The Variation of Emission Measure Versus Temperature During Solar Flares Observed by the Yohkoh SXT and GOES

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**Abstract.** Using *Yohkoh* SXT and *GOES* data, we have calculated the variation of temperature, \( T \), versus emission measure, \( EM \), in the flare decay phase. There were 45 flares which had good coverage by both SXT and *GOES* for the entire flare, with a single peak in soft X-rays. The *GOES* temperature is typically higher than the SXT temperature, and the cooling times as measured by *GOES* are shorter than those measured using SXT. This shows that the flare plasma is not isothermal and that higher temperature plasma cools faster. From an analysis of differential emission measure models, we estimate the dependence of the plasma cooling time as a function of temperature.

1. Introduction

Solar flares as seen by the *Yohkoh* Soft X-ray Telescope (SXT) typically start with a clearly defined structure, often a single or multiple loop source. As a flare progresses, it usually evolves into one bright source, observed to be at a loop-top, when loop structure is discernible. This source dominates the gradual phase of the soft X-ray emission, and is where the highest temperatures are observed (Feldman et al. 1994).

The plasma in the loop cools by heat conduction or radiation. The purpose of this study is to examine the variation of the plasma temperature and emission measure during the decay phase and see how this variation compares with expected behavior.

The SXT has the ability to determine the plasma temperature using the ratio of the responses through two different filters (McTiernan et al. 1993). The best filter pair to use for flares is the thick Aluminum (Al12) and Beryllium (Be119) filter pair. Note that, if the plasma is not isothermal, different filter pairs give different temperature measurements.

From the start of the *Yohkoh* mission until 1 Jan 1995, the SXT observed 1261 events in flare mode which had non-zero emission for both the Al12 and Be119 filters. *GOES* data for this period is also available. The temperatures and emission measures for the *GOES* data were obtained using the ratios of the responses of the two *GOES* channels in a similar manner to the SXT.

There were 45 flares which had both SXT and *GOES* coverage for the entire flare, with single peaks in the emission measure for both instruments, and SXT flare mode observations that lasted long enough for the SXT emission...
measure to decrease by a factor of 4 from its maximum. Two effects reduced the
sample to such a small number: (1) GOES is a full-sun instrument and flares
unrelated to the initial flare can occur during the decay phase; events of that
type were discarded. (2) SXT often misses the early part of the flare; often the
GOES temperature (and possibly the SXT temperature) peaked before the SXT
observations began; flares for which the maximum SXT temperature or emission
measure were obtained for the initial filter pair were discarded.

2. Results

For both the SXT and GOES, the temperature peaks before the emission mea-
sure, by a long as a few minutes. Thus there is cooling while the emission
measure is still increasing. This is typical behavior, and has been related to
evaporative conductive cooling (Antiochos & Sturrock, 1978). The GOES maxi-
imum temperature is higher than the SXT maximum temperature by an average
of 15%. The GOES T and EM peaks occur before the SXT peaks, and the
GOES emission decays faster than the SXT emission. This behavior is seen in
most, but not all, flares. The value of T that is observed depends on the en-
ergy bandpass of the detector used, and it is clear from this that the plasma is
not isothermal. We characterize this by using the differential emission measure
(DEM), q(T), which denotes the emission measure per unit T as a function of
T. The total emission measure is \( \int q(T) dT \), and the response in a given detector
channel (or filter) is given by \( \int q(T) \ast g(T) dT \), where g(T) denotes the response
of that channel to a plasma at T. The GOES detector bandpass extends to
higher energy (> 20 keV) than the SXT detector (< 10 keV), so it is sensitive
to higher temperature plasma.

It is also clear that higher temperature plasma cools faster. This is true
for conductive cooling; the standard value for conductive cooling time is \( \tau_c =
1.5 \times 10^{-9} n L^2 / T^{3/2} \), where \( n \) is the plasma density, and \( L \) is the loop half-length.
For SXT and GOES, the observed cooling time is longer than \( \tau_c \), and much
shorter than the radiative cooling time, \( \tau_r = 3450 T^{3/2} / n \). (This expression for
\( \tau_r \) is valid if the slope of the radiative loss function for high T is \( -0.5 \); Cargill,
Mariska & Antiochos, 1995.)

The estimates of the conductive and radiative cooling times depend on the
plasma density. This is available from SXT data, but only after assumptions
regarding the geometry of the flare and the filling factor. We would like to avoid
this and look at the variation of the cooling times with temperature.

We thus combine the GOES and SXT data to model the DEM and fit the
data to an emission measure that is a power law in temperature; i.e., \( q(T) =
A T^{-\alpha} \), for 5 MK < T < T_c, where T_c is a high temperature cutoff. The emission
measure as a function of time is shown in Figure 1 for three different values of T
for a flare that occurred on 2 Nov 1991. We see the behavior that we expect; the
higher T plasma peaks earlier, and decays faster. For 31 MK, the decay half-
time, is \( \tau_q \approx 1 \) min. At 18 MK, \( \tau_q \approx 3 \) min, and for \( T = 6 \) MK, \( \tau_q \approx 14 \) min.
The uncertainty in the estimated decay time is roughly the time between SXT
Be119 exposures, approximately 15 seconds.

Figure 2 is a plot of the emission measure decay time, \( \tau_q \) versus T. Here
the decay time increases slightly to a maximum at a break temperature of \( T_b \approx \)
9 MK, and then decreases. This is not unusual behavior; it is seen in 23 of the 45 flares analyzed. To quantify the decay time as a function of $T$ we fit the high $T$ part of the curve to a power law, $\tau_q \propto T^5$, as indicated by the line on the plot. The value of the slope, $S = -2.36$, is close to the standard value for conductive cooling which is $-2.5$. These are not necessarily comparable; cooling times are calculated by assuming an isothermal plasma with a temperature that varies with time, while $\tau_q$ is the decay time of the amount of plasma at a given temperature. The plasma in the interval $q(T)\,dT$ at one time is not necessarily the same as the plasma in the same interval at a later time.

For the 45 flares analyzed, the slope, $S$, of the variation of the decay time is typically between $-1$ and $-2.5$, with a 11 flares outside of the range. Since $\tau_q$ is not directly comparable to the cooling times usually seen in the literature (i.e., $\tau_r \propto T^{1.5}$ and $\tau_c \propto T^{-2.5}$), which refer to the cooling time of an isothermal plasma, we can only speculate. The fact that the decay time decreases with increasing $T$ indicates that heat conduction is the important heat loss process for high temperature plasma during the flare decay. The slope of the $T$ dependence is not always as large as would be expected from purely conductive cooling (also the actual cooling time tends to be longer than the estimates of $\tau_c$, as mentioned in the introduction). This may be due to continued heating during the decay phase. For flares where the decay time increases with $T$ below some $T_b$, radiative or quasi-static cooling may be important.
3. Conclusions

The main conclusions that should be drawn from this work are:
(1) The solar flare soft X-ray plasma is not isothermal. The value of temperature depends on the energy (or wavelength) range covered by the detector; for an isothermal plasma, both instruments would measure the same temperature.
(2) The higher temperature plasma peaks earlier and cools faster.
(3) Combined SXT and GOES data can be fit by a Differential Emission Measure function that is a decreasing power law in $T$ with a high temperature cutoff. A more complex form for the DEM is not an option with broad-band detectors.
(4) The decay time of the emission measure varies as $\tau_q \propto T^S$, with a broad peak in the distribution at $S \approx -1.7$. This is not directly comparable to the typical radiative and conductive cooling times, but the decrease in decay time with temperature indicates that conductive cooling is the important cooling process for the high $T$ plasma in the decay phase of soft X-ray flares.

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References