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ANALYSIS OF THE TEMPERATURE AND EMISSION MEASURE OF SOLAR CORONAL ARCADES AND TEST OF A SCALING LAW OF FLARE/ARCADE LOOP LENGTH

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ABSTRACT

We analyze 17 arcades to study the relations between solar flares and arcades. Soft X-ray images taken with *Yohkoh*'s soft X-ray telescope are used to derive T_0, EM_0, and temporal variation of T_{arc} and $\mathrm{EM}_{\mathrm{arc}}$, where T_{arc} and T_0 are the temperatures of an arcade and prearcade region and $\mathrm{EM}_{\mathrm{arc}}$ and EM_0 are the volume emission measures of an arcade and prearcade region. It is found that $T_0 \sim 2$ MK and $T_{\mathrm{arc}} \sim 4$ MK. We also estimate prearcade coronal electron density n_0 and arcade electron density n_{arc} to find that n_{arc} is comparable to n_0 ($n_{\mathrm{arc}} \sim n_0 \sim 10^8$ cm^{-3}). Using these observed EM, T, and n_0, we calculate the theoretical loop length L_{theor} based on the scaling law for solar and stellar flares derived by Shibata & Yokoyama and compare it with observed flare/arcade loop length L_{obs}. The result shows a good correlation between them ($L_{\mathrm{theor}} \sim L_{\mathrm{obs}}$) and indicates the need of plasma β for the scaling law ($L_{\mathrm{theor}} \propto \mathrm{EM}^{3/5} T^{-8/5} n_0^{-2/5} \beta^{-6/5}$). This supports the theory of the scaling law and is indirect evidence that flares and arcades are heated by the same magnetic reconnection mechanism.

Subject headings: Sun: corona — Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

A large-scale arcade with a cusp structure can sometimes be seen in quiet regions of the solar corona (Tsuneta et al. 1992; McAllister et al. 1992; Acton et al. 1992), as shown by a soft X-ray image taken with the *Yohkoh* soft X-ray telescope (SXT; Tsuneta et al. 1991). It has been confirmed that an arcade is often associated with a filament eruption in multiwavelength observation (Hanaoka et al. 1994; McAllister et al. 1996a; Khan et al. 1998; Mouradian et al. 1998). Some arcades are associated with coronal mass ejections (CMEs; Hudson, Haisch, & Strong 1995; Weiss et al. 1996) and have an influence on the Earth. On 1994 April 14, a giant arcade occurred on the disk, whose width between footpoints reached about 5×10^5 km (McAllister et al. 1996b). This giant arcade preceded a large geomagnetic storm. It has also been revealed that a large helmet streamer appears on the limb after a filament eruption and/or a CME. Such a large helmet streamer formation occurred on the limb on 1992 January 24 (Hiei, Hundhausen, & Sime 1993). The large helmet streamer is possibly a side view of the giant arcade. The arcade and the flare were thought to be different phenomena, since most of the arcades are not noticed from the *GOES* X-ray light curve. However, SXT images show some arcades have the cusp structure similar to the flare cusp, and hence it is argued that the arcade may share the same heating mechanism as the solar flare, although there is no quantitative study comparing physical parameters between the flare and the arcade statistically.

Recently, Feldman, Laming, & Doschek (1995) found that there is a correlation between the temperature and the emission measure for solar and stellar flares. Shibata & Yokoyama (1999, 2002) presented a theory to explain this universal correlation. This theory is based on two-dimensional magnetohydrodynamic (MHD) simulations by Yokoyama & Shibata (1998) that aimed to study the physics of the flare with two-dimensional MHD simulations of the reconnection including heat conduction and chromospheric evaporation and showed a simple scaling law among T, n_0, L, and B, where T is the temperature of the flare loop, n_0 is the electron number density of the preflare corona, L is the typical loop length of solar and stellar flares, and B is the coronal magnetic field strength. They further noticed that L can be derived from T, EM, and n_0, where EM is the volume emission measure of the flare loop:

$$L \simeq 10^9 \left(\frac{\mathrm{EM}}{10^{48}\ \mathrm{cm}^{-3}}\right)^{3/5} \left(\frac{n_0}{10^9\ \mathrm{cm}^{-3}}\right)^{-2/5} \left(\frac{T}{10^7\ \mathrm{K}}\right)^{-8/5} \ \mathrm{cm}. \tag{1}$$

Using this scaling law, they estimated L from the EM-T diagram. However this equation has not yet been tested by observations.

We analyze SXT data to derive the temperature T_{arc} and the emission measure $\mathrm{EM}_{\mathrm{arc}}$ of 17 arcades in this Letter. From these parameters L_{theor} ($=L$) can be estimated and compared with the observed loop length L_{obs} of solar flares and arcades, which statistically confirm equation (1). For flares, we use the data of Akiyama (2001). The selection of SXT data is described in § 2. The analysis of arcades is reported in § 3. Physical parameters of the arcades and the scaling law for L are discussed in § 4.

2. *YOHKOH*/SXT DATA SELECTION

The SXT data in this Letter were obtained with either the thin aluminum filter (Al.1) or the AlMgMn sandwich filter (AlMg). We use full-frame images that were taken with a time cadence of 2–60 minutes. The field of view of these data is $10' \times 10'$, and pixel size is $4''.9$.

We survey giant arcades observed with SXT between 1992 and 1999 under the following criteria: (1) the maximum length of the arcade along the magnetic neutral line is longer than 5×10^9 cm, (2) more than 50% of the arcade is located within heliographic longitudes E65–W65 and latitudes N65–S65, and (3) the arcade is observed with two filters (Al.1 and AlMg filters) under a time cadence sufficient for deriving the peak emission measure. It is found that 17 arcades meet the above

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TABLE 1
PHYSICAL PARAMETERS OF ARCADES

Day	Start[a]	End[b]	Location[c] (deg)	T_0 (MK)	n_0 ($\times 10^8$ cm^{-3})	T_{arc} (MK)	EM$_{arc}$ ($\times 10^{47}$ cm^{-3})	n_{arc} ($\times 10^8$ cm^{-3})	L_{obs} ($\times 10^{10}$ cm)	L_{theor} ($\times 10^{10}$ cm)	n_{arc}/n_0
1992 Apr 27	10:15	27:08	N40W25	1.9	2.1	4.4	3.7	2.2	1.6	1.4	1.0
1992 Jul 16	03:00	34:01	N40E25	2.2	0.76	2.9	0.62	0.65	2.0	1.4	0.85
1992 Jul 20	12:40	20:08	N40E10	1.8	0.93	2.5	0.25	1.2	0.96	0.98	1.3
1992 Nov 04	20:47	40:17	N30E17	1.8	1.6	2.4	1.6	0.88	2.2	2.4	0.53
1993 Jan 16	13:23	15:17	S30W20	2.1	1.0	3.9	3.0	2.1	1.5	2.0	2.1
1993 Jan 26	04:00	24:15	S35W14	1.8	1.7	4.1	2.4	1.4	1.9	1.3	0.78
1994 Mar 2	16:28	25:17	S25W40	1.9	1.4	2.8	0.65	1.1	1.4	1.2	0.74
1994 Apr 14	04:37	17:49	S45E57	1.6	1.1	1.8	3.4	0.42	4.6	6.9	0.37
1995 Feb 17	16:37	21:37	S20W25	1.7	1.1	2.3	0.22	1.1	0.94	0.99	1.1
1997 Feb 06	23:48	42:03	S40W40	1.7	1.0	2.1	1.3	1.4	1.5	3.3	1.4
1998 Mar 10	09:06	22:27	S23E17	2.3	0.69	4.3	0.32	3.7	0.49	0.54	5.4
1998 Jun 22	04:36	16:19	S42W24	2.7	0.47	3.7	0.34	0.91	1.3	0.82	1.9
1998 Oct 15	06:31	18:11	N28E08	1.8	1.4	3.5	0.59	1.7	1.0	0.82	1.2
1999 Apr 17	06:07	15:20	S28W03	1.7	1.3	2.6	0.59	1.7	0.99	1.3	1.4
1999 Apr 18	07:20	11:19	N23E04	2.1	0.71	3.5	0.54	1.9	0.92	0.99	2.6
1999 Sep 16	17:18	22:43	N43W33	1.7	2.0	3.2	1.5	1.2	1.7	1.4	0.60
1999 Oct 13	10:20	20:03	N45E01	1.8	1.4	3.9	1.4	1.0	1.9	1.1	0.72
Mean	...	...	...	1.9	1.3	3.2	1.3	1.5	1.5	1.7	1.4

[a] Start time when we confirmed the beginning of an arcade.
[b] End time when we derived temperature and emission measure.
[c] Location of an arcade at the beginning.

criteria (Table 1). Figure 1 shows soft X-ray images of a typical arcade that occurred on 1992 July 20. Cusp shapes are clearly seen. Similar cusp shapes are also seen in most of the events.

3. DATA ANALYSIS

It is not easy to derive the physical parameters of the arcade, since the arcade has low intensity and the background intensity is not negligible. Average temperature and emission measure of the arcade are derived with their net total intensity. The net intensity of the arcade is derived by subtracting the total intensity of the prearcade region from the total intensity of the arcade.

We use the filter ratio method (Tsuneta et al. 1991; Hara et al. 1992) to derive T and EM, which needs two X-ray images taken at the same time with different filters. A pair of SXT images taken with the Al.1 and AlMg filters is used, whose time interval is less than 3 minutes, and it is assumed that the intensity do not change much in this interval. Therefore, we do not use the interpolation of the intensity. In this way, T_{arc} and EM$_{arc}$ as well as T_0 and EM$_0$ are calculated, where T_0 and EM$_0$ are the temperature and emission measure of the prearcade region. Figure 2 shows the temporal variation of T_{arc} and EM$_{arc}$ of the arcade shown in Figure 1. Errors of T_{arc} and EM$_{arc}$ due to photon noise are negligible.

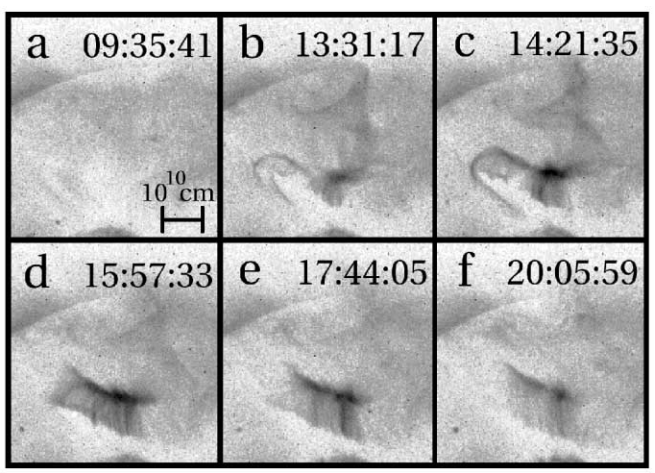

FIG. 1.—SXT images of arcade formation on 1992 July 20. Panels *a–f* show the temporal change. See also Fig. 2 for time profiles corresponding to some of the panels.

We derive n_{arc} and n_0 to study the difference between the arcade and the prearcade regions, where n_{arc} is the arcade coronal electron density. It is defined that EM $= n^2V$, where V is the volume, and hence we must estimate the coronal/arcade volume (V_0 and V_{arc}). Assuming the coronal pressure scale height H_0 as the typical coronal height to estimate V_0, we calculate H_0 with T_0 ($H_0 = R_gT_0/\mu g_\odot$, where R_g is the gas constant, μ is the mean molecular weight, and $g_\odot$ is the gravitational acceleration on the photosphere). Typically, $H_0 \sim 10^{10}$ cm. V_0 is estimated in this way, and n_0 is derived from EM$_0$. In the case of the arcade, a length between footpoints L_{obs} is measured from an SXT image by an eye estimate. Here it is assumed that the cusp height is comparable to L_{obs} as in Shibata & Yokoyama (1999). The length of a magnetic neutral line along an arcade is typically twice as long as L_{obs} (Isobe, Shibata, & Machida 2002). The volume of an arcade is assumed to be $V_{arc} \simeq 2L_{obs}^3$. Consequently, n_{arc} is estimated from EM$_{arc}$.

As a result, we found that $n_{arc} \sim n_0 \sim 10^8$ cm^{-3}, $T_0 \sim 2$ MK, and $T_{arc} \sim 3$–4 MK. These values are consistent with previous results (Hara et al. 1994; Sturrock, Wheatland, & Acton 1996; Wheatland, Sturrock, & Acton 1997). Table 1 shows T_0 and n_0 estimated from 17 prearcade regions. T_{arc}, n_{arc}, and L_{obs} in Table 1 are simultaneous with maximum EM$_{arc}$. Hence, T_{arc} in Table 1 may be lower than maximum T_{arc} by 1–2 MK (see Fig. 2). In the event shown in Figures 1 and 2, T_{arc} is ~ 2.5 MK, which is lower than maximum $T_{arc} \sim 3.5$ MK.

4. DISCUSSION

4.1. *Electron Density and Temperature*

In the previous section we derived the physical parameters of the arcades and found that typically T_{arc} is 4 MK and n_{arc} is 10^8 cm^{-3}. This n_{arc}-value is not much different from n_0. In the case of the flare and the active region, n_0 is typically 10^9 cm^{-3} (Yashiro 2000), while the electron density n_{flr} of the flare loop is $\sim 10^{10}$–10^{11} cm^{-3} (Akiyama 2001). This increase of n_{flr} is

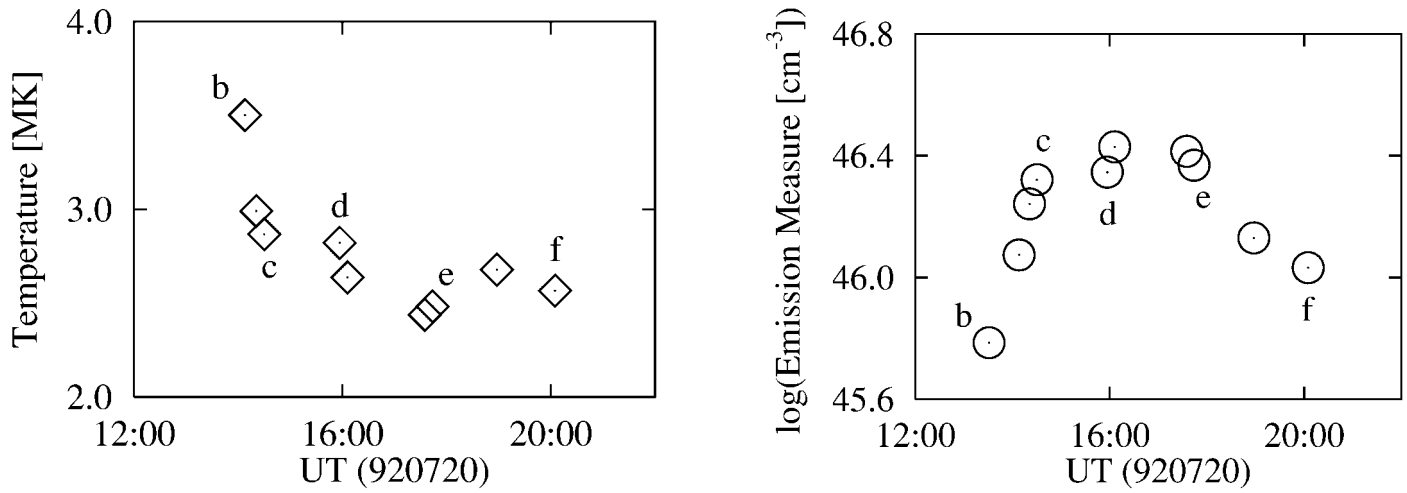

FIG. 2.—Time profile of temperature (*left panel*) and emission measure (*right panel*). Most of the arcades do not show the rise phase of the temperature. Labels refer to the times of images shown in Fig. 1

caused by chromospheric evaporation (Neupert 1968; Hirayama 1974). Hence, our results indicate that chromospheric evaporation is not occurring or is very weak in the arcade. It is known that Hα ribbons associated with arcades are faint (Hanaoka et al. 1994; McAllister et al. 1996a). This also supports weak evaporation in the arcade.

It is generally thought that the chromospheric evaporation is caused by the conduction heating flux and nonthermal high-energy electrons. Considering the balance between magnetic reconnection heating and conduction cooling, Yokoyama & Shibata (1998) derived a scaling law for the flare loop temperature T:

$$T \simeq 10^7 \left(\frac{B}{50\ \mathrm{G}}\right)^{6/7} \left(\frac{n_0}{10^9\ \mathrm{cm}^{-3}}\right)^{-1/7} \left(\frac{L}{10^9\ \mathrm{cm}}\right)^{2/7} \mathrm{K}. \quad (2)$$

This scaling law has been confirmed for flares and microflares observed by SXT (J. Kiyohara et al. 2002, in preparation). Substituting the typical values of B, n_0, and L in equation (2), we obtain

$$T \simeq 3.7 \times 10^6 \left(\frac{B}{5\ \mathrm{G}}\right)^{6/7} \left(\frac{n_0}{10^8\ \mathrm{cm}^{-3}}\right)^{-1/7} \left(\frac{L}{10^{10}\ \mathrm{cm}}\right)^{2/7} \mathrm{K}. \quad (3)$$

Using the data taken with the NASA/National Solar Observatory Spectromagnetograph (Jones et al. 1992) at the Kitt Peak Vacuum Telescope on 1999 April 17 and 18, September 16, and October 13, we found the mean observed magnetic field strength B_{obs} to be 7.2 $\pm$ 2.6 G on the photosphere. On the basis of these observations, the typical field strength is taken to be about 5 G.

Typical temperature 3.7 MK in equation (3) is consistent with the observed temperature of arcades. With these typical values, the conductive thermal flux ($=\kappa_0 T^{7/2}/L$) in the flare is about 230 times as large as that in the arcade. Here $\kappa_0 \simeq 10^{-6}$ cgs is Spitzer's thermal conductivity. The conductive thermal flux causes weak evaporation in the arcade and a difference of the electron density between the flare and the arcade. Shibata & Yokoyama (1999) considered the balance between the enthalpy flux of the evaporated plasma flow and the conduction heating flux and derived the particle number density of the evaporated plasma n_{evap} ($\simeq 10^5 T^2/L$ cm^{-3}). From this equation, n_{evap} is $\sim 10^{10}$ cm^{-3} in the flare and $\sim 10^8$ cm^{-3} in the arcade. The difference in the electron density can be explained in this way.

T_{arc} and n_{arc}, which are lower than those of the flare, make low intensity of the arcade. While the X-ray intensity from the flare dominates the whole X-ray intensity of the Sun, the X-ray intensity from the arcade is often less than 10% of the rest of the Sun. Hence, the arcade cannot be detected with spatially unresolved observations, such as those made with *GOES*.

4.2. *Scaling Law of Loop Length*

Using equation (2), Shibata & Yokoyama (1999) derived equation (1). In order to derive this equation, they assumed two relations: (1) the volume of the flare is $V \simeq L^3$ (EM $\simeq n^2 L^3$), and (2) the gas pressure of the flare loop is as high as the magnetic pressure ($2nk_{\mathrm{B}}T \simeq B^2/8\pi$, where k_{B} is Boltzmann's constant). They derived equation (1) by eliminating B from equation (2) with these relations and found that this equation is useful to explain the length of the flare loop.

To derive L_{theor} we use observed parameters (T, EM, and n_0). Akiyama (2001) measured T_{flr}, $\mathrm{EM}_{\mathrm{flr}}$, and A_{flr} using SXT data, where A_{flr} is the area of flare loop. Here we assume L_{obs} of flares is approximately the square root of A_{flr}. For all flares, n_0 is assumed to be $\sim 5 \times 10^9$ cm^{-3}. Since Yashiro (2000) calculated a mean electron density for an entire active region ($n_0 \sim 10^9$ cm^{-3}) and minimum n_{flr} is $\sim 10^{10}$ cm^{-3}, we assumed $n_{0,\mathrm{min}} \sim 10^9$ cm^{-3} and $n_{0,\mathrm{max}} \sim 10^{10}$ cm^{-3}, where $n_{0,\mathrm{min}}$ and $n_{0,\mathrm{max}}$ are minimum and maximum preflare coronal densities. Figure 3 (*left panel*) shows comparisons of 10 samples between L_{obs} and L_{theor} with $n_{0,\mathrm{min}}$ and $n_{0,\mathrm{max}}$. It is found that $L_{\mathrm{obs}}(n_{0,\mathrm{max}}) = 0.4 L_{\mathrm{obs}}(n_{0,\mathrm{max}})$ from equation (1). This implies that n_0 has a little influence on L_{theor}. It is thought that $n_0 = 5 \times 10^9$ cm^{-3} is appropriate.

In the case of the arcade, let us consider whether the above assumed relations 1 and 2 are proper. Although Shibata & Yokoyama (1999) assumed $V_{\mathrm{flr}} \simeq L^3$, SXT images show clearly $V_{\mathrm{arc}} \neq L^3$. EM is defined as well as in § 3:

$$\mathrm{EM} \simeq 2n^2 L^3. \quad (4)$$

Here three typical values are calculated to be consistent with ob-

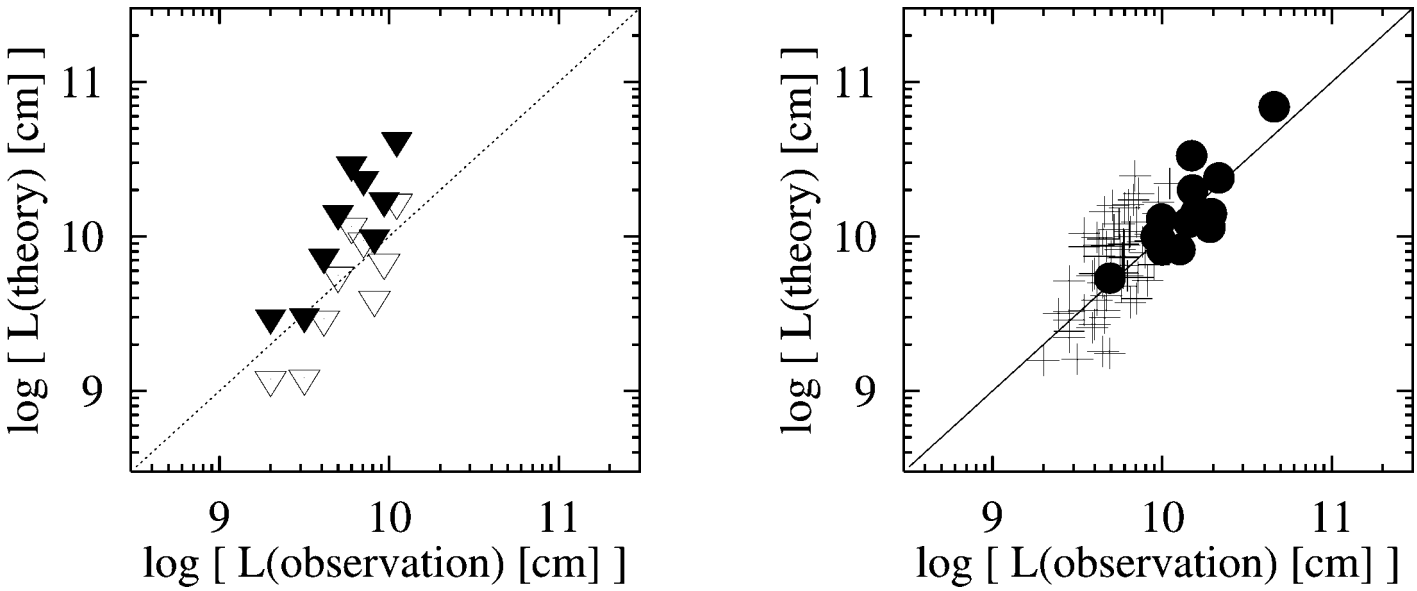

FIG. 3.—Comparison between $n_{0,\min}$ and $n_{0,\max}$ (*left panel*) and $L_{\rm theor}$ and $L_{\rm obs}$ (*right panel*) for arcades and flares. Filled triangles indicate the case of $n_{0,\min}$, and open triangles indicate the case of $n_{0,\max}$. Filled circles show arcades from eq. (6), and crosses show flares from eq. (1).

served values ($\mathrm{EM}_{\rm arc} = 8 \times 10^{46}$ cm^{-3}; $n_{\rm arc} = 2 \times 10^{8}$ cm^{-3}; $L_{\rm obs} = 10^{10}$ cm). Next, we consider the validity of the pressure balance assumption ($2nk_{\rm B}T \sim B^2/8\pi$). Using typical $T_{\rm arc}$, $n_{\rm arc}$, and B, we calculate β [$=2nk_{\rm B}T/(B^2/8\pi)$] and find that $\beta \sim 0.2$;

$$2nk_{\rm B}T \simeq 0.2\,\frac{B^2}{8\pi}\,. \tag{5}$$

Eliminating B and n from equations (3), (4), and (5), we get

$$L_{\rm theor} \simeq 10^{10}\left(\frac{\rm EM}{8\times10^{46}\ \rm cm^{-3}}\right)^{3/5}\left(\frac{n_0}{10^{8}\ \rm cm^{-3}}\right)^{-2/5} \times\left(\frac{T}{3.7\times10^{6}\ \rm K}\right)^{-8/5}\ \rm cm. \tag{6}$$

Figure 3 (*right panel*) shows comparisons between $L_{\rm obs}$ and $L_{\rm theor}$; crosses indicate a flare and filled circles indicate an arcade. Data points of arcades were derived from equation (6) and those of flares were derived from equation (1). $L_{\rm theor}$ roughly match $L_{\rm obs}$ in this figure. From a least-squares fitting program in linear scale, a gradient is ~1.1 for only flares, ~1.5 for only arcades, and ~1.25 for flares and arcades.

In this Letter we found that the scaling law for T is applicable to the arcade. This scaling law indirectly proves that the magnetic reconnection heating is common to the flare and the arcade. Hence, it is important that this scaling law may be useful to the stellar flare. When the scaling law of L is applied to the stellar flare, the dependence of β should be considered. Using $\mathrm{EM} \simeq n^2L^3$, $2nk_{\rm B}T = \beta(B^2/8\pi)$, and equation (2), we get

$$L \simeq 10^{9}\left(\frac{\rm EM}{10^{48}\ \rm cm^{-3}}\right)^{3/5}\left(\frac{n_0}{10^{9}\ \rm cm^{-3}}\right)^{-2/5} \times\left(\frac{T}{10^{7}\ \rm K}\right)^{-8/5}\left(\frac{\beta}{1.0}\right)^{-6/5}\ \rm cm. \tag{7}$$

L is larger in the case of $\beta < 1.0$ than in the case of $\beta = 1.0$.

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