Refinements to flare energy estimates - a follow-up to "Energy Partition in Two Solar Flare/CME Events"

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Abstract.

Emslie et al. [2004] reported estimates of the energy in the different flare and CME components of two major solar events with unprecedented observational coverage, one on 21 April 2002 and the other on 23 July 2002. Based on these estimates, it appeared that the summed energy content of the different flare components was significantly lower than the total energy of the CME, leading them to reach the "cautious" conclusion that "in both events the coronal mass ejection has the dominant component of the released energy," amounting to approximately 30% of the available magnetic energy. In this note, we present revised estimates of the flare thermal energies in the two events, and also add a consideration of the total radiant energy of the events obtained by scaling the measured soft X-ray luminosity based on SORCE total solar irradiance measurements for the 28 October 2003 event. Recognizing that many of these energetic components are inter-related, we also take care to distinguish between "primary" components of energy (e.g., the magnetic field), "intermediate" components (e.g., accelerated particles and thermal plasma), and "final" components (e.g., kinetic energy of ejecta, radiant energy in various wavebands). We note that since the values of these components are not all independent, careful tallying is necessary to arrive at an overall energy budget for the event. The best estimates for the energies of the various components still show that the CME contains the greatest fraction of the released energy in both events. However, given the large uncertainties in the energies of the different flare components and the higher estimates of radiant energy obtained by scaling from the SORCE measurements, the results are also consistent with the flare and CME energies in both events being comparable, with a common value of $\sim 10^{32}$ ergs.

1. Introduction

A solar flare/coronal mass ejection (CME) event is basically a process in which stored magnetic energy is converted into various forms that propagate in the solar atmosphere and through interplanetary space. Determining the partition of energy amongst the various components provides valuable information about the fundamental energy release process or processes.

Ultimately, all of the energy released in a flare/CME event appears either in ejected particles and fields, or as enhanced radiative output. No controversy about the large energy involved in radiation exists observationally, even though the relevant UV observations remain surprisingly incomplete. *Canfield et al.* [1980] estimated a partial set of radiative components of a flare on 1973 September 5 in order to estimate the total radiated energy. Following a somewhat different approach, *Emslie et al.* [2004] studied the partitioning of energy in two specific solar flare/CME events, using as much reliable data as was available, not only on radiative output, but also on the energy of the ejected CMEs and solar energetic particle streams. They also used hard X-ray and gamma-ray observations to deduce the energy transported by intermediate entities, such as energetic electrons and ions, and reached the "cautious" conclusion (paragraph [56]) that "in both events the coronal mass ejection has the dominant component of the released energy."

In discussing the energetic content of components such as accelerated electrons and ions, it is important to realize that the energy inferred to be present in these particles is far greater than that in the corresponding diagnostic radiation fields (hard X-rays and gamma rays, respectively) used to obtain the energy estimates. Further, as noted in paragraph [55] of *Emslie et al.* [2004], "not all these energy contents are independent: for example, the energy in non-thermal electrons is converted through Coulomb collisions into energy in the thermal plasma. Hence, one should not simply sum these individual components to get a 'total' energy for the event." They go on to say (paragraph [56]) that "the rest of the energy deposited by these particles is presumably converted into radiation in other wavebands, e.g., EUV, optical." In tallying the total energy released in a given event and in ascertaining the relative contributions of various components of released energy, it is therefore important to "do the books" correctly, with explicit recognition of the transformation of energy from one form to another. Specifically, the energy emitted in optical and UV emission must be considered (at least in part) as a redistribution of the accelerated particle components already evaluated, not as an extra amount of energy to be added to the flare budget. In this paper we present revised energy budgets for the two events studied by *Emslie et al.* [2004] with the above comments in mind.

2. Radiated Energies

2.1. Soft X-rays

A major challenge to the estimation of flare energetics lies in the estimation of the energy that heats the soft X-ray-emitting flare plasma. This is primarily because both

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the volume filling factor (that determines the instantaneous energy content) and the conductive cooling rate (that determines the rate at which new energy must be supplied) are largely unknown. *Emslie et al.* [2004] assumed that the filling factor was unity and that conductive cooling was negligible compared to radiative cooling. The first assumption results in an over-estimate of the thermal energy; the latter in an under-estimate (see equation [1] of *Emslie et al.*, [2004]). They estimated the total energies required to heat and maintain the plasma at temperatures above ~ 10 MK to be $10^{31.3^{+0.4}_{-1}}$ ergs for the 21 April flare and $10^{31.1^{+0.4}_{-1}}$ ergs for the 23 July flare. These numbers are given in their Table 3 and labeled as U_{th}. In fact, these numbers for each flare are the sum of the peak thermal energy of the plasma plus the additional energy required to maintain the plasma with the measured emission measure and temperature during the decay phase of the flare.

We here report on two revisions to these numbers and a clarification. One change resulted from a numerical error and requires that all the time-integrated radiated energies be increased by a factor of 3. The other results from the new estimates of temperatures and emission measures from GOES data given by *White et al.* [2005] using the latest version of the Chianti atomic data base. This requires an increase in the calculated temperatures of $\sim$1 MK and a decrease in the calculated emission measures by a factor of ~ 4 if coronal abundances are used. Fortunately, these two revisions serendipitously almost cancel one another out.

In addition to these two revisions of the numbers, we have clarified the division of energy input between the impulsive and gradual phases of the flares and between the thermal energy of the plasma (U_{th} in Equation (1) of *Emslie et al.*) and the radiated energy from the plasma. A firm lower limit to the radiated energy can be rather straightforwardly obtained as a function of time from the GOES soft X-ray data. Assuming a single temperature plasma, the temperature and emission measure can be obtained as a function of time throughout the flare using the prescription given by *White et al.* [2005]. Then the radiative loss rate from plasma at that temperature can be calculated using the Chianti version of the *Cox and Tucker* [1969] radiative cooling rates for coronal abundances. Integrating these values over the duration of the flares gives values of U_R of $10^{31.3}$ ergs for the 21 April flare and $10^{31.0}$ ergs for the 23 July flare. Note that no knowledge of the source volume, density, or filling factor is required to make this calculation. The quoted uncertainties of a factor of two are based on the uncertainty in the iron abundance, the radiative loss curve, and the emission measure and temperature estimates.

The agreement within uncertainties between these radiated energy numbers and the inferred peak energies for the soft-X-ray-emitting plasma (U_{th}^{peak} in Table 1) suggests that the simplifying assumptions of neglecting conductive cooling and unit filling factor are not unreasonable. In particular, the volume filling factor for the soft-X-ray-emitting plasma cannot be too small (< 0.01), otherwise the plasma energy calculated using the RHESSI source areas would be significantly below this lower limit.

The results of these calculations for the two flares of interest are given in Table 1, which is a modified version of Table 3 in *Emslie et al.* [2004]. We separate the peak energy in the thermal plasma U_{th}^{peak} from the total energies radiated during the impulsive and gradual phases. The best comparison with the thermal plasma energies given by Emslie et al. is with the total radiant energies U_R listed in Table 1 as being "From GOES plasma." The differences are less than a change of 0.1 in the logarithm.

2.2. Optical and EUV

Two of the best-studied radiative signatures of solar flares are emission in Hα (chromospheric) and soft X-rays (coronal; e.g., *Thomas and Teske*, 1971). However, the total radiant energy of a flare is thought to be a factor of between 5 and 20 larger than the energy in either of these two components [*Hudson and Willson*, 1983; *Hudson*, 1991; *Shimizu*, 1994]. Clearly, the energy radiated in the optical and UV continua is an important component of the released energy in a flare. No direct measurements of these components were available for the two events studied by *Emslie et al* [2004]. They avoided the use of proxies and ensemble-average scaling laws [e.g., *Hudson et al.*, 1978], but in order to extend their analysis to include the important optical and UV radiative components, we here take the (cautious) step of using a scaling law based on the first measurement of total flare irradiance.

Recently, *Kopp et al.* [2004] and *Woods et al.* [2004], utilizing the the Total Irradiance Monitor (TIM) on The Solar Radiation and Climate Experiment (SORCE) were able to measure the total irradiance of a solar flare for the first time. They found a total radiated energy $U_R = 4.6 \times 10^{32}$ ergs for the X17 flare of 28 October 2003. (This must be considered a lower limit, since the excess emission could be measured for only 20 minutes at the peak of the event whereas it was seen with GOES for at least 6 hours.) The integrated radiated energy in the GOES $1-8$Å soft X-ray band was only 5.4×10^{30} ergs for the whole event. Thus, the SORCE direct measurement indicates that the total radiant luminosity ($L_{\rm total}$) was some 100 times the X-ray luminosity (L_X), significantly larger than the ensemble average factor of 5 - 20 cited in the preceding paragraph. We do not have total irradiance observations for the flares analyzed by *Emslie et al.* [2004], but a scaling of the GOES X-ray fluence for the $1-8$Å band using $L_{\rm total}/L_X = 100$ gives total radiant energies $U_R \equiv L_{\rm total}$ of $10^{32.1}$ ergs for both the 21 April 2002 and 23 July 2002 flares. These estimates of the total radiated energy U_R are well above the GOES-inferred lower limits in Table 1.

3. "Intermediate" Energy Components

An important aspect of the *Emslie et al.* [2004] paper is the explicit calculation of the energy in precipitating electrons and ions from observations of hard X-rays and gamma-rays, respectively. They obtained values between $\sim 10^{31.3}$ and $10^{31.9}$ ergs for the two events, albeit with quite large uncertainties (see their Table 3). It should be noted that these energies are *not* directly observed in some radiated component; rather they are *inferred* from the hard X-rays and gamma-rays that the particles produce and which typically amount to only some 10^{-5} of the energy in the producing particles. The remainder of the particle energy goes to heat the ambient plasma and ultimately produce optical and/or UV emission, depending on the penetration depth of the particles. Because of the possibility for "double-counting" that this raises, we present in Table 1 separate tabulations of energy values corresponding to "primary" components (i.e., the magnetic field), "intermediate" components (i.e., those that are produced directly during the energy release process and that subsequently transport energy throughout the flare plasma, such as nonthermal particles), and "final" components (i.e., those that leave the system, such as interplanetary high-energy particles, bulk mass motion in the CME, and radiation). This distinction helps to avoid multiple counting in assessing the total energy released to produce the different flare aspects of the events since, clearly, it is not correct to simply add the energies of inter-related components to arrive at a total energy for the event.

Where possible, we have further divided the flare components in Table 1 into those pertinent to both the impulsive and gradual phases of the flare, i.e., before and after the

Table 1. CME/Flare Energy Budget for the 21 April and 23 July 2002 events. (Revised version of Table 3 in *Emslie et al.* [2004])

Mode	Symbol	21 April 2002 Impulsive	21 April 2002 Gradual	21 April 2002 Total	23 July 2002 Impulsive	23 July 2002 Gradual	23 July 2002 Total
Primary							
Magnetic	U_{B}	-	-	32.3 ± 0.3	-	-	32.3 ± 0.3
Flare							
Intermediate							
Electrons ($> E_{\mathrm{min}}$)	U_{e}	31.3 ± 0.5	-	31.3 ± 0.5	31.5 ± 0.5	-	31.5 ± 0.5
Ions (> 1 MeV nucleon^{-1})	U_{i}	< 31.6	-	< 31.6	31.9 ± 0.5	-	31.9 ± 0.5
Thermal Plasma ($T > 5$ MK)	U_{th}^{peak}	$31.1^{+0.4}_{-1.0}$	-	-	$30.4^{+0.4}_{-1.0}$	-	-
Final - Radiant Energy							
From GOES plasma	U_R	30.4 ± 0.3	31.1 ± 0.3	31.3 ± 0.3	29.6 ± 0.3	31.0 ± 0.3	31.0 ± 0.3
Assuming $L_{total}/L_X = 100$	U_R	31.5 ± 0.3	32.1 ± 0.3	32.2 ± 0.3	31.3 ± 0.3	32.1 ± 0.3	32.2 ± 0.3
CME							
Kinetic	U_{K}	-	-	32.3 ± 0.3	-	-	32.0 ± 0.3
Gravitational Potential	U_{Φ}	-	-	30.7 ± 0.3	-	-	31.1 ± 0.3
Energetic Particles at 1 AU	U_{p}	-	-	31.5 ± 0.6	-	-	< 30

time of peak energy in the soft X-ray emitting plasma. This enables a comparison to be made between the energy in electrons and ions accelerated during the impulsive phase and the energy in the thermal plasma as it appears during the impulsive and gradual phases. As has been found previously, the accelerated particles carry a surprisingly large fraction of the released energy during the impulsive phase of these two flares but relatively little, if any, during the gradual phase. It is interesting to note that the SORCE detection of the total irradiance of the 28 October 2004 flare suggests that the total-irradiance light curve peaked prior to the GOES soft X-ray peak, showing that, for that flare at least, most of the energy release occurred during the impulsive phase. The gradual energy release after the soft X-ray peak appears to be purely thermal for these two events since there was no *RHESSI* detection of hard X-rays or gamma-rays at this time. The energy release during the gradual phase is difficult to estimate because of the uncertainty in the conductive cooling rate. We have assumed that this is negligible compared to the radiative cooling so the quoted energies should be considered as lower limits. With this proviso, the total energy released in each of the two phases appears comparable for both events.

The results in Table 1 show, not surprisingly, that the energy in the hot thermal plasma, the total radiant energy and the energy in "intermediate" forms such as accelerated electrons and ions, are comparable in magnitude. Since, as pointed out above, it would be incorrect to sum these (interrelated) components to obtain the total flare energy, we see why *Emslie et al.* [2004] reached the cautious conclusion that the characteristic energy of any "flare" component is still an order of magnitude or so less than the kinetic energy in the CME. However, given the large uncertainties in the estimated values of all the component energies, the total flare energy could be significantly higher than any of the component energies calculated here, and indeed comparable to the energy in the CME. Interestingly, within the admittedly large uncertainties, the estimated energy in > 1 MeV ions in the 23 July event could be even *larger* than the CME kinetic energy. Also, if we scale the soft X-ray radiant energy by the same factor derived from the SORCE total irradiance measurements, we get total flare radiated energies equal to the CME energies in both cases. Thus, it is entirely possible that for the two events studied by *Emslie et al.* [2004], the flare and CME energies were, in fact, comparable.

4. Conclusions

Flares and CMEs each constitute large energy releases from coronal magnetic storage; however, the total energy and its partition amongst the different components still remain difficult to assess. Newer data (and theory) have sharpened our estimates for the different components, as reported by *Emslie et al.* [2004]. In this paper, we have added an estimate of the total radiant energy using the soft X-ray luminosity of the two events studied in that paper and applying a scaling based on concurrent observations of soft X-ray and total radiant luminosities in a third event. We have also made two compensating adjustments to the calculation of the energy in the thermal flare plasma. With these changes, we find that the energy estimates based on the assumptions of negligible conductive cooling and an X-ray filling factor of unity agree remarkably well with estimates of the total radiated energy. Furthermore, although the CME kinetic energy remains the largest term in the estimated energy budget for each event, we must, given the large uncertainties of all the component estimates, allow for the possibility that the flare and CME energies are all approximately equal, with a value $\sim 10^{32}$ ergs for both events.

Proxy-based scaling laws (such as the one used to determine the total radiant energy U_R in this paper) are some-times all we have to estimate unobserved components of the flare energy. However, it is clearly preferable, where possible, to analyze observations of specific events, rather than to employ arguments based on ensemble averages. Hence we encourage (and are indeed currently engaged in) analyses of specific events for which extensive observations, relating more directly data to the many different components of the released energy, are available. In particular, we look forward to future measurements of the increase in the total solar irradiance during a flare in coincidence with the detailed observations of the different flare and CME components that have been discussed here and in *Emslie et al.* [2004]. Until then, we are limited to using proxy scalings and simplifying assumptions to fill in the gaps in our knowledge in order to make the best possible estimates of the total energy released in a flare/CME event.

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