ENERGY DISSIPATION MECHANISMS IN FLARE STARS

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Flare stars derive their name from intermittent increases in luminosity which have certain characteristics reminiscent of solar flares (e.g. enhanced strengths of emission lines in the stellar spectrum during the outbursts). When a flare star is observed in a filter which transmits, say, the violet part of the visible spectrum, the increase in luminosity during a flare may range from noise level up to perhaps 100 times the quiescent brightness. During a flare, certain spectral features of the quiescent star (e.g. molecular bands) remain visible, indicating that the flare occupies only a fraction of the visible disk. Thus, analagous to a solar flare, a stellar flare is confined to a single active region. However the total power is large enough to affect the integrated light from the stellar disk. In contrast, the largest solar flare ($E_{tot} \approx 10^{32}$ ergs) has a rate of energy release ($L \approx 10^{29}$ erg/sec) which is so small that a distant observer would record such a flare as a luminosity increase of less than $10^{-4} L_{sun}$. However, even apart from the flares themselves, it has become apparent in recent years that flare stars in their "quiescent state" provide some extreme contrasts with the sun.

As a result, models which have been proposed for solar flares may be testable in stellar flares over a broader range of physical conditions than is possible in the sun. In order to quantify this statement, we will first summarize the relevant physical conditions in the atmosphere of a flare star. (See Part I below.) We will find that even outside flares, the dissipation of mechanical energy in the atmospheres of flare stars is in a certain sense qualitatively different from what is observed in the sun, and is therefore of interest in its own right. In Part II, we will discuss energy dissipation in flares. However, we shall find that, at least in the very coolest flare stars, the distinction between the flaring and the non-flaring states of the star becomes difficult to define.

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PART I. CHARACTERISTICS OF FLARE STARS

Physical parameters

Flare stars are cool dwarfs, with spectral class mainly of type M. In young clusters (e.g. Orion, Pleiades), flare stars of spectral type K are also observed, but flares on stars of spectral class G or earlier have very rarely been detected (even if one believes the scattered and unconfirmed reports; cf. Kunkel, 1975). The exceptional case of the sun has already been noted: if this G2 dwarf were at a distance of even the nearest star, its classification as a flare star would be highly unlikely.

Effective temperatures, T_{eff}, of flare stars range from ~4000 K to 2200 K (Pettersen, 1980). The prototype flare star, UV Ceti, has $T_{eff} = 2950$ K. For purposes of scaling various physical quantities from the sun ($T_{eff} = 5780$ K), the flare stars can be considered as having $T_{eff} \approx 0.5\ T_{eff}(sun)$.

The absolute visual luminosities M_V of many flare stars are known with some precision, because the stars are close enough to be susceptible to astrometry. Thus , UV Ceti has $M_V = 15.85$. In order to determine total luminosities of these stars, photometry must extend to wavelenths of several microns. For the coolest flare stars, the bolometric corrections exceed 5^m (Pettersen, 1982). For UV Ceti, the bolometric luminosity is some 800 times less than the solar luminosity.

Thus, the radius of UV Ceti is smaller than the solar value by a factor of 7 ± 1. Other flare stars have radii which are somewhat larger than this: the mean value of log R/R(sun) in a sample of 35 flare stars (Pettersen, 1980) is -0.49, i.e. the mean radius is 2.2 times larger than that of UV Ceti.

Reliable masses of some flare stars are now available (cf. Mullan, 1976). In the case of UV Ceti, in particular, the mass is accurately known, 0.108 M(sun). Along the lower main sequence, the mass-radius relation can be described fairly well by $M \sim R^{\alpha}$, where α is very close to unity (Hoxie, 1973). Hence, the gravitational acceleration g in the atmospheres of the flare stars is essentially proportional to R^{-1}: g exceeds the solar value by factors of 3-6 among the flare stars.

Because of the reduced effective temperature, molecules (especially H_2) form in the upper photospheres of flare stars. Dissociation of these molecules gives rise to a new convection zone high in the photosphere of these stars (in addition to the hydrogen ionization zone, which lies beneath the photosphere). As a result, convection sets in at a much higher level in the atmosphere than in the sun. This new convection zone creates a remarkable signature in the broad-band colors of cool dwarfs: this signature has been detected by Mould and Hyland (1976). Hence, the convection zone which is nearest to the chromosphere and corona of a flare star is composed predominantly of molecular hydrogen, with a mean molecular weight μ which is therefore larger than in the solar convection zone by a factor of 2.

The reason for discussing the above quantities in detail is that we wish to estimate the scale-height of the convection zone which is nearest to the corona. The pressure scale height H_p is proportional to $T_{eff}/\mu g$, and so, combining the above estimates, we find that in the flare stars, H_p is smaller than H_p(sun) by factors of order 12-24.

Convective time scales

For purposes of coronal heating, it is important to estimate the period at which the mechanical power generated within the convection zone is a maximum. To first order, this maximum can be characterized by the time-scale of convective overturning. With typical cell dimensions of order L, the convective overturning time-scale is $t_c \approx L/v_c$, where v_c is the convective flow velocity. In the sun, the granules have typical sizes of $L \approx 10^3$ km and convective flows are typically in the range of 1-3 km/sec. (Theoretical models of solar convection also predict maximum convective velocities in the solar convection zone of about 3 km/sec; cf. Mullan, 1971). Hence, the overturning time-scale is about 500 seconds in the sun. Actually, the mean lifetimes of the granules is also about 400-500 seconds (cf. Leighton, 1963), which indicates that convection cells in the turbulent solar convection zone persist for about one overturning time and then lose their identity. (The Reynolds numbers of the solar convection zone are too high to allow the formation of steady hexagonal cells of Benard type.)

In red dwarfs, spectral line broadening shows no evidence for flows in the atmosphere which are faster than 1-2 km/sec. Model convection zones for such stars also suggest (Mullan, 1971) that the maximum convective velocities are not much less than in the sun, $v_c \approx 2$ km/sec. Hence, in red dwarfs, the convective velocities may be less than solar values by a modest amount, say 1.5.

We can now estimate the period at which the convection zone power is maximum in red dwarfs:

$$\frac{t_c\ (\mathrm{RD})}{t_c\ (\mathrm{sun})} = \frac{L\ (\mathrm{RD})}{L\ (\mathrm{sun})}\ \frac{v_c\ (\mathrm{sun})}{v_c\ (\mathrm{RD})}$$

It is usually assumed that the dimensions of convection cells scale with the pressure scale height. Adopting this assumption, we find $t_c\ (\mathrm{RD}) \approx (0.06\text{-}0.13)\ t_c(\mathrm{sun})$. This leads to

$t_c(\mathrm{RD}) \approx 30\text{–}70$ seconds

This result will be of significance when we discuss the heating of loops in the coronas of flare stars.

Starspots

A prominent characteristic of most flare stars is that their surfaces are not uniformly bright. Dark spots are inferred to exist on the surface, at times covering up to 10% or more of the visible disk. More typically, the spots may occupy a few percent of the surface. This is to be compared with a maximum reduction of order 0.1% in the case of large sunspots. The origin of large dark spots on flare stars is not definitively known. However, by analogy with the solar case, the spots are believed to be caused by localized clumpings of vertical magnetic field lines. An indirect argument in favor of this interpretation can be made on the basis of the rotation periods of spotted stars: in a sample of 16 stars which are known to be chromospherically active and for which rotation periods are known, the six stars which are known to be definitely spotted are the six stars with the shortest rotational period (Vogt, 1983). Short rotation periods ($P \lesssim 7$ days), or equivalently, fast rotation velocity ($V \gtrsim 5$ km/sec) appear to be the single best criterion for defining the group of spotted stars, and such stars are also expected to have the most efficient dynamos for creating magnetic fields. Thus, the possibility that starspots on flare stars are associated with magnetic fields (as in the sun) appears plausible. Magnetic field strengths in spots in red dwarfs have not yet been measured. However, the upper limits which are available on the measured field strengths are such that fields of order 10 kilogauss could exist in the spots without contradicting any of the current data on flare stars (Mullan, 1979). The best evidence at present for the presence of fields in flare stars is the occurrence of high degrees of circular polarization in the radio emission from flares (Spangler et al., 1975; Gibson, 1983), but these data are not suitable for estimating the field strength. An indirect method of estimating the magnetic field strength on the surface of BY Draconis (based on broad-band optical linear polarization) suggested that indeed fields of order 10 kilogauss might have been present at the time the polarization was observed (Mullan and Bell, 1976).

The question arises: what is the ultimate disposition of the missing flux from the dark spots? In the presence of a vertical magnetic field, the normal convective motions cannot occur freely. The convective efficiency is therefore reduced, although it cannot be suppressed entirely, since the electrical conductivity is not infinite. Residual convection interacts with the field and causes emission of MHD waves of various modes. The joint effect of reduction in convective efficiency and emission of MHD waves cool the spot. Some years ago, a self-consistent model of a spot, in which the convective efficiency is reduced by an amount which depends on the electrical conductivity, and this reduced efficiency is compensated by emission of Alfven waves (Mullan, 1974a, 1974b), was calculated for both sunspots and starspots. In these models, the missing flux was carried to a large extent by the Alfven waves. These waves are strongly reflected off the steep density gradient near the surface of the spot, and so, in a sunspot, for example, the missing flux is effectively trapped inside the sun, under normal conditions. If, however, the Alfven waves could leak into the corona, their mechanical energy would be so large compared with the normal mechanical energy flux which heats the corona that the corona over a sunspot would appear to be in a continual state of "flaring". During certain solar flares, the reflection conditions over the umbra of a spot are altered, and at such times, the leakage of umbral Alfven waves into the corona may contribute significantly to the energy budget of the flare (Mullan, 1981). For the most part, however, in the case of a sunspot, the missing flux remains trapped inside the sun (Willson et al., 1981).

A small fraction of the missing flux may appear in the form of a faint bright ring around a sunspot (Fowler et al., 1983). The emission in the ring amounts to several percent of the missing flux. The maximum intensity in the ring seems to be too bright to be due to reduction in convective efficiency alone (Fowler et al., 1983). It is possible that the ring is a manifestation of Alfven waves leaking out of the umbral walls. This would be in accord with the proposal that a sunspot is the site of a large flux of wave energy, capable of contributing significantly to coronal heating and/or flaring, if conditions are favorable.

In the case of starspots, it has been pointed out by Gershberg (1983) that the missing flux is close to the X-ray flux emitted by the stellar corona. He suggests, therefore, that the MHD waves in a starspot may have somehow found a way to leak much more efficiently into the stellar corona than in the case of a sunspot. Once the waves reach the corona, they dissipate rapidly and heat the corona. In fact, the quiescent coronae of red dwarfs are observed to be hotter than the mean solar corona (Golub, 1983). In this view, therefore, the corona of a flare star is essentially in a state of continual "flaring" due to the efficient leakage of Alfven waves from the starspot into the corona. In this regard, it is worth noting that some of the statistical properties of stellar flares can be understood if stellar flares also are powered by the missing flux from starspots (Mullan, 1975b). This raises the important question as to the distinction (if any) between coronal heating and flaring. We will see below that in the case of the coolest flare stars, this distinction may become difficult to make.

There is no quantitative estimate at present of the change in bolometric luminosity of a flare star when a starspot is present on the surface. Thus it is not known to what extent the missing flux of a starspot is stored beneath the surface.

Chromospheres

The most prominent characteristic in the quiescent optical spectra of flare stars is strong emission in the Balmer lines of hydrogen. In the case of a star as hot as the sun (T_{eff} = 5780 K), the radiation from the photosphere is so strong that the formation of, say, the H_α line has a large (if not dominant) contribution from this radiation. The remainder of the solar H_α line is formed by collisional processes in the chromosphere. However, in the case of red dwarfs, the effective temperatures are so low that the radiation field from the photosphere makes a negligible contribution to the formation of the Balmer lines. (In the case, e.g. that the stellar energy distributions can be represented as black bodies, the intensity at the Balmer limit in a flare star is weaker than in the sun by a factor of order 600.) As a result, the Balmer lines in flare stars are formed essentially entirely by collisions in the chromosphere, and therefore the Balmer lines in flare stars become good diagnostics of the physical conditions in the stellar chromospheres.

The modelling of Balmer lines in red dwarfs by means of a full non-LTE treatment has been reported by Kelch et al. (1979) and Cram and Mullan (1979). In these papers, the chromosphere is parametrized by imposing a temperature rise from the top of the photosphere (where the temperature is T_{min}) up to a point (the "top" of the chromosphere) where the hydrogen is beginning to ionize rapidly, at temperatures of 8000-9000 K. The mass loading at the latter point, m_0, is the main parameter which characterizes these model chromospheres. In order to drive the first three Balmer lines into prominent emission features (as they are observed to be in flare stars), it turns out that log m_0 must exceed -4.5 to -4.0 (Cram and Mullan, 1979). Converting to pressures, $p_0 = m_0 g$ (where log g $\approx$ 5 in red dwarfs), we find p_0 (i.e. the pressure at the "top of the chromosphere") to be greater than 3 dyn/cm^2. By comparison, the quiet sun has $p_0 \approx 0.2$ dyn/cm^2. Hence, even if the Balmer emission in flare stars is coming from the entire surface of the star, the chromospheric densities are at least 10 times higher than in the sun. However, in practice, the Balmer emission is probably concentrated in a few active regions across the stellar disk. Therefore, the true pressures in the active regions are even higher than those estimated above. In fact, certain features of stellar flare spectra (Cram and Woods, 1983) suggest that flares occupy only a small fraction (order 10%) of the visible disk. Active regions may therefore occupy only 10% of the visible surface also. We conclude that the enhancement by a factor of $\Delta N \sim 10$ in densities in the upper chromosphere mentioned above are lower limits to the true enhancements: the latter, ΔN, are likely to be in the range from 10-100. If this scaling holds throughout the chromosphere, then flare stars are characterized by the chromospheres which are 10-100 times denser than the solar chromospheres.

These dense chromospheres require enhanced mechanical energy to heat them. Linsky et al (1982) have estimated the required energy fluxes by summing over the radiative losses in as many spectral lines as were accessible to them, including emission lines of MgII, CaII, FeII, and Balmer lines. If we express by F_{ch} the fraction of the photospheric flux which is required to balance the radiative losses in the various chromospheric lines, then for red dwarfs with active chromospheres F_{ch} turns out to be 3-10 times larger than the solar value. Thus, flare stars are more efficient than the sun at converting thermal into mechanical energy for the heating of their chromospheres, by factors of 3-10. This estimate of course says nothing about the source of the mechanical energy: it does not even specify the direction from which the energy comes. We shall see below that the energy which heats the chromosphere in an M dwarf may be provided from above.

Coronae

The fraction of the photospheric flux which is required to account for the radiation from the quiescent corona of a flare star, F_{cor}, has been found to be unexpectedly high: values as high as 10^{-3}-10^{-2} have been reported. The value of F_{cor} seems to reach a peak of $\sim 10^{-2.2}$ among stars with B-V ≈ 1.5 (i.e. spectral type M0 - M2), falls off at later spectral types, to less than $\sim 10^{-3.1}$ at B-V ≈ 2.0 (at spectral type ~M6; for conversion of B-V colors to spectral type, cf. Mould and Hyland, 1976). (These values of F_{cor} have been derived from X-ray fluxes given by Golub (1983) and bolometric luminosities provided by Pettersen (1983).) By comparison, the solar value is $F_{cor}(sun) \approx 5 \times 10^{-6}$ (Withbroe and Noyes, 1977) (quiet sun). It appears therefore that flare stars are at least 100 times more efficient at heating their coronae than the sun is. This is a striking characteristic of flare stars, and it has the effect that M dwarfs contribute appreciably to the X-ray background from the sky (Rosner et al., 1981).

Spectral lines which are formed in the transition region between chromosphere and corona have also been observed by Linsky et al. (1982) in the spectra of flare stars. These lines also show that the transition regions in flare stars are heated with an efficiency which is some 100 times greater than in the sun. This has led Linsky et al to conclude that the process which heats transition regions and coronae in red dwarfs is different from that which heats chromospheres.

In the sun, the mechanical energy which is deposited in the chromosphere is typically 10 times greater than the mechanical energy which is deposited in the corona (Withbroe and Noyes, 1977). In flare stars, the situation is qualitatively the opposite: the mechanical energy deposited in the corona appears to be almost an order of magnitude greater than that which is deposited in the chromosphere. In fact, it has been suggested (Cram, 1982) that the chromospheres of M dwarfs may be heated almost entirely by X-rays from the overlying coronae. Apparently, in the flare stars, the corona is more effectively coupled to the source of mechanical energy than the chromosphere is. This is an important distinction which may be important in understanding the dissipation of energy in the atmospheres of flare stars.

PART II. FLARES

In principle, a flare represents a short-lived localized enhancement in the rate of dissipation of mechanical energy, relative to the rate of dissipation in the "quiescent" atmosphere. The result is an increase in radiation from all levels of the atmosphere, including X-rays from the corona, emission lines from the transition region and chromosphere, and most significantly, "white-light" optical continuum. The latter feature is much more common in stellar flares than in solar flares.

Time-scales

When a stellar flare is observed through a broad-band optical filter, the flare appears typically as a rapid rise in brightness followed by a slower decline to normal light. All of the parameters of a flare light curve are quite variable from one flare to the next, such as the rise time, the decay time, the maximum amplitude, the total energy, and the time interval which has elapsed since the preceding flare. Despite these irregularities, there are some statistical trends which have been established. For example, the rate of occurrence, R, of a flare whose maximum brightness in a particular filter (say the U filter) is equivalent to a star of magnitude m_U behaves as $R = \exp a(m_U - m_0)$. Here, m_0 is a parameter which increases in the fainter flare stars, which a is almost constant from one star to the next. According to this formula, faint flares may be occurring very frequently in a star, but still remain undetectable against the statistical fluctuations which are intrinsic to our measurements of the "quiescent" photon flux from the star. This is an important consideration, and we shall return to it subsequently.

If we consider flares regardless of amplitude, then it appears that, in general, the time intervals Δt between successive flares can be fairly well described by a Poisson distribution (Oskanyan and Terebizh, 1970), i.e. and flares can be considered to be in general random events, with no connection between any one flare and either the preceding or following flare. An important exception to this general behavior, however, appears at the shortest time intervals, $\Delta t = \lesssim 10$ minutes. At such intervals, there is observed to be (in some of the flare stars at least) an excess (by a factor of ~ 2) over the numbers of flares which would be expected if the Poisson distribution were extrapolated to these intervals. The cause of this excess is not known with certainty, but sympathetic flaring is one possible explanation for it (Mullan, 1975a): if this is correct, then the upper limit of about 10 minutes on Δt would correspond to the time required for a disturbance (presumably an MHD wave) to propagate from the site of the first flare to a flare site at the maximum possible distance, i.e. at the antipodal point. With stellar radii of (1-2) x 10^{10} cm, this interpretation would suggest MHD propagation speeds of 500-1000 km/sec in the flare stars. Now flare disturbance waves sweeping out through the solar corona after certain flares ("Moreton waves") also travel at speeds of 500-1000 km/sec (Uchida, 1968): such speeds are probably characteristic of the Alfven speed in the corona. This is the first indication that despite the higher densities which characterize the upper atmospheres of the flare stars relative to the sun (ΔN = 10-100), the Alfven wave speeds might be rather similar. This would require that the coronal magnetic fields be stronger than in the sun by factors of $\Delta N^{1/2} \sim 3$-10. Such enhancements are consistent with the discussion of surface fields given above, where the strengths in starspots were estimated to be of order 10 kilogauss or more, i.e. at least 3 times as strong as in sunspots.

As regards the decay times in stellar flares, Kunkel (1975) has found that the time scale $t_{0.5}$ for the flare light to decay by 0.5 magnitudes is related to the absolute magnitude of the star:

$$\log_{10} t_{0.5} = 1.084 - 0.119 \, M_V$$

Where $t_{0.5}$ is in minutes. Hence, in the faintest flare stars (M_V = 16-19), $t_{0.5} \approx$ 4-10 seconds. The rise times are even shorter. These are average time-scales: in individual flares, the light curve may evolve so rapidly that even time constants of one second are not sufficient to resolve the peak of the curve (Moffett, 1974). Optical flares on the sun evolve on considerably longer time-scales, of order one minute or so. Very rapid variations in optical emission are a striking characteristic of stellar flares.

Energies

As regards total energies of flares, these can be derived for specific band-passes, e.g. the U filter, E_U. The frequency of occurrence ν of flares of energy E_U has been derived by Lacy et al. (1976): $\log \nu \propto -\beta \log E_U$. The numerical values of β lie in an interesting range: they are close to unity, especially among the fainter stars. The significance of this is that the total power radiated by a flare star in the form of flares is dominated by large flares if β is less than unity, and by small flares if β is greater than unity. In the former case, one can distinguish, meaningfully, between flaring and non-flaring behavior. However, in the case of the faintest flare stars, the star's output of energy in "flares" is dominated by the smallest events, which can hardly be distinguished from the noise. Such stars are in a sense in a state of continual flaring, and therefore it becomes increasingly difficult among the faintest stars to draw a line of demarcation between what we would call bona-fide "flaring" and what we would call more or less continuous heating of the upper atmosphere by mechanical energy release.

The maximum energy recorded in an optical flare is 6 x 10^{34} ergs in YZ CMi (Kunkel, 1969). Flares with total energies greater than 10^{34}ergs in the U-filter alone have also been reported for YY Gem (Lacy et al., 1976). Major uncertainty surrounds the correction of these estimates for energy radiated by the flare outside the band-pass of observation: the uncertainties are at least as large as an order of magnitude (Mullan, 1976). The reason for the uncertainties is that the true nature of flare radiation has not yet been identified with certainty. Different investigators have proposed to fit various spectral features with radiation from a black body, from recombining hydrogen plasma, from deep in the photosphere where negative hydrogen ions can form, and radiation from optically thin coronal plasma. Unfortunately, predictions of (e.g.) flare colors by all of these models agree fairly well with observations, and so no discrimination on the basis of flare colors is reliable. Moreover, there is no estimate whatever of the mechanical or magnetic energy carried away from stellar flares by blast waves. [In solar flares, these components often dominate the energy budget of the flare.] Thus, the above estimates are certainly lower limits on the total energy released in a large stellar flare.

The source of this energy has not yet been definitely determined. One suggestion which has recently been advocated as a source of energy in certain stellar flares is the release of energy when matter falls on to the surface of the star. The arguments in favor of this model are based on a short-lived increase in absorption which is observed just prior to certain flares. The increase in absorption has been reported at optical wavelengths (Giampapa et al., 1982) and also at X-ray wavelengths (Haisch et al., 1983). The interpretation is based on an analogy with a class of solar flares called "disparitions brusques" where material which was originally suspended above the surface in a prominence is disturbed (for some reason), and falls to the surface, releasing its original potential energy in the process. The enhanced absorption observed just prior to the stellar flare is attributed to the prominence material before it releases its energy.

Now, the suspension of prominence material above a stellar surface requires a magnetic field. Hence, in a sense, the infall model of stellar flares is a magnetic model. However, other stellar flares (which show no evidence for pre-flare absorption) in all likelihood derive their energy from magnetic fields, but more directly, probably by converting magnetic free energy into fast particles or hot gas. As was mentioned above, the existence of magnetic fields in stellar flare plasma is most obviously suggested by intense (almost 100%) circular polarization of flare radio emission.

Magnetic fields

A convenient classification of magnetic energy release in solar flares has been proposed by Spicer and Brown (1981), involving electric currents which flow either parallel to the field ($j_\parallel$) or perpendicular to it ($j_\perp$). In both cases, flare onset occurs when something happens locally to enhance the Joule dissipation rate, j^2/σ, by a large factor. For example, if turbulence sets in, the conductivity σ will drop rapidly from its classical (Spitzer) value to a much lower value σ_t. Whatever the details are, the resulting effect is the conversion of magnetic energy into fast electrons and hot gas. It is useful to keep these ideas in mind also in attempting to interpret stellar flares.

For example, conduction of heat away from the flare site towards the surface of the star forces the "top of the chromosphere" downwards into deeper layers. This effect can explain rather well the spectroscopic characteristics (line strengths, line widths and continua) of certain optical flares (Cram and Woods, 1982). On the other hand, if the fast electrons are the dominant agent for transporting flare energy away from the site of primary energy release, they may create shock waves which propagate upwards (into free space) and downwards (into the dense photosphere). Because of the denser gas in flare star atmospheres, the downward propagating shock wave can create an appreciable optical thickness in the visible part of the spectrum ($\tau_{4500A} \approx 1$) before dissipating. As a result, this shock-heated and shock-compressed material can act as an efficient source of "white-light" continuum in certain stellar flares (Livshits et al., 1981). The faint photospheric background against which a stellar flare is observed (T_{eff} = 3000 K, rather than 5780 K as in the sun) also helps to make it easier to detect the continuum in stellar flares than in solar flares.

Accepting the magnetic source of stellar flare energy, the properties of stellar flare plasma allow one to place lower limits on the field strengths in the flare region. Stern et al. (1983) and Haisch (1983) have done this for a large X-ray flare in a Hyades star: the lower limits on the field are 350-700 gauss. If we apply analogous arguments to a large solar flare ($E = 10^{32}$ ergs, volume = 10^{29} cm^3), the lower limit on the flare field (assuming complete annihilation of the field) is 160 gauss. However, it is known that the fields existing near flare sites in the sun (in spots) are larger than this by factors of 10-20. If similar factors apply to stellar flare case, the flare fields of 350-700 gauss may be consistent with surface fields of 5-14 kilogauss. Thus, these flare fields may not seriously constrain the values of field strength on the surfaces of red dwarfs.

X-ray data on stellar flares have provided important information on the temperatures of flare plasma (Haisch, 1983); it is remarkable that temperatures of a few times 10^7 K are recorded, close to the values observed in solar flares, despite the fact that the total energies in stellar flares may exceed those in solar flares by more than an order of magnitude. If flares are powered by magnetic energy, the thermal energy density of the flare plasma, 2NkT, should be comparable to the pre-flare magnetic energy density, $B\ /8\pi$ (Moore and Datlowe, 1975). Then the similarity of temperatures in solar and stellar flares suggests that B^2/N values are similar, i.e. the Alfven speeds at the sites of stellar flares are apparently not very different from those at the sites of solar flares. This confirms the conclusion derived above on the basis of sympathetic flares, i.e. the Alfven speed in flare star coronae may be similar to the solar value.

Given the central role of magnetic fields in stellar flares, the higher densities which are characteristic of flare star atmospheres will affect the rate of energy release. Consider, for example, the general class of flare models in which the flare energy comes from dissipation of the current in a loop (cf. Spicer and Brown, 1981). In these models, the flare begins when the parallel current exceeds a critical value, $j_c = Nev_c$ where v_c is a critical velocity which depends on the temperature. When $j > j_c$, the conductivity becomes turbulent, σ_t, and the Joule dissipation rate, j_c^2/σ_t, becomes locally very large. This is thought to be the cause of primary flare energy release. Now, the temperatures in solar and stellar coronal loops are not very different (about 2 x 10^6 K): hence, v_c is about the same in both solar and stellar flares. Thus, $j \propto N$, and therefore the rate of flare energy release, j_c^2/σ_t is proportional to N^2/σ_t. Since $\sigma_t \sim N^\gamma$, [where $\gamma \approx +0.5$ (cf. Rosner et al. 1978)] the rate of Joule dissipation at the site of primary flare energy release in flare stars is larger than in the sun by factors of order $\Delta N^{1.5} \approx 10^{1.5} - 10^3$. These large increases relative to the sun are likely to be an important factor in understanding why stellar flares evolve much more rapidly than solar flares.

Another advantage of the detection of X-rays from stellar flares is that it has allowed the possibility of estimating certain properties of the sources of the X-rays. With certain assumptions about flare cooling, Haisch (1983) has estimated that the X-rays are emitted by loops with lengths which range from (2-6) x 10^9 cm up to >6 x 10^{10} cm. Using different reasoning, Kodaira (1983) has estimated loop lengths of order 10^{10} cm in a particular flare on YZ CMi. Loops of length 10^{10} cm are comparable in extent to the radius of flare stars. Hence, the footprints of such loops on the surface of the star must also be comparable in extent to the stellar radius: such footprints would be suitable candidates for some starspots. Flaring loops in the sun are typically an order of magnitude shorter than the loop lengths mentioned above (typically 10^9 cm). In view of the similarity in Alfven speeds in the coronas of the sun and flare stars (see above), this leads us to expect that the resonance time-scales of coronal loops in flare stars might be an order of magnitude longer than in the sun.

Periodicity or quasi-periodicity

Some indication in support of this comes from recent radio data. Linsky et al. (1983) have detected a radio flare in the star L726-8A (dM5.5e) with the usual characteristics of large flux (10 mJy) and a high degree of circular polarization. However, the interesting feature was the presence of quasi-periodic structure in the flare emission, with periods of 50-60 seconds, extending over about 6 cycles. The authors suggest that this might be caused by Alfven waves oscillating along a large loop (of length (1-2) x 10^{10} cm). An independent example of periodic behavior following a flare in the optical region was reported by Rodono (1974): there, the light level fluctuated with a very regular peiord (≃13 seconds) for several dozen cycles. It is not clear that this periodicity is attributable to the same source as in the radio flare of Linsky et al. (1983), but the strict periodicity is striking.

It has been known for many years that flare radio emission from the sun also shows periodic or quasi-periodic behavior after certain flares (Abrami, 1970; de Groot, 1970; Rosenberg, 1970; McLean et al. 1971). The periodic behavior is most clearly observed at low frequencies (100-300 MHz), corresponding to source heights of 0.2-0.3 R(sun) above the photosphere. At such frequencies, the observed periods are well defined, and from event to event span the range 1.7-3.1 seconds. At higher frequencies of observation, the variations are not as strictly periodic: moreover, the quasi-periodicities span a range which is wider than the above range (Maxwell and Fitzwilliam, 1969). The physical interpretation of the quasi-periodic behavior at higher frequencies may be different from that of the strictly periodic behavior at lower frequencies (Maxwell and Fitzwilliam, 1969). For example, the lack of strict periodicity at higher frequencies may be due to confusion of many loops of varying sizes which lie within the beam width when the latter is observing deep levels of the atmosphere, whereas at lower frequencies, which are sensitive to higher lying loops, individual loops may be detectable, standing in isolation above the background. However, even at microwave frequencies, strict periodicity is occasionally observable: a well-documented case is that reported by Gaizauskas and Tapping (1980) who observed a complex active region (non-flaring) in which a source persisted at a period of 2.5 seconds for many hours.

Coupling with convection zone

Comparing the 50-60 second quasi-periodicity in the stellar radio flare reported by Linsky et al. (1983) and the 13-second periodicity reported in the optical (Rodono, 1974) with the typical solar periods reported above, it appears that stellar flares favor periods which are longer than in the sun. The increase in the stellar periods relative to the sun covers a wide range ~ (4-40), with a mean which may be about an order of magnitude longer than in the sun. This is consistent with loops on flare stars being about an order of magnitude longer than in the sun, provided the Alfven wave speeds are comparable.

The significance of this result can be seen by noting that the preferred periods of mechanical energy generation in the convection zones of flare stars are $t_C \approx$ 30-70 seconds (see above), and this range overlaps with the estimates of 13-60 seconds for the preferred periods of oscillation of coronal loops, t_A. Hence, coronal loops in these stars may be almost ideally matched to the convection zone as regards period. Ionson (1983) has given the following formula for the efficiency of coupling, ε, between convection zone and coronal loops:

$$\varepsilon = \frac{t_C}{t_A} \frac{1}{\left[1+\left(\frac{t_C}{t_A} - \frac{t_A}{t_C}\right)^2\right]}$$

In certain flare stars, ε must be close to unity. In contrast, in the sun, where $t_C \approx$ 500 seconds, while $t_A \approx 2.5$ seconds, Ionson's formula leads to $\varepsilon \approx 0.005$. Hence, the efficiency of coupling to the corona is larger by a factor of order 10 in certain flare stars then in the sun. As we noted above, the efficiency of coronal heating in red dwarfs (as evidenced by the coronal X-rays) is indeed larger than the solar value by factors of order 10^2.

This leads us to conjecture that as one examines stars which lie further and further down along the main sequence, one is observing a better and better matching of the source of mechanical energy (in the convection zone) with the load where that energy is eventually deposited (coronal loops). To the extent that this conjecture is true, the corona of the certain red dwarfs are fed with such high levels of mechanical energy that they may be considered to be in a state of quasi-continual flaring. In such stars, the boundary between coronal heating and flaring may be quite indistinct. The statistical data of Lacy et al. (1976) on optical flares provides support for this idea: among the cooler red dwarfs, the stars emit most of their "flare" power in small events.

Ultimately, as one examines stars farther along the main sequence, $t_C$may continue to even smaller values, while $t_A$may continue to increase. In that case, ε would have a maximum value when $t_C = t_A$, but would than decrease rapidly ($\sim(t_C/t_A)^{-3}$) at later spectral types. This may help to explain why the coronal heating efficiency, F_{cor}, has a rapid decline at the latest spectral types (Golub, 1983), after passing through a large maximum at B-V = 1.5. The chromospheres in the coolest M dwarfs would therefore not have access to the X-ray heating which seems to heat the active chromosphere stars (Cram, 1982). Such chromospheres would therefore be quite weak: there is observational support for this prediction (cf. Giampapa, 1983).

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DISCUSSION

Sturrock: Since the Alfvén speed is about 500 km/s and the length of a flare loop is about 10^{10} - 10^{11} cm, I would expect the time scale of energy release to be 10^2 - 10^3 s. However, the time curves show a rise time of about 1 sec. How can one uderstand this discrepancy?

Mullan: The rising part of a flare light curve represents the rapid release of energy at the "spark point" where the flare was initiated. This flare emission is mainly optical continuum (in the so-called "spike flares" where the rise time is very short), and is distinguished from the flare emission later on, which is mainly emission lines. The continuum can be interpreted consistently as thermal bremsstrahlung from the coronal flare plasma, while the emission lines emerge from denser gas (cf. Mullan, Ap.J. 210, 1976). Thus, the later emission in the flare represents the after effects of the "spark", after the "conflaguration" has spread out over the entire volume of the available flux tube. The conflagration time scale is indeed 100-1000 seconds, as you point out. But the rapid rise time scale represents only emission from a localized region at the "spark point" itself, and is therefore characterized by a much more rapid time evolution. However, the energy emitted in the rise phase is only a small fraction of the total flare energy: the main energy release comes about when the entire available volume is engulfed by the spreading conflagration.

Kundu: I have two comments: 1) When you drew the analogy between solar radio oscillations with a periodicity of approximately 2.5 sec and red dwarf flare star oscillations with a periodicity of a few tens of seconds, you should remember that in the example from Culgoora, there was a shock wave (type II burst) which was responsible for compressing the plasmoid (type IV) and producing oscillations. In the optical stellar flare that you showed from Rodono, was there any evidence of a shock in the flare? How are the oscillations produced in the stellar flare? 2) The other radio oscillations that you referred to (paper by Gary et al. 1982) - I believe it is the paper in which they invoked masering to explain the stellar variability. One must not forget that in the case of solar masers, we have millisecond time structure, whereas with the VLA we have only a time constant of 10 sec. So, in spite of a high brightness temperature, they conceivably could not have been observing "stellar masers"!

Mullan: 1) In Rodono's optical flare data (on an early type flare star, of spectral type K), there is no evidence for or against the existence of a shock wave. In stellar flares, observers in radio bands have occasionally discussed the presence of type II bursts on the basis of time lags between features on the "light curves" of the flare at different frequencies. But no such data were available in conjunction with Rodono's oscillations. In the optical stellar flare, there is no clear answer to the mechanism which creates the oscillations. However, their highly regular behavior suggests a rather strict time-keeping mechanism, and the only one which comes to mind is oscillations in a flux tube which preserves its identity and gross structure intact for the duration of the flare oscillations. 2) You are correct in saying that the oscillations in the radio flare from L726-8A were reported in a paper where Gary et al. favor a maser interpretation. However, they did discuss the possibility that the oscillations might involve bouncing MHD waves on a closed flux tube, and, although Gary et al. finally viewed the latter interpretation with less enthusiasm than they viewed the maser interpretation, my own prejudice is that their data are quite consistent with the MHD bouncing wave interpretation. Note also that the star observed by Gary et al. was of considerably later spectral type (M6) than Rodono's star (K), and this would be consistent with our claim that the bounce time, t_A, increases as the spectral type becomes later.

Rust: In trying to use the rise times for solar and stellar flares to deduce properties of the chromospheres, you make two errors: 1. Flares, as you admit, happen in the corona. The chromospheric flare happens only because heat or particles or photons from the corona excite the chromosphere. We learn nothing about the density of the chromosphere from the rise time of the flare. 2. Observations of white-light flares show rise times of a few seconds, not one minute as you claim (see papers by Zirin and by Rust and Hegwer). Thus solar and stellar optical flare rise times are about the same.

Also, pay attention to the fact that there is no single density relationship between the corona and the chromosphere. Coronal holes have a density perhaps as low as 10^{-7} cm^{-3}, but active region loops may have 10^{11}cm^{-3}. Yet, under each, the chromosphere is essentially the same. You cannot scale density from the chromosphere into the corona.

Mullan: 1) The first "error" is not an error: you have misinterpreted as coronal bremsstrahlung (Mullan, Ap.J. 210, 1976), and is therefore a signature of the stellar corona. Admittedly, the chromosphere of the star contributes to the flare later, but at maximum continuum emission, we are seeing the corona. The rise time therefore is a measure of a coronal process, and is therefore sensitive to the density in the corona. The latter is proportional to the density in the chromosphere (see below). 2) Your admission that solar white light flares have rise times of a few seconds, taken in conjunction with the observation that rapid stellar flares can evolve on times of less than one second, still allows us to conclude that the evolution of stellar flares is faster than solar flares. Thus, qualitatively, my conclusion is unchanged. Quantititatively, the ratio may be less extreme than I quoted. However, the origin of white light emission in solar flares is not yet known with certainty. Since stellar optical continuum is coronal in origin, we should strictly compare the stellar rise times with the rise time for the thermal plasma in the solar corona, i.e. the time-scale on which the soft X-rays (not the impulsive X-rays which are chromospheric in origin due to precipitating electrons) rise. The soft X-rays generally show a rather gradual behavior, with time-scales which are longer than a few seconds. Thus, even in a quantitative sense, my estimates of the ratio of relevant time-scales may not be far off the true mean value.

I strongly disagree with your final statement. The chromosphere in an active region is certainly different from the chromosphere in a coronal hole. The densities are higher, the macro-turbulent broadening is larger (especially if the active region is young), and the energy requirements differ by more than an order of magnitude. The work of Linsky, Shine, Withbroe, and Noyes, and many others has shown this to be the case. In an active region, the calcium emission cores are much stronger and wider than they are in a quiet region (such as a coronal hole), and Linsky and co-workers have systematically examined how the pressure at the "top" of the chromosphere must be varied in order to fit the observed calcium emission in various features. The results is that the pressure is lowest in quiet regions, increases with increasing activity, and is highest in flares. Exactly the same sequence of pressures can be derived completely independently for the coronal gas from X-ray pictures (such as the AS&E photos during Skylab): the coronal gas pressure is lowest in coronal holes and quiet regions, and increases in active regions (especially young ones), reaching maximum values in flares. Thus there is a one-to-one correspondence between chromospheric pressures (densities) and coronal pressures (density).

Bell: Have you tried using J-K or some similar IR color in your plot of X-rays versus B-V, as B-V is so much affected by TiO in M dwarfs.

Mullan: No. The X-ray data were plotted by Golub (1983), and he used the most common colorimetric data available in the reference literature, i.e. B-V. As you say, it would be interesting to re-plot the figure with a temperature index which was less susceptible to distortions by (e.g.) molecular bands. However, for many of the stars in Golub's sampel, J-K colors may not be readily available.