Chapter 1

Introduction

The discovery of the RS CVn binaries was intimately related to the discovery of starspots, an interesting episode of astronomical history.

Douglas S. Hall
1.1 Atmospheric activities in the Sun

The atmosphere of the sun consists of three regions, namely, the photosphere, the chromosphere and the corona. Most of the visible light comes from the photosphere; this is the part of the Sun we see naturally. When the light from the photosphere is blocked out, as occurs in the time of total solar eclipse, then we see the light coming out from chromosphere and corona. The sun emits electromagnetic radiation at different wavelengths such as radio, ultraviolet, X-rays and gamma rays, originating from different regions of the sun.

The photosphere is one of the coolest and densest regions of the sun. The photospheric temperature ranges from 6600 K at the bottom to 4400 K at the top. Over all effective temperature is 5780 K and at this temperature only small fraction of the gas is in ionized state. The prominent signatures of the photospheric activities are sunspots, faculae, granules and supergranules. Sunspots appear as dark spots on the surface of the sun. The sunspot temperature is found to be around 1000-2000°K lesser than the surrounding. A typical sunspot has a central dark region called umbra which is surrounded by less darker penumbra. The presence of very strong magnetic field (about 2-3 KGauss) is found in sunspots and this indeed reflects their magnetic origin. The magnetic field is the strongest and radially oriented in the umbra and weaker and more horizontal in the penumbra region. A sunspot usually appears in pairs and having opposite magnetic polarity. The numbers of sunspots and hence total sunspot area is found to be modulating with 11-year cycle. Faculae are bright features seen in the regions with fairly strong magnetic fields and they can occupy more solar surface than sunspots. With help of the powerful telescopes, a detailed look at the photosphere reveals millions of angular shaped bright features, which
are called granules. Granules are created by the hot bubbles of gas rising from the solar interior and reaching up to solar surface. This mechanism of energy is called convection.

The chromosphere is a thin region of the Sun’s atmosphere just above the photosphere where the temperature rises from 6000 °K to about 20,000 °K. The structure of the chromosphere is dominated by the magnetic field, while the oscillations and flows play a major role in chromospheric dynamics. The interaction between fields and flows in complicated geometry makes the chromosphere into one of the most challenging regions of the solar atmosphere. The main features found in the chromosphere are chromospheric network, plages and spicules. The chromospheric network is a web-like pattern most easily seen in red Hα and singly ionized Ca II H & K emission lines. The chromospheric network outlines the supergranule cells and it is due to presence of bundles of magnetic field lines, which are concentrated. Plages are bright chromospheric regions oftenly associated with the Sunspots. Plages may also be linked with concentrations of magnetic fields and form a bright network of chromospheric emissions. Spicules are small, jet-like eruptions seen throughout the chromospheric network. They appear as short dark streaks in the Hα image of the sun. The linkage between the chromospheric and corona occurs in a very thin transition region, less than 100 thousand meter thick.

The Corona is the outermost and rarefied region of the solar atmosphere. The temperature of this region is about 10⁶ K. The corona displays variety of features including solar flare, prominences, coronal mass ejection etc. Prominences are dense cloud of material suspended above the surface of the sun by loops of magnetic field and it is seen projecting out above the limb of the sun. The relatively calm solar atmosphere sometimes suddenly streams away solar matters (protons and electrons) from the sun, which carries
energy up to $10^{25}$ joules in 100 to 1000 seconds are called solar flares, which produces copious amount of radiation across the whole electromagnetic spectrum.

In general at some level all stars are probably spotted, but enhanced solar like magnetic activity such as dark spots, highly energetic flares, facular networks, chromospheric plages, emission from the transition region and corona seem to be inherent properties of late type stars regardless of their evolutionary stages. Stellar magnetic activities with far extreme activity level than their solar counterparts have been found in several groups of stars and these groups are broadly known as Chromospherically Active Stars. The chromospherically active stars include single and binary stars as well as pre- and post-main sequence stars having rapid rotation and deep convective layers. Some of the observed properties and physical characteristics of chromospherically active stars are listed below.

1. Starspots can blanket up to 50% of a hemisphere of the active star, whereas sunspots cover only about 0.2% of the solar hemisphere during the sunspot maximum
2. Show excess of ultraviolet light, which can be attributed to the enhanced activity of the stellar chromosphere
3. Emission lines in the far ultra-violet spectrum produced in the transition region, a layer between the chromosphere and corona, is more intense than corresponding solar lines
4. Coronal emission at soft X-ray region is about 1000 times stronger than that of sun.
5. Flare like radio emission at centimeter wavelength can be found 1000 times greater than the similar radio flaring observed on the Sun.
6. Magnetic field of several thousand Gauss with a filling factor up to 60% have been measured by specialized technique or deduced indirectly, which is far greater than the Sun’s global magnetic field of only 1 or 2 Gauss.

7. Mass loss in a stellar wind, inferred from orbital period changes and also from mass determination and evolutionary consideration is about 100 times greater than the mass from Sun in the form of the solar wind.

8. Long-term activity cycle, analogous to the 11-years solar cycle, suggested by photometric studies of starspot coverage and mean brightness level.

At present at least ten different groups of chromospherically active stars such as RS CVn binaries, BY Dra, T Tauri, FK Comae, W Uma etc. have been classified according to their properties of being a member of single or binary system, evolutionary stage and rotation period. As far as strength of activity among these active stars is concerned RS CVn binaries may be considered as the group leader.
1.2 Chromospherically Active Stars: Types

1.2.1 RS CVn Binaries

RS Canum Venaticorum (RS CVn) type stars constitute a sub-class of the chromospherically active binary systems, whose defining characteristics have evolved since Struve (1946) first called attention to this group of stars. Oliver (1974) was the first to formally propose a set of observational characteristics to define the RS CVn criteria. The working definition of RS CVn binaries used today is based on the classification criteria first proposed by Hall (1972, 1976) with some modifications made by Fekel, Moffit & Henry (1986). The term RS CVn binary is applied to system that has the following observational characteristics.

1. Presence of strong Ca II H & K, and Hα emission in the spectrum.
2. Variable light curves arising primarily due to rotational modulation of the stellar light by large starspots on the surface of the cooler component.
3. The binary should consist of one hotter component of the spectral type F or G and luminosity class V or IV. The secondary cooler companion is usually a sub-giant or giant more massive K-type star. Both stars typically lie well inside their Roche lobe.

RS CVn binaries have been subdivided into three sub-groups according to their orbital period: (i) Short Period Systems ($P_{orb} \leq 1$ day), (ii) Classical RS CVn ($1 \leq P_{orb} \leq 14$ days), (iii) Long period system ($P_{orb} \geq 14$ days).

Hall originally suggested a list of 24 candidates having some of these characteristics (Hall 1976). However, now this number has grown to over 300. RS CVn binary can be eclipsing or non-eclipsing systems. Out of 206 RS CVn binary listed in second edition of Chromospheric Active Binary Stars (CABS) (Strassmeier et al. 1993) only 47 systems are
found to be eclipsing systems and very few spotted eclipsing binaries have been discovered afterward (Cutispoto et al. 1997). Eclipsing binary systems provide not only accurate knowledge of orbital inclinations and other useful stellar parameters such as masses, radii, effective temperatures etc, but they can also be used effectively to deduce spatial surface brightness distribution of the cool active components by a technique known as eclipse mapping. In order to investigate various properties of the chromospherically active binary stars, we compiled 289 chromospherically active stars from various sources. (Henry et al. 1995b; 1999; Cutispoto et al. 1997; Messina 1999) including 206 stars from CABS.

1.2.2 BY Dra Stars

The BY Draconis type stars, named after groups prototype BY Dra, is another main subgroup of chromospherically active stars. Physically they are dKe and dMe stars, that is, late dwarfs having hydrogen line and often Ca II H & K emissions in their spectra. The variability is produced by axial rotation of a star with non-uniform surface brightness (a region of cool spots localized on one hemisphere). Unlike the RS CVn binaries, however, they can be either binary or single, although they show similar phenomenon of chromospheric activity. This fact was used to prove that occurrence in a binary is not directly responsible for the chromospheric activity.

1.2.3 Solar-type Stars

Stars on the lower main-sequence are known to show chromospheric activity, similar to that on the Sun, which is detected, e. g., in the Ca II H & K emission (Wilson 1978). The solar variations, which never exceed a few tenths of a percent, are clearly associated with the motion of sunspots across the solar disk, and result from a blockage of radiant flux (Frohlich 2002). The amplitude of the stellar variability can be as large as several percent
in some cases. It appears to be analogous to the solar phenomenon and is caused by star spots. The survey by Radick et al. (2000) revealed that with a precision of about 0.003 mag none of the variable stars had a spectral type earlier than F7 or later than K2, although the list of stars included A0 to K8 candidates. Thus, the starspot phenomenon in solar-type stars peaks seemingly at the effective temperature range from 6400 K to 4900 K. Evidence linking the photometric variability of solar-type stars to the sunspot phenomenon is provided by the fact that continuum variability seems to occur in antiphase with variations in Hα and Ca II H & K emission variations (Dorren & Guinan, 1982). The anticorrelation implies that the surface activity of such stars is confined to localized activity centers that include both emission plages and dark spots, similar to active regions observed on the Sun. Moreover, short-term stellar light variations may be largely explained as rotational modulation by active regions which can persist for several rotation periods (Lockwood et al. 1984). It has been firmly established that magnetic activity in solar-type stars declines with age and that it is closely related to a loss of angular momentum throughout the main-sequence lifetime (Skumanich 1972; Noyes et al. 1984; Baliunas et al. 1995; Gudel et al. 1997). Thus, young stars exhibit high average levels of activity and rapid rotation, while stars as old as the Sun and older have slower rotation rates and lower activity levels.
1.2.4 Tauri Stars

T Tauri stars are a class of young low mass stars, named after its prototype star T Tau. First recognized by Joy (1945), these stars are found to lie above the main sequence in the HR diagram, and have inferred ages that span a range between $10^5$ year to a few times $10^7$ years with masses below 3 solar masses. In the current understanding of the formation of low mass stars, T Tauri stars represents the earliest evolutionary stages that are visible in optical. These systems also display many currently poorly understood phenomena some of which (discs, jets, outbursts etc.) are also seen in others, less well observed. The similarity of T Tauri stars to the conditions prevailing in the early solar system provides further interest, and point towards studies of the nature and formation of other planetary system. T Tauri stars can be further classified into two groups -

1. Classical T Tauri stars (CTTS)
2. Weak Line T Tauri stars (WTTS)

Using the existence of Li I (6707 Å) absorption, one can establish the pre-main sequence nature of stars in both groups observationally. This quantity provides a good measure of youth since Li is rapidly depleted by nuclear burning as the star approaches the main sequence. The CTTS are then distinguished by their high equivalent width of H$_\alpha$ (10 Å), while stars with lower H$_\alpha$ equivalent width are classified as WTTS. Both CTTS and WTTS share some common properties; for example, variability at optical wavelengths and, quite frequently high levels in X-ray emission. The most important difference is that CTTS have spectra that show excess above the stellar photospheric level at both infrared and ultraviolet wavelengths, while WTTS show no ultraviolet excess and little or no excess at infrared wavelengths. Optical variability of T Tauri stars is commonly attributed to the rotation of
an asymmetric distribution of the star spot on the stellar surface, which may be cooler (primarily in WTTS) or hotter than the stellar photosphere (in CTTS). These variations provide a straightforward way to measure the stellar rotation period independent of unknown inclination of the rotation axis to the line of sight. The rotation period thus derived is found to be relatively long with CTTS rotating a factor of $\frac{g}{97}$ slower than WTTS.

1.2.5 FK Comae Stars

FK Comae stars represent a small group of extremely rapidly rotating G-K giants, named after prototype FK Com, with strong emission from the chromosphere and transition region. The prototype FK Com is the most rapidly rotating of all, with a mean period of 2.4 days. As originally defined by Bopp & Stencel (1981) the class included late-type giants with high values of $v$ sin $i$, i.e., short rotation period but no sign of large velocity variations. According to the photometric observations, active regions of FK Com show “flip-flop” effect (Jetsu et al. 1991; Jetsu 1993), which means that the dominant part of spot activity shifts in longitude to the other side of stellar surface (i.e. a longitude shift by about 180 deg) and remains there for a period of time. The time difference between the two shifts seems to vary from a few years to about a decade (Jetsu et al. 1991, Jetsu 1993) with recent photometric observations showed evidence for new “flip-flop” which is the forth detected during 26.3 years (Jetsu et al. 1994b).

Algol and W Uma type classical eclipsing binaries also reveal solar like chromospheric activity and X-ray emission but in very large scale. FK Com rotates so rapidly that the most reasonable evolutionary scenario involves the coalescence of W Uma type binaries into a single object (Boop & Stencel 1981; Rucinski 1992). Furthermore, it
has also been proposed that the progenitors of W Uma could be shorter period BY Dra or RS CVn stars and eventually W Uma would coalesce into FK Comae stars (Guinan & Gimenez 1993).
1.3 Starspots:

1.3.1 A Photometric signature of the Strong Stellar activity

The most features of RS CVn binaries and other chromospherically active stars is the presence of huge cool spotted regions usually recognized starspots. In the beginning there was ambiguity about the spot temperature i.e. spots are bright hot or dark cool regions (Vogt 1981a) and later on some confusion arose due to the Zebra model (Peterson and Hawley 1992). It has now been well established that indeed spots are dark cool regions on the stellar photosphere. The detail about spots effective temperature, their distribution on the stellar surface size and spot filling factor are usually obtained by modeling photometric broad bandpass light and color curves, localized features in spectral line profile (Doppler imaging) and temperature sensitive TiO bands. The temperature difference between photosphere and starspots ($\Delta T$) for various spotted stars is found to range from $\approx 500$ $^\circ$K to $2300$ ($\Delta T/T_{\text{phot}} \sim 0.14$ to 0.4) with uncertainty in the temperature measurements of about 100 to 200 $^\circ$K (Vogt 1981 b; Poe and Eaton 1985; Kang & Wilson 1989; Zeilik et al. 1989; Strassmeier and Olah 1992; Strassmeier 1994 ; Mekkaden & Raveendran 1998; Catalano et al. 2002; Alekseev et al. 2003). Photometric light curve modeling reveals the presence of few discrete huge spots (most often two or three spots) which is 100 to 1000 times larger than total sunspot filling factor (Poe & Eaton 1985; Strassmeier 1992; Lanza et al.1998; Olah et al.1999; Padmakar & Pandey 1999; Olah 2001.Ribarik et al. 2003). The light curve modeling is not effective for small spots, polar spots and uniformly distributed spots across the stellar surface, and hence get only reliable information about localized relatively large and medium size spots situated near stellar equator. From modeling of molecular TiO Bands Neff et al. (1995) and
later on O’Neal et al. (1996, 1998 b), Wasatonic et al. (2001) claimed that spots could surprisingly fill up to 60 % of stellar surface. Numerous Doppler images of different chromospherically active stars seem to be supporting the view that spots are really huge localized features on the stellar surface. But the overall shape of starspots and temperature distribution could be very complex than the standard two component sunspots (Strassmeier et al.1991; Weber & Strassmeier 1998; Berdyugina et al. 1999; Vogt et al. 1999; Kovariet et al. 2004). Sunspots are restricted within the ± 35° latitudinal belts but, starspots can be found anywhere on stellar surface, Vogt & Penrod 1983; Strassmeier 19991; Hatzes 1995; Weber & Strassmeier 1998; Bruls et al. 1998; Vogt et al. 1999, Olah et al. 2001, Ribarik et al 2003. Sunspots lifetime ranges from some hours to a days, whereas starspots on active stars can survive for months to years and some times even decades long.

**Fig1.1:** The cyclic variation in the orbital period of prototype RS CVn (Courtesy Rodono et al.1995)

The laws which govern the life of the starspots was carried out first time by Hall & Bushy (1990) and later on extended by Hall & Henry (1994). According to them lifetime of any starspot is given by two laws which are:
1) Relatively large spots are disrupted by shearing of the differential rotation and their lifetimes can be calculated by the relation

\[
T_1 = \frac{P}{0.020285 r_s^2} k \quad (r_s \leq 20^\circ)
\]

\[
T_2 = \frac{P}{(0.020285 r_s^{0.06})} k \quad (r_s > 20^\circ)
\]

2) Whereas relatively small spots lifetime is governed by spots and stellar radii

\[
\log(T_2) = 0.13 r_s + 0.49 R_* - 1.95
\]

3) Here spot lifetimes \(T_1\) and \(T_2\) are in years, \(P\) is stellar rotation period in days, \(k\) is differential rotation coefficient, \(r_s\) and \(R_*\) are spot and stellar radii.

1.3.2 Ca II H & K and H\(\alpha\) Emission

As it is well known that enhanced emission cores in the Ca II resonance lines (H & K), and H\(\alpha\) lines are among the primary optical indicators of the chromospheric activity. The H\(\alpha\) emission is found to be much stronger when the spot is in view and almost disappears when the spot recesses from the view. A correlation between H\(\alpha\) and Ca II H & K emission has been found in single stars too. The H\(\alpha\) absorption cores first deepen as the Ca II H & K emission increases and then falls quite rapidly (Strassmeier et al. 1990). However, in RS CVn binaries, the situation is much more complex due to contribution from the two stars to the spectrum. A collaborative efforts to search for the periodic variation of chromospheric and transition region line intensities have been carried out by Rodono et al. (1986). This variation has been found in all of the emission lines, and they appear to be correlated with the optical light. This correlation is more complicated than a simple rotational modulation scenario (Byrne 1989).
1.3.3 Molecular Lines in Starspots

For stars with intense chromospheric activity, molecular lines provide evidence of cool spots on their surfaces. If the effective temperature of the stellar photosphere is high enough, molecular lines can be formed only in cool starspots. The first detection of molecular bands from starspots was reported by Vogt (1979) for a star whose spectral type was not compatible with the presence of TiO and VO bands. From the relative strengths and overall appearance of the molecular features, an equivalent spectral type of the spot spectrum was estimated to be as late as M6. A phase dependent variation in the strength of TiO band was detected by Huenemoerder et al. (1989), with TiO being strongest at the photometric minimum. This observation also confirmed that the photometric modulation is indeed caused by cool spots on the stellar surface. A comparison of photometric variations with TiO band strengths provided a reliable estimate of unspotted stellar magnitudes (Berdyugina et al. 1998, 1999). Systematic long term studies carried out by Neff et al. (1995) and O’Neal et al. (1996) reveals that the TiO bands at 7100 Å and 8860 Å have

**Figure 1.2**: Spectra of the TiO molecular bands in 7055 Å (left) and 8860 Å (right) regions (Neff et al. 1995).
different temperature sensitivity (Figure 1.2). The ratio of these two TiO bands strengths depends only on spot temperature, whereas their absolute band depth depends on total spot area.

1.4 Techniques for Studying Starspots

1.4.1 Light-curve Modeling

Since the discovery of stellar photometric variations due to cool spots, generally two approaches have been used to model such variations in order to deduce starspot properties. One is based on a trial and error direct light curve modeling when assuming a number of certain circular (or of other pre defined shape) spots causing the variations. Numerical techniques employing this approach have been developed by Budding (1977), Vogt (1981), Rodono et al. (1986), Dorren (1987), Strassmeier (1988) and Kiurkchieva (1990). A technique taking into account time evolution of starspots has been proposed by Strassmeier & Bopp (1992). It allows for detecting spot appearance and disappearance on time scales from a few to a hundred days. A zonal model with (near) equatorial inhomogeneous bands of spots was considered by Eaton & Hall (1979) and Alekseev & Gershberg (1996). A disadvantage of the above-mentioned models is that they have many free parameters, and the shape of spots or of spot distribution has to be assumed. Moreover, the solution is not unique.

To avoid many assumptions, an alternative approach performing light-curve inversion (LCI) into an image of the stellar surface has been developed. An inversion technique is usually applied to the photometric light curves in the two temperature approximation. Inversion or modeling of light-curves is clearly less informative than techniques, which are based on spectroscopic observations. Continuous and frequent
photometric data allow for conclusions on longitudinal spot patterns and their long-term evolution. More detailed information on the spot pattern from light curves can be obtained in the case of eclipsing binaries by the eclipse mapping technique. This method employs the opportunity to scan the stellar disk in finer detail by the eclipsing companion. The inversion techniques based on the Maximum Entropy and Tikhonov regularization methods were developed by Rodono et al. (1995), Collier Cameron (1997), and Lanza et al. (1998).

1.4.2 Doppler Imaging

During the last two decades the Doppler imaging technique has been extensively employed for studying starspots on the active stars. The main idea of the technique is to use high resolution spectral line profiles of rapidly rotating stars for mapping the stellar surface. This idea was first formulated by Deutsch (1958), while the first inversion technique with minimization was developed by Goncharskii et al. (1977). It was first used for mapping chemical peculiarities on the surface of Ap stars. Modeling of photometric variations of late-type active stars has revealed that cool starspots are often quite large, covering up to 20% of the stellar surface. Such starspots should have resulted in noticeable line profile variations which were first observed in spectra of the RS CVn type star V711 Tau, and from which the first Doppler image of a spotted star was obtained by Vogt & Penrod (1983). The Doppler imaging technique aims to restore starspot distribution information which is contained in time varying line profiles of rotating stars. If the star rotates rapid enough so that the rotation broadening of a line profile is significantly larger than the local line profile at a single point on the stellar surface, then a cool spot on the stellar surface will result in a “bump” in the profile (Figure 1.3). This “bump” moves across the profile, as the star rotates, with the velocity amplitude depending on the spot latitude.
Fig 1.3: Spectral line profiles for a model fast rotating star with no spots (dashed line) and with a spot moving across the disk as the star rotates (solid line) (Courtesy: Berdyugina 2005).

Inversion of a time series of the stellar line profiles results in a map or an image of the stellar surface. The rate of migration of “bump” reveals the spots latitude; better determined the shorter the integration time and the more numerous the spectra per rotation cycle. However, spots change within a few stellar rotation and may be even from one rotation cycle to the next. Therefore, one cannot add spectra to missing phases from another rotational cycle. All this makes Doppler imaging a difficult and time consuming technique. A recent overview of the strengths and weaknesses of the Doppler imaging technique is given in Rice (2002).

A number of numerical codes for Doppler imaging of cool stars based on the Maximum Entropy method (MEM) have been developed by Vogt et al. (1987), Rice et al. (1989), Brown et al. (1991), Collier Cameron (1992, 1995), Jankov & Foing (1992), and

For the last two decades almost 65 cool stars comprising of 29 single stars and 36 are components in close binaries have been studied with the surface imaging technique (see, for an overview, Strassmeier, 2002). Out of these 31 stars were observed only once, while 12 stars are being monitored for several years. The total number of Doppler images is 245 as of June 2002 (Strassmeier 2002)
Fig 1.4 Stellar surface brightness distribution of the UX Ari obtained by applying Doppler technique

Fig 1.5 Schematic representation of formation of the bump inside absorption profile due to presence of the dark spot on stellar surface (Courtesy Vogt & Penrod 1983)
1.4.3 Zeeman Doppler Imaging (ZDI)

The presence of strong magnetic field is supposed to be playing a crucial role in information and modulation of all kinds of atmospheric activities seen on the sun as well as on chromospherically active stars. Studying the topology of magnetic fields and their possible relations with atmospheric activities is quite important in order to understand their physical origin, i.e. whether they are produced within the stellar plasma through hydrodynamical processes (dynamo fields) like that of the sun or represent a fossil field from its previous evolutionary stage like those of chemically peculiar stars. Historically all attempts to detect stellar surface magnetic field by conventional photo-polarimetric methods either by measuring circular or linear polarizations, have essentially failed (Brown & Landstreet 1998; Borra et al. 1984), probably due to the presence of small scale bipolar networking spread across the disk, canceling their mutual effect in circular polarization and hence yielding under detectable magnetic filed. Another option to extract disk averaged field strength and the fractional surface area covered by field (called filling factor) is based on measuring Zeeman broadening using very high-resolution spectroscopic technique. The different broadening between lines that are highly and weakly sensitive to magnetic field yields the filling factor, as well as average field strength.

The obvious advantage of this method is that magnetic field regions with opposite polarities at the surface of the star no longer cancel their mutual spectroscopic signatures as happens in the case of conventional polarimetric and Zeeman broadening techniques have been very successfully used to detect or at least suggest, the presence of magnetic fields (field strength upto few K gauss, with filling factor upto 50 %) in nearly 50 late type stars including pre-main sequence T Tauri stars (Marcy 1984; Saar 1988; Basri et al.1992 ).The
major drawback of these two techniques are their limited capability to provide spatial information and detail of the actual magnetic topology. In order to get magnetic surface maps of rapidly rotating active stars, Semel (1989) proposed to couple these techniques with Doppler imaging and this way a new technique called Zeeman Doppler Imaging (ZDI) was introduced into stellar astronomy. This method was successfully used to obtain the first direct detection of magnetic field in cool star V711 Tau by Donati et al. (1990).

The detailed formulations of ZDI are given by Semel (1989) and its instrumental techniques are described subsequently by Semel et al. (1993). Usually stokes V signatures in individual line profiles are found to be too small in late-type stars (are greater than 0.3 %) to be used to get reliable field spatial distribution on stellar surface. In order to overcome this problem polarization information from thousands of spectral lines are simultaneously extracted with the help of cross-correlation tools such as ‘Least Squares Deconvolution’ (Donati et al.1997). The trajectory of stoke V signature across the line profile provides positional information of the localized field, while their amplitude modulations yields the orientations of field lines within magnetic regions. Typical ZDI images of V711 Tau giving radial, azimuthal and meridional field components are shown in Fig 1.6. Using ZDI technique magnetic fields have been detected in about 20 objects of various evolution stages so far (Donati et al. 1992, Donati et al.1997) and detailed structural maps have successfully been obtained for six of them (Donati & Cameron 1997; Donati et al. 1999; Donati 1999).
Figure 1.6: Flattened polar view of the brightness and magnetic distribution at the surface of the V711 Tau at epoch 1995.94 (Courtesy Donati 1999).

Continuous accumulations of magnetic maps obtained by ZDI can be used to study the temporal evaluation of the magnetic field in a way very similar to what is done for the sun. Recently, 6 years time series of magnetic field and brightness surface images of the V711 Tauri and of the young dwarf LQ Hydrae have been published by Donati (1999). This very valuable work suggests that toroidal components of large scale field structures do indeed evolve on a time scale of about a decade. Further, it has also been found that significant fractions of the total magnetic fields of these two stars are stored in the azimuthal region. Surprisingly simultaneously obtained magnetic field maps reveal very
weak spatial- correlation between surface brightness inhomogeneities and magnetic regions. Unlike starspots, magnetic active regions do not seem to be confined in latitude. These two astonishing and unexpected results suggest that magnetic regions in these two and like-wise in other similar stars could be considered as enhanced analogue of solar intra-network field.

1.4.4 TiO absorption band

Titanium-Oxide (TiO) and Vanadium-Oxide (VO) molecular bands are very prominent features in the red region of cool late type stars spectra. Being high temperature sensitive they are used for the quantitative measurements of effective surface temperatures of these stars (Valenti et al. 1998). Spectral features of TiO bands are found to exist on spectra of stars cooler than ~4000 °K (in late K and M type stars) and stars warmer than this are usually free from these molecular absorption features.

**Figure 1.7** TiO, 7055 Å and 8860 Å in three rotational phases (Courtesy M. Zborill, Astrophysics Institute Postdam Germany)
As RS CVn binaries belong to the spectral family of late G to early K-type, they were supposed to have no such spectral features at all. However, during 1978 Steve Vogt found strengthening of individual TiO and VO bands at the phase spot visibility. Though it was known that TiO bands can be used as an effective tool to study starspot in very early stage. Its quantity uses started only by 1987. Huenemoerder & Ramsey (1987) synthesized the average II Peg spectrum in the two regions near 7100 Å and 8600 Å. They added, properly aligned and weighted spectrum of an inactive K2 V star, to simulate unspotted photosphere and a spectrum of M giant for the spotted region. Inspired by these pioneering studies Neff et al. (1995) started a systematic long-term program to utilize this specific virtue of TiO bands to measure starspots area and temperature of late-type stars. They noticed that both TiO bands (7100 Å and 8860 Å) have different sensitivity. The ratio of these two TiO bands strengths depends only on spot temperature, whereas their absolute band depth on total spot area. They found that unspotted photosphere of II peg has temperature of ~ 4800 K whereas starspots must be cooler than ~1300 K from their surrounding which was consistent with temperature obtained by Doppler imaging and/or broad band photometry. Furthermore they found that spot filling factor varies from 54% to 64% and hence more than 545 stellar visible hemisphere was found to be always covered by dark cool polar spots or spot uniformly distributed on stellar surface, which was surprisingly much greater than found by other techniques. In other to enhance this procedure O’Neal; et al. (1998) introduced spectral synthesis techniques, which uses spectra of inactive M stars to model the spotted regions. These proxy spectra are weighted by their relative continuum fluxes and by a surface-area-filling factor to reproduce spectra of the active star.
The normalized spectrum of the active star, $F_{\text{total}}$ can be written as:

$$F_{\text{total}} = f_s R_\lambda F_s + (1- f_s) F_Q / (f_s R_\lambda / g_{\lambda 97}) + (1- f_s) \quad (1)$$

Where $f_s$ is the spot filling factor weighted by limb darkening, and $F_s$ and $F_Q$ are the normalized comparison spectra for the spot and non-spot regions of the star, $R_\lambda$ is the continuum surface flux ratio between the spot and quiet photosphere. To compute $R_\lambda$, O’Neal et al. (1998) used Kurucz model atmosphere code ATLAS9. Interns of weights, above relation (1) can be written as:

$$F_{\text{total}} = W_s F_s + W_Q F_Q \quad (2)$$

Comparison with equation (1) implies that

$$W_Q = (1- f_s) F_Q / [(f_s R_\lambda / g_{\lambda 97}) + (1- f_s)] \quad (3)$$

$$W_s = (f_s R_\lambda) / [(f_s R_\lambda) + (1- f_s)] \quad (4)$$

This gives the following relation for the spot-filling factor

$$F_s = R_\lambda / (W_s R_\lambda - 1) \quad (5)$$

The molecular bands of interest from the synthesized spectra were fitted to the observed spectra of spotted active stars by STARMOD code. Using this spectral synthesis technique O’Neal et al. (1998b) were able to measure spot temperatures and filling factor of eight late type active stars.

We can discriminate white-light plages and cool starspots contributions by combining the TiO curves with V-band and near IR light curves. Herbst et al. (1990) found enhanced TiO absorption bands in V410 Tau (WTTS) during the (maximum spot Coverage) which is a good agreement with the cool starspots model (Lesniak et al. 2003).
1.4.5 Line Depth Ratios (LDR)

The line depth ratios (LDR) are a powerful tool to determine the spot temperatures of slowly rotating chromospherically active binary system. Using this technique, one can easily discriminate the stellar surface temperatures and be able to resolve the temperature difference $\leq 10$ K. Particularly, the bumps in stellar line profile are the strong representative of cool starspots. From the Doppler image of a fast rotating star it is easy to determine the Doppler shift (spots migration) of the bump in the line profile. But for slowly rotating star it is very difficult to detect the Doppler shift of the bump in the line profile except a slight rotational modulation of the central line depth. In the slowly rotating star the passage of cool spots produces different amount of modulation at the line depth, which depends on the temperature sensitivity.

In LDR technique, several physical variables interact simultaneously and each impressing their signatures on the spectral lines. To measure the line depth ratios of slowly rotating star, at first, one has to select two lines, one insensitive and one very sensitive to temperature. Due to presence of cool spots on stellar surface the line depth ratio of temperature sensitive lines will change. The variation of depth ratios only depend on the sensitivity of the specific lines considered for this technique and will be unaffected by spot filling factor. Gray et al. (1996a, 1996b) applied this method to detect temperature variations in the 5 to 15 K range due to the activity cycle and rotational modulation of cool starspots. Catalano et al. (2002) found a well-defined rotational modulation of average temperature with amplitude ranging from 119 to 117 K for three RS CVn systems.
It is not possible to determine starspots size and temperature using only photometric or spectroscopic data. But by adopting an analytical approach on both temperature and light curve amplitudes we may get a unique solution (Catalano et al. 2002).

1.5. Starspot Properties

1.5.1 Lifetimes

Lifetimes of starspots can be determined from long-term observations which are, for instance, provided by continuous photometric data. Hall & Henry (1994) analyzed several dozen spotted stars and concluded that lifetimes of relatively small spots are proportional to their sizes, which is consistent with sunspot properties. Lifetimes of relatively large spots are possibly limited by a shear of surface differential rotation. On the other hand, large spots causing prominent light curve minima apparently can survive for many years, despite differential rotation, and form centers of activity known as active longitudes. This may even be true for pre-main-sequence stars like T Tauri and solar-type stars. For instance, based on a comparison of the Doppler image with photometric spot models, Hatzes (1995) suggested that the spot on V410 Tau has survived on the stellar surface for about 20 years. Doppler images suggest, however, that these regions often consist of several smaller spots. Lifetimes of those spots are yet to be analyzed.
1.5.2 Temperature

Observed amplitudes of the optical brightness modulation imply that a large fraction of the stellar photosphere is covered by cool starspots. The largest ever observed light curve amplitude $V = 0.65$ magnitude of a spotted star was reported for the weak-line T Tauri type star V410Tau (Strassmeier et al. 1997). Two RS CVn type stars HD12545 and II Peg have been observed at the largest $V = 0.63$ magnitude by Strassmeier (1999) and Tas & Evren (2000), respectively. Such big amplitudes in brightness variations are accompanied by large in-phase variations of color, suggesting the presence of cool spotted areas covering up to 20% of the entire stellar surface or about 40% of the stellar disk (Figure 1.6). Our current knowledge on starspot temperatures is based on measurements obtained from simultaneous modeling of brightness and color variations, Doppler imaging results, modeling of molecular bands and atomic line-depth ratios, the later being the most accurate method. A representative sample of starspot temperatures for active dwarfs, giants and subgiants is shown in Figure 1.8.

![Figure 1.8](image)

Figure 1.8: Doppler image (left panel) of the RS CVn type star HD12545 at the time of its largest amplitude of brightness variations (Strassmeier 1999). Spot temperature (right panel) contrast with respect to the photospheric temperature in active giants (squares) and dwarfs (circles). Thin lines connect symbols referring to the same star. The thick solid line is a second order polynomial fit to the data excluding EK Dra. Dots in circles indicate solar umbra ($T = 1700$ K) and penumbra ($T = 750$ K) (Courtesy: Berdyugina 2005)
As seen from the plot, there is a clear tendency for spots to be more contrasting with respect to the photosphere in hotter stars: The temperature difference between spots and the photosphere decreases from about 2000 K in G0 stars to 200 K in M4 stars. There seems to be no difference in this property between active dwarfs and giants, at least for G-K stars implying that the nature of starspots to be the same in all-active stars. Also a weak-line T Tauri star V410Tau seems to follow the relation. The only exception found is a young solar analogue EK Dra whose starspot temperature, estimated from light-curve modeling and Doppler imaging, significantly deviates from the relation. However, the value obtained from molecular band modeling fits the sequence quite well (O’Neal et al. 2004).
1.5.3 Active Longitudes

Decades of continuous photometric monitoring of RS CVn binaries revealed that large spots maintained their identities for years which were interpreted as a signature of one or two active longitudes similar to the distribution of solar energetic areas (Zeilik et al. 1988; Olah et al. 1988; Henry et al. 1995; Jetsu 1996). Whether such a structure has a preferred orientation with respect to the line of centers in a binary, and how long it survives, was a matter for a long debate (Hall 1996). Berdyugina & Tuominen (1998) showed that active longitudes on RS CVn binaries are permanent but can continuously migrate in the orbital reference frame, and generally have no preferred orientation. The active longitudes are separated by 180± on average and differ in their activity level. Periodic switching of the dominant activity from one active longitude to the other results in a so-called “flip-flop” cycle (Berdyugina & Tuominen 1998). A further analysis of photometric data confirmed the existence of active longitudes on RS CVn binaries (Lanza et al. 1998; Rodono et al. 2000). Two active longitudes seem to be a conspicuous pattern of the stellar activity. Besides RS CVn binaries, this feature has been found in the spot distribution on FK Com type stars (Jetsu et al. 1993, 1999; Korhonen et al. 2002) as well as in very active young solar analogues (Berdyugina et al. 2002; Jarvinen et al. 2005; Berdyugina & Jarvinen 2005). The analogy with solar active longitudes is further supported by the longitudinal distribution of sunspots (Berdyugina & Usoskin 2003). Large sunspot groups in both Northern and Southern hemispheres are preferably formed around two active longitudes which are separated by 180° and persistent for at least 120 years. Similar to young solar-type dwarfs, the two active longitudes on the Sun are long-lived quasi-rigid structures.
1.5.4 Differential Rotation

Differential rotation of stars plays an important role in the generation of magnetic fields in the convection zone. In the Sun, it is involved in transformation of a weak large-scale poloidal field into a stronger toroidal component. By analogy, stellar activity is most probably also connected to differential rotation. On the Sun the differential rotation is observed in relative motion of sunspots and can be expressed in the form

\[ \Omega = \Omega_0 - \Delta \Omega \sin^2 \psi \]

where \( \psi \) denotes solar latitude, \( \Omega_0 \) is the rotation rate at the equator, and \( \Delta \Omega \) is the difference in rotation rate between the pole and the equator. The strength of differential rotation can be quantified by rotational shear \( \Delta \Omega \) or its reciprocal \( 2\pi / \Delta \Omega \), which is the time the equatorial regions need to lap the pole, i.e., the lap time. It can also be characterized by the relative differential rotation rate, which is expressed as the ratio of the rotational shear to the equatorial velocity

\[ \alpha = \Delta \Omega / \Omega_0 \]

For instance, on the Sun with \( \Delta \Omega = 0.055 \text{ rad d}^{-1} \), the lap time is 115 days, and \( \alpha = 0.2 \).

On stars these characteristics can be estimated from observations with various methods, for instance: Fourier analysis of light curves (Lanza et al. 1993), cross-correlation of successive stellar Doppler images (Donati & Collier Cameron 1997), direct spot tracking (Collier Cameron et al. 2002), Fourier transform of rotationally broadened line profiles (Reiners & Schmitt 2002), parameter fit in Zeeman Doppler imaging (Petit et al. 2002) etc.

Long-term photometric monitoring of starspot modulation reveals changes in the seasonal rotation period which indicate the presence of differential rotation on stellar surfaces and of changes in spot latitudes (Hall 1991; Henry et al. 1995; Messina & Guinan,
Confronting the range of seasonal variations and the mean rotation period yields a possible correlation between them in the sense that slower rotators show larger period variations. A majority of stars show, however, a significantly smaller differential rotational than that observed on the Sun. Differential rotation rates estimated for RS CVn binaries as given in Table 1.1 clearly show weak solar-type differential rotation. Similar behavior is found in periods obtained from variations of chromospheric Ca II H & K emission line fluxes. Over timescales of many years, the rotation period was found to show a sinusoidal variation which can be attributed to the solar-type activity cycle (Donahue et al. 1996).

Though it is believed that differential motion is a consequence of the Coriolis effect on rising and falling convective motions, the actual mechanism is still not well understood.

As the differential rotation is one of the ingredients of linear dynamo theory, and it also plays a very crucial role in disrupting starspots (Guinan & Gimenez 1993; Hall & Henary 1994), measurements of the strength of differential rotation and its possible functional relation with latitude is indeed very important.
Table 1.1: Differential rotation rates for chromospherically active stars

<table>
<thead>
<tr>
<th>Star</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>II Peg</td>
<td>$-0.05 \text{ -- } +0.015$</td>
</tr>
<tr>
<td>IM Peg</td>
<td>$-0.03$</td>
</tr>
<tr>
<td>UX Ari</td>
<td>$-0.02$</td>
</tr>
<tr>
<td>HU Vir</td>
<td>$-0.011 \text{ -- } +0.006$</td>
</tr>
<tr>
<td>HR1099</td>
<td>$-0.004$</td>
</tr>
<tr>
<td>UZ Lib</td>
<td>$-0.0026$</td>
</tr>
<tr>
<td>EI Eri</td>
<td>$+0.002$</td>
</tr>
<tr>
<td>RT Lac</td>
<td>$\sim +0.003$</td>
</tr>
<tr>
<td>IL Hya</td>
<td>$+0.004$</td>
</tr>
<tr>
<td>RS CVn</td>
<td>$-0.01 \text{ -- } +0.04$</td>
</tr>
<tr>
<td>HR7275</td>
<td>$-0.022 \text{ -- } +0.04$</td>
</tr>
<tr>
<td>$\sigma$ Gem</td>
<td>$+0.038$</td>
</tr>
<tr>
<td>$\lambda$ And</td>
<td>$+0.04$</td>
</tr>
<tr>
<td>V1149</td>
<td>Ori $+0.08$</td>
</tr>
<tr>
<td>KU Peg</td>
<td>$-0.09 \text{ -- } +0.34$</td>
</tr>
<tr>
<td>V815 Her</td>
<td>$+0.184$</td>
</tr>
</tbody>
</table>
1.5.5 Polar Spots

Spot latitudes can be directly recovered from Doppler images. Interesting and still controversial features in stellar Doppler images are large polar spots, the cool active regions over the stellar poles. Out of 65 stars, whose surfaces were mapped with the Doppler imaging technique, 36 showed prominent polar spots (Strassmeier 2002). Earlier studies, however, suggested that latitudinal distribution of spot activity may depend on the rotational period, since fast rotators apparently show a tendency for polar spots, while slow rotators more often have high-latitude spots not covering the pole (Hatzes 1998). Such a feature appears to be a convenient compensation for a uniformly distributed spot area which cannot be recovered from rotational modulation of spectral lines and of light curves. The reliability of polar spots has been thoroughly discussed (Strassmeier et al. 1991; Schussler & Solanki 1992; Piskunov & Wehlau 1994; Strassmeier & Rice 1998). For instance, the chromospheric activity could reduce absorption in cores of strong spectral lines, which can be interpreted as presence of cool polar caps. To investigate such a bias in Doppler imaging Unruh & Collier Cameron (1997) used Na D lines which are sensitive to the chromospheric temperature structure and found that the images obtained from Na D lines show less high-latitude structure and give more reliable light-curve predictions than images derived previously from fits to several weaker photospheric lines. A long-term Doppler imaging monitoring of the active component of HR1099 (V711Tau) suggests that starspots form at low or intermediate latitudes and then slowly migrate towards the pole on time scales of a few years (Vogt et al. 1999).
1.6 Activity Cycles in Chromospherically Active Stars

It is well known that our Sun exhibits 11-years sunspot cycle, and 22-years magnetic activity cycle. In fact several time scales of cyclic behavior of overall solar activity can be found. The most pronounced are:

• the commonly known 11-years sunspot cycle
• the 80 years long so-called Gleissberg cycle
• 200-300 years of long pseudo-cycle

In the course of 11-years cycle, solar output is highest when the Sun is covered with sunspots since the regions around the spots (faculae, plages) actually emit more energy than when sunspots are absent. It is unclear, however, how far other stars follow the Sun as a role model.

Monitoring Ca II H & K emission lines on solar-type dwarfs, pioneered by O. Wilson at Mt. Wilson Observatory, has led to the detection of solar-like activity cycles in such stars (Baliunas et al. 1995). However, this photospheric-chromospheric correlation cannot be reproduced for evolved G and K stars (Choi et al. 1995). In addition, contemporaneous photometric and chromospheric H & K emission time series study for 35 stars revealed that the luminosity variation of young stars anti-correlates with their variation in chromospheric emission (Radick et al. 1998), i. e., young stars become fainter near their activity maxima, while older stars, including the Sun, become brighter at maximum activity.

First well-known attempt to study the long-term photometric variability of chromospherically active stars was by Phillips & Hartmann (1978) by their collection of photographic magnitudes from archival plate and new photoelectric measurements. They
found 50 to 60 years of long-term variation for BY Dra and CC Eri. A similar result was published shortly thereafter by Hartmann et al. (1981) for V833Tau, and was later confirmed by Bondar (1995). The accuracy of the photographic measurements was usually no better than ±0.1 magnitude, and sometimes even worse, and this in turn, demanded the need of long-term photoelectric monitoring of chromospherically active stars. However, because of the relatively short time-base of the more accurate photoelectric observations, it was not possible to find well-determined cycles in that measures alone. Nevertheless, cycles were searched for and possibly found for a few very active systems (Strassmeier et al. 1997 and references therein), but the cycle periods were either resembling the solar value or were similar to the length of the given database. Berdyugina & Tuominen (1998) found active longitudes and cycles in four RS CVn systems from phase changes of the two minima of the spotted light curves. Analysis of the long-term light behavior of ten rapidly rotating chromospherically active stars by Olah et al. (2000) reveals that the active stars may have more than one period similar to solar activity cycle. It is now well established that many chromospherically active stars show long-term light variation.

In the past several attempts have been made to search for a relationship between cycle length and stellar properties such as rotation, age, mass, Ca II H & K emission-line flux and depth of convection zone for solar-type stars (Baliunas 1985; Baliunas et al. 1996; Saar & Baliunas 1992; Baliunas et al. 1996; Ossendrijver 1997; Brandenburg et al. 1998; Saar & Brandenburg 1999). Olah et al. (2000) explored the relationship between the normalized cycle period and the rotation period for a sample of ten stars, using the photometric data. They also used previously determined cycle period by different techniques and concluded that activity cycle length of chromospherically active stars is
correlated with rotation period and/or Rossby number in the sense that cycle lengths were generally longer for stars with longer rotation periods.