THE CORRELATION OF SOLAR FLARE TEMPERATURE AND EMISSION MEASURE EXTRAPOLATED TO THE CASE OF STELLAR FLARES

U. Feldman, J. M. Laming,1 and G. A. Doschek
E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375-5352
Received 1995 June 14, accepted 1995 July 25

ABSTRACT

We discuss an extrapolation of a recently discovered correlation between temperature and emission measure derived from X-ray spectra for the peak of solar flares, to temperatures and emission measures characteristic of stellar flares. We find surprisingly good agreement between the parameters derived for stellar flares by various authors, and the extrapolation of the results from the survey of solar flares.

Subject headings: stars: flares — X-rays: stars

1. INTRODUCTION

The observations of stellar flares in UV and X-ray wavebands are by now well established. The papers of Stern, Underwood, & Antiochos (1983) and Landini et al. (1986) provide convenient summaries of observations using the Einstein and Exosat observatories. Flares on dMe stars generally have emission measures between $10^{51}$ and $10^{54}$ cm$^{-3}$ and temperatures of $1 \times 10^7 - 4 \times 10^7$ K, whereas RS CVn binaries can have emission measures as high as $10^{55}-10^{56}$ cm$^{-3}$ and temperatures in excess of $3 \times 10^7$ K. These numbers are to be compared with "generic" solar values of $10^{56}-10^{58}$ and $5 \times 10^8 - 3 \times 10^9$ for emission measure and temperature, respectively.

A recent survey of solar flares observed by instruments on the Yohkoh spacecraft (Feldman et al. 1996a) has revealed remarkable correlations between the peak temperature of a flare and its emission measure or X-ray flux over the range of observed parameters relevant to solar flares. Our purpose in this letter is to examine extrapolations of these correlations to the parameter regimes described above to see whether stellar flares fit the same general patterns.

2. SOME SALIENT OBSERVATIONS OF STELLAR FLARES MADE SINCE THE EPOCHS OF EINSTEIN AND EXOSAT

Stern et al. (1992) observed large X-ray flares on the active binary Algol with the Ginga satellite. They observed a small flare with emission measure about $1 \times 10^{55}$ cm$^{-3}$, and a large flare, with approximately an order of magnitude more emission measure. These results were derived by fitting the observed proportional counter (Large Area Counter) spectra to a single-temperature thermal bremsstrahlung continuum, and a single Gaussian component to fit the observed Fe line feature at 6.7 keV. Both events reached temperatures about $7 \times 10^7$ K, although for the larger observed flare, the peak temperature (and peak Fe line equivalent width) occurred about 5 hr before the peak emission measure. For comparison with the solar work to be described below, the temperature at the peak of the large flare was $5 \times 10^7$ K. Due to poorer time resolution the peak emission of the smaller flare cannot be so well defined, so we do not consider this event any further, other than to mention that it appears entirely consistent with the eventual conclusions of this letter. The quiescent spectrum of Algol also indicates emission measures up to $1 \times 10^{53}$ cm$^{-3}$ (Antunes, Nagase, & White 1994; Stern et al. 1995), but note that Stern et al. (1992) subtracted the quiescent Ginga Algol spectrum from the flaring spectrum so as to isolate just the flaring plasma.

Similarly, flares have been observed on the RS CVn stars π Peg (Doyle et al. 1991) and UX Ari (Tsuru et al. 1989), also by the Ginga satellite. Doyle et al. (1991) report a temperature of $6.5 \times 10^7$ K at the time of highest observed X-ray emission from the flare, when the emission measure was $2.5 \times 10^{50}$ cm$^{-3}$. Note that this is not the peak of the flare as defined below, since this presumably occurred when the satellite detectors were switched off for passage through the South Atlantic Anomaly, the flare (and the parameter values above) being detected upon exit. A similar situation occurred with the UX Ari flare, where the actual peak was again probably missed by the satellite, but the highest observed temperature and emission measure coincide, and have values $8 \times 10^7$ K and $1 \times 10^{50}$ cm$^{-3}$, respectively.

Algol however is a close binary system in which the secondary fills its Roche lobe, and as such perhaps might not be particularly instructive in comparison to the Sun. Similar objections might also be made to RS CVn systems, since although no Roche lobe overflow is thought to occur, the system is close enough that the stars can be tidally locked, giving rise to substantially stronger magnetic dynamos than would be the case for a single star. Hence we also discuss observations by EUVE of a large flare on AU Mic (Culy et al. 1993; Monsignori Fossi & Landini 1994). The EUVE spectrometers are sensitive between 80–700 Å with a resolving power of about 200–300. Thus the observed spectral data in general contain many lines, some of which have diagnostic potential. Using only the observed line intensities, Monsignori Fossi & Landini (1994) constructed an emission measure curve that gives a maximum of about $1 \times 10^{52}$ cm$^{-3}$ at a temperature of about $1.5 \times 10^7$ K. Such an emission measure is unable to explain the high level of continuum observed in this spectrum. Culy et al. (1993) give a peak emission measure of $6 \times 10^{55}$ cm$^{-3}$ for the larger flare observed, which appears much more consistent with the observed continuum. However such an emission measure must exist at temperatures higher than those which would produce lines in the EUV, which

1 Also SFA, Inc., Landover, MD 20785.
under conditions of ionization equilibrium means temperatures higher than $T = 5 \times 10^7$ K.

Cully et al. (1993) also discuss the light curve of the large flare observed on AU Mic. It is interesting to compare this with the long duration solar flares described by Feldman et al. (1995a). In both cases, the flare decay phase light curves are of similar duration, and are well described by exponentials.

3. X-RAY FLUX AND EMISSION MEASURE AS A FUNCTION OF PEAK TEMPERATURE IN SOLAR FLARES

In a recent paper Feldman et al. (1996a) studied properties of solar flares during their peak emission. In particular they examined changes in X-ray fluxes and emission measures as a function of electron temperature. The study included 868 flares observed by the Bragg Crystal Spectrometer (BCS) on the Japanese satellite Yohkoh between 1991 October and 1994 December.

Electron temperatures, during flare maximum, were obtained from relative intensities of He-like lines and the adjacent Li-like dielectronic recombination satellite lines in Fe, Ca, and Ni. The fluxes were obtained from two data sets, from the intensities of the He-like resonance lines measured by BCS and from the electrical currents generated in the 1–8 Å ion chamber on the Geostationary Operational Environmental satellites (GOES). Emission measures ($\int n_e^2 dV$ where $n_e$ is the electron density and $dV$ is a volume element) were calculated from the measured fluxes and electron temperatures. Garcia (1994) describes the GOES 1–8 Å ion chamber, its effective wavelength band, and the conversion of ion chamber currents into fluxes and emission measure values. Feldman et al. (1996a) detail the BCS measurements. They describe the spectral lines used for different temperature regimes, and the methods of deriving fluxes, electron temperatures, and emission measures.

The peak fluxes as measured by the GOES detectors varied by some four orders of magnitude between $2 \times 10^{-8}$ and $2 \times 10^{-4}$ W m$^{-2}$, or, according to the traditional GOES classifications, between X-ray classes A2 and X2. The very large size crystals employed by the BCS enabled, for the first time, detailed studies of very faint flares. The size large crystals also caused the detectors on BCS to saturate as a result of the emission from flares with fluxes of about $2 \times 10^{-5}$ watt meter$^{-2}$ (X-ray class M2) and larger. As a result, temperatures given by Feldman et al. (1996a) for flares of X-ray class M2 and larger should be regarded as lower limits.

Garcia & McIntosh (1992) published a list containing the hottest and brightest flares as measured by GOES from 1977 to 1991. They include all the major events of the last two solar cycles (cycles 21 and 22). The list includes X-ray classes, temperatures, and emission measures for 53 flares.

In Figure 1 we display the GOES fluxes as measured by the 1–8 Å ion chamber versus electron temperature for the 868 flares measured by Feldman et al. (1996a). In Figure 2 we display emission measure versus electron temperature. As in Figure 1 the list includes the 868 flares measured by Feldman et al. (1996a) and 51 of the 53 flares measured by Garcia & McIntosh (1992). Two of their flares with unusually high temperatures were excluded from the figure. An extrapolation of the data points to higher values can be used as an estimate of emission measure versus temperature. An increase of the emission measure by an order of magnitude increases the average electron temperature by $\sim 6 \times 10^6$ K degrees. Thus, starting from $3.6 \times 10^7$ K, where the average emission measure is $1 \times 10^{53}$ cm$^{-3}$, we obtain temperatures of $4.2 \times 10^7$, $4.8 \times 10^7$, and $5.4 \times 10^7$ K for emission measures of $1 \times 10^{50}$, $1 \times 10^{51}$, and $1 \times 10^{52}$, respectively. Thus the emission measures of $1 \times 10^{50}$ and $6 \times 10^{51}$ quoted previously for Algol and AU Mic respectively would suggest temperatures of $5.4 \times 10^7$ and $5.0 \times 10^7$, in good agreement with the temperatures inferred above from the solar flare observations. The results for π Peg and UX Ari are in less good quantitative agreement, but still show the same trend of increasing temperature with increasing emission measure. It is important to remember here that the peak emission in these two events was missed.
because of spacecraft passage through the South Atlantic
Anomaly, and so we do not really have as direct a comparison
as we would like between these two events and the other
flares discussed. For this reason we do not discuss further
the apparent break in the slope of emission measure against
temperature.

4. THE EFFECT OF THE DISTRIBUTION OF EMISSION MEASURE
WITH TEMPERATURE ON ABUNDANCE DETERMINATIONS

One further intriguing aspect to the studies of Algol is the
measurement of the abundance of Fe relative to H by mea-
suring the intensity of Fe lines relative to the thermal
bremsstrahlung continuum. Stern et al. (1992) measured an
underabundance of Fe relative to H with respect to solar
photospheric values. Similar underabundances were noted by
Doyle et al. (1991) and Tsuru et al. (1989) in π Peg and UX
Ari, respectively. Working with data from the EUVE satellite,
Stern et al. (1995) found a similar underabundance of Fe in
Algol from EUV lines of Fe consistent with their earlier X-ray
measurements with Ginga. While it is difficult to explain the
X-ray measurements, workers in the EUV should beware of
line-to-continuum measurements in the light of the thrust of
this letter. EUV lines will not necessarily be produced from
the same plasma as the thermal bremsstrahlung continuum,
especially in stellar flares where the extrapolation of solar
results predicts large emission measures at temperatures too
high to produce any lines in the EUV, but certainly capable of
producing copious continuum. However the Stern et al. (1995)
abundance measurement was made during a quiescent phase
of Algol, and so should still be sound on these grounds.

5. SUMMARY AND CONCLUSIONS

We have demonstrated that the correlation recently discov-
ered between temperature and emission measure at the flare
peak for a large sample of solar flares over 4 orders of
magnitude in the emission measure can be extrapolated by
approximately 4 more orders of magnitude in this parameter
to provide a good description of stellar flares. This behavior
complicates models where flares are produced by many similar
elementary flare bursts, with larger flares having more bursts
than smaller flares, since one would expect temperature to be
independent of emission measure if the elementary flare
bursts in large flares were the same magnitude as those in
small flares. If the burst model is to be consistent with our
results, the elementary burst must produce higher tempera-
tures in events with large emission measures than is the case is
small emission measure events.

REFERENCES