4. POLARIZATION

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RECENT RESULTS FROM ULTRAVIOLET AND OPTICAL SPECTROPOLARIMETRY OF HOT STARS

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Abstract. The first comprehensive linear polarization data on hot stars covering the spectral range from 1500 to 7600Å are presented. These results are based on recent observations made with the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE), combined with ground-based observations from the Pine Bluff Observatory. Implications of the data for models of the circumstellar envelopes of hot stars are discussed, with particular emphasis on the surprising results found for the rapidly rotating Be stars. In particular, WUPPE discovered that the continuum polarization in Be stars decreases into the ultraviolet, which was not predicted by models prior to the observations. Time variability in the optical data is also discussed. Possible interpretations of these results are examined in the light of recent new models for Be star disks.

1. Introduction

The first flight of the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE) aboard the Astro-1 mission in December 1990 provided an opportunity to obtain the first spectropolarimetry of hot stars in the ultraviolet. Ongoing ground-based support observations for this mission are being obtained at the University of Wisconsin's Pine Bluff Observatory (PBO), and have produced a valuable data set of optical spectropolarimetry for a broad range of hot stars. The combination of WUPPE and PBO data gives the first comprehensive linear polarization data covering the spectral range from 1500 to 7600Å.

2. Observations

2.1. Optical Spectropolarimetry

The optical observations were made with the PBO 0.9-m telescope and a dedicated spectropolarimeter. The PBO instrument is designed to be the complementary optical counterpart of WUPPE, measuring spectra and polarization from 3200 to 7600Å, with a spectral resolution of about 25Å. For details on the design of the instrument and the data reduction process, see Nordsieck *et al.* (1992). Observations of specific WUPPE targets were made contemporaneously at PBO. In addition, survey observations of a sample of Be stars have been made over the past 4 years, permitting a study of spectropolarimetric variability in Be stars.

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2.2. Ultraviolet Spectropolarimetry

The ultraviolet observations were made in December 1990 using WUPPE, a 0.5-m f/10 Cassegrain telescope and spectropolarimeter; the design permits two orthogonally polarized beams to be recorded simultaneously on a dual intensified Reticon array. WUPPE obtains simultaneous spectra and polarization measurements, with a spectral resolution of about 12Å, from 1500 to 3200Å. For details about the instrumentation and design of WUPPE, see Nordsieck *et al.* (1993).

Several types of hot stars were observed with WUPPE, including OB supergiants (Taylor *et al.* 1991), Wolf-Rayet stars (Schulte-Ladbeck *et al.* 1992), OB main sequence stars (which were observed primarily as probes of interstellar polarization; Clayton *et al.* 1992), and Be stars (Bjorkman *et al.* 1991, 1993). Due to space limitations, only the results from the Be stars will be discussed in detail in these proceedings. The interested reader is referred to the above references for details on results of other types of hot stars.

Three Be stars were observed with WUPPE: ζ Tau, π Aqr, and PP Car. Contemporaneous PBO observations were made for ζ Tau and π Aqr (PP Car is a southern object). Figs. 1 and 2 show the combined WUPPE and PBO data for ζ Tau and π Aqr, respectively. Details regarding the data reduction process and interstellar polarization removal are found in Bjorkman *et al.* (1991). No interstellar removal was done for ζ Tau, since its interstellar polarization is small.

At the time of the Astro-1 mission, ζ Tau was in a typical high-polarization state, with a large polarization Balmer jump and strong line depolarization effects in the optical data. ζ Tau had shown this level of polarization over the previous two years, with only small variations at the level of about 0.1 per cent. π Aqr, on the other hand, was in a very low polarization state to which it had declined over the previous 18 months, from a peak of 1.5 per cent polarization (at around 4000Å) to the low of about 0.6 per cent. The optical data show that no polarization Balmer jump was present in π Aqr at the time of the WUPPE observations. The variability of π Aqr is discussed further in a later section.

3. UV Continuum Polarization of Be Stars

The typical models used to make predictions of the shape of polarization vs. wavelength assume that the polarization is a result of electron scattering of stellar flux within the circumstellar disk, reduced by the competing effects of hydrogen opacity within the disk material and dilution by unpolarized emission from the disk. Electron scattering alone produces a per cent polarization %P, vs. wavelength λ, curve which is flat, but the hydrogen bound-free opacity produces the characteristic "sawtooth" shape of the standard models. These models assume single scattering, i.e. that the elec-

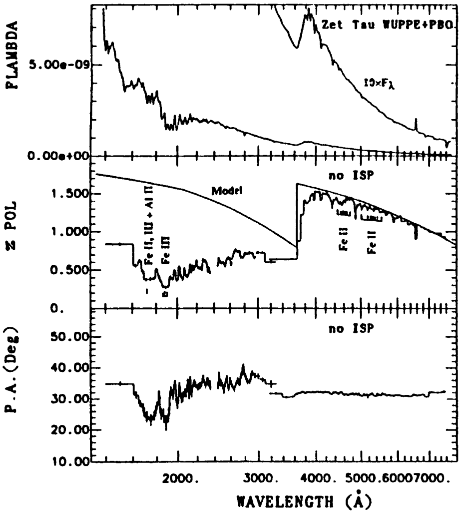

Fig. 1. Combined WUPPE and PBO data for ζ Tau. The upper panel shows the flux, the middle panel shows the % polarization, and the lower panel shows the polarization position angle. The WUPPE data are binned to a constant error of 0.02% and the PBO data to 0.01%. The solid line in the center panel indicates typical model predictions of the UV polarization continuum. (Figure from Bjorkman *et al.* 1991.)

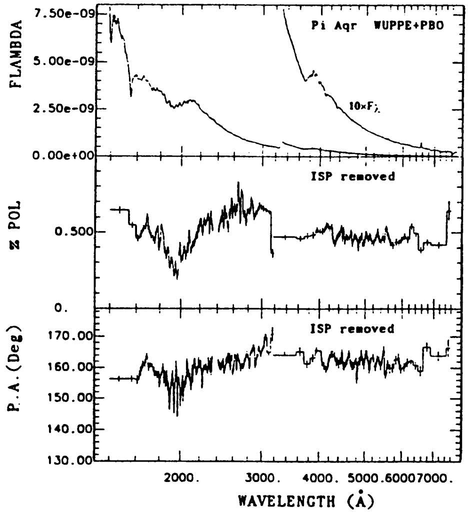

Fig. 2. Combined WUPPE and PBO data for π Aqr. The panels are the same as shown for ζ Tau. Both the WUPPE and PBO data have been binned to a constant error of 0.02%. An estimate of the interstellar polarization has been removed from these data. Note the lack of a polarization Balmer jump, as compared with ζ Tau. (Figure from Bjorkman *et al.* 1991.)

tron scattering optical depth $\tau_e < 1$. Models prior to the flight of WUPPE predicted that the polarization would rise dramatically into the UV (e.g. Poeckert & Marlborough 1978; Cassinelli, Nordsieck & Murison 1987).

Several key features of the polarization data for ζ Tau and π Aqr are apparent, especially when contrasted with model predictions as in Fig. 1, which shows a comparison of the data for ζ Tau with a model prediction from Cassinelli *et al.* (1987). The "sawtooth" shape of the predicted polarization vs. wavelength in Fig. 1 is characteristic of all the existing models, and serves to illustrate the difference between the data and the models.

Firstly, although the general shape of the continuum polarization vs. wavelength curve matches fairly well with the model predictions in the optical, the UV polarization disagrees with the models in the case where a large polarization Balmer jump is present. While the models predicted there should be a strong increase in polarization toward shorter wavelengths in the UV, the data actually show a constant or slightly declining continuum polarization with decreasing wavelength.

Secondly, there are strong, broad UV polarization dips around 1700 and 1900 Å, corresponding to the location of numerous Fe lines in the spectra of both stars. Note that the 1700 Å dip is more pronounced in ζ Tau than in π Aqr, which may be an indication of differences in the density or temperature of the circumstellar material around the two stars. There is also a rotation of the polarization position angle across the UV polarization dips, but not across the polarization Balmer jump.

Thirdly, the optical data show depolarization effects across the Balmer hydrogen lines, as has been reported by others, as well as depolarization of Fe II lines in ζ Tau (Fig. 1). Since the Fe lines are much weaker than the hydrogen lines in the spectrum, the dilution effect from disk emission in the Fe lines is smaller, and hence the reduction in polarization may be instead an "attenuation" effect arising from the actual removal of polarized light from the line of sight. This implies that the Fe absorption occurs primarily in the disk, close to the star.

3.1. Implications for Models of Be Star Disks

The differences between the observations and the predictions point out several changes which must be made in the next generation of models for Be star polarization. Clearly the metal line opacities in the polarizing region must play an important role in UV (and also optical) %P vs. λ characteristics, suggesting that, in particular, Fe line opacities must be accounted for in any model for the UV polarization of Be stars. Line blanketing by Fe II and Fe III lines, as well as other metal lines, is apparently quite important in determining the wavelength dependence of polarization, especially in the UV. Initial simple models incorporating Fe line opacities show that this approach can probably come close to matching the observed UV polarization (A.D. Code, private communication).

Several other factors which could affect the wavelength dependence of the continuum polarization may also have to be considered—for example, the effect of gravity darkening. The von Zeipel theorem predicts that the equatorial regions of a rapidly-rotating star will have a cooler effective temperature than the polar regions. If the scattering region producing the polarization is located primarily in an equatorial disk, then the scattered radiation originates primarily in the cooler equatorial regions of the star, while the direct (unscattered) radiation originates primarily in the polar regions. Hence, this gravity darkening could change the wavelength dependence of the measured polarization, which is just the ratio of the cooler scattered flux to the hotter direct flux. However, while it does decrease the continuum polarization in the UV, gravity darkening alone does not appear to be adequate to explain the discrepancies between the observations and the model predictions (Bjorkman & Bjorkman 1994).

A potential difficulty for new models will be to explain the rotation in position angle across the Fe lines in the UV, which was seen in all three Be stars observed with WUPPE. This may be a result of optical depth effects in the Fe lines, but the details of how this translates into the disk geometry and density distribution must be worked out.

4. Optical Polarimetric Variability

Examination of the PBO optical data set provides information on the polarimetric variability of Be stars. The best studied case, with 40 observations from August 1989 through December 1992, is the Be star π Aqr. Fig. 3 shows the average polarization of π Aqr as a function of time, along with the variations in the equivalent width of the Hα emission line. Note that at least two, and possibly three, polarimetric "outbursts" were observed in π Aqr over the span of about 4 years. When the polarization was high, π Aqr showed a strong polarization Balmer jump similar to that seen in ζ Tau (see Fig. 1). When the polarization was low, π Aqr showed no polarization Balmer jump, just as is seen in Fig. 2.

The 1991 outburst (centered on JD 2448477), which was particularly well covered temporally, gives a good indication of typical time scales for such variations. The rise time of the outburst was about 3 months, with a comparable falloff time after the peak polarization was reached. Note also that the Hα equivalent width showed very little change during the time that the polarization level was changing dramatically. This implies that most of the variability is occurring at small radii, and not throughout the large Hα emitting region.

4.1. Contemporaneous UV Wind Line Variability

Examination of UV spectra of π Aqr from the archives of the International Ultraviolet Explorer (IUE) satellite as well as IUE data taken contemporaneously with the Astro-1 mission show an interesting change in the UV wind line profiles just prior to one of the polarimetric outbursts. Fig. 4 shows the IUE spectra around the N V ($\lambda\lambda$1238, 1242Å) region. As shown in this figure, on 21 November 1990 N V was in absorption with weak high velocity components. (This observation was taken in support of the ROSAT X-ray satellite All-Sky Survey. Note that Meurs *et al.* (1992) reported from the X-ray survey data that π Aqr had a value of $\log L_x/L_{bol} \approx -6.5$, which is strong for a B star, and that the spectrum was fairly hard.) Fifteen days later (during the Astro-1 mission) on 6 December 1990, the IUE data show that N V had developed a strong, low velocity ($\approx$ 200 km s^{-1}) discrete absorption component (DAC) in both components of the doublet line. Ten days later the DAC's in the N V had weakened considerably.

The development and disappearance of the low velocity DAC's in N V corresponded with the onset of a polarimetric outburst, which began some-

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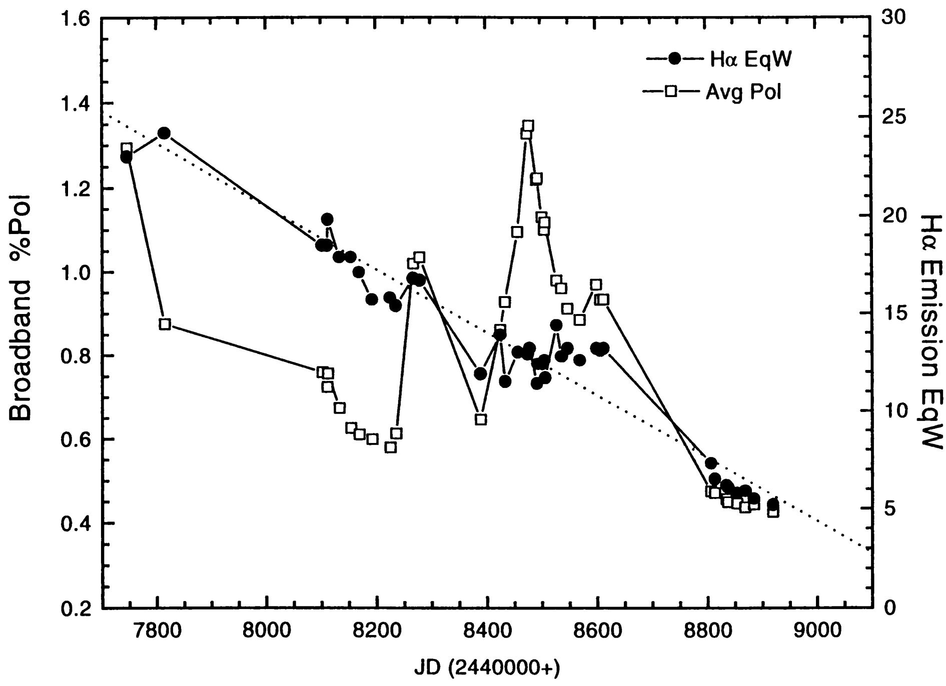

Fig. 3. Time variability of π Aqr. The open squares are the polarization level averaged over the entire wavelength range of the PBO observations; the filled circles are the Hα line emission equivalent width in Å. Note the major polarimetric outburst around JD 2448477, as well as possible outbursts around JD 2448260 and JD 2447750. The Hα equivalent width changed little during these times.

time between 30 November 1990 and 10 December 1990. While there is not sufficient temporal coverage of IUE archival data to say whether such developments always occur prior to a polarimetric outburst, it is certainly a tantalizing hint that there may be a connection between changes in the wind and changes in the disk. The fact that the DAC developed at low velocities, more typical of disk velocities, also supports the idea that these wind changes may be associated more closely with the disk than with the polar wind. The WCD model of disk formation around rotating stars (see J.E. Bjorkman, these proceedings) would predict such a connection, especially in superionized lines such as N V.

4.2. Interpreting the Variability of π Aqr

The observed timescale for polarimetric outbursts of π Aqr provides some potentially difficult constraints on models which might be proposed as the underlying cause of the variability. Since the outburst is fairly slow develop-

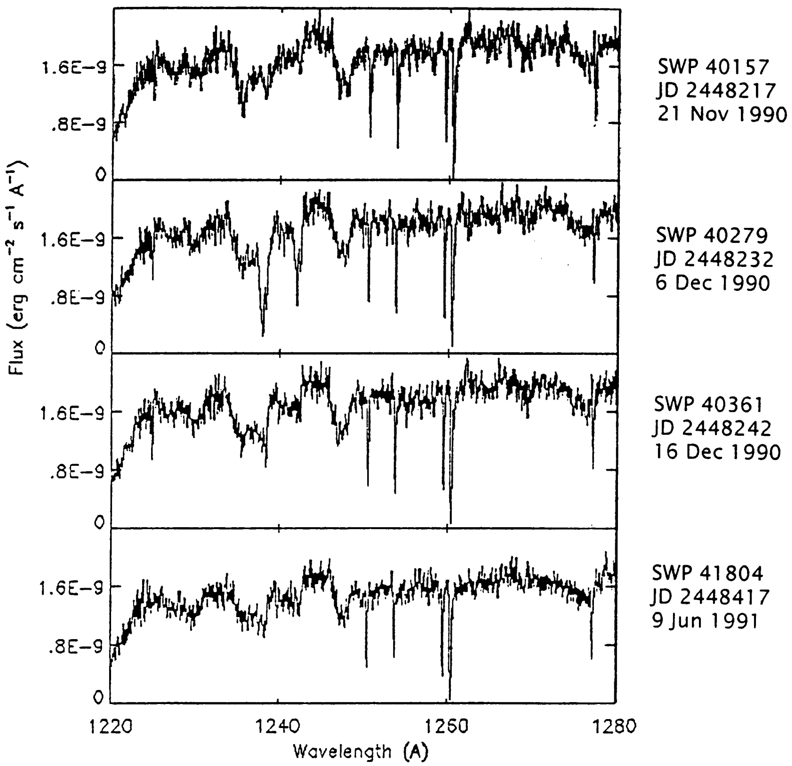

Fig. 4. Variability in the N V line profiles of π Aqr around the time of the beginning of a polarimetric outburst. The data are from the IUE satellite. The polarimetric outburst began between 30 November and 10 December 1990, or around the time of the development of the low-velocity discrete absorption component seen in the second panel. The IUE image number, Julian Date, and calendar date of the IUE observations are listed beside each panel.

ing, whatever produces the changing polarization must be stable over times of several months.

Assuming typical velocities of 100 km s^{-1} in the disk, the flow time for a density perturbation in the disk to move a distance of 1 stellar radius is only about 1 day. In the wind, where velocities are more typically 1000 km s^{-1}, the equivalent flow time would only be about 2 hours. This rules out any changes related to flow times in the disk or in the wind. Also, for the spectral type of π Aqr, the rotation timescale is only about 2 days, assuming an inclination angle of 90°.

Clearly, none of these time scales are long enough to explain the sustained and apparently smooth polarimetric changes over time scales of months. This would seem to rule out anything as simple as density perturbations (blobs) moving through the wind or disk. Also, the lack of much change in the Hα equivalent width suggests that the polarimetric changes are primarily due to changes in the inner part of the circumstellar envelope and that these changes do not affect the much larger region that produces the Hα emission.

Other suggestions to explain the polarimetric variations include increased mass-loss rate from the star (perhaps driven by an increased UV continuum flux, evidence for which is seen in the IUE data), which increases the mass in the disk due to the WCD mechanism, or a one-armed spiral density wave in the disk (which has also been proposed to explain V/R variations in Be stars). However, details of such pictures are not well enough developed yet to determine whether they might work in the case of π Aqr. There are also some potential problems with explaining the variability seen in the UV wind line profiles near the times of the polarimetric outbursts.

5. Future Work

The sample of hot stars with UV spectropolarimetric measurements will be increased by the flight of the Astro-2 mission, currently scheduled for launch in December 1994. For the Be stars, the effects of spectral type, rotation rate, and shell vs. non-shell classification on the UV polarization will be investigated. New predictions of the UV continuum polarization will be developed to include the effects of iron line opacities as well as to test predictions of new models for Be stars, such as the WCD model.

In the optical, the complete sample of Be stars observed spectropolarimetrically at PBO will be analyzed to investigate the prevalence of polarimetric outbursts and to determine whether the time scales observed in π Aqr are typical for such outbursts. Analysis of the optical and UV polarization characteristics can give useful information about the nature of the circumstellar envelopes which is complementary to what can be learned from spectroscopy and photometry. Ideally, one would prefer to have a complete set of contemporaneous spectroscopy, photometry and spectropolarimetry to analyze concurrently.

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Discussion

Smith: I would like to add one more logical possibility to your list of speculations for π Aqr's high-energy behavior in 1991. Imagine that you had a distribution of hot spots on the surface of π Aqr at that time that locally mimic an O-star's atmosphere. Then, locally, these spots would be expected to set up O-star-like winds, and therefore DAC's in the UV resonance lines. They would also tend to give you (according to J. Cassinelli's paper) slightly enhanced X-rays than those expected for a B2 star.

Bjorkman: Yes, that might be a possibility. I think the details of whether such a picture could explain the observations of DAC's in conjunction with polarization outbursts would have to be worked out, but that is true for all of these speculations.

Stee: Have you used single scattering for your computation? Multi-scattering close to the star (where the density is higher) may be a way to decrease polarization. Also, did you find any correlation between $v \sin i$ and polarization?

Bjorkman: Our calculations so far are quite simple and only assume single scattering. However, Barbara Whitney at CfA has done some preliminary

Monte-Carlo simulations which account for multi-scattering in an optically thick disk. She finds that although the optically thick case does produce somewhat lower overall polarization, the wavelength dependence doesn't change very much. So while the multi-scattering may help to lower the polarization some, the preliminary indications are that it will not explain the non-rising UV continuum polarization.

Hubert: Did you observe any important variability in ζ Tau? This star has begun a new sequence of activity (V/R variations and RV variations) since 1991.

Bjorkman: We have been monitoring ζ Tau for the past 4 years. During that time we have seen small-scale (at about the 0.1 per cent level) variability in the polarization level, but nothing comparable to the outburst changes we have seen in π Aqr. We are continuing to monitor it, however.

Ghosh: You have observed an increase of the equivalent width of N V during the outburst of an edge-on Be star. We have also observed an increase in the equivalent width of the absorption lines of Si II, Fe II, and N II (in the optical) in the pole-on Be star, μ Cen. Do you think that matter exists in the polar region, which we have proposed, based on our observations?

Bjorkman: If these lines are seen in absorption and if the star is truly pole-on, then obviously there must be some material in the polar region. Since the equivalent width increased, the amount of material seen through the column to the star must have increased. This does not necessarily mean, however, that there is more material in the polar regions than in the disk.

Peters: I would not expect the von Zeipel effect to be very important. According to current thought the Be-shell stars are viewed equator-on. In the case of ζ Tau, $v \sin i = 220 \approx v_{\mathrm{eq}}$, which implies that $v_{\mathrm{eq}}/v_{\mathrm{crit}} \approx 0.4$. Therefore, the decreases in the temperature of the equator would be extremely small.

Bjorkman: You are correct that the temperature difference is probably small for ζ Tau, and thus unlikely to produce a large effect. The model results which I showed here were just intended to illustrate that gravity darkening can have an effect on the UV continuum polarization, and that it goes in the right direction to help with the discrepancy with the models. However, as I said, we do not think that gravity darkening alone will provide nearly enough of a change to explain the WUPPE observations, and the Fe line opacities will definitely play the dominant role.

Hummel: I have two questions. First, why did you start your observations with shell-type Be stars?

Bjorkman: The fact that WUPPE observed 3 Be shell stars and no non-shell stars was purely a coincidence. We had originally planned to observe

8 Be stars, of which some were Be and some were Be-shell. However, due to some problems during the Astro-1 mission, many planned observations were lost, and unfortunately the small number of observations that we did get included only shell stars. We hope to remedy that on Astro-2, which will fly in December 1994 if the current schedule holds.

Hummel: Second, what are the problems with associating the UV data to the density wave model?

Bjorkman: While the density wave model has potentially the right timescale for the polarization changes, the DAC's in the wind lines were observed at blue-shifted velocities of about 200 km s^{-1}. The spiral density wave model requires a Keplerian disk, which implies that the disk is not expanding. If these DAC's were caused by such a spiral density wave in the disk, they should not be blueshifted, but should occur close to zero velocity.

Baade: If the detection of variability is a stated goal, it may be advantageous to look at stars with weak Hα emission. For instance, there are long series of spectra of μ Cen which show that it underwent little Hα outbursts at a rate of up to one per 10–20 days. This is in line with the polarimetric and photometric monitoring of ω Ori by Hayes & Guinan, who found numerous polarization outbursts with a rise time of 1–2 days (as in μ Cen). I happened to obtain one Hα profile of ω Ori during such a high polarization state, and it had anomalously broad wings, which, if attributed to scattering, are consistent with the polarization data. Hα outbursts of μ Cen also seem to start with very broad Hα emission.

Bjorkman: It would be very interesting to try and correlate the polarimetric behavior with detailed line profile observations. Our current instrument does not provide the necessary spectral resolution to see line profile changes in any detail. I think it would be quite useful to coordinate observations of spectropolarimetry with high resolution Hα observations.