STELLAR ACTIVITY

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1) INTRODUCTION

Stellar flares were first discovered by Hertzsprung in 1924 as a two magnitude increase, in an unusually short time, of the brightness of the star DHCar

This initial discovery was soon forgotten and one has to wait 1947 to see the subject of stellar flares attract again the attention of the astrophysicists. At that time it was observed that the brightness of the star UV Cet changed by an order of magnitude in three minutes.

Since then, a large observational material has been accumulated, both on the properties of the stars which are the sites of the flaring process, and on the stellar flares themselves.

The general conclusion which comes out when studying this material is that although the energy involved in the stellar flaring process is much larger than in the solar case, solar and stellar flares as well as the associated magnetic activity are of a basically similar character although stellar flare appear to be 2-4 order of magnitude more energetic, and on the average much faster (see Gershberg 1978, for a good review of eruptive stellar phenomena).

2) FLARE STARS

Flare stars, or "UV Ceti type stars" are far from being rare exotic stars. Of the 33 stars which lie within 4 pc of the sun, at least 13 are known to be UV Ceti type flare stars.

They are found in the lower end of the main sequence in the Hertzsprung-Russell diagram, being dwarves of late type (dM), with masses ranging from 0.06 $M_{\odot}$ to 0.6 $M_{\odot}$, surface temperatures 2700°K - 4000°K and radius 0.2 to 0.6 $R_{\odot}$ and which exhibit strong permanent hydrogen line emission (dMe).

Joy and Abt, 1974, have shown that the proportion of flare stars among a particular spectral type increases from a few percent for dM0 stars up to nearly 100 % for dM 5.5 and later type stars.

Statistical studies, reviewed by Gershberg, 1978, indicate that flare activity is inherent for stars, the age of which are within 3 10^5 to 10^{10} years, the older ones having a lower flare activity than younger ones.

As most of the stars with spectral type later than mid F, they present evidence of having stellar chromosphere by showing H and K Calcium emission line. But as pointed out by Giampapa, 1980, the radiative losses due to this emission, estimated by the excess flux in these lines over the expected H and K line flux for a stellar atmosphere in radiative equilibrium, seem to be systematically larger for dMe stars than for non flaring (dM) stars of the same effective temperature.

Similarly, the characteristic presence of the hydrogen Balmer line emission indicates the presence of a hot and dense chromosphere (Gershberg, 1975, Cram and Mullan, 1979) with electron densities of 10^{12} cm^{-3} at the height where the temperature is of the order of 10 000° K.

Based on solar experience it is not unreasonable to expect the Balmer and Ca II H and K emission to predominantly originate in localized active regions.

This is supported by the fact that at times , Balmer emission in excess to the continuum is absent. Moreover the equivalent width of the emission lines show variations of up to a factor of three at times when no flares can be detected photometrically ; with time scales of a day or less, a time too short to allow a uniform chromosphere to respond to a change of its boundary conditions. (Bopp, 1974)

The U.V. spectrum of dwarf stars appear to be generally similar to that of the sun in that they exhibit the typical lines of the transition zone and lower corona. However while quiet dwarves have line ratio and surface fluxes roughly similar to that of the sun, for flare stars, the surface fluxes can be up to 20 times larger and are more reminiscent of a solar active region plage. (see the review by Dupree and Hartmann, 1979).

Let us now end this brief description of the atmosphere of flare stars, by noting that there are now direct evidence of the presence of Coronae in these cool active dwarf stars, thanks to the X-ray observations made on board of the Einstein Satellite (see the review by Vaiana, 1980). Their X-luminosity ranges from 10^{27} to 10^{30} erg/sec with a ratio $L_X/L_{opt} \simeq 10^{-4}$ to 10^{-1}.

Thus these flare stars appear to possess extremely active atmospheres, compared to those of quiet stars of the same spectral class. When looking at many of their properties, it is tempting to interpret this activity as a sign of the presence of active regions, just like on the sun, the various level of atmospheric activity of a particular star being related to percentage of the stellar disk covered by these active regions for that particular star (see Giampapa 1980) .

We are then immediately led to the question: do stellar spots exist also on these stars? The answer is yes. Indeed, among dMe Stars, a number exhibit quasi sinusoïdal variations in their V light, with periods of the order of a few days, and varying phases and amplitudes. This is the so called BY Draconis Syndrome. (see for example Bopp and Espenak 1977).

This is interpreted as a non uniform brightness distribution accross the stellar disk, which combined with the rotation of the star, produces the variation of the light received at the earth. An example taken from Petterson, 1980, is shown in figure 1.

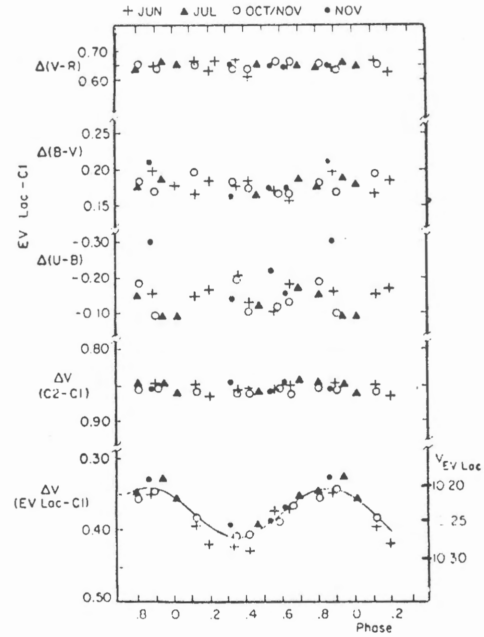

Figure 1. Magnitude and color or EV Lac relative to a nearby comparison star. The right hand scale gives the magnitude of EV Lac itself. The solid curve in the lowest panel result from a fit with a rotation period of 4.378 days (equatorial velocity : 4.2 ± 0.5 km/s ; Pettersen 1980).

A little more than ten stars are known to posses this type of variability but there are good reasons to believe that all dMe stars are affected by it.

All present models rely on the hypothesis of the existence of giant dark spots covering up to 20 % of the visible stellar hemisphere, and temperatures lower by 200 - 1500°K than the surrounding photosphere. The changes in amplitude or phase are then interpreted as the growth or decay of the star spot.

By analogy with the sun, these spots were though to be produced by the emergence of strong magnetic fields.

However, although searches for fields on late type dwarves have be made for quite a long time, it was not until very recently that the direct confirmation by Robinson (1980) of the existence of such fields was obtained. He used a method based on the deconvolution of a field perturbed line profile by that of a very similar field insensitive line. This method, in principle, is not sensitive to the averaging effects which affect the conventionnal stellar field measurements of unresolved bipolar fields regions.

He was able to determine the magnetic field strength for two dMe stars, ξ Boo and 70 Oph A with respective amplitude of 2500-3000 gauss and 1800 gauss, covering respectively 40-45 % and 7-10 % of the star's surface.

3) STELLAR FLARES

Before entering the discussion of stellar flares let us give a very brief overview of what we know of solar flares, as the result of the numerous investigations in the whole spectral range of electromagnetic radiation (see the report from the Skylab Solar Workshop II, Sturrock, 1980).

As far as comparison with stellar flares goes, let us stress that it is now commonly accepted that solar flare regions contain both a hot and a cool plasma.

The latter is responsible for the optical emission which constitutes the much studied " chromospheric flare " as seen for example in Hα . Spectral observations of the optical line emission indicate that they are formed in a thin layer a few ten of kilometers wide, of dense ($n_e \simeq 10^{12}$ - 10^{13} cm^{-3}) chromospheric plasma situated within the lower 5000 km of the solar atmosphere.

The hot, X ray emitting plasma ($\simeq 10^7$ °K, $n_e \simeq 10^{10}$ cm^{-3}, emission measure 10^{48}- 10^{50} cm^{-3}) is observed at the top of closed magnetic field lines bridging the magnetic neutral line which separates opposite polarity regions of the chromospheric flare. Estimate of the energy content of the thermal X-ray plasma, at flare maximum, indicate that a major part of the total energy released in the flare goes into that plasma. Thus it can be taken as a good witness of the flare energetics.

The flash phase of duration 10 - 100 seconds is clearly the phase, when the primary energy release takes place ; during that period, magnetic energy is probably transferred to the coronal flare plasma, the temperature of which is sufficiently high to drive, through conduction, chromospheric evaporation, which increases rapidly the density of the X ray plasma as it cools.

The cool plasma, during the process, is heated through various processes : non thermal electrons, thermal conduction, X rays, motions according to its magnetic connection with the corona.

Figure 2, show the result of an extensive statistical study by Drake, 1971, showing the distribution of rise times and total X ray radiated by a large sample of X ray bursts (within the frequency range 2-12 Å).

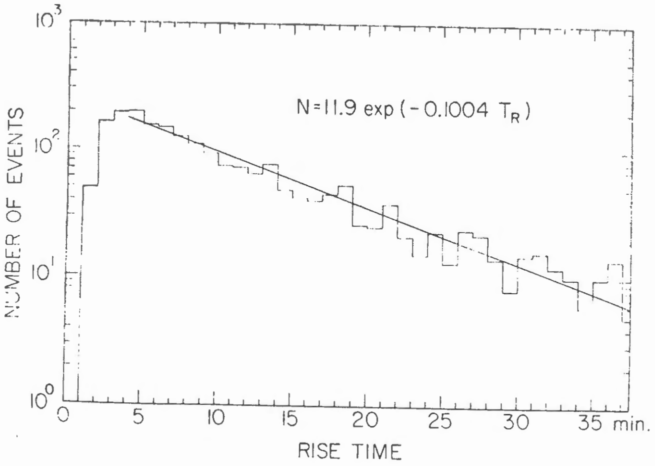

Figure 2a (see legend on next page)

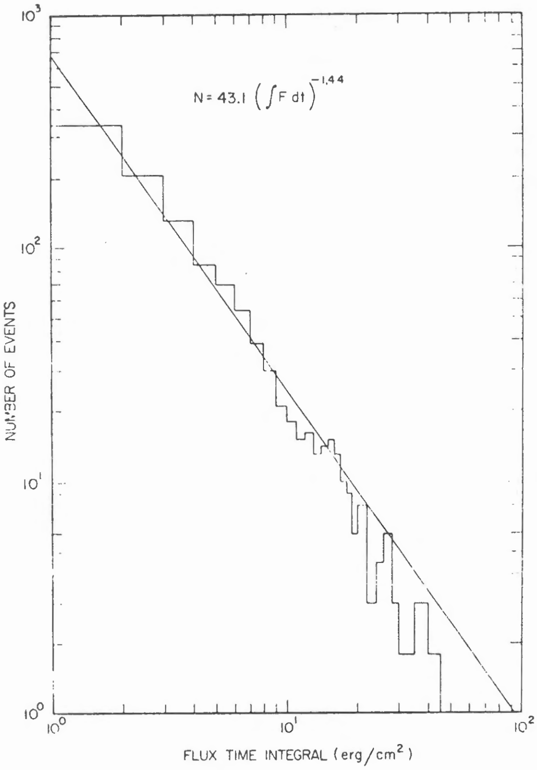

Figure 2b

Figure 2 : a) Differential distribution of 2-12 Å-ray bursts with respect to the value of the time integral of the burst flux for the duration of the burst. The straight line is a least-squares fit over the region indicated.

b) Differential distribution of 2-12 Å-ray bursts with respect to rise time. The straight line is a least-squares fit over the region indicated. (Drake, 1971).

On the other hand, Kahler, 1978. by comparing X-ray images and X-ray flux profiles was able to show a number of correlations between rise time, energy and the flare loop morphology. For example :

rise time t_r (minutes) $= 0.63\ V^{0.34}$

energy E (ergs) $= 0.11\ V^{0.60}$ (V : flaring volume)

Let us now come to stellar flares.

Most of the stellar flares observations have been made in the optical domain, and it is only very recently that a much wider frequency coverage has been obtained.

In the optical domain, a light curve for a typical flare is characterised by a sharp spike of enhanced brightness (rise time of the order of a few seconds to a few minutes, i.e. much shorter than for a typical solar flare) followed by a much slower phase of return towards "quiet" brightness level (this phase may last from a few minutes to several hours). In figure 3, is shown the light curve for a flare on the prototype star UV Ceti (Bopp and Moffet, 1973) which exhibits these characteristics, together with the timing of the various radiative processes which characterise the optical flare : enhancement of the hydrogen emission lines, of Ca II, He I, occasionally He II, just as in solar flares.

Note however that not all flares have this spiky structure ; some have a much more gradual rise and fall ("slow flares"). Only in spike flares, is the continuum also enhanced during the fastest phase of the flare process.

The flares certainly originate from localised region of the stellar disks since 1) cold atmosphere characteristics (such as the TiO absorption band) persist in the stellar spectra during a flare, 2) the smallest flare time scales have proven to be smaller than the time needed for ligth to travel accross the stellar disk.

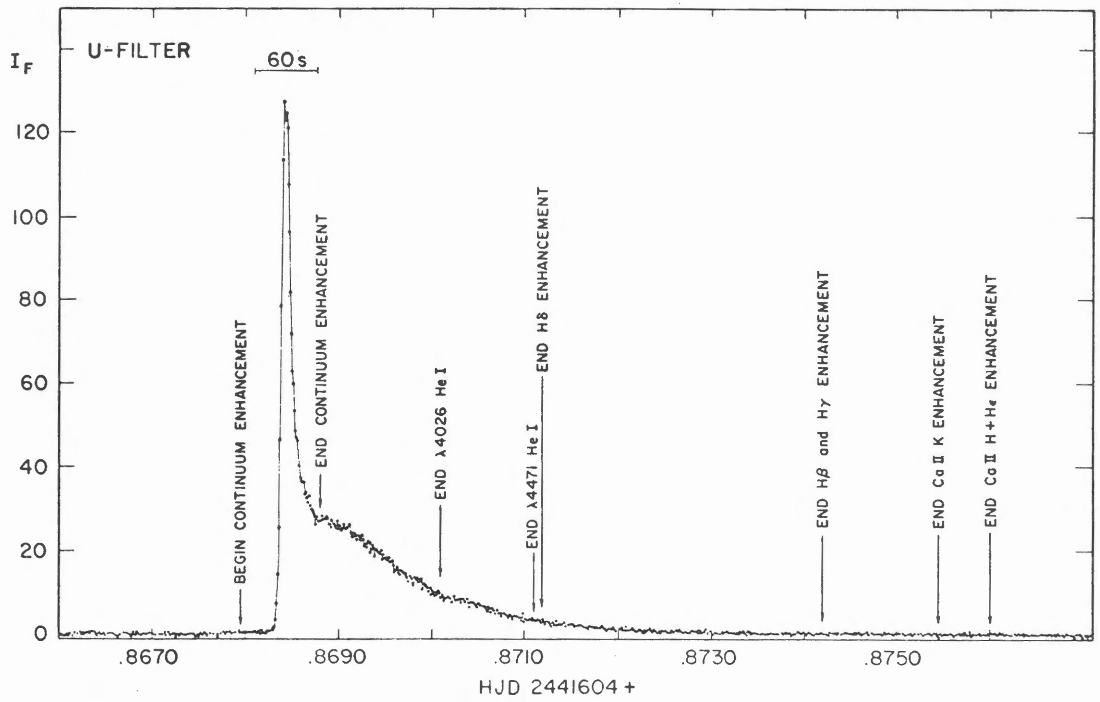

Figure 3. Light curve of a flare on UV Ceti in U-bandpass with integration time of 1 s. Vertical arrows indicate the times at which the various spectral features were noted ($I_f = \frac{I(t) + I_o}{I_o}$; I_o "quiet" intensity, I(t) total intensity) (Bopp, Moffet, 1973).

A number of empirical relations have been shown to relate some characteristics of the flares with the absolute visual magnitude M_V or effective temperature of the star. For example the duration T of the flash phase has a relatively well definite value for a given star and varies like

$$\log T = 2.862 - 0.119 M_V \qquad (T \text{ in seconds})$$

from star to star, while a flare of ultraviolet magnitude U occur at a mean rate $R(U)$.

$$R(U) = e^{\alpha(U-U_o)} \text{ per day}$$

where α is roughly independant of the star, $\alpha \simeq 0.9 - 1$, whereas the "typical" ultraviolet flare magnitude U_o varies from star to star (Kunkel, 1975). Another piece of information concerns the total visible energy emitted during the duration of the flare was obtained by Lacy et al, 1976. In figure 4 the frequency of flare occurence versus the energy of flares is shown for UV Ceti, and exhibits a remarquable saturation at low energy.

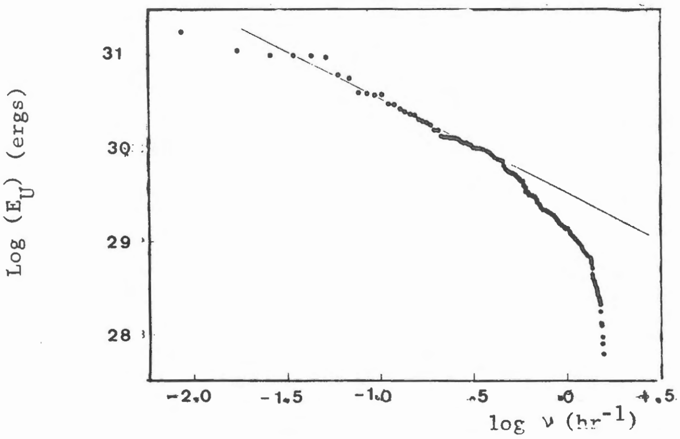

Figure 4. UV Cet cumulative distribution of flare energy as derived from U data.

As pointed out by Rosner and Vaiana, 1978, this is hardly interpretable by selection effects due to the difficulty of detecting low energy flares, since then one would expect the frequency of flares to decrease below a certain energy threshold. Furthermore all dMe stars studied by Lacy et al, covering a wide bande of quiescent luminosity, exhibit the same behaviour.

Thus this reflects most probably a intrinsic behaviour of the stellar flare mechanism. When comparing to the figure (2a), one notices that no such behaviour appears in the solar case.

Finally let us mention that

a) It appears that (Lacy et al, 1976) intrinsically brighter stars have more energetic but much less frequent flares than fainter ones. This law must clearly break for luminosity smaller than the solar one, since it would predict much more energetic flares than actually observed.

b) The flare activity of a particular star measured for example by the excess intensity emitted by flares in a given spectral band, during a certain time, divided by that time, correlates well with the indices of chromospheric activity as defined above. See figure 5, Gershberg et al, 1971)

3b) The radio flare

The first positive detection of radioemission from the flare star UV Ceti was reported in 1968 by Lovell et all (1968).
In figure 6 B shown a radioburst observed at 196 and 3/8 MHz and associated with a flare on Wolf 424 (Spangler and Moffett, 1976). These radiobursts are several Jy in amplitude and may have durations from several seconds up to several hours.

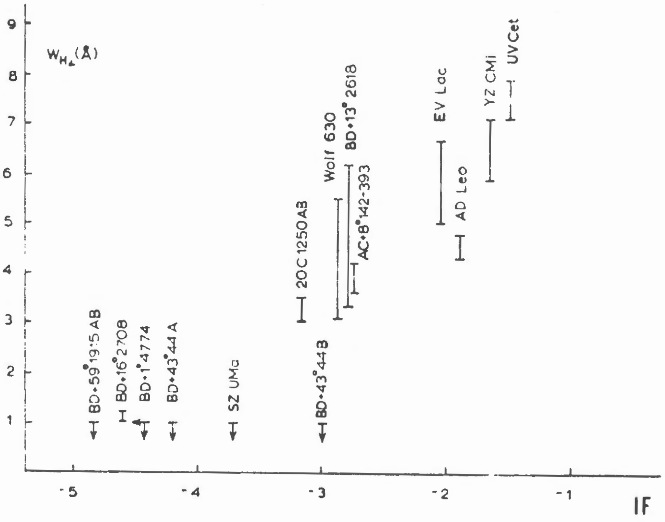

Figure 5 a) Correlation between flare activity levels of stars and H_α emission equivalent width in their quiet state spectra.

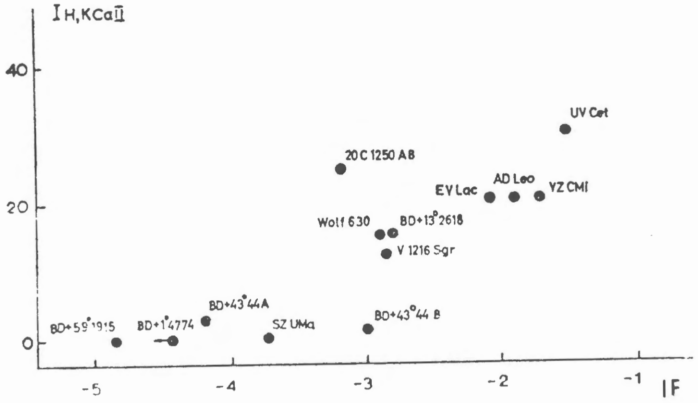

Figure 5 b) Correlation between flare activity levels of stars and Ca emission intensities in their quiet state spectra.
(The flare activity index IF is a measure of the energy emitted by the flaring process by unit time, Gersherg et al, 1971).

Recently, Nelson et al (1979) have undertaken a correlative study of optical and radio emission of flares on 14 flares stars.

They observed, with the Culzoora Radioheliograph (80 and 160 Mhz) meter wave emission of variable intensity originating from the close vicinity of 11 of the examined stars.

A typical radio burst duration was ~ 2 hours ; some were highly circularly polarized ; the intensity ratio between the two observing frequencies indicate a non thermal spectrum.

Evidence from the positions of the flare sources at 160 Mhz suggest that the burst sources are, at least in some cases, displaced from the star. Their brightness temperature at 80 Mhz is $\sim 10^{14} - 10^{15}$ °K if they are assumed to cover ~ 1 % of the stellar disk ; this rules out any explanation in terms of incoherent emission.

The relationship between optical and radioflares is a very complex one ; one does not observe any correlation between the respective amplitudes of the optical

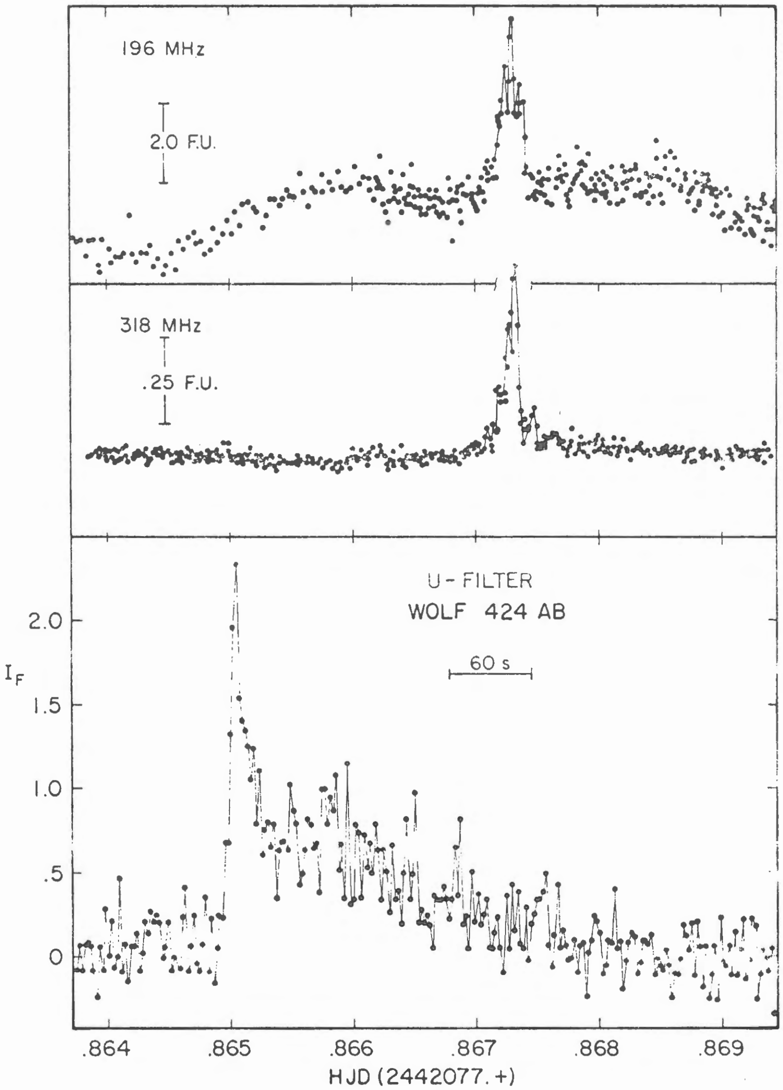

Figure 6 . Optical and radio observations of flare from Wolf 424, 1974 January 30 (Spangler and Moffet, 1976).

and radio emissions. The time delay between these two emissions is extremely variable ; the radio burst can occur before the radio event, or up to 5 minutes later, as one would expect from a perturbation travelling from the flare site to the outer layers of the star (Kahn, 1974).

3c) The EUVX flare

Detection of transient X-ray emission from YZ CHi and UV Ceti (Heise et al, 1975), and transient EUV emission from Proxima Centauri (Heish et al, 1977) widened considerably the wavelength range over which stellar flares could be observed.

Recently Hahn et al, 1979, obtained with the A.2 experiment on board HEAO 1, the first X-ray spectrum of s stellar flare on AT MIC ; they concluded that this spectrum is consistent with the thermal emission of a 4 Kev plasma, with its 6.7 kev iron Kα line.

The total X-ray luminosity L_X during this particular flare was $\simeq 10^{31}$ergs/s, and the emission measure EM $\simeq 10^{54}$ cm^{-3} (compare with typical values for a solar flare $L_X \simeq 10^{27}$ ergs/s, EM $\simeq 6\ 10^{49}$ for a very large solar flare).

Combining their own observations and previous ones, Kahn et al, assuming that all soft X-ray or EUV emission was of a thermal nature, and estimating the optical luminosity of the corresponding flares when they were no directly available by using the empirical laws mentionned above, were able to derive the ratio L_X/L_{opt} for eigth stellar flares. Although there is a large scatter in the values of L_X/L_{opt} they are systematically larger than those predicted by a model by Mullan, 1976, based on conductive cooling of the soft X-ray flare plasma.

CONCLUSION

In view of the recent developments of the diagnostic of chromosphere-coronae-stellar wind complexes, the phenomenon of flare stars poses an intriguing problem.

One of the outstanding results of these last years in the physics of stellar atmosphere has been to show that among late type stars, which all show sign of chromospheres some had very active ones (Linsky, 1980), which presumably are related to the presence of extended solar plage-like regions, i.e. to strong magnetic field eruption at the stellar surface.

Flare stars certainly belong to the class of stars with active chromospheres. Now why do the signs of flare activity disappear with increasing stellar mass, the earliest stellar type for which flaring has been detected being dK 7 ?

Most probably the answer must be related to the interaction between the convection and rotation in stars. Indeed, there are some indications for stars with active chromospheres being also fast rotators ; in that respect, flare stars for which the rotation has been measured using the BY Draconis syndrome, show faster rotation that quiet stars of the same stellar type.

They are also in the range of masses where the convection zone covers a significant portion of the stellar radius and eventually for masses $\sim 0.2\ M_\odot$ the whole stellar radius.

In that case, it is reasonable to expect that these stars will have different patterns of differential rotation than stars with shallow convection like the sun (Gilman, 1980). In particular the scales of the dominant modes, and the influence of rotation or convection will be larger than for stars of the same type but with slow rotation.

Thus one expects, if dynamo theories of the $\alpha\omega$ - type are at work in these stars (Mullan, 1974), that the generated fields have large values, and exhibit clearly large scale coherence, an occurrence which could modify the process of emergence of fields at the stellar surface.

That subject is still a matter of controversy in the case of the sun ; flare stars may help to progress in the understanding of this basic mecanism of stellar activity by providing example of stars with different regime of rotation and convection. This touches the question of comparability of solar and stellar activity.

Indeed, the sun is a slowly rotating star, with a " quiescent " chromosphere, compared to other stars of the same spectral type (see Smith, 1980).

This most probably explains, why the physics of the fine details of stellar flare activity is so similar between the sun and flare stars, there are nevertheless strong differences between the two kind of objects.

A number of related questions are : are there spot cycles in flare stars, possibly masked by the intense sporadic activity ? What becomes of the convective flux blocked in the giant star spots ? (Hartmann and Rosner, 1979) What is the effect of magnetic braking due to flaring on the distribution of angular momentum ? etc... (Carasco et al, 1980).

Finally let us mention that magnetic activity related to fast rotation is increasingly invoked to explain phenomena like those occuring in T. Tauri stars, RSCVn binaries etc... (Gershberg 1978, Hall, 1980).

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