AN OVERVIEW OF SOLAR AND STELLAR FLARE RESEARCH

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Abstract. An overview of the many topics discussed at IAU Colloquium No. 104 is presented as an introduction to the Proceedings. Suggested areas for future research emerging from the conference are summarized.

1. Background

Solar and stellar flare research were carried out in remarkable isolation from each other until the mid-1970s. Solar flares were observed in Hα, and their radio, X-ray, and energetic particle outputs were studied, but until the recent initiation of a white light flare patrol program, only a few dozen white light flares had been observed in over a hundred years of solar observation. On the stellar side an almost exactly opposite situation prevailed: optical flaring was virtually the only observable phenomenon and was a frequent occurrence in the class of UV Ceti-type flare stars, a subset of the dMe and dKe population.

The stellar emphasis shifted considerably with the first X-ray detections of flares on UV Ceti, YZ CMi, and Proxima Centauri in 1974–1975 so that by the time of the 1982 Catania IAU Colloquium, *Activity in Red Dwarf Stars*, space observations of flare stars was an exciting topic. Nonetheless, participation at that meeting was mainly limited to the stellar community. Recently there has been an increase in the number of investigators who actually do research on both sides and in particular, the Solar Maximum Mission seems to have spurred quite a bit of research activity on the stellar side, such as in the application of solar flare magnetohydrodynamic loop models to stellar observations.

This colloquium was the first major meeting to bring together solar and stellar topics and investigators on an even footing. Approximately 200 scientists from 29 countries met for five days at Stanford University, and the following is an overview of what was said and learned in that exchange.

2. Where Do Flares Occur?

Although apparently brought about by photospheric motions, solar flares are primarily a coronal phenomenon involving magnetic structure interactions and reconfigurations. Unfortunately, very little hard data actually exists on the coronal magnetic field. Apart from field line modeling extrapolated from photospheric vector magnetograms, radio observations offer the best possibility at present of measuring field strengths, although this technique is intrinsically model-dependent. Zheleznyakov reported on the detection of radio emission at 1658 MHz interpreted as thermal cyclotron radiation and, using

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a model, a field strength of ≈ 200 G was derived for a coronal loop containing $T \sim 4 \times 10^6$ K plasma.

In the photosphere, a confusing variety of magnetic situations have been associated with flare production: flux emergence, decreasing flux, adjacent increasing *and* decreasing flux. Livi presented evidence that cancellation of flux is the common denominator herein, and that flares are centered around cancellation sites; that is to say, flares occur at or between opposite polarity features that are cancelling. It remains to be seen if cancellation always leads to flares and if the cancellation process can lead to storage of energy for subsequent release as a flare. Another flare-conducive condition is magnetic shear, and the relationship of a sheared magnetic configuration to bipolar cancellation is an open topic. Machado *et al.* (1988) have proposed that a flare basically consists of one bipole impacting one of more adjacent bipoles, with the X-ray emission concentrated in the impacting bipole at the onset; thereafter it may spread throughout the interacting bipole systems, but it does not concentrate at the impact point.

While individual magnetic bipoles on the Sun tend to last for about 2 weeks on average, regions of enhanced and persistent activity last for one to several solar rotations. Gaizauskas emphasized that it is not just the local conditions at the flare site that are important, but that 'multiple structures are involved in the energy release' which are not 'uncoupled from a global background'. This is clear from the many kinds of flare precursors: for example, homologous flares show that flare-producing stresses of similar sort can keep building up over some time and sympathetic flares demonstrate that flare-triggering excitations can travel between adjacent or even remote active regions, and on an even more global scale surviving for several solar rotations, there is the existence of clusters or nests of active region production and superactive regions giving rise to major flares. Unfortunately there is no precursor that *always* predicts a flare.

Progress on the stellar side has accelerated primarily as a result of taking a multi-spectral approach to flare observations, made possible recently by increased instrumental sensitivities and by the dogged persistence of teams of investigators willing to split up and travel to opposite ends of the Earth to simultaneously 'catch a flare' with different instruments. This has paid off slowly but surely though in making plausible physial parameters emerge from what are now many different spectral combinations of data.

On stars, of course, there is very little data concerning magnetic fields, but advances are taking place, in deconvolving field strengths from filling factors using detailed differential intercomparison of profiles (in unpolarized light) of magnetically sensitive (i.e., having a high Landé g factor) and insensitive lines which are otherwise similar in their formation, the so-called 'Robinson technique'; the classical method based on circular polarization line differences used on the Sun fails in the stellar case since, without spatial resolution, the overall north and south polarities cancel out leaving no measurable net magnetic flux to detect. The Robinson-type method has now been used to measure about 50 late-type stars. While this method in principle yields both an average field strength, B, and an average filling factor, f, there are important limitations and challengeable assumptions underlying this application: These were summarized by

Linsky (cf. also Hartmann, 1987). Perhaps the most important problem is that the stellar atmospheric structure is not the same inside and outside of magnetic flux tubes and starspots – sunspots are obviously much darker than the rest of the Sun – and this difference in 'visibility' may account for some of the anomalously high filling factors ($f \approx 0.9$) which have been found. Among the emerging trends noted by Linsky, an important one appears to be $\langle B \rangle \sim \langle P_g^{1/2} \rangle$, which is, however, far from being established at this point.

Concerning the types of stars that flare, as summarized by Pettersen, activity has been reported now along the entire Main Sequence and in many evolved stars, although the reality of a good number of the events may legitimately be questioned, since they are often only a single, weakly observed occurrence; one can also never be sure that the event did not occur on an undetected faint, red companion. Flaring T Tauri stars, and the several hundred flaring objects reported in Orion and in the Pleiades are definitely young; on the other hand, other stars observed to flare are well along in stellar evolution. In close binaries, it is possible that flare-like activity is related to mass transfer. To date, confirmed, solar-like flares have been seen only on stars having outer convection zones. It has been proposed that dynamo processes originate primarily in the radiative core/convection zone interface, suggesting that fully convective stars would manifest little activity. Stars fainter than $L = 3 \times 10^{31}$ ergs s^{-1} ($M = 0.3\,M_\odot$) are fully convective, but Pettersen reports no evidence of a qualitative change in the flaring properties at this important breakpoint; rather he finds a continuous linear relationship between the maximum time-averaged flare luminosity, $\langle L_f \rangle$, for a given class of star (individual stars of a given class vary widely, of course) and the volume of the convection zone V_{conv}. (He claims a similar relation for maximum X-ray luminosity: $L_x \sim V_{\text{conv}}$).

There are now about 80 'classical' dKe/dMe red dwarf flare stars identified. Their ratio of time-average flare luminosity to bolometric luminosity can reach $\langle L_f \rangle / L_{\text{bol}} = 1\text{–}3 \times 10^{-3}$ and including other non-photospheric energy fluxes could result in a ratio on the order of 10^{-2} for the non-photospheric power fraction, whereas in the Sun this is certainly no more than $\sim 10^{-5}$. Mullan speculated that this ratio might climb high enough to alter the internal constitution and equilibrium of these stars from that predicted using standard models. The exact evolutionary status of these stars is uncertain, but in fact they all 'age' quite slowly, the Main-Sequence lifetimes being: $\approx 40 \times 10^9$ yr for a dK5, $\approx 70 \times 10^9$ yr for a dM0, and $\approx 270 \times 10^9$ yr for a dM5, i.e., longer than the present age of the Universe. Among evolved stars, the RS CVn binaries are a growing class of flaring objects, along with mass transfer systems of the Algol-, W UMa-, and FK Com-types. The cluster flare stars tend to be on or near the Main Sequence (cf. Mirzoyan and Ambaryan, 1988, for field and cluster flare star comparisons).

There are significant differences between RS CVn and dMe flares as summarized by Byrne. In general the RS CVn events can be up to two orders of magnitude more energetic than dMe flares; the RS CVn flares are also of much longer duration, with IUE ultraviolet line enhancements lasting up to 7 hours; and flare temperatures, derived from low resolution soft X-ray spectra, are found to be in the range $T = 1\text{–}5 \times 10^7$ K for the dMe stars, but can apparently range up to $T = 10^8$ K in RS CVn flares.

Radio flares have been observed in dMe and dKe stars, in RS CVn systems, pre-Main-Sequence stars and X-ray binaries as reviewed by Kuijpers. While radio emission is small in terms of the flare energy budget, it is of potentially tremendous use as a signature of physical processes; unfortunately, the interpretation of this is very model-dependent. Also, as pointed out by Kundu, while radio flares on RS CVn stars are probably due to a radiative mechanism identified and associated with solar flares – non-thermal gyrosynchrotron emission – flares on dMe stars appear to be due to an as yet unidentified coherent mechanism. Mullan addressed the question of whether the electron cyclotron maser might be the mechanism, and concluded that the requirements for producing this type of radiation are incompatible with stellar flare loop model parameters (which are of course derived from models). VLBI observations imply that the size of the RS CVn radio sources are comparable to the size of the star itself.

3. The Characteristics of Solar Flares

The different 'phases' of a solar flare are partially a problem of semantics, but also a genuine problem of identification and categorization of phenomena that 'always occur' in a flare – given an observation of sufficient sensitivity. Sturrock argued for four phases: (1) an *activation phase*; (2) an *impulsive phase*; (3) a *gradual phase* in which particle acceleration continues to take place; and (4) a *late phase* dominated by soft X-ray emission cooling the hot plasma, although even during this late phase there is likely to be some energy release (continued heating) taking place. Many other researchers however refer to the entire soft X-ray phase as the gradual phase, distinguishing only an impulsive and a gradual phase. On the stellar side, it has only been possible, because of wavelength and sensitivity limits, to observe the late phase in X-rays. However, the phenomenon of negative infrared preflaring could be an important manifestation of pre-impulsive phase activation resulting in the ejection of obscuring prominence-like material. In one study discussed by Gaizauskas, surging arches preceded just over half the observed flares. On the Sun a flare-preceding Coronal Mass Ejection may sometimes involve more kinetic energy than the 'flare itself'. The point is that mass motions caused by magnetic reconfiguration could be the real flare onset, or even the dominant mode of magnetic energy dissipation.

During the impulsive phase, energy release can attain a rate of 10^{30} ergs s^{-1}; moreover the length scales of the process involved are probably well below 1 arc sec (~ 700 km); and the time-scales range down to at least the 10–100 ms regime as shown by hard X-ray bursts. Dennis summarized five possible mechanisms for transporting energy from the corona to loop footpoints: (1) thermal plasma with $T \geq 10^8$ K (i.e., so-called thermal model); (2) fast electrons with energies ~ 10–100 keV (i.e., so-called thick-target model, and at present the most 'popular'); (3) relativistic electrons; (4) protons with energies ≤ 1 MeV; and (5) protons with energies ≥ 1 MeV, the distinction between (2) and (3), and (4) and (5), relating to different resultant X-ray production mechanisms. The thick-target model in which electron beams produce heating and X-ray bremsstrahlung has been the most successful to date, although proton beams with energies of ~100–1000 keV are being seriously investigated as an alternative; both linear polarization of chromospheric lines and a red-shifted Lα line are predicted from this mechanism.

Thick-target interacting electron beams heat efficiently: the ratio of collisional losses to X-ray bremsstrahlung is $\sim 10^5$. On the other hand, due to the much lower energy per particle, heating by electron beams of necessity involves more particles, hence, more charge, than proton beams; and this means that such collective processes as, for example, a neutral return current need to be dealt with in that case. (Such a current can even arise in the case of conduction if a sufficiently intense heat flux is required; in which case classical conduction conditions no longer apply.) Yet another point is that the number of electrons accelerated exceeds the number initially in the coronal loop: where do they come from?

During the impulsive phase γ-rays are also observed and their spectra consist of: electron bremsstrahlung, nuclear lines, and pion decay emission, with the nuclear lines dominating in the 1–10 MeV range. The SMM γ-ray spectrometer (GRS) has observed over 150 flares as discussed by Rieger; the Japanese Hinotori satellite also observed solar flare γ-rays. An important observation is that the majority of γ-ray flares are seen at the limb; this supports the thick-target electron beam impulsive phase model since bremsstrahlung radiation is anisotropic and for an electron beam impinging vertically on the lower atmosphere, there would be a greater likelihood of seeing the resultant bremsstrahlung out the side (~90°) of a limb flare than back out the top (~180°) of a disk flare. (Compton scattering destroys this effect for hard X-ray bremsstrahlung.) Evidence for such a directivity also comes from analysis of 'stereoscopically observed flares' using ISEE-3 in conjunction with Pioneer Venus and from the determination of an apparent systematic increase of GRS flare luminosity toward the limb. Unfortunately, while the above observation fits nicely into a concept of beam heating, another γ-ray observation is puzzling: the fact that γ-rays attributed to pion decay persisted for 30 min following a 65 s impulsive phase flare indicating that ion acceleration somehow continued long after the impulsive phase in that event.

Four intriguing SMM results are: (1) that non-thermal broadening of soft X-ray lines indicative of random mass motions often takes place before the impulsive phase; (2) during the impulsive phase blue shifts appear (in 80% of BCS-observed M- and X-flares) provided that there is a high enough signal to temporally resolve this short-lived event; (3) blue-shifts of this sort are absent for flares past 60 deg in longitude; and (4) the densities derived from line ratios are in general much higher than those derived from emission measures, implying very small filling factors and, hence, very filamentary magnetic structure. These results could be mutually consistent if preflare activation is a process of many magnetic reconnections taking place in numerous adjacent filamentary loops, with this eventually leading to chromospheric evaporation and, hence, directed upflows into the now heated loops. Maximum upward velocities may reach 1000 km s^{-1}.

The soft X-ray phase typically manifests plasma temperatures, $T \approx 15\text{–}20 \times 10^6$ K. Early on it was thought that the time integral of the hard X-ray light curve equalled the current value of the soft X-ray light curve, which would imply that all energy input occurred in the impulsive phase with relatively slow eventual loss via soft X-ray cooling, but, in fact, the evidence for post-impulsive phase continued heating in many flares is now considerable.

Pallavicini, Serio, and Vaiana (1977) introduced the concept of two distinct types of flares: (1) small compact events ($E \sim 10^{30}$ ergs) on a short time-scale ($t \sim 10^3$ s) thought to occur in one or more loops without disrupting the basic magnetic configurations versus (2) more energetic ($E \sim 10^{32}$ ergs) and longer lived ($t \sim 10^4$ s) two-ribbon flares involving disruptive opening up of magnetic arcades. Švestka called these *confined flares* when the late phase involves only cooling and *dynamic flares* or *long-decay flares* when there is continued energy release. These categorizations are basically the same as the compact versus two-ribbon types, bearing in mind that *most* compact flares involve more than just a single loop, although there are, according to Švestka, indeed a few good single-loop flares. On the other hand there are flares which fit neither of the categories, or which show characteristics of both. Of course, many 'single-loop events' prove to be anything but simple when other diagnostic data in addition to images are available: Švestka cited examples in which filling factors may be as low as 0.01, indicative of highly filamentary structure, and other cases which clearly indicate the presence of both hot (10^7 K) and cool material (10^4 K) in the same flaring region – also a likely sign of filamented structure.

Dröge found that these two categories of flares can be distinguished by their electron energy spectra as measured *in situ* by spacecraft outside the Earth's geomagnetic field. The long duration events (two-ribbon flares presumably) give rise to electrons having a single power-law exponent in their ~ 0.1–100 MeV spectra suggesting a single acceleration mechanism; flares lasting < 1 hr generate more complex electron distributions.

The opening up and reconnection of field lines that makes a two-ribbon, or even 'n-ribbon' flare, is an important physical process that may go on for hours releasing energy and creating huge post-flare loops; soft X-ray loops grew for 11 hours in one Skylab event; HXIS observed similarly long-lived giant X-ray arches. Moreover, during this long period there must be continuous input of material from the footpoints to fill the loops, which means that there must be considerable heating at the footpoints to evaporate material into the coronal loops. Blue shifts indicating upflows on the order of 0.5–10 km s^{-1} have been observed which could supply the 10^{16}–10^{17} g required to fill dense ($n_e \sim 10^{12}$ cm^{-3}) post-flare loops; and in between the ribbons, redshifts indicative of cooling, falling matter have been observed. As the loops cool, they are also observed to shrink in size.

Mass motions associated with flares rarely exceed velocities of 20 km s^{-1} in chromospheric elements, but in the corona there is a wide range of velocities from, say, 20–2000 km s^{-1}. Martin placed the dynamic coronal components of flares into the following categories: erupting filaments, expanding clouds, flare-loops, flaring arches, and surges. Although involving material in the low corona, all of these are observable in Hα. Švestka pointed out that there are several examples of flares in which analysis shows that thermal energy in the late phase has gone more into mass motions rather than radiation or conduction. It has been proposed that Coronal Mass Ejection is a propagating compressive response to a flare; however the CME-flare relationship is not yet clear, and an up-to-date commentary on this issue may be found in Harrison and Sime (1989).

4. The Optical or White-Light Flare

In the dMe stars, optical flares are dominated by blue continuum radiation best seen in the *U*-band where the contrast with the photospheric continuum is greatest; *U*-band flares can be as bright as $\Delta U \approx 5$ mag. The general trend is for Balmer line enhancement to precede a continuum rise, but once started the continuum dominates over lines (H, He, Ca II) in the *U*- and *B*-bands; then after the continuum fades out, the enhanced emission lines remain prominent for some time. Overall, though, most of the energy is in the continuum. Bolometric energies involved can exceed 10^{37} ergs, although this is rare and from flare colors one infers, $E_{\text{bol}} \approx 6 \times E_{\text{opt}}$ and $E_{\text{opt}} \approx 3\text{–}5 \times E_U$. Other approximate relationships for stellar flares are: $E_{\text{opt}} = 10 \times E_{\text{Balmer}} \approx 30 \times E_{\text{H}\alpha}$. For the dMe stars, approximately equal amounts of energy are emitted in X-rays, the UV and the optical continuum. Tuominen reported on past and present efforts to detect polarization changes during flares, but to date no conclusive flare-related polarization effects have been measured.

There are tight correlations among flare contributions by the Balmer lines, chromospheric lines (Mg II), transition region lines and X-rays which, according to Shakhovskaya, do not depend on the energy of the individual flare nor upon the star. The following important statistical relation has been noted: a relation between optical flare energy and flare frequency which appears to be a power law for both the Sun and dMe stars: $\nu(E) \sim E^{\beta}$ with $\beta \approx 0.4\text{–}1.4$.

On the Sun, the white-light flare (WLF), reviewed by Neidig, represents the most extreme conditions found in flares and is the solar analog of the classical stellar flare. WLF emission appears as bright patches, waves or ribbons often containing brighter kernels ($< 3''$) and about 15 yr^{-1} are now seen using a small aperture patrol telescope. WLFs are probably not a special class of solar flare, rather just a matter of detection threshold: a GOES M2 flare or stronger in a large, active region would likely show white light flare kernels. WLFs are 'blue' like stellar flares, this due to Balmer continuum, at $T_{\text{eff}} \approx 10^4$ K, and the appearance of many short wavelength lines. The largest recently monitored WLF had peak power, $P = 2 \times 10^{29}$ ergs s^{-1} and $E > 3 \times 10^{31}$ ergs, which, however, is still 10^{-3} times fainter than the brightest of stellar flares. In the bright kernels of WLFs, optical continuum radiative losses exceed those in optical emission lines; in one case, $P_{\text{cont}} > 60 \times P_{\text{H}\alpha}$; allowing for other emission lines leads to the conclusion that perhaps 90% was continuum emission for this event. Filling factors are still unknown, of course and even a properly calibrated WLF spectrum has not yet been taken.

The WLF appears to originate above the $\tau = 1$ level, in the upper photosphere and/or chromosphere. Hydrogen recombination is responsible for much of the emission in flares showing Balmer jumps, and in flares of this type, $n_e > 10^{13}$ cm^{-3}. Some WLFs do not show Balmer jumps and in those cases the emission might be attributed to free-free, Paschen recombination or H$^-$ emission. The huge radiative losses of WLFs poses a major problem to mechanisms of energy transport: conductive heating from the corona would require such high temperature gradients that the emission measure in the WLF temperature interval would be too small; irradiation by soft X-rays is not feasible since $L_z < L_{\mathrm{opt}}$.

Thez WLF power tracks the hard X-ray emission and this is the basis for theoretical investigations by Aboudarham and Henoux into how electron beams can bring about enough non-thermal hydrogen ionization – primarily in the low chromosphere – to account for the white light emission via recombination in the Paschen continuum. Further down in the atmosphere, at the temperature minimum and upper photosphere, the temperature is increased by about 240 K due to radiative heating by chromospheric continuum radiation, and as a result, n_e is increased leading to a significant increase in the H$^-$ population. Overall, these models show that white light emission can be explained by electron bombardment, but heating the upper photosphere directly by the electron beam is out of the question since $E > 900$ keV electrons would be necessary to penetrate to this depth.

Mullan addressed the issue of whether electron beam heating could also explain the properties of the stellar optical flare. In his analysis, the electron beam peaks in energy at ~ 20 keV, and the question then is whether there is enough energy flux of 20 keV electrons to penetrate effectively to the chromospheric level; there is a discrepancy in the assumed conditions for this analysis, since Aboudarham and Henoux showed that only $E > 70$ keV electrons actually reach the solar chromosphere. An 'electron beam flare' would also produce strong Hα Stark wings, whereas a beam stopped in the corona but creating a thermal conduction front propagating into the chromosphere, a 'thermal conduction flare', would have no Stark wings nor central reversal. Conditions on the Sun could go either way, but using the Proxima Centauri flare loops deduced by Haisch (1983) as an examplar, Mullan found that a 20 keV beam would not penetrate to the chromospheric level.

5. The Question of Microflaring

A major issue today is whether flaring and microflaring account for the heating of solar and stellar coronae. The balloon observations of Lin *et al.* (1984) are usually cited as an observational basis, since they were the first high resolution (~ 11 keV), hard X-ray (≥ 20 keV) detections of events having peak fluxes 10–100 times lower than normal flares at a rate (at least during the 141 min observing window) of once every 5 min somewhere on the Sun. However, related observations go back to *Skylab* in which the solar transition region shows continual small-scale activity as identified by Emslie and Noyes (1978) in EUV bursts seen simultaneously in several lines spanning the temperature range from the chromosphere to the corona. Bruner and Lites (1979) observed transient, red-shifted brightenings – such as intensity increases by as much as a factor of 5 in less than 30 s – in the transition region C IV line above active regions and sunspots by using the OSO-8 spectrometer, and these were subsequently also seen in HRTS spectra (Dere *et al.*, 1981). The SMM–UVSP has observed such burst activity in detail (Porter, Toomre, and Gebbie, 1984), and stochastic fluctuations were found on time-scales of a minute or less. Athay (1984) analyzed C IV enhancements in an active region, finding order-of-magnitude increases in the intensities along with high velocities during the rise phases. There also seem to be density enhancements during such bursts (Hayes and Shine, 1987). Moreover, bursts are not confined to active regions; Nishikawa (1986) found time-varying EUV sources in *Skylab* spectroheliograms of quiet-Sun network and cell interiors. Porter *et al.* (1987) showed that C IV brightenings in the quiet Sun occur directly over the neutral lines of small magnetic bipoles that, on the basis of 10830 Å dark point correspondences, are *possibly* X-ray bright points. These brightenings occur mostly in the network but sometimes in the cells. Individual impulsive brightenings have lifetimes of ~ 10–40 s either as isolated events or as repeated fluctuations at a single site. Most recently, Haisch *et al.* (1988) actually observed the soft X-ray fluctuations in large active region coronal loops which, based on their size, ought to be the archetypes of steady, large-scale structures.

In Parker's view, flares, microflares and the X-ray corona all result from the same process: magnetic neutral point reconnection. Waves cannot heat the corona since there is no correlation between brightness and size of coronal structures as one would expect: the theoretical expectation is that the smaller the region, the smaller the fraction of the wave-power spectrum to do the heating... and this is not seen. Attention has focused on the continuous random displacement of loop footpoints by granular motions as the likely driving mechanism of coronal heating. The key point is that with the gas pressure being $\sim 10^{-2}$ of the magnetic pressure, any non-potential field must be force-free, i.e., $\nabla \times \mathbf{B} = \alpha \mathbf{B}$, but although α must be constant along a given field line, the physical helicity randomly goes in both directions and so 'internal tangential discontinuities develop across which the magnitude of the field is continuous but the direction changes discontinuously' and this results in dissipation, the characteristic scale of which Parker estimated from the characteristic scale of the footpoint shuffling process to be $\sim 10^{24}$ ergs, which he has labeled a *nanoflare*. In this view, a continuous succession of nanoflares produces the general glow of the individual X-ray loops. Moreover, it appears that a burst of reconnection may occur when a critical level of discontinuity is exceeded; the typical flare is then seen as a 'coordinated burst of nanoflares throughout a finite volume of field'. An important point is that while there may be a triggering site – probably where two loops interact – most of the energy released appears to come from throughout the loops involved. The closest we have come to seeing nanoflares is perhaps in the $\sim 10^4$ decimetric spikes of $\sim 10^{26}$ ergs each observed (cf. Dennis' article) during some impulsive flares.

On the stellar side, it has been shown that there is a relationship between mean optical flare power and X-ray luminosity and this has been invoked by a number of investigators (present author included) as evidence that flaring is the source of coronal heating. Shakhovskaya pointed out that the flare power-frequency relation is relevant to this argument in that the microflaring (small E) end of the $\nu(E) = E^{\beta}$ relation will only contribute a small additional fraction (say 10%) to the observed $\langle L_f \rangle$ for the many stars having a relatively large β, which may not be enough to bring the ratio $\langle L_f \rangle / L_x$ up to unity. The problem is, of course, that neither $\langle L_f \rangle$ nor L_x are very precisely determined; moreover in the case of L_x the measurement only refers to a single epoch in virtually all cases and it is well established that the Sun varies by an order of magnitude in L_x over its cycle.

Interestingly, just as observations of the phenomenon of microflaring on the Sun are increasing in number, the stellar microflaring case is suffering some observational setbacks, one of which was presented at the conference by the Crimean Astrophysical Observatory group. They used the Soviet 6-m telescope in a mode which gave them the arrival time of each photon with a precision of 5×10^{-8} s; claiming a temporal resolution on the order of 3×10^{-7} s, they find no evidence of *optical* microflaring in timescales of 10^{-6}–10^{-1} s. However, Tovmasyan and Zalinyan (1988) have published observations of flares lasting less than 1 s. Then there is the conflicting evidence for a general level of variability in the X-ray flux of dMe stars: Ambruster, Sciortino, and Golub (1987) find evidence of such microflaring-like behaviour in Einstein observations; Collura, Pasquini, and Schmitt (1988) find no such evidence in Exosat observations! On the other hand the sought after solar analog of the stellar X-ray microflare – fluctuations of sufficient degree in soft X-ray flux to be observable if the Sun were an unresolved point source at stellar distances – has recently been found in the temporal variation of the large active region loops observed by Haisch *et al.* (1988) with SMM.

6. Theoretical Questions

Helioseismology now indicates that there is little or no vertical gradient in the solar angular velocity, Ω, which undermines the foundation of the $\alpha\omega$ dynamo concept; Ω varies primarily with latitude, and this together with the helicity of the convection generates vertically propagating dynamo waves which can still lead to bands (2–4×10^5 km wide) of azimuthal field (3–10×10^3 G) moving along the bottom of the convection zone (2×10^5 km). A new effect identified recently by Parker is that such bands obstruct upward convective heat transport resulting in 'cool shadows' above the magnetic bands which in turn suppress the magnetic buoyancy. Underneath each band there is an accumulation of heat, however, which may via the Rayleigh–Taylor instability locally initiate thermal plumes buoyant enough to penetrate to the surface and thereby create active regions. This still does not explain why the field is so intensely concentrated into finely structured loops in which flares originate above the surface. The explanation of that may lie in the fact that such field concentration may represent an energy minimum condition, in that there is less obstruction of convective heat transport if the same amount of magnetic field is compressed into discrete fibrils than uniformly distributed. The physical mechanism for achieving this could be downdrafts in the fibrils. It appears likely at this point that the concentration of field into fibril structures is a near-surface phenomenon.

Having established (perhaps) how magnetic flux concentrations originate below the solar surface, their extension into the solar atmosphere and their energy-releasing interactions therein are the next considerations. In the solar atmosphere, magnetic reconnection at current sheets or in current-carrying arches is thought to be the mechanism responsible for the rapid release of energy. Two key questions are: (1) How are magnetic fields stressed on time-scales of hours to days and spatial scales ranging from network magnetic elements to complexes of activity; (2) which instability finally sets in to release some of this built-up energy? Sakurai discussed these issues and especially the difference between the termination of an equilibrium sequence in which the resulting perturbation is uni-direcitonal and an explosive instability in which the new configuration which a system moves toward is determined by initial infinitesimal perturbations. While the concept of 'loss of equilibrium' resulting in magnetic field eruptions is appealing, Sturrock argued that this does not, in fact, occur; he has found that 'the magnetic field develops in a well-behaved manner and shows no evidence of catastrophic behaviour'.

Coronal mass ejections could result from a purely MHD instability resulting from lengthwise shearing of the 'quonset hut' magnetic arcade spanning a neutral line. Beyond a critical shear, the field energy exceeds that of a configuration in which the field lines extend to infinity, and this results in a jump from the closed sheared to the open potential configuration. Coronal gas is ejected outward with the expanding field. Moore presented results showing that the decrease in the volume-integrated, filament-traced magnetic field appears to agree well with estimates of the total flare/CME energy suggesting that magnetic expansion is the primary source of energization.

The next question after that of energy release is, of course, 'How is this energy converted into particle beam acceleration?' and this question was addressed by both Cargill (who gave the invited presentation of Vlahos) and by Rieger. Vlahos pointed to three critical observations that suggest 'new thinking' on particle acceleration and transport in solar flares: (1) the hard X-ray microflaring discussed above; (2) short duration (≤ 100 ms) radio spikes in the 200–300 MHz band; and (3) the timing and duration of γ-ray observations. The excellent temporal correspondence between γ-rays and hard X-rays at the outset of the impulsive phase demonstrates that in a single step electrons can be accelerated impulsively to ~ 100 MeV. The explanatory requirements for any acceleration mechanism are thus several: it must account for the proper electron and proton acceleration time-scales, particle energy spectra, correct ratio of particles, and it should have a properly high efficiency (or else another energy sink or channel would need to be identified). Overall it appears that particles are accelerated to all energies almost simultaneously.

There are three generic types of particle acceleration mechanism: coherent, Fermi or stochastic, and shock wave. The first of these can result from the action of a DC electric field or a narrow band electromagnetic wave; the electric field can appear from magnetic reconnection or from double layers. Stochastic acceleration can result from Alfvén waves having wavelengths on the same scale as the particle gyroradii. The shock wave theory combines coherent and stochastic elements. None of these are yet 'on firm ground'. Vlahos and Cargill have explored the interesting consequences of many small, localized energy releases in a highly structured (fibrous) corona: nonlinear particle and shock interactions will heat and/or accelerate particles over a much larger volume. They emphasize the consequences of such global coupling and urge a de-emphasis on the single loop model.

7. Hydrodynamic Models

Hydrodynamic models have been developed which simulate the response of plasma confined within a rigid loop when subject to heating having a given temporal and spatial profile. Such models represent the thermal phase of compact flares in other words. These models are, of course, not restricted to the simple analytical approximations of purely radiative or purely conductive cooling. (Conduction really just redistributes the energy to some other place where it usually winds up being radiated away.) Peres described an application of one such model, which was first applied to SMM observations specifically to the light curves and time histories of the line profiles of soft X-ray lines. Such analysis can model the secondary effects of a flare – plasma motion, hard X-ray impulsive response, soft X-ray late-phase light curves, line profile responses – but not specifically address the primary causes of a flare. Such a model can be applied to a stellar flare X-ray and temperature light curve (but cf. below).

Poletto showed that a reconnection model of two-ribbon flares developed for interpretation of solar SMM data could be also successfully be applied to stellar X-ray light curves. In her model, the open magnetic field created by an eruption closes back to a lower, potential energy state; reconnection occurs at progressively higher levels in the corona corresponding to the rising post-flare loops. The time profile of the magnetic energy release is then compared to the X-ray light curve. An Exosat-observed flare on EQ Pegasi was interpreted in this way, although a major uncertainty is exactly what fraction of the released magnetic energy goes into the prolonged soft X-ray emission and how this fraction might change throughout the course of the flare.

Unfortunately neither of these analyses is unique: the X-ray event the author observed on Proxima Centauri with Einstein (Haisch *et al.*, 1983) has since been successfully modeled both ways!: as a compact event by Reale *et al.* (1988) using the hydrodynamics simulation and as a two-ribbon event by Poletto, Pallavicini, and Kopp (1988) using their reconnection model! On the other hand, Schmitt presented a very reassuring result relating to stellar flare analysis: he analyzed a *solar* flare observed by Einstein via X-ray scattering from the Earth's upper atmosphere, analyzed it as one would an unresolved stellar flare, and then checked that analysis against SMM observations of the same event. In general, the basic physical parameters derived from the spatially unresolved IPC observation were verified.

Antonucci reviewed high temperature solar flare diagnostics and showed that significant spectral differences are predicted by different heating functions in the compact loop model, but because of count rate limitations of the SMM, these rapidly changing signatures cannot yet be satisfactorily resolved. Thus even on the Sun, with its high flux, time resolution is still a major limitation for identifying the initial processes of a flare.

As for the very concept of a flare loop model, the above notwithstanding, Emslie said forthrightly: '...the assumption of an isolated, rigid, unyielding, non-evolving field structure is a highly questionable one.' For example, gas pressures during a flare *can* reach ambient magnetic pressures; heating mechanisms *can* act primarily on electrons or, conversely, ions, etc.

8. For the Future

The following potpourri that emerged during the conference is offered as a collection of possibly useful ideas and hopefully stimulating suggestions.

Foing suggested a number of areas in which improved observations of stellar flare spectra can be expected to address specific outstanding problems of flare physics. For example, high time-resolution observations of Hα line profiles during the impulsive phase should be able to distinguish signatures of electron beam heating, proton beam heating and conductive heating. Major profile changes have already been measured: extremely broad Stark wings have been seen in some of the Balmer lines along with pronounced red asymmetries, and this is consistent with an electron beam-induced pressure wave propagating down into the chromosphere; Mg II line shifts have also been observed, but while the Ca II lines brighten they appear to not otherwise be significantly altered. Better high time-resolution observations should result in valuable new diagnostics.

Recently Canfield *et al.* (1987) evaluated the equality of upward momentum (derived from blue-shifted soft X-ray lines) and downward momentum (derived from redshifted Hα) in solar flares and found a rough equality. Mullan attempted to make similar arguments for stellar flares, but for lack of simultaneous data was forced to do this using heterogeneous observations. A significant discrepancy emerged: namely that the downward momentum appeared to exceed the upward momentum by as much as five orders of magnitude.

The measurement of electron densities at various temperatures using line ratios during flares has been attempted with IUE, but using HST this could become a powerful tool, since this will allow the derivation of stellar flare volumes.

IRAS data indicate that unusual infrared excesses may be present in the quiescent dMe spectrum. Mullan suggested that this could be a signature of synchrotron radiation suggesting the presence of relativistic electrons even in the quiet coronae of dMe stars.

It was proposed by Rao that the impulsive component of some 'superflares' has indeed already been observed – in the form of cosmic γ-ray bursts, and that the corresponding late-phase has been observed in the form of 'fast-transient X-ray' (FTX) events observed during the Ariel V and HEAO-1 sky surveys. Such superflares would be extremely energetic, 5–7 orders of magnitude beyond a solar flare, and he proposed that they take place in the inter-star region of an active binary.

Schmitt suggested using microwave bursts as proxies for the extremely faint expected stellar hard X-ray impulsive phase emission.

It appears that the transition region differential emission measure should decrease in response to conductive flare heating, since a steepening temperature gradient requirement more than compensates for the transition region 'moving to lower levels in the atmosphere'. But since UV line fluxes rise along with the hard X-ray burst and such bursts have also shown evidence of being co-spatial (UVSP and HXIS), this argues for electron beams as the preferred heating mechanism. Should we ever be in a position to observe stellar hard X-rays (perhaps by proxy as suggested above), such a UV/hard X-ray (anti-)correlation would be a diagnostic of the stellar flare heating mechanism.

Regarding the underlying origin of flares, Bumba and Hejna examined the large-scale distributions of magnetic field on the Sun and found a correlation of enhanced flare activity with the redistribution of global magnetic fields. They raised the possibility that the accumulation of magnetic energy in the coronal field configuration may be less important than direct input of magnetic energy into the atmosphere from below for flare production.

The question of periodicity in occurrence of flares is still wide open; there are conflicting claims. Finding a stellar analog of the 152-day solar periodicity would be an important discovery.

Zirin has stated that 'all flares are associated with filaments'; Sakurai discussed how a magnetic island formed in an arcade may undergo explosive kink instability, or, in observational terms, filament activation. The relationship of the evolution of the prominence magnetic field *and* the role of the cool material itself is an important area of future research. In the stellar case, negative, pre-flare dips in the photometry together with simultaneous high time-resolution line spectrometry may be the key to observing the mass motions that accompany/trigger a flare.

Establishing a relationship between change in magnetic energy of a flaring volume with the energy of a flare would be a tremendous step forward; to date only a qualitative relationship has been established, for example, the untwisting of chromospheric fibrils.

The possibility of spatially resolving flare sources using very large baseline interferometry is an exciting prospect; exploratory efforts have been carried out on RS CVn systems using microwave VLBI.

Although the flare is believed to be energized by magnetic reconnection, the alternative of double-layer formation should be considered.

Since the magnetic Zeeman broadening increases as λ^2, perfecting and using the Robinson technique on infrared lines holds much promise for observing B and f on stars.

9. Concluding Remarks

Having discussed these many new, exciting, and even exotic measurements and theoretical models, it is worthwhile to return for a moment to classical solar Hα observations, as reviewed by Martin in her article on mass motions, since practically all aspects of a flare manifest themselves in some way and at some time in Hα. There are several parting thoughts worth keeping in mind, since they clearly exemplify the complexity of 'real flares': (1) Chromospheric flares consist of a succession of elementary localized brightenings which shows that the chromospheric flare elements are individual sub-arc sec structures. (2) These fine-scale strutures evolve at different rates and with different phases, so that even in the 'overall' decay phase, newly forming chromospheric flare elements can appear; this points out a real problem in defining flare phases, because a whole flare does not form simultaneously. (3) Remote brightenings can take place up to a few × 10^5 km from the primary flare site, and this demonstrates the long distance interconnectedness of magnetic structure. (4) Surges show material rising, stopping and falling back down, which is what one would expect for material confined by magnetic flux tubes, but the downflow is not always along precisely the same path as the upflow which probably demonstrates that the magnetic field can change significantly on this time-scale. (5) Flaring arches are similar to surges but appear to show a clump of material flowing upward, traversing an arch-like path, and descending to another point in the atmosphere, and this shows that material can indeed flow from one end of a loop to the other.

It is impossible to obtain observations of this sort for stars, but as summarized in the review by Burne, significant progress is being made in measuring mass motions associated with stellar flares through high time-resolution spectroscopy. Especially in the dMe stars, flare lines stand out prominently in the spectrum above the emission from the rest of the star, and so new high-technology techniques for obtaining time-honored spectral information hold considerable promise.

This was a highly productive conference, and I have no hesitation in saying that the four years (!) of preparation and planning by myself and my colleague, Prof. Marcello Rodono, that brought it about were well worth it in the end. Two themes clearly emerged: (1) the key to progress in flare research lies in a multispectral approach with as much temporal and spectral resolution as the photon fluxes allow; and (2) the key to understanding the physics lies in a dynamic interaction between solar and stellar investigations and investigators.

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