EMPIRICAL MODELS OF STELLAR FLARES : CONSTRAINTS ON FLARE THEORIES

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ABSTRACT

A review is presented on empirical flare models of UV Cet type stars based upon optical, UV, X-ray, and radio observations. The observational constraints on the flare energetics, nature of radiation sources, and flare structures are discussed, with special attention to the geometrical dimension and the magnetic field of the flaring region. The hot-plasma model in the solar analogy is critically examined by comparing it with observations. Possible future observations are suggested to tighten the constraints on the stellar flare theories.

INTRODUCTION

The purpose of this paper is to critically review the empirical models for flares of UV Cet-type stars and to propose possible improvement which may lead to tightening constraints on flare theories. Observed flare phenomena are very varied on the Sun as well as on stars. The primary energy sources are generated under various conditions instantaneously or continuously, and the subsequent dissipative processes are even more manifold than the primary processes, depending upon the physical configurations in the adjacent regions. Consequently it would be misleading to construct a model flare based upon data taken piecewise from different events. The most orthodox way is to construct a model for a given flare event using only the data proper to the specific event. For this purpose it is essential to make simultaneous observations over a range of wavelengths as wide as possible. I adopt as the most successful and as the 'reference flare' in this paper the 1979 Oct. 25 event of YZ CMi observed in X-ray, optical and radio regions by Kahler et al (1982). Although this flare showed fine structures composed of three peaks each separated by about 23 sec, its light curve was essentially of type I according to the classification

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of Oskanian (1969). Gershberg and Chugainov (1968) found this type to be the most frequent and the brightest among different types in their statistical study of optically detected stellar flares. I believe, therefore, that the Oct. 25 event is a good choice as a reference flare at this moment.

In contrast to the solar case, we cannot disentangle the aspect effects in the stellar case. Some may be beyond -the-limb events in which we can observe only the radiation coming from the upper part of the flaring region. The X-ray flare of Proxima Cen observed by Haisch et al (1981) on 1979 Mar 6 might have been a beyond-the-limb or close-to-the-limb case because no optical flare was detected for this event. The aspect affects the outcoming radiation when there are substructures in the form of threads or columns which are optically thick along the length but thin in cross-section or when the generation and propagation of radiation is directional. In this matter we are bound by statistical studies.

Solar flares have often been compared with stellar flares as guides in constructing models (Kahler and Shulman 1972, Mullan 1976, Kahn et al 1979, etc.). Since the solar white-light flares are most similar to stellar flares in emitting pronounced optical continuum, we exclusively refer to white-light flares in solar case when not otherwise stated. A general description of white-light flares is found in Svestka (1976), and detailed studies of individual cases are given in McIntosh and Donnelly (1972), Kane and Winckler (1969), Mastus and Stover (1967), Donnelly (1971), Machado and Rust (1974), and Dezso et al (1980). The white-light flares comprise a group of the strongest solar flares some of which are accompanied by gamma-ray radiation. The radiation characteristics of a white-light flare observed on 1967 May 23 according to Kane and Winckler (1969) and Hudson (1972) are compared with those of the reference flare in Table 1.

In section 2 the observed time-profiles of stellar flares are summarized and compared with those of solar flares. The source models for flare radiations in the optical, X-ray, and radio regions are reviewed in sections 3,4 and 5, respectively. Finally empirical models of stellar flares are discussed in section 6.

LUMINOSITY PROFILES

Figure 1 shows schematized time-profiles of the reference flare, based upon figure 2 of Kahler et al (1982). In drawing this I have ignored fine fluctuations in order to make the global features clear. The optical continuum radiation shows an impulsive component and a succeeding gradual component which are typical for type-I flares. Balmer-line emission shows essentially a gradual component, although a small impulsive component may exist. Profiles of soft X-ray and dm

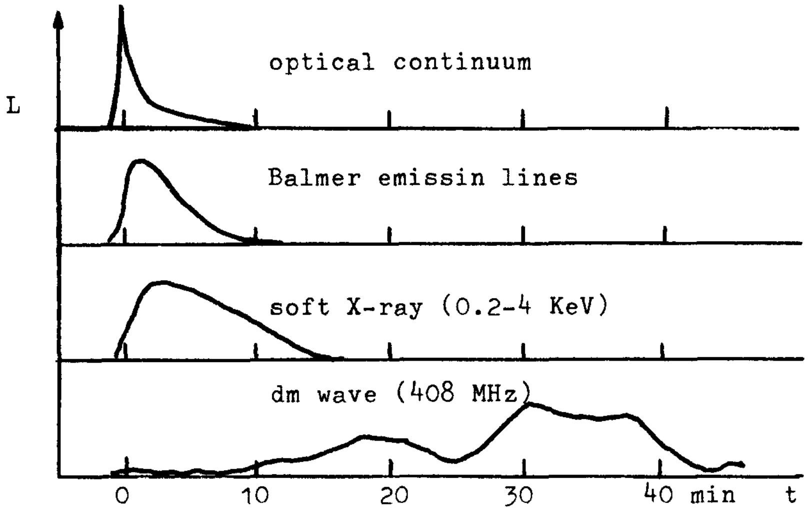

Figure 1. Time profiles (schematic) of 1979 Oct.25 flare of YZ CMi, according to Kahler et al (1982).

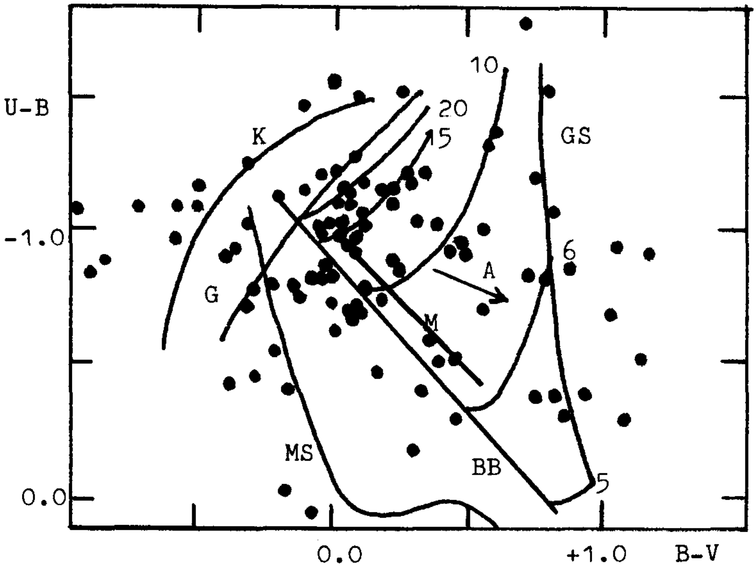

Figure 2. Color domains of light-source models. K and G: Kunkel's (1970) and Gershberg's (1967) nebular models, 2x10^{4}K; upper left for cooler models.GS:Grinin and Sobolev's(1977) warmed photosphere model:Curves combining the thin and thick cases are labelled with T(x10^{3}K).M:Mullan's(1976) hot-plasma model;$T_0=10^{7.9}-10^{4.2}$K. A:decay;BB:black body, and MS:main sequence. Dots: Observed flare colors.

radio-wave emissions consist of gradual components. It is important to notice that the maxima of the Balmer line emission and of the soft X-ray emission are delayed by one or two minutes after the peak of the optical continuum. This fact indicates that the radiation in the optical continuum of the impulsive component is not a secondary effect subsequent to the soft X-ray phenomena, but rather that the gradual components in Balmer line emission and soft X rays are the aftermath of the impulsive phenomena or that their energy is continuously supplied after the impulsive phase. The gradual component in the optical continuum, however, may be closely related to the gradual component in soft X-rays, as suggested by Kahler et al (1982).

By referring to McIntosh and Donnelly (1972) and Kane and Winckler (1969), we find strong similarities between stellar and solar flares, as far as the time-profiles of the optical continuum, Balmer line emission, and soft X-rays are concerned. In the case of solar flares, hard X-ray, EUV and microwave radio radiation, are detected to show a prominent impulsive component. Donnelly (1971) found that radio bursts below 500MHz are poorly correlated with these impulsive events for the solar case, just as we find for the stellar case (cf.Lovell 1971).

The luminosities for specific photon-energy ranges are summarized in Table 1. The data for the reference flare are adopted from Kahler et al (1982). The luminosity for the dm wave L(dm) was estimated by multiplying the flux at f=410MHz with an arbitrary range of about 400MHz. An upper limit is given for cm wave luminosity which is estimated from the minimum detectable signal of Algonquin dish, 20mjy.The upper part of the table shows the ratios of the maximum luminosities in individual passbands although the maximum occurred at different moments in different channels. The ratios of the luminosities at the moment of the maximum of the optical impulsive component are given in the lower part of the table. Note that passbands are slightly different between the stellar and the solar data, but the minor factors do not affect the following discussions. The solar data concerning HI, EUV, and soft X-ray at impulsive peak are adopted from McIntosh and Donnelly (1972) and Donnelly (1971). The value L (Hα)/L(opt)$\gtrsim$0.04 was estimated for the flare regions which were directly related to whitelight kernels. I could not find the ratio L (Hα)/L(soft X)specifically for solar white-light flares, so I referred to general statistics by Thomas and Teske (1971) which were cited by Kahler et al (1982). Kahler et al adopted a mean value 1.6, but the passband of soft X-rays was 8-12A. The corresponding value appears now as about 0.6 in Table 1, referred to a passband 2-12A. I have adopted also a value about 0.2 which was observed for the brightest flare of class 3 among Thomas and Teske's sample, because this flare may come closest to white-light flares in its magnitude.

Inspecting Table 1, I find that the luminosity profile of the

Table 1. Luminosity levels of flares.

Data are adopted from Kahler et al (1982), Kane and Winckler (1969), and Hudson(1972)

	YZ CMi	Sun
	$\Delta U = 1.9$ flare 1979 Oct. 25	white-light flare 1967 May 23
peak		
L(soft X) erg/sec	8×10^{28} (0.2-4.0 KeV)	2×10^{27} (1 - 6 KeV)
peak ratio		
L(opt)/L(soft X)	∿ 2 (3500-6500 A)	∿ 1 (3500-6500 A)
L(dm) /L(soft X)	∿ 10^{-5} (200 -600MHz)	∿ 10^{-7} (300 -900MHz)
L(hardX)/L(softX)	------	10^{-5} ($\gtrsim$ 20 KeV)
L(cm) /L(soft X)	$< 6\times10^{-5}$ (3 - 9 GHz)	5×10^{-6} (3 - 9 GHz)
L(Hα)/L(soft X)	∿ 0.2	∿ 0.2 1) ∿ 0.6 2)
L(EUV)/L(soft X)	------	∿ 2 3) (10-1030 A)
at the impulsive peak		
L(Hα)/L(opt)	$\lesssim$ 0.1	$\lesssim$ 0.04 4)
L(soft X)/L(opt)	∿ 0.1	∿ 0.1 5)

1) A importance 3 b flare, Thomas and Teske(1971).
2) Transformed from the value cited in Kahler et al.(1982).
3) Statistical value, McIntosh and Donnelly(1972).
4) Directly related with white-light kernels only, McIntosh and Donnelly(1972).
5) Donnelly(1971).

reference flare of YZ CMi resembles closely that of the solar white-light flare. When we assume the same luminosity ratios for the stellar and the solar flare, we expect a hard X-ray luminosity of about 8×10^{23}erg/sec for the stellar event, that is a flux of about 2×10^{-16} erg/cm^2 sec. This flux corresponds to about 4×10^{-9} counts/cm^2 sec in 30keV photons. The expected cm wave luminosity is about 4×10^{23} erg/sec, and the corresponding flux is about 1.5 mJy, which is lower by one order of magnitude than the detection threshhold (20 mJy) of the radio telescopes used by Kahler et al (1982) (see also Moffett, Helmken, and Spangler 1978). The expected EUV luminosity is estimated at about 3×10^{29} erg/sec for the reference flare of YZ CMi. The luminosity for 2000-3000A may be estimated at L(UV)=1-5×10^{28} erg/sec. Haisch et al (1981) cited a detection limit of about 1×10^{29} erg/sec in their IUE observation of Proxima Cen, that is, about 5×10^{29} erg/sec in the case of YZ CMi. In both cases the expected UV flux is lower than the IUE detection limit cited by Haisch et al.

We know another example of a type-I stellar flare which was detected simultaneously in soft X-ray and optical light ; Heise et al (1975) reported observation of peak luminosity L(0.2-0.28keV)=6×10^{28} erg/sec for an optical flare of ΔV=2.3 mag of UV Cet. Using the apparent visual magnitude of UV Cet V= 12.3 and the absolute calibration by Oke and Schild (1970), I estimate the V-band luminosity of the flare at 6.6×10^{29} erg/sec. When the empirical conversion equations among U,B,V, and total optical energy given by Lacy, Moffett, and Bopp (1976) are applied, the peak luminosity L(opt) of the flare is found to be 2.5×10^{30} erg/sec. The peak luminosity in another soft X-ray band L(1-7keV), which compares better with the data in Table 1, remained undetected. The upper limit was given as L(1-7keV)<1.8×10^{30} erg/sec. Fortunately Heise et al detected a flare of YZ CMi in both soft X-ray bands, but without optical coverage. Assuming that the energy spectrum in the soft X-ray region was similar between these two flares, I estimate the peak luminosity of the UV Cet flare in the 1-7 keV band at L(1-7keV)=1×10^{30} erg/sec. Accordingly the resulting ratio is L(opt)/L(soft X)=2.5, which is compatible with corresponding values in Table 1. There were some disagreements among previous investigators about the optical/X-ray luminosity ratio of stellar flares and also of solar flares (cf.Kahler and Shulman 1972, Tsikoudi and Hudson 1975, Mullan 1976, Haisch et al 1977, Karpen et al 1977, Haisch et al 1978 and Kahn et al 1979). As for stellar flares, the disagreements were mainly caused by different ways of evaluating and defining the respective luminosities. As for solar flares, white-light flares were not always referred to. Another source of the discrepancy seems to be the lack of recognition that the time profiles are different between the optical and X-ray emissions.

There is no a priori reason to suppose that the luminosity ratios between different passbands be similar in different flares. If they turn out to be similar, however, one may assume a unit flare and regard all flares as a sum of many unit flares with more or less similar physical structure.

3. SOURCE MODEL FOR OPTICAL LIGHT

The physical nature of the light source has been investigated based upon the observed light curve, the broad-band colours at the peak and their later evolution, and the spectroscopic features (emission lines, Balmer jump). Studies of light curves were rewieved by Gershberg and Chugainov (1968), and the color studies were summarized by Cristaldi and Rodonò (1975). A good summary of spectroscopic observations is given in Schneeberger et al (1979).

Time resolved spectroscopic observations by Kunkel (1970), Moffett and Bopp (1971), Bopp and Moffett (1973), and recent multichannel photometry by Mochnacki and Zirin (1980) made it clear that the contribution of emission lines to the total optical luminosity is only about 5% at the impulsive peak and increases up to 40% in the late phase. No significant polarization has been reported for optical flare light (cf.Karpen et al 1977). Since the intense visible continuum distinguishes stellar flares from solar flares, its interpretation is of primary importance. In the last decade we were confronted with three categories of working hypotheses about the light source: fast-electron model, hot-plasma model, and nebular model.

The fast-electron model was proposed by Gurzadyan (1965, 1966,1972) to account for the observed continuum and was found to be successful in reproducing the broad-band colors by the inverse Compton effect of relativistic electrons (1-10MeV). This model, however requires too much energy input (about 10^{51} erg), and is due for revision since we now know that UV Cet-type stars have chromosphere-corona envelopes which are more rich in material than that of the Sun (Haisch et al 1980, Vaiana et al 1981, Giampapa, Worden and Linsky 1982), probably related to magnetic fields (Gray and Linsky 1981, Topka and Marsh 1982, Robinson, Worden and Harvey 1980). The large number of relativistic electrons in the Gurzadyan model would strongly interact with coronal plasma and the stellar surface (cf.Arutyunyan 1979). The resulting emitted radiation must dominate over the inverse Compton effect. Consequently I am inclined to retain only the essential feature of this model, namely, the non-thermal high-energy particles being a possible primary energy source.

The hot-plasma model was adopted by Andrews (1965) to explain the observed flat continuum (cf. Kodaira and Ichimura 1975) and the decay time-scale by bremsstrahlung of hot gas ($T \gtrsim 10^6$ K). As a single-layer model led to an increase of optical continuum with plasma cooling, the model was later refined by Mullan (1976, 1977) and Kodaira (1977), who included stratification effects and their time variation. In the refined model, the heat energy of hot plasma is partially radiated off as thermal bremsstrahlung but also conducted towards the stellar surface. The conducted energy flux is then efficiently radiated from denser and cooler layers. The flare soft X-rays are emitted from the hotter upper part ($T \gtrsim 10^6$K) while the optical light is predominantly from the cooler lower part ($10^5 \gtrsim 10^4$K). Mullan adopted the temperature structures of equilibrium models by Shmelva and Syrovatskii (1973) and showed that the model colors correspond well to the observed ones. Mullan and Tarter (1977) pointed out that a furter improvement of this model may be possible when the back-heating effect of the stellar surface by flare X-rays is taken into account. Cram (1982) showed that even at the quiescent phase, the back-heating effect of the coronal X-rays strongly affects the energy balance in the chromosphere of dMe stars. The hot-plasma model thus developed may explain the main features of flare soft X-rays, as will be discussed below, but leaves the details of the physical conditions of the dense lower part ($T \lesssim 10^4$ K) unspecified. This model is valid only for the gradual components and not for the rise of the impulsive optical light.

The nebular model was developed by Gershberg (1964, 1967a, 1967b) and Kunkel (1970) to represent the observed Balmer emission lines and Balmer jump. Recombination spectra are assumed to be emitted from a homogenous layer of electron density typical for the chromosphere, $N_e = 10^{13}-10^{14}$ cm^{-3}. They found a temperature range $T_e = 2-3 \times 10^4$K appropriate in order to reproduce the observed Balmer decrement ($H\gamma/H\beta = 1.1-1.5$) and the Balmer jump ($I_-/I_+ = 4-5$), but failed to reproduce the observed broad-band colors.

The model colors are generally too blue and become bluer with decreasing temperature or density, contrary to the observations (see Figure 2). Thereupon Gershberg (1967b) suggested bremsstrahlung as an additional component, and Kunkel (1970) suspected admixture of slightly heated (about 100K) photospheric radiation.

Grinin and Sobolev (1977) proposed to shift the location of the "nebula" to a lower, cooler and denser layer ($T = 0.5-1 \times 10^4$ K, $N_e = 10^{15}-10^{17}$ cm^{-3}) than Gershberg and Kunkel had assumed. As the reason for this, they pointed out that the hot nebula of $T = 2-3 \times 10^4$ K would give a rise not only to HI and HeI lines but also to strong lines of HeII and of other highly ionized atoms, which were not detected in stellar flare spectra (cf. Bopp and Moffett 1973, Schneeberger et al 1979). The high density they adopted corresponds to that of the bottom of the chromosphere or of the upper photosphere (cf. Giampapa, Worden, and Linsky 1982). In this model, when the temperature is low, the dominant H^- opacity leads to a relatively flat continuum from the optically thin layer, and, when the temperature increases, sharply increasing HI opacity leads to a black-body-like radiation from an optically thick layer (see Figure 2). It is notable that Machado and Rust (1974) interpreted the continuum of white-light waves (but not the white-light kernels themselves) caused by a solar white-light flare as a free-bound radiation from a layer of 8500K, with an optical thickness at 5000A of 0.1. Grinin and Sobolev (1977) found that their "warmed photosphere" model of T= 8500K emits optical light as observed in stellar flares. Their picture may effectively be the same as that presented by Cram and Woods (1980), who increased the pressure at the bottom of the transition zone by 1-2 orders of magnitude and laid the photosphere-chromospheric temperature minimum deeper for the flaring relative to the quiescent region.

By assuming a black-body optical continuum, Mochnacki and Zirin (1980) found a peak color temperature of T=8500-9000K from their multichannel measurement of a flare of YZ CMi which had apparently a similar magnitude as the reference flare in Table 1. They obtained a projected area of about 10^{19} cm^2 for the blackbody emitter. Kahler et al showed that the reference flare also had a projected area of about 10^{19} cm^2 when a black body of 8500K was assumed as optical light source. In Mochnacki and Zirin's observation, the color temperature increased before the impulsive peak and then decreased down to 5000-6000K, while the projected area reached a maximum a few minutes later than the impulsive peak.

The spectroscopic observations by Kunkel (1970), Moffett and Bopp (1971), and Bopp and Moffett (1973) revealed that HeI emission lines appear sporadically or weak around the impulsive phase, and that CaII H and K lines decay slower than Balmer lines. These facts suggest that the temperature of the light-emitting region reaches the maximum around the impulsive phase and decreases gradually. Their observations as well as those by Gershberg and Chugainov (1967) also revealed that in some flares the half widths of emission lines increased up to about several tens km/sec during the impulsive phase of less than a few minutes and then rapidly returned to normal. In another case, they observed so-called "red asymmetry" of line wings with a corresponding velocity of 600-1100km/sec during the impulsive phase, which had been known for solar flares (cf. Svestka 1966). Although Schneeberger et al (1979, 1980) detected no significant line broadening for a $\Delta U=0.5$ flare of AD Leo and for $\Delta U=1.5$ flare of YZ CMi, it seems to me that dynamical phenomena are involved during the impulsive phase, which, however, may not be manifested clearly under certain aspect conditions. The motion has probably directivity. McIntosh and Donnelly (1972) reported that eruptive Hα structure of 600-1000km/sec are often observed for solar white-light flares seen near the limb.

A valuable study was done by Katsova et al (1980) and Livshits et al (1981) concerning the dynamical response of chromospheres to an impulsive energy injection at the top. Their one-dimensional study shows that the shock waves propagate both upwards and downwards. The post-shock layer of the downwards wave becomes in some cases optically thick, therefore, it may produce the continuum discussed above. (A one-dimensional dynamical heat propagation into the corona was discussed by Syrovatskii and Shmelva 1972). They assumed the duration of a unit injection of energy of flux $F=10^{12}$ erg/cm^2 sec to be about 10 sec, and that the impulsive phase of a flare consists of a group of such pulses. As a physical heat-source model for this, they assumed, as Hudson (1972) and Machado and Rust (1974) did for solar white-light flares, the "thick-target mechanism" for non-thermal high-energy particles.

4. SOURCE MODEL FOR SOFT X-RAYS

The termal nature of stellar flare radiation was clearly confirmed for the first time by Kahn et al (1979). Their data points (0.2-10keV) from the HEAO-1 A-2 experiment observation of a flare of AT Mic on 1977 Oct.25 fit well to the energy distribution from a thin thermal plasma of $T=3\times10^7$ K. They believe they have identified the 6.7 keV Kα line of FeXXV which supports the hot thermal nature of the source. A pulse-height analysis of the soft X-ray data of a flare on Proxima Cen by HEAO-2's IPC experiment by Haisch et al (1980) yielded a maximum temperature of $T=1.7\times10^7$ K during the rising phase of the soft X-ray flux, which then decreased to 1.2×10^7 K at the beginning of the decay phase. The above authors derived emission measures EM= 1.4×10^{54} cm^{-3} for AT Mic, 7.5×10^{50} cm^{-3} for the rising phase of a Proxima Cen flare, and 1.2×10^{51} cm^{-3} for the decay phase of the Proxima Cen flare, by referring to the radiative power calculated by Raymond, Cox, and Smith (1976). Based upon the thin-thermal-plasma interpretation, Kahler et al (1982) showed that the reference flare of YZ CMi reached a maximum temperature of $T=2\times10^7$ K with an emission measure of $EM=4\times10^{51}$ cm^{-3} around the flux maximum of soft X-rays. Both temperature and emission measure gradually decreased in the decay phase, parallel with the flux. The increase of emission measure during the rising phase of soft X-ray flux strongly suggests that either the plasma density or the volume (or both) rapidly increased during the optical impulsive phase. As a comparison Kahn et al cited an extremely strong solar flare of 1972 Aug.4 (cf. Colgate 1978) which had a peak luminosity L(soft X)=4×10^{27} erg/sec with $EM=6\times10^{49}$ cm^{-3}, whose magnitude is thus comparable to that of our reference solar white-light flare in Table 1. Although the plasma temperatures are comparable in the solar and stellar flares, the maximum emission measure seems to be larger in strong stellar flares than in the strongest solar flares by a factor of up to 10^2-10^4. By applying the principles of the hot-plasma model studied by Kodaira (1977) and Mullan (1977) to the decay phase of the reference flare, we find that the radiative cooling rate is comparable to the conductive cooling rate of the hot plasma. The observed decay time scale $t=10^3$ sec then suggests an electron density of $N_e=10^{11}$ cm^{-3}. The volume turns out to be about 10^{29} cm^3.

The lenght scale may be estimated from the expansion time scale of hot plasma, which may be regarded equal to the delay time of the soft X-ray maximum relative to the optical impulsive peak, t=100sec. The resulting length scale is $L= 10^{10}$ cm, which is comparable to the stellar radius, $R=0.5$-2×10^{10} cm. Accordingly the dimension of the cross-section is estimated at $A=10^{19}$ cm^2. This corresponds to 0.5-3% of the stellar disk and is comparable to the area for impulsive white-light emission estimated by Kahler et al (1982), and by Mochnacki and Zirin (1980) (see section 3). This area and length estimate is also consistent with the conductive cooling rate required. The thermal energy contained in the hot plasma at the beginning of the decay phase was found to be $E= 4\times10^{31}$ erg for this model of the reference flare. The total emission of the gradual and impulsive optical light are comparable to this. Accordingly the total flare energy amounts to more than 10^{32} erg.

The expansion phase of the soft X-ray plasma might be explained by the particle injection model of Livshits et al (1981). One of their models for an injection flux $F=3\times10^{12}$ erg/cm^2 sec and a pulse duration t=10sec, that is, a total energy of $E= 3\times10^{32}$ erg for an area of $A= 10^{19}$ cm^2, shows an expansion of the upper chromospheric material with a velocity of 10^3 km/sec after it is heated to $T \gtrsim 10^7$ K. When pressure balance is assumed between the soft X-ray plasma and the magnetic field which probably confines the plasma, one finds a field strength of $B= 10^2$ gauss.

5. SOURCE MODEL FOR RADIO WAVE EMISSION

A review of radio wave observations of stellar flares in the early period was given by Lovell (1971). He reported observations of radio flares in the 200-400MHz range which were temporally correlated with optical flares, but found also numerous cases in which only radio or optical emission was detected. There seems to be no clear correlation between the observed luminosities of the two emissions. When they are temporally correlated, the time profiles of the dm-m wave emission are generally much broader than those of the optical impulsive peak, sometimes even broader than that of HI lines of soft X-ray gradual component. Radio emission rises much slower than the latter, but in some cases isolated sharp peaks stand out above the broad components. The radio maximum mostly appears a few to several minutes later than the optical peak but the rise often begins one to a few minutes before the start of the sharp optical rise. In some small flares, the radio maximum appears even before the optical peak. When a flare was observed in two pass bands, the flux in the low-frequency band (say 200 MHz) is found to be larger than that in the high-frequency band (say 400 MHz) by a half order of magnitude or more, indicating a rather steep spectrum.

This diverse behavior of dm-m wave flares was further confirmed by Lovell et al (1974), Spangler, Shawman, and Rankin (1974), Spangler and Moffett (1976), and by recent investigations coordinated with X-ray observations (Karpen et al 1977, Kahler et al 1982). Spangler and Moffett (1976) underlined that there are no systematic correlations in the morphology of time profiles between radio and optical flares. The above facts suggest that the radiation source of the dm-m wave is not directly related to those of optical and soft X-ray emissions. Since the electron density for the plasma frequency f=400MHz is about $N_e=2x10^9$ cm^{-3}, the emitting region of dm-m wave may lie outside the dense soft X-ray plasma ($N_e=10^{11}$ cm^{-3}).

The reference flare of YZ CMi follows the general trend of stellar radio flares. The delay time of this flare, however, was much longer than the values cited above as average; 20-60 minutes. Such a large delay was observed for an extremely strong flare of YZ CMi by Lovell (1971) on 1969 Jul. 19. The dm-m wave enhancement of this $\Delta V=1.8$ flare continued over 4 hours after the optical impulsive peak and the first broad maximum appeared 30-60 minutes after the flare start. Judging from the optical peak luminosity $L(opt)=4x10^{30}$ erg/sec, this flare was one and half orders of magnitude stronger than the reference flare. Its dm-m wave luminosity is estimated at $L(200\text{-}600MHz)=10^{26}$ erg/sec. Thus the ratio $L(dm)/L(opt)=2.5x10^{-5}$ turns out to be comparable with the value $L(dm)/L(opt)=5x10^{-6}$ in the reference flare. If the spectrum falls off according to f^{-n}, the index n is about -1.5 for the 200-400MHz region. By extrapolating this, one obtains a flux of about 8mJy at 1428MHz for the reference flare, which lies far below the detection limit (100mJy) of the observation by Kahler et al (1982).

Detections of cm wave flares were reported by Karpen et al (1977), Gibson and Fisher (1980), and Haisch et al (1981). Most of the flux levels detected with single-dish telescopes were close to the detection limit and the observed flare durations were less than one integration time (a few minutes), accordingly, these data must be applied with caution. Haisch et al (1981) found three cases correlated with optical flares of Proxima Cen. One of them occurred simultaneously with a $\Delta U=4.5$ optical flare, the others with a delay of 2-5 minutes. When the simultaneous one is scaled to the reference flare according to the U magnitude, one would expect a flux level of only 0.03 mJy. The event reported on YZ CMi by Karpen et al (1977) had no optical coverage. It emitted 1.2 Jy at 160 MHz and 78 mJy at 5 GHz. The latter level is anomalously high compared with levels less than about 10 mJy observed by Haisch et al (1981) in Proxima Cen (see also Moffett, Helmken, and Spangler 1978). Gibson and Fisher (1980) reported that their 4.9 GHz VLA observation of YZ CMi indicated a significantly lower flux level and a much longer duration than single dish observations had suggested. The detected cm wave emission, therefore, might be the high-frequency tail of the gradual dm-m wave component.

It should be noted that quiescent coronal emissions in cm waves were also detected using VLA by Gray and Linsky (1981) and by Topka and Marsh (1982). The former detected 1.6 mJy emission from UV Cet, and the latter 0.7 and 0.4 mJy emissions from the binary components of EQ Peg. They interpreted these by gyroresonance of thermal electrons in their coronae.

The most interesting feature of the radio emission related to stellar flares is the high degree of circular polarization (50-100%) observed by Spangler, Rankin and Shawman (1974) at 430 MHz and by Gibson and Fisher (1980) at 4.9GHz. This suggests gyroresonance or gyrosynchrotron radiation in magnetoactive plasma as an emission mechanism. The gyrofrequency, which should be less than the observation frequency, corresponds to a magnetic field less than about B=50 gauss. The luminosity L(dm) of the reference flare, however, is too high to be interpreted as of thermal origin because the brightness temperature becomes higher than $T= 10^{13}$ K even when an area comparable to the whole stellar disk is assumed. This situation, the long delay time, and the gradual nature of the dm-m emission of the reference flare suggests that any sort of non-thermal emission process was induced by a series of large-scale structure changes of coronal magnetic field which followed the initial localized event.

6. DISCUSSION

A framework of a stellar flare model might be deduced from the considerations in the preceeding sections. A flare event presumably starts with a structural change of magnetic field, which first begins locally and slowly, supplying energy to particles and plasma, and appears as a gradual rise of chromospheric line emission and soft X-ray emission, sometimes also of dm wave emission. At a certain phase of the structural change a series of intense impulsive energy releases occur within limited regions, which leads to a sudden heat-up of the chromosphere. This produces shock waves propagating downwards and rapid upwards expansion of the heated plasma. The post-shock dense layers emit impulsive optical light, while the expanded thin hot plasma emits soft X-rays whose luminosity increases with increasing matter supply and decays gradually due to radiative and conductive cooling. The downwards heat conduction and the back-heating of the soft X-rays supplies the energy for the gradual component of the optical emission. Weak, gradual energy release may continue for a substantially longer period than the impulsive phase, contributing to stimulation of the gradual soft X-ray and optical emissions. Partially as an aftereffect of the intense energy release,but more likely as a continuation of the general structural change of the magnetic field, non-thermal energy release occurs in the magneto-active corona and gives rise to the gradual dm-m wave emission.

So far as this rough scenario of a flare event is concerned, we see a broad similarity between the stellar flare and the solar white-light flare and feel almost justified in applying the same model to both. There is, however an outstanding difference in magnitude between them. Although the estimated area $A= 10^{19}$ cm^2 is comparable to the Hα area of a solar flare of importance 3 (cf. Svestka 1976), the energy of the reference flare which was emitted in the observed radiations ($E \gtrsim 10^{32}$ erg) is two orders of magnitude larger than the strongest solar flares, and comparable to the total energy of the most powerful solar flare, most of which, however, is deposited in the shock wave. Flares of the same magnitude as the reference flare occur on YZ CMi every 10 hours on average (cf.Lacy, Moffett, and Evans 1976) and the mean luminosity radiated by flares of this class amounts up to 3×10^{27} erg/sec, which is about 3×10^{-6} of the stellar luminosity. In the solar case, flares of importance class $\gtrsim 3$ occur 20-30 times in a year around the sunspot maximum, thus the mean luminosity of these flares is about 10^{26} erg/sec, 2.5×10^{-8} of the solar luminosity. A stellar flare theory must first of all account for this efficient energy accumulation and release in the form of flare radiation.

Since the solar white-light kernels occupy only about 1/100-1/30 of the total flaring area (cf.McIntosh and Donnelly 1972), one may presume either that the total flaring area in the solar sense was about 10^{21} cm^2 for the reference flare, that is, almost the whole hemisphere of YZ CMi, or that the flaring region of YZ CMi was covered almost exclusively by white-light kernels. In the former case, the physical structure of a stellar flare may be replaced by that of strongest solar flares, except for collective effects which certainly become prominent if the whole hemisphere should be covered by the strongest (solar) flares. The question of how the vast area can simultaneously become unstable, remains to be solved.

In the latter case, we may suspect differences in the physical structure of flares. When we fail to detect the impulsive microwave component from stellar flares in contrast to the solar case, it would indicate that the primary energy release generally occurs in a deep layer where the plasma frequency exceeds microwave frequencies; the density of the layer must be as high as $N_e = 10^4$ cm^{-3} corresponding to the density of the transition zone to upper chromosphere. If this is the case, one may further assume that the efficiency in the thermalization process of any non-thermal primary energy input and in the radiation process is much higher under this conditions, what would conform to the empirical picture.

Assuming that the energy of a homogenous magnetic field is converted into heat, the minimum magnetic field required for the reference flare is $B=10^{4.5}/(LA)(0.5)$ gauss, L and A being the height (in 10^3 Km) and the area (in 10^{19} cm^2) of the volume in which magnetic energy is to be consumed. The area A can vary between 1 and 100. If L=1 for the chromospheric scale, B=3000-300 gauss, while, if $L=10^2$ for the coronal scale, B=300-30 gauss, which appears not unreasonable. This concept leads to a picture of a stellar flare in which a large quantity of magnetic energy ($E \gtrsim 10^{32}$ erg) is converted into heat in a dense layer ($N_e \gtrsim 10^{11}$ cm^{-3}) of an area of $A=10^{19}$ cm^2 The question remains how to convert it into heat!

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DISCUSSION

Gershberg: It seems to me that if you wish to constrain theory you should use not the mean flare energy but rather the extreme case. There are known at least three optical flares which are more energetic than the mean by two orders of magnitudes viz. the 1969 YZ CMi, your own flare (on EV Lac) and the flare observed some months ago in Soviet Middle Asia. In all these cases the optical energy only exceed 10^{34} ergs. This appears to me to be a real constraint for the theories.

Kodaira: My answer would be that since such cases are rare they do not contribute significantly to the average energy output.

Priest: Can I just give a "back-of-the postage-stamp" type of estimate in how you can ... (part of the recording lost) ... the energy should scale as B^2 times l^3. The timescale should scale as the length-scale over the Alfvèn speed squared. So if you eliminate l between these two there results an expression for W. Now assume that a stellar flare is 10^3 times larger in energy than a solar flare. Assume the timescale is a factor of 10 shorter and that the density is a factor of 10 larger. Put these into this expression and you find that the magnetic field has to be a factor of 30 times larger than in the Sun. The magnetic field in the solar case is between 100 and 500 G; then in the stellar case we expect it to be 3 - 10kG, assuming of course that we are dealing with the same mechanism.

Weiss: This would be pushing things. One can image sunspot-strength fields extending over large regions but not fields of 10kG.