STELLAR FLARE SPECTRAL DIAGNOSTICS: PRESENT AND FUTURE*

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Abstract. Stellar spectral diagnostics are of utmost importance to test fundamental concepts of flare physics such as particle beam versus suprathermal heating, atmospheric response, mass motions, microflaring, statistics and recurrence of flares, flare activity and stellar interior. We review some of these diagnostics (from photometry, optical, and ultraviolet spectroscopy at medium- and high-spectral resolution, X-ray, and radio observations). Specific diagnostics from line and continuum fluxes, density sensitive lines, broadening and velocity field effects and the comparison with semi-empirical models are also described.

Some results on stellar flares obtained from previous multi-wavelength observing campaigns are presented. Future satellite missions and ground-based observatories, with new techniques for obtaining high spectral and temporal resolution, are discussed in light of their possible contribution to our understanding of solar and stellar flares.

1. Fundamental Scientific Issues

The advent of new satellites and large ground-based telescopes with increasing sensitivities, spectral resolution and time resolution will allow us to obtain spectral data of solar quality on stellar flares. These new stellar flare observations, in addition to the data gathered over the last 10 years, will provide a deeper understanding in several fundamental areas.

1.1. Energy transport mechanism: particle beam vs heat conduction

Two types of theories have been proposed to explain how the flare energy, which is released in the upper corona by magnetic field reconnection, is transported down to the lower layers; these theories assume either beams of energetic particles or thermal conduction. Different predictions come from these theories: Brown (1971) gives the absorption coefficient of an electron beam according to the energy per electron. Therefore, depending on the penetration length, electrons of a given energy (e.g., 20 keV) can reach the chromosphere, transporting significant energy and producing a detectable signature, for example in Balmer line wings. If the electrons are stopped in the corona, thermal conduction is then required to transport most of the energy downwards. These analyses have been refined in order to take into account non-classical Coulomb effects and the role of currents and wave-particle interaction. Emslie and Nagai (1985) predict a different temporal evolution of transition region lines by the two mechanisms, which can be checked observationally using far UV and extreme UV spectroscopy.

Canfield and Gunkler (1985) have calculated Hα enhanced wings as a signature of

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nonthermal electron beams during the chromospheric evaporation phase. These predictions require a test with high-resolution spectra and sufficient time resolution.

Heritschi *et al.* (1989) have discussed how proton beams seem better able than electron beams to explain solar flare observations in a more physically consistent way. Hénoux (1989) showed that the observed polarisation in the Hα line tends to also favour the role of protons. All these aspects require observational checks with high time resolution during the stellar flare impulsive phase.

1.2. Atmospheric response to flares

In order to constrain our knowledge of flare physical quantities such as the overall energy budget, density and volumes, it is necessary to observe the atmospheric response to stellar flares. The spectral energy distribution and decay time-scales reflect the atmospheric parameters. In this respect, solar white-light flares are relevant, but cooler stars provide a low photospheric background against which the flare signature can be seen with high contrast. In addition, rapid rotation and deep convection zones in some stars lead to efficient magnetic field generation and to frequent and energetic flare activity. Stellar flare studies require high speed photometric and spectroscopic observations from the ground, and simultaneous multi-wavelength coverage from radio observations and satellites at higher energy (X-ray, UV).

On the Sun, flare diagnostics from accelerated particles observed at 1 AU, γ-ray and hard X-ray radiation contain very valuable information. The energy carried away by ejected material and accelerated particles may in fact dominate in the solar flare energy budget.

In the stellar flare case, particles, γ-rays, and hard X-rays are unobservable with available instruments. For hard X-rays, a collecting area equivalent to a soccer field was quoted (Schmitt, Lemen, and Zarro, 1989) for detecting solar-like flares on nearby stars. However, as hard X-rays arise mainly for bremsstrahlung emission by high-energy electrons, gyrosynchrotron radio emission may provide a proxy for the characterisation of these particles.

Soft X-ray flare measurements have been obtained using the Einstein and Exosat satellites; they have permitted us to measure the X-ray luminosity, temperatures, time-scales, and overall X-ray losses, which can constrain loop models to provide lengths and electronic densities (Haisch, 1983).

Ultraviolet observations obtained with IUE permit emission measure analysis of the transition region plasma; also line ratios can provide density diagnostics, and UV continua provide information on the chromospheric temperature structure during flares.

Optical observations show the response of different continua, hydrogen Balmer and Paschen series lines, and lines formed at higher excitation temperatures or by different processes (collisional, photo-ionisation, photo-excitation).

Infrared measurements, such as those obtained by Rodonò *et al.* (1984) showing the first detection of a 'negative infrared flare', can provide constraints on theories predicting changes in the H^- opacity, or inverse Compton effect of relativistic electrons on IR photons.

Radio observations, once we have identified the emission/absorption mechanisms (gyrosynchrotron, self-absorption, ...) will give information on magnetic field intensity and geometry, and on the electron beam parameters, especially with the advent of dynamic radio spectra observations (Bastian and Bookbinder, 1987).

Different solar flare models have been developed by Machado *et al.* (1980), Damé and Cram (1983), Aboudarham and Hénoux (1986), and Avrett, Machado, and Kurucz (1986). They allow us to estimate where in the atmosphere the radiation at a given wavelength comes from and to quantify some open issues. What are the heating processes? How can we derive a complete energy budget from the available X-ray, transition region line, and optical studies? How can we derive densities, volumes, and temperature regimes of the flaring plasma? What do the time-scales (rise and decay at different wavelength) tell us about the dynamics of flares and atmospheric properties? All these questions require simultaneous multi-wavelength observations.

1.3. Mass motions, ejected components, and momentum balance

Solar observations from SMM (Antonucci *et al.*, 1982, 1984) show the presence of Ca XIX blueshifts of the hot plasma during the impulsive phase, suggesting a chromospheric evaporation scenario. Simultaneous Hα redshifts as studied by Zarro and Canfield (1989) confirm this interpretation and indicate a momentum balance between the evaporated material ejected at a velocity estimated from these blueshifts and the compressed chromospheric Hα material. There is no chance to measure such XUV line blueshifts on stars, but stellar Hα redshifts should be observable. An indirect diagnostic of the 'well' area where impulsive explosions occur is possible from photometry (de Jager *et al.*, 1986, 1989). From these observations, one can test whether this scenario of chromospheric evaporation and impulsive phase explosion and corresponding momentum balance applies.

Evidence of filament eruption as obscuring material has been reported by Haisch *et al.* (1983) to fit X-ray spectral data during a flare on Proxima Centauri. Rodonò *et al.* (1979) have reported negative preflare dips from optical light curves, indicative of ejected material obscuring the disk. Hénoux (1988) studied this effect, calling it a black and white flare in analogy with the effects of Scotch whisky. Collier-Cameron and Robinson (1988, 1989) observed in the star AB Dor that such ejected material can be traced from its velocity-varying absorption in Hα when these clouds transit over the visible disk, and they developed a method of cloud imaging from time-resolved high-resolution spectroscopy.

Mass motions can be studied from their Doppler effect in line profiles, such as the Mg II line wing broadening reported during a flare on the star UX Ari (Simon, Linsky, and Schiffer, 1980). Linsky *et al.* (1989) and Neff, Brown, and Linsky (1989) reported IUE observations of a flare on V711 Tau showing observable shifts and broadening in the Mg II and C IV lines. A blue-shifted emitting Hα component suggesting a rising material during a flare was reported on UV Cet. Also, Doyle *et al.* (1989) reported Balmer line broadenings, which may be interpreted as turbulence and possible multiple velocity components rather than the Stark effect.

Solar observations from the ground and from satellites show discrete ejections in the form of coronal mass ejections, eruptive filaments, sprays, and surges. Observations with the HRTS instrument (Brueckner and Bartoe, 1983; Brueckner *et al.*, 1986) show jets, coronal bullets, and turbulent flows at small scales.

An important question is to learn what part of a stellar wind comes from coronal mass ejections, coronal transients, or other aspects of flares. In order to learn the role of flares in the mass and momentum balance, it is necessary to measure mass motions with high spectral resolution, and to probe the ejected material quantities by different techniques (photometric absorption in X-ray, UV, optical, and spectral imaging).

1.4. Microflaring, flaring, and coronal heating

The origin of the coronal heating is still unknown. One hypothesis is that that solar-like coronae are heated by flaring and microflaring (Butler *et al.*, 1986). As has been studied in the laboratory and in the magnetosphere, preflare plasma is believed to convert magnetic energy into heat by reconnection and the dissipation of magnetic waves or electric currents. There is indeed an indication of this conversion at small scales. On the Sun hard X-ray microflares have been reported by Lin *et al.* (1984) and also UV line brightenings by Withbroe, Habbal, and Ronan (1985). Also, X-ray brightenings of active region loops observed with SMM confirm the existence of underlying microflare activity (Haisch *et al.*, 1989). Parker (1988) has invoked microflares or even nanoflares as a contribution to coronal heating.

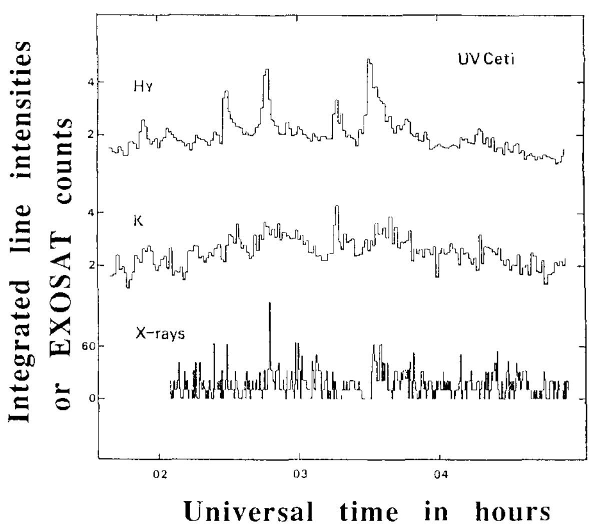

Fig. 1. The soft X-ray flux detected with the Exosat CMA from UV Ceti on 6 December, 1984 is compared with the Hγ and Ca II K fluxes measured from the ESO 3.6 m telescope. Correlated events in the three diagnostics confirm the existence of small flares and imply that much of the low-level X-ray flux previously considered to be quiescent probably originates from small flare events (Butler *et al.*, 1986). One can notice also the different time behaviour of the line fluxes, with an impulsive component for the Hγ line, while the Ca II K is more gradual (courtesy, Butler, Rodonò, and Foing, 1988).

On flare stars, a correlation was found between the optical flare power and the average X-ray luminosity independently by Doyle and Butler (1985) and Skumanich (1985, 1986). From X-ray measurements the general presence of a hot component at $T > 10^7$ K consistent with continuous flaring is found in a wide range of cool stars. Einstein, and especially the Exosat satellite with its long eccentric orbit have permitted studies of the short-term X-ray variability and the detection of low-energy flares.

Making use of simultaneous measurements from Exosat and ESO 3.6 m spectroscopy, Butler *et al.* (1986) have reported a temporal correlation between Hγ flux and X-rays in some dMe stars. Sporadic X-ray variations (cf. Figure 1) which are a signature of solar-like compact flares, contribute significantly to the average X-ray flux, indicating that the concept of a steady and quiescent corona may be of little value for these stars. By extrapolating the X-ray vs Hγ correlation to smaller energy, Butler *et al.* (1986) have argued that microvariations in the Balmer lines (observations made possible with the high S/N allowed by large ground-based telescopes) may correspond to X-ray microvariations below the detection threshold of Exosat and other X-ray satellites. Future statistical studies with more sensitive instruments and correcting for the detection threshold and for the merging of several small events are required for progress in this area.

1.5. Statistics and recurrence of flares

The basic question of what powers the flares has received a promising answer from solar observations and theory; the twisting of magnetic loop footpoints by turbulent-convective photospheric and sub-photospheric flows may be the magnetic energy storage process. Other changes of field configurations, such as magnetic field cancellation and association with the magnetic inversion line have been observed on solar flares. Van Ballegooijen (1985) suggested that the distribution of flare frequency $\nu(E)$ versus energy E corresponds to the distribution of magnetic field energy $B^2/8\pi$ for a given scale L. This hypothesis may be checked from statistical studies of solar Hα flares, hard X-rays flares, and microflares.

From statistics of stellar optical flares, Gershberg and Shakhovskaya (1983), and Pettersen, Coleman, and Evans (1984) derive a power-law histogram $\nu(E) \sim E^{-\beta}$ with $\beta \sim 0.5$–1.2. However, the statistical treatment of low-energy events must be refined. Studies can be extended to include small flares and microflares by spectroscopic monitoring of the Hα or Balmer lines for events with no detectable optical continuum counterpart.

It is important to have continuous coverage to have complete statistics and to assess the flare-integrated energy content. The classification and physical understanding of different flare phenomena may be useful in determining different key parameters and processes. The studies of flare recurrence either on short time-scales (homologous or sympathetic flares, destabilisation of nearby loops, etc.) or on longer time-scales (clustering periodicities, flaring active longitudes), may provide some clues on the small-scale and large-scale distribution of magnetic field on the stellar surface.

1.6. Flare activity as a diagnostic of magnetic and interior properties

We have seen that X-ray observations provide information on magnetic loop scale lengths and that radio gyrosynchrotron emission from stellar flares allows us to estimate the magnetic field intensity. Several empirically-derived parameters are needed to establish a link between flare activity and the global properties of a star: (1) an estimate of the bolometric flux of flare emission from the observed optical, UV and X-ray radiation, (2) a measurement of mass motions as an indicator of matter expansion or chromospheric evaporation during the flares, and (3) a diagnostic of conduction transport. The overall energy content may be compared with that inferred from magnetic field distribution measurements through the Zeeman line-broadening technique (Saar, Linsky, and Beckers, 1986), the degree of spottedness (cf. Rodonò *et al.*, 1986), or the distribution of chromospheric active regions (Foing *et al.*, 1988). Additionally, from inverse imaging techniques such as rotational modulation (Char and Foing, 1989), Doppler imaging (Vogt and Penrod, 1983; Vogt, Penrod, and Hatzes, 1987; Jankov and Foing, 1987), Zeeman–Doppler (Donati, Semel, and Praderie, 1988), or eclipse imaging, one may crudely reconstruct the distribution of stellar active structures. These techniques will provide critical data with which to test our ideas about flare build-up in the stellar context. Studies of flare frequencies and energies also provide a tool for probing the magnetic field distribution and sub-photospheric dynamics.

The subsurface source of flare energy can be studied by separating the dependence on spectral type (convection zone depth), rotation, age, and evolution (cf. Skumanich, 1986). Different kinds of flares on other stars should be studied especially in the extreme cases of very thin convection zones (minimal expected dynamo) and of magnetic field covering nearly all of the stellar surface. Also, the effect of interconnecting magnetic fields in close binary systems should be considered.

2. Spectral Diagnostics

2.1. Photometric diagnostics

Since the bulk of photospheric radiation from late-type stars is emitted in the optical and infrared range, sufficient contrast is required to detect and quantify flares against this background. Whereas solar optical white-light flares are rare events, broad-band optical enhancements are observed regularly in M-dwarf flare stars, due to the faint background, especially in the U band. Thus, U-band enhancements up to 5 magnitudes are observed while I-band enhancements are only a few hundredths of magnitude.

During the impulsive phase of solar white-light flares, the optical continuum shows a strong Balmer discontinuity, and is generally flat during the decay phase. Rust (1986) attributes the impulsive spectrum to heating in the lower chromosphere producing H free-bound and free-free emission, while the decay phase emission is produced by the H^- continuum. The mechanism by which the strong soft X-rays could penetrate the upper photosphere, ionize H and produce sufficient H^- emission could be tested by detailed simultaneous optical and X-ray observations.

2.2. Optical spectroscopy

Optical spectroscopy at low resolution permits a more accurate investigation of the free-free, and the Paschen and Balmer bound-free continua. Flare spectra at medium resolution such as the one displayed in Figure 2 provide measurements of line fluxes.

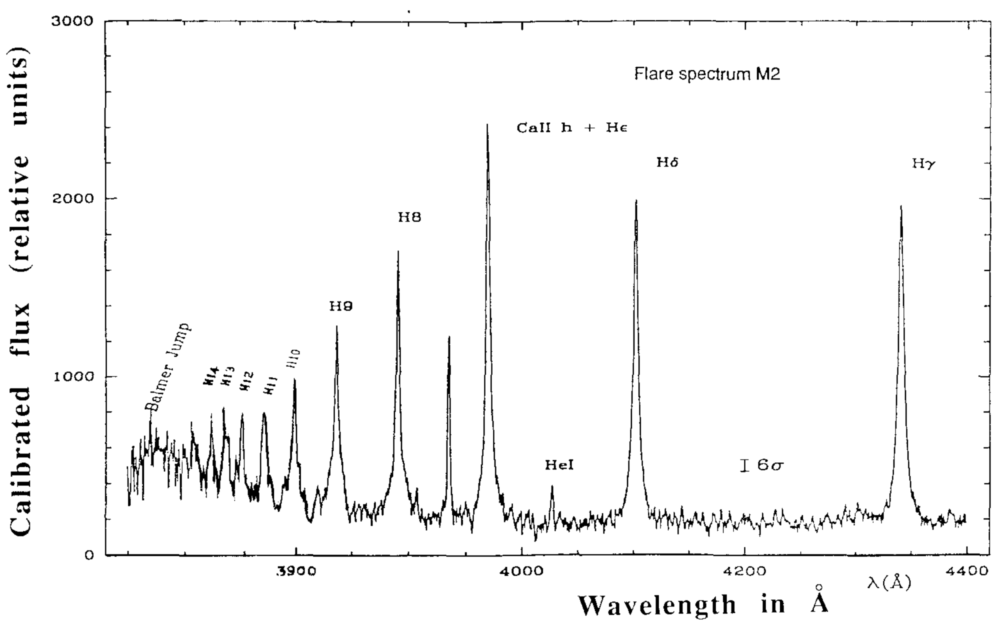

Fig. 2. Calibrated AD Leo flare differential spectrum (difference between flare and preflare spectra) obtained at the ESO 3.6 m telescope with the IDS spectrograph from 3600–4400 Å on 28 March, 1984. The spectrum is the difference between raw flare spectrum (at time indicated by tag M2 on upper Figure 3(b)) and a mean preflare spectrum. One can observe the increase of Balmer emission and wing broadening, the appearance of higher members of the Balmer series, and the emission of He I line at 4026 Å (courtesy, Rodonò *et al.*, 1989).

Balmer decrements may be used to diagnose typical temperatures and densities during flares (Butler *et al.*, 1987). The time behaviour of different line fluxes can be followed as in Figure 3. Chromospheric line fluxes strengthen during flares and decay more slowly than the optical continuum. For a given line, the dependence of line emission efficiency on temperature may be calculated, assuming for instance 'partial LTE' between higher levels of Rydberg series (for which Saha and Boltzmann equations are assumed valid for the corresponding populations), and the line flux evolution would reflect the change of the electron temperature during the decay phase (Houdebine *et al.*, 1989). Some constraints on the temperature and density structure can be obtained from line fluxes, especially in the optical range from Balmer lines, He and higher excitation lines. The role of photoionisation and photoexcitation of these lines by soft X-ray and XUV radiation should be estimated. The broadening and merging of higher Balmer lines

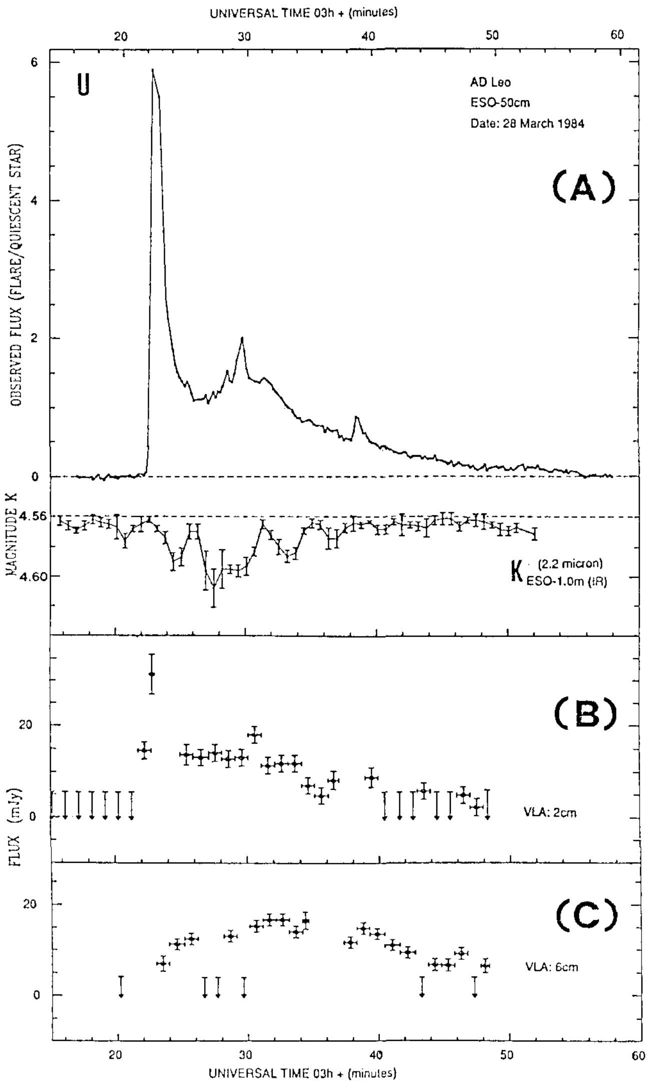

Fig. 3a. Time evolution of broad-band flux measurements during the AD Leo flare: (A) showing distinct impulsive and gradual phases in the *U* band and the first detected 'infrared negative flare' in *K* band at 2.2 micron; (B) the impulsive behaviour in the VLA 2 cm radio flux; (C) the gradual increase and decay of the VLA 6 cm band.

dominated by the Stark effect can be used to estimate electron densities in the chromosphere (Donati-Falchi, Falciani, and Smaldone, 1985). Measurement of the broadening of the lower Balmer lines, which are less affected by the Stark effect, together with line shifts, provide information on the large-scale flows during flares.

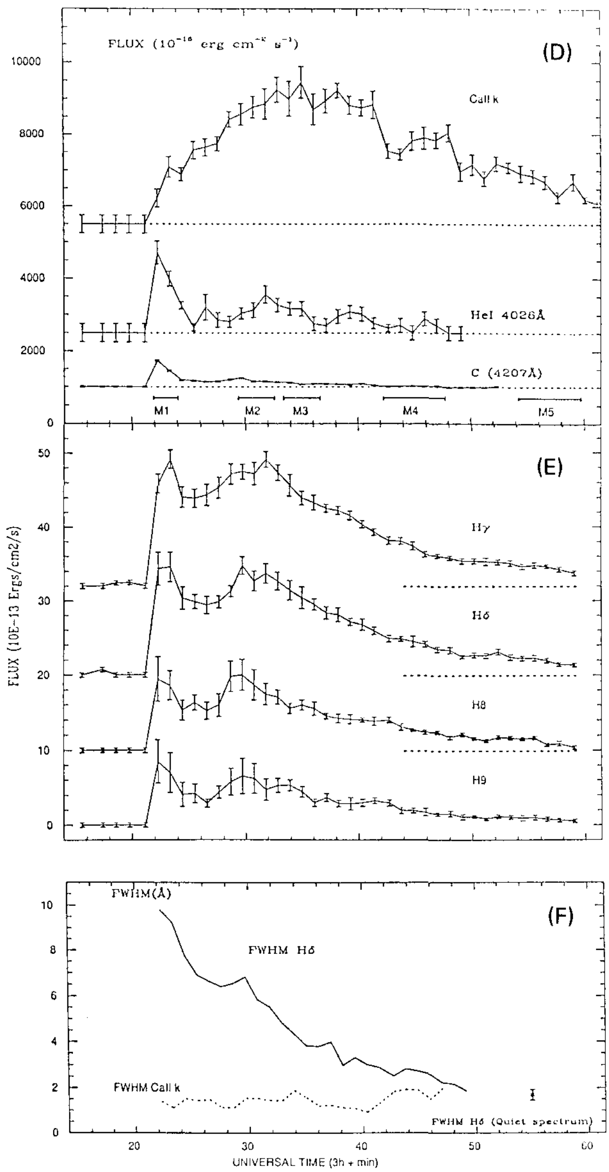

Fig. 3b. Variation of line fluxes from ESO 3.6 m spectroscopy of the AD Leo flare: (D) Ca II K line flux evolution showing only a gradual phase; impulsive variation of He I 4026 Å line similar to the variation of the continuum band at 4207 Å; (E) evolution of Balmer line fluxes with different delays and time profiles; (F) variation of the Balmer Hδ line width during the flare from 10 Å to its preflare value of 2 Å FWHM, while no variation of Ca II width is detected (courtesy, Rodonò *et al.*, 1989a).

2.3. Optical diagnostics at high spectral resolution

At high spectral resolution (20000–100000) and reasonable signal to noise (> 50) optical flare spectroscopy allows the study of Stark broadening in the Balmer lines, He I and Ca II lines; velocity fields associated with thermal, turbulent, or directed motion; and the time and velocity-dependent signature of ejected components (cf. Figures 4 and 5) in emission or in absorption. Also high spectral resolution is required to separate blends by photospheric lines or molecular bands which are important for cool stars, and allows us to measure the core filling and flare signature in photospheric lines. The observed chromospheric profiles such as those shown in Figures 4 and 5 can be com-

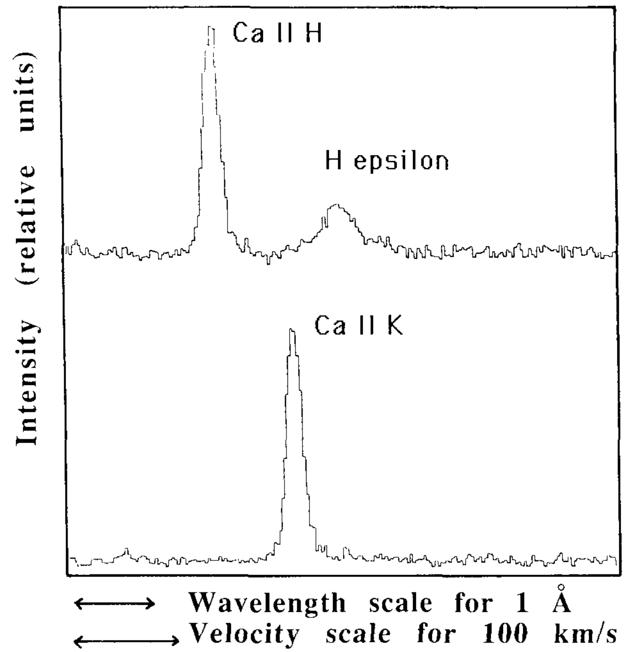

Fig. 4. AD Leo composite spectrum (of 4 spectra taken out of noticeable flare equivalent to a 2.5 hour exposure) obtained at the CFH 3.6 m telescope with the Coudé spectrometer and reticon detector at 50000 spectral resolution. Note the difference in the wings of Ca II H & K and Hε lines, and the corresponding broadening scale. The line profiles can be compared with semi-empirical chromospheric calculations.

pared with semi-empirical calculations (cf. Figure 6) using atmospheric models with different temperature stratifications. Those models consistent with the observations provide a vertical scale and information on the depth of formation of each spectral line, and also indicate the likely excitation and ionisation mechanisms. The presence of velocity gradients can be diagnosed from line shifts, asymmetries and detailed line profiles but this diagnostic is crude because of the interplay between the flare geometry in 3 dimensions, the dynamics, the NLTE radiative transfer effects and redistribution effects. However, it is hoped that a new generation of flare models which include the coupling between dynamics and radiation self-consistently will shed light on the principal mechanisms at work during the atmospheric response to flares.

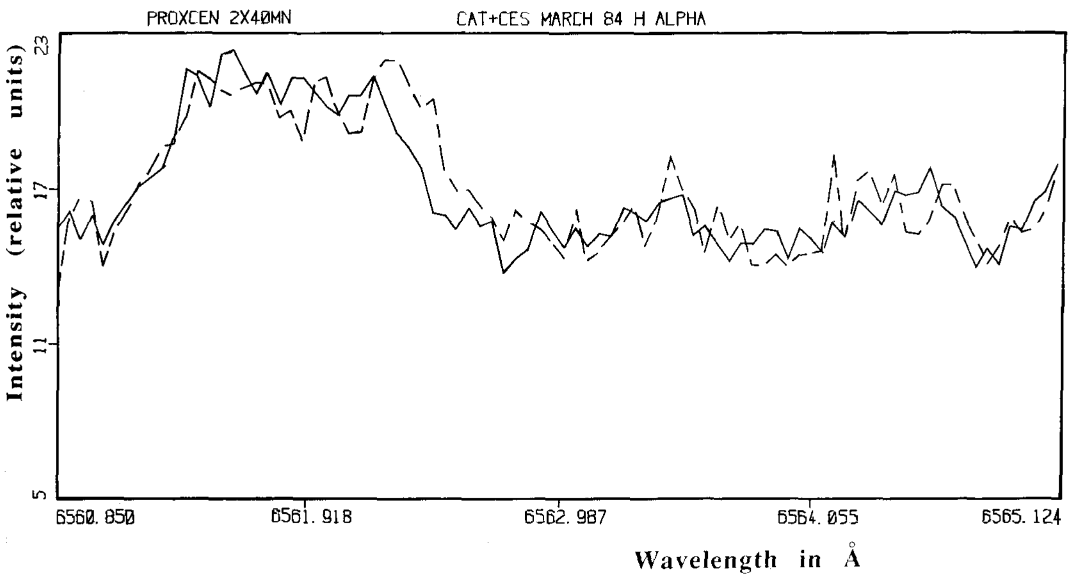

Fig. 5. Comparison between two 40 min exposure spectra of Prox Cen in Hα observed with the CAT 1.4 m telescope + CES spectrometer and reticon at ESO. The superposition shows an asymmetric broadening of the line, possibly due to a Doppler-shifted component. Provided the S/N and time resolution are sufficient, line asymmetries and velocity components can be monitored as flare motion diagnostics, as suggested in these Hα studies.

2.4. Ultraviolet spectral diagnostics

There is an enormous literature on solar flare optical + UV + X-ray flare diagnostics (cf. Feldman, 1981; Dere and Mason, 1981; and Dupree, 1978, for these aspects).

For stars, the 1200–3200 Å ultraviolet range covered by the IUE spectrograph is rich in spectral emission lines of species such as C I, O I, Si II, Fe II formed at 4000–6000 K at the base of the chromosphere, the Lα line and the C II 1335 Å at top of the chromosphere, and lines of Si III, C III, Si IV, O IV, C IV, and N V formed in the transition region at 30000–150000 K. For collisionally excited resonance lines, the surface flux is related to the emission measure EM = $\int_{\Delta T} N_e^2 \, dh$ over the temperature range ΔT of line emission. For intersystem lines which are collisionally excited but depopulated by line radiation and collisions (proportional to the electron density), the observed line ratios provide a measure of electron densities and thus the emitting volume at the temperature of line formation. The presence in the UV spectrum of lines formed over a wide range of temperature and excited by different processes permits us to infer the distribution of emission measure with temperature and to constrain assumptions about the geometry, temperature distribution, and electronic density stratification.

Optically thick chromospheric resonance lines and other transitions have been computed using various non-LTE codes in order to characterise the temperature and density distribution in active stars and flares. Rapid increases in UV line fluxes and continua

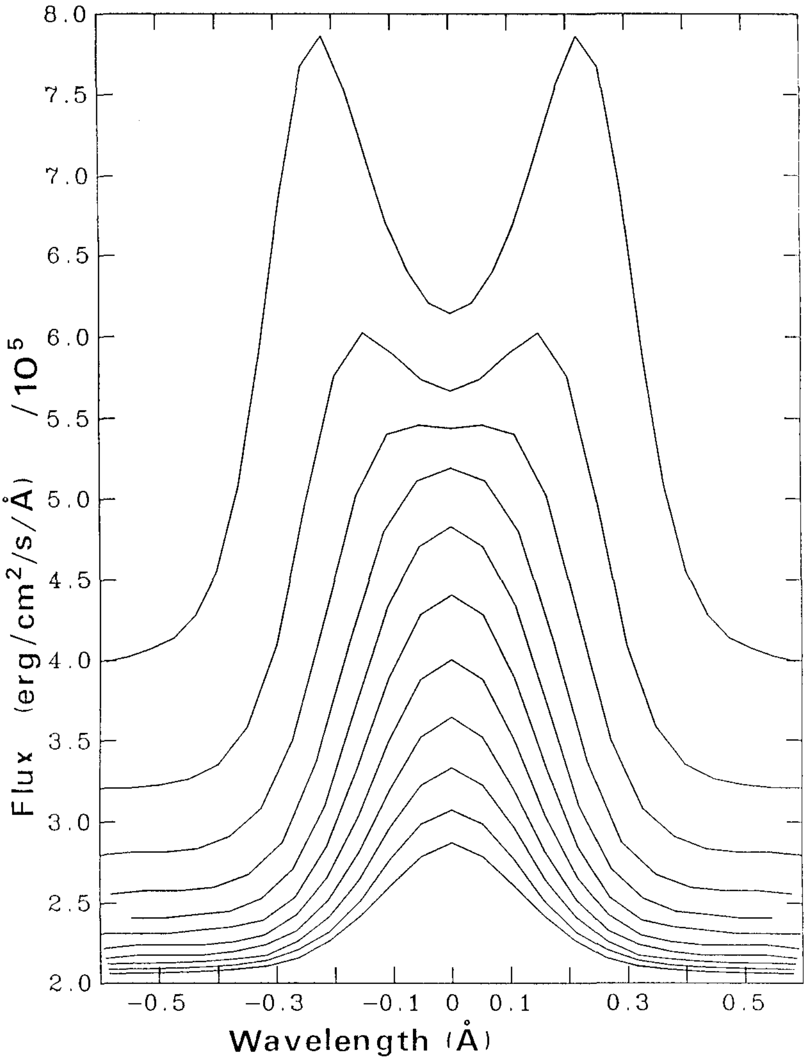

Fig. 6. Calculation of Balmer line profiles for a dMe atmospheric model using an adaptation of the M. Carlsson code with 16 levels and 12 transitions considered for the H atom. The diagram shows the lines from Hγ down to H14 (courtesy, Houdebine and Panagi, 1989).

have been detected during flares on dMe, RS CVn, and other flare stars. In particular, UV continua as observed on the Sun at 1600 and 2200 Å allow us to probe the temperature minimum region and middle photosphere, which play important roles in the flare-energy balance (cf. Foing, Bonnet, and Bruner, 1986; Foing *et al.*, 1986).

Because of its limited sensitivity and operational constraints, IUE cannot observe stellar flares with time resolution less than 10 minutes. The Goddard high-resolution spectrograph and the faint object spectrograph on space telescope will improve the sensitivity, time resolution and spectral resolution significantly over that of IUE but with a decreased spectral range and scheduling flexibility. Also the large oversubscription will make it difficult to monitor flare stars and to coordinate multi-wavelength observations. Other instruments such as the ST imaging spectrograph, or the Lyman mission will extend the spectral range. With its 900–1200 Å prime spectral region and 30000 resolution, Lyman will observe the H-Ly series, the important O VI, S VI, C III lines at temperatures between 2×10^5 and 10^6 K, and include lines of the ions N I–III, P II–V, S III–VI, C I–IV. Useful density ratios are available for several of these ions. Also the coverage of the 100–912 Å range will extend the temperature range up to 2×10^7 K by observation of ionisation stages of Fe II–XXIV, and of the He I and He II Lyman series. Simultaneous coverage of the complete 1200–3200 Å range is also required in a future successor to IUE. USSR instruments such as SUVT-170 planned for a 1995 launch with spectrometers covering the 1100–1900 Å and 1900–3500 Å ranges with resolution modes of 0.1, 3, and 30 Å, or the EUVITA instrument on Spectrum X planned for 1993 should be useful for flare studies.

These future satellites with their anticipated UV coverage, spectral resolution, and temporal resolution of 10–100 s, should permit studies of thermal conduction, chromospheric evaporation, mass ejections, flare expansion, radiation, and dynamics on a number of flare stars.

2.5. X-ray spectral diagnostics

The use of X-ray photometry and spectroscopy was described previously by Schmitt (1989) in this conference as a way to study the 10^6–10^8 K plasmas in stellar flares. Calculations of the emergent spectrum show the dominant role of emission lines for $T < 2 \times 10^6$ K and of the bremsstrahlung continuum at higher temperatures. Low-resolution spectroscopy ($E/\Delta E$ = 10–30), as was achieved with the Einstein solid state spectrometer, allows one to match an observed spectrum with a theoretical spectrum from a 2-temperature plasma folded with the instrumental response. This technique can also be applied to the analysis of low-resolution spectra to be obtained with the JET-X instrument onboard Spectrum-X, and later with higher throughput and time resolution by instruments on AXAF and by XMM/Focal plane imager. Moderate resolution spectroscopy ($E/\Delta E$ = 100–300) such as with the Objective Grating Spectrometer (OGS) on Einstein and Transmission Grating Spectrometer (TGS) on Exosat allowed to resolve spectral lines and to infer EM(T) distribution for the coronae on Capella and σ^2 CrB (Mewe *et al.*, 1982). Also density-sensitive ratios from He, Be, and C iso-electronic sequences allow us to infer densities and thus emitting volumes of the hot flaring plasma. With the enormous throughput of grating spectrometers on AXAF and XMM, moderate resolution with 100 s time resolution of bright flares on dMe and RS CVn system should be feasible (Linsky, 1987).

2.6. Radio observations

The usefulness of the radio spectral region for studying the hot thermal plasma and nonthermal electrons in coronal flare plasmas is described in Kuijpers (1989) and

Kundu, White, and Schmahl (1989). The spectral, temporal, and polarisation properties of different emission mechanisms, both coherent or incoherent are described in reviews by Kuijpers (1985), Dulk (1985), and Melrose (1987).

Gyrosynchroton emission from mildly relativistic electrons in magnetic loops was invoked by Linsky and Gary (1983) for dMe stars and also by Mutel *et al.* (1985) to explain VLBI observations of RS CVn systems. However, radio emission during flares with brightness temperature > 10^{13} K (confirmed from spike rise times faster than 0.2 s in AD Leo, Lang *et al.*, 1985) and 100% circular polarisation is explained as a coherent process such as electron-cyclotron maser or plasma radiation. Recently, Bastian and Bookbinder (1987) obtained the first dynamic spectra of flares on UV Ceti analogous to radio bursts observed on the Sun, thus inaugurating a new tool for radio flare studies.

3. Multi-Wavelength Diagnostics

For solving the scientific questions raised earlier, diagnostics are available in different wavelength ranges and at various spectral resolutions. These tools help to describe some of the existing processes at work during flares and to quantify some physical properties of flare plasmas. In order to give a more complete description at different heights and temperature regimes in the flaring atmosphere, these diagnosis should be used simultaneously (Foing *et al.*, 1988; Linsky, 1988).

As an example, we show the results of a multi-wavelength flare campaign (cf. Rodonò *et al.*, 1984, 1989a, b) on AD Leo, including ultraviolet spectroscopy with IUE, *U*-band photometry, optical spectroscopy in the range 3600–4400 Å, infrared photometry from ESO and radio observations with the VLA. The *U*-band photometry (Figure 3(a)) shows a rapid increase followed by several spikes. Simultaneous with the *U* spikes and with a similar temporal light curve, the 2 cm radio emission showed an increase during the flare. The 6 cm emission, on the other hand, gradually reached a peak flux some 15 min later than the impulsive phase. A very exciting result came from the infrared photometry with the 2.2 μm *K*-band showing a decrease or 'infrared negative flare' simultaneous with the optical flare but with characteristics different from those predicted by the inverse Compton effect or H^- opacity explanations.

The Ca II K line fluxes (cf. Figures 2 and 3(b)) show a much more slowly increasing excitation during the gradual phase of the flare than the Balmer lines. The He I 4026 Å line exhibits an impulsive behaviour in the flare spectra. The flux in the Balmer lines began to increase coincident with the continuum flare, but with a delay in the peak emission and a double-peaked light curve. Most of the Balmer emission occurs in the cooling plasma during the flare decay phase. Different time behaviour of the Balmer line fluxes can occur (Houdebine *et al.*, 1989) as the result of different flare temperatures as a function of time which in turn determine the 'emission efficiency' which is different for each line. A difference in the Balmer line broadening was also observed (e.g., a width of 10 Å in the Hδ Balmer line during the flare but only 2 Å in the quiet spectrum), whereas the Ca II K width appears to remain constant within our measurement uncertainties.

The temporal correlation of soft X-rays and Balmer Hγ line emission reported by Butler *et al.* (1986) from coordinated Exosat observations and ESO optical spectroscopy is an example of coordinated observations that provide insights into physical processes and the energy balance during flares. From observations of flares in soft X-rays and Balmer lines on different stars (such as UV Ceti, YZ CMi, Gl 644, and the Sun), Butler, Rodonò, and Foing (1988) propose that there is an almost equal amount of energy in the time-averaged soft X-ray flare emission and in the flux from the Balmer and Lyman lines. This puzzling result, which appears to be valid over four decades of flare energy, should be tested systematically by observing Lyman and Balmer H lines together with lines at higher excitation and simultaneously with the soft X-ray and EUV Lyman continuum below the 912 Å limit, that may control the ionization and excitation of H and other important transitions.

Coordinated multi-wavelength campaigns (Foing *et al.*, 1988) involving future X-ray and UV satellites and ground-based instrumentation with good simultaneity and continuous coverage are needed to extend our understanding of stellar flares. Such campaigns will require special efforts for organisation, observations, calibration, data analysis, and theoretical interpretation.

4. Conclusions: Requirements for Future Stellar Flare Observations

For the diagnostics of flares, we have seen that multi-band photometry over the whole range (radio, infrared, optical, ultraviolet, X-ray) with time resolution of 0.1–1 s is necessary for the timing of the flare impulsive phase. Medium-resolution spectroscopy in the optical and ultraviolet with a time resolution of 10–30 s is required to study line fluxes and continua diagnostics, for emission measure analysis, and to evaluate density-sensitive line ratios. High-resolution spectroscopy of line profiles provides insight into the plasma dynamics, and the radiative and excitation mechanisms.

All of these tools covering the full electromagnetic range must be used simultaneously with enough time resolution to study the flare plasma over its complete temperature range and including its nonthermal high-energy component. The development of new instruments and satellite missions must take into account this multi-wavelength coverage requirement. The need for simultaneous and continuous coverage requires the organisation of coordinated multi-wavelength observing campaigns (Foing *et al.*, 1988), and the use of networks of photometers and spectrometers around the globe (Catala and Foing, 1988). An important ingredient is the knowledge of the magnetic field distribution and large-scale motions for studying build-up conditions prior to stellar flares. Finally, a strong interaction between solar and stellar flare physics, together with atomic, plasma, and radiative transfer physics should extend the success of this IAU Colloquium on *Solar and Stellar Flares*. Those communities should jointly develop diagnostic methods, interpretative tools and theories for understanding the new observational results made possible with the next generation of space and ground-based instruments.

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References

Aboudarham, J. and Hénoux, J. C.: 1986, *Astron. Astrophys.* **156**, 73.
Antonucci, E., Gabriel, A. H., and Dennis, B. R.: 1984, *Astrophys. J.* **287**, 917.
Antonucci, E. *et al.*: 1982, *Solar Phys.* **78**, 107.
Avrett, E. M., Machado, M. E., and Kurucz, R. L.: 1986, in D. Neidig (ed.), *The Lower Atmosphere of Solar Flares*, National Solar Observatory/SPO.
Bastian, T. S. and Bookbinder, J.: 1987, *Nature* **326**, 678.
Brown, J. C.: 1971, *Solar Phys.* **18**, 489.
Brueckner, G. E. and Bartoe, J. D.: 1983, *Astrophys. J.* **272**, 329.
Brueckner, G. E. *et al.*: 1986, *Adv. Space Res.* **6**, No. 8, 263.
Butler, C. J., Rodonò, M., and Foing, B. H.: 1988, *Astron. Astrophys.* **206**, L1.
Butler, C. J., Rodonò, M., Foing, B. H., and Haisch, B. M.: 1986, *Nature* **321**, 679.
Butler, C. J., Doyle, J. G., Foing, B. H., and Rodonò, M.: 1988, in O. Havnes and B. R. Pettersen (eds.), *Tromso Midnight Sun Conference on Activity in Cool Star Envelopes.*
Canfield, R. D. and Gunkler, T. A.: 1985, *Astrophys. J.* **288**, 353.
Catala, C. and Foing, B. H. (eds.): 1988, *1st MUSICOS Workshop on MUlti SIte COntinuous Spectroscopy*, Observatoire de Paris-Meudon.
Char, S. and Foing, B. H.: 1989, in *Modeling the Stellar Environment: How and Why?*, Editions Frontières, Gif/Yvette.
Collier-Cameron, A. and Robinson, R. D.: 1988, in A. K. Dupree and M. T. Lago (eds.), *Formation and Evolution of Low Mass Stars*, D. Reidel Publ. Co., Dordrecht, Holland.
Collier-Cameron, A. and Robinson, R. D.: 1989, *Monthly Notices Roy. Astron. Soc.* **236**, 57.
Damé, L. and Cram, L.: 1983, *Solar Phys.* **87**, 329.
De Jager, C. *et al.*: 1986, *Astron. Astrophys.* **156**, 95.
De Jager, C. *et al.*: 1989, *Astron. Astrophys.* **211**, 157.
Dere, K. P. and Mason, E.: 1981, in F. Q. Orrall (ed.), *Solar Active Regions.*
Donati, J. F., Semel, M., and Praderie, F.: 1988, in C. Catala and B. H. Foing (eds.), *1st MUSICOS Workshop on MUlti SIte COntinuous Spectroscopy*, Observatoire de Paris-Meudon, p. 37.
Donati-Falchi, A., Falciani, R., and Smaldone, L. A.: 1985, *Astron. Astrophys.* **152**, 165.
Doyle, J. G. and Butler, C. J.: 1985, *Nature* **313**, 378.
Doyle, J. G. *et al.*: 1989, *Astron. Astrophys.* (in press).
Dulk, G. A.: 1985, *Ann. Rev. Astron. Astrophys.* **23**, 169.
Dupree, A. K.: 1978, *Adv. Atomic Molecular Phys.* **14**, 393.
Emslie, G. and Nagai, F.: 1985, *Astrophys. J.* **288**, 779.
Feldman, U.: 1981, *Phys. Scripta* **24**, 681.
Foing, B. H.: 1989, *Irish Astron. J.* (in press).
Foing, B. H., Bonnet, R. M., and Bruner, M.: 1986, *Astron. Astrophys.* **162**, 292.
Foing, B. H. *et al.*: 1986, in D. Neidig (ed.), *The Lower Atmosphere of Solar Flares*, NSO/SPO, p. 319.
Foing, B. H., Butler, C. J., Haisch, B. M., Linsky, J. L., and Rodonò, M.: 1988, in C. Jaschek and C. Sterken (eds.), *Coordination of Observational Projects*, Cambridge University Press, Cambridge, p. 197.

Gershberg, M. R. E. and Shakhovskaya, N. I.: 1983, *Astrophys. Space Sci.* **95**, 235.
Haisch, B.: 1983, in P. B. Byrne and M. Rodonò (eds.), *Activity in Red Dwarf Stars*, D. Reidel Publ. Co., Dordrecht, Holland, p. 255.
Haisch, B. M. *et al.*: 1983, *Astrophys. J.* **267**, 280.
Haisch, B. M., Strong, K. T., Harrison, R. A., and Gary, G. A.: 1989, *Astrophys. J. Suppl.* **68**, 371.
Hénoux, J. C.: 1989, unpublished poster at *IAU Colloq. 104 on Solar and Stellar Flares.*
Hénoux, J. C. and Aboudarham, J.: 1988, in C. Catala and B. H. Foing (eds.), *1st MUSICOS Workshop MUlti SIte COntinuous Spectroscopy*, Observatoire de Paris-Meudon, p. 89.
Heritschi, D., Raadu, M. A., Vial, J. C., and Malherbe, J. M.: 1989, in B. M. Haisch and M. Rodonò (eds.), *IAU Colloq.* **104**, 'Solar and Stellar Flares', Poster Papers, Publ. Catania Astrophys. Obs., Special Volume, p. 321.
Houdebine, E. R. and Panagi, P.: 1989, *Astron. Astrophys.* (submitted).
Houdebine, E. R., Butler, C. J., Rodonò, M., Panagi, P., and Foing, B. H.: 1989, in B. M. Haisch and M. Rodonò (eds.), *IAU Colloq.* **104**, 'Solar and Stellar Flares', Poster Papers, Publ. Catania Astrophys. Obs., Special Volume, p. 59.
Jankov, S. and Foing, B. H.: 1987, in J. L. Linsky and R. E. Stencel (eds.), *Cool Stars, Stellar Systems, and the Sun,* Springer-Verlag, Berlin.
Kuijpers, J.: 1985, in R. M. Hjellming and D. M. Gibson (eds.), *Radio Stars*, D. Reidel Publ. Co., Dordrecht, p. 185.
Kuijpers, J.: 1989, in *IAU Colloq. 104 on Solar and Stellar Flares* (this volume).
Kundu, M. R., White, S. M., and Schmahl, E. J.: 1989, in *IAU Colloq. 104 on Solar and Stellar Flares* (this volume).
Lang, K. *et al.*: 1985, in M. Zeilik and D. M. Gibson (eds.), *Cool Stars, Stellar Systems and the Sun*, Springer-Verlag, Berlin.
Lin, R. P., Schwartz, R. A., Kane, S. R., Pelling, R. M., and Hurley, K. C.: 1984, *Astrophys. J.* **283**, 421.
Linsky, J. L.: 1987, *Astrophys. Letters and Comm.* **26**, 21.
Linsky, J. L.: 1988, in F. Cordova (ed.), *Multiwavelength Astrophysics*, Cambridge University Press, Cambridge.
Linsky, J. L. and Gary, D. E.: 1983, *Astrophys. J.* **274**, 776.
Linsky, J. L. *et al.*: 1989, *Astron. Astrophys.* **211**, 173.
Neff, J. E., Brown, A., and Linsky, J. L.: 1989, in B. M. Haisch and M. Rodonò (eds.), *IAU Colloq.* **104**, 'Solar and Stellar Flares', Poster Papers, Publ. Catania Astrophys. Obs., Special Volume, p. 111.
Parker, E. N.: 1988, *Astrophys. J.* **330**, 474.
Pettersen, B. R., Coleman, L. A., and Evans, D. S.: 1984, *Astrophys. J. Suppl.* **54**, 375.
Rodonò, M., Pucillo, M., Sedmak, G., and de Biase, G. A.: 1979, *Astron. Astrophys.* **76**, 242.
Rodonò, M. *et al.*: 1984, in *Proc. 4th IUE Conference*, ESA SP-218, p. 247.
Rodonò, M., Foing, B. H., Linsky, J. L., Butler, J. C., Haisch, B. M., Gary, D. E., and Gibson, D. M.: 1985, *ESO Messenger* **39**, 9.
Rodonò, M. *et al.*: 1986, *Astron. Astrophys.* **165**, 135.
Rodonò, M. *et al.*: 1989a, in B. M. Haisch and M. Rodonò (eds.), *IAU Colloq.* **104**, 'Solar and Stellar Flares', Poster Papers, Publ. Catania Astrophys. Obs., Special Volume, p. 53.
Rodonò, M. *et al.*: 1989b (in preparation).
Rust, D.: 1986, in D. Neidig (ed.), *The Lower Atmosphere of Solar Flares*, NSO/SPO.
Saar, S. H., Linsky, J. L., and Beckers, J. M.: 1986, *Astrophys. J.* **302**, 777.
Schmitt, J. H., Lemen, J. R., and Zarro, D.: 1989, in *IAU Colloq. 104 on Solar and Stellar Flares* (this volume).
Simon, T., Linsky, J. L., and Schiffer, F. H.: 1980, *Astrophys. J.* **239**, 911.
Skumanich, A.: 1985, *Australian J. Phys.* **38**, No. 6.
Skumanich, A.: 1986, *Astrophys. J.* **309**, 858.
van Ballegooijen, A. A.: 1985, *Astrophys. J.* **298**, 421.
Vogt, S. S. and Penrod, G. D.: 1983, *Publ. Astron. Soc. Pacific* **95**, 565.
Vogt, S. S., Penrod, G. D., and Hatzes, A. P.: 1987, *Astrophys. J.* **321**, 496.
Withbroe, G. L., Habbal, S. R., and Ronan, R.: 1985, *Solar Phys.* **95**, 297.
Zarro, D. M. and Canfield, R. C.: 1989, in B. M. Haisch and M. Rodonò (eds.), *IAU Colloq.* **104**, 'Solar and Stellar Flares', Poster Papers, Publ. Catania Astrophys. Obs., Special Volume, p. 53.