Mem. S.A.It. Suppl. Vol. 5, 52

Memorie della
Supplementi

Stellar magnetic activity: the solar-stellar connection

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Abstract. The atmospheres of late-type stars are site of strong magnetic fields responsible for their non-radiative heating. Magnetic activity phenomena are often analogous to those observed on the Sun, but there are also phenomena which strongly deviate from the solar ones. Exploiting the solar–stellar connection is instrumental to a better understanding of the whole phenomenology of stellar activity. In this paper some of the results from the investigation on active cool stars are given: from the discovery of stellar activity cycles, to the characteristics of the active regions in the outer atmospheres. I also show how important is to understand magnetic activity phenomena when extrasolar planets are searched around solar-type stars.

Key words. Cool stars – magnetic activity – solar-stellar connection

1. Introduction

Magnetic activity phenomena, analogous to the solar ones, are widely observed in cool stars. Spots in the stellar photospheres produce rotational modulation of the optical light curves and Doppler shifted features migrate along the line profiles as the star rotates. Indeed, magnetic activity is also responsible for emission lines in the UV/FUV spectra, and for the whole X-ray and radio stellar emission. In RS CVn-type binary systems, in dMe stars, and in young rapidly rotating stars, magnetic activity is of paramount interest because of its extreme characteristics. In fact, in these stars more than 50% of stellar photospheres are covered by spots, chromospheric and transition region lines show fluxes close to the saturation regime, and X-ray luminosity can even reach a few percent of the stellar bolometric luminosity. Many active stars show activity cycles with characteristics similar to the solar 11-years cycle, but there are also phenomena that do not have analogous on the Sun, e.g. polar spots. We need to test models of physical processes responsible for structure and dynamics of the solar atmosphere as stellar parameters change, e.g. stellar mass, rotation regime, chemical composition and binarity.

Pursuing solar and stellar research in parallel has a long tradition at Catania Astrophysical Observatory. In this paper I show some results obtained on active cool stars from long-term optical monitoring, from UV spectral monitoring, and from UV high resolution spectroscopy. Recent results on stellar coronae can be found in a review by Favata & Micela (2003).

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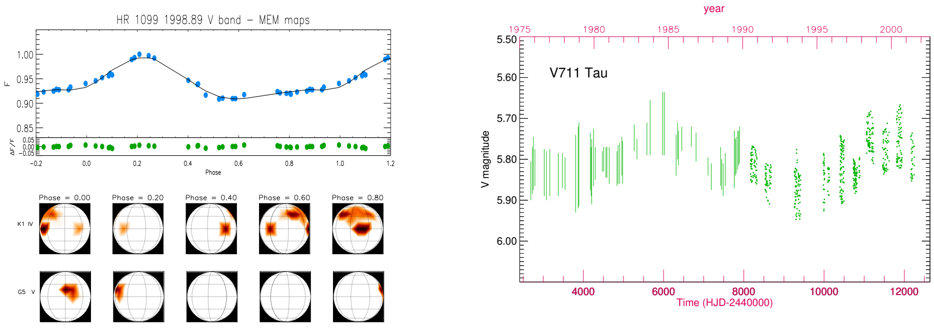

Fig. 1. Left Panel: V-band light curve of the RS CVn-type star HR 1099, its model (continuous line) and maps of the distribution of the spot filling factors, at five rotation phases (Garcia-Alvarez et al. 2003). Right panel: Sinoptic curve of HR 1009 from Messina et al. (2002). For each seasonal V-band light curve, the difference between light maximum and light minimum is plotted. The variation in time of light maximum shows that spot filling factor changes periodically.

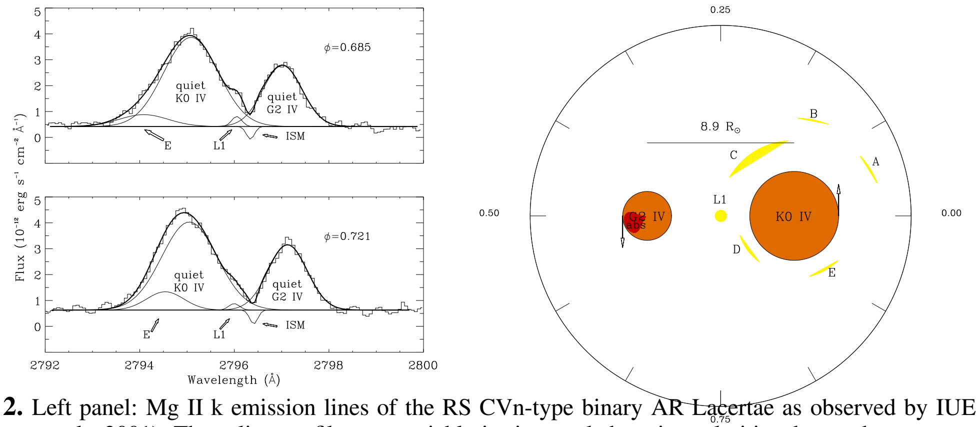

Fig. 2. Left panel: Mg II k emission lines of the RS CVn-type binary AR Lacertae as observed by IUE (Pagano et al. 2001). These line profiles are variable in time and show irregularities due to the presence of active regions in the stellar chromospheres traveling from the blue to the red across the line profile as the star rotates. The E component is due to an active region, the L1 feature is due to emission near to the system center of mass, while ISM is the absorption component due to the interstellar medium. Right panel: a sketch showing the location of the active regions (A through E), of an absorption feature (abs), and of an emission region near the system center of mass (L1).

2. Cool star photospheres and activity cycles

The long-term monitoring of cool star photospheres, started at Catania Observatory in the Sixties, has provided us information on the structure and evolution of stellar spots. As shown in Fig. 1 (left panel), V-band light curves of active stars are rotationally modulated. These curves can be modeled to obtain maps of the distribution of the spotted regions (see Lanza et al. 1998). By using regularization criteria it is possible to constrain the spot filling factors and longitudes of active regions. Fig. 1 (right panel) shows how the pattern of variability changes with time as spots and their cycles evolve. By modeling light curves monitored during tens of years, Lanza et al. (1998), Rodonò et al. (2000) and Lanza et al. (2002), for example, derived the presence of spot cycles, of preferred longitudes for stellar activity, and the flip-flop effect, i.e., the periodical swapping of the preferred longitudes.

Doppler images of active stars have been obtained by several authors (see Strassmeier et al. 2002) and accurate information on differential rotation rates have been obtained. Donati & Collier Cameron (1997) found that over a range of periods spanning two orders of magnitude, differential rotation depends very weakly if at all on rotation rate. For example, the equator of the young rapidly rotating star AB Dor despite a rotation period of about 12 h, and its non solar-like polar spots, laps high latitudes every 110 d; the Sun makes the same in 120 d.

3. Spectral images of stellar chromospheres

Starting from the early Eighties, thanks to UV, FUV and X-ray satellites, the investigation on stellar magnetic activity was extended to the outer stellar atmospheres. Maps of the chromosphere of RS CV-type stars with rotation rate $\leq$ 3 day have been obtained by monitoring the Mg II h&k lines by means of IUE (Walter et al. 1987; Neff et al. 1989; Busà et al. 1999; Pagano et al. 2001). As shown in Fig 2 irregularities in the emission line profiles due to patches of plasma at $T_e \sim 10^4$ K migrate from the blue to the red line wings with the star rotation. From their radial velocity curves it is possible to locate their longitudes and latitudes and/or their distances from the photosphere. In such a way, cool prominences have been found at distance of 1-2 stellar radii, and close to the Lagrangian point L1. For RS CVn-type stars and for rapidly rotating K giants, cool prominences extended up to 1–2 stellar radii have been also found by monitoring H_α lines (Frasca et al. 2000). Therefore, cool plasma ($T_e \sim 10^4$ K), probably confined by magnetic fields, is co-spatial with higher temperature plasma ($T_e \sim 10^7$ K) that embeds the circumstellar environment as suggested by X-ray data (e.g., Siarkowski et al. 1996).

4. Plasma dynamics in transition regions and coronae

High resolution UV spectra of magnetic active stars have been used to study the dynamic of the transition region and corona. The strongest transition regions lines ($T_e \sim 10^5$ K) of active stars show broad wings, as illustrated in Fig. 3 for the dM1e star AU Mic. As firstly suggested by Linsky & Wood (1994) these broad wings are analogous to the solar transition region explosive events (Dere et al. 1997) which can be considered a form of microflaring, a viable source of the outer atmosphere heating. The broad components in most active stars account for a relevant percentage of the total line emission (from 25% to 66%) as shown by Wood et al. (1997).

All of the F-K dwarfs and giants show that the resonance and intersystem lines are redshifted, and that the redshifts of the line centroids increase with increasing temperature of line formation up to 10^5 K or more (see Pagano et al. 2000 and references therein), as shown in Fig. 4-left panel for α Cen A. According to Teriaca et al. (1999), in solar active regions the lines formed in the range from $T \sim 2 \times 10^4$ K to $\sim 5 \times 10^5$ K are red-shifted, with a maximum of red-shift (about 15 km s^{-1}) at $\sim 10^5$ K, and blue-shifted at higher temperatures (about –10 km s^{-1} at $T \sim 10^6$ K). However, in the quiet Sun the maximum of Doppler shift is reached at a slightly higher temperature, $T \sim 1.9 \times 10^5$ K, and then decreases to a blue-shift of about –2 km s^{-1} at $T \sim 6.3 \times 10^5$ K. Transition region models computed for the Sun (Reale et al 1996) predict larger redshifts in regions permeated by strong magnetic fields than in quiet regions. However, stars like AU Mic, which has an average magnetic flux density much larger than the solar one, does not show the expected trend (see Fig. 4-right panel). Additional observations of M dwarfs are needed to determine whether this unexpected absence of a trend is a consequence of the strong magnetic field, high activity level, high gravity, or late spectral type.

UV spectra of cool stars include also lines formed at $\sim 10^7$ K, which permit measurements of line shapes and velocity shifts that

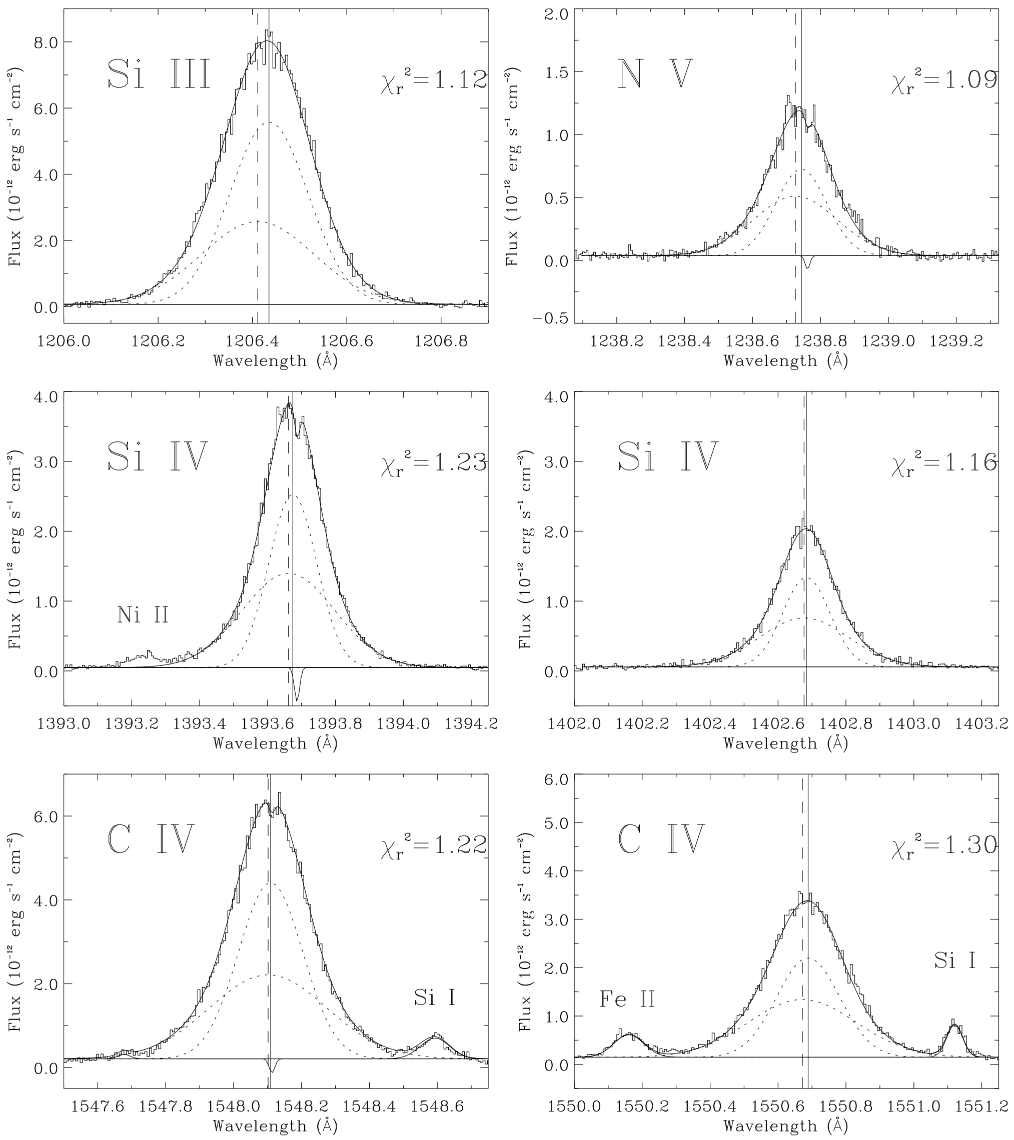

Fig. 3. The transition region lines of Si III, N V, Si IV, and C IV of the dM1e star AU Mic observed by HST/STIS (Pagano et al. 2000). As in other magnetic active stars, these lines show broad wings, that are interpreted as due to a diffuse background of microflares from plasma at T^5 K.

are not yet feasible with observations of other coronal emission lines in the EUV and X-ray spectral ranges. Ayres et al. (2003) have surveyed an extensive sample of late-type stars, and demonstrated that the known coronal iron forbidden lines (Fe XII and Fe XXI) occur in a wide range of active stars, at levels generally related to the soft X-ray flux. The Fe XXI 1354 Å feature is dominated by thermal broadening in most cases, and normally does not exhibit a bulk redshift (or blueshift). The general lack of bulk Doppler shifts in the Fe XXI fea-

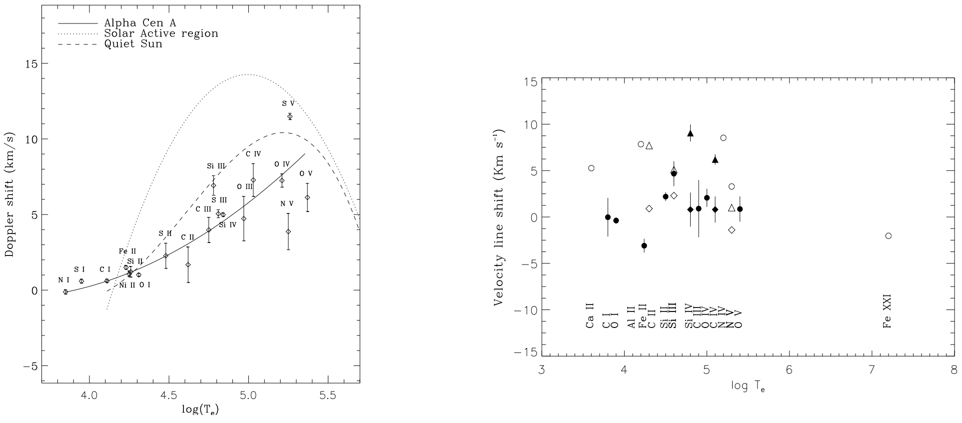

Fig. 4. Doppler shifts of chromospheric and transition region lines of α Cen A (left panel) and AU Mic (right panel) relative to the photospheric radial velocity as a function of the temperature of line formation.The dotted and dashed lines are fits to the Doppler shifts for a solar active region and the quiet Sun, respectively, by Teriaca et al. (1999). While α Cen A shows a solar like behavior, this is not the case for the more active dMe star AU Mic.

tures, as shown in Fig. 5 for AU Mic (Pagano et al. 2000), suggests that the hot, high emission measure zones in the stellar corona likely are trapped in confining structures, presumably analogous to solar magnetic loops. Any motions in such structures must be very subsonic and symmetrical (like a siphon flow).

5. Effects of stellar activity on extrasolar planets detection

In the forthcoming years space telescopes like COROT and Kepler will provide us with thousands of optical time series going from one month up to a few years with a sampling rate of a few tens of minutes and an accuracy of 10^{-6}–10^{-5} mag. The main purpose of such instruments is to detect Earth-like planets through the periodic light dimming produced by their transits across the disk of the parent star. Stellar activity is a potential source of noise in the detection of planetary transits because the rotational modulation of the active regions produces peaks in the Fourier spectrum of the time series at the rotation frequency and its harmonics that can hide the peaks produced by a planetary transit. In the case of the Sun, the transit of an Earth-like planet would produce a relative dimming of the order of 10^{-4} in the optical band, whereas active regions can produce variations with an amplitude about one order of magnitude larger. As show in Fig. 6, Lanza et al. (2003) demonstrated that the probability to detect a planet are increased if a Fourier analysis is performed on the residuals obtained by subtracting the best fit spot model from the observed light curve. Moreover, the capability to predict the light curve variability induced by stellar activity are a must for the preparation of the tools to best analyze photometric data acquired by the dedicated space missions.

6. Conclusions

I have presented here some of the results obtained by studing stellar magnetic activity in the framework of the solar–stellar connection. Most of our knowledge on cool star photospheres and coronae derives from the possibility to monitor stellar photometric and spectroscopic variability. Time is in fact a key parameter for highly not stationary phenomena

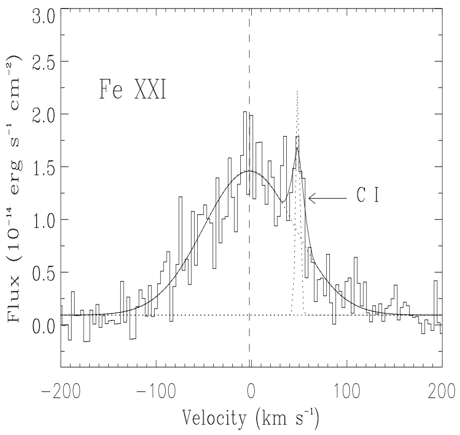

Fig. 5. The Fe XXI 1354 Å line profile and the blended C I line shown by an HST/STIS spectrum of AU Mic from Pagano et al. (2000). The radial velocity of the Fe XXI 1354 Å line is the same as the photosphere, indicating that the coronal plasma is nearly stationary and does not participate in the stellar wind. The non-thermal width of the Fe XXI resulted subsonic, therefore no supersonic turbulent motions are at work in the corona, hence shock waves are not an important heating mechanism in this corona.

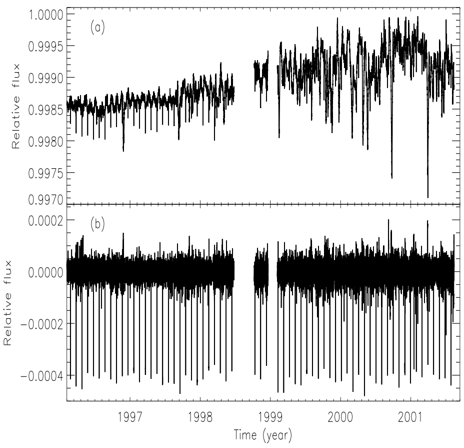

Fig. 6. Panel a: the Total Solar Irradiance light curve, as measured by SoHO/Virgo, with superposed the transit of an Earth-like planet of radius $R = 2.3R_{\oplus}$ and orbital period of 30.0 d. Panel b: the same time series after subtracting the best model light curve (from Lanza et al. 2003).

as those at work in stellar outer atmospheres. However, only a few monitoring data are available up to date for stellar chromospheres and transition regions. A great contribution to the investigation on stellar activity, from pre-main-sequence to late phases of stellar evolution, would come from future UV/FUV telescopes, e.g., WSO/UV (Pagano et al. 2003), provided with high resolution spectroscopy and deep imaging instruments but also capable to supply monitoring data.

Acknowledgements. I want to thank all colleagues of the Catania Cool Stars Group (http://www.ct.astro.it/coolstars/) in collaboration with whom my research on stellar activity is everyday conducted.

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