variability of X-ray emission are very promising for identifying the origin of X-rays from early-type stars. If the magnetic axis does not coincide with the axis of rotation, the observed X-ray emission of hot gas near the current sheet may be modulated because of the eclipse of the current sheet as the star rotates. Expected modulation of X-ray emission may be as high as $\sim 50\%$ for the OB stars and is small for the W-R stars of which X-rays are generated at a distance $r \sim r_{\rm abs} \gg R(v_\infty/v_{\rm rot})$ where the magnetic field is toroidal. In the model of Lucy & White (1980) it is natural to expect that the distribution of strong shocks in the outflowing gas is symmetric with respect to the axis of rotation. In this case there is no reason to expect any X-ray modulation due to stellar rotation.

It should be noted that if an early-type star belongs to a binary system, of which the other component is also an early-type star, the X-ray emission generated in the region of stellar wind collision may be much stronger than the X-ray emission which is inherent in the components even if the binary system is very wide (Prilutskii & Usov 1975, 1976; Usov 1991). For example, most probably, the strong X-ray emission of the binary system AS 431 ($L_X \simeq 3 \times 10^{33}$ ergs s^{-1}) is generated due to the stellar wind collision despite the orbital period of this binary being as large as 10^3 yr (Caillaut et al. 1985; Moran et al. 1989). Therefore, the values of X-ray luminosity calculated above and the predictions discussed are valid only for single early-type stars.

We thank Leon Mestel for helpful comments.

REFERENCES

Abbott, D. C., Bieging, J. H., Churchwell, E., & Torres, A. V. 1986, ApJ, 303, 239
Akasofu, S. I. 1980, Planet. Space Sci., 28, 495
Baker, D. N., & Stone, E. C. 1977, J. Geophys. Res., 82, 1532
Barker, P. K. 1986, PASP, 98, 44
Bieber, J. W. 1984, in Magnetic Reconnection in Space and Laboratory Plasmas, Geophysical Monograph 30, ed. E. W. Hones, Jr. (Washington, DC: AGU Press), 185
Bieber, J. W., & Stone, E. C. 1980, Geophys. Res. Lett., 7, 945
Bieging, J. H., Abbott, D. C., & Churchwell, E. B. 1989, ApJ, 340, 518
Brown, R. L., & Gould, R. J. 1970, Phys. Rev., D1, 2252
Caillaut, J. P., Chanan, G. A., Helfand, D. J., Patterson, J., Nousek, J. A., Talacko, L. O., Bothun, G. D., & Becker, R. H. 1985, Nature, 313, 376
Carlberg, R. G. 1980, ApJ, 241, 1131
Cassinelli, J. P., & Olson, G. L. 1979, ApJ, 229, 304
Castor, J. I., & Lamers, H. J. G. L. M. 1979, ApJS, 39, 481
Castor, J. I., & Simon, T. 1983, ApJ, 265, 304
Chlebowski, T. 1989, ApJ, 342, 1091
Conti, P. S., & Ebbets, D. 1977, ApJ, 213, 438
Cooke, B. A., Fabian, A. C., & Pringle, J. E. 1978, Nature, 273, 645
Coppi, B., & Friedland, A. B. 1971, ApJ, 169, 379
Friend, D. B., & Abbott, D. C. 1986, ApJ, 311, 701
Gaetz, T. J., & Salpeter, E. E. 1983, ApJS, 52, 155
Galeev, A. A., Pilyugin, N. N., & Usov, V. V. 1989, in Proc. Joint Varenna-Abastumani Internat. School and Workshop, Plasma Astrophysics, ESA SP-285 (Noordwijk: ESTEC), 125
Havnes, O., & Goertz, C. K. 1984, A&A, 138, 421
Heyvaerts, J., Priest, E. R., & Rust, D. M. 1977, ApJ, 216, 123
Hones, E. W., Jr. 1979, Space Sci. Rev., 23, 393
Hutchings, J. B. 1981, PASP, 93, 50
Lucy, L. B. 1982a, ApJ, 255, 278
———. 1982b, ApJ, 255, 286
Lucy, L. B., & Solomon, P. 1970, ApJ, 159, 879
Lucy, L. B., & White, R. L. 1980, ApJ, 241, 300
MacGregor, K. B., Hartmann, L., & Raymond, J. C. 1979, ApJ, 231, 514
Mestel, L. 1968, MNRAS, 138, 359
Mestel, L., Moore, D. W., & Perry, J. J. 1976, A&A, 52, 203
Mestel, L., & Spruit, W. E. 1987, MNRAS, 226, 57
Milroy, R. D. 1984, in Magnetic Reconnection in Space and Laboratory Plasmas, Geophysical Monograph 30, ed. E. W. Hones, Jr. (Washington, DC: AGU Press), 305
Moffat, A. F. T., Firmani, C., McLean, I. S., & Seggewiss, W. 1982, in Wolf-Rayet Stars: Observations, Physics, Evolution, ed. C. W. H. de Loore & A. J. Willis (Dordrecht: Reidel), 577
Moran, J. P., Davis, R. J., Bode, M. F., Taylor, A. R., Spencer, R. E., Argue, A. N., Irwin, M. J., & Shanklin, J. D. 1989, Nature, 340, 449
Mullan, D. J. 1983, Irish Astr. J., 16, 107
Nerney, S., & Suess, S. T. 1987, ApJ, 321, 355
Ness, N. F. 1965, J. Geophys. Res., 70, 2989
Owocki, S. P., Castor, J. L., & Rybicki, G. B. 1988, ApJ, 335, 914
Owocki, S. P., & Rybicki, G. B. 1984, ApJ, 284, 337
Petschek, H. E. 1964, in The Physics of Solar Flares, ed. W. N. Ness, NASA SP-50, 425
Pollock, A. M. T. 1987, ApJ, 320, 283
Priest, E. R. 1984, in Magnetic Reconnection in Space and Laboratory Plasmas, Geophysical Monograph 30, ed. E. W. Hones, Jr. (Washington, DC: AGU Press), 63
Prilutskii, O. F., & Usov, V. V. 1975, Astron. Circ., 854, 1
———. 1976, Soviet Astron., AJ, 90, 2
Seward, F. D., Forman, W., Giacconi, R., Griffiths, R., Harden, F. R., Jr., Jones, C., & Pye, J. 1979, ApJ, 234, L55
Sturrock, P. A. 1968, in IAU Symp. 35, Structures and Development of Solar Active Regions, ed. K. O. Kiepenheuer (Dordrecht: Reidel), 471
Švestka, Z. 1976, Solar Flares (Dordrecht: Reidel)
Sweet, P. A. 1969, ARA&A, 7, 149
Syrovatskii, I. N. 1981, ARA&A, 19, 163
Uesugi, A., & Fukuda, I. 1982, Revised Catalog of Stellar Rotational Velocities (Kyoto University Press)
Usov, V. V. 1992, ApJ, 389, 635
Weber, E. J., & Davis, L., Jr. 1967, ApJ, 148, 217
Williams, P. M., van der Hucht, K. A., Pollock, A. M. T., Florkowski, D. R., van der Woerd, H., & Wamsteker, W. M. 1990, MNRAS, 243, 662
Withbroe, G. L. 1971, in The Menzel Symposium, ed. K. B. Gebbie, NBS SP 353, 127