Energy Partition in Four Confined Circular-Ribbon Flares

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Abstract In this study, we investigate the energy partition of four confined circular-ribbon flares (CRFs) that occurred close to solar disk center. The flares are observed simultaneously by the Solar Dynamics Observatory (SDO), the Geostationary Operational Environmental Satellites (GOES), and the Ramaty Hight Energy Solar Spectroscopic Imager (RHESSI). We calculate different energy components, including the radiative outputs in the ranges 1 – 8 Å, 1 – 70 Å, and 70 – 370 Å, total radiative loss, peak thermal energy derived from GOES and RHESSI, nonthermal energy in flare-accelerated electrons, and magnetic free energy before the flares. It is found that the values of energy components increase systematically with the flare class, indicating that more energy is involved in larger flares. The magnetic free energies ($E_{mag}$) are larger than the nonthermal energies ($E_{nth}$) and radiative outputs, which is consistent with the magnetic nature of flares. The ratio $E_{nth}/E_{mag}$ of the four flares, being 0.70 – 0.76, is considerably higher than that of eruptive flares. Hence, this ratio may serve as an important factor for discriminating confined from eruptive flares. The nonthermal energies are sufficient to provide the heating requirements including the peak thermal energy and radiative loss. Our findings impose constraints on theoretical models of confined CRFs and have potential implications on space weather forecast.

Keywords Flares, dynamics · Flares, energetic particles · Heating, in flares · Magnetic fields, corona

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1. Introduction

Solar flares and coronal mass ejections (CMEs) are the most energetic phenomena in the solar system and are considered the main source of space weather (Fletcher et al., 2011; Webb and Howard, 2012; Gopalswamy, 2016; Patsourakos et al., 2020). The accumulated magnetic free energy ($10^{29} - 10^{33}$ erg) in active regions (ARs) is released within a short period of time via magnetic reconnection (e.g. Antiochos, DeVore, and Klimchuk, 1999; Amari et al., 2000; Chen and Shibata, 2000; Lin and Forbes, 2000; Moore et al., 2001). The released energy goes into the thermal energy of localized hot plasmas, kinetic energy of reconnection outflows, kinetic energy of CMEs, nonthermal energies of the accelerated electrons and/or ions, and radiation from radio to hard X-ray (HXR) and even $\gamma$-ray wavelengths (Forbes and Acton, 1996; Stoiser et al., 2007; Kretzschmar et al., 2010; Milligan et al., 2012; Caspi, Krucker, and Lin, 2014; Inglis and Christe, 2014; Warmuth and Mann, 2016a,b). According to their association with CMEs, flares are classified into confined and eruptive types (e.g. Moore et al., 2001; Cheng et al., 2011; Su et al., 2011, 2015; Veronig and Polanec, 2015; Li et al., 2020; Kliem et al., 2021). A large number of confined flares result from failed filament eruptions due to the strong confinement of the overlying field (Ji et al., 2003; Liu et al., 2014; Sun et al., 2015; Zhang et al., 2015; Yang and Zhang, 2018; Yan et al., 2020). Sometimes, confined flares are triggered by loop-loop interaction (Su et al., 2013; Kushwaha et al., 2014; Ning et al., 2018).

Contrary to two-ribbon flares, circular-ribbon flares (CRFs) are a special type that consist of a short, compact inner ribbon and a bright, outer ribbon with a circular or elliptical shape (Masson et al., 2009; Joshi et al., 2015; Liu et al., 2015; Hernandez-Perez et al., 2017; Devi et al., 2020; Kashapova et al., 2020; Prasad et al., 2020; Joshi, Joshi, and Mitra, 2021). The three-dimensional (3D) magnetic configuration of CRFs is usually related to a fan-spine structure associated with a magnetic null point (Wang and Liu, 2012; Zhang et al., 2012; Sun et al., 2013; Hou et al., 2019; Lee et al., 2020; Liu et al., 2020; Yang et al., 2020; Zhang et al., 2021). CRFs are occasionally accompanied by coronal jets or cool surges (Zhang et al., 2016; Li et al., 2017; Xu et al., 2017; Zhang et al., 2020; Dai et al., 2021). The dynamic evolution of CRFs, including magnetic reconnection near the null point, particle acceleration and precipitation, chromospheric evaporation and condensation, are found to resemble those of two-ribbon flares (Zhang, Li, and Ning, 2016; Zhang, Li, and Huang, 2019).

Till now, comprehensive investigations on the energetics of eruptive flares are abundant (Emslie et al., 2004, 2005, 2012; Milligan et al., 2014; Warmuth and Mann, 2016a,b). The energy partition in flares and CMEs are comparable, especially for X-class eruptive flares (Feng et al., 2013). Using multiwavelength observations from the Atmospheric Imaging Assembly (AIA; Lemen et al., 2012) on board the Solar Dynamics Observatory (SDO), the energetics of nearly 400 eruptive flares were studied in detail (Aschwanden, Xu, and Jing, 2014; Aschwanden et al., 2015, 2016, 2017). However, the investigation on energy partition in confined flares is rare. Thalmann et al. (2015) studied an X1.6 flare in active region (AR) 12192 on 22 October 2014. The nonthermal energy ($\approx 1.6 \times 10^{32}$ erg) in flare-accelerated electrons is found to account for $\approx 10\%$ of the free magnetic energy before the flare. Kushwaha et al. (2015) studied an M6.2 flare in AR 10646 on 14 July 2004. The time evolution of the thermal energy is found to show a good correlation with the variation in cumulative nonthermal energy, validating the well-known Neupert effect in confined flares. Zhang et al. (2019) explored various energy components in two homologous confined CRFs of the same class (M1.1) in AR 12434, including the peak thermal energy, nonthermal energy in electrons, total radiative loss of the hot plasma, and radiative outputs in 1 – 8 Å and 1 – 70 Å. The two flares have similar energy partition, and the nonthermal energy is sufficient to provide the heating requirement incorporating the peak thermal energy and radiative loss.
In this study, we select four confined CRFs near solar disk center observed by SDO/AIA (Song and Tian, 2018). In Section 2, we briefly describe the data sets and calibration. We are not interested in the triggering mechanism of each flare, which has been extensively studied. Instead, we focus on the estimation of various energy components in Section 3. The results are compared with previous findings in Section 4. Finally, a summary is given in Section 5.

2. Data Sets and Calibration

The date/time, location, and GOES class of the four flares (CRF1, CRF2, CRF3, and CRF4) are listed in Table 1. Among the four flares, two are M-class and the others are C-class. The flares were observed by SDO/AIA in extreme-ultraviolet (EUV) wavelengths (131, 171, and 304 Å). The AIA level_1 data were calibrated using the standard Solar Software (SSW) program aia_prep.pro. In Figure 1, the 171 Å images illustrate the whole evolution of the flares (see also the online movies: CRF1_2012_May_10.mp4, CRF2_2013_Nov_07.mp4, CRF3_2013_Dec_29.mp4, CRF4_2014_Mar_05.mp4). The four flares share a basic similarity in evolution. The inner ribbons and part of the outer ribbons brightened first. Then the rest of the outer ribbons brightened sequentially, which is consistent with previous findings (Li et al., 2017; Xu et al., 2017). Finally, the brightness of flare ribbons declined gradually with time and died out. It is noted that CRF1 was associated with a blowout coronal jet propagating in the northwest direction, while the remaining three flares were not associated with jets.

The line-of-sight (LOS) and vector magnetograms of the photosphere were observed by the Helioseismic and Magnetic Imager (HMI; Scherrer et al., 2012) on board SDO with cadences of 45 s and 720 s, respectively. The HMI level_1 data were calibrated using the SSW program hmi_prep.pro. Pre-flare vector magnetograms were used to extrapolate the coronal magnetic field. Figure 2 shows vector magnetograms of the four ARs hosting the flares. We carry out potential field extrapolations based on the LOS magnetograms using the Green function method (Chiu and Hilton, 1977; Seehafer, 1978). To carry out the nonlinear force-free field (NLFFF) modeling, we use vector magnetograms and the “optimization” method (Wiegelmann, Inhester, and Sakurai, 2006; Wiegelmann et al., 2008). Pre-processing of the photospheric magnetograms is conducted before the NLFFF extrapolation. Figure 3 shows the nonpotential magnetic configurations (blue lines) of the four flares. The background images of each panel are EUV 304 Å images of the corresponding flares. It is clear that the magnetic configurations of the four flares are dome-like, implying the existence of the well-known fan-spine topology (e.g. Sun et al., 2013; Zhang et al., 2021). For CRF1, the direction of the possible spine line is consistent with the axis of the blowout jet (panel a). Besides, the footpoints of field lines match the ribbons of the flares well, thus validating the reliability of the NLFFF extrapolation.
Figure 1 Snapshots of the four flares in AIA 171 Å. The top row is for CRF1 and the bottom row is for CRF4. Four animations of this figure are available online (CRF1: CRF1_2012_May_10.mp4, CRF2: CRF2_2013_Nov_07.mp4, CRF3: CRF3_2013_Dec_29.mp4, CRF4: CRF4_2014_Mar_05.mp4).

The solar irradiance from a broad band ranging from 1 – 70 Å was directly measured by the EUV SpectroPhotometer (ESP) belonging to the Extreme Ultraviolet Variability Experiment (EVE; Woods et al., 2012) on board SDO. The Multiple EUV Grating Spectrographs (MEGS)-A from EVE, covering a 6 – 37 nm range, records a complete spectrum with a time cadence of 10 s and a spectral resolution of 1 Å. The standard SSW program `eve_integrate_line.pro` is employed to integrate irradiance over 70 – 370 Å using the EVS spectral data from MEGS-A. The soft X-ray (SXR) fluxes of the flares in 1 – 8 Å were recorded by GOES spacecraft. The isothermal temperature \( T_e \) and emission measure (EM) of the SXR-emitting plasma are derived from the ratio of GOES fluxes (White, Thomas, and Schwartz, 2005). The HXR fluxes at different energy bands are obtained from the Ramaty Hight Energy Solar Spectroscopic Imager (RHESSI; Lin et al., 2002). We make HXR images using the CLEAN method (Hurford et al., 2002) at energy bands of 3 – 6 and 6 – 12 keV. The observational properties of the instruments are listed in Table 2.

3. Energy Partition

Using multiwavelength observations, we calculate different energy components, including: (i) radiative outputs in the ranges 1 – 8 Å, 1 – 70 Å, and 70 – 370 Å; (ii) radiative loss from
Figure 2 HMI vector magnetograms of the four ARs hosting the flares. NLFFF extrapolations were performed using these magnetograms. The red boxes indicate regions used for calculating the magnetic free energy, where flares took place.

Figure 3 Nonpotential magnetic configurations of the four flares (blue lines). The background images of each panel are AIA 304 Å images of the flares.

the SXR-emitting plasma; (iii) peak thermal energy of the SXR-emitting plasma; (iv) kinetic energy in flare-accelerated electrons; and (v) magnetic free energy.
Table 2  Description of the observational parameters.

| Instrument | λ (Å) | Cadence (s) | Pixel size (″) |
|------------|-------|-------------|----------------|
| SDO/AIA    | 131, 171, 304 | 12          | 0.6            |
| SDO/HMI    | 6173  | 45, 720     | 0.6            |
| SDO/EVE    | 1 – 70 | 0.25        | …              |
| SDO/EVE    | 70 – 370 | 10         | …              |
| GOES       | 1 – 8  | 2.05        | …              |
| RHESSI     | 3 – 50 keV | 4.0        | 4.0            |

3.1. Radiative Outputs

As described in Feng et al. (2013), the radiative output of a certain waveband (λ) is derived by integrating the background-subtracted light curve (fλ(t)),

\[ U_\lambda = 2\pi d^2 \int_{t_1}^{t_2} f_\lambda(t) \, dt, \]  

where \( d \approx 1.496 \times 10^{11} \) m (1 AU) indicates the distance between the Sun and Earth, \( t_1 \) and \( t_2 \) represent the lower and upper time limits (Zhang et al., 2019).

In Figure 4, the left panels show SXR light curves of the flares in 1 – 8 Å, with dashed lines indicating the background fluxes during them. The right panels show background-subtracted light curves of the flares. The radiative output \( U_{1–8} \) is calculated by integrating the background-subtracted fluxes between the two dashed lines. The values of \( U_{1–8} \), falling in the range \((0.13–1.63) \times 10^{28} \) erg, are listed in the second column of Table 3.

Likewise, the left panels of Figures 5 – 6 show light curves of the four flares in the ranges 1 – 70 Å and 70 – 370 Å. The right panels show the background-subtracted light curves of the flares. The radiative outputs \( U_{1–70} \) and \( U_{70–370} \) are calculated in the same way. The values of \( U_{1–70} \), falling in the range \((2.8–41) \times 10^{29} \) erg, are listed in the third column of Table 3. The values of \( U_{70–370} \), falling in the range \((1.8–19.0) \times 10^{28} \) erg, are listed in the fourth column. It is seen that \( U_{1–70} \) is 15 – 24 times larger than \( U_{70–370} \) and is ≥ 200 times larger than \( U_{1–8} \), which is consistent with previous results for eruptive (Feng et al., 2013) and confined flares (Zhang et al., 2019). The total radiative output \( U_{1–370} \) in 1 – 370 Å of the flares is estimated to be the sum of \( U_{1–70} \) and \( U_{70–370} \), i.e. \( U_{1–370} = U_{1–70} + U_{70–370} \).

3.2. Radiative Loss from the SXR-Emitting Plasma

The total radiative loss from the hot plasma emitting SXR can be expressed as:

\[ T_{rad} = \int_{t_1}^{t_2} EM(t) \times \Lambda(T_e(t)) \, dt, \]  

where \( \Lambda(T_e) \) denotes the radiative loss rate (Cox and Tucker, 1969), \( EM(t) \) and \( T_e(t) \) represent the time evolution of EM and \( T_e \). Figure 7 shows the dependence of \( \Lambda \) on \( T_e \) in the range of \( 10^6 – 10^8 \) K obtained from CHIANTI 9.0 database by adopting the coronal abundances (Dere et al., 2019).

Figure 8 shows EM(t) and \( T_e(t) \) of the four flares derived from GOES observations. The vertical dashed lines indicate \( t_1 \) and \( t_2 \) for the integral in Equation 2. The values of \( T_{rad} \), being \((0.75–2.9) \times 10^{29} \) erg, are listed in the fifth column of Table 3. It is seen that \( T_{rad} \) is several tens of times higher than \( U_{1–8} \) (Feng et al., 2013; Zhang et al., 2019).
3.3. Peak Thermal Energy of the SXR-Emitting Plasma

The thermal energy of the hot plasma of the flares is expressed as:

$$E_{th} = 3n_e k_B T_e f V = 3k_B T_e \sqrt{EM \times fV},$$

where $n_e$ is the electron number density, $V$ is the total volume of the hot plasma, and $f \approx 1$ denotes the filling factor (Emslie et al., 2012; Warmuth and Mann, 2016b). In the following, we calculate the peak thermal energy derived from GOES and RHESSI (Warmuth and Mann, 2016b).

For CRFs, whose outer ribbons hardly expand with time, $V \approx A^{3/2}$ is assumed to be constant, where $A$ denotes the flare area encircled by the outer ribbons (Zhang et al., 2019). Figure 9 shows 131 Å images of the four flares encircled by the white boxes when their brightness is nearly maximal. AIA 131 Å channel is dominated by the emission of the Fe XXI
line \( (\log T \approx 7.05) \) during the flares (Lemen et al., 2012). In Figure 10, the 131 Å light curves of the flares (blue lines) are compared with the SXR light curves (purple lines), showing that the light curves have good agreement with correlation coefficients of 0.96, 0.80, 0.94, and 0.90, respectively. Therefore, the hot plasma observed in 131 Å serves as a proxy of the SXR-emitting plasma. The areas of the flares are calculated by summing up the pixels whose intensities are above an ad hoc criterion, which is taken to be \( \approx 20 \) times higher than the average intensity of the nearby quiet region. The projection effect of \( A \) is corrected by multiplying by a factor of \((\cos \mu)^{-1}\), where \( \mu \) presents the longitude of the flare core. The corresponding values of \( A \) and \( V \) in 131 Å are listed in the second and fourth columns of Table 4. Combining the four flares in this study with the two M1.1 flares in AR 12434, it is found that the thermal source volumes are systematically larger in M-class flares than in C-class flares (Warmuth and Mann, 2020).

Equation 3 indicates that the peak thermal energy is reached when \( T_e \sqrt{\text{EM}} \) is maximal. Using observations from GOES (Figure 8), we calculate the peak values of \( E_{\text{th,G}} \), which are listed in Table 3 and Table 4. The peak values \( E_{\text{th,G}} \) fall in the range \( (5.3 - 24.6) \times 10^{29} \) erg.

Figure 5  Left panels: light curves of the flares in 1 – 70 Å observed by SDO/EVE. The dashed lines indicate the background fluxes during the flares. Right panels: background-subtracted light curves of the flares in 1 – 70 Å. The vertical dashed lines represent the lower and upper time limits of the integrals in Equation 1.
Figure 6  Left panels: light curves of the flares in 70–370 Å observed by SDO/EVE. The dashed lines indicate the background fluxes during the flares. Right panels: background-subtracted light curves of the flares in 70–370 Å. The vertical dashed lines represent the lower and upper time limits of the integrals in Equation 1.

Figure 7  Radiative loss rate \( \Lambda(T_e) \) as a function of temperature \( (T_e) \) calculated from CHIANTI 9.0 database.
Figure 8  Time evolutions of $T_e$ and EM of the four flares obtained from GOES observations.

Table 3  Event list with component energies in units of $10^{29}$ erg. The second to fourth columns are the radiative outputs in 1 – 8 Å, 1 – 70 Å, and 70 – 370 Å. $T_{rad}$ represents the total radiative loss of the SXR-emitting plasma. $E_{th,G}$ and $E_{th,R}$ represent the peak thermal energy derived from GOES and RHESSI observations, respectively. $E_{nth}$ indicates the nonthermal energy in flare-accelerated electrons. $E_{mag}$ indicates the magnetic free energy stored in the ARs before the flares.

| Flare | 1–8  | 1–70 | 70–370 | $T_{rad}$ | $E_{th,G}$ | $E_{th,R}$ | $E_{nth}$ | $E_{mag}$ | $E_{nth}$/$E_{mag}$ |
|-------|------|------|--------|----------|------------|------------|----------|----------|-------------------|
| CRF1  | 0.163| 41.0 | 1.90   | 2.9      | 20.00      | 6.26       | 130      | 172.0    | 75.6%             |
| CRF2  | 0.085| 17.0 | 0.73   | 2.8      | 24.60      | 4.43       | 4.6      | 69       | 97.6%             |
| CRF3  | 0.030| 6.1  | 0.30   | 0.75     | 5.27       | 3.45       | 1.5      | 19       | 25.2%             |
| CRF4  | 0.013| 2.8  | 0.18   | 0.86     | 5.34       | 2.88       | 1.9      | 13       | 17.6%             |

The total heating requirements of the flares, including the peak thermal energy and radiative loss, are estimated to be $(0.6 – 2.7) \times 10^{30}$ erg. The conductive energy loss is not considered in this study since conduction could be severely suppressed or conduction loss is recycled through conduction-driven evaporation (Warmuth and Mann, 2020). Note that CRF1 was accompanied by a blowout jet. The total thermal energy of CRF1 and the jet is estimated to be $(2.3 – 2.5) \times 10^{30}$ erg, considering that the thermal energy of the jet accounts for $\frac{1}{7}$ to $\frac{1}{4}$ of the flare at the jet base (Shimojo and Shibata, 2000).

Figure 11 shows the HXR images of the four flares near the HXR peak times. The energy bands are 6 – 12 keV for the two M-class flares and 3 – 6 keV for the two C-class flares. It is clear that the HXR source is unique and small for each flare. The contours of 50% peak intensities are drawn with black lines. The 6 – 12 keV sources of the two M-class flares and 3 – 6 keV sources of the two C-class flares are considered. The area of the thermal source observed by RHESSI is taken to be the total area of the pixels within the black lines. However, we find that the area and volume are comparable for different energy bands. The corresponding values of $A$ and $V$ are listed in the third and fifth columns of Table 4.
Figure 9  AIA 131 Å images of the four flares near their peak times. Intensity contours of the images are drawn with black solid lines. The white boxes indicate the areas used for calculating the light curves in Figure 10.

Table 4  Evaluation of the physical parameters of the flares. The area ($\times 10^{18} \text{ cm}^2$) and volume ($\times 10^{28} \text{ cm}^3$) are calculated in AIA 131 Å and in HXR. The peak thermal energy ($\times 10^{29} \text{ erg}$) of the hot plasma is derived from GOES observation ($E_{\text{th,G}}$) and RHESSI observation ($E_{\text{th,R}}$), respectively.

| Flare | $A_{131}$ | $A_{\text{HXR}}$ | $V_{131}$ | $V_{\text{HXR}}$ | $E_{\text{th,G}}$ | $E_{\text{th,R}}$ |
|-------|-----------|-----------------|---------|-----------------|-----------------|-----------------|
| CRF1  | 4.63      | 2.69            | 1.00    | 0.44            | 20.00           | 6.26            |
| CRF2  | 4.86      | 1.78            | 1.07    | 0.24            | 24.60           | 4.43            |
| CRF3  | 2.11      | 2.46            | 0.31    | 0.39            | 5.27            | 3.45            |
| CRF4  | 2.16      | 2.36            | 0.32    | 0.36            | 5.34            | 2.88            |

Figure 12 shows selected HXR spectra of the four flares obtained from RHESSI observations. The spectra are fitted with a combination of a thermal component and a thick-target nonthermal component. The fitting is performed using the standard SSW program thick2.pro in the OSPEX package. The parameters of the thermal component, including $T$ in units of MK and EM in units of $10^{49} \text{ cm}^{-3}$, are labeled. Using Equation 3, the peak thermal energies ($E_{\text{th,R}}$) derived from RHESSI are calculated and listed in Table 3 and Table 4. The ratio of $\frac{E_{\text{th,G}}}{E_{\text{th,R}}}$ is obtained and listed in the eighth column of Table 3. It is revealed that the ratio is greater than 1.0 for all events, which is consistent with previous results (Warmuth and Mann, 2020).
Figure 10  AIA 131 Å light curves (blue lines) and SXR light curves (purple lines) of the four flares.

Figure 11  HXR images of the four flares near the HXR peak times. The energy bands are 6 – 12 keV for the two M-class flares and 3 – 6 keV for the two C-class flares, respectively. The black lines represent contours of 50% peak intensities.
Figure 12  Selected HXR spectra of the four flares obtained from RHESSI observations and the corresponding normalized residuals of the spectral fitting. The observed data are represented by the points with error bars. The fitted thermal and nonthermal power-law components are drawn with dot-dashed lines and dashed lines, respectively. The sum of both components are drawn with thick solid lines. The fitted parameters, including $T$ in units of MK, EM in units of $10^{49}$ cm$^{-3}$, and the power-law index of the electrons are labeled.

3.4. Nonthermal Energy in Flare-Accelerated Electrons

To estimate the nonthermal energy in flare-accelerated electrons, we integrate the power of the injected electrons ($P_{nth}$) over time (Ning and Cao, 2010):

$$E_{nth} = \int_{t_1}^{t_2} P_{nth}(t) dt = \int_{t_1}^{t_2} \frac{dE_{nth}}{dt} dt,$$

(4)
where $t_1$ and $t_2$ represent the start and end times of the flare at the energy band of 25 – 50 keV. Here, $P_{nth}(t)$ can be calculated by integrating the electron power-law spectrum above a low energy cutoff ($E_c$) and below a high energy cutoff ($E_h \approx 30$ MeV):

$$P_{nth}(t) = \frac{dE_{nth}}{dt} = \int_{E_c}^{E_h} A_0 E_0^{-\delta} dE_0,$$

(5)

where $A_0$ is the electron flux in units of $10^{35}$ electrons s$^{-1}$, and $\delta$ is the power-law index of the nonthermal electrons (see Figure 12). The values of $E_c$ are 20, 30, 23, and 28 keV, respectively. Using Equation 4 and the above parameters, we estimate the total nonthermal energy in flare-accelerated electrons. The values of $E_{nth}$, falling in the range $(1.3–13) \times 10^{30}$ erg, are listed in the ninth column of Table 3. The ratio of $E_{nth}/E_{th,G}$ is between $\approx 2.4$ and $\approx 6.5$. It should be emphasized that these calculated values are lower limits of real nonthermal energies, which rely sensitively on $E_c$ (Warmuth and Mann, 2020). Besides, we do not consider the nonthermal energy in flare-accelerated ions.

3.5. Magnetic Free Energy

As mentioned in Section 2, Figure 2 shows the vector magnetograms of the four ARs where the flares took place. Both potential field and nonpotential field extrapolations are performed. Figure 3 shows the nonpotential magnetic field lines (blue lines) of the magnetic configuration. The magnetic free energy ($E_{mag}$) is defined as the excess magnetic energy of the NLFFF ($E_{np}$) relative to the energy of potential field ($E_p$):

$$E_{mag} = E_{np} - E_p = \int_V \frac{B_{np}^2 - B_p^2}{8\pi} dV,$$

(6)

where $B_{np}$ and $B_p$ stand for the nonpotential and potential field strength, respectively. We calculated $E_{mag}$ in the flare regions as enclosed by the red boxes in Figure 2. The estimated $E_{mag}$, ranging from $1.8 \times 10^{30}$ to $1.7 \times 10^{31}$ erg, are listed in the tenth column of Table 3. It is obvious that the free magnetic energies are larger than the nonthermal energies and radiative output in the range 1 – 370 Å, indicating that the accumulated free energy before the flare is sufficient to provide the kinetic energy in flare-accelerated electrons and radiation, thus validating the magnetic nature of confined flares (Priest and Forbes, 2002). The ratio of $E_{nth}/E_{mag}$ for CRFs falls in the range of 70 – 76% (see the last column of Table 3), which is much higher than that of X-class eruptive flares (Feng et al., 2013; Thalmann et al., 2015). In other words, more free energy is converted into the kinetic energy of flare-accelerated electrons in confined flares than in eruptive ones, because a large fraction of the free energy is converted into kinetic, thermal, and potential energies of CMEs for eruptive flares (Reeves et al., 2010; Emslie et al., 2012; Feng et al., 2013).

4. Discussion

As mentioned in Section 1, Zhang et al. (2019) explored the energy partition in two M-class CRFs. The radiative outputs in 1 – 8 Å and 1 – 70 Å are obtained using the observations of GOES and SDO/EVE. The total radiative loss and peak thermal energy are calculated using the observations of GOES and SDO/AIA. The nonthermal energy of electrons is derived using the observation of RHESSI (see their Table 2). The radiation in 70 – 370 Å, total solar
Figure 13  Energy components of the four events in this study and the previous two events in Zhang et al. (2019). The six events are arranged with increasing flare importance (see text for details). The radiative outputs in 1 – 8 Å, 1 – 70 Å, 70 – 370 Å, total radiative loss, peak thermal energy derived from GOES and RHESSI, nonthermal energy in electrons, and magnetic free energy are labeled with red squares, green rectangles, blue diamonds, cyan hexagons, magenta triangles, yellow triangles, orange triangles, and black circles, respectively.

irradiance, nonthermal energy of ions, and dissipated magnetic free energy are estimated according to previous statistical works (Woods et al., 2004; Emslie et al., 2012; Aschwanden et al., 2017). In this study, we calculate the radiation in 70 – 370 Å using the observations of SDO/EVE and magnetic free energy using magnetic extrapolations based on the vector magnetograms from SDO/HMI. The results combining these six events with increasing flare importance (or peak GOES flux) are plotted in Figure 13. The orders of magnitude of the energy components are clearly seen. Moreover, for each component, the values increase systematically with flare importance, suggesting that more energy is involved in larger flares. Our findings are in accordance with previous statistical results (Warmuth and Mann, 2020).

In Figure 14, the left panel shows a scatter plot of the six events. The relationship between the nonthermal and thermal energies is illustrated with cyan circles, while the relationship between the nonthermal energy and heating requirement (including the thermal energy and radiative loss) is illustrated with magenta circles. There is a good linear correlation between the nonthermal and thermal energies, validating previous results for nine medium-sized flares (Saint-Hilaire and Benz, 2005). It is obvious that the nonthermal energies are higher than the heating requirements of the hot plasma, at least for the six events we have studied. Kushwaha et al. (2015) investigated an M6.2 confined flare on 14 July 2004. The peak thermal and nonthermal energies are calculated to be $3.89 \times 10^{29}$ erg and $3.03 \times 10^{30}$ erg, respectively. Hence, the ratio of $E_{nth}/E_{th}$ reaches $\approx 7.5$, which is consistent with the present work.

The right panel of Figure 14 shows a scatter plot of the six events to illustrate the relationship between the maximal temperatures of GOES ($T_G$ in MK) and RHESSI ($T_R$ in MK). It is seen that $T_R$ is higher than $T_G$ in most cases and a good linear correlation exists between the two parameters. A linear fit yields $T_R = 1.65 T_G - 5.85$, which lies between $T_R = 1.12 T_G - 3.12$ (Battaglia, Grigis, and Benz, 2005) and $T_R = 1.78 T_G - 4.61$ (Warmuth and Mann, 2016a). It is noted that our study has limitations due to the small sample size. Additional statistical studies using more events and numerical simulations are worthwhile to draw a decisive conclusion.
5. Summary

In this article, we investigate the energy partition of four confined circular-ribbon flares that occurred near solar disk center. Using multiwavelength observations from SDO, GOES, and RHESSI, we calculate different energy components, including the radiative outputs in 1–8 Å, 1–70 Å, and 70–370 Å, total radiative loss, peak thermal energy derived from GOES and RHESSI, nonthermal energy in flare-accelerated electrons, and magnetic free energy before the flares. The main results are as follows:

i) The energy components increase systematically with the flare importance or peak GOES flux, indicating that more energy is involved in larger flares. The magnetic free energies are larger than the nonthermal energies and radiative outputs of the flares, which is consistent with their magnetic nature. The ratio $\frac{E_{\text{nth}}}{E_{\text{mag}}}$ of the four flares, being 0.70–0.76, is considerably higher than that of eruptive flares. Hence, this ratio may serve as an important factor to discriminate confined from eruptive flares. The nonthermal energies are sufficient to provide the heating requirements including the peak thermal energy and radiative loss.

ii) Our findings impose constraints on theoretical models of confined CRFs and have potential implications for space weather forecast. Statistical studies based on a larger sample are especially needed to draw decisive conclusions.

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