IS THE GALACTIC CORONA PRODUCED BY GALACTIC FLARES?

by

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ABSTRACT

We consider the effect of the differential rotation of the disk of the Galaxy on magnetic field which penetrates the disk. The magnetic field will be progressively distorted from a potential (current-free) form and will at some stage become unstable. We expect, from knowledge of solar flares, that an MHD instability, a resistive instability, or a combination of the two, will result in the release of the excess magnetic energy and that part of the released energy will be converted into heat. By estimating the energy release and the rate at which this process will occur and by assuming that this energy input is balanced by radiation, we obtain estimates of the parameters of the resulting plasma. It appears that this process alone can heat a galactic corona to temperatures of order 10^6 K.

I. INTRODUCTION

The diffuse soft x-ray ($E \lesssim 1$ keV) background has been attributed to a coronal-type plasma of $T \sim 10^6$K which occupies a substantial fraction of the galactic volume (see Tanaka & Bleeker, 1977, for a review). Models for the creation of this high-temperature interstellar medium (ISM) component through supernova explosions have been developed by Cox and Smith (1974), Smith (1977), and McKee and Ostriker (1977). Spitzer (1956), Shapiro and Field (1976), and Chevalier and Oegerle (1979) have analyzed the dynamics and energy balance of the hot ISM component; using the supernova heating mechanism, they predict the formation of a corona extending several kiloparsecs or more above the plane of the Galaxy. We wish to suggest an alternative process for heating such a corona.

Various lines of evidence indicate that the Galaxy is permeated by a magnetic field, possibly of complex structure. For the same reason that, if a magnetic field originates in the solar photosphere, it is energetically favorable for the field to extend far out into the corona, we may infer that, if there is magnetic field in the disk of the galaxy, this field will also extend far outside the disk into what may be termed a "coronal" region.

In the case of the sun, energy is released impulsively at coronal heights during flares (Svestka, 1976; Sturrock, 1979). It is generally agreed that the energy released during a flare is stored above the photosphere in the form of the free energy of a current-carrying magnetic field. The influence of differential photospheric motion on magnetic flux threading the photosphere necessarily leads to non-potential field configurations and hence to free magnetic energy.

Given the fact that the disk of the Galaxy is in a state of differential rotation, and given the reasonable assumption that magnetic field threads the disk of the Galaxy and extends out into a galactic corona, the same ingredients are present in the Galaxy as lead to flare activity in the case of the sun. The purpose of this article is to propose that galactic flares provide a substantial energy input to the interstellar medium, and thus heat the coronal plasma responsible for the diffuse soft x-ray background.

II. ANALYSIS

This analysis will be confined simply to order-of-magnitude estimates of the effects of flare activity on the galactic corona. The arguments and analysis will run parallel to an earlier similar discussion of solar flares (Sturrock, 1974). We consider what is initially a closed magnetic-field structure of mean strength B (gauss) in the form of a flux tube. Because of the differential rotation of the Galaxy, both ends of such a flux tube are being twisted in the same sense, as viewed from the disk of the Galaxy, but in opposite senses with reference to the flux tube itself. If, at some time, a particular flux tube contains a potential field, then some time later the twisting of the field will lead to a helical configuration of the magnetic field. Unless the plasma stresses are large, the field will tend to adopt a force-free configuration.

Theoretical studies indicate that a force-free field becomes MHD-unstable when the distortion from the current-free form reaches a critical level. Numerical studies (Barnes and Sturrock, 1972) indicate that, when the distortion exceeds the critical level, a closed magnetic-field configuration is likely to erupt to form an open configuration which necesarily involves one or more current sheets. These sheets can then reconnect by nonlinear processes (Petschek, 1964) arising from the tearing-mode instability (Furth et al., 1963), returning the field to its current-free form and, in the process, releasing a large fraction of the initial free energy associated with the coronal currents.

Another somewhat simpler possibility is that a sheared magnetic-field configuration is at some stage subject to resistive instabilities which immediately return the field to the current-free form (Spicer, 1977).

Studies carried out during the recent Skylab Workshop on Solar Flares led participants to the view that both processes probably occur in the sun and are responsible for different types of solar flares (Sturrock, 1979). It is also possible (Sturrock and Uchida, 1979) that the heating of the normal corona may be due to the same processes occurring in magnetic fields of such configuration that the onset of instability is non-explosive rather than explosive (Sturrock, 1966).

We suppose that, when a galactic flare occurs, energy in the amount $\varepsilon \frac{1}{8\pi} B^2$ per unit volume is released in such a form as to heat the coronal plasma. The coefficient ε will be the product of two terms, ε_1 and ε_2, where ε_1 is the ratio of the magnetic free energy to the initial current-free magnetic energy, and ε_2 is the fraction of the magnetic free energy which goes to heat the plasma. The calculations of Barnes and Sturrock (1972) indicate that flare action can occur after magnetic field lines are twisted by half a complete rotation and that, at that time, $\varepsilon_1 \approx 1$. We make the simple assumption that, during an eruption, one half of the free energy of the force-free field survives as the free energy associated with the current sheet. We further assume that, when reconnection occurs in the current sheet, one half the energy goes into heat and the rest into mass motion. Hence we assume that $\varepsilon_2 \approx 1/4$ so that $\varepsilon \approx 1/4$. Assuming that the energy released during one flare is almost all radiated away by the time of the next flare, we see that, directly after a flare,

$$3nkT = \varepsilon \frac{1}{8\pi} B^2 \qquad (2.1)$$

where the gas is assumed to be almost pure hydrogen which is almost fully ionized and n is the density of either electrons or protons.

If the plasma loses energy primarily by radiation, we may introduce the radiative-cooling time scale τ_R defined by

$$\eta = 3nkT\,\tau_R^{-1} \quad (2.2)$$

where η (erg $cm^{-3}s^{-1}$) is the radiative rate. We adopt for η the form

$$\eta = \Gamma n^2 T^{\gamma} \quad (2.3)$$

given by McKee and Cowie (1977) in the range $10^5 < T < 10^{7.6}$, where the radiation rate is well represented by the above equation with $\Gamma = 10^{-18.2}$ and $\gamma = -3/5$.

The effect of differential rotation of the Galaxy is such that any element of area exhibits an "orbital" rotation and, in addition, a "planetary" rotation which may be characterized by a vorticity given by

$$\omega = r\,\frac{d\Omega}{dr}, \quad (2.4)$$

where $\Omega(r)$ is the angular velocity of the Galaxy at radius r. Hence a small flux tube which emerges from one location in the disk and returns to another location at about the same radius will be twisted at both ends in such a way that the flux tube is given a helical twist. We expect that the tube will become MHD unstable when the twist reaches a critical value. Numerical studies (Barnes and Sturrock, 1972) indicate that this value corresponds to half a complete rotation which would result from a rotation of $\pi/2$ at each end. Hence we may estimate the time between flares τ_F (s) from

$$\omega\,\tau_F \approx \pi/2. \quad (2.5)$$

We find from Mihalas and Routly (1968) that, over the range of radii 3 kpc to 13 kpc, ω has a value close to 30 km $s^{-1}kpc^{-1}$ or $10^{-15.0}s^{-1}$. Hence we obtain the estimate $\tau_F = 10^{15.2}$.

If the corona plasma reaches an approximate steady state in which heating by flares is balanced by cooling by radiation, then

$$\tau_R \approx \tau_F \equiv \tau . \quad (2.6)$$

We obtain from (2.1), (2.2), and (2.3), the following estimates of the time-average values of the density and temperature:

$$\left. \begin{aligned} n &= 10^{9.3}\, B^{16/13}\, \tau^{-5/13} \\ T &= 10^{4.1}\, B^{10/13}\, \tau^{5/13} , \end{aligned} \right\} \quad (2.7)$$

which for the above estimate of τ becomes

$$\left. \begin{aligned} n &= 10^{3.5}\, B^{16/13} , \\ T &= 10^{9.9}\, B^{10/13} . \end{aligned} \right\} \quad (2.8)$$

If the magnetic field, which contains the coronal plasma, extends out to a distance L (cm) from the disk, then the emission measure H, defined by

$$H = n^2 L, \quad (2.9)$$

will have the value

$$H = 10^{7.0}\, B^{32/13}\, L . \quad (2.10)$$

III. DISCUSSION

Analysis of the soft x-ray background indicates that the plasma responsible for this emission probably has a complex thermal structure (see, e.g. Cash et al., 1976; Burstein et al., 1977; Stern and Bowyer, 1979). Nevertheless, for the order-of-magnitude analysis presented here, we may adopt as typical coronal parameters a temperature of $\sim 10^{5.8}$K and an emission measure of $\sim 10^{16.2}$ cm^{-5} (5.10^{-3} pc cm^{-6}). We see from equation (2.8) that this temperature is consistent with the present model if the mean magnetic field strength in the local region of the galactic corona is $\sim 10^{-5.3}$ gauss. For comparison, we note that Badhwar and Stephens (1977), on the basis of an analysis of the hydrostatic equilibrium of the gas-field system in the solar neighborhood, conclude that the magnetic field strength in the neighborhood of the sun is about $(5 - 6) \times 10^{-6}$ gauss, and that Ruzmajkin and Sokolov (1977), on the basis of an analysis of pulsar data, conclude that the local magnetic field strength is $(2.1 \pm 1.1) \times 10^{-6}$ gauss. Our theoretical estimate of the required magnetic field strength agrees with these two (observationally derived) estimates as well as they agree with each other.

We now see also from equation (2.8) that, with the above estimate of the magnetic field strength, we expect the electron density in the galactic corona to be about $10^{-3.0}$ cm^{-3}. We also see from equation (2.9) that the inferred emission measure $H \approx 10^{16.2}$ is obtained if the corona extends out to a distance $L \approx 10^{22.2}$, i.e. 5kpc.

It is necessary to compare the above estimate of L with the scale height h (cm) of plasma in the galactic corona. We note

$$h = \frac{kT}{mg} , \qquad (3.1)$$

and note that the mean mass m (g) has the value $10^{-24.1}$ if the plasma is mainly fully ionized hydrogen, and that the gravitational acceleration g (cm s^{-2}) is approximately $10^{-8.1}$ in the range 1 kpc to 5 kpc of the galactic plane (Allen, 1973; p. 250), so that, numerically,

$$h \approx 10^{16.3}\ T. \tag{3.2}$$

We find that, for the estimated temperature $T \approx 10^{5.8}$, $h \approx 10^{22.1}$. Hence, if the value of L is in fact set by the extent of the magnetic flux tubes which contain the plasma in the local region of the galactic corona, the scale height is sufficiently large to fill the flux tubes with plasma. If, on the other hand, the magnetic flux tubes extend well beyond 5 kpc, then the extent of the coronal plasma may be attributed to the scale height.

If the latter is the correct interpretation, we may use (3.2) in (2.10) to obtain an expression for H in terms of B only. Then (as we have seen) our choice of B fits both T and H. However, our initial equations [(2.1) and (2.2)] are based on the assumption that n and T are uniform for any flux tube, and this assumption must be relaxed if the scale height is less than the height of the flux tubes.

The fact that the present model gives approximate order-or-magnitude agreement with observational data does not establish its validity; it simply indicates that more detailed investigation should be pursued. In particular, it is necessary to relax the "steady-state" assumption and to investigate the time development of heating, cooling and mass flow. The condition (2.1) is valid directly after a sudden release of energy, whereas condition (2.6) is valid for a long-term average of the coronal conditions. If τ_R were in fact short compared with τ_F, then energy released during a flare would rapidly radiate away so that the time-average temperature would be less than the immediate post-flare temperature. If, on the other hand, τ_R were large compared to τ_F, then energy released during flares would accumulate with the possible result that the plasma stress eventually exceeds the possible magnetic stress. This would result in an opening of the magnetic field with loss of the coronal plasma.

If τ_E (s) is the time scale for the release of energy in a flux tube, then (Sturrock, 1974)

$$\tau_E = \frac{R}{v_R} \tag{3.3}$$

where R (cm) is the radius of the flux tube under consideration and v_R (cm s^{-1}) is the reconnection rate. Following Petschek (1964), we estimate that

$$v_R \approx 10^{-1} \; v_A \tag{3.4}$$

where v_A is the Alfven speed. Since the mass density of fully ionized hydrogen is 2nm, where m is the mean particle mass,

$$v_A = B(8\pi nm)^{-1/2} \approx 10^{11.3} \; B \; n^{-1/2} \; . \tag{3.5}$$

Hence, using (2.7), we obtain

$$\tau_E = 10^{-5.6} \; R \; B^{-5/13} \; \tau^{-5/26} \tag{3.6}$$

or, for the value $\tau = 10^{15.2}$,

$$\tau_E = 10^{-8.6} \; R \; B^{-5/13} \; . \tag{3.7}$$

If we consider the value $B = 10^{-5.3}$, we find that, for R in the range $10^{21.5}$ to $10^{22.2}$ (1 kpc to 5 kpc), τ_E is in the range $10^{14.9}$ to $10^{15.6}$. It appears, therefore, that τ_E is comparable with τ_F. This suggests that the corona will be approximately in a steady state so that the heating is more like the steady heating of an active region rather than the impulsive heating of a flare.

We should also examine the rate of energy loss through thermal conduction to the galactic disk, to compare with the energy loss rate by radiation. If τ_H (s) is the time scale for cooling of the galactic plasma by thermal conduction, then τ_H may be estimated from

$$3\,nkTL = F\,\tau_H, \tag{3.8}$$

where F (erg cm^{-2} s^{-1}) is the heat flux along the magnetic field. This may be estimated from

$$F \approx \kappa\,T\,L^{-1} \approx 10^{-6}\,T^{7/2}\,L^{-1}, \tag{3.9}$$

if we use the Spitzer (1962) form of the thermal conduction coefficient. Hence we obtain the estimate

$$\tau_H = 10^{-9.4}\,L^2\,n\,T^{-5/2}. \tag{3.10}$$

For the values $L = 10^{22.2}$, $n = 10^{-3}$ and $T = 10^{5.8}$, we obtain $\tau_H = 10^{20.5}$, giving a cooling time of 10^{10} y. This is much longer than the radiation cooling time, confirming that radiation is the dominant mechanism for energy loss. On the other hand, τ_H is comparable with the age of the Galaxy, so that the energy flow from the corona to the galactic disk is sufficient to produce the "evaporation" (Neupert, 1968; Antiochos and Sturrock, 1978) necessary to provide the coronal plasma.

It has been known for some time that there are high-velocity clouds (HVC) and intermediate-velocity clouds (IVC) of neutral hydrogen outside the galactic plane. Verschuur (1975), in reviewing this topic, suggests that there is more than one type of cloud and notes several possible interpretations. Shapiro and Field (1976) have developed a "galactic fountain" model involving an upward streaming hot gas which cools and condenses into a cool component. Our comparison between the galactic corona and the post-flare plasma in the sun suggests that some of these clouds may be the galactic analogues of "coronal rain" which often occurs in the loop prominence systems formed by some large solar flares (Tandberg-Hanssen, 1974). It has been shown by Goldsmith (1971) and by Antiochos (1976) that the latter may be understood as the result of thermal instability in the hot dense plasma which forms in the coronal volume of an active region as the result of a flare.

Following Field (1965) and Antiochos (1976), we note that the condition for thermal instability is that the wave number k (cm^{-1}) of the small-amplitude wave should satisfy the inequality

$$k^2 < k_c^2 = \kappa^{-1}\left(\frac{n}{T}\frac{\partial\eta}{\partial n} - \frac{\partial\eta}{\partial T}\right). \quad (3.11)$$

On using the form (2.3) for η and the Spitzer form for the thermal conductivity κ, we find that

$$k_c = 10^3\ (2-\gamma)^{1/2}\ \Gamma^{1/2}\ n\ T^{\gamma/2 - 7/4}. \quad (3.12)$$

With the values of γ and Γ appropriate to the range $10^5 < T < 10^{7.6}$, this becomes

$$k_c = 10^{-5.9}\ n\ T^{-41/20}. \quad (3.13)$$

For the values $n = 10^{-3}$, $T = 10^{5.8}$, we find that $k_c^{-1} = 10^{20.8}$. Since this estimate of k_c^{-1} is considerably less than our estimate of L, we expect that thermal instability will lead to the formation of condensations with dimensions (along the magnetic field) of 200 pc or more. When formed, these condensations should fall towards the galactic plane with speeds approaching the free-fall speed $(2\,gL)^{1/2}$. For $L = 10^{22.2}$, this corresponds to a velocity of $10^{7.2}$ cm s^{-1} or about 170 km s^{-1}; the inferred speeds of high-velocity clouds are of this order of magnitude, and the inferred speeds of intermediate-velocity clouds (which extend up to high galactic latitudes) are somewhat less. Hence it seems possible that some moving clouds are the galactic analogues of coronal rain, although Verschuur (1975) discredits the view that most clouds are moving towards the galactic plane.

Finally, we note that the proposed parameters for the plasma and magnetic field may be compared with data for the rotation of radio waves which enter the Galaxy from extragalactic sources (Gardner and Whiteoak, 1966). The rotation ψ (radian) of the polarization of a radio wave of wavelength λ_m (meters) is normally written as

$$\psi = R_M \lambda_m^2 \tag{3.14}$$

where

$$R_M = 10^{-12.6} \int n\, B_{\parallel}\, ds, \tag{3.15}$$

where $B_{\parallel}$ is the component of magnetic field along the propagation path. Hence we may estimate the maximum magnitude of R_M from

$$R_M \approx 10^{-12.6}\, n\, BL. \tag{3.16}$$

For the values $B = 10^{-5.3}$, $n = 10^{-3}$ and $L = 10^{22.2}$, this leads to a maximum value of R_M of order 20. This estimate appears to be consistent with the upper limit of values of the rotation measure for high galactic latitudes (Gardner and Whiteoak, 1966, Fig. 9).

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