SOLAR AND STELLAR FLARES: QUESTIONS AND PROBLEMS

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Abstract. Although progress has been made in understanding certain aspects of the physics of solar and stellar flares, there are a number of topics which, in the author's opinion, still pose a problem. We summarize these topics here.

1. Introduction

The purpose of this article is to go beyond a review of solar and stellar flares which appeared in this journal more than a decade ago (Mullan, 1977), and to touch upon certain aspects of solar and stellar flares where, in the author's opinion, problems still persist in the physical interpretation of the phenomena. The approach will be to focus on matters which can be discussed quantitatively for *both* solar and stellar flares. As a result, certain topics which are of great current interest in solar flares (e.g., chemical anomalies in solar energetic particles, high-time resolution observations of X-rays, directivity of gamma-ray emission, neutron production, and decay, etc.) will not be discussed here because current stellar data cannot contribute to a resolution of the problems.

2. Physical Conditions in Stellar Flares

In order to discuss meaningfully the nature of physical problems in flares, the first question we need to ask is: what are the physical conditions in flares? For the sake of definiteness, we shall refer to the parameters derived by Haisch (1983) for a sample of eight flares which were observed by the Einstein IPC detector. For each flare, Haisch analyzed the time behavior of the soft X-ray emission during the time period following maximum intensity. During this decay phase, he extracted three quantities from the IPC data: the emission measure (EM), the temperature (T), and the decay time (τ). Three assumptions were made in order to interpret the data: (a) each flare was assumed to occur in a loop of length L and aspect ratio 0.1; (b) the magnetic field B in the loop was assumed to be strong enough to contain the flare plasma (hence, $B^2 > 8\pi p_g$, where $p_g = 2N_e kT$ is the gas pressure in the flare plasma); and (c) the radiative and conductive cooling times of the flare plasma were assumed to be equal. From these, Haisch derived values of L and N_e, and a lower limit on B.

As an example, for flare number 2 on Proxima Centauri in Haisch's table, we find $EM = 10^{51}$ cm^{-3}, volume $V = 10^{27}$ cm^3, $N_e = 9 \times 10^{11}$ cm^{-3}, $L = 5 \times 10^9$ cm, $T = 4 \times 10^7$ K, and $B > 500$ G. For future reference, we note that the Alfvén speed in this case has a value $v_A > 1200$ km s^{-1}, and because of assumption (b), the lower limit on v_A depends only on T.

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We may ask: how reliable are these parameters? To answer this question, we make the following three points. (i) Schmitt *et al.* (1987) have examined data from Einstein IPC during time intervals when the IPC happened to be scanning the Earth. Time profiles of the X-ray emission during such intervals have revealed certain events which look like solar flare profiles. Schmitt *et al.* interpret these events indeed as solar flare X-rays scattered off the Earth's atmosphere. They then subject the events to exactly the analysis used by Haisch (1983) and find values of N_e and L which are quite consistent with the values derived directly for compact loop flares in the Sun. (ii) Are radiative and conductive cooling times really equal in flares? Strong *et al.* (1986) have used SMM data to show that in fact these two time-scales may be quite different. In six flares which they analyzed, they extracted the two time-scales from inferred values of N_e, T, and L, and found the ratio of the time-scales to vary between 0.2 and 20. However, the estimates of the time-scales are uncertain because of unknown filling factors and unknown extent of inhibition of conduction. (iii) Reale *et al.* (1988) have constructed a hydrodynamical model of a flare in a loop, and applied it to flare No. 2 on Proxima Centauri. These authors make no assumption about equality between radiative and conductive cooling times. They fit the decay of the X-rays with a model which has the same T and EM as Haisch (1983), but with N_e lower by a factor of about 5, and L larger by a factor of 2–3. Since T is unchanged, $v_A > 1200$ km s^{-1} as before.

In view of these results, it seems acceptable to use the physical parameters derived by Haisch (1983) in order to make order-of-magnitude estimates of various effects in stellar flares.

3. Radio Flares

The first problem we turn to concerns radio emission. Radio flares in M dwarfs, as well as microwave 'spike bursts' in solar flares, are observed to have brightness temperatures well in excess of 10^{10} K (e.g., Mullan, 1985), indicating the presence of a coherent emission process. The most widespread model for explaining the coherent emission is the electron cyclotron maser (ECM) (Melrose and Dulk, 1982). Electrons are supposed to be accelerated somehow in the initial flare release, and they stream towards the footpoints of the magnetic loop. Some of the electrons reach the chromosphere, and are lost there. The remaining electrons mirror, and create a loss-cone distribution in the loop. If physical conditions are right, this distribution is unstable to the growth of electromagnetic (*em*) waves at the electron cyclotron frequency Ω_e (and possibly harmonics thereof): the waves can tap the free energy available in the loss-cone distribution. The mode of the *em* waves in a cold plasma is x-mode if the ratio $R = \omega_p/\Omega_e$ is < 0.3, where ω_p is the electron plasma frequency. The x-waves can escape and be observed directly: this is the most direct mechanism for producing coherent radio emission. In a warm plasma, the upper limit on R increases with increasing temperature (Winglee, 1985), but this is not a significant factor for the values of T mentioned above. A beneficial side product of x-mode emission (as well as explaining directly the coherent radio emission) is that coronal heating also occurs by means of these x-modes: they can escape the source region and be absorbed as a second harmonic elsewhere.

For $0.3 < R < 1.3$, *em*-waves no longer dominate in the instability: rather, electrostatic modes do. Since these are not *em*-waves, they cannot explain directly the observed radio waves: some mechanism must first convert them to *em*-radiation. For R values of a few (say, 3–4), maser emission becomes more difficult in the context of ECM, but not impossible (e.g., see Louarn *et al.*, 1987). For R of order 10 or more other sources of maser action must be considered (e.g., Kuijpers, 1985).

The upper limit on R for direct *em*-maser emission is equivalent to a lower limit on the Alfvén speed. Thus, $R < R_c = 0.3$ corresponds to $v_A > v_{Ac} = 23000 \text{ km s}^{-1}$. Hence, direct *em*-maser radiation can occur only in regions of very high Alfvén speed.

Do such regions exist in solar and/or stellar flares? In the Sun, VLA data allow one to measure both B and N_e. In a sunspot loop, Lang (1983) reported $B = 600$ G and $N_e = 10^9 \text{ cm}^{-3}$, corresponding to $v_A = 42000 \text{ km s}^{-1}$. In such a loop, direct ECM emission is possible. However, a sunspot loop is a region of exceptionally large B and unusually low N_e, and is, therefore, the most favorable site for finding large v_A: other loops in solar active region will undoubtedly have lower values of v_A. For example, results by Lang *et al.* (1987) for an active region loop indicate v_A of less than 6000 km s^{-1}. Such a loop would not be a candidate for direct ECM emission.

In stellar loops, the results of Haisch (1983) indicate lower limits on the values of v_A which are in all cases of order 1000 km s^{-1}. Unless the lower limits are very far from the true values, the conclusion is that direct ECM emission cannot be operating in flare star loops. If we wish to save the hypothesis of direct ECM emission for the Haisch flares, we require either an increase in B by a factor of 23, or a decrease in N_e by a factor of more than 500. Thus, in Proxima Centauri, we require $B = 11.5$ kG (if the density remains unchanged), or N_e must be reduced to less than $2 \times 10^9 \text{ cm}^{-3}$. Now, fields of order 10 kG may very well exist on flare star surfaces (Mullan, 1984a): in fact, fields of 5–6 kG have already been detected in some such stars (Saar *et al.*, 1987), and even higher fields are almost certainly be present (but currently undetectable) in cool spots. However, increasing B to more than 1700 G means that emission at Ω_e would emerge at frequencies too high to be detected by the VLA at 6 cm. And as regards the densities, Katsova *et al.* (1987) have shown from X-ray data that the mean densities at the base of coronae in cool dwarfs are in the range 10^9–10^{10} cm^{-3}: therefore, the loop on which the ECM should occur would have a density no greater than the average coronal density. This seems unlikely in a loop which is the site of a flare: such loops in the Sun are found to have densities which are considerably enhanced relative to the average. For example, Canfield (unpublished paper at this conference) has reported that preflare densities in solar flare loops are 100–1000 times the average density. Moreover, in order to create any ECM, a loss-cone distribution must be set up: this requires that electrons in the loss-cone be already removed by the chromosphere. The latter will be heated by the loss-cone electrons, and so, before the ECM occurs, the loop will already be filling up with material evaporated off the chromosphere, there by further enhancing the density in the loop.

We conclude that, using Haisch's stellar loop parameters for post-maximum conditions in stellar flares, it is unlikely that direct *em*-maser emission at Ω_e (as occurs in the simplest version of ECM) is at work. Undoubtedly *some* maser process is at work, perhaps involving nonlinear conversion of plasma waves into *em*-radiation (see Kuijpers, 1985), and perhaps involving different processes in different flares (Bastian and Bookbinder, 1987), but direct *em*-maser emission should not be assumed as a universal explanation of coherent radio emission from dMe flares.

On the other hand, radio bursts from RS CVn stars (which are sometimes discussed as an analog of radio bursts from dMe stars) do not usually need a maser mechanism to account for them. Therefore, the present discussion is not applicable to RS CVn bursts. It should not be assumed uncritically that bursts in RS CVn stars necessarily involve the same physical processes as those on dMe stars (Mullan, 1985).

4. Penetration of Particle Beams and Photons

A problem related to the topic of electron beams arises in connection with the electron densities discussed above. The excitation of an optical flare in a solar/stellar chromosphere is believed to depend on the propagation of a disturbance downward from the site of initial energy release in the corona: when this disturbance penetrates into the chromosphere, the optical flare can begin. Candidates for the disturbance are beams of charged particles or photons. In this section, we are mainly concerned with the following question: can an electron beam penetrate to the chromosphere of a flare star? At the end of this section, we mention briefly the effects of photons, and we return in Section 5 to the question of proton beams.

The answer depends on the column density ξ through which the beam must pass between its source and the chromosphere. An electron of energy E keV can penetrate to $\xi_p(E) = 6 \times 10^{19}(E/20)^2$ cm^{-2} if the only stopping mechanism is Coulomb collisions (Brown, 1971): this figure is reduced somewhat if allowance is made for excitation of plasma oscillations by the passing beam (Hamilton and Petrosian, 1987).

In the Sun, values of ξ on different loops can be estimated from typical solar loop parameters: with $L = (0.3\text{–}3) \times 10^9$ cm and $N_e = (1\text{–}100) \times 10^9$ cm^{-3}, solar loops have ξ ranging from 3×10^{17} to 3×10^{20} cm^{-2}. Thus, for some loops, ξ is less than $\xi_p(E = 20)$, and in such loops, an electron beam of energy 20 keV (which is the energy at which non-thermal electron beams in the Sun seem to contain most of their energy) can indeed reach the chromosphere. If the electron beam has a large enough flux, the chromosphere is explosively evaporated, and the Hα line develops strong Stark wings (Canfield *et al.*, 1984). We may refer to this case as 'an electron beam flare' in the chromosphere. On the other hand, some loops contain so much material that ξ is in excess of $\xi_p(\mathrm{E} = 20)$: in such loops, 20 keV electrons are stopped before they reach the chromosphere. They deposit their energy in the corona, and then a thermal conduction front propagates down into the chromosphere. In this case, the Hα line is narrow, with no Stark wings, and no central reversal (Canfield *et al.*, 1984). We may refer to this as a 'thermal conduction flare' in the chromosphere.

In the case of flare stars, using the ranges of loop parameters listed by Haisch (1983), namely $L = (0.2\text{–}6) \times 10^{10}$ cm and $N_e = (1\text{–}30) \times 10^{12}$ cm^{-3}, we find that

$\xi = 2 \times 10^{21}$–2×10^{24} cm^{-2}. In all cases, such loops have column densities greatly in excess of $\xi_p(E = 20)$. This suggests that in stellar flares, it may be difficult to find an example of a pure 'electron beam flare' in the chromosphere: rather, most chromospheric flares in M dwarfs may be thermal conduction flares. This is consistent with a suggestion proposed some years ago that thermal conduction is the primary physical agent which couples coronal plasma to the chromospheric emitting material in stellar flares (Mullan, 1976). Of course, if stellar flares produce most of their beam energy as electrons of significantly higher energy (say 1 MeV, although there is no evidence to support this) or protons with energies of tens of MeV, then such beams may penetrate to the chromosphere in all but the densest of the loops we have considered here.

In the present discussion, we have used Haisch's flare parameters which pertain to the post-maximum phase. We may, therefore, be overestimating somewhat the loop column densities in the early stages of the flares. But our overestimates would have to be as large as 30–30 000 in order to alter the conclusion that thermal conduction flares dominate optical flares in M dwarfs. In this regard, in a sample of flares observed with high spectral resolution by Schneeberger *et al.* (1979), the width of Hα did not increase, although the overall intensity did. In these flares, there was also no strong indication of any central reversals in Hα. Such behavior in Hα is consistent with the thermal conduction class of flare discussed by Canfield *et al.* (1984).

Let us turn briefly to photons as a possible agent in the process whereby primary energy release in the corona is communicated to the chromosphere/photosphere in order to cause the 'optical flare'. The importance of X-ray emission in this regard in solar flares can be seen most readily by examining data from one subset of solar flares, namely, the white-light flares (WLF; see Neidig, this volume). In these flares, continuum emission originates in the lower chromosphere and/or the upper photosphere. If the emission occurs in the photosphere, Neidig rules out electron beams, proton beams, thermal conduction, and soft X-rays as agents to power a white light flare. But the light curve of such flares tracks the hard X-ray emission (at energies of 50–100 keV) during both the impulsive and the gradual phases of the flare: this suggests that hard X-rays may play an important role in initiating the optical flare. A non-LTE radiative transfer model which explains the correlation between hard X-rays and white light solar flares has been proposed by Aboudarham and Henoux (this volume).

In stellar flares, the possibility that X-ray photons can contribute significantly to the optical light curve was demonstrated some years ago (Tarter and Mullan, 1977).

A hybrid mechanism can be imagined in which both a particle beam and the photons which the beam creates as it enters the dense lower atmosphere may be responsible for communicating the original energy release down to the optical flare region. This is obviously a highly nonlinear process. See Aboudarham and Henoux (this volume) for a solar flare model involving an electron beam plus its hard X-rays, and see Grinin and Sobolev (1989) for a stellar flare model involving a proton beam plus its photons. In both cases, the particle beam first penetrates a certain distance, and then the photons take over and penetrate considerably deeper into the atmosphere. In particular, in a case considered by Grinin and Sobolev, although the beam itself (composed of 10 MeV protons) produces maximum heating rates at a column density of about 10^{22} cm^{-2}, the heating due to the photons produced by the proton beam reach their maximum rate at deeper than 10^{24} cm^{-2}. Moreover, the amplitude of the photon heating exceeds the direct particle heating by about one order of magnitude.

5. Momentum Balance in Stellar Flares?

An interesting question has arisen in solar physics recently concerning momentum balance in flare plasma. Once the initial energy is released in a flare, it flows downward towards the chromosphere, either as a conduction front or as an electron beam. The chromosphere is heated and as a result, material is evaporated upwards into the corona. To balance the upward momentum, chromospheric material also moves downward. Is there evidence that the upward and downward momenta are balanced?

Canfield *et al.* (1987) have evaluated both upward and downward momenta in a solar flare. The downward momentum can be evaluated from red-shifted Hα data:

$$p_d = \mu m_{\rm H} N_c S_c v_d^2 \tau ,$$

where μ is the mean molecular weight, $m_{\rm H}$ is the mass of a hydrogen atom, N_c is the chromospheric density prior to the flare, S_c is the area of the chromospheric region where Hα is red-shifted, v_d is the downflow velocity of the Hα material, and τ is the duration of the red-shifted phase in Hα. The upflow momentum can be evaluated from blue-shifted data from the soft X-ray lines emitted by the evaporated plasma:

$$p_u = \mu m_{\rm H} v_u ({\rm EM} \times V)^{0.5} ,$$

where v_u is the blue shift of the soft X-ray plasma, EM is its emission measure, and V is the volume of the soft X-ray plasma. In the solar flare studied by Canfield *et al.*, it appears that indeed p_d is equal to p_u to better than one order of magnitude.

Let us now apply the argument to stellar flares. Using Haisch's data, we have EM = 10^{51} and $V = 10^{27}$ c.g.s. No direct observations of blue-shifted X-ray lines have been reported for stellar flares. But it is expected that upward expansion velocities will be no more than a few times the local sound speed. A value of v_u = 600 km s^{-1} has been suggested by Reale *et al.* (1988). We adopt 100–1000 km s^{-1} here. Then the upward momentum per unit mass is 10^{46}–10^{47} c.g.s.

For the downward momentum, red-shifted Hα has been observed to persist for up to τ = 120 s in large stellar flares (e.g., Bopp and Moffett, 1973). The amount of redshift is difficult to quantify. But the red wing of Hα is observed to extend to velocities of about 1100 km s^{-1} (Bopp and Moffett, 1973). This suggests that the peak of the red-shifted component in Hα may lie at velocities of several hundred km s^{-1}. We adopt v_d = 300–500 km s^{-1} here. For the area of the chromosphere which is participating in the downflows, we note that Cram and Woods (1982) require from their Hα modelling that as much as 10–20% of the visible disk area must be emitting in Hα. We take 10% here, and therefore find that for a star such as Proxima Centauri (with radius 10^{10} cm^2),

$S_c = 3 \times 10^{19}$ cm^2. For flare stars of larger mass, a representative flare area may be taken to be 10^{20} cm^2. (This is certainly larger than solar flare counterparts: further arguments in favor of larger area in stellar flares can be found in Neidig (this conference).) Finally, for the pre-flare chromospheric density, we note that in general, the chromosphere/corona of flare stars are denser than their solar analogs by factors which may be as large as 10–100 (e.g., Mullan, 1977). In the solar flares analyzed by Canfield (unpublished paper at this conference), the preflare densities were found to be 2–3 $\times 10^{13}$ cm^{-3}: scaling these upwards by factors of a few, we suggest $N_c = 10^{14}$ cm^{-3} in the pre-flare loops on flare stars. Chromospheric densities outside flares have been evaluated by Pettersen (1989) for a sample of 8 flare stars of comparatively early spectral types (K5–M1): he finds densities of 5×10^{11}–5×10^{12} cm^{-3}. Canfield has stressed that chromospheric densities in a pre-flare loop are higher than quiescent values by factors of 100–1000. Hence, our choice of $N_c = 10^{14}$ cm^{-3} for the pre-flare chromosphere seems conservative.

Are our choices of flare parameters consistent with other information on stellar flares? To answer this, we note that with the above choices of N_c and v_d, the flare energy flux which drives chromospheric evaporation must be about $F_{ce} = 4 \times 10^{13}$ ergs cm^{-2} s^{-1} (see Fisher, 1987). Therefore, over a flare area of S_c, a total energy of $E_{ce} \approx 10^{34}$ ergs is available for chromospheric evaporation in a flare lasting ≈ 10 s. The total output of flare energy cannot be smaller than this (cf. Fisher, 1987). Are such energies reasonable for stellar flares? Energies of order 10^{33} ergs are observed in the B band alone in large flares of solar neighborhood flare stars: even larger energies are observed in Orion and Pleiades flare stars (Shakhovskaya, 1979). The total optical energies of stellar flares in larger than B-band energy by a factor of 4.2. Also, bolometric energies in large flares must also include X-ray, EUV, and mass motions. The latter numbers are very uncertain, but may be as much as 10–100 times the optical energy (Gershberg and Shakhovskaya, 1983). Hence, total energy releases of a few times 10^{33} ergs are expected to be available in flares with B-band energies of 10^{31}–10^{32} ergs. Flares of such energies are not rare events on solar neighborhood flare stars: they are observed with frequencies of once every 1–10 hours (Shakhovskaya, 1979). Hence, our choice of parameters are not excessive from the point of view of energetics.

With the above choices, we find that the downward momentum per unit mass is $10^{50.5}$–10^{51} c.g.s. These figures suggest that there is a discrepancy between upward and downward momenta in stellar flares in the sense that the downward momentum exceeds upward momentum by a factor which may be as large as 5 orders of magnitude.

Significant revisions must be made in one or more of the above physical parameters if this discrepancy is to be removed. Perhaps a beam of *protons* rather than electrons is created in stellar flares: this would provide downward momentum while slowing down the process of chromospheric evaporation (Van den Oord, 1987). Independent arguments for the possible presence of proton beams in stellar flares have been presented by Simnett (1989).

6. Sub-Surface Source of Flare Power: Solar-Stellar Differences

We now turn to the problem of energizing the activity in a flare star atmosphere. (By 'activity' we refer to both flare activity and 'quiescent' coronal heating.) The ultimate source of activity is mechanical energy which creates stresses in the atmospheric magnetic fields. The questions we ask here are: what flux of mechanical energy is required in flare star atmospheres? and is that flux available from the convection?

To answer the first question, we need to evaluate the non-radiative energy budget of the atmosphere both in its quiescent condition and also during flares. It is convenient to express the energy requirements of the various parts of the atmosphere as a ratio R_f of the total power output of the star.

Vilhu and Walter (1987) have examined a sample of F–M dwarfs and have determined radiative losses in UV lines from the chromosphere, in transition region (TR) lines, and in coronal X-rays. Expressed in terms of R_f, these quantities are found to span ranges of several orders of magnitude for stars of a given spectral class. However, there are apparently 'saturated' levels above which no star in the sample was found to lie. For the UV chromospheric lines, the TR lines, and the X-rays, the saturated values of R_f were found to be about 10^{-3}, 10^{-4}, and $10^{-2.5}$, respectively. In dMe stars, Balmer line emission may also contribute, making R_f as large as 10^{-3}–10^{-2}. There may also be significant mechanical energy deposited into the upper photosphere of M dwarfs. This could re-emerge as enhanced radiation in the H^- continuum or in the large number of weak spectral lines which are formed near the temperature minimum (Rutten *et al.*, 1989): of the latter contributions to the mechanical energy budget we have no current knowledge. Hence, in quiescent conditions, the mechanical energy flux which must be supplied to the atmosphere of a dMe star almost certainly saturates at a value which is at least of order 1% of the total power of the star.

Estimates of the time-averaged power in flares are subject to large uncertainties. For example, the amount of emission in Lyman lines and continuum is a complete unknown, as is the amount of mechanical energy associated with mass ejections (Gershberg and Shakhovskaya, 1983). In view of the work of Kahler *et al.* (1988), the lack of information on mechanical energy is particularly serious. The maximum energy released in a stellar flare will remain uncertain until the mechanical energy can be evaluated. In optical light, the upper limits on flare energy in the Sun are about 10^{32} ergs, and in the stars, 10^{34}–10^{35} ergs. Mechanical energy requirements cause the solar value to be increased by a factor of about 10 (Webb *et al.*, 1980). If the stellar flares have a comparable correction, then the maximum energy in a stellar flare may be of order 10^{36} ergs. Combining these results with the rate at which flares are observed to occur, we find that the mean power in stellar flares may be a few percent of the total stellar power. This result depends on the bolometric correction for flare light, and the averaged flare power may be as large as 10% of the total stellar power output (Mullan, 1977).

We, therefore, ask: is there enough mechanical energy in an M dwarf to amount to 1–10% of the total power output from the star and to provide up to 10^{36} ergs in the largest flares? We can summarize two different approaches to this problem, one based on a general discussion of convection, the other based on specific models of the stellar envelope.

First, according to standard models of convection, based on the Boussinesq approximation (in which the convecting gas is assumed incompressible except for the buoyancy effects), the flux of kinetic energy associated with convection is about 1% of the thermal flux, and is directed upwards (Mullan, 1984b). In fact, the mixing-length theory of convection assumes that the flux of kinetic energy in the convection zone is negligible: the only important flux is supposed to be the upward flux of heat. Hence, a 1% level for the kinetic energy flux is acceptable from a consistency point of view. But it barely suffices to supply the mechanical energy needs of the flare stars.

Second, McClymont and Fisher (1988) have evaluated the amount of mechanical energy available to drive solar flares in three different scenarios: (a) photospheric dynamo, (b) coronal storage, and (c) energy available in an erupting flux tube. To evaluate (a) and (b), they propose that mechanical energy can be supplied from the convection zone in the form of Alfvén waves (the flux rope acting as a conduit): the difference between (a) and (b) is that in (a), Alfvén waves emerge only over the course of the flare itself (assumed to last one hour), whereas in (b), the waves emerge over the course of one day prior to the flare and are stored in the corona. Therefore, they integrate the available mechanical energy flux in convection down to the level inside the convection zone from which Alfvén waves could have propagated to the surface in a time of (a) one hour, (b) one day. For the convection zone, they adopt a standard mixing-length model. They find that in (a), the available power suffices to power only the subflares, whereas in (b), flares with energies up to (1–3) $\times 10^{31}$ ergs can be powered, i.e., enough for a major flare. As for (c), the energy available in an active region of area 10^{19} cm^2 and field strength 1000 G is 10^{33} ergs, enough for the largest flares (including mechanical energy requirements). We have repeated their calculations for the case of two flare stars, one with mass 0.6 M(Sun) (see model in Schwarzschild, 1958, where again, a standard mixing-length model is assumed), and the second with a mass so small that the star is completely convective (for which we assume a polytrope with index 1.5). Then for (a), we find maximum powers of up to 10^{28} ergs s^{-1}, sufficient to power a very small stellar flare. For (b), the energy which can be tapped in one day is found to be 10^{34} ergs for the 0.6 M(Sun) star, and about 10^{36} ergs for the completely convective star (given a surface area of the flux tube of 10^{20} cm^2: Cram and Woods, 1982). The reason that these energies are larger than solar is a combination of the higher density in the deep convection zone and the larger surface area of the flux tube. As for (c), using the available magnetic flux (Saar *et al.*, 1987), we find that total energies of 10^{36} ergs are available. Thus, it appears that, using one-dimensional mixing-length models of convection zones, the mechanical energy in the convection zone of lower main sequence stars is sufficient (but only just!) to power the largest stellar flares.

However, this conclusion depends on adopting a mixing length theory of convection, i.e., a one-dimensional model. But the convection zone is in fact composed of compressible gas, and this has been taken into account only recently in 3-D modelling of convection (Chan and Sofia, 1984). The 3-D calculations show that the upflows and downflows are very different in character. Because of the density stratification, downflowing gas becomes concentrated into strong plumes whereas the upflows spread out over large areas. The downdrafts are sites of high-speed flows: hence, when one takes a horizontal average over a plane in the convection zone, one finds that the flux of kinetic energy is no longer the negligible amount which had been assumed in mixing-length theory: the KE flux now rises to the startling value of about 50% of the upward heat flux. Even more surprising, the KE flux is directed *downwards*, and the heat flux must increase locally to 50% larger values to compensate for the downdrafts. Hence, in contrast to mixing-length theory, the flux of KE in stellar convection is by no means negligible compared with the heat flux.

This remarkable new view of the convection zone leads to new questions about the heating of flare star atmospheres. How does the KE flux which is mainly downward couple to stresses in the surface magnetic fields which give rise to magnetic activity? Can electrodynamic coupling still be used to estimate the coupling effects (Mullan, 1984b)? How do the strong downdrafts interfere with the buoyancy of magnetic flux ropes? Is it acceptable to use the mixing length model of the convection in calculating thermal shadowing effects of a flux tube? In a completely convective star, do the downdrafts extend all the way to the center of the star? (As to where exactly on the main sequence stars become completely convective, there are still uncertainties: the critical mass may be lower than previously suspected, cf. Cox *et al.*, 1981.) In a star with a radiative core, how do overshoots of the strong downdrafts affect the physical conditions at the core-envelope interface? Do they interfere with dynamo activity at the interface? Do they give rise to significant *g*-mode pulsations in the core? And finally, how will the estimates of available flare power (based on McClymont and Fisher (1988) arguments) be altered? (The total energy in erupting flux will not be altered.)

7. Kinetic Energy Flux: Mass Loss?

Although the kinetic energy flux *inside* the convection zone is of interest as the origin of mechanical energy (see Section 6), a more directly observable manifestation of KE flux *outside* the star is associated with mass loss. Here we ask the questions: do flare stars lose mass at a rate which is significant for the interstellar medium? and do flare stars necessarily lose mass via the same mechanism as the Sun?

In the Sun, the KE flux $F(\mathrm{KE})$ associated with mass loss (10^{12} g s^{-1} at speeds of 300 km s^{-1}) is about 10^{27} ergs s^{-1}. Compared with the flux of mechanical energy required to heat the solar corona ($F(\mathrm{Cor})$ = a few times 10^{28} ergs s^{-1}; cf. Holzer, 1980), the Sun diverts less than 10% of its coronal energy supply into kinetic form. To understand why this percentage is so small, we note that the mass loss from the Sun occurs mainly as a result of the gradient in thermal pressure: thus, mechanical energy emerging from the convection zone is first converted into disorganized form (i.e., heat), and then a steady organized flow is driven by the gradients in thermal pressure. This is an inherently inefficient method of organizing flow, and it is therefore not surprising that the ratio of $F(\mathrm{KE})$ to $F(\mathrm{Cor})$ is rather small in the Sun.

However, in the solar wind, there are also transients which may carry up to 10% of the mass flux of the wind: this figure is based on estimates from coronagraph data (Howard *et al.*, 1985), and refers only to transients with masses in excess of about 10^{14} g. No knowledge is currently available as to the contributions which small transients (masses less than 10^{14} g) make to the overall mass flux, although it is possible that the fraction may be large in coronal holes (cf. Holt and Mullan, 1987). The large transients detected by the coronagraphs are mostly due to filament eruptions: in these events, a magnetic configuration is somehow driven (presumably by convective pushing of the footpoints) to a condition where magnetostatic equilibrium can no longer exist. With the breakdown of equilibrium, the unbalanced magnetic forces drive outflows with high efficiency. Certain coronal transients were initially classified as being caused by flares rather than being associated with eruptive filaments. However, recent studies suggest that certain flares may actually be a response to a filament eruption (i.e., coronal transient), rather than the reverse (cf. Kahler *et al.*, 1988). In fact, the bulk of the energy release in a solar flare may not be in the visible flare at all, but rather in the coronal mass ejection (Webb *et al.*, 1980). It appears that most (if not all) coronal transients originate in a failure to find magnetic equilibrium. If this is so, then coronal transients rely directly on magnetic forces to drive mass loss.

The conclusions of Kahler *et al.* (1988) have an important implication for our study of flare stars: they suggest that for every stellar flare, there may be an associated mass ejection which actually contains most of the energy release. Now, in the Sun, there is a well-known anti-correlation between the sites of magnetic activity and the sites of mass loss: active regions contain mainly closed magnetic loops, and the associated averaged mass loss rate in transient activity is small, whereas solar mass loss occurs mainly via thermal expansion in magnetically quiet regions (coronal holes). This anti-correlation may have biassed our expectations of the mass loss process in other stars so much that we may have overlooked an important point: the Sun, from the viewpoint of magnetic activity, is a very poor specimen compared with many lower Main-Sequence stars.

As an indication that the magnetic activity on the Sun is at a low level compared with the levels on dMe stars, we may cite the magnetic fluxes on M stars: they are larger than solar by several orders of magnitude, with average fields stronger (up to 5–6 kG), and areal coverage factors much larger (60–90%) (Saar *et al.*, 1987). Hence, the fact that magnetically driven mass loss constitutes only a small fraction of the total mass loss from the Sun does *not* mean that the same will apply to flare stars. Let us explore the possibility that in fact, *mass loss from M dwarfs may be qualitatively distinct from the solar case*: in the M dwarfs, we speculate that the mass loss rate due to magnetic forces (i.e., coronal transients) may be much greater than the mass loss rate due to thermal driving (i.e., steady coronal expansion). Can we find support for this proposal?

Since the M dwarfs are as a whole much more magnetically active than the Sun, it seems likely that magnetically driven mass loss in flare stars will be of considerably greater significance than in the Sun. Thus, if equipartition of sorts exists in the coronae of flare stars, we may have F(KE) of the same order as F(Cor). And if reconnection is responsible for driving mass (see Waldron and Mullan, 1987), then F(KE) may actually exceed F(Cor): at a reconnection site, it is important to recognize that magnetic

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energy is converted directly into *kinetic* form, and the appearance of thermal energy is only secondary. (For a discussion of how kinetic energy may be converted ultimately to thermal energy in the context of a flare, see Bornmann, 1987.)

Suppose flare stars have $F(\mathrm{KE}) = F(\mathrm{Cor})$. Then since flare stars have $F(\mathrm{Cor})$ up to 1% of the bolometric power, a star of spectral class, say dM4–5e, with $M_V = 11$–12 and $M_{\mathrm{bol}} = 9$–10 will have $F(\mathrm{KE})$ of order 4×10^{29} ergs s^{-1}, i.e., some 400 times the solar value. The wind speed is expected to be comparable to the escape speed v_e from the stellar surface: on the lower main sequence, where stellar radii scale almost exactly with stellar mass, v_e remains essentially unchanged. Hence, the mass loss from the above M dwarf is expected to be some 400 times solar, i.e., about 6×10^{-12} solar masses yr^{-1}.

The significance of mass loss from M dwarfs was pointed out by Coleman and Worden (1976). Since M dwarfs are the most numerous population in the galaxy (there are 10^{11} of them), they supply a significant amount of material to the interstellar medium (ISM) if each M dwarf loses on average 10^{-12} solar masses yr^{-1}. (O stars, Wolf–Rayet stars, and planetary nebulae all contribute about 0.1 solar masses yr^{-1} to ISM.) With the above estimates of mass loss from a dM4–5e star, it is apparent that in fact M dwarfs might be a significant (or dominant) contributor to ISM.

Is there any evidence for mass loss from cool dwarfs? As far as I know, there are no reports of detection of mass loss from individual M dwarfs. However, a K2 dwarf in the binary V471 Tauri has recently been found to be losing mass (Mullan *et al.*, 1988; Mullan *et al.*, 1989). The K2 dwarf does *not* overflow its Roche lobe: the Roche surface is larger than the stellar radius by a factor of about 40%. We are, therefore, talking of 'ordinary' mass loss from the corona of the K2 dwarf. Discrete absorption features have been detected in lines of Mg I, Mg II, Fe I, and Fe II in high-resolution IUE spectra. The discrete features are variable in strength on time-scales ranging from days to months. Analysis of the Mg II absorption allows us to derive a lower limit on the mass loss rate in the discrete features: it is 10^{-11} solar masses yr^{-1}. Moreover, the discrete absorption features are observed in ions which are formed at remarkably low temperatures (no more than a few times 10^4 K). In the solar wind, low temperatures are a characteristic signature of coronal transients (presumably because they are magnetically isolated from the effects of thermal conduction, and because of adiabatic cooling). The fact that the discrete features are observed to be time variable in V471 Tauri is also consistent with transient behavior. Arguments can be made that there is no significant mass loss rate in higher temperature gas (Mullan *et al.*, 1989): thus, the wind from the K2 dwarf in V471 Tauri seems to be dominated by coronal transient material, rather than by matter which has expanded from a thermal corona. If this conclusion can be substantiated, the wind from this star is quite different from the solar wind.

Now, the K2 dwarf in V471 Tauri is rotating rapidly (70–80 km s^{-1}), and might be expected to have strong magnetic fields. In fact, on the basis of observed period changes, the field at the base of the convection zone can be estimated (Applegate and Patterson, 1987): it is indeed large, almost 10^6 G. There are detectable flares (Young *et al.*, 1983), which is unusual in a star of such early spectral type: activity must be at a very high level in this star. The high level of magnetic activity indicates that magnetic flux loops on the surface of the K2 dwarf are frequently out of equilibrium: hence, the optical magnetic activity may be only the tail of a distribution of magnetic energy releases, with most of the energy being released as transient mass loss. The ratio of magnetically driven mass flux to coronal expansion in this star appears to be much higher than in the Sun.

Rapidly rotating K dwarfs have been reported also in the Pleiades: the rotational velocities are 100 km s^{-1} or more (Van Leeuwen and Alphenaar, 1983). The existence of such rapid rotation in young stars is a consequence of contraction along the evolutionary track towards the Main Sequence. Since the 'rotation-activity' connection applies equally to single stars and binary members (Basri, 1987), we expect that the rapid K rotators in the Pleiades will also lose mass at a rate some orders of magnitude greater than solar. In fact, the fastest rotating Pleiades K dwarf has Hα emission which suggests a mass loss rate of up to 10^{-9} solar masses yr^{-1} (Marcy *et al.*, 1985).

As regards M dwarfs, the only evidence so far for mass loss occurs in cataclysmic variables. In these systems, the measured quantity is the mass capture rate by the white dwarf: presumably the mass loss rate by the red dwarf is larger than the transfer rate by a few orders of magnitude. In these systems, the transfer rates can be as large as 10^{-7} solar masses yr^{-1} (Patterson, 1984): but in those cases, Roche-lobe overflow is probably responsible for the extremely large mass loss rates. These results, therefore, tell us very little about mass loss from the corona of an individual M dwarf. But the argument presented above suggests that attention should be paid to the possibility that M dwarfs with efficient coronal heating may be important suppliers of mass to the ISM.

To summarize this section, we have proposed that the mass loss process in active stars may be dominated by magnetically driven transients, rather than by thermal expansion of a hot corona. Our proposal is at odds with what is known about the solar wind, but this is not necessarily critical: after all, the Sun is, from a magnetic standpoint, a comparatively inactive and uninteresting star. If, as we propose, mass loss from active dwarfs is dominated by magnetic loops which have lost equilibrium, then it is not necessary for all of the material on an erupting loop to be carried out in the wind: some of it may fall back to the surface of the star. This would give rise to red-shifted material in the spectrum: such material is indeed observed in the spectra of V471 Tauri (Mullan *et al.*, 1989). There is also a report of both blue-shifted and red-shifted material in the surroundings of T Tauri stars (Mundt, 1984): these stars are also candidates for preferential mass loss by magnetic driving, since their coronal emission is frequently very weak, suggesting that thermally-driven expansion in these systems may contribute little to mass outflow.

8. Flare Energy Release: Reconnection Modelling

It is very likely that the release of energy in a solar/stellar flare is related to magnetic reconnection in some way. The question we ask here is: how is the process of magnetic reconnection to be modelled in a flare?

Starting with the initial work by Sweet and Parker in the 1950's, and until very recently, the modelling has been entirely in two dimensions. In 2-D, steady reconnection

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can occur in the vicinity of an X-type neutral point: magnetic islands form and saturate when they reach equilibrium, after which they evolve resistively. An extensive discussion of the various scenarios which have been proposed for steady 2-D reconnection has been provided by Forbes and Priest (1986).

Addition of fluid turbulence to 2-D reconnection has been modelled by Matthaeus and Lamkin (1985): in this case, local potential wells form in the flow and enable efficient electric field acceleration on the neutral line. In the context of solar flares, acceleration to energies of order 1 GeV is possible.

In reality, however, magnetic reconnection will occur as a 3-D process. In this case, magnetic islands may overlap, and if they do, the field lines will wander stochastically, so that no equilibrium is possible. If the overlapping islands happen to have opposite helicities, tearing mode turbulence (TMT) will occur. Spicer (1976) was the first to provide a discussion of 3-D effects and how they affect the energy release in solar flares. More recently, Strauss (1988) has used his 'reduced MHD equations' (which are written for the approximation of long thin flux tubes and strong axial fields) to obtain approximate numerical estimates of certain aspects of TMT in the context of solar flares and solar coronal heating.

The effects of TMT are to lead to relaxation of the current *gradients*, in contrast to the effects of resistivity, which lead to a relaxation of the currents themselves. In the presence of TMT, Ohm's law for the mean magnetic field includes not only the usual terms for induction electric field and Joule heating, but also a term representing diffusive decay of the current gradient: the 'diffusion coefficient' in this term Strauss refers to as 'hyperresistivity'. The energy of the mean field decreases with time not only because of Joule heating but also (and more especially, in solar coronal conditions) because energy is converted into magnetic and kinetic energy of TMT by the hyperresistivity. When the turbulence level becomes high enough, the effects of hyperresistivity dominate the resistive term and determine the growth rates of TMT. In this limit, Strauss finds an approximate expression for the hyperresistivity which is consistent with laboratory and simulation data. With this estimate, he finds that decay of magnetic energy due to hyperresistivity is more rapid than that due to turbulent resistivity by a factor of 10^9 in the solar corona. The heating which is produced by TMT is significantly larger than previous estimates of coronal heating rates in reconnection sites. Moreover, the onset of TMT leads to rapid expansion of the current sheet to a thickness of order ML (where M is the inflow Mach number, typically 0.03–0.3, and L is the length of the sheet). Hence, the volume of the coronal material which can participate in reconnection is no longer confined to a singular line, but is finite and large.

Further work remains to be done in the context of solar and stellar flares in order to determine how important the effects of hyperresistivity in fact are in helping us to understand the rapid release of magnetic energy in 3-D reconnection.

9. 3-D Geometry of Current Sheets

What is the geometrical structure of the flare site in a stellar atmosphere?

In the simplest model of 2-D reconnection, the initial release of flare energy occurs in a current sheet close to an X-type neutral line, and is, therefore, in principle confined to an infinitesimal volume. From that small volume, the release of energy must propagate elsewhere to ensure that a sufficiently large volume of the atmosphere contributes to the energy release which is observed. There may be a problem, however, with the propagation phase: not only must a certain (large) amount of energy be released in the flare, but it also must be released on a time-scale which is short (less than 1 s in stellar flares). The question is: are the transport properties of the solar/stellar atmosphere adequate to handle the rapid transfer of triggering information from the neutral line to the entire volume of flaring plasma which must be 'processed' if the total energy release of the flare is to be accounted for? The answer is that, in at least some cases, the plasma properties must be pushed to extremes to do this (Low and Wolfson, 1988).

It seems preferable, therefore, to imagine the reconnection site in terms of a 3-D structure from the beginning. (This is especially true now that detailed modelling of reconnection processes are being done in 3-D, cf. Strauss, 1988.) Rather than starting with the concept of an X-type neutral *line* as the site of initial energy release, the relevant entity in modelling flare physics should be the separatrix *surface*: this is the surface which partitions the magnetic field in the stellar atmosphere into flux cells. Each cell is distinguished by a unique field line connectivity, and when one crosses the separatrix surface, there is an abrupt reorientation of magnetic field vectors. The shape of the separatrix surface is determined by magnetic tension and pressure forces which arise when the photospheric motion causes the foot points of magnetic field lines to move in various directions: as long as the foot points remain rooted in a given flux cell (i.e., as long as global connectivity is preserved), a current sheet forms over the entire separatrix surface. The current sheet is formed even if there were no neutral points present in the initial field configuration (Low and Wolfson, 1988).

Lines along which two separatrices intersect are called separator lines: these are potential sites for initiation of reconnection and double layers (Baum and Bratenahl, 1980). However, the existence of current sheets over the entire surface of the intersecting separatrices is an important aspect of ensuring that a finite volume can be processed quickly.

Thus, from the point of view of modelling flares, it would be helpful to know the 3-D structure of separatrix surfaces and their intersections. Using a small personal computer, Baum and Bratenahl (1980) have provided an instructive example. Since that time, I would have anticipated that the availability of graphics packages and CAD/CAM routines for personal computers should have opened up a much more extensive vista on the shapes and geometry of separatrix surfaces. As far as I know, however, this has not happened in the astrophysical literature. In my opinion, it would be a worthwhile exercise to compile an atlas of representative surfaces and intersections for comparison with imaged flare data from (say) SMM.

10. Coronal Heating and Flares

Is there a continuum between coronal heating and flares? In terms of the separatrix surfaces discussed above, Low and Wolfson (1988) propose an answer to this question. They propose that if the magnetic free energy in a current sheet is small, then the currents can dissipate resistively, and Joule heating can occur in a non-explosive manner, thereby heating the 'quiet' corona. If, on the other hand, the magnetic free energy in the sheet is large, the sheet may go unstable by tapping into the free energy to drive tearing modes, leading to an explosive dynamical phase in which the bulk of the stored free energy is released rapidly. The latter case would appear as a flare.

Recent results by Machado *et al.* (1988) have a bearing on this suggestion. Machado *et al.* have surveyed a number of flares for which SMM provided images and for which magnetogram data were available. They find that in all cases, multiple loops were involved in the flares, with interactions between neighboring loops. The loops participating in the flares were classified in two categories, active and passive. The most pronounced energy releases occurred in loops which, according to the magnetograms, had been sheared prior to the flare, thereby building up a store of magnetic free energy: these were referred to as active loops. Other loops seemed to serve merely as repositories of energy injected from outside: these loops were found to have little free energy stored (according to the magnetograms), and were referred to as passive. Initially, energy release occurs in a single loop or at the interaction site between two loops. In the impulsive phase of the flare, the initiating loop and the impacted loop show strong brightenings simultaneously. Most of the total energy in the impulsive phase is released inside the initiating loop and/or inside one or more adjacent loops, rather than at the interaction site. Thus, interaction of loops is important for triggering a flare, but most of the energy released comes not from the triggering stie: rather, it comes from a reservoir throughout the loops.

These results seem to be very consistent with the suggestions of Low and Wolfson as far as flares in the Sun are concerned. However, we note that the theoretical question as to how magnetic energy is actually stored in coronal currents is not yet settled (cf. Chiueh and Zweibel, 1989). In the coronal heating problem, it may be equally important to consider not only the current sheets, but also concentrated vorticity structures: 3-D simulations of turbulent magnetofluids suggest that large amounts of kinetic energy are also dissipated in vortices (Dahlburg *et al.*, 1988).

Can flare stars help us in addressing the question of the connection between flaring and coronal heating? Several authors have suggested that coronal heating in flare stars is due to microflaring (e.g., Doyle and Butler, 1985; Skumanich, 1985; Katsova *et al.*, 1987) although these suggestions have been questioned by Ambruster *et al.* (1987).

In this regard, a further question arises on the basis of recent infrared data: namely, it appears that even in 'quiescent' coronal conditions, relativistic electrons may be present in the corona of dMe stars. To explain this claim, we note that a recent study of flare stars using the IRAS data (Mullan, Stencel, and Backman, 1988) has found that, of 74 flare stars observed by IRAS, 15 have been detected at a wavelength of

100 microns with fluxes which exceed the photospheric values by factors of 10^2–10^3. Moreover, the fluxes at 100μ exceed those at 60μ by a factor of at least 2–3 on average. Referring to work by Ohki and Hudson (1975) on possible infrared signatures of solar flares, the IRAS results suggest that a possible candidate for the infrared emission is synchrotron radiation. No other emission mechanism can cause a significant increase between 60 and 100μ. Now, the IRAS scans were made at random during the one-year lifetime of the satellite: each scan lasted no more than a few seconds, and a total of 10–20 were made on each star. Thus, it seems unlikely that IRAS would have 'caught' 20% of the stars in a flaring state. Instead, the IRAS data probably refer to quiescent conditions. If this is true, then there must be significant populations of relativistic electrons in the quiet coronae of flare stars. Hence, coronal heating in these stars must involve efficient acceleration of relativistic electrons.

The possibility that superthermal electrons are present in the quiescent coronae of flare stars has previously been discussed on the basis of microwave emission. How are such electrons accelerated? A current sheet model for accelerating a nonthermal population of electrons in quiescent flare star coronal has been formulated by Holman (1986): if the X-ray emitting coronal plasma is heated by current sheet dissipation, an electric field of about 3% of the runaway field accelerates sufficient nonthermal electrons to account for the observed microwave emission. However, it is not yet clear that the same population of electrons extends to the relativistic energies with sufficiently large fluxes to explain the observed infrared fluxes.

If, in fact, relativistic electrons are present in quantity in the corona of a flare star in its quiescent state, the hypothesis that broadband optical polarization may be due to synchrotron emission (Mullan, 1975) should be re-examined.

The presence of mildly relativistic electrons in the Sun's atmosphere outside flares has been discussed by Chiuderi Drago *et al.* (1987). Quantitative estimates were made of the number density of such electrons (10^{-4} times the ambient number density), and of the magnitude of the electric field required to do so. The electric field is found to be about 5% of the runaway value: this is comparable to the value estimated in flare stars by Holman (1986).

11. Flare Magnetic Fields: Origins?

The final question we ask here is: where do the magnetic fields which give rise to solar/stellar flares originate? Are they produced by a dynamo in the outer convection zone? As far as energetics are concerned, we have already seen (Section 6 above) that there is just enough mechanical power in convection to power the largest solar and stellar flares: the margin is uncomfortably small. Since flare energy release cannot be 100% efficient, it would have been preferable to have, say, one order of magnitude excess of mechanical energy: but our estimates suggest that the convection zone does not seem capable of supplying such an excess. This is not the only difficulty with a convection zone dynamo. (For a summary of difficulties encountered in the Sun, see the article entitled 'The Dynamo Dilemma' by Parker (1987).) In the case of the Sun, the following points can be made.

(a) Helioseismological data suggest that the angular velocity gradient in the convection zone has the wrong sign to make the simplest $\alpha\omega$-dynamo consistent with the observed equatorward drift of sunspots (Duvall and Harvey, 1984). (b) Large flares appear in favored longitudes which persist in solid-body rotation for 20–30 years (Bai, 1988): this suggests that the fields responsible for the large flares are not affected by latitudinal differential rotation (LDR). How deeply into the Sun does the observed LDR penetrate? Duvall *et al.* (1986) find that the surface LDR persists essentially unchanged throughout the entire convection zone. Bai's results, therefore, suggest that the flare fields may originate from below the convection zone. (c) Flare periodicity at about 152 days has now been confirmed in a variety of data sets, showing phase coherence through at least two solar cycles. Bai (1987) argues that the underlying cause of the periodicity involves in some way the entire Sun, although rotational beating of g-modes is not an acceptable explanation. (d) Dicke (1982) has argued that the temporal distribution of solar cycles does not show the random distribution of phases which one would expect if each cycle were due to the appearance of new flux erupting randomly through the surface. Instead, the timing of the solar cycles appears to be controlled by a high-Q oscillator deep inside the Sun. (e) R. Davis and collaborators have reported a possible anti-correlation between solar neutrino flux and sunspot number (e.g., Bahcall *et al.*, 1988): although the statistical significance is rather small, the existence of such a correlation would indicate that surface fields are somehow coupled to the innermost core of the Sun.

In the case of stellar dynamos, it should be pointed out that observations of the Ca K fluxes are now available for about 100 stars ranging in spectral type from F to M. (The sample contains mostly G and K stars: there is only one M dwarf.) Main-Sequence stars in this range show a very large range in the properties of the convection zone, with Rossby numbers spanning a range of about 30. However, when the cycle periods are plotted as a function of Rossby number, they exhibit no systematic behavior whatever (Baliunas, 1986). It seems natural to expect that if the convection zone is the seat of the stellar dynamo, there ought to be a clearly discernible trend in the period as the convection zone properties vary so dramatically along the Main Sequence. Yet such a trend is not apparent in the cycle periods which are currently available.

On the basis of these points, we are led to ask: could the flare fields in the Sun and stars originate in a region other than the convection zone? For example, the core of the Sun may have a large magnetic field (up to 10^8 G) without violating any observational limits on surface oblateness or neutrino fluxes. Dicke (1979) has shown that stars of solar type (i.e., having radiative cores) can have stable magnetic cores provided that the rotation is fast enough to stabilize gravitational perturbations. (The fields must be contained in the nuclear generation regions so that gradients of molecular weight are present.) Perhaps the solar cycle may be modelled as an oscillation of some kind in this core field.

Some years ago (1949–1979), various suggestions were made ascribing the solar cycle to the solar core, but so far, no quantitative modelling of any such model has been produced (cf. Parker, 1987). The recent emergence of arguments against the simplest

$\alpha\omega$-dynamo models in the Sun and flare stars may perhaps spur research activity in such alternative directions. For example, the persistent flare longitudes (Bai, 1988) may reflect preferred axes of the core magnetic field. A displacement of the core field slightly from the equatorial plane could explain why north-south asymmetries are observed in solar activity: thus, of 850 flares observed in 1975, northern hemisphere flares predominate in all categories of flare grouping at greater than 99% confidence level (Wilson, 1987), and solar rotation also shows a long-lasting north-south asymmetry (Bieber, 1988). More than one symmetry axis in the solar core is required to account for distortions in the solar surface (Dicke, 1982), perhaps indicating the presence of a quadrupole field in the core. The presence of a strong field in the core would help to explain why the properties of the Sun along the rotation axis are discernibly different from those in the equatorial plane (Duvall *et al.*, 1986). And if a strong field in the nuclear-energy generating core of the Sun undergoes an oscillation of some sort, the change in local thermodynamic quantities may help to explain the solar-cycle dependence of neutrino emission (Bahcall *et al.*, 1988).

From this viewpoint, we would expect that, as long as a radiative core exists in a lower Main-Sequence star, the core field would survive and drive activity, independent of the properties of the convection zone (as observed). Only when the core disappears altogether would we need to switch to a dynamo action rooted in the convection zone itself. However, we note that the observational signatures, if any exist, of an alteration in emission characteristics at the onset of complete convection are, to say the least, confusing at the present time. For example, the distribution of X-ray luminosity appears to change markedly at $R - I = 1.3$, corresponding to spectral types M2–M3 (Bookbinder *et al.*, 1986), whereas X-ray variability amplitude does not seem to undergo a transition until the spectral class is as late as, or later than, M5 (Ambruster *et al.*, 1987). On the other hand, the chromospheric properties of M dwarfs, as seen in Hα, do not appear to undergo any abrupt changes in nature at the transition to complete convection (Giampapa and Liebert, 1986).

Finally, since a critical rotation must be exceeded to stabilize the magnetic core (Dicke, 1979), we propose that the distinction between dMe stars and dM stars (which rotate faster and slower than 5 km s^{-1}, respectively, cf. Bopp *et al.*, 1981) may give rise to a novel 'rotation-activity connection': we suggest that the dMe stars have been successful in retaining their strong magnetic cores because their rotational velocities are large, whereas the dM stars have been unable to retain such cores.

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