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Correlative Analysis of Hard and Soft X-rays in Solar Flares using CGRO/BATSE and YOHKOH

FINAL REPORT

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1. INTRODUCTION

[redacted] Investigator Program. The objective of this work is to study different mechanisms of solar flare heating by comparing their predictions with simultaneous hard and soft X-ray observations. The datasets used in this work consist of hard X-ray observations from the *CGRO* Burst and Transient Source Experiment (BATSE) and soft X-ray observations from the Bragg Crystal Spectrometer (BCS) and Soft X-ray telescope (SXT) on the Japanese *Yohkoh* spacecraft.

2. WORK PERFORMED

(a) Assembling of Datasets

Hard X-ray data necessary for the proposed study were obtained by searching the CGRO/BATSE archive at the Solar Data Analysis Center (SDAC). The search focussed on impulsive single-loop solar flares for which BATSE Large Area Detector (LAD) Continuous Data (CONT) were available during the hard X-ray rise phase. The CONT data consist of 2.048 second time resolution hard X-ray spectra in 16 channels spanning the range 20 keV to above 300 keV. The high signal-to-noise CONT spectra provide information on the energy spectrum of accelerated electrons on a timescale comparable with simultaneous soft X-ray observations ($\approx$ 3 secs).

Soft X-ray data were obtained by searching the SXT and BCS archives at the SDAC, the Institute of Space and Astronautical Science (ISAS) in Japan, and the Naval Research Laboratory (NRL). The SXT data consist of full-Sun and partial frame filter images in the 2–10 Å soft X-ray range at approximately 2 arcsec spatial resolution. The images provide loop geometry information during and pre- and main flare phases. The BCS data consist of Ca XIX spectra in the 3.16–3.2 Å soft X-ray range and provide diagnostics of the flare temperature and density. A total of 100 flares were found for which simultaneous *CGRO* and *Yohkoh* were available.

(b) Data Reduction

Reduction of BATSE/CONT data required convolving a model photon spectrum with the detector response matrix (DRM) and comparing it with the measured count spectrum at various intervals during the hard X-ray impulsive phase. The model spectrum consisted of thermal bremsstrahlung emission plus a power-law component $I = a\epsilon^{-\gamma}$. The parameters of the model spectrum were adjusted to minimize χ^2. This analysis was performed using the SPEX

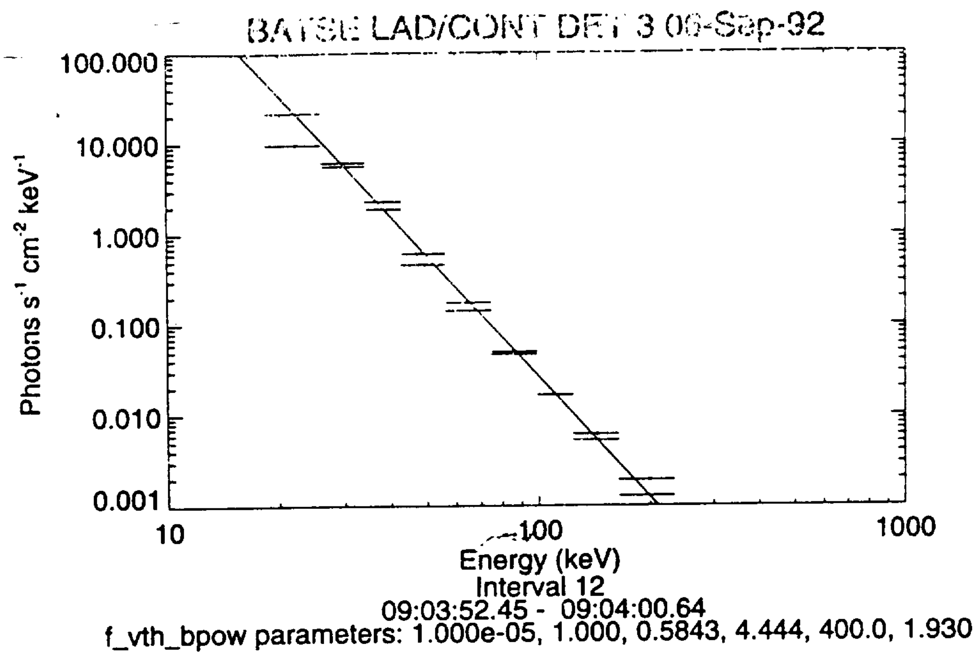

Figure 1. Power-law fit to the BATSE LAD CONT spectrum at the time of the first hard X-ray burst for a flare observed on 6 September 1992

of the flare plasma. The latter is given by $n \simeq \sqrt{EM/2fAL}$, where A and L denote the cross-sectional area and half-length, respectively, of the flare loop. The parameter f is the loop filling factor which is determined from the data analysis.

(c) Data Analysis

The simultaneous hard and soft X-ray data were analyzed using a flare heating model in which plasma is Joule-heated by magnetic field-aligned coronal currents, and electrons are runaway-accelerated simultaneously by DC-electric fields (Holman 1985, Tsuneta 1985). A novel analysis technique was developed in which the DC-electric field strength could be derived by solving a simplified equation of energy balance. The energy balance equation (integrated over the loop volume) is given by:

$$V dU/dt = V_c Q_{curr} - V P_{rad} \qquad (2),$$

where $U = 3nkT$ is the total thermal energy of the flare loop, Q_{curr} is the current heating rate (assumed uniform along the loop), and $P_{rad} = 2.2 \times 10^{-19} n^2 T^{-1/2}$ is the energy loss due to radiation. The parameters n and T refer to

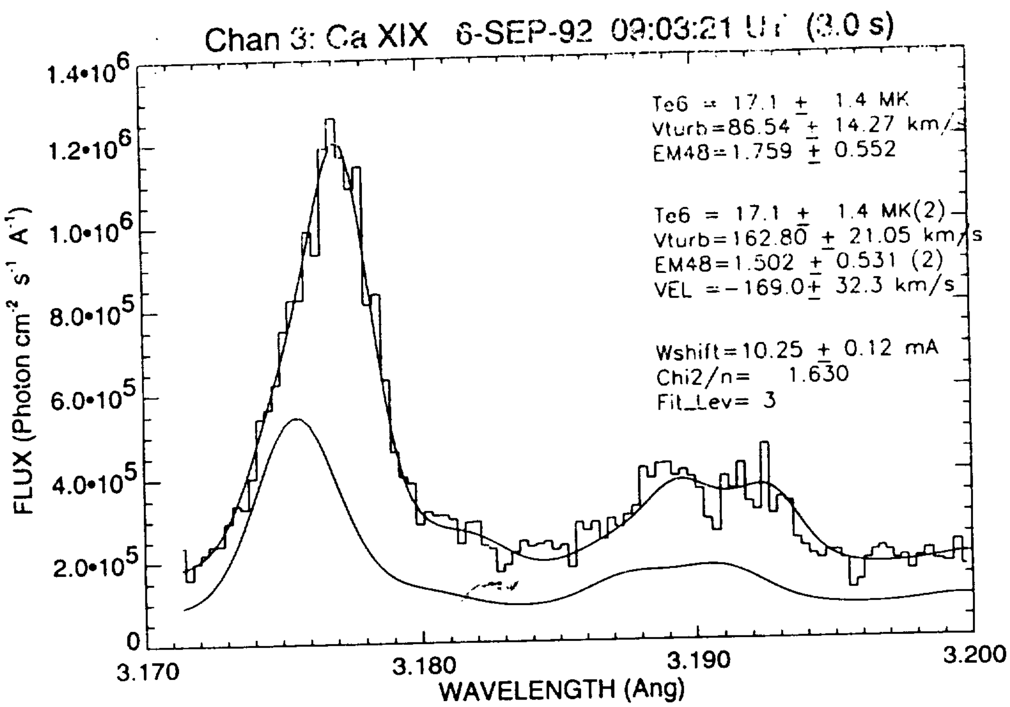

Figure 2. Spectral fit to BCS Ca XIX spectrum for a flare observed on 6 September 1992 showing two-component temperature fit to line profile.

$$Q_{curr} = nkT\nu_e(E/E_D)^2 \qquad \text{ergs cm}^{-3}\ \text{s}^{-1} \tag{3}$$

where $\nu_e \approx 3.2 \times 10^2 nT^{-3/2}$ s^{-1} is the thermal collision frequency (for classical resistivity), E is the electric field strength (assumed uniform along the loop length), and $E_D = 7 \times 10^{-8} nT^{-1}$ volts cm^{-1} is the Dreicer field. The Dreicer field is the field strength at which all the electrons in the plasma undergo thermal runaway.

Given T and n from soft X-ray observations, the energy balance equation is reduced to the two unknowns: E and f. Two different methods were developed and applied for solving the energy equation assuming different constraints on the unknown parameters.

Method (1): Constant Filling Factor

It is expected that the observed plasma will be filamented into numerous unresolved structures. Electrodynamic arguments indicate that filamentation is necessary to ensure a stable current system in which the overall self-induction magnetic field of current-carrying electrons is less than the ambient magnetic field strength. Substituting Q_{curr} into equation (2), the following dependence of E on the filling factor f was derived:

$$E = E_D\sqrt{\frac{(\dot{U} + P_{rad})}{fnkT\nu_e}} \tag{4}$$

The parameter f was assumed to be constant in time and a grid of solutions for E as a function of time was

the observed flux. In this case, the density within the current-heated region was too low to provide a large enough population of thermal electrons to undergo runaway. For $f < .001$, runaway acceleration also failed to match the observed number flux. Examination of equation (5), shows that $\dot{N}_{run} \sim \exp(-E_D/E)$. Since $E_D \sim n$, the runaway rate drops exponentially with increasing density. Physically, the runaway electrons become thermalized by collisions when the density in the current-heated region becomes very large.

Method (2): Constant Low-energy Electron Cutoff

The assumption of a filling factor that is constant in time is likely to become invalid as the flare energy is distributed throughout the loop system and the heating process extends to possibly multiple loops. The following method was developed to avoid this assumption.

Combination of the observed nonthermal thick-target flux [equation (1)] with the predicted runaway electron flux [equation (5)] gives an expression for the current-heating and acceleration volume V_c. Elimination of V_c from the energy-balance equation reduces it to a function of the unknowns, $\epsilon = E/E_D$ and E_{crit}. Substitution of $E_{crit} = m_e(E_D/E){v_e}^2/2$ further reduces energy-balance to an equation in the single unknown E.

Using the soft X-ray inferred values of n and T, no physically plausible solutions for E could be derived to satisfy this equation. In general, it was found that for the typical range of soft X-ray electron temperatures of $10 - 25 \times 10^6$ K during the flare, the predicted number flux of runaway electrons was 2–3 orders of magnitude below that required to explain the observed nonthermal electron flux implied by BATSE observations. One possible resolution of the discrepancy is to invoke some form of anomalous resistivity that increases the effective collision

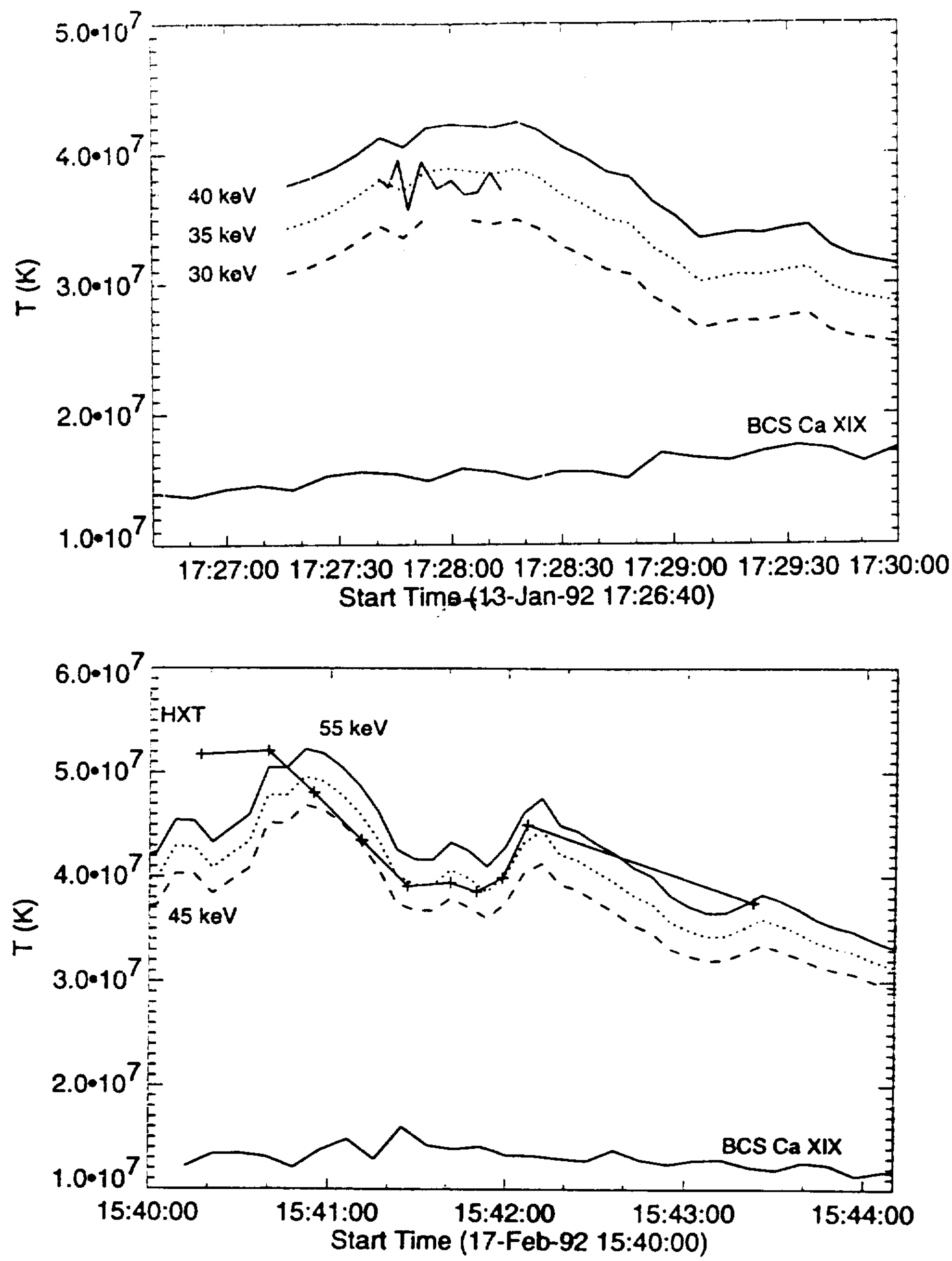

Figure 4. Temporal variations of the the high-temperature component deduced from solving energy-balance in a loop with a DC-electric field component. Shown are different temperature variations in two flares (observed by CGRO/BATSE and *Yohkoh*) for different values of the critical energy above which electrons are accelerated by electron runaway. The computed temperatures are compared with the temperatures inferred from *Yohkoh* HXT and BCS. The computed temperatures are more consistent with the super-hot temperatures implied by HXT than the cooler soft X-ray temperature implied by BCS.

The main thrust of the analysis was to investigate how coronal currents and their associated DC-electric fields can be used to self-consistently explain thermal and nonthermal emissions in solar flares. The analysis technique involved the solution of a simplified energy-balance equation in a quasi-static loop that was uniformly heated by field-aligned currents. The energy-balance equation was reduced to the three unknowns: electric field strength E, filamentation factor f, and electron low-energy cutoff E_c. A family of solutions for E was derived using two different methods. In the first method, f was assumed constant in time and derived by matching the predicted runaway electron flux with the BATSE-computed nonthermal flux. In this case, the energy-balance solutions required that the filamented subregions occupy a volume that is $\lesssim 10^{-3}$ of the total loop volume. Such filamentation is necessary to ensure a sufficiently high density of thermal electrons to undergo runaway acceleration. Strong filamentation of current-heated plasma is consistent with electrodynamic constraints that require a stable current system. In the second method, the acceleration region was assumed to be at a different temperature from the thermal soft X-ray emitting plasma. In this case, the energy-balance solutions required that the acceleration region have temperatures that are characteristically superhot.

Based on the joint analysis of *CGRO* and *Yohkoh* data, it is concluded that current heating and runaway acceleration mechanisms provide a viable means of explaining and understanding thermal and nonthermal processes in solar flares. The above results have been presented at several meetings, including the "High Energy Solar Physics Workshop" held in August 1995 at GSFC, Maryland, and a workshop on "Observations of Magnetic Reconnection in the Solar Atmosphere" held in Bath, England in March, 1996. These results are being prepared for publication in the *Astrophysical Journal.*

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13. ABSTRACT *(Maximum 200 words)*

We propose to continue a study that we have commenced under the Cycle 2 and 3 Guest Investigator programs. Our broad aim is to test the validity of different flare models by comparing their predictions with simultaneous CGRO BATSE hard X-ray and Yohkoh soft X-ray observations. For the Cycle 4 program, we will focus on current heating and electric field acceleration models. We will use BATSE spectral observations in the 20–300 keV provided by the Large Area and Spectroscopy detectors to determine the nonthermal hard X-ray emission component that is related to the rate $\dot{N}$ of accelerated electrons. We will use Yohhok soft X-ray observations to deduce the temperature T, density n, and associated thermal heating rate Q in the flare plasma. We have developed an analysis technique that combines $\dot{N}$ and Q in a novel way to determine the strength and variation of the DC-electric field in solar flares.

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