SOLAR-LIKE ACTIVITY IN LATE-TYPE STARS

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Abstract

Solar active structures such as magnetic flux tubes or large-scale active regions in the chromosphere and transition region have been studied from images and spectra in UV continua or chromospheric lines formed at different heights and temperatures. These active structures, reflecting subphotospheric magnetic field and the underlying dynamo and participating in the heating of the upper atmosphere, are also of particular importance for the study of stellar magnetic fields, internal dynamics, chromospheres and coronae.

In the frame of the solar observations of chromospheric structures and dynamical phenomena, current chromospheric models should be improved by incorporating velocity fields and inhomogeneities. As a collaboration involving IAS/LPSP, OAT Trieste, IAC Canarias, we have obtained a series of high-resolution high signal to noise spectra of the main chromospheric lines (Ca II H & K and infrared triplets, Mg II h & k, Hα) for a sequence of active and quiescent late-type dwarfs from F8 to K5. These observations serve as a constraint on such chromospheric models, and bring information on mechanisms governing the stellar activity and dynamo. The rotational modulation of fluxes and asymmetries allows to diagnose active regions on slowly rotating stars, which method is illustrated with Ca II observations of α Cen B.

For active fast-rotating stars the monitoring of line-profile changes gives even more detailed information on surface-structure distribution. Such observations were obtained for the RS CVn system HR1099 along its orbital period in photospheric and Hα lines. A Doppler imaging reconstruction method was developed: synthesis of rotationally-broadened line profiles for unsptotted and spotted stars, an empirical model of the inhomogeneous surface temperature distribution, calculation of a series of spectra at different orbital phases, application of different inversion algorithms to provide an image reconstruction.

As a joint programme between Armagh and Catania Observatories, JILA and LPARL and IAS/LPSP for the study of solar-type activity in RS CVn and UV Ceti type stars, we have organized a series of coordinated campaigns of observations from IUE, EINSTEIN, EXOSAT, GINGA satellites, VLA, ESO, CFHT, Kitt Peak and other ground-based observatories. We highlight some results obtained from this collaborative effort, especially the simultaneous multi-site, multi-wavelength (from the radio, infrared, visible, ultraviolet to the X-ray range) space/ground-based observations of active surface structures and flare events on RS CVn and dMe stars. We discuss the need to coordinate future synoptic observations at all accessible wavelengths for these objects which are highly variable on all timescales from seconds to years.

1. Introduction

The past 10 years have been very fruitful for the growth of a new subdiscipline in astrophysics: the "solar-stellar connection", in which for the first time phenomena on stars and the Sun are directly intercompared and solar processes are better understood by modelling such phenomena in stars with different parameters. Among the accomplishments of this field in the last 10 years is the recognition that starspots, active regions, intense heating in chromospheres and coronae and other aspects of stellar activity are fundamentally magnetic in character.

The interest for studying chromospheres of late-type stars, apart from its own challenge of a complex plasma laboratory where magneto-hydrodynamic and thermodynamic processes occur, arises also from the fact that chromospheres are excellent test benches for using, testing and improving radiative-transfer and modelling theories under conditions of non-LTE and non radiative equilibrium. It is also possible to diagnose from the chromospheric structure and dynamics the trace of subjacent phenomena associated with the existence of the magnetic fields in stellar surfaces, that are governed by the convective and internal properties of the stars.

With the advent of observations at high angular, spectral and temporal resolution of the solar chromosphere in different domains of the electromagnetic spectrum, it has been possible to analyse the effects due to the spatial heterogeneity, the magnetic field or the velocity fields. In the solar chromosphere, dynamical phenomena are observed, such as oscillations and waves (for instance on board the OSO 8 satellite or from the ground in Ca II H and K). Models for the time-resolved response of the chromo-
phere to waves and oscillations have been performed by calculating synthetic profile variations (Gouttebroze and Leibacher 1984) and compared consistently with the observations. The shocks in the tenuous higher chromosphere involve nonlinear changes in the profile which keep an asymmetry signature in a time average. Also, systematic downflows are observed in network regions as an indication of a possible vertical circulation pattern of the material in the chromosphere.

2. Observations of solar fluxtubes, coronal loops and flares with the Transition Region Camera

2.1. Magnetic fluxtubes. Highly spatially-resolved observations of the magnetic field in the photosphere have shown the existence of elementary field concentrations in "flux tubes" of 1.5 kG of size less than one arcsec. These tubes, which have their origin from the coupling between convection and the magnetic field in the subphotosphere, are swept by the supergranular motions in the boundaries, which are cospatial with the 0^\circ.2 filigree emission in white light (Dunn 1973) or the enhanced emission network observed in chromospheric spectroheliograms. The correlation between the chromospheric emission and the magnetic flux has been shown by Skumanich et al. (1975). The vertical structure of these tubes can be studied with high spatial resolution observations of emission excesses at different wavelengths corresponding to different temperatures. For instance, 1" resolution pictures obtained with the Transition Region Camera (Bonnet et al. 1980; Foing and Bonnet 1984a; Foing, Bonnet and Bruner 1986) in the 220 nm continuum formed in the medium photosphere, in the 160 nm ultraviolet continuum formed near the temperature minimum region, in the Ly\alpha line at the base of the transition region at 20,000 K, or in the C IV transition-region line at 10^5 K, allow to span different altitudes for the diagnostic of these flux tubes and loops.

2.2 Thin flux-tube model. The fine structure of the chromospheric network shows up on the 160 nm continuum pictures. The excess emission in the network element can be understood as the effect of the difference of brightness temperature at optical depth \( \tau = 1 \) inside and outside the network element. We have shown (Foing and Bonnet 1984a) that, due to the different depth of formation (Wilson effect), the enhancement is proportional to the vertical temperature gradient, to the gas pressure scale height \( H \) and to \( \log(1-1/\beta_c) \) where \( \beta_c = 8\pi
\]

\[ BP_i/B^2 \]

is the ratio between the external gas pressure and internal magnetic pressure. The thin flux-tube model relies on a series of approximations that are valid between the photosphere and the temperature minimum:

(i) thin-tube approximation allowing to neglect the magnetic tension forces;
(ii) horizontal and vertical hydrostatic equilibrium that takes into account the magnetic pressure \( B^2/8\pi \);
(iii) thermalisation of the fluxtubes with the surroundings (Foing 1983). On the basis of these assumptions, one shows that the stratification inside and outside the tube is the same and that the \( \beta_c \) ratio \( 8\pi P_i/B^2 \) remains constant with height. The internal pressure varies as

\[ p_i = (\beta_c - 1) B^2/8\pi = P_i^0 \exp(-h/H), \]

magnetic field and flux-tube radius vary with height as

\[ B = B^0 \exp(-h/2H) \]

and\[ R = R^0 \exp(h/4H). \]

The comparison of these predicted quantities at different heights for a flux tube of \( B^0 = 1.2 \) kG and \( R^0 = 150 \) km at photospheric level has been made consistently with the observations obtained by the TRC and on whitelight high-resolution ground-based images (Foing, Bonnet and Bruner 1986).

2.3 Observations of coronal loops. Rocket photographs have shown that the material at \( T > 2 \times 10^5 \) K is in the form of loop structures connecting regions of opposite polarity observed with ground-based magnetographs. Loops have been observed also at the limb and on the disk by the Transition Region Camera in Ly\alpha or C IV at ranges of temperatures from \( 2 \times 10^4 \) to \( 10^5 \) K (Bonnet et al. 1980), showing the coexistence of multi-temperature plasmas. On the Ly\alpha filtergrams obtained by the TRC, the loop structure of active regions is well shown, and we can observe several dark or white threadlike structures of length smaller than 10", extending out of active regions or crossing the network boundaries. This shows again that the upper chromosphere and corona cannot anymore be described by an homogeneous plane-parallel model and that the basic structures are loops. The fact that they are observed both in absorption and emission suggests that a very heterogeneous distribution of the plasma temperature and electronic density delineates the loop magnetic field. Also, dark absorbing loops are visible at apparent coronal heights. The analysis of Ly\alpha radiative transfer in loops on the disk or at the limb has been addressed by Gouttebroze et al. (1986) to provide a quantitative diagnostic from Ly\alpha filtergrams. On overexposed pictures at the limb, loop structures extending 10–20° above the limb are

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easily observed. They reveal the very fine geometry of the magnetic field lines above the network. The contribution of the C IV emission was distinguished from the EUV continuum emission in the TRC filtergrams. Near the limb the loop geometry in C IV has been compared to the Lyα emission. Diagnostics in strong emission lines or in temperature or density-sensitive ratios, or emission-measure analysis can provide constraints on the modelling of these structures. Some scaling laws such as $T_m = (LP)^{1/3}$ have been proposed between the loop maximum temperature $T_m$, loop length $L$ and base pressure $P$. The interest of developing, interpreting and extending these analysis methods and scaling laws seems very relevant for stellar studies.

2.4. Observations needed at high angular, spectral and temporal resolution. However, there are still a lot of theoretical problems remaining about flux-tubes, loops and active structures on the Sun. Issues such as the constitution of loops and magnetic structures, their stabilities, their filling with material, their magnetic field configuration, the radial and longitudinal gradients of temperature and density, the dissipation mechanisms and length/time scales, the role of flows and dynamics, the origin of the solar wind, and the energy balance are not well known. New observations are then necessary to study elementary magnetic structures and physics: observe at limb, resolve loop constitution (one or several rectilinear tubes), observe presence of cool kernels imbedded in hot loops, measure magnetic field in flux tubes (Zeeman effect) or in coronal loops (Hanle effect), observe field configuration and the variation of diameter with length, observe transverse and longitudinal variation of $N_e$, $T$, $V$ from monochromatic or ratio high-resolution images as provided by coronal spectrometers, measure lagrangian flows and changes of parameters related to waves, observe phenomena close to the dissipation scale, observe interaction between loops and reconnection, observe flares at high resolution. We need to study the structure and dynamics of the flux tubes and loops which are the building blocks of the upper atmosphere. Space observations with the best spatial and spectral resolution have covered limited spectral ranges, but only snapshot observations are available with rocket experiments. With the expected performances of the coordinated coronal instruments, the SOHO satellite (ESA/SSD 1985, 1987) should provide a deep investigation at high resolution of the physics of coronal loops in order to understand the mass and energy balance in the solar chromosphere and corona. This study is of relevance not only for the field of solar-terrestrial physics, but is of interest for the study of stellar magnetic fields, chromospheres and coronae and constraints on the underlying dynamo.

3. Constraints on chromospheric modelling of solar-like stars

3.1 Semi-empirical solar models. Basic and powerful tools for the study of the solar chromosphere are the semi-empirical models, constructed by using observations either of EUV continua formed at different heights in the chromosphere (as was derived by Vernazza, Avrett and Loeser 1981 (VAL) from Skylab observations), or from the modelling of strong chromospheric lines like Ca II H and K observed from the ground, or Mg II h and k Lyα from space (as observed from OSO 8; Lemaire 1981). The current models rely on approximations of plane parallel geometry, homogeneity and hydrostatic equilibrium, with a very simple treatment of microturbulent velocities. Such models from the relation between temperature and height allow to calculate iteratively the pressure, ionization balance, population levels, mean intensity and the emergent spectra in different lines and continua. The predictions can then be compared to observational parameters or directly to the spectra, and the input model modified to allow a better adjustment to the data. Such models (VAL) are also very useful in indicating typical heights of formation in the atmosphere for different spectral features.

However, images of the Sun obtained from Ca spectroscheiograms or EUV images show the inhomogeneity of the solar chromosphere (at large scale for the network and plages, and at small scale for the structure and properties of magnetic elementary flux tubes). Multicomponent models from the very quiet Sun inside supergranular cells almost free from magnetic fields to the enhanced network (VAL), as well as models of active components (model of plage from OSO 8, Ca II, Mg II, Lyα observational constraints) or of flare components (Machado et al. 1980) have also been developed. From these models, the net radiative losses in the main line transitions and continua can be calculated as in Avrett (1984), showing the role of the Ca II, Hα, H', Mg II and Lyα losses in the chromospheric energy balance at different heights. It must be stressed that these lines provide complementary and partially overlapping constraints on the temperature structure, and of the physical conditions (including the velocities) at the heights where they are formed.
3.2 Our general chromospheric programme of observations. On the basis of this experience in solar chromospheric research, and of the advent of instruments for stellar spectroscopy providing chromospheric profiles with a quality comparable to that of solar data, we have set up a network of collaboration between 3 institutes (IAS/LPSP Verrières, OAT Trieste and IAC Canarias) and defined a general program of observations and modelling of chromospheres in late-type dwarfs (Beckman et al. 1984; Foing et al. 1985). We have obtained, for a sequence of active and quiescent dwarfs from spectral types F8 to K5, a series of spectra at high resolution and high signal to noise in the main chromospheric lines of Hα, Ca II infrared triplet and Ca II H and K from ESO with the CES, and h and k lines of Mg II from the IUE satellite. The stars were selected to exhibit different degrees of chromospheric activity, as estimated from Ca II H chromospheric core emission. When comparing the Hα profiles of these pairs of active/quiescent stars, a difference was also found in the core due to the different chromospheric contribution over the background photospheric absorption profile due to the intrinsic S/N and to the precision of our registration procedures. A similar emission was also measured in the cores of the Ca II infrared triplet lines at 8498 A and 8542 A.

3.3 Information from calibrated line profiles. The chromospheric spectra have been calibrated in order to estimate the absolute excess chromospheric fluxes either by using literature values for the normalisation of the continuum or pseudocodinum. Another method was also used for Ca II H and K profiles (cf. Castelli et al. 1988) by adjusting synthetic photospheric profiles computed under LTE and radiative equilibrium to the observed photospheric lines in the Ca II H wings. Line-core intensity indices or normalised chromospheric fluxes must be measured with a sufficient accuracy in order to derive a reliable relation with the stellar parameters (effective temperature, gravity, rotation) that can be compared to the predictions of theories of chromospheric heating and stellar dynamos. Specific information about the radiative transfer opacity effects and about the dynamics at given heights in terms of microturbulent, macroturbulent, systematic flows and waves, requires a precise measurement of possible different spectral signatures of these processes in the line profiles. Also, the differences between active and quiescent profiles for stars of the same spectral type can be discussed within an extended solar-type multicomponent description.

The evidence for large-scale structures (similar to solar plages) has been indicated by variations of activity indices during the rotational period of the star. Different techniques can be applied for analysis of the spectroscopic variability associated with the chromospheric or photospheric activity, including rotational modulation of fluxes, profiles, velocity shifts, line bisectors and asymmetries, multivelocity components and Doppler imaging of the stellar surface inhomogeneities.

4. Spectroscopic variability associated with chromospheric activity

4.1. Variability of Ca II H and K flux and profile. Flux variability of Ca II H and K in solar-like stars was studied by Wilson (1978) in his classic work on magnetic activity cycles. Short-term H and K flux modulation was observed by Vaughan and Preston and used by them to compute rotational periods. The relation (period of activity-age) using H and K was studied by Vaughan and Preston (1980).

The possibility to use high S/N profiles instead of fluxes can give us three new types of information: (i) Proportion of active (i.e. plage + network) to quiet stellar cover, given a knowledge of the intrinsic profile emitted by each component; (ii) The presence of velocity fields in three dimensions: the presence of an asymmetry or the position of a bump in the line profile and the speeds with which these features change should be used to distinguish vertical quasi-convective or wave motions from the projected rotational motions of plages; and (iii) Intensity and velocity can be combined via the technique of Doppler imaging to produce maps of stellar surfaces specifying active and quiet regions.

We show in Figure 1 an example of the spectroscopic change that can occur due to the change of activity cover during a rotational period. The K2V star α Cen B was observed with the CAT + CES (ESO) at a resolution R = 10^5 and at high signal to noise. The observations span a duration of 11 days in June 1985, in two groups 8/9 June and 17/19 June. The photospheric spectrum is constant, but the chromospheric emission profile shows a very clear change. There is a difference profile in α Cen B reminiscent of a solar plage spectrum, corresponding to 20% change in the Ca II-H index (integrated flux over 1A) over minimum phase, and to a FWHM of 33 km s^-1. In contrast, the G2V star α Cen A does not show any measurable change to within an impressive 0.3% RMS error across the spectrum. These observational results illustrate how similar techniques could be applied to diagnose surface structures.
4.2 Multi-components. In general the observed integrated flux over the stellar surface is
\[ F(\lambda) = \int I(M, \lambda - \lambda_0 - \lambda_{\text{rot}})(1 + \epsilon \cos \theta) \, \cos \theta \, d\Omega \]
where the centre to limb factor \( \epsilon \) may depend on the wavelength \( \lambda \) and on the component (quiet, network or plage) and \( \lambda_{\text{rot}} \) is the radial projection of the rotational velocity. The use of a strong rotational velocity to provide a Doppler image is described further in the paper, and the possibility for making velocity diagnostics on slower rotators in Crivellari et al. (1987). At first, we restrict ourselves to the variability of the profile due to rotational modulation by active structures in the case of a multicomponent description. Based on the previously described solar analogy, three components models can be developed for stellar chromospheres, including a quiet stellar background virtually free of magnetic field, a network magnetic structure distributed homogeneously over the stellar surface, and an enhanced emission from plages at given positions.

If rotational velocity information is neglected, the flux from the star can be expressed as
\[ F = F_Q (1 - f_N - \Sigma f_{QN} I_Q / F_Q) + f_N F_N + \Sigma f_i I_P \]
where
\[ f_P(t) = A_i \cos \theta_i (1 - \epsilon_i^Q + \epsilon_i^P \cos \theta_i) \]
is an equivalent projected filling factor of the plage of area \( A_i \), specific intensity \( I_i, F_P \) being an average plage flux and \( f_P = A_i \cos \theta_i (1 - \epsilon_i^Q + \epsilon_i^P \cos \theta_i) \)
the corresponding subtracted filling factor from quiet emission. If we compare two phases of observation, the only terms left in
\[ F_2 - F_1 = \Sigma_2 - \Sigma_1 (f_P^i I_i - f_P^N I_Q) \]
If the centre to limb effect difference is neglected \( \epsilon_i^Q = \epsilon_i^P = \epsilon_i \) and, if we assume a fixed profile for the plage contribution \( I_i - I_Q = a_i F_P(\lambda) \), this profile can be determined from
\[ F_2 - F_1 = I_P(\lambda) (\Sigma_2 - \Sigma_1 f_P^i a_i) \]

Our full methodology for plage studies is thus: seek out stars with time-independent Ca II H fluxes and "low activity" profiles to yield a representative quiet spectrum \( F_Q \); seek out stars with small variations in fluxes and "high activity" profiles to yield a plage spectrum \( F_P \); monitoring of stars with flux-varying spectra during one period to derive, from the time behaviour of the projected filling factor \( f_P^i(t) \), information about the surface distribution of plages.

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5. Indirect imaging of active fast rotating stars

5.1. Stellar photospheric spots. The evidence for stellar photospheric spots can be obtained in the case of RS CVn or BY Dra systems from periodic modulation of the photometric light curve. Migration of these photometric waves can also be observed as an indication of the change in the spot distribution over the surface. Modelling of the spotted image has been implemented for describing the photometric observations (Rodono et al. 1986; Cameron and Horne 1986). Basic considerations about the imaging of spotted stars from high-resolution high signal to noise spectroscopy of photospheric lines have been given by Vogt and Penrod (1983). Intensity and velocity can be combined via the technique of Doppler imaging to produce maps of stellar surfaces specifying active and quiet regions. Spectra of the RS CVn type binary HR1099 were obtained in December 1984 with the CAT + CES at ESO in the 6430 A range at different phases, and around the Hα line showing the spectral changes due to the orbital motion of the system. The rotational broadening of both components and the bump changes in the primary spectrum were monitored and analysed for the Doppler imaging of the spotted component.

5.2. Method for Doppler imaging. The apparent stellar surface can be divided in strips of equal radial velocity (and then of equal Doppler position in the observed profile), which projections at a given phase are given on the stellar image defined as a grid of intensity pixels. The position of a spot can be obtained from the intersection of these projections at different phases. Two methods can be distinguished, depending whether narrow-band photometry of the continuum simultaneous to the spectroscopy, is available. The reconstruction of the image from such projections is an ill-conditioned problem, due to several sources: (i) the deconvolution, (ii) the matrix for the transformation contains systematic and random errors, (iii) details observed close to the limb are a source of instability for the global reconstruction of the image. Additional constraints, including a priori information, must be used to regularise the solutions.

5.3. Line profile synthesis and inverse Doppler imaging. We have produced first a test image (Jankov 1987; Jankov and Foing 1987) of the primary star of the RS CVn system HR1099, with the spot positions given by Gondoin (1986) and the elements of the system by Fekel (1983). The input temperature of the spot of 3500 K over the unspotted photosphere at 4700 K and spot areas are selected by us on the basis of typical values quoted in the literature. Noise-free synthetic spectra were then calculated from our assumed input image and system elements at different phases. We used the previous synthetic spectra in order to test our code for iterative image reconstruction from spectra: different norms could be defined in the space of the solutions giving different methods and algorithms: (i) one reconstruction giving more weight to the χ² adjustment to the spectra, (ii) another giving more weight to the distance to a homogeneous distribution. The second constraint method gives a more regular solution, closer to the input image. The comparison between such reconstructed image and the artificial input image allows to estimate critically the performances of the inverse Doppler imaging method, under different working conditions of noise and a priori information.

The actual performances of observational instruments, developed methods and physical constraints allow to obtain information about the inhomogeneous distribution on a stellar surface, and even to obtain an indirect image of a star. A sophisticated treatment must be applied on high-quality data. The work must be continued: (i) for finding an optimal mode of observation according to the instrument performances and stellar characteristics, (ii) for using an optimal reconstruction method, (iii) for getting information on the physical conditions used as constraints for the models, (iv) for deriving the vertical structure of active regions localised by indirect imaging from multispectral observations. The high quality of the data and of such interpretative techniques is required to tackle problems related to theories of activity phenomena and of the magnetic field distribution and dynamo in stars different from the Sun.

6. Coordinated multiband space and ground-based observations of surface structures and flares on late-type stars

6.1 Enhanced solar-like activity in RS CVn and dMe systems. The evidence collected from dedicated observations of active stars in the last ten years is strongly suggestive of a solar-type scenario with activity levels a few orders of magnitude higher. Activity phenomena are usually observed in RS CVn and dMe stars because of (i) contrast effects with the high-temperature flare radiation and (ii) deep convection zones and high rotation rates leading to differential rotation and efficient dynamos. They manifest themselves as flux variation in the continuum and emission lines over a wide range of wavelengths on timescales ranging from a
few seconds, minutes (flares), hours and days (rotational modulation by active structures), to months and years (active-region evolution, cyclic activity and differential motions).

6.2 Active surface structures. In particular the presence of plages and spots has been inferred from periodic low-amplitude photometric and spectral-feature variations due to rotational modulation of spot-plage visibility (cf. Rodono et al. 1986, 1987). Systematic observations like those carried out at Catania Observatory for RS CVn and other active stars, have shown almost sinusoidal light curves to become multipeaked or even flat, suggesting variations in the spot number and distribution over the stellar surface. Spot and plage modelling (Byrne et al. 1987) indicates that their physical characteristics are close to the solar ones, but they can cover up to 50% of the stellar surface. From simultaneous optical and IUE observations (Rodono et al. 1986), a close spatial correlation between spots and chromospheric/transition-region plages is apparent. High-resolution spectroscopic observations of lines at different phases of the rotational period of active stars obtained with IUE or from the ground has allowed us to develop "spectral imaging" on IUE Mg II data (Walter et al. 1987; Neff 1987), or "Doppler imaging" techniques for recovering the spatial distribution of surface activity over the star (Jankov and Foing 1987). The objectives of such studies are to obtain the geometric distribution of activity phenomena, to understand the differences with their solar equivalent, to model the active and quiescent atmospheric regions, to study the correlation between the structures observed at different heights, and to monitor the changes associated with active region behaviour, cyclic activity, dynamo phenomena and differential rotation.

6.3. Multiband observations of stellar flares. Flares are the most complex and violent phenomena observed on these stars. Flare events have typical timescales of 10 s for rise and 100 s for decay. Simultaneous photometry and spectroscopy of flares has shown that emission-line enhancements of different species take place as the response of the stellar atmosphere to the flare-energy release. The first IUE observations of a stellar flare were obtained by Haisch and Linsky (1980). Soft X-ray flares were also detected by the SAS–3, HEAO1 and EINSTEIN satellites. Also, the detection of microwave emission from UV Ceti-type stars was interpreted as a gyrosion emission from the flare's relativistic electrons. Our group has undertaken several campaigns of coordinated X-ray, UV, optical, infrared and radio observations of flare stars and RS CVn binaries, involving ESO and CFH in March 1984, in December 1984, in March 1985, in February and September 1987. An infrared decrease was for the first time detected during a flare, simultaneous with photometric, spectroscopic and radio (VLA) changes (Rodono et al. 1984, 1985). We also showed, from the correlation of ESO 3.6m spectroscopy and EXOSAT, the importance of microflares for the coronal heating of those stars (Butler et al. 1986). The latest campaign has involved GINGA, IUE, VLA and optical/IR telescopes on Mauna Kea and La Palma in March 1988.

The scientific objectives of this flare program (cf. Foing 1988) are to determine: (i) the energy budget for a typical sample of flares, (ii) the respective roles of radiation from the corona (as shown by the X-rays), conductive losses through the transition region (UV radiation), and expansion (as indicated from velocity-field measurements), and (iii) the temperatures, densities and volumes of the hot flaring plasma. Our methods of investigation for these programmes require that we obtain simultaneous observations at all accessible wavelengths, due to the transient behaviour of activity phenomena, especially for flare events that affect different atmospheric levels on a very short time scale.

7. An international co-operation for the study of surface structures and flares on late-type stars

The scientific need for multi-wavelength multisite observations of these intrinsically variable active stars has stimulated us to organize coordinated campaigns of observations, collect and analyse the observations jointly, employing the various areas of expertise of our collaborating groups (Armagh and Catania observatories, IAS/LPSP, JILA and Lockheed), and their access to large telescopes and satellite observatories. The theoretical interpretation of data corresponding to very different wavelengths and emission mechanisms is then discussed in conjunction with the knowledge of solar physics and general astrophysics (MHD, stellar atmospheres, etc).

This collaborative research was set in the context of programmes accepted for ESA/NASA satellites (IUE, EXOSAT) and for large ground-based telescopes at ESO, CFHT, Kitt Peak, AAT, Canarias observatories. The unexpected longevity of the IUE satellite, together with the archives for IUE and EXOSAT and our access to new ground-based telescopes, provides further perspective to the program. The future mission of the Space Telescope will offer instruments (especially the HRS spectrograph) to push researches far beyond their
present limits. It is necessary to prepare these scientific programmes and to insure the overall expertise (observations, data reduction, archival, analysis, scientific interpretation).

8. Conclusion

The field of “solar-stellar connection” is now in an exciting situation which evolves rapidly. Stimulants for this new research topic include future stellar observations by satellites which study stellar X-rays and ultraviolet spectra, by powerful ground-based radio and optical/infrared telescopes and instruments and by new theoretical/interpretative techniques. For solar physics, the availability of ground-based data or future space observations (as from SOHO) at high angular, spectral and time resolution or probes of the internal structure and dynamics through solar seismology, will give a challenge to the understanding of coronae, non-thermal phenomena, magnetic processes and dynamo theories. It is then necessary that the solar and stellar communities involved in this “solar-stellar connection” not only add up their resources, but develop joint scientific projects and instrumental programmes. It is crucial that ideas and work be exchanged between the groups having the complementary expertise in collecting multi-frequency observations, in developing diagnostics methods, in quantifying the link between stellar internal dynamics and their manifestation in the outer atmosphere through activity phenomena.

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References

THE ACTIVITY-ROTATION RELATION AND THE CONVECTIVE TURN-OVER TIME OF
LOW-MASS STARS

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Specific spectral signatures, such as emission components of resonance lines and X-ray emission originate or are strongly enhanced in solar chromospheric and transition-region plages, loops, bright points, etc. The presence of similar signatures and their average strength are commonly used to define the “activity” level of late-type stars. It is now widely accepted that the “activity” is magnetic in origin and that local magnetic fields are generated through field amplification by the dynamo mechanism (Parker 1955) in the interplay between convection and rotation.

Following the early results by Skumanich (1972) on the Ca II H and K lines, several authors have explored correlations between rotation and activity indicators. The Ca II H and K line emission fluxes have been shown to be proportional to the angular rotation \( \omega \) (Vaughan et al. 1981, Ballinas et al. 1983, Schrijver 1983), while X-ray emission fluxes have been shown to be compatible with power-law dependences on the rotation (Ayres and Linsky 1980, Pallavicini et al. 1981). Walter (1982) found that the dependence of \( L_x/L_{bol} \) on the rotation period could be represented either by an exponential law or by a power law with a break in slope near 12 days. Marilli and Catalano (1984) showed that different activity indicators from the chromosphere to the corona are well represented by exponential dependences. Noyes et al. (1984), in the framework of the dynamo theory, tried to fit observations of the Ca II emission with the dynamo parameter \( R = P_{rot}/\tau_c \) (Rossby number), where \( \tau_c = \nu_c/2\tau \) is the convective turn-over time, \( \nu_c \) the convection velocity and, \( \tau \) the characteristic length of convection (mixing-length). They adopt the ratio \( L_{HK}/L_{bol} \) as activity parameter and a pre-defined polynomial representation of \( \tau_c \) as a function of \( (B-V) \). The turn-over times they deduce from the best fit to the data agree fairly well with the values calculated by Gilman (1980) from convection parameters evaluated one scale height above the bottom of the convection zone and for a ratio of the mixing length to the pressure scale height \( \alpha = 1.9 \). A similar result has been found by Doyle (1987) using normalized emission luminosities of the Mg II h and k lines.

In this report I present some results on the study of the activity-rotation relation we are doing at Catania for single main-sequence stars later than F7, for which well-determined rotation periods and Ca II H and K or Mg II h and k emission fluxes are available. We have reexamined the chromospheric emission—rotation correlation (Marilli et al. 1986) adopting the line emission luminosity as activity