HIGH-RESOLUTION SPECTROSCOPY OF COOL STARS AT ESO

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Abstract. We present an overview of the instrumentation presently available at La Silla for high-resolution spectroscopy, and we discuss several programs that have been carried out recently using these instruments. Discussed topics include the determination of chromospheric radiative losses in the Ca II H and K lines and in Hα, the search for rotational modulation in Hα and in the Li I 6708 Å line, the measurement of stellar rotation rates, and the investigation of Lithium abundance in RS CVn binaries and other chromospherically active stars.

1. Introduction

Over the past decade the study of F to M stars has enjoyed a veritable renaissance. Observations from space at X-ray and UV wavelengths have definitely proved that cool stars have chromospheres, coronae, and winds similar to those observed on the Sun, although often on a much more energetic scale. Optical photometry and spectroscopy from the ground have revealed a wealth of activity phenomena, such as spots, plages and flares, that are likely due to the emergence of magnetic fields at the stellar surface. Radio observations with improved sensitivity have shown that many types of cool stars, including M dwarf flare stars, RS CVn binaries, and pre-main sequence objects, are often strong sources of variable non-thermal radio emission.

High-resolution optical spectroscopy plays a central role in the study of the physics of cool stars. Much of the physical information is contained in lines that are easily accessible from the ground provided the suitable instrumentation is available. In many cases, the physical information is contained in subtle modifications of the line profiles or in spectral features that are either very weak, or blended with other lines. Therefore high resolution and high S/N observations are required in order to extract the physical information contained in the data.

Recent developments in detector technology, together with the availability of an increasing number of high-resolution spectroscopic facilities at several places in the world, have greatly improved our capability of using optical data to address the basic questions of
Figure 1. A summary of the possible configurations for high resolution spectroscopy presently available at ESO La Silla.
cool star research. New improved techniques, such as Doppler imaging, Fourier analysis of line profiles, spectral synthesis, Zeeman spectroscopy and the study of line bisectors, have become accessible for use on observational data. These new techniques, and the astrophysical results obtained by using them, are illustrated in other contributions to this volume. In this paper we follow a different approach. We focus on only one spot (the European Southern Observatory at La Silla, Chile) and we discuss the kind of high-resolution work that can be done for cool stars using the instrumentation available there. In so doing, we will be guided by our own research and by the experience we have gained as users of ESO facilities over a period of several years.

2. Instrumentation for high resolution spectroscopy at ESO

The European Southern Observatory at La Silla, Chile, has one of the worldwide most powerful batteries of spectrographs and telescopes for high resolution spectroscopy. With the exception of extremely high resolution ($R \geq 3 \times 10^5$), ESO provides the whole range of resolving powers from $R \approx 3 \times 10^4$ up to $R \approx 2 \times 10^5$, several choices for wavelength coverage and the possibility, using 4m class telescopes, of reaching faint objects. In this contribution we will not consider the EMMI spectrograph at the NTT telescope, which will greatly enhance the actual ESO capabilities.

The spectrographs available at present are basically three, but they can be used in several combinations of telescopes, cameras and detectors, giving different characteristics and performances. The possible combinations are given in Fig. 1. In order to show in some detail the capabilities of the three instruments we will discuss each of them separately on the basis of our experience. More technical information can be found in the ESO Operating Manuals (Pasquini and D'Odorico 1989, Lindgren and Gilliotte 1989a, b).

2.1. The Cassegrain Echelle Spectrograph (CASPEC)

CASPEC is mounted at the cassegrain focus of the 3.6m telescope. The echelle orders are cross dispersed by a grating producing two dimensional formats. The compression of orders allows a large wavelength coverage per frame (900-1000 Å with the short camera and a 16×10 mm chip), combined with a quite high resolving power ($R = 3 \times 10^4$ for a 15×15 μm pixel and the short camera). This coupling of large spectral coverage per frame and high resolution, together with the capability of observing relatively faint objects, is one of the most useful features of the instrument. With larger format CCD's it will be possible to get up to 1500-2000 Å in one frame. If, instead of the short camera, the long camera is used, the instrument resolving power is doubled, but the size of the CCD's presently available at La Silla does not allow a perfect order overlapping, and gaps between adjacent orders are present.

CASPEC has been used for many kinds of investigations, ranging from the determination of stellar abundances (e.g. Spite and Spite 1987, Gratton and Sneden 1988, Magain 1989, Molaro and Bonifacio 1990), to accurate radial velocity determinations (Dubath et al. 1990) and the study of chromospheric activity in M dwarf stars and T Tauri stars (Finkenzeller and Basri 1985, Pasquini et al. 1990). Particularly relevant with respect to the latter topic is the fact that CASPEC enables the observation of many interesting lines simultaneously. Fig. 2a, for instance, shows the Ca II H and K and the Balmer Hγ, Hδ,
He lines in the relatively faint dM3.5e star LDS 587b (V = 12.8) observed simultaneously in one CASPEC frame (2 hour integration, RCA high resolution CCD). Fig. 2b shows the He I 5876 Å, the Na D1 and D2 and Hα lines observed simultaneously in the same star just one hour after the spectra shown in Fig. 2a (CASPEC + RCA high resolution CCD, 30 minutes integration).

The use of a 2-dimensional echelle format allows high resolution and large spectral coverage, but has some inconveniences that are more severe than for other, more conventional spectrographs. For instance:

a) the inclination of the orders makes it difficult to obtain a precise order extraction. A sophisticated software is necessary for extracting the maximum of the information contained in the data.

b) The non-perfect mechanical stability of the spectrograph (we remind that the spectrograph is mounted at the bottom of the telescope and moves together with it) may produce small order shifts (by 0.5-1 pixel) during long integrations. In order to take them into account wider flat fields must be taken, with the telescope at the position of the object.

c) The spectrograph presents a conspicuous interorder scattered light (up to the 5% level). This inconvenience is somewhat compensated by the wide order separation, that allows evaluation of this effect even in the blue (where the orders are more packed together).

The observer ability of correcting for these effects will at the end determine the real quality of the data. The MIDAS echelle package provides several options for the reduction of CASPEC data. The package is under constant updating and a manual for echelle reduction should be available shortly. In any case, the proper reduction of echelle data requires long time and experienced observers.

The limiting magnitudes for CASPEC are strongly dependent on the wavelength region observed and on the chip used. For low S/N observations the limiting factor is the detector read out noise (RON). A new CCD is available for CASPEC (Tektronix 27×27 μm pixel size, RON = 8 e−/pixel). With this chip and the short camera it is possible to obtain spectra of 17th magnitude objects with S/N ≈ 5 in 1 hour integration at R=20,000. Although observations with very low S/N are generally not very used for stellar spectroscopy, they can be the optimum for special applications. For instance, using software masking and cross correlation techniques, it is possible to obtain accurate radial velocities from spectra covering large wavelength ranges but having S/N of ≈2 (Dubath et al. 1990). In a case like this, CASPEC could provide useful data for stars as faint as 19th magnitude with longer exposures and/or lower RON chips.

2.2. The Coudé Echelle Spectrograph (CES)

The CES, with all its possible combinations, is one of the most powerful high resolution spectrographs in the world. The maximum reachable resolving powers range from R≈ 6×10^4 (short camera + CCD) up to R ≈ 2.4×10^5 (scanner with double pass). With the latter configuration it is possible to obtain data of extremely high quality, approaching the resolving power and S/N typical of solar data. Although the scanner can be used only for observing very bright stars, and the wavelength coverage for each observation is only a few Å, the detailed study of a few bright objects is fundamental for the interpretation of
Figure 2a. (see caption on next page)
Figure 2. (cont’d from previous page) Spectra of the dMe star LDS 587b obtained simultaneously in various spectral lines using CASPEC. a) Ca II H and K and Balmer Hδ, Hγ and Hε lines; b) He I 5876, Na D₁ and D₂ and Hα lines. All spectra in Fig. 2a were obtained in one exposure. The spectra in Fig. 2b were obtained one hour after those of Fig. 2a (from Pasquini, Bouchet and Gouiffes 1990).
lower resolution data, for resolving stellar blends and, in general, for the study of stellar atmospheres (e.g. Kurucz 1990). For instance, by applying techniques such as the study of line bisectors, Dravins and coworkers have performed a detailed study of stellar granulation in late-type stars (see Dravins 1987a, b, 1990).

The CES is mounted at the coudé focus of the CAT 1.4m telescope and this spectrograph is the only one permanently used at La Silla. The discussion of all possible uses of this instrument is beyond the scope of this paper, but we will give several examples in the following sections. Trying to summarize the main CES features, we can say that:

a) it provides very high resolving power;
b) the instrumental response is very clean;
c) it presents a very low level of scattered light and is very stable;
d) it has a good peak efficiency, around 15 %;
e) although covering only one order per frame (≈ 30-80 Å), it can easily be moved from one wavelength to another in a few minutes.

With the short camera and CCD, the combination CAT+CES is very powerful when working close to the spectrograph + detector peak efficiency: for instance, at a resolving power of 60,000, a S/N of 100 can be obtained for a 10.5th magnitude object in 2 hours integration. With the Long Camera and CCD at the maximum resolving power (≈ 100, 000), the limiting magnitude is ≈ 9.5, while it drops to ≈ 7.3 for the Long-camera with Reticon detector at R=100,000. Only very bright stars can be observed with the scanner (the limiting magnitudes are ≈ 4.0 and 2.5 in single and double pass, respectively). The above numbers (which refer to a S/N of 100 and 2 hours integration time) should be taken as indicative, since they strongly depend on the seeing and the global efficiency (including the echelle blaze) at the selected wavelength.

As an example, we show in Fig. 3 six one-hour spectra of the FU Ori star Z CMa in the Na D1 and D2 lines taken in six successive nights. In one hour integration it was possible to obtain a S/N of ≈ 130 for this 9th magnitude object at the spectral resolution of 0.1 Å. The high resolution and S/N of these spectra should allow a detailed study of the variations in the line wings induced by the presence of a variable, strong, stellar wind (Pasquini and Reipurth 1990).

A new possibility has been implemented two years ago for the CES. The 3.6m telescope can in fact be connected to the CES via optical fibres (D’Odoro et al. 1990). This configuration gives a gain of 1 to 1.5 magnitudes with respect to what obtained using the CAT (the exact value depends on the selected central wavelength). Although this improvement may seem small, it opens entirely new perspectives in high-resolution spectroscopy of faint stars.

When used with the CAT and CCD detector, the CES suffers one strong limitation: it is not easy to obtain extremely high S/N ratios (≥500). The flat fielding procedure becomes in fact the real limiting factor. There are two reasons for this:

a) the RCA CCD used with the CES shows residual pixel to pixel variations (on the order of 0.2 %) which are not easily eliminated, unless the spectrum is spread over many CCD columns. The causes of this behaviour are not yet fully understood;
b) the flat field obtained using an internal lamp follows a slightly different light-path than the light from the star, thus illuminating the slit in a different way.

Mem. S.A.It., 1990
Figure 3. Six one-hour spectra of the 9th magnitude FU Ori star Z CMa in the Na D line region obtained on six consecutive nights using the CES (from Pasquini and Reipurth 1990).
So far the most successful method for flat fielding CES spectra has been to observe early-type stars as close as possible in position to the objects under investigation, trailing them along the slit. Apart from the fact that this procedure cannot be used for all spectral regions, it is very time consuming. Following the experience gained with the fibre link to the 3.6m telescope, ESO is planning to implement a fibre link also between the CAT and the CES. This link will allow a far more precise and stable flat field correction as well as the collection of the total stellar light by using an image slicer and spreading the spectrum over several CCD columns. In this way it will be possible to obtain very high S/N spectra using only one frame. The installation of fibres will also eliminate possible misalignments between the telescope and the spectrograph light paths caused by the frequent earthquakes affecting La Silla.

2.3. The ECHELEC spectrograph

For many years the coudé spectrograph at the 1.5m ESO telescope has been used for stellar spectroscopy (i.e. Dravins 1981) and we were probably among the last users of this instrument (Pasquinii and Pallavicini 1990). Although the optical quality and efficiency of the spectrograph (especially in the blue) were quite good, the advent of linear, more sensitive detectors has made this instrument, which worked with photographic plates, obsolete. As substitute ESO has renewed the ECHELEC, a coudé spectrograph with echelle cross dispersed format. The output format is very similar to that of CASPEC, the major difference being that the ECHELEC interorder space is much larger and therefore the covered wavelength range per frame is only $\approx 250 \, \text{Å}$. The maximum achievable resolving power is around $3 \times 10^4$ and the limiting magnitude around 9. It can be used only for wavelengths bluer than $\approx 5500 \, \text{Å}$ and when the central wavelength is chosen, it cannot be changed during the night. Although it is a very stable instrument, it presents several problems which are inherent to cross dispersed spectrographs (see the discussion of CASPEC above), enhanced by its peculiar optical light path. With respect to the other two spectrographs, the ECHELEC definitely presents more serious problems. Nevertheless, it has been widely used for several studies in which a broad spectral range was required and the use of the CES would have resulted too time consuming. It is typically used for stellar abundance and radial velocity measurements. Because of its good blue response, it is also suitable for the determination of chromospheric emission in the Ca II H and K lines (e.g. Tagliaferri et al. 1990).

A study is presently being carried out at La Silla to look for a possible replacement of this instrument with a more versatile and efficient one, that could offer a larger choice of resolving powers and wavelength ranges.

3. Ca II H and K emission

In the study of stellar activity, the H and K lines of Ca II are probably the best studied lines. The reason for this is largely historical: sensitized photographic plates have a relatively good blue efficiency, and the Ca II H and K lines with their short wavelengths (3968 and 3933 Å, respectively) were easily accessible to these detectors. This is also a more physical reason: because of the peculiar flux distribution of late-type stars, the Ca II lines show, for a fixed amount of chromospheric flux, the largest line-to-continuum contrast with
Figure 4. Ca II H and K spectra of cool stars obtained with the CES (upper panel, from Pasquini, Pallavicini and Pakull 1988) and with the coude spectrograph at the 1.5m ESO telescope (lower panel, from Pasquini, Pallavicini and Dravins 1989) The high-resolution CES spectrum in the upper panel was obtained by combining two different exposures centered at the H and K line, respectively.
respect to all other chromospheric lines in the visible spectrum. Chromospheric activity in late-type stars, therefore, is most easily detectable in these lines.

Several investigations of Ca II emission in late-type stars have been carried out by us and other groups using high-resolution observations obtained with various spectrographs at La Silla (Pasquini et al. 1988, 1989, 1990, Pasquini 1990a, Crivellari et al. 1987, Rebolo et al. 1989). Examples of the Ca II H and K profiles obtained with the Coudé Spectrograph at the 1.5m ESO telescope and with the CES are given in Fig. 4.

The primary purpose of our work was to enlarge the sample of stars for which absolute chromospheric fluxes at the star surface were available. It is important to note, in fact, that most studies of Ca II lines carried out in the past were based on narrow-band photometry and relative fluxes (see, for instance, the Mt. Wilson \(R_{HK}\) index, Noyes et al. 1984). Although useful for other purposes, those data are not suitable for comparing stars of different colours and for detailed chromospheric modelling. Absolute surface fluxes, instead, have the advantage of allowing a comparison between stars of different spectral types and luminosity classes, independently of other stellar parameters such as radius and effective temperature. A calibration of the Ca II lines in absolute flux units was developed by Pasquini, Pallavicini and Pakull (1988) on the basis of the narrow-band photometry of Catalano (1979). This calibration utilizes the pseudo-continuum at 3950 Å as a reference point and can be used with spectra that encompass only a narrow spectral range such as those obtained with the CES (for which the available spectral range is only \(\approx 30\) Å). This calibration has been shown by Pasquini, Pallavicini and Dravins (1989) to be in good agreement (to within \(\approx 20\)% with that of Linsky et al. (1979), which uses a larger passband.

Since the absolute fluxes derived using the Pasquini et al. (1988) calibration are based on a comparison between the intensities of the H (or K) central reversals and of the pseudocontinuum at 3950 Å, it is extremely important to verify that the flat fielding procedure does not introduce spurious trends between line center and the reference point. This point has been discussed in detail by Rebolo et al. (1989) who found a systematic “tilt” in the Ca II H spectra obtained by them with the CES. The good agreement found between the K line fluxes determined by Pasquini et al. (1988) and those of other authors for the stars in common, shows that this effect was not significant in the Pasquini et al. sample. In general, however, a careful observational strategy needs to be adopted in order to derive accurate values of Ca II H and K line fluxes when using a spectrograph like a CES with only a narrow spectral range available (see Pasquini 1990a for details).

Once the spectra have been calibrated, two additional steps are necessary in order to derive chromospheric radiative losses in the Ca II lines. First, the emission in the central line core must be measured by integrating the line profile between the \(K_1\) minima. This measurement requires a spectrograph with good efficiency and spectral resolution and very low level of scattered light. The Ca II emission core in quiet stars can be, in fact, only a few percents of the adjacent pseudocontinuum, though being much larger for the most active stars. Secondly, the photospheric contribution must be subtracted from the total flux in the line core. Generally this subtraction is done by using computed photospheric models (Kelch et al. 1978, 1979). With these techniques, new Ca II K line absolute fluxes have been determined for nearly 200 stars, covering a large fraction of the cooler half of
Figure 5. H-R diagram for evolved stars with Ca II K line absolute fluxes measured from high-resolution spectra. Evolutionary tracks for several initial masses are superimposed. Different symbols refer to different levels of chromospheric activity (from Pasquini, Brocato and Pallavicini 1990).

Figure 6. Separation of the Ca II K$_1$ minima and of the K$_2$ emission peaks as a function of the K$_3$ central intensity for an unbiased sample of solar-type stars. Solar data are also shown for comparison. Open squares indicate stellar data, filled squares the values for the Sun at maximum and minimum activity, and filled triangles the data for three solar plages (from Pasquini 1990a).

Another motivation for Ca II H and K line spectroscopy comes quite naturally: high-resolution observations are needed for all problems that cannot be tackled with narrow-band photometry or low-resolution spectroscopy. A good example, for instance, is the study of evolved stars. For these stars, narrow-band photometry or low-resolution spectroscopy do not provide reliable chromospheric indices (the emission core can be in fact as wide as several Å) and do not allow the detailed study of line asymmetries, stellar winds and mass losses. They also do not provide a precise measurement of the width of the Ca II emission core, which is a sensitive indicator of the stellar absolute magnitude (Wilson and Bappu 1957). By using high-resolution spectroscopy and the Wilson-Bappu width, Pasquini, Brocato and Pallavicini (1990) were able to construct an HR diagram for evolved stars with measured Ca II chromospheric fluxes. This diagram is shown in Fig. 5 where different symbols indicate stars with different levels of chromospheric activity.

In Fig. 5 we have also plotted for comparison theoretical evolutionary tracks for stars of different masses and solar abundances, computed according to Brocato et al. (1989) and Castellani et al. (1990). Stars indicated by filled symbols have high chromospheric fluxes (typically larger than \( \approx 10^6 \) erg cm\(^{-2}\) s\(^{-1}\)), while stars indicated by open symbols have low chromospheric fluxes (typically lower than \( \approx 10^5 \) erg cm\(^{-2}\) s\(^{-1}\)). Stars indicated by asterisks are intermediate between these two groups and have chromospheric fluxes roughly comparable to the Sun. The comparison with evolutionary tracks show some interesting trends. Low mass stars ascending the Red Giant Branch (RGB) show very low levels of chromospheric activity, while massive yellow supergiants appear chromospherically very active. These trends can be interpreted in terms of dynamo-driven activity and suggest that magnetic fields are important for the heating of stellar chromospheres in yellow supergiants. These massive stars do not suffer magnetic braking while on the main-sequence; they show enhanced chromospheric activity only when they move out of the main sequence and develop an outer convective zones. Low-mass stars, on the contrary, have already suffered magnetic braking during main-sequence lifetime (e.g. Skumanich 1972) and cannot sustain a vigorous dynamo process during the subsequent RGB phase.

The use of high-resolution spectroscopy (at \( R = 60,000 \)) and the possibility of obtaining a sufficiently high S/N ratio (\( \geq 50 \)) at the bottom of the deep Ca II lines allow a quantitative comparison between stellar data and high-resolution solar data. This is important in order to determine to what extent the solar analogy can be applied to other stars. With this in mind, Pasquini (1990a) selected a volume limited sample of southern G-type stars and measured their chromospheric Ca II K line fluxes using the CES with short-camera and CCD detector. The results have been compared with solar full-disk data obtained at different epochs during the solar cycle (White and Livingston 1981) as well as with spatially resolved Ca II data (Shine and Linsky 1972). In Fig. 6 we show the separation of the \( K_1 \) minima and of the \( K_2 \) emission peaks as a function of the \( K_3 \) central intensity. Open squares indicate stellar data, filled squares the values for the Sun at maximum and minimum activity during cycle 21, and filled triangles the data for three solar plages. In spite of the large scatter for low activity stars, there is a good similarity between the behaviour of solar and stellar data. Note also that the most active stars in the sample behave similarly to solar plages, thus indicating that a large fraction of their surface must
be covered by active regions similar to those observed on the Sun.

4. \( \text{H}\alpha \) emission

In principle, \( \text{H}\alpha \) can be an excellent chromospheric indicator for several reasons:

a) the \( \text{H}\alpha \) spectral range is easily accessible to modern solid-state detectors, like Reticon and CCD’s;

b) the energy distribution for late-type stars favours observations in this region rather than, e.g., in the Ca II H and K lines;

c) radiative losses in the \( \text{H}\alpha \) line may be a dominant cooling term for the chromospheres of late-type stars and active systems, as indicated by the prominent \( \text{H}\alpha \) emission of dMe stars and some RS CVn binaries.

For these reasons, increasing attention has been devoted recently to the \( \text{H}\alpha \) line (see review by Bopp 1990 elsewhere in this volume). In normal stars, a filling-in of the \( \text{H}\alpha \) core by chromospheric activity is often observed (Cayrel et al. 1983, Zarro and Rodgers 1983). For solar-type stars, Herbig (1985) was able to quantify this effect in terms of net chromospheric fluxes at the star surface and showed that these fluxes correlate well with the Ca II H and K line. In more active systems, such as RS CVn binaries, the \( \text{H}\alpha \) line is usually filled-in and occasionally appears in emission. This is typically the case for the most active RS CVn systems as well as for T-Tauri stars (Bopp 1990, Basri 1990).

Observations in the \( \text{H}\alpha \) line have been carried out at ESO for various classes of southern late-type stars. The purpose was twofold. First, we wanted to estimate the contribution of the \( \text{H}\alpha \) line to the total energy budget of stellar chromospheres, and see how this contribution varies with spectral type; secondly, we wanted to investigate \( \text{H}\alpha \) emission in chromospherically active stars, including southern RS CVn candidates and "post-T Tauri" stars.

4.1. Stellar surveys in \( \text{H}\alpha \)

An extensive survey of \( \text{H}\alpha \) emission has been carried out in a sample of 85 dwarfs and subgiants of spectral type F8 to K5 (Pasquini and Pallavicini 1990). Several ESO instruments were used, including the Coudé Spectrograph at the 1.5m ESO telescope with photographic plates as well as the Coudé Echelle Spectrograph (CES) at the 1.4m CAT. With the latter, both the Short- and the Long-Camera were used with, respectively, a CCD detector and the Reticon. Most of the data were obtained with the CAT + CES + Short Camera + CCD at a resolving power \( R \approx 60,000 \). These are also the data of best quality in the sample. A few examples of the acquired spectra are given in Fig. 7 where stars of similar spectral type, but different levels of chromospheric activity are compared.

In order to derive \( \text{H}\alpha \) absolute chromospheric fluxes, we have developed a calibration procedure similar to that developed by Linsky et al. (1979) for the Ca II H and K lines. The calibration is based on narrow-band photometry and utilizes a 50 \( \text{Å} \) interval which extends from 6550 to 6600 \( \text{Å} \). The most critical step in the calibration procedure is the subtraction of the underlying photospheric contribution, which is not as well defined as for the Ca II H and K lines. Theoretical models, that have been successfully applied to these lines, do not appear sufficiently accurate for \( \text{H}\alpha \). Also empirical procedures, such as comparison with inactive stars of similar spectral type, are not accurate enough, because
Figure 7. Hα spectra of F8 to K5 stars obtained using the CES. Stars of similar spectral type but different levels of chromospheric activity are plotted in each of the four panels (from Pasquini and Pallavicini 1990).
all stars, even the quietest ones, appear to have some degree of chromospheric emission.

The procedure we have used is similar to that proposed by Herbig (1985) for solar-type stars and, in fact, extends his method to cooler objects. It relies on the use of the Ca II K line as a primary chromospheric indicator and on extrapolating the Hα vs. Ca II flux-flux relationships to zero chromospheric flux. Even so, the correction for the underlying photospheric contribution cannot be determined very precisely especially for K stars. The obvious conclusion is that Hα, while appearing a good activity indicator in a qualitative sense, is difficult to use in a quantitative way. The contrast between active and inactive stars is typically much smaller in Hα than in the Ca II lines, thus requiring data of extremely high quality to allow a reliable estimate of chromospheric radiative losses.

In spite of these difficulties, the survey has provided some interesting results. For instance, we have found evidence that the ratio of Hα to Ca II K line radiative losses increases towards cooler stars, suggesting that this effect, which is well known to be prominent in M dwarfs, may be already significant for K stars. This is shown in Fig. 8 where we plot the ratio of Hα to Ca II K line fluxes vs. the colour index (V-R). We also plot in the same figure (filled symbols) the mean ratios for different spectral types, together with their ±1σ standard deviations. While this ratio appears to be approximately constant at a value ≈ 0.5 for stars bluer than (V-R) = 0.73, it is significantly larger (≈ 1) for K3-5 stars. Note however the large scatter, and the fact that our conclusion depends critically on our ability to correct for the photospheric contribution. More observations of K stars, especially at the latest spectral types, should be carried out to confirm the trend emerging from Fig. 8.

For solar-type stars, we find a strong similarity between our stellar data and observations of spatially resolved solar regions. The filling-in of the Hα core observed in active stars is comparable to that observed from solar plages. The flux-flux diagrams have similar slopes as for the Sun, with Hα emission increasing more slowly than Ca II emission for increasing stellar activity. This suggests, in agreement with results from the analysis of Ca II and ultraviolet lines (Cappelli et al. 1989, Pasquini 1990a), that in order to explain the chromospheric emission of the most active stars it is necessary to postulate the presence of stellar plages analog to the brightest ones observed on the Sun, covering a large fraction of the stellar surface.

More recently, several Hα surveys of Li-rich K-type giants and of post-T Tauri candidates have also been started. The observations are being obtained with the CAT + CES + Short-Camera + CCD at a resolution of 50,000, as well as at lower resolution with the ECHELEC at the 1.5m telescope and with the Boller & Chivens spectrographs at the 2.2m and 1.5m telescopes. The purpose of these observations is to investigate the relationship between Li abundance and chromospheric activity, as well as to indentify pre-main sequence objects among field stars. An important class of these stars are the “post-T Tauri” or “naked-T Tauri” stars, i.e. stars that are still approaching the main-sequence, but have lost the circumstellar envelopes (and hence the most extreme properties) of classical T-Tauri stars. Lindroos (1986) has suggested to search for post-T Tauri stars among visual binaries with early-type primaries and late-type secondaries. Since the two components of the binary have the same age, it is likely that the late-type companions are still approaching the main sequence. An extensive survey of Lindroos’ stars both in Hα and in the Li 6708 Å line has been carried out by Pallavicini, Pasquini and Randich (1990). Similarly,
**Figure 8.** Ratio of $\mathrm{H}\alpha$ to Ca II K line absolute surface fluxes vs. (V-R) colour index for a sample of F8 to K5 dwarfs. Filled symbols indicate mean values and associated $\pm 1\sigma$ dispersions for stars of various spectral types (from Pasquini and Pallavicini 1990).

**Figure 9.** $\mathrm{H}\alpha$ profiles of the spotted star AB Dor (HD 36705) at different phases. Deep absorption occurs at the time of maximum spot visibility, while the profile goes into emission around the maximum of the photometric light curve. The data were obtained using the CES and CCD detector (from Cutispoto and Pallavicini 1990).
Tagliaferri et al. (1990) have carried out spectroscopic observations in Hα, Ca II and Li I for a sample of X-ray selected stars detected serendipitously by the EXOSAT satellite. This sample of X-ray bright objects is expected to include a large fraction of active stars, including RS CVn binaries and post-T Tauri stars.

4.2. Variability of Hα emission

Emission in the core of the Hα line is believed to originate from chromospheric plages on the surface of active stars. On the Sun, bright chromospheric plages are often, though not exclusively, associated with dark spots and it is likely that the same occurs also for stars. If spots and plages are distributed non-uniformly over the stellar disk, one would expect to see rotational modulation in broad-band photometric data and in Hα. Moreover, if plages are closely associated with spots, the variations of Hα line emission should be in antiphase with the photometric variations (i.e. maximum Hα emission should occur at the minimum of the photometric light curve). Previous observations have sometimes confirmed the above predictions (e.g. Nations and Ramsey 1980). More often, however, the observations have provided contradictory results which have been attributed either to intrinsic short-term variability in Hα or to a complex distribution of spots and plages over the stellar disk (see Bopp 1990).

In order to investigate whether Hα variations were indeed correlated with photometric variations, simultaneous photometric and spectroscopic observations were carried out at ESO in December 1989 (Cutispoto and Pallavicini 1990). Four "spotted" stars were observed (HR 1099, YY Men, AB Dor and IL Hya). The photometric observations were carried out over a three week period using the 50cm ESO telescope equipped with a single-channel photometer and standard UBV(RI) filters. Spectroscopic observations in the Hα line were obtained with the CAT + CES + CCD over five consecutive nights simultaneously with the start of the photometric observations.

All stars showed clear photometric variations with amplitude of \( \approx 0.1 \) to 0.2 magnitudes. Significant changes with phase were observed in the profile of the Hα line, which were most likely produced by surface inhomogeneities. Except for AB Dor, the observed profile variations did not change the general appearance of the Hα line, which was in emission in HR 1099 and YY Men and in absorption (partially filled) in IL Hya. Also the equivalent width of the line changed little. Striking variations were observed instead for AB Dor in which the Hα profile changed from deep absorption to emission at different phases (see Fig. 9).

Twelve Hα spectra were obtained for AB Dor which covered all phases from the optical maximum to the minimum. During this period, the Hα profile changed gradually showing that the observed variations were not chaotic but were due instead to the star rotation. Contrary to expectations, the variations of the Hα line were in phase with the photometric light curve, i.e. Hα emission was at maximum at the time of minimum spot visibility. Detailed comparison of the photometric and spectroscopic data shows in fact that the Hα profile was in absorption at the minimum of the photometric light curve, and reversed to emission at the time of minimum spot visibility.

The results obtained for AB Dor contrast with the simple picture of a single hot plage closely associated in space with a cool spot. Rather, they suggest a more complex distri-
bution of hot and cool regions over the surface of the star, the bright plage regions being apparently the dominant features on the hemisphere of the star opposite to that dominated by the dark spots. Alternatively, the deep absorption profiles observed at the time of maximum spot visibility could be produced by the passage of dense clouds of absorbing material such as those found for AB Dor by Collier Cameron and Robinson (1989). If this is the case, our observations provide evidence that this prominence-like corotating Hα clouds are preferentially associated with the spotted hemisphere of the star.

5. Rotation

The determination of rotational velocities for late-type stars is important for many reasons. For instance, knowledge of stellar rotation rates appears to be essential for investigating the processes of chromospheric and coronal heating, and the origin of surface activity in cool stars. It is generally believed, in fact, that surface activity results from magnetic fields that are generated by a dynamo mechanism that involves rotation and convection (see, e.g., Pallavicini 1984). Chromospheric Ca II emission and coronal X-ray emission have both been shown to correlate with rotation in late-type stars (Pallavicini et al. 1981, Noyes et al. 1984), but larger samples need to be investigated in order to determine the exact functional form of this dependence. Unfortunately, the determination of rotational rates for late-type stars is by no means a trivial task.

The intrinsic breadth of absorption lines in the solar spectrum is \( \approx 7 \text{ Km s}^{-1} \), while the rotational velocity of the Sun is only \( 2 \text{ Km s}^{-1} \). Hence, rotational broadening in late-type stars is generally a subtle effect. In addition, at the typical rotational velocities expected for G and later type stars, other broadening mechanisms, such as macroturbulence, become comparable to rotation. It is important, therefore, to have high-resolution, high S/N observations as well as sophisticated techniques of line profile analysis that allow separation of macroturbulence and rotation. These techniques have been developed by a number of authors (e.g. Smith and Gray 1976, Gray 1981 and 1982, Soderblom 1982).

The CES is an ideal instrument for determining accurate values of \( \text{V}_{\text{sin} i} \) for slowly-rotating late-type stars. With this instrument, rotational velocities \( \text{V}_{\text{sin} i} \) have been measured for a sample of 87 stars of spectral type F5 to K5 and luminosity classes III, IV and V (Gray and Pallavicini 1989, Soderblom, Pendleton and Pallavicini 1989, Pallavicini and Soderblom 1990). The observations were obtained using the Long-Camera and the Reticon detector at a nominal resolving power of \( 1 \times 10^5 \). Spectra were obtained at central wavelengths of 6020, 6250 and 6450 Å. These spectral regions are rather clean and contain a number of unblended, intermediate-strength lines that are particularly suitable for the measurement of rotational velocities. In a few cases, spectra centered near the Li I 6708 Å line were also used. In this case, the analysis was done using the Fe I line at 6705 Å.

The technique used for extracting rotational velocities is based on the comparison of the observed profiles with a grid of computed profiles obtained by artificially broadening a narrow line absorption spectrum derived from stellar model atmospheres. The broadened profiles take into account the effects of both rotation and macroturbulence. In order to discriminate between competing broadening mechanisms, the comparison is better made in the Fourier domain, taking advantages of the fact that profiles broadened by different mechanisms have distinctly different Fourier transforms.

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Figure 10. Rotation rates $v \sin i$ and radial-tangential macroturbulence velocities $\zeta_{RT}$ for class III giants. Solid squares indicate data obtained with the CES and Reticon detector, open circles indicate coude data from the University of Western Ontario and the McDonald Observatory (from Gray and Pallavicini 1989).
The results for class III giants confirm the low rotational velocities typically observed for these stars. In Fig. 10 we have plotted the new measurements for giants (Gray and Pallavicini 1989, filled symbols) together with the results of a larger sample observed at the University of Western Ontario and the McDonald Observatory (Gray 1989). All data have been reduced using the same technique. As shown in the figure the observed velocities are all lower than 7 Km s\(^{-1}\) and tend to decrease towards later spectral types. The derived macroturbulent velocities for giants are in the range \(\approx 4-7\) Km s\(^{-1}\). The rotational velocities of G and K dwarfs are also typically low (a few Km s\(^{-1}\)), although in a few cases rotational rates as high as \(\approx 10\) Km s\(^{-1}\) have been observed (Pallavicini and Soderblom 1990). These more rapidly rotating stars are typically younger objects with high chromospheric activity. Some of the new ESO data, together with data from Lick and Kitt Peak, have been used by Soderblom, Pendleton and Pallavicini (1989) to provide a list of F and G standard stars to be used for measurements of stellar rotation using cross-correlation techniques. The inclusion of F stars in the sample allows coverage of a broader range of rotational velocities, up to \(\approx 50\) Km s\(^{-1}\). For stars rotating faster than \(\approx 10\) Km s\(^{-1}\), use of cross-correlation techniques and standard stars is in fact a simpler and efficient way for determining stellar rotation rates.

6. Lithium abundance

It has been known for a long time that the abundance of Lithium in population I stars depends on both mass and age (e.g. Herbig 1965). The current interpretation is that Lithium is progressively depleted by the action of convective currents that transport Li-rich surface material to deeper layers, where Li is destroyed by nuclear reactions at temperatures greater that \(\approx 2.5 \times 10^6\) K. Cooler stars have deeper convective zones, and hence higher temperatures at their base; therefore they are expected to deplete Li more efficiently. New high-resolution, high S/N spectra obtained at ESO using the CES have confirmed this basic trends (Rebolo et al. 1986, Pallavicini, Cerruti-Sola and Duncan 1987, Pallavicini et al. 1990, Pasquini 1990b). More importantly, these new observations have shown that the classical picture was too much oversimplified, casting doubts on the use of Li as an age indicator.

For instance, Pallavicini, Cerruti-Sola and Duncan (1987) have shown that a high-Li abundance is a necessary, but not sufficient condition for stellar youthness. A number of solar-type stars exist that have a high Li abundance, but are certainly not young. A well-known example is \(\beta\) Hyi, a G2 IV star older than the Sun, whose Li abundance is a factor \(\approx 30\) larger than the solar value (we remind that the latter is \(\log n(Li) \approx 1.0\) in a scale where \(\log n(H) = 12.00\)). Another puzzling result is the report of anomalously strong Li in several K-type stars, including members of RS CVn binaries. The late-type components of these active binaries are typically evolved objects (Popper and Ulrich 1977) and no appreciable Li is expected in these stars.

In order to determine how common a strong Li line is in RS CVn binaries and other chromospherically active stars, Pallavicini, Randich and Giampapa (1990) have carried out an extensive Li survey using the CES at ESO equipped with the Short-camera and CCD detector. The program stars were selected from lists of active stars and RS CVn candidates drawn on the basis of reported Ca II emission in low-resolution objective prism
spectra. In total, the sample comprises more than 60 southern stars of spectral types G and K and luminosity class V, IV and III. The observations were carried out in several runs between November 1986 and April 1990. In all cases, a 50 Å region around the Li I line at 6708 Å was observed at a nominal resolving power of 50,000. Examples of the acquired spectra are shown in Fig. 11. The measured equivalent widths were converted to Li abundance using the curves of growth of Pallavicini, Cerruti-Sola and Duncan (1987). For rapidly rotating stars, corrections were made for the contribution of the Fe I line at 6707.44 Å to the Li blend.

The results of the survey are summarized in Fig. 12 where the derived Li abundances are plotted as a function of the effective temperature (filled symbols). The results for a sample of field stars observed with the same spectrograph are also shown for comparison (open symbols, from Soderblom 1985 and Pallavicini, Cerruti-Sola and Duncan 1987). While chromospherically active stars with log \( T_{\text{eff}} \) \geq 3.75 do not show any significant departure from the typical behaviour of normal field stars, there is a clear excess of Lithium for the cooler stars. In particular, Lithium is present in most K-type stars in the sample, and only a few of them do not show a detectable Li line. This conflicts with the current finding that Li is completely depleted in K-type stars, except in very young objects. Note also the extremely high Li abundances of a few stars at the top of the diagram; their Li abundances are comparable to or larger than the primordial Li abundance for population I stars, suggesting that these stars are most likely pre-main sequence objects or very young stars.

Before trying to explain the anomalously strong Li line observed in many K-type chromospherically active stars, it is important to determine whether this is a genuine abundance effect. Giampapa (1984) has suggested that stellar surface activity can significantly affect the strength of the Li line. In sunspots, for instance, the Li 6708 Å line is observed to be a factor \( \approx 20 - 40 \) times stronger than in the undisturbed solar photosphere, and large spots (covering up to 20-40 % of the stellar surface) are known to exist on the active components of RS CVn binaries. If this is the case, rotational modulation of the Li line in antiphase with the photometric variations should be seen.

This test was carried out at ESO in December 1987 by Pallavicini, Cutispoto and Randich (1990). Four spotted stars were observed nearly simultaneously in the Li I line (using the CES) and in broad-band \( UBV(RI) \) filters (using the ESO 50cm telescope). The photometric observations were carried out over a two-week period immediately preceding the spectroscopic run; the observations at the CES were carried out over 6 consecutive nights. The observed stars were HR 1099, YY Men, AB Dor and IL Hya. In all cases, clear photometric variations (with amplitudes of \( \approx 0.05 - 0.1 \) magnitudes) were observed, but there was no rotational modulation of the equivalent width of the Li line. This negative result indicates that large cool spots are not a viable explanation for the presence of the Li line in K-type RS CVn binaries and other chromospherically active stars, and that the observed Li excess must be a genuine abundance effect.

One possible explanation is that some of the late-type components of RS CVn binaries have evolved from late-A or early-F progenitors with shallow convective zones and hence small Li depletion on the main-sequence (Fekel et al. 1987). Another possibility is suggested by the rapid rotation typically found for these stars (a large majority of which are
Figure 11. Spectra of the RS CVn binary IL Hya and of the presumably very young star HD 219025 in the Lithium region obtained with the CES (from Pallavicini, Randich and Giampapa 1990).

Figure 12. Lithium abundance vs. effective temperature for a sample of chromospherically active stars and RS CVn binaries (filled symbols) and for field stars (open symbols). All data were obtained with the CES (from Pallavicini, Randich and Giampapa 1990).

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close binaries whose rotation is enforced by tidal interaction). As discussed by Randich and Pallavicini (1990), the absence of an efficient braking of the outer layers of the star may have prevented Li depletion by the mechanism recently proposed by Pinsoneault et al. (1990). According to this mechanism, Li depletion occurs mainly by mixing due to radial differential rotation when the outer layers of a star are braked more rapidly than the interior. Lack of efficient braking in tidally coupled binaries may have prevented them from depleting Li. Although the reasons for the excess Li observed in many K-type chromospherically active stars are not yet fully understood, it is likely that this effect results from a combination of shallow convective zones in main-sequence progenitors and absence of efficient rotational braking in tidally-coupled binaries.

7. Conclusion

In this paper we have given several examples of the kind of spectroscopic studies of cool stars that can be carried out using high-resolution facilities presently available at La Silla. Our selection has been heavily biased towards our own research and does not intend to be exhaustive. Although very limited in scope, it provides however a glimpse of the many different topics that can be addressed in the general areas of surface activity, chromospheres, chemical abundances and rotation of cool stars. A more comprehensive discussion of these and other topics, based on observations obtained at La Silla and other observatories, can be found in the various contributions to this volume.

A new facility will become available shortly at La Silla. This is the ESO Multi-Mode Instrument (EMMI) installed at the 3.5m NTT telescope (D’Odorico 1990). This instrument provides a large number of different capabilities (wide field imaging, long slit, low and medium resolution spectroscopy, high-resolution echelle spectroscopy), with the possibility to change from one mode to the other in a few seconds. In the echelle mode EMMI will reach resolving powers of ≈ 30,000 in the red-channel (4000-11000 Å). This, combined with the excellent performance of NTT, will offer new possibilities for high-resolution spectroscopy of a variety of astrophysical objects, including stars. Even more exciting possibilities are expected for the middle and late 90’s when new very large telescopes will become available at several places in the world. Use of these telescopes in combination with adequate spectroscopic facilities will open new realms to high-resolution spectroscopy of astrophysical objects.

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References

Bopp, B.W.: 1990, this volume.
Pasquini, L.: 1990a, in *Surface Inhomogeneities in Late-type Stars* (P.B. Byrne and D.J. Mullan eds.), in press.