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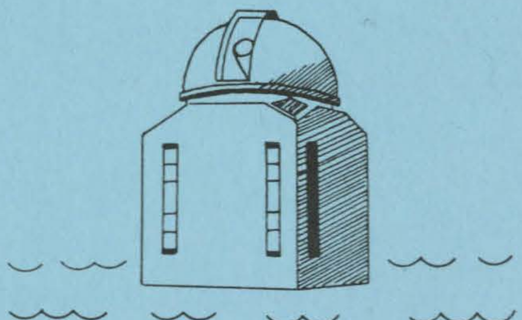

THE THERMAL X-RAY PLASMA IN SOLAR FLARES

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ABSTRACT

The observational knowledge of the thermal X-ray plasma in solar flares and its physical interpretation are reviewed, including results from Skylab prior to the Skylab Solar Workshop on Solar Flares. The review covers the main results and ideas in the published literature through 1977.

THE THERMAL X-RAY PLASMA IN SOLAR FLARES

A. Introduction

Every Hα flare is accompanied by a burst of soft X-rays (photon energy < 10 keV). The spectra of these bursts show that these X-rays are emitted from thermal plasmas at temperatures of the order of 10^7 K. The soft X-rays are therefore referred to as "thermal X-rays" and the $T \sim 10^7$ K emitting plasma is called the "thermal X-ray plasma". In addition to soft X-rays, flares commonly emit hard X-rays (photon energy > 10 KeV) during the fast rise phase of the soft X-ray burst. It is possible that the hard X-rays are also emitted from a thermal plasma, but if so, this plasma is of much higher temperature ($T > 10^8$ K) and is thus physically distinct from the $T \sim 10^7$ K component. To avoid any confusion, we emphasize that throughout this review the term "thermal X-rays" refers to the soft X-ray emission and "thermal X-ray plasma" refers to the $T \sim 10^7$ K component of the flare plasma.

All Hα flares evolve through at least three phases: rise, maximum and decay. These phases are well displayed by the thermal X-ray time profile, whereas the hard X-rays, which are emitted either by non-thermal electrons or by very high temperature electrons, are detectable only during the rise phase.

Therefore, the maximum phase and decay phase together are often referred to as the thermal phase of the flare. Estimates of the energy content of the thermal X-ray plasma in the thermal phase indicate that a major part of the total energy released in a flare goes into this plasma. Moreover, during the thermal phase all flare emission from chromospheric through coronal temperature levels may well be supplied by heat transfer from the thermal X-ray plasma. Hence, the thermal X-ray plasma is obviously one of the main physical components of a flare, and as it apparently dominates the energetics of the thermal phase, the thermal X-ray plasma poses the central physical problem of the thermal phase.

The purpose of this review is to outline the state of observational knowledge of the X-ray plasma and its physical interpretation as of the beginning of the Skylab Solar Workshop on Solar Flares. First, the observed characteristics and the physical properties derived from the observations are summarized. The basic physical questions posed by the observational results are then considered, and current physical ideas and models which have been proposed in answer to these questions are briefly reviewed. The research papers cited in connection with results reviewed here are offered only as representative examples; no attempt has been made to indicate priority or to cite all relevant papers. For a more comprehensive review of the thermal X-ray flare observations and their interpretation, and for a more complete guide to the literature, the reader is referred to the recent monograph on solar flares by Svestka (1976a).

B. Observed Properties

1. Morphology

Soft X-ray filtergrams from Skylab have established that the basic structural form of the thermal X-ray plasma in flares is that of closed loops or arches (Vorpahl et al., 1975; Kahler et al., 1975). The X-ray arches bridge the magnetic neutral line between opposite-polarity regions of the chromospheric flare (Vaiana and Giacconi, 1969; Widing and Cheng, 1974; Pallavicini et al., 1975; Vorpahl, 1976). EUV and XUV spectroheliograms have confirmed that the highest-temperature ($T \sim 10^7$ K) plasma is situated over the neutral line and between the lower-temperature components of the flare, which are on opposite sides of the neutral line (Neupert et al., 1974; Widing and Cheng, 1974; Cheng and Widing, 1975). Thus, the observations show that the thermal X-ray plasma is contained in the upper portions of closed magnetic field arches rooted in the chromospheric flare.

The X-ray arches in a flare generally are clustered together in the form of a dome or arcade. Particularly during the early stages of a flare, a bright core strand is often embedded in a larger, more diffuse arch or set of loops (Vaiana and Giacconi, 1969; Vorpahl et al., 1975; Petrasso et al., 1975; Pallavicini et al., 1975). The core connects the brightest parts of the chromospheric flare. In addition, there may be one or more small bright X-ray knots, sometimes located near the ends of the loops (Kahler et al., 1975). The X-ray knots are similar to Hα kernels observed in some flares, and may be small regions of emerging bipolar magnetic flux (Kahler et al., 1976).

The X-ray flare evolves in size, shape and structure by individual loops and knots increasing and decreasing in brightness. Both the core loops and the knots tend to be brightest early in the flare while the diffuse envelope is still increasing in size (Vorpahl et al., 1975; Kahler et al., 1975; Pallavicini et al., 1975; Widing and Dere, 1976; Dere et al., 1976). In the later stages of the flare, the compact bright features fade and become less distinguishable from the surrounding envelope. In general, the lifetimes of component structural features and the lifetime of the flare as a whole scale with size: the greater the length scale the longer the lifetime. Individual bright strands or knots a few times 10^3 km in diameter might remain visible for 5 to 10 minutes. Very roughly, small flares of overall length scale less than a few times 10^4 km (subflares) last for less than an hour (Moore and Datlowe, 1975), whereas large flares of length scale of the order of 10^5 km last for more than an hour.

2. Temperature and Emission Measure

Even when no flares are in progress, almost all of the solar X-ray flux shortward of 20 Å is emitted from the enhanced corona in active regions (Goldberg, 1967; Vaiana et al., 1976). The steady-state temperature of the coronal plasma in an active region is usually less than 4×10^6 K and approaches this value only during epochs of high flare productivity in the active region (Neupert, 1969). The factor by which the X-ray flux is increased by a flare increases very rapidly with decreasing wavelength shortward of 20 Å (Allen, 1973; Moore, 1976). This shows that the average temperature of the plasma contributing to the $\lambda < 20$ Å flux is significantly higher in a flare than in a non-flaring active region. It is this high-temperature component of the flare plasma which we refer to as the "thermal X-ray plasma" in the flare.

For an isothermal volume of coronal plasma, the shape of the X-ray spectrum is specified by the temperature, while the amplitude of the spectrum is set by the emission measure (the integral of n_e^2 over the volume: $\int n_e^2 dV$) (Tucker and Koren, 1971). Consequently, although the thermal X-ray plasma in a flare is certainly not isothermal, representative values for the temperature and emission measure for this component of the flare can be derived by fitting computed spectra for isothermal coronal plasma to the observed flare flux in two or more wavelength intervals shortward of 20 Å (Culhane et al., 1970; Horan, 1971; Datlowe et al., 1974; Moore, 1976).

During the rise and maximum phases of flares, the temperature of the thermal X-ray plasma in the isothermal approximation is invariably of the order of 10^7 K. The temperature increases to a peak early in the rise phase and then slowly decreases throughout the remainder of the flare. In most flares, the temperature peaks in the range 1-3 x 10^7 K and remains above or near 1 x 10^7 K until well after the time of maximum thermal X-ray flux. In contrast to the evolution of the temperature, the emission measure, after increasing steeply in the rise phase, continues a progressively slower increase to a relatively flat maximum somewhat after the maximum in the X-ray flux. The emission measure at its maximum is in the range 10^{48} - 10^{49} cm^{-3} in subflares (Hα area ~1 sq. deg.), and can exceed 10^{50} cm^{-3} in class 3 flares (Hα area ~20 sq. deg.) (Datlowe et al., 1974; Dere et al., 1973).

Since the thermal X-ray plasma is contained in closed magnetic flux tubes and merges with the lower-temperature plasma at the feet of these tubes, and since different X-ray loops in a flare display different evolutions, the thermal X-ray plasma is necessarily not isothermal. The precise shape and amplitude of the thermal X-ray spectrum of a flare are determined by the distribution of emission measure with temperature. This distribution can be estimated by fitting the resulting calculated X-ray spectrum to three or more observed fluxes from different intervals of the X-ray spectrum and/or from individual XUV emission lines emitted by the plasma (Dere et al., 1974; Dere et al., 1976). These analyses indicate, in agreement with the isothermal results, that for the $T \gtrsim 10^7$ K plasma (1) an appreciable fraction of the plasma is at temperatures above 2 x 10^7 K only during the rise phase, (2) the emission measure continually increases until after the X-ray flux begins to decrease, and (3) the emission measure at maximum is in the range 10^{48} - 10^{49} cm^{-3} for subflares.

Flare temperatures and emission measures derived from broad-band soft X-ray filtergrams from Skylab are in general agreement with the above results derived from broad-band soft X-ray flux monitors (Vaiana et al., 1976). Intensities and intensity ratios from X-ray filtergrams of different passbands give temperatures of the order of 10^7 K and emission measures of several times 10^{49} cm^{-3} for a class 1 flare. The Skylab X-ray filtergrams show a general correlation between intensity and temperature of large-scale coronal features, coronal holes having the lowest temperatures (~10^6 K) and flares the highest. This suggests that the intense cores and kernels in the X-ray images of flares are of higher temperature than the surrounding envelope. However, it is doubtful that any such temperature difference of the order of 10^7 K or less can be established directly from present filtergram pairs because of low temperature discrimination at temperatures above about 10^7 K (Kahler, 1976).

EUV spectroheliograms from Skylab have also confirmed 10^7 K temperatures for the thermal X-ray plasma in flares during the rise and maximum phases (Widing and Cheng, 1974; Cheng and Widing, 1975; Widing and Dere, 1976). The upper portion of flare arches visible on X-ray filtergrams are also visible on EUV spectroheliograms in the 263 Å line of Fe XXIII and in the 255 Å line of Fe XXIV. The presence of appreciable amounts of Fe XXIV requires temperatures in excess of 10^7 K. The measured ratios of the Fe XXIV line intensity to the Fe XXIII line intensity correspond to temperatures in the range 1-2 x 10^7 K for the emitting flare plasma.

3. Density

Upper and lower limits on the density of the thermal X-ray plasma in a flare can be estimated from the spectrum of the "gradual rise and fall" thermal microwave emission observed from this plasma (Hudson and Ohki, 1972). From a study of 15 flares, Hudson and Ohki found that the optical depth of the T ~ 10^7 K plasma to microwaves is usually of the order of 1 at 3 x 10^9 Hz and much less than 1 above 4 x 10^9 Hz. For a plasma depth of less than 10^5 km, unit optical depth at 3 x 10^9 Hz requires that the electron number density be greater than 10^{10} cm^{-3}; for negligible attenuation above 4 x 10^9 Hz, the plasma frequency must be less than 4 x 10^9 Hz, which sets an upper limit of 2 x 10^{11} cm^{-3} for the electron density. Thus the thermal microwave observations indicate that the electron number density of the thermal X-ray plasma is usually in the range $10^{10} < n_e < 2 \times 10^{11}$ cm^{-3}.

If a measure of the volume of the T $\gtrsim 10^7$ K plasma is available, an average value for n_e in the thermal X-ray plasma can be obtained from the volume emission measure, $\int n_e^2 dV$. Cheng and Widing (1975) used this approach to derive the electron density for 5 flares for which both EUV spectroheliograms from Skylab and broad-band soft X-ray flux measurements from SOLRAD-9 were obtained near thermal X-ray maximum. For each flare the volume was estimated from the Fe XXIV 255 Å image, the temperature was obtained from the Fe XXIV 225 Å / Fe XXIII 263 Å intensity ratio, and the emission measure was derived from this temperature and the 0-3 Å flux observed from SOLRAD-9. The volumes ranged from 10^{26} cm^3 for a subflare to 10^{27} cm^3 for a class 1B flare; the temperatures were all in the range 1-2 x 10^7 K, and n_e was found to be of the order of 10^{11} cm^{-3} for each of the 5 flares. From a similar analysis of the same 1B flare, using 2-17 Å passband X-ray filtergrams exposed for the core region of the X-ray flare, Pallavicini et al. (1975) also found $n_e \sim 10^{11}$ cm^{-3} for the $T \gtrsim 10^7$ K plasma in the core arches near flare maximum.

Analogous to the average density obtained from the volume emission measure and the volume estimated from an image, an average value of n_e for an emission feature on an X-ray filtergram can be obtained from the linear emission measure along the line of sight ($\int_0^d n_e^2 \, d\ell$) and the depth of the feature (d) estimated from the image. The linear emission measure is derived from the image intensity passed by the filter and by the plasma temperature, which can be estimated from the ratio of image intensities passed by two filters of different passbands. Flare X-ray filtergrams from Skylab have given linear emission measures of the order of 10^{31} cm^{-5} for the thermal X-ray plasma in arches of diameter of the order of 10^9 cm, which gives a value of n_e of the order of 10^{11} cm^{-3} (Vaiana et al., 1976).

Analogous to the correlation between intensity and temperature, the Skylab X-ray filtergrams show an even stronger general increase of density with intensity for large-scale coronal features from coronal holes ($n_e \sim 10^8$ cm^{-3}) to flares (Vaiana et al., 1976). Again, this suggests that the bright cores and kernels in the X-ray images of flares are of higher density than the surrounding envelope. Clearly, features which are both brighter and more compact than surrounding features must have either higher density or higher temperature or both. However, because of the poor temperature discrimination above about 10^7 K with present filtergrams (Kahler, 1976), temperature enhancements (of less than about a factor of 2) cannot be unambiguously separated from density enhancements in the $T \gtrsim 10^7$ K flare plasma.

4. Energy and Mass Content

As indicated above, the thermal X-ray plasma in large subflares (Hα area $\approx$ 2 sq. deg.) have been found to have $T \sim 10^7$ K, $n_e^2V \sim 10^{49}$ cm^{-3} and $n_e \sim 10^{11}$ cm^{-3} at flare maximum. These values give a thermal energy content ($3 n_e k TV$) of 4×10^{29} erg, which is of the order of the total energy thought to be released in flares of this size (Svestka, 1976b). (In making this estimate, we have used a density typical of the thermal X-ray core of a subflare. Note that for given values of T and n_e^2V, the energy content is inversely proportional to n_e, so that we have underestimated the energy content by the factor that 10^{11} cm^{-3} is an overestimate of the "average" density of the $T \sim 10^7$ K plasma.) The emission measure and density of the thermal X-ray plasma at flare maximum in class 3 flares have not been well measured, but it appears that the emission measure typically exceeds 10^{50} cm^{-3} and that n_e does not exceed 10^{11} cm^{-3}. Taking $n_e^2 V \gtrsim 10^{50}$ cm^{-3}, $n_e \lesssim 10^{11}$ cm^{-3} and $T \sim 10^7$ K gives $3n_e kTV \gtrsim 10^{31}$ erg, which is at least a significant fraction of the total energy ($\sim 10^{32}$ erg) thought to be released in a class 3 flare. Moreover, the thermal energy content is always less than the total thermal energy generated in the flare because the cooling processes continually remove energy from the X-ray plasma even while it is being heated. Thus, the above estimates of the energy content demonstrate the importance of the thermal X-ray plasma in the physics of flares.

Using the values for $n_e^2 V$ and n_e adopted above in our estimates of the energy content, we obtain of the order of 10^{14} gm for the mass ($m_p n_e V$) of the $T \sim 10^7$ K plasma at maximum in a large subflare and in excess of 10^{15} gm for the mass content of the thermal X-ray plasma in a class 3 flare. Again, just as for the energy content, for a given emission measure the mass content is inversely proportional to the density.

In the absence of a flare, the coronal number density in an active region is less than 10^{10} cm^{-3} (Vaiana et al., 1976). Since the number density of the thermal X-ray plasma in a subflare is of the order of 10^{11} cm^{-3}, virtually all of the mass in the thermal X-ray plasma must be supplied from outside the volume occupied by this plasma. This mass must come from the surrounding corona and/or the underlying chromosphere. If the mass were supplied mostly from the preflare active region corona, the mass in a volume at least 10 times larger than that of the flare would have to be compressed into the flare volume. The Skylab X-ray filtergrams show no evidence for this; when a flare occurs, the intensity of the active region corona surrounding the flare does not decrease. Hence, the Skylab observations strongly indicate that most of the mass of the thermal X-ray plasma in flares is supplied from the chromosphere.

5. Magnetic Field Strength

If the thermal X-ray plasma in flares is contained in magnetic field arches, as appears to be the case, then the pressure of the confining magnetic field must exceed the pressure of the confined plasma: $B^2/8\pi > 2n_e kT$. Flare plasma having $T \sim 10^7$ K and $n_e \sim 10^{11}$ cm^{-3} requires a magnetic field strength of the order of 10^2 gauss or greater for confinement. By fitting potential field lines, computed from photospheric magnetograms, to observed post-flare arches, Roy (1972) showed that field strengths of this magnitude at the tops of flare arches are reasonable for flare arches of length scale in the range 10^4 to 10^5 km.

6. Summary

The major points of our assessment of the present observational knowledge of the thermal X-ray plasma in flares are the following.

1. The thermal X-ray plasma is contained in closed magnetic arches which are rooted in the chromospheric flare.

2. The evolution and structure of the thermal X-ray flare parallel those of the chromospheric flare.

   a. Initial rapid growth on a time scale of minutes is followed by maximum and decay on a time scale of tens of minutes to hours, with larger flares having the longer times.

   b. The brightest X-ray arch or group of arches (the "core" of the X-ray flare) is rooted in the brightest parts of the chromospheric flare. The cross-sectional area of the core arch is typically substantially less than the length of the arch.

   c. Length scales increase with time; the arches become longer, fatter and more diffuse. The typical overall length scale at flare maximum ranges from 10^4 km for small subflares to 10^5km for class 3 flares.

3. During the rise and maximum of the flare, the temperature of the thermal X-ray plasma at the top of the arches is of the order of 10^7 K. The temperature peaks during the rise phase.

4. The volume emission measure during flare maximum ranges from less than 10^{48} cm^{-3} for small subflares

to more than 10^{50} cm^{-3} for class 3 flares. The maximum emission measure is usually attained shortly after the maximum in the thermal X-ray flux ($\lambda < 20\,\mathring{A}$).

5. The electron density in the core arches of the thermal X-ray flare is usually of the order of 10^{11} cm^{-3} at flare maximum in small flares, and is probably somewhat less in large flares.
6. The magnetic field threading the core arches is of the order of 10^2 gauss or larger.
7. The spatial variation of the temperature, density and magnetic field in the $T \gtrsim 10^7$ K plasma, either along or across flare arches, is as yet poorly known. Either the density or the temperature or both are less in the diffuse envelope surrounding the core than in the core.
8. The energy required to produce and maintain the thermal X-ray plasma in a flare is of the order of the total energy released in the flare (if present estimate for total flare energies are not much too small).
9. Most of the mass of the thermal X-ray plasma is supplied from the chromosphere rather than from the surrounding preflare corona.

C. Physical Interpretation

1. Definition of the Problem

The observations, particularly the EUV and X-ray pictures from Skylab, have firmly established that the thermal X-ray plasma in flares is contained in closed magnetic arches. Hence, the physical problem of the thermal X-ray plasma can be stated by the following question: How do the X-ray arches form and evolve?

This general question has the following five major facets.

1. What is the magnetic field configuration in which or from which the X-ray arches are formed?
2. How is the plasma heated?
3. What is the duration of the heating?
4. How does the plasma cool?
5. How is the mass supplied from the chromosphere?

Each of these questions identifies a basic aspect of the physics of the thermal X-ray plasma, and is presently unresolved. The general goal of the physical interpretation of the observed properties and evolution of the plasma is to answer these questions in terms of physical processes and physical laws. In the following subsections, the main ideas and uncertainties at present in the physical interpretation of the thermal X-ray plasma are discussed with regard to these questions.

2. Magnetic Field Configuration

On the basis of both observational evidence and theoretical considerations, it is widely accepted that the immediate source of the energy released in a flare is the nonpotential magnetic field in the chromosphere and corona in the vicinity of the flare (Sweet, 1969; Schmidt, 1969; Syrovatsky, 1972; Sturrock, 1973; Colgate, 1977), and this is the only possibility considered here. By definition, the nonpotential component of the magnetic field in the solar atmosphere is maintained by electric currents within the field in the chromosphere and corona. The magnetic field configurations of present flare models based on non-potential fields are of two general classes:

1. current-sheet configurations, in which there are non-force-free sheets of high current density which separate much larger domains of disparate field direction and much lower current density (Sturrock, 1968, 1972; Kopp and Pneuman, 1976; Heyvaerts et al., 1977);
2. force-free configurations, in which all of the electric current of the nonpotential magnetic field flows very nearly along the field lines (Alfven and Carlqvist, 1967; Piddington, 1974; Spicer, 1977; Colgate, 1977).

In current-sheet models, the X-ray arches are formed by magnetic field reconnection at the current sheet; the closed magnetic field lines which thread the thermal X-ray plasma connect foot points which were not connected before the flare.

As long as the reconnection process continues, field lines initially located sequentially farther from the current sheet move to the current sheet and reconnect, and the envelope of newly-formed closed magnetic arches continues to grow. An expanding arcade of closed magnetic field, such as the X-ray arches and post-flare loops observed in flares with a simple two-ribbon pattern of chromospheric emission, is produced by reconnection of open field lines (i.e., field lines which extend out into the solar wind) at a single vertical current sheet (Sturrock, 1968; Kopp and Pneuman, 1976). More complex arrangements of X-ray arches rooted in more complex chromospheric emission patterns result if the magnetic field lines on one or both sides of the current sheet are closed, or if there are multiple current sheets.

A current sheet may form gradually, e.g. as new bipolar flux emerges in a monopolar region of an established active region (Heyvaerts et al., 1977), or perhaps by gradual opening of the outer field lines in a large active region (Sturrock, 1968). It has also been proposed that in many flares the current sheet may be formed suddenly at the onset of the flare as a result of MHD instability in a previously force-free configuration (Barnes and Sturrock, 1972; Parker, 1975). The filament eruption which often initiates a simple two-ribbon flare may be the result of such an MHD instability. The filament eruption may open the magnetic field and set up the open vertical current sheet configuration needed for this type of flare (Hirayama, 1974; Kopp and Pneuman, 1976). Another possibility for the transient formation of an open current sheet is that the closed field of an active region might be blasted open by the plasma pressure generated in the flash phase of the flare (Schmidt, 1969). In this case, most of the thermal energy generation in the flare would occur prior to the formation of the open current sheet.

The magnetic field configuration in force-free models is basically a twisted closed magnetic arch or set of arches. The twist is maintained by the force-free current which flows along the field lines in the arch. The twist may be present in the field when it emerges through the photosphere, or it may be built up in the field later by differential horizontal flows in the photosphere (Tanaka and Nakagawa, 1973) or by propagation of twist up the field lines from below the photosphere (Piddington, 1974). When a flare occurs, some of the current is dissipated and the twist in the arch is relaxed, but there is no change in the basic topology of the field configuration. If the flare has an arcade of X-ray arches or any other assembly of multiple arches, the same magnetic arches, each with axial twist, are present in the preflare configuration. The structure of the flare may evolve by progressive detonation of adjacent arches (Vorpahl, 1976).

So, there is this basic difference between current-sheet models and force-free models in the way that the thermal X-ray arches are formed: in current-sheet models, the closed magnetic arches which contain the thermal X-ray plasma result from a change in the topology of the field configuration and are not present in the preflare configuration; whereas in force-free models, these magnetic arch structures are already present in the preflare configuration. However, the two classes of models are not mutually exclusive; there is no a priori reason why both types of flares cannot occur on the sun.

3. Heating

The release of the nonpotential magnetic field energy in a flare is similar in broad outline in both current-sheet models and force-free models. A flare commences when the current density exceeds some critical value above which a plasma instability results in a drastic increase in the resistivity in the region of high current density. This critical current density might be attained either gradually, through slow build-up of a current sheet or force-free twist, or suddenly as a result of an MHD instability which occurs at some lower value of current density. The anomalous resistivity then results in rapid current dissipation and reconnection or untwisting of the nonpotential magnetic field. The electrostatic fields, plasma turbulence and magnetic field stresses which can occur in this process can plausibly produce the various forms and amounts of plasma kinetic energy (high-energy particles, thermal plasma, bulk mass ejections and blast waves) which are observed in flares.

Due to the complexity of the MHD and plasma processes thought to operate in the magnetic energy $\rightarrow$ plasma energy

conversion in flares, it is very difficult to specify from theory the products of the conversion in any quantitative detail, such as the fraction of released energy which goes directly into bulk mass motion or the total energy and energy spectrum of the impulsive electrons. In particular, it is very uncertain just how the thermal X-ray plasma is generated. Three basically different schemes have been proposed:
(1) direct heating of the plasma in the upper portion of the magnetic arches by current dissipation (Spicer, 1977; Colgate, 1977); (2) heating near the top of the arches by shock waves which are formed either directly (Petscheck, 1964) or indirectly (Kopp and Pneuman, 1976) by the reconnection process;
(3) heating at the feet of the arches by the impulsive high-energy electrons impinging on the chromosphere (Sturrock, 1973; Lin and Hudson, 1976; Antiochos and Sturrock, 1976a). Clearly, to help decide between these possibilities, it is important to try to deduce from observations whether the thermal X-ray plasma is heated primarily at the tops or at the feet of the arches.

Another uncertainty bearing on the heating mechanism is whether the impulsive electrons which produce the impulsive hard X-rays are thermal or non-thermal. If these electrons are thermal, then their total energy is much less than the energy of the thermal X-ray plasma produced in the flare, and hence cannot be the source of heating for the thermal X-ray plasma (Brown, 1974). If the impulsive hard electrons are non-thermal, then their total energy is comparable to the total energy released in the flare, and these electrons then may well generate all of the thermal X-ray plasma (Lin and Hudson, 1976).

A key question is whether there is appreciable heating of the thermal X-ray plasma after the flash phase. The duration of the heating is a basic criterion for the flare energy-release mechanism, determines the nature of the energy balance of the thermal phase, and bears directly on the total energy released in a flare. If the thermal X-ray plasma is mainly a secondary product of the impulsive electrons, then in most flares the bulk of the heating must be accomplished in the flash phase. Conversely, continued strong heating after the end of the impulsive hard X-rays in the flash phase would indicate an important additional mode of heating. If heating stops at the end of the flash phase, then the thermal phase is essentially a cooling process; if the heating continues well past the flash phase, then the thermal phase represents a balance between heating and cooling of the thermal X-ray plasma (Moore and Datlowe, 1975). Obviously, continued heating in the thermal phase requires a greater total energy released in the flare.

The total heating of the thermal X-ray plasma of course must be balanced by an equal amount of cooling over the lifetime of the flare. Moreover, at any instant in the flare, the rate of change of the energy content of the thermal X-ray plasma is just the difference between the rate at which energy is added by heating and the rate at which energy is removed by cooling processes. Hence, the presence and strength of any heating of the X-ray plasma in the thermal phase can be deduced from the rate of change of the energy content and the cooling loss rate, if these rates can be determined accurately enough from observations and modeling. The energy content and its decay time define a minimum possible cooling rate. If the actual cooling rate can be shown to be larger, then there must be continued heating. The stronger the cooling, the greater the required heating, and the greater the required total thermal energy generated in the flare. Thus, both the duration of the heating and the total amount of heating can, in principle, be obtained from observations and analysis of the cooling of the thermal X-ray plasma.

4. Cooling

The problem of the cooling of the thermal X-ray plasma is inherently simpler than that of the heating because the configuration of the plasma as it cools is much better known. Since the thermal X-ray plasma is contained in the upper portions of closed magnetic arches, only the following three basic modes of cooling are available.

1. Radiative cooling: emission of radiation directly from the $T \sim 10^7$ K plasma.
2. Conduction cooling: heat conduction down the legs of the arch.

3. Expansion cooling: adiabatic expansion down the legs of the arch.

Expansion cooling is probably of secondary importance during the thermal phase because pressure equilibrium should be established along the arch in a much shorter time than the time scale of the thermal phase. The pressure equilibration time is of the order of the sound travel time, $\tau_s = L/a_s$, where L is the length of the arch and a_s is the sound speed in the thermal X-ray plasma ($a_s \approx 2 \times 10^4 \ T^{1/2} \text{cm sec}^{-1}$ for fully ionized solar plasma). So, for $T \sim 10^7$K, τ_s ranges from of the order of 10 sec for subflares ($L \sim 10^9$ cm) to of the order of 10^2 sec for the largest flares ($L \sim 10^{10}$ cm), which times are much shorter than even the flash phase. Thus, it appears that in the thermal phase the bulk of the thermal X-ray plasma is approximately in pressure equilibrium, so that expansion cooling is relatively unimportant, and the main question is that of the relative importance of radiative cooling and conduction cooling (Culhane et al., 1970; Moore and Datlowe, 1975).

For static plasma in a magnetic arch of constant cross section, the ratio of the radiative cooling rate $\dot{E}_r$ to the conduction cooling rate $\dot{E}_c$ is given approximately by

$$\frac{\dot{E}_r}{\dot{E}_c} = \frac{\Lambda_r(T)}{\kappa(T)} \frac{L^2 n_e^2}{T} \qquad (1)$$

(Moore and Datlowe, 1975), where the thermal conductivity

$\kappa(T)$ is given to a good approximation by $10^{-6}T^{5/2}$ erg sec^{-1} K^{-1} cm^{-1}, and the radiative cooling coefficient $\Lambda_r(T)$ is approximately constant in the vicinity of $T = 10^7$ K, where it has a value of about 2×10^{-23} erg cm^3 sec^{-1}. So, for $T \backsim 10^7$ K,

$$\frac{\dot{E}_r}{\dot{E}_c} \approx 2 \times 10^{-17} \frac{L^2 n_e^2}{T^{7/2}} . \tag{2}$$

For a subflare with $T = 10^7$ K, $L = 10^9$ cm and $n_e = 10^{11}$ cm^{-3}, we obtain $\dot{E}_r/\dot{E}_c \approx 6 \times 10^{-2}$. This value may be fairly representative for larger flares as well since the density of the thermal X-ray plasma is probably lower in flares of larger scale.

It appears from the above estimate that the thermal X-ray plasma is cooled mainly by conduction. However, this estimate neglects the fact that in real flares the cross-sectional area of the magnetic arch should continually decrease from the top to the feet (Antiochos and Sturrock, 1976a). In addition, the downward heat conduction probably results in chromospheric evaporation and mass flow up the legs of the arch (Antiochos and Sturrock, 1976b). The conduction cooling of the $T \sim 10^7$ K thermal X-ray plasma is inhibited by both of these effects, and the actual conduction cooling rate may be as much as a factor of 10 less than for the simple model considered above. Consequently, our above estimate actually indicates that radiative cooling and conduction cooling are of roughly equal importance.

The relative strength of radiative cooling and conduction cooling depends very strongly on the temperature of the thermal X-ray plasma [equation (2)], mainly due to the temperature dependence of the thermal conductivity. This strong temperature dependence, along with the above conclusion that $\dot{E}_r$ and $\dot{E}_c$ are of the same order for $T = 10^7$K, requires that conduction cooling strongly dominates when the temperature is even moderately above 10^7 K and that radiative cooling rapidly becomes dominant as the temperature drops below 10^7 K.

For the simple case of static plasma in an arch of constant cross-sectional area and under the same approximations used above for estimating $\dot{E}_r/\dot{E}_c$, the conduction cooling time $\tau_c \equiv E/|\dot{E}|_c$ is given by

$$\tau_c \approx 4 \times 10^{-10} \frac{L^2 n_e}{T^{5/2}} \text{ sec} , \quad (3)$$

and the radiative cooling time $\tau_r \equiv E/|\dot{E}|_r$ is given by

$$\tau_r \approx 2 \times 10^7 \frac{T}{n_e} \text{ sec} , \quad (4)$$

for $T \sim 10^7$ K. Taking the values $T = 10^7$ K, $L = 10^9$ cm, $n_e = 10^{11}$ cm^{-3} for a subflare, we obtain $\tau_c \approx 1 \times 10^2$ sec and $\tau_r \approx 2 \times 10^3$ sec, where again, due to the neglect of tapering of the arch and chromospheric evaporation, τ_c is underestimated and might actually be as much as an order of magnitude larger. Thus, the expected cooling time for the thermal X-ray plasma in a subflare is of the order of 10^3 sec or 15 minutes, in reasonable agreement with the observed decay of the thermal X-rays from subflares. If the electron density of the thermal X-ray plasma is of the order of 10^{10} cm^{-3} in a class 3 flare with $L \backsim 10^{10}$ cm^3, then both τ_c and τ_r are an order of magnitude longer than in subflares. This gives an expected decay time of a few hours for class 3 flares, again in reasonable agreement with the observations.

The above estimates of cooling times show that conduction and radiation can easily provide enough cooling to explain the observed decay of the thermal X-ray plasma in flares. Whether the observed decay implies that there is continued heating in the thermal phase of course requires a more detailed analysis and is presently an open question.

5. Mass Supply

As was discussed in Section B.4, the Skylab X-ray filtergrams clearly show that most of the mass in the thermal X-ray plasma in a flare is not present in the corona prior to the flare. Therefore, the mass must be supplied from the chromosphere during the flare. However, the manner in which chromospheric matter is brought into the thermal X-ray plasma is not established.

The most widely held view is that the mass comes up the legs of the thermal X-ray arches as a result of heating of the chromosphere at the feet of the arches, i.e., chromospheric evaporation (Hudson and Ohki, 1972; Sturrock, 1973; Hirayama, 1974; Lin and Hudson, 1976; Antiochos and Sturrock, 1976b;

Colgate, 1977). The main unresolved question for this process is whether the evaporation is driven mainly by heating of the chromosphere by the impulsive non-thermal electrons (Sturrock, 1973; Lin and Hudson, 1976) or by heat conduction from the thermal X-ray plasma at the top of the arches (Colgate, 1977). Thus, the nature of the mass supply as well as that of the heating of the thermal X-ray plasma depends critically on whether the impulsive electrons are the primary energy supply for the thermal X-ray plasma.

Another possibility for the mass supply is that the mass is carried up from the chromosphere by the magnetic field as it undergoes rapid drastic changes in configuration such as evidenced by filament eruptions. This process certainly brings chromospheric matter into the corona in many flares, but it is difficult to determine how much is brought up or how much of it becomes thermal X-ray plasma. Moreover, in some flares there is no filament eruption and no apparent reordering or eruption of magnetic field lines at the level of the chromosphere. So, it appears that chromospheric evaporation must be the dominant mode of mass supply at least in some cases. However, mainly due to scarcity of appropriate spectral data, the presence or absence of the required mass upflow from the feet of the arches has not yet been observationally established.

REFERENCES

Alfven, H. and Carlqvist, P.: 1976, _Solar Phys._ 1, 220.

Allen, C.W.: 1973, _Astrophysical Quantities_, Athlone Press, University of London, p. 194.

Antiochos, S.K. and Sturrock, P.A.: 1976a, _Solar Phys._ 49, 359.

Antiochos, S.K. and Sturrock, P.A.: 1976b, "Evaporative Cooling of Flare Plasma", preprint, SUIPR Report No. 676.

Barnes, C.W. and Sturrock, P.A.: 1972, _Astrophys. J._ 174, 659.

Brown, J.C.: 1974, in G. Newkirk Jr. (ed.), _Coronal Disturbances_ (IAU Symp. 57), p. 395.

Cheng. C.-C., and Widing, K.G.: 1975, _Astrophys. J._ 201, 735.

Colgate, S.A.: 1977, "A Phenomenological Model of Solar Flares", LA-UR-77-1342, submitted to _Astrophys. J._

Culhane, J.L., Vesecky, J.F., and Phillips, K.J.H.: 1970, _Solar Phys._ 15, 394.

Datlowe, D.W., Hudson, H.S., and Peterson, L.E.: 1974, _Solar Phys._ 35, 193.

Dere, K.P., Horan, D.M., and Kreplin, R.W.: 1973, in H.E. Coffey (ed.), _Report UAG-28, Part II_, World Data Center for Solar-Terrestrial Physics, Boulder, Colorado, U.S.A., p. 298.

Dere, K.P., Horan, D.M., and Kreplin, R.W.: 1974, _Solar Phys._ 36, 459.

Dere, K.P., Horan, D.M., and Kreplin, R.W.: 1977, _Astrophys. J._ 217, 976.

Goldberg, L.: 1967, _Ann. Rev. Astron. Astrophys._ 5, 279.

Heyvaerts, J., Priest, E.R., and Rust, D.M.: 1977, _Astrophys. J._ 216, 123.

Hirayama, T.: 1974, _Solar Phys._ 34, 323.

Horan, D.M.: 1971, _Solar Phys._ 21, 188.

Hudson, H.S. and Ohki, K.: 1972, Solar Phys. 23, 155.

Kahler, S.: 1976, Solar Phys. 48, 255.

Kahler, S.W., Krieger, A.S., and Vaiana, G.S.: 1975, Astrophys. J. 199, L57.

Kahler, S.W., Petrasso, R.D., and Kane, S.R.: 1976, Solar Phys. 50, 179.

Kopp, R.A. and Pneuman, G.W.: 1976, Solar Phys. 50, 85.

Lin, R.P. and Hudson, H.S.: 1976, Solar Phys. 50, 153.

Moore, R.L.: 1976, "Scientific Uses, Performance Requirements and Preliminary Design Considerations for a Solar XUV Spectral Irradiance Monitor", Big Bear Solar Observatory Report #0158.

Moore, R.L., and Datlowe, D.W.: 1975, Solar Phys. 43, 189.

Neupert, W.M.: 1969, Ann. Rev. Astron. Astrophys. 7, 121.

Neupert, W.M., Thomas. R.J., and Chapman, R.D.: 1974, Solar Phys. 34, 349.

Pallavicini, R., Vaiana, G.S., Kahler, S.W., and Krieger,A.S.: 1975, Solar Phys. 45, 411.

Parker, E.N.: 1975, Astrophys. J. 201, 494.

Petrasso, R.D., Kahler, S.W., Krieger, A.S., Silk, J.K., and Vaiana, G.S.: 1975, Astrophys. J. 199, L127.

Petschek, H.E.: 1964, in W.N. Hess (ed.), AAS-NASA Symp. on the Physics of Solar Flares, Goddard Spaceflight Center, p. 425.

Piddington, J.H.: 1974, Solar Phys. 38, 465.

Roy, J.-R.: 1972, Solar Phys. 26, 418.

Schmidt, H.U.: 1969, in C. deJager and Z. Svestka (eds.), COSPAR Symp. on Solar Flares and Space Research, North-Holland, Amsterdam, P. 331.

Spicer, D.S.: 1977, Solar Phys. 53, 305.

Sturrock, P.A.: 1968, in Kiepenheuer (ed.), Structure and Development of Solar Active Regions (IAU Symp. 35), Reidel, Dordrecht-Holland, p. 471.

Sturrock, P.A.: 1972, Solar Phys. 23, 438.

Sturrock, P.A.: 1973, in R. Ramaty and R.G. Stone (eds.), High Energy Phenomena on the Sun Symp. Proc., Goddard Space Flight Center, p. 3.

Svestka, Z.: 1976a, Solar Flares, D. Reidel Publishing Co., Dordrecht, Holland.

Svestka, Z.: 1976b, ibid., p. 306.

Sweet, P.A.: 1969, Ann. Rev. Astron. Astrophys. 7, 149.

Syrovatsky, S.I.: 1972, in C. deJager (ed.), Solar-Terrestrial Physics/1970, Part I, Reidel, Dordrecht-Holland, p. 119.

Tanaka, K. and Nakagawa, Y.: 1973, Solar Phys. 33, 187.

Tucker, W.H., and Koren, M.: 1971, Astrophys. J. 168, 283.

Vaiana, G.S. and Giacconi, R.: 1969, in D.A. Tidman and D.G. Wentzel (eds.), Plasma Instabilities in Astrophysics, Gorden and Breach, New York, p. 91.

Vaiana, G.S., Krieger, A.S., Timothy, A.F., and Zombeck, M.: 1976, Astrophys. and Space Sci. 39, 75.

Vorpahl, J.A.: 1976, Astrophys. J. 205, 868.

Vorpahl, J.A., Gibson, E.G., Landecker, P.B., and Underwood, J.H.: 1975, Solar Phys. 45, 199.

Widing, K.G. and Cheng, C.-C.: 1974, Astrophys. J. 194, L111.

Widing, K.G. and Dere, K.P.: 1977, Solar Phys. 55, 431.

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