Session I

"STELLAR SURFACE MAPPING TECHNIQUES"

DOPPLER IMAGING OF STELLAR SURFACES

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1. Introduction

The process of recovering the geometric information encoded in the time varying line profiles of rotating stars to obtain maps or images of the surface features on those stars has come to be known in stellar astronomy by the title "Doppler imaging", although other titles have been used. The principles of Doppler imaging are fairly well known, but the extent of application has been less than might have been expected given the ready availability now of the electronic detectors, the large telescopes and the computing power needed to undertake this sort of imaging.

2. General Principles of Doppler Imaging

The inversion process to produce images of surface features on stars that are essentially spherical is straightforward in concept. To understand the essentials, first think of a star that might have a single small cool starspot on its surface. If the star is rotating quickly enough that the rotational broadening of the profile is significantly larger than the local line profile at a single point on the stellar surface, the observed stellar line will show a "bump" that will move across the profile as the star rotates, moving from the blue wing to the red as is illustrated in figure 1. Small spots on the surface of the star are mapped onto the stellar line profile at any given phase such that the forward calculation gives a well defined location for the "bump" in the profile but the reverse calculation of mapping the "bump" onto the star's surface gives a locus of points on the stellar surface that could be occupied by the spot source. The indeterminacy is resolved by taking multiple observations at reasonably well spaced phases. As can be seen, the phase when the profile "bump" crosses the line centre gives the longitude of the spot and the latitude is logically deduced from the temporal

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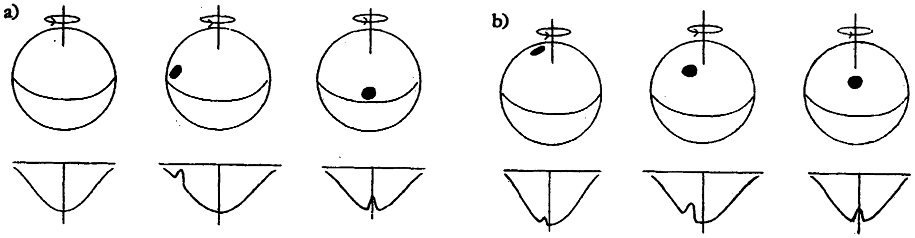


Figure 1. An illustration of the mapping of a single cool spot feature onto a spectral line profile for the star. The left sequence (a) is for a low latitude spot and the right sequence (b) is for a high latitude spot. The figures are arranged with increasing rotational phase from left to right

behaviour of the "bump". Low latitude spots would give a profile "bump" that is evident for half a rotational phase and that moves from the extreme blue to the extreme red across the profile (figure 1b). Higher latitude spots (figure 1a) display a "bump" that is evident for a much larger fraction of the rotational phase and that actually moves from red to blue briefly, after first coming into view over the pole of the star, before reverting to the more normal direct blue to red motion. The excursion of the "bump" in wavelength is much smaller for these high latitude spots. For cool stars where the surface features are cool spots locally radiating less light in the continuum the "bump" is like an emission peak in the line profile. For those of us who also work with Ap stars where the surface anomalies are usually spots of enhanced abundance, the "bump" is a small valley of greater line depth.

In all cases, the surface features are much more complicated than a simple circular spot so the mapping process for real stars is, of course, more complex than the preceding paragraph would suggest. I will outline some of the approaches to image reconstruction shortly but first a bit of history.

3. A Brief History of Star Mapping With Comments on Bill Wehlau's Role

The first significant efforts to map surface anomalies on stars goes back to the work of Deutsch (1958). Deutsch was attempting to reconstruct the surface distribution of elements and the magnetic field on an Ap star by expanding the distribution as a very much truncated spherical harmonic expansion. He then calculated the appearance of the curve of variation for the equivalent width, radial velocity and magnetic field as a Fourier series giving a linear relation between the coefficients of the spherical harmonic expansion and the Fourier coefficients of the observed variations. This was very ingenious but quite limited in potential since the resolution on the stellar surface was very low and the photographic data available then fell short of the needs of any mapping work. Following Deutsch's work, there was a lull of about a decade until the work resumed and then the emphasis gradually changed to working with the stellar profiles rather than line strength variations. At the same time that Bill Wehlau and I were making an effort to apply a modification of the Deutsch technique to the Ap star HD 173650 (Rice, 1970), Pyper (1969) was doing the same sort of project with α^2 CVn. The interesting aspect of α^2 CVn is that the line profiles show obvious components that are clearly separated out during the rotational cycle so Pyper could not only apply the Deutsch approach but she could also identify spots based on the profile behaviour. She did not, however, connect the profile variations to the surface features through a rigorous mathematical treatment. Others had become interested in profile behaviour at about this time and it seems appropriate here, since we have dedicated this meeting to Bill Wehlau, to comment that Bill had shown an interest in the profile-to-image connection as early as his paper on χ Ser (Wehlau, 1967) where he comments on the expectation of profile distortions in rapidly rotating Ap stars. In the early 1970s, Bill supervised a thesis (Falk and Wehlau, 1974) where the Deutsch spherical harmonic expansion technique was used to give a formal method of reconstructing the surface inhomogeneities of stars from their Doppler broadened line profiles. While the limitations of this approach were severe, especially given the very abbreviated spherical harmonic expansion and the fixed Gaussian profile shapes, this may well have been the first true "Doppler imaging" in the sense that we mean it today.

A number of trial and error routines were used in the early 1970s to recover maps from rotationally-modulated profiles but during the mid 1970s a team of Russian Astronomers (Goncharski *et al.*, 1977, 1982) developed the first digital computer code for inverting the profile information in a series of line profiles to recover the map using minimization techniques. The appearance of solid state detectors in the form of Reticons in the late 1970s made the potential for these techniques very great. The mapping of several Ap stars using Reticon data and the Russian code quickly followed when Vera Khokhlova approached Bill Wehlau and myself at the Montreal IAU in 1979 to suggest we collaborate on these projects. The results of this collaboration first appeared in 1981 for the Ap star ϵ UMa (Rice, Wehlau, Khokhlova and Piskunov, 1981).

The beginnings of cool star work with Doppler imaging is most notably connected with the work of Vogt, Penrod and Hatzes. The first project was a manual trial and error approach to mapping HR 1099 (Vogt and

Penrod, 1983) followed by the publication of a formal inversion routine (Vogt, Penrod and Hatzes, 1987) using software first developed by Skilling and Bryan (1984) called MEMSYS. It was in the 1987 work that they introduced the famous "vogt star" and it was also in these papers that the term "Doppler imaging" was first introduced and this term has since been widely used.

While the Russian-Canadian group of Piskunov, Rice and Wehlau migrated from Ap stars to cool star work through collaborations with Tuominen and Strassmeier, the Vogt and Penrod cool star work lead Hatzes into Ap stars. As these groups broadened their application of imaging and refined their programs, others were extending imaging work they had begun independently. Here I name but a few. Cameron had extended work done on mapping stellar spots from photometry and joined the Doppler imaging community with considerable valuable contributions. The work of Kurster and the work of Jankov and Foing has contributed in a major way to the field in the last few years. In a very challenging area of work, the French astronomers Semel and Donati along with Brown and Rees of Australia and independently Piskunov of Russia, have extended the spectroscopic observations to include high resolution Zeeman spectroscopy. The analysis of these data to give both the magnetic map as well as the temperature or abundance map has come to be known as Zeeman Doppler imaging. This is the new frontier that many are joining in exploring and Bill Wehlau had shared in that enthusiasm by championing the construction of a Canadian IQUV spectropolarimeter which is near completion now.

4. The Technique of Doppler Imaging

4.1. GENERAL PRINCIPLES

The common approach to Doppler imaging begins with writing the forward integral (equation 1) representing the translation of a surface map to an observed line profile (see Rice, Wehlau and Khokhlova (1989) for example).

$$R_{calc}(\lambda,\phi)=\frac{\int\int I_l[M,\theta,\lambda+\Delta\lambda_D(M,\phi)]\cos\theta dM}{\int\int I_c(M,\theta)\cos\theta dM}, \tag{1}$$

In equation 1, $R_{calc}(\lambda,\phi)$ is the residual intensity of the line depth that would be observed at phase ϕ, I_c and I_l are the intensities of the continuum and the line, M is the position on the stellar disk specified by latitude and longitude, θ is the angle between the normal to the surface at M and the line of sight, and $\Delta\lambda(M,\phi)$ is the Doppler shift at M due to rotation of the star.

Obtaining an image of the surface distribution of temperature (or abundance) on a star is a matter of obtaining temperature (abundance) as a function of M. This "image" of the surface distribution of temperature (abundance) is used in the calculation of I_c and I_l in equation 1. An essential part of the iterative inversion process used to recover the image is that an error function is made up which contains the sum of the squared differences between R_{calc} and R_{obs}, where R_{obs} represents the actual observed line profiles of the star at various phases of its rotation. The function is

$$E = \sum_{\phi} \sum_{\lambda} [R_{calc}(\lambda, \phi) - R_{obs}(\lambda, \phi)]^2 + f(M). \qquad (2)$$

To get the stellar map (or image) one uses minimization techniques to go from a simple initially assumed map of physical parameters over the stellar surface to converge through iterations that are designed to minimize E to get the simplest map that fits the observed line profile data to within the expected error of that data. Typically a technique such as conjugate gradients is used for the minimization.

The function f(M) in equation 2 is a penalty function whose role is to increase E if detail appears in the map that exceeds the minimum necessary to fit the data to the level of the formal error. In practice, if the data are of good S/N the choice of this function is of little significance since external error usually predominates (continuum fitting error, incomplete cosmic ray extraction etc). The usual choice is between a Tikhonov (1963) function and the image entropy function (Narayan and Nityananda, 1986) but large differences are not evident between the images recovered using either penalty function and in particular, feature location in the resultant map is essentially unaffected. There are some quite interesting qualitative differences though between the images obtained if these penalty functions are used quite aggressively as is illustrated in Piskunov *et al.* (1990).

Several problems with the early work on Doppler imaging became generally apparent and were mostly resolved by the late 1980s. One was that the choice of grid on the star can seriously affect the weight the process gives to different elements over the surface of the star. The early work based on the approach outlined in Goncharski *et al.* (1982) used a simple grid of elements with equal angular extent in latitude and longitude. The polar elements are thus of much smaller area and the minimization process tended to ignore these elements and give emphasis to the subsolar line. The solution was a simple weighting of the gradient components for these elements that was inversely proportional to surface area of the element (see Piskunov and Rice (1992)). As well, when the earliest versions of this code were developed, computing time was less available and the code used the Minnaert formula for the local line profile rather than tables of synthesized line profiles as is common now.

The major distinction between minimization using equation 1 for stellar imaging and, say, medical imaging is that the relationship between the physical variable being mapped (either temperature or abundance) and the residual intensity in the line is a very non-linear relationship. None of the continuum intensity, the line profile or the line strength, scale in a very linear fashion with either temperature or abundance as we are all well aware, for example, through our experience with curve-of-growth. The work of Vogt, Penrod and Hatzes made use of the imaging code called MEMSYS. This program presupposes that the forward calculation from image **I** to line profile data **D** can be formulated as a matrix equation that can be written simply as $\mathbf{IR} = \mathbf{D}$. The process requires that the transfer matrix **R** be calculated before the iteration is begun to find **I**. This is not simply a matter of finding the inverse of the transfer matrix (see Vogt, Penrod and Hatzes (1987)). While MEMSYS handles the image reconstruction process quite ably, the major problem is that to write the forward matrix **R** in the first instance one must assume an invariant profile shape. While it can be argued that this linearization of the forward problem poses little problem for cool spotted stars, it has greater potential for problems with Ap star mapping. More recent versions of the program (Hatzes, 1988) have been produced to allow successive adjustments of the transfer matrix using profiles appropriate to the evolving image.

4.2. NOTABLE CONTRIBUTIONS

Major contributions to the development of Doppler imaging have come from other sources. Cameron and Horne (1985) introduced information from rotationally-broadened line profiles as a supplement to photometric data in using a maximum entropy approach to finding the images of spotted stars. Subsequently Cameron (1990) contrasted the use of filling-factor as an image parameter in Doppler imaging rather than the use of bolometric flux. He presented the case that the two temperature filling-factor approach avoids having "hot spots" appear in the resultant images. Jankov and Foing (1992) have an extensive article on "tomographic imaging" in which they undertake a lengthy analysis of Doppler imaging based on a linearized forward equation similar to the matrix formulation of Vogt *et al.* (1987). Numerous issues such as binarity and optimal observing strategies are dealt with in this paper. Kurster (1993) has a major paper on Doppler imaging with a CLEAN-like approach. He has significant conclusions that include the point that major uncertainties in imaging arise mostly because of a true lack of information in the data and that adapting different approaches to solving the ill-posed problem of extracting an image from equation 1 and equation 2 doesn't resolve this fundamental problem. He also comments that the major reconstruction problem is in getting the relative temperature (or abundance) values correct since the feature locations and shapes are fairly robust.

4.3. TESTING

Piskunov (1990) has the title "The Art of Surface Imaging". I don't know whether he intended by this title that we should emphasize the observing skills and the need for experience that go into successful Doppler imaging but that is what that particular title conveys to me. As I indicated above, Kurster has commented in writing, and many of us realize from practice, that there must be great emphasis on the care and attention taken in selecting suitable objects and picking the lines to be used for imaging and then the data reduction must be undertaken with extreme care. No computing algorithm can compensate so that you can get a good image from bad data but a relatively unsophisticated program can give you a reasonable image from good data on a well chosen object using a well chosen line.

If we have good data and a decent program, the choice of parameters in the reconstruction becomes our next concern. Obviously the choice of the parameters for the local line profile is much more critical if Vsin(i) is small and relatively unimportant when Vsin(i) is large but I shall ignore this issue of how to select log(gf), the excitation potential, the microturbulence etc. since it is a very long topic and properly belongs in the realm of a discussion on spectrum synthesis. A number of papers mentioned below have briefly discussed what can happen if you are seriously wrong in your choice of these parameters. Much more important to accurate reconstruction, especially in the more common case where the Vsin(i) is over about 35 $km.s^{-1}$, is the choice of the geometric parameters i and Vsin(i).

Numerous papers are now available that compare test images before and after recovery given the various impediments to accurate recovery mentioned above. The earlier papers by Vogt *et al.* (1987) and Rice *et al.* (1989) covered the issues of the intrinsic limits to recovery such as the total ambiguity between hemispheres that occurs if the star's inclination is near 90 deg and the lack of latitude resolution that occurs near the equator. The effects of errors in the assumed parameters for the recovery such as errors in Vsin(i), atomic parameters for the line, inclination and phase gaps are all illustrated. Piskunov (1990) covers much the same set of topics and attempts to quantify the limits of error somewhat in pointing out that the recovery is reasonably insensitive to errors in i such that errors up to +/-10 deg have little effect on the recovered image but errors of greater than 1 or 2 $km.s^{-1}$ in Vsin(i) cause relatively serious problems. With these errors in Vsin(i), the higher spatial frequency detail is left reasonably undisturbed, but there is an equator-to-pole gradient that appears on the map that can mimic pole features or equatorial belts.

In later testing, Rice (1991) discussed the degradation in the recovered values of abundance for Ap stars and Piskunov and Wehlau (1994) discussed the detectability of cool polar caps on late type stars and found that spots on the visible pole can be recovered reliably. Since we seem generally agreed that the biggest impediments to obtaining an accurate image seem to be more matters of the quality of data, a most appropriate article is that by Unruh and Cameron(1995). In that article they discuss the effect on the resultant image of various errors in the calculated local line profile but they go on to include the first serious look at the effect on the image of blending in the observed line. Unruh and Cameron conclude that very close blends are less important but that as the blending line is located farther from the principal line, artifacts begin to appear in the recovered image that in extreme cases can look like a broad, dark band. This, of course, is a major concern if we are trying to assess the reality of apparent polar spots.

Comparisons of the various techniques used by Piskunov, by Vogt and Hatzes, and by Rice and Wehlau have been made using EI Eri as a test star (see Strassmeier *et al.* (1991)). The three groups all worked independently from the same data representing three different sets of observations assembled by Strassmeier. Generally the Rice-Wehlau and Vogt-Hatzes maps were very similar to one another and to an earlier map generated by Strassmeier from one of the sets of observations. The differences with Piskunov's maps are still a matter that we debate vigorously from time to time. Overall, I think the comparison was quite satisfactory given the state of Doppler imaging at that time.

4.4. ZEEMAN DOPPLER IMAGING

Variations on Doppler imaging to adapt it to more complex geometries and to spectropolarimetry have been introduced in the last few years. A very challenging adaptation is the introduction of Zeeman Doppler imaging used to recover both the stellar image in terms of a temperature or abundance map and the magnetic field map given spectroscopic data that is fully or partially analyzed for polarization. For the present the most widespread applications of ZDI are in reconstructions from just the I and V spectropolarimetry (Semel, 1989, Donati and Semel (1990), Brown *et al.*, 1991). The observations for ZDI are, of course, more difficult since an analyzing module must be mounted ahead of any oblique reflections in the telescope mirror train and the analyzed light piped to the coude spectrograph, usually by fibre optics. The image reconstruction is also much more challenging since the calculation of the local line profiles involves the magnetic vector and becomes sufficiently involved that the use of some optimized algorithm such as the DELO algorithm (Rees 1989) is required. The advantage of preparing a table for interpolation to get the local line profile is lost in ZDI since the table becomes so large it exceeds the computation needed if you simply calculate the local profile as required.

4.5. BINARY STARS

I will just note here that there has been some interesting work done in imaging binary stars using the line profile information. In particular I will cite, without comment, the article by Rutten and Dhillon (1994) on tomography of interacting binaries and the article by Vincent *et al.* (1993) on techniques in imaging eclipsing binary stars.

5. A Biased Review of Some Results

In this section I intend only to remark on a few stars that have interested me particularly. I haven't the space or the knowledge to do justice to a full review of images of stars in all stellar classes where images exist.

5.1. THE AP STARS

There have been several publications with Doppler images of Ap stars. I will give a brief sample here of more recent images, those done with electronic detectors. I will leave for a more complete history of the field the images that were constructed in the 1970s from photographic data. The sample of papers here includes images of numerous stars in the thesis of Hatzes (1988). The list of stars in that work includes ϵ UMa, γ^2 Ari, 56 Ari, θ Aur, BP Boo, 45 Her, 11 Ori, CU Vir, v For and ω Herc, The two stars ϵ UMa and θ Aur have been well examined by others (Rice *et al.* (1981), Rice and Wehlau (1990) and Khokholova *et al.* (1986)) and ϵ UMa was included in the thesis work of Donati (1990). Maps of three other stars have recently been published. They are: 84 UMa (Rice and Wehlau (1994a)), 17 Com (Rice and Wehlau (1994b)) and ET And (Piskunov *et al.* (1994). The prominence of ϵ UMa and θ Aur in this list is not accidental since these two stars are fairly close to ideal for Doppler imaging among the Ap stars. With a $Vsin(i)$ of about 33 $km.s^{-1}$, with very small Zeeman splitting and being the brightest Ap star, ϵ UMa is ideal. Similarly, for θ Aur the magnetic field is moderate and well established and the star is also very bright and has a larger but manageable $Vsin(i)$. Of current interest is that Rice and Wehlau (1990) discussed the symmetry of the abundance patterns on these two stars in terms of ring patterns about the presumed location of the magnetic poles based on the work of Borra and Landstreet (1974) and Bohlender and

Landstreet (1990). The conclusion of Rice and Wehlau on the location of the centre of symmetry for the Fe and Cr abundance pattern on ϵ UMa differed in latitude from that concluded by Donati. What is quite exciting is that Gonzalez and Artru (1994) discovered a very dramatic variation in the line profiles of the OI triplet near 7775Å and maps from this triplet give a very definitive ring with a clearly definable location for the axis of symmetry. Bill Wehlau and I obtained data on this star as did J.-F. Donati and we are in substantial agreement on the maps. Results from the work of Donati are to appear at this meeting and I fear the conclusion is that, while the longitude is not in dispute, his earlier evaluation of the latitude of the axis of symmetry corresponding to the positive magnetic pole, is closer to the current result than ours was. While the final conclusions about this star have yet to be written, I feel we are very close to a consensus on its surface map.

Overall the research objective for the Ap stars is to correlate the magnetic field structure with the abundance patterns on the stars' surfaces. Theorists can test their diffusion models and models of the physics of the magnetic fields against these data. At present we have an incomplete grasp of this correlation since there are two approaches to modelling Ap stars. One is to map those stars that have sufficiently high Vsin(i) and small magnetic field that we can use conventional Doppler imaging. This gives maximal information on the abundance pattern but very little on the field structure. The other is to work on stars with very small Vsin(i) and very large field so that the Zeeman splitting is evident in conventional spectrograms. This allows us to deduce the magnetic structure well but leaves the abundance pattern less well determined. An example of this last approach is the mapping of 53 Cam by Landstreet (1988). These two approaches are serving us quite well for the time being but the proper answer is to do high dispersion spectropolarimetery in all Stokes' parameters so that we can obtain both the detailed abundance pattern and the field structure. We have both the hardware and software initiatives in progress to give us the data needed for the *simultaneous* solution for both the field and the abundance patterns.

5.2. COOL STARS

5.2.1. *RS CVn Stars*

In mapping the cool stars with their more sunspot like features, our initial objectives are to establish behaviour patterns for the cool features such as determining preferred spot location (and in particular perhaps whether there are polar spots), spot size and numbers, spot migration and lifetimes and differential rotation from deformation over time of the spot patterns.

The ultimate goal will be to tie such statistics to an evolutionary sequence and in particular, hopefully, an evolutionary sequence for solar like stars. In this endeavor one need hardly mention that we will always have a blind spot because we will be restricted to observing the behaviour of rapidly rotating stars (at least rapid compared to the sun) and we will undoubtedly find the goal of detecting spots as small as large sunspots on even rapidly rotating stars an unattainable one through Doppler imaging. Nonetheless, there is much to be learned about solar behaviour by studying more rapidly rotating solar kin at earlier and later evolutionary stages.

It is significant that a remarkable body of information about spot behaviour on cool stars had been deduced from photometry alone (Hall, 1990). In the Doppler images of the weak lined T Tauri star V410 Tau, there are some striking visual confirmations of these deductions as well as important additions to that which was conjectured on the basis of the photometric observations. Photometry does little for us in establishing whether polar spots exist and is weak at ascertaining latitudes but does do a good job of establishing lifetimes for substantial spot features and can be used to estimate differential rotation.

The RS CVn stars have perhaps been the favoured target among the cool stars for Doppler imaging and one issue has been debated strongly about the resultant images. Because of the flattened bottom to the line profiles, there has always been the suggestion that these stars exhibit strong polar cap spots. While there are those who are still uncomfortable with this idea, it seems to me that the consensus from images of HR 1099 (Donati *et al.* 1992, Vogt 1988), EI Eri (Strassmeier *et al.* 1991), UZ Lib (Strassmeier 1995), HD 106225 (HU Vir) (Strassmeier 1994), UX Ari (Vogt and Hatzes 1991) and HD 155555 and HD 32918 (an FK Comae star imaged by Kurster *et al.* 1992) is that large polar cap spots are the norm for more rapidly rotating RS CVn stars and that these large polar spots may change in appearance but are persistent. In contrast, it would seem from the image of σ Gem (Hatzes 1993) that possibly the RS CVn stars with longer periods of the order of 20 days or more might have little in the way of polar spots. One interesting aspect of the Hatzes (1993) paper is the essential agreement with Piskunov and Wehlau (1994) that Doppler images can be recovered down to $V\sin(i)$ of 15 $km.s^{-1}$ or so.

The equatorial spots generally seem to be much smaller and more transient with lifetimes perhaps of the order of several months to a year or so (see the references above for HR 1099, HD 106225 and EI Eri). So far little has been inferred about the differential rotation directly from the Doppler images, largely because of the more transient nature of the equatorial spots. Hall (1990) summarized some photometric work on differential rotation for us so that we might make comparisons and concluded that for these generally rapidly rotating stars it seemed to be an order of magnitude or more less than the sun. (In this discussion I assume differential rotation is meant in the sense of the difference between the polar period and the equatorial period divided by the equatorial period.) Strassmeier (1994) used both Doppler images and photometry to address the issue for HD 106225 and found that successive Doppler images seemed to support a calculation from photometric data giving differential rotation that was an order of magnitude less than the sun. Further, the sense was that the polar regions have the shorter periods. This was almost identical to the conclusions of Vogt and Hatzes (1990) from their work on UX Ari.

5.2.2. *Young Dwarf and T Tauri Stars*

Less work has been done on the fainter T Tauri and young main-sequence objects. Two young rapidly rotating early K dwarf stars have been imaged, AB Dor (Kurster *et al.* 1994) and LQ Hya (Strassmeier *et al.* 1993). LQ Hya has also been imaged by Saar et al. (1992, 1993). Generally there is no strong polar feature (although Cameron and Unruh (1994) suggest a polar ring-like feature since 1992 for AB Dor) and so far nothing to really help with the issue of longevity of spots or differential rotation. The spot features appeared to be extended areas of temperature depression by only a few hundred Kelvins. Kurster *et al.* (1994) argue that the CLEAN algorithm they are using is more prone to seeing these as groups of smaller spots, akin to solar activity, but it is not totally convincing that they have shown this for AB Dor. I suspect they are right in general for these two stars that the large "cool" patches really are spot groups.

The weak lined “naked” T Tauri star V410 Tau has had two good images made with different equipment. (see figure 2). The images were separated in time by about 13 months (see Strassmeier *et al.* 1994) and Rice and Strassmeier (1995). The interesting points of comparison in these images are that a) there is no strong polar spot, b) the strong, multilobed high latitude feature seen at phase 0 deg in the right image of figure 2 has remained relatively stable in appearance over 13 months but it has moved in longitude c) there is apparently another very strong feature in the southern hemisphere seen near phase 0 deg in both images of figure 2 and d) there is an equatorial feature seen near the equator at a longitude of approximately 80 deg in both images in figure 2. If we assume that the feature mentioned above as item d) is the same in both images, then we can calculate a value for differential rotation that is very close to what Hall (1990) estimates for V410 Tau. The differential rotation works out to two orders of magnitude less than the sun and in the sense that the polar regions have the longer period (i.e. the same sense as solar differential rotation). We seem to have an indication that the high latitude spots are much longer lived than a

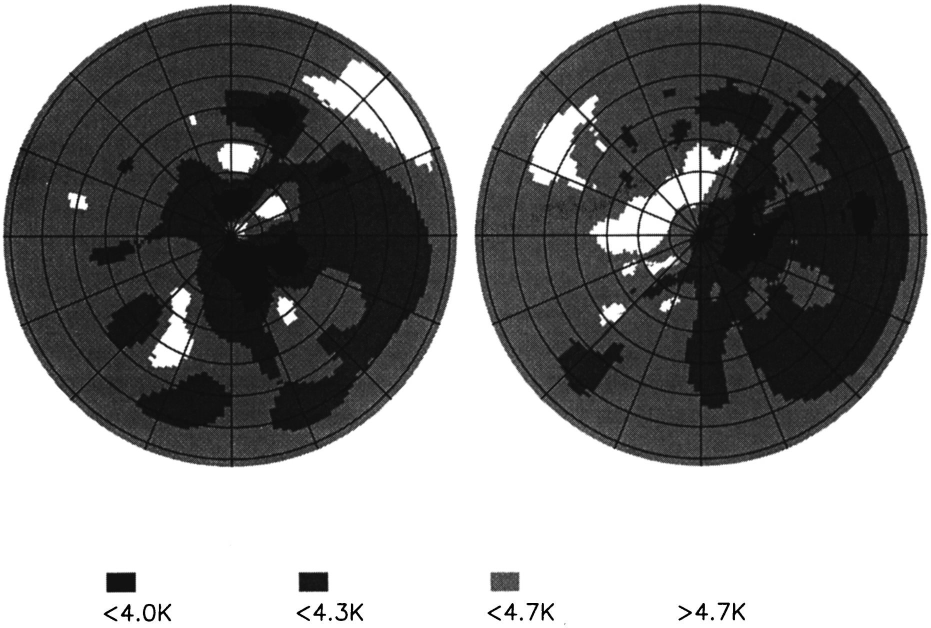


Figure 2. Two images of V410 Tau taken 13 months apart. A pie graph is used to highlight the differential rotation. In each image the zero of longitude is to the left of centre and 90 deg is toward the top. The lines of latitude and longitude are spaced at 22.5 deg and the rotational pole is at the centre. The sense of rotation is clockwise. The left image represents V410 Tau as it appeared in Nov. of 1992 and the right image represents V410 Tau as it appeared in Dec 1993.

year and possibly the appearance of the high latitude multilobed feature represents a spot that is big and very long lived so that even with very small differential rotation, there is the appearance of shear.

An additional image of V410 Tau is available (Joncour *et al.*, 1994) but did not help in the interpretation of figure 2, however as I write this I have just seen the paper by Hatzes (1995) giving an image of V410 Tau at almost the same time as the 1993 image above. As luck would have it, Hatzes uses a different ephemeris and has assumed rotation opposite to our figure in showing the results but they are surprisingly similar. This in spite of his choice of i being 54 deg compared with our 70 deg.

Upon reviewing the very small amount of information available on differential imaging and large polar cap spots, I might hazard the guess that large polar cap spots are associated with negative differential rotation (opposite the sense for the Sun) and that the absence of these large caps or the presence of only broken features at the pole might be associated with differential rotation in the solar sense.

5.2.3. *A Precataclysmic Variable*

Very recently Ramseyer and Hatzes have published the first maps of a precataclysmic variable, V471 Tau, a K2V star with a white dwarf companion. They found cool spots that reinforce the presumption that there is magnetic activity on the K2V star. This bolsters the argument for magnetic braking in such systems as a mechanism for causing the decay of the white dwarf orbit. Two major spot regions were revealed. One is a large polar spot and the other a cool spot region at the subwhite dwarf point.

6. Tribute to Bill Wehlau

It's common to end a review like this with a remark about how much has been done and how much remains to be done but at this meeting I'd like to finish with an observation about the work of Bill Wehlau. As I look over the list of references I have compiled, I see many references to Bill's work but rarely is Bill the first author. That is no indication of his lack of leadership for he certainly was a leader, but rather it is a reflection of his personality. With Bill as co-author, alphabetical order normally prevailed in the listing of authors. For Bill it was important that the contributions of those who have gone before should always be recognized. For his own part, he found satisfaction in the progress he saw in stellar astronomy. We have lost a wonderful friend with his passing and I am delighted that we have this meeting dedicated to him!

References

Bohlender, D. and Landstreet, J. (1990) *ApJ*, **358**, L25
Borra, E. and Landstreet, J. (1980) *ApJS*, **42**, 421
Brown, S., Donati, J.-F., Rees, D., and Semel, M. (1991) *A&A*, **250**, 463
Cameron, A. C., (1990) *Surface Inhomogeneities on Late-Type Stars*: Lecture Notes in Physics 397, P. Byrne and D. Mullan (eds.), Springer-Verlag, p. 33
Cameron, A. C., and Horne, K. (1985) *Cool Stars, Stellar Systems and the Sun*, Lecture Notes in Physics 254, M. Zelik and D. Gibson (eds.), Springer-Verlag, p .205
Cameron, A. C., and Unruh, Y. (1994) *MNRAS*, *269*, 814
Deutsch, A. (1958), in IAU Symposium 6, *Electromagnetic Phenomena in Cosmical Physics*, B.Lehnert (ed.), Cambridge University Press, p.209
Donati, J-F. (1990) *Thesis*, University of Paris
Donati, J-F., Brown, S., Semel, M., Rees, D., Dempsey, R., Matthews, J., Henry, G. and Hall, D.S. (1992) *A&A*, **265**, 682
Donati, J-F. and Semel, M. (1990) *Solar Phys.*, **128**, 227
Falk, A. and Wehlau, W. (1974) *ApJ*, **192**, 409
Goncharski, A., Stepanov, V., Khokhlova, V., Yagola, A. (1977) *Sov. Astron. Letters*, **3**, 147
Goncharski, A., Stepanov, V., Khokhlova, V., Yagola, A. (1982) *Sov. Astron.*, **26**, 690
Gonzalez, J.-F., and Artru, M.-C. (1994) *A&A*, **289**, 209
Hall, D. (1990) *The Sun and Cool Stars: Activity, Magnetism, Dynamos*, IAU Colloq. 130, I. Tuominen, D. Moss and G. Rüdiger (eds.), Springer-Verlag, p. 353

Hatzes, A. (1988) *Doppler Imaging of the Magnetic A(P) Stars*, PhD Thesis, University of California, Santa Cruz

Hatzes, A. (1993) *A&A*, **410**, 777

Hatzes, A. P. (1995) *ApJ*, **451**, 784

Jankov, S. and Foing, B. (1992) *A&A*, **256**, 533

Joncour, I., Bertout, C. and Menard, F. (1994) *A&A*, **285**, L25

Khokhlova, V., Rice, J. and Wehlau, W. (1986) *ApJ*, **307**, 786

Kürster, M. (1993) *A&A*, **274**, 851

Kürster, M., Hatzes, A., Pallavicini, R. and Randich, S. (1992) *Cool Stars, Stellar Systems and the Sun*, M. Giampapa & J. Bookbinder (eds.), *PASPC* **26**, p. 249

Kürster, M., Schmitt, J., and Cutispoto, G. (1994) *A&A*, **289**, 899

Landstreet, J. (1988) *ApJ*, **326**, 967

Narayan, R. and Nitananda, R. (1986) *ARA&A*, **24**, 127

Piskunov, N. (1990) *The Sun and Cool Stars: Activity, Magnetism, Dynamos*, IAU Colloq. 130, I. Tuominen, D. Moss and G. Rüdiger (eds.), Springer-Verlag, p.309

Piskunov, N., Ryabchikova, T., Kuschnig, R. and Weiss, W. (1994) *A&A*, **291**, 910

Piskunov, N., Tuominen, I. and Vilhu, O. (1990) *A&A*, **230**, 363

Piskunov, N. and Rice, J. (1993) *PASP*, **105**, 1415

Piskunov, N. and Wehlau, W. (1994) *A&A*, **289**, 868

Ramseyer, T.F. and Hatzes, A.P. (1995) *AJ*, **110 (3)**, 1364

Rees, D., Murphy, G. and Durrant, C. (1989) *ApJ*, **339**, 1093

Rice, J. (1991) *A&A*, **245**, 561

Rice, J. and Strassmeier, K.G. (1995) *A&A*, in press

Rice, J. and Wehlau, W. (1990) *A&A*, **233**, 503

Rice, J. and Wehlau, W. (1994a) *PASP*, **106**, 134

Rice, J. and Wehlau, W. (1994b) *A&A*, **291**, 825

Rice, J.B., Wehlau, W.H. and Khokhlova, V. (1989) *A&A*, **208**, 179

Rice, J.B., Wehlau, W.H., Khokhlova, V. and Piskunov, N. (1981) *Upper Main-Sequence Chemically Peculiar Stars*, 23rd Liege Astrophysics Coll., p. 265

Rutten, R. and Dhillon (1994) *A&A*, **288**, 773

Saar S.H., Piskunov, N., and Tuominen, I. (1992) 7th Cambridge Workshop, *Cool Stars, Stellar Systems and the Sun*, M. Giampapa & J. Bookbinder (eds.), *PASPC* **26**, 255

Saar, S.H., Piskunov, N. and Tuominen, I. (1993) 8th Cambridge Workshop, *Cool Stars, Stellar Systems and the Sun*, J.-P. Caillault (ed.), *PASPC* **64**, 661

Semel, M. (1989) *A&A*, **225**, 456

Skilling, J. and Bryan, R. (1984) *MNRAS*, **211**, 111

Strassmeier, K.G. (1994) *A&A*, **281**, 395

Strassmeier, K.G. (1995) *A&A*, submitted

Strassmeier, K.G., Rice, J., Wehlau, W., Vogt, S., Hatzes, A., Tuominen, I., Piskunov, N., Hackman, T. and Poutanen, M. (1991) *A&A*, **247**, 130

Strassmeier, K.G., Rice, J., Wehlau, W., Hill, G., Matthews, J. (1993) *A&A*, **268**, 671

Strassmeier, K.G., Welty, A., and Rice, J. (1994) *A&A*, **285**, L17

Tikhonov, A. (1963) *Sov. Math. Dokl.*, **4**, 1624

Unruh, Y. and Cameron, A.C. (1995) *MNRAS*, **273**, 116

Vincent, A., Piskunov, N. and Tuominen, I. (1993) *A&A*, **278**, 523

Vogt, S. (1988) *The Impact of Very High S/N Spectroscopy on Stellar Physics*, IAU Symp. 132, G. Cayrel and M. Spite (eds.), Kluwer Dordrecht, p. 253

Vogt, S. and Hatzes, A. (1990) *The Sun and Cool Stars: Activity, Magnetism, Dynamos*, IAU Colloq. 130, I. Tuominen, D. Moss and G. Rüdiger (eds.), Springer, p. 297

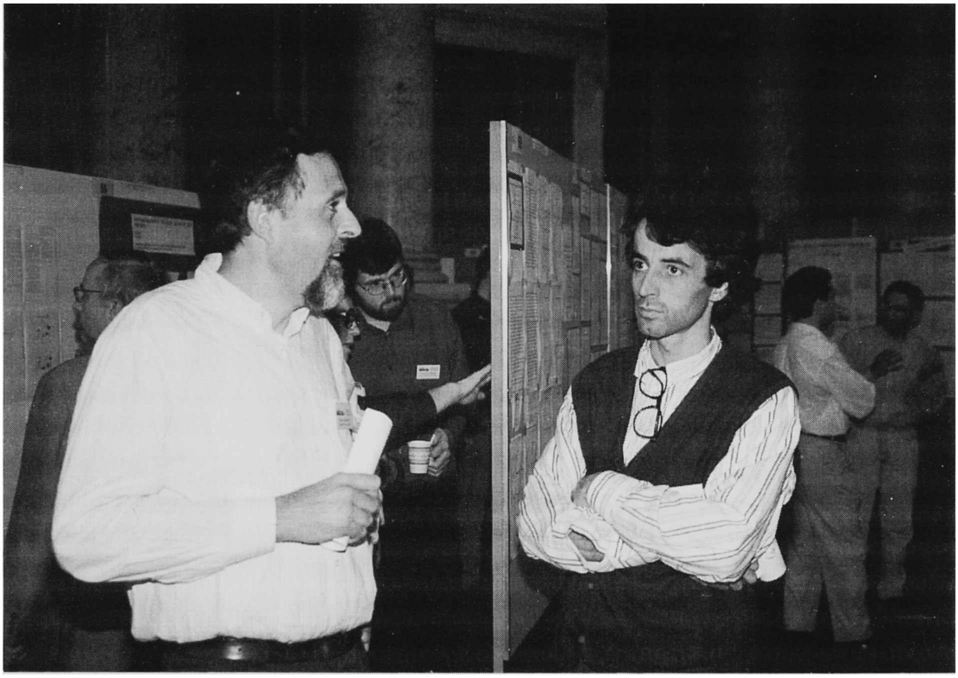
Vogt, S. and Penrod, G. (1983) *PASP*, **95**, 565

Vogt, S., Penrod, G. and Hatzes, A. (1987) *ApJ*, **321**, 496

Wehlau, W. (1967) *The Magnetic and Related Stars*, R. Cameron (ed.), Mono Book Corp., Baltimore, p. 441

Wehlau, W., Rice, J., Piskunov, N. and Khokhlova, V. (1982) *Sov. Astron. Letters*, **8**, 15

The "anglo/franko-canadian" axis. John Rice (*left*) and George Michaud.



Martin Stift (*left*) is talking about ADA while Jacques Babel is probably thinking about the Universe in generell.