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Solar polarimetry with ZIMPOL

Plans for the future

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Abstract. ZIMPOL (Zurich Imaging Polarimeter) has been developed since the early 1990s, and various versions at increasing levels of sophistication have been used with great success at different telescopes (IRSOL, McMath-Pierce, DST, SST, VTT). The main idea behind ZIMPOL is to overcome the problem of making fast polarization modulation compatible with the slow read-out of large-scale CCD sensors. This is done by creating fast, hidden buffer storage areas within the CCD, and by shifting the photo charges at kHz rates between the illuminated and the buffer storage areas in synchrony with the modulation. ZIMPOL is not dependent on the type of modulator used. Although most observations have been done with piezo-elastic modulators, FLCs and Pockels cells have also been used. A version of the ZIMPOL sensor with an array of cylindrical microlenses to optimize the efficiency has recently been implemented. An overview is given of the present status and the future plans with the ZIMPOL systems.

1. Introduction

Spectro-polarimetry has become the key tool of observational solar physics, because it allows us explore magnetic fields in a quantitative way. It is now recognized that magnetic fields are responsible for almost all variability in the universe on intermediate time scales, including all of stellar activity. The Sun serves as a prototypical astrophysical object that allows us to explore the fundamental physical processes that take place everywhere in the universe.

Modern observational astronomy is done with large CCD-type imaging detectors. The usual application is of course to record normal intensity images for different wavelengths, either in the focal plane of a spectrograph or behind a filter system. In polarimetry the desired task is to image the full Stokes vector, i.e., to record four simultaneous images of the four Stokes parameters I, Q, U, and V. This is a challenging task, not only because we go from imaging of a scalar (the intensity) to a 4-vector, but in particular because most of the interesting polarization signatures have very small amplitudes. The main challenge is to eliminate as far as possible the various noise sources that generate spurious polarization, while working with large detector arrays.

The technological breakthrough that occurred with the introduction of ZIMPOL (Zurich Imaging Polarimeter) was through the creation of hidden fast buffers in the CCD sen-

Send offprint requests to: J.O. Stenflo sor, which could allow fast modulation and synchronous demodulation of all Stokes parameters simultaneously (Povel 1995, 2001). Thereby the two main noise sources of spurious polarization, seeing and gain-table noise, could be eliminated, such that the only remaining limit to the attainable polarimetric precision is the quantum limit set by the photon Poisson statistics. With the large, photon-collecting aperture of the McMath-Pierce facility at Kitt Peak, ZIMPOL has routinely recorded Stokes spectra with a noise of less than 10^{-5} in the degree of polarization, in combination with high spectral resolution (e.g. Stenflo 1994).

2. Basic philosophy behind ZIMPOL

A polarization image, e.g. Stokes Q/I, is formed from the difference between two images that represent orthogonal polarization states. If the two images are recorded simultaneously, i.e., spatially separated with a beam splitter, the seeing noise will in principle subtract out (assuming no differential aberrations), but the gain-table noise due to the different pixel sensitivities will remain. With flat-fielding the gain-table fluctuations may be reduced to about 0.5%, but this is far from sufficient, since we need to be more than two orders of magnitude better to explore the really interesting polarization physics.

Semel's beam exchange technique (Semel, Donati, & Rees 1993; Semel 1995) allows significant suppression of the gain-table noise when using a beam splitter system, but it requires two separate exposures with different seeing distortions, and only one of Q, U, or V can be recorded at a time.

To eliminate gain-table noise one needs to use the same detector area for the orthogonally polarized images, which can be done by modulating the polarization state. Since then the images are temporally (instead of spatially) separated, they will contain different seeing noise, unless the temporal separation is less than a few milliseconds. Therefore the modulation has to be fast enough, i.e., in the kHz range. The problem with this is that large CCD arrays have a slow readout, far slower than what would be needed to beat the seeing frequencies.

The technological breakthrough of ZIMPOL was to overcome the incompatibility problem between fast modulation and slow readout. The solution is to create fast, hidden buffer storage areas within the CCD sensor, and cycle the photo charges between these storage areas in synchrony with the polarization modulation. What is done conceptually in a ZIMPOL system that simultaneously records all four Stokes parameters is that four simultaneouos image planes are created within the CCD, one exposed and three hidden image planes. The synchronous demodulation of the modulated beam is done by cycling the photo charges at the kHz modulation rate between the four image planes. Only after many thousand modulation cycles, after the CCD has been filled, it is read out. The readout then contains the four simultaneous images that represent different polarization states. Through simple linear combinations of these four images we obtain images of the four Stokes parameters. When dividing with the sum image to obtain the fractional polarizations Q/I, U/I, and V/I, the gain table divides out entirely, so flat-fielding is not needed for these polarization images.

The problem with the implementation of this idea is that commercially available detector arrays with such fast, hidden buffers do not yet exist. One therefore has to come up with a trick to modify existing CCD systems such that they can achieve the desired goal. While all CCDs have slow readout, certain types of CCDs allow the charges to be shifted laterally at fast rates by a few rows in both directions. The trick is therefore to mask sections of such CCDs and use the unexposed, masked areas of the CCD as the hidden buffers. In the first implementation of the ZIMPOL system, ZIMPOL-1 in 1994 at Kitt Peak, we had every second pixel row masked, which allowed us to record two Stokes parameters, e.g. I and Q, simultaneously. A few years later we implemented as the second generation a system with four image planes, ZIMPOL-2, allowing the simultaneous recording of all four Stokes parameters. For each group of four pixel rows three are masked and one is open. The photo charges are cycled horizontally between the rows in each group. Since this is done in synchrony with the modulation, the image planes correspond to different polarization states.

A few years ago a UV sensitive version of ZIMPOL-2 was introduced (Gandorfer et al. 2004), which allows high-precision spectro-polarimetry all the way down to the atmospheric cut-off near 300 nm. Another major improvement is the recent implementation of using an array of cylindrical micro-lenses to prevent light losses on the masked portion of the detector. Each cylindrical micro-lense has a width of four pixel rows and assures that all the photons are channelled to the unmasked pixel rows. Without such lenses 3/4 of the light falls on the masked portion and is therefore wasted. Several years ago we tried to implement such micro-lenses, but these attempts failed, since micro-lenses with sufficiently short focal length that would be needed to match the f-ratio of the telescope could not be manufactured. This problem was solved only during the last few months, and a ZIMPOL detector with a well functioning micro-lense array was successfully used for the first time in a ZIMPOL observing run at the SST on La Palma in October 2006.

Figure 1 illustrates the principle for the simultaneous recording of the four Stokes parameters with ZIMPOL (Stenflo, Keller, & Povel 1992). Although this scheme was published in 1992, 14 years ago, its implementation has taken a long time. Thus, as just mentioned, micro-lenses were successfully implemented only in October 2006. The modulation scheme depicted on the right-hand side of the figure is based on two phase-locked piezo-elastic modulators. However, to this date we have not yet succeeded in implementing such phase-locking of resonant devices (cf. next section). Still, in spite of these deficiencies and the considerable room for improvements, the scientific results obtained with ZIMPOL so far have been overwhelmingly successful. Since a perfect, ideally optimized ZIMPOL system cannot be built with a modest budget and small staff, our strategy has been to develop it incrementally, with scientifically useful new versions of the system after each incremental improvement, which may be used to push the limits of the state of the art in imaging polarimetry, and allow us each time to look at the Sun with improved "eyes".

In the future the ZIMPOL technology might become obsolete when a CMOS technology becomes available, which would allow fast buffer storage areas vertically below the pixels, such that masked detectors would no longer be needed. This technology however lies an undefined number of years ahead in the future and requires major financial investments to become a reality. Fortunately we do not have to wait for this, since the function of such CMOS systems for polarimetry are presently well emulated by ZIMPOL.

3. Modulation systems used with ZIMPOL

A polarimetric instrument system based on a modulation technique consists of two main parts: (1) The modulation package, which should be placed as early as possible in the optical path of the telescope, to minimize the instrumental polarization, and (2) the demodulating detector system in the final focal plane of the telescope (which can be the focal plane of a spectrograph or of a filter system). Sometimes there is the misunderstanding that the ZIMPOL system is based on a certain type of modulator or modulation scheme. This is not so at all. ZIMPOL can be used with any type of modulator or modulation scheme. What is unique about ZIMPOL and its novel technology is contained in the demodulating detector system, not in the modulation system.

Since ZIMPOL can be used with any modulation system, we have experimented with the use of the three main types of modulators, which can modulate the polarization in the kHz range, namely piezo-elastic modulators (PEMs), ferro-electric liquid crystals (FLCs), and Pockels cells (KDPs). They all have their advantages and disadvantages. The PEMs have been the easiest and most reliable type, and therefore practically all scientific results from ZIMPOL that have been published have been

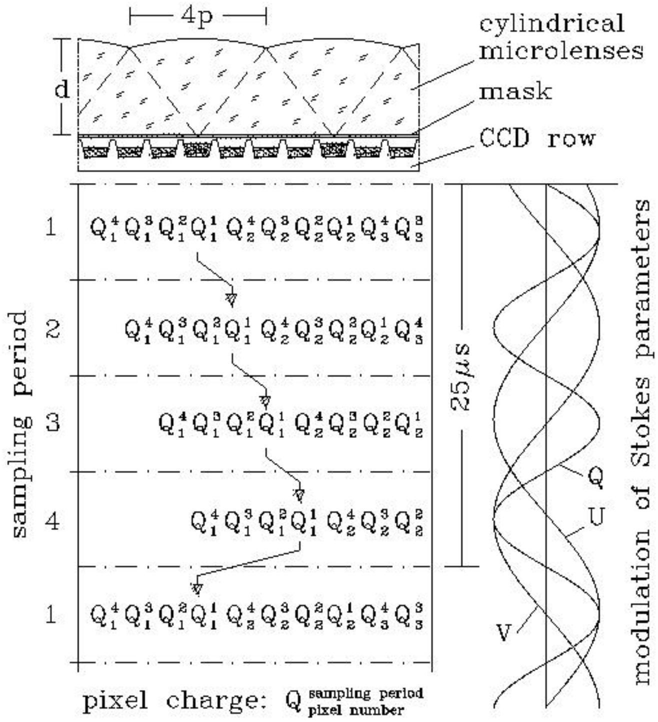

Fig. 1. Illustration of the demodulation principle in the ZIMPOL detector. A mask deposited on the CCD covers three out of every four pixel rows. An array of cylindrical microlenses prevents light loss on the masked area by focussing all the photons on the unmasked pixel rows. The charges are cycled between the four pixel rows in synchrony with the piezoelastic modulation of the four Stokes parameters. From Stenflo, Keller, & Povel (1992).

based on the use of PEMs. Here follows a summary of their properties.

3.1. Piezo-elastic modulation (PEM)

In a PEM a piezo-electric transducer excites a standing sound wave in a glass plate of high optical quality. The glass plate oscillates at its resonant frequency, which is determined by its physical dimension (its length equals half the wavelength of the standing sound wave). The modulation frequency therefore cannot be chosen. For the PEMs that we have been using the fundamental frequency is 42 kHz, which is much higher than needed to eliminate seeing noise (1 kHz would be sufficient). To bring the frequency down one would have to use a larger-size modulator, but since the modulators we use are already quite large, one has to live with the high modulation frequencies in the case of PEMs.

Another drawback of PEMs is that the wave form of the modulation cannot be chosen. As it is a resonant oscillation, the wave form is always sinusoidal, while the optimum wave form would be rectangular.

Since the stress-induced birefringence and thus the retardance oscillates sinusoidally, while the response of the Stokes parameters is in terms of sine or cosine of the retardance, the modulation of the Stokes parameters is given by the sine of sine and cosine of sine functions. When expanded in Bessel functions, it follows that in the usual PEM modulation scheme Stokes V is modulated at the fundamental frequency (42 kHz in our case), while Stokes Q

and U are modulated at the second harmonic (84 kHz) (cf. Stenflo 1994).

Since PEMs are resonant devices it is very difficult, if at all possible (we have in any case not yet succeeded), to phase-lock two PEM modulators with different orientations of their optical axes, which is needed if we are to record Q and U simultaneously. Since such a phase-locked PEM system has not yet been implemented, all our scientific observing programs have been based on modulation with a single PEM, which allows simultaneous recording of three but not four Stokes parameters. We do this by first recording I, Q, and V, and then by mechanically rotating the modulation package by 45° to record I, U, and V. For long integrations, to build up photon statistics, one alternates back and forth between these two positions such that the Q and U recordings are interlaced in time.

With all these significant drawbacks one may wonder why we have stuck with PEMs for almost all our scientific observing runs with ZIMPOL. The reasons are the significant advantages of PEMs, and the serious problems with the other types of modulators (cf. the following subsections).

The main advantages of PEMs are:

- They are easy to handle, are stable and reliable, and require very little electrical power.
- They have superior optical quality over a large area, since one can choose any optical material polished to highest standards.
- We have chosen PEM glass material that has excellent UV transmission all the way down to the atmospheric cut-off near 300 nm.
- The modulation amplitude can easily be set electronically to give optimum modulation efficiency for any given wavelength.

3.2. *Ferro-electric liquid crystals (FLC) and Pockels cells*

As these types of modulators are non-resonant devices they have the following major advantages:

- The modulation frequency can be chosen to a more desirable value than the high PEM frequencies, like 1 kHz, which would be fully sufficient for eliminating seeing noise.
- The modulation wave form can be chosen to be rectangular, which gives maximum modulation efficiency.
- The phase-locking of two non-resonant modulators is no problem, so all four Stokes parameters can be recorded simultaneously without any need for mechanical rotations.

Unfortunately these modulator types have serious disadvantages. The most important ones are the following:

- It has not yet been possible to manufacture Pockels cells with sufficient optical quality over the needed aperture size.
- The optical quality and transmission of FLC's are inferior to those of PEMs.
- FLCs cannot be used in the UV below 400 nm. The Second Solar Spectrum is extremely rich in the UV.
- FLCs age rather fast, while PEMs live almost forever.

4. Main scientific applications of ZIMPOL

By completely eliminating the two main noise sources in imaging polarimetry (seeing and gain-table noise), ZIMPOL is able to measure much weaker polarizations than other imaging systems, down to below 10^{-5} if enough photon statistics is obtained. This has allowed us to gain access to the wealth of polarized spectral structures in the Second Solar Spectrum. The richness of this new world of polarization physics only became evident when ZIMPOL was first put to use at the McMath-Pierce facility at Kitt Peak in 1994-95 (Stenflo & Keller 1996, 1997). With its extraordinary polarimetric sensitivity ZIMPOL is at a great advantage in comparison with other systems for explorations of the Second Solar Spectrum, since most of the scattering polarization and Hanle effect signatures are very weak. It is therefore natural that almost all the solar work with

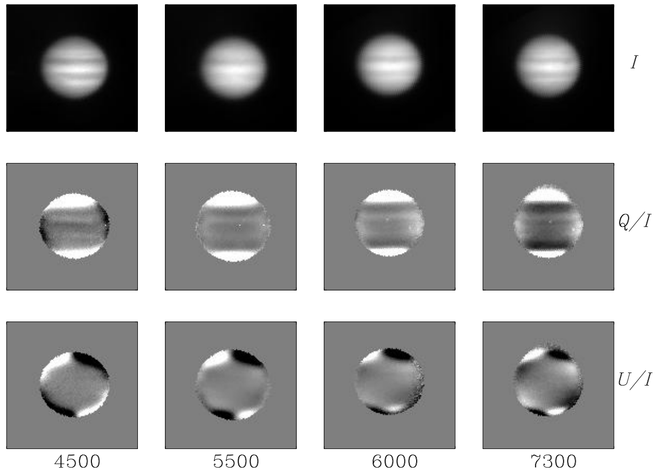

Fig. 2. Stokes images of Jupiter as recorded with ZIMPOL at the McMath-Pierce facility (Kitt Peak) in different wavelength bands. The filter wavelengths in Å are given below each panel column (cf. Gisler & Schmid 2003; Schmid et al. 2005).

ZIMPOL has focused on the Second Solar Spectrum and the Hanle effect.

In recent years we have also been developing versions of ZIMPOL that are optimized for non-solar applications. We are now participating in the Planet Finder project SPHERE for the development of next-generation instrumentation for ESO's VLT with the aim of finding and imaging extra-solar planets. A key component of this Planet Finder instrument is a ZIMPOL polarimetry system that will detect the polarization signature of the planet against the unpolarized halo around the star (Schmid et al. 2006). Since the reflected light from the planetary atmosphere when it is illuminated from the side by the central star will be strongly polarized, the extrasolar planet will in images of the linear polarization (Q/I and U/I) stand out with high contrast against the largely unpolarized halo background, while in the intensity image the planet will be drowned out by the background.

Planets polarize strongly even in backscattering geometry. An example of this is given in Fig. 2, where we show recordings of Jupiter in intensity and linear polarization, made with ZIMPOL at the McMath-Pierce facility (Kitt Peak). The most conspicuous feature is the strong (about 7%) linear polarization in the polar regions. The electric vector of the polarization is oriented perpendicular to the nearest Jupiter limb, in contrast to what we are used to from limb polarization on the Sun, where it is oriented parallel to the limb. The difference lies in the circumstance that for Jupiter the illumination is such that we see back scattered radiation. Single scattering with a scattering angle of 180° (back scattering) would give zero polarization (for symmetry reasons), so the polarization that we see arises due to multiple scattereing in Jupiter's atmosphere in the presence of a radial density gradient. In the solar case the scattering geometry near the limb approximates a 90° scattering geometry, which produces linear polarization oriented perpendicular to the scattering plane (parallel to the limb) in a single scattering event.

4.1. Examples of solar applications

The Second Solar Spectrum represents a new and largely unexplored territory that is extremely rich in spectral structures with fascinating physical properties that do not show up in the ordinary intensity spectrum. Examples of such phenomena, which previously were largely unfamiliar to astrophysics, are quantum interferences between atomic levels (including the interference between the magnetic substates, which is the essence of the Hanle effect), hyperfine structure and isotope signatures, high-contrast molecular spectral structures, effects of optical pumping, as well as still unexplained effects. Therefore this fertile territory is extremely attractive for scientific exploration, but it is observationally very demanding, since a polarimetric sensitivity better than about 10^{-4} is needed to access most of these polarimetric structures. Since ZIMPOL can do better than 10^{-5} (provided that we collect sufficient photons by using a large telescope and long integration times, as is the case for our Kitt Peak observations), it is uniquely suited for explorations of the Second Solar Spectrum. For this reason our science programs with ZIMPOL have almost exclusively focused on explorations of the Second Solar Spectrum.

Since results about the Second Solar Spectrum with ZIMPOL have been presented in a number of published reviews on the subject, most recently in Stenflo (2004, 2007), we limit ourselves here to two examples to illustrate what ZIMPOL can do. One particular capability is that we can use ZIMPOL with its full polarimetric sensitivity throughout the whole visible spectrum and the UV, all the way down to the atmospheric cut-off near 3000 Å. Our examples are therefore chosen from the UV range that cannot be accessed by other imaging polarimeters.

Figure 3 illustrates the rich molecular signatures that we see all over the Second Solar Spectrum. The left panels show a recording in a weakly magnetic region near the west solar limb (at $\mu = 0.10$). While the magnetic signatures show up in the circular polarization (V/I), they do not leave a visible trace in the linear polarization, which only shows the molecular scattering polarization in Q/I (linear polarization oriented parallel to the limb), with no sign of spatial variation along the slit or Hanle effect signatures (there is no significant polarization in U/I). In the right panels the slit has been shifted only a few arcsec away from the limb (to $\mu = 0.14$), to come close to a nearby sunspot. Now signatures of the transverse Zeeman effect show up strongly in the atomic lines, both in Q/I and U/I, while there is no clear trace of the Zeeman or Hanle effects in the molecular lines. This relative immunity of molecular lines to magnetic fields, which has been given a theoretical explanation by Berdyugina, Stenflo, & Gandorfer (2002), makes them important as reference lines when we for instance want to explore solar-cycle variations of scattering polarization and the Hanle effect in atomic lines.

Among all the lines in the whole solar spectrum above 300 nm the Cr I 3593.5 Å line stands out as the champion in terms of largest polarization amplitude (Gandorfer 2005; Stenflo 2007). The reason why this particular line wins has not yet been clarified. The left panels in Fig. 4 show a Stokes recording in strong faculae rather far from the limb (at $\mu = 0.32$). Except for the core and wings of the Cr I 3593.5 Å line the linear polarization is characterized by the signatures of the transverse Zeeman effect in the various spectral lines. The wings of the Cr I line exhibit the signature of the non-magnetic scattering polarization in Q/I and seem to be rather immune to the magnetic fields, with the possible exception of a weakening of the Q/I polarization in the red wing. The line core is dominated by the transverse Zeeman effect in Q/I, while in U/I the line core definitely behaves qualitatively differently, most likely due to strong Hanle rotation of the plane of polarization, such that scattering polarization with negative sign shows up prominently in the U/I core. Note the abrupt sign reveresals along the slit in the circular polarization.

The right panels in Fig. 4 show a recording in a quiet solar region near the east limb (at $\mu = 0.10$). Here there is a complete absence of signatures from the transverse Zeeman effect. Instead the linear polarization is dominated by the scattering polarization in the Cr I line throughout the whole spectral field of view. The many dark bands in Q/I are due to the numerous blend lines, which depolarize the scattering polarization in the wings of the Cr I line, which extend over the whole spectral field of view and beyond. These bands are absent in U/I, since the Hanle effect does not operate in the wings, and therefore U/I is zero there. All the spatial variations of the linear polarization

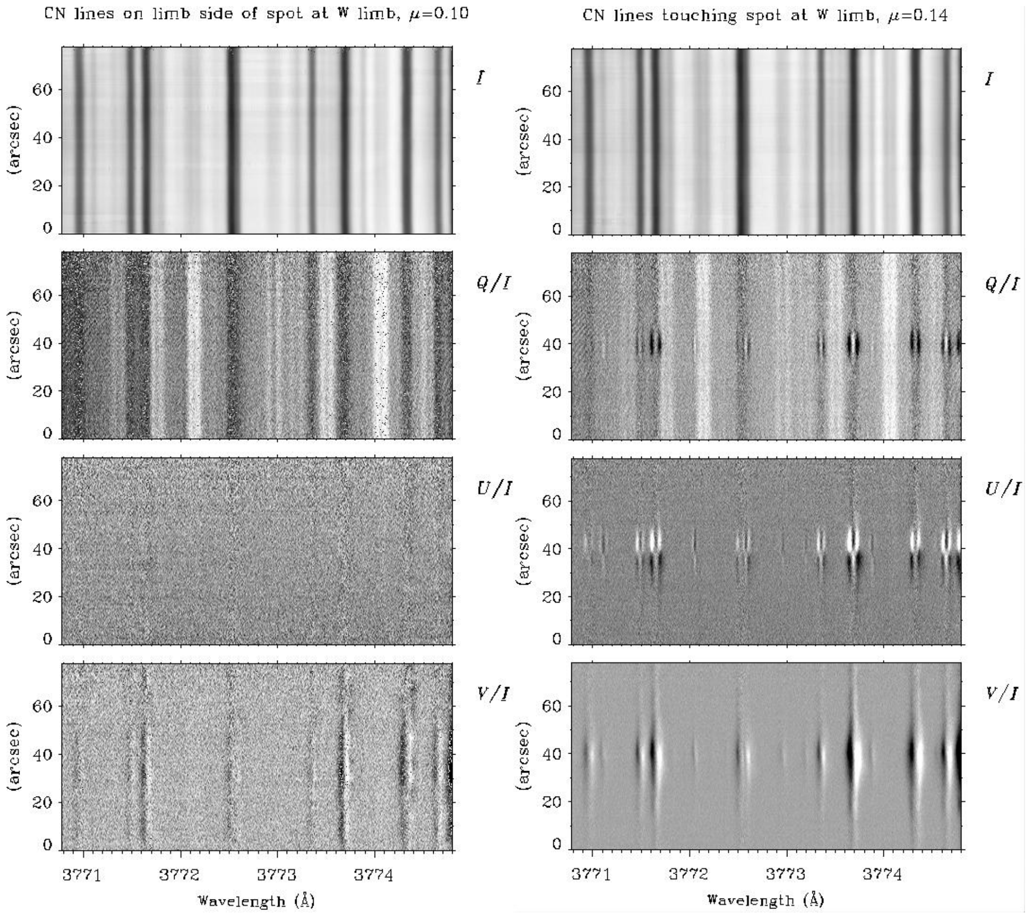

Fig. 3. Stokes vector images in the molecular CN lines at 3771–3775 Å. Note that the scattering polarization in Stokes Q remains practically constant along the slit, while the atomic lines exhibit local signatures of the transverse Zeeman effect. This illustrates the relative immunity of molecular lines to magnetic fields, as explained in (Berdyugina, Stenflo, & Gandorfer 2002).

along the slit occur in the Doppler core of the Cr I line, in Q/I due to Hanle depolarization, and in U/I due to Hanle rotation.

5. Future developments for solar applications

We are currently constructing a new generation of our ZIMPOL systems, which we call ZIMPOL-3. It has a completely overhauled, modernized electronic design and larger CCD sensors, which are equipped with microlenses to optimize the photon efficiency. Two such complete ZIMPOL systems, including optics, will become available in the course of 2007, one for permanent use at IRSOL (Istituto Ricerche Solari Locarno), the other for use in special observing campaigns at external telescopes.

A tunable narrow-band filter system based on two Y-cut lithium-niobate Fabry-Perot etalons will be used in combination with ZIMPOL for monochromatic Stokes vector imaging of the scattering polarization and the Zeeman-Hanle effect (Feller, Boller, & Stenflo 2007). A mobile telecentric version has been

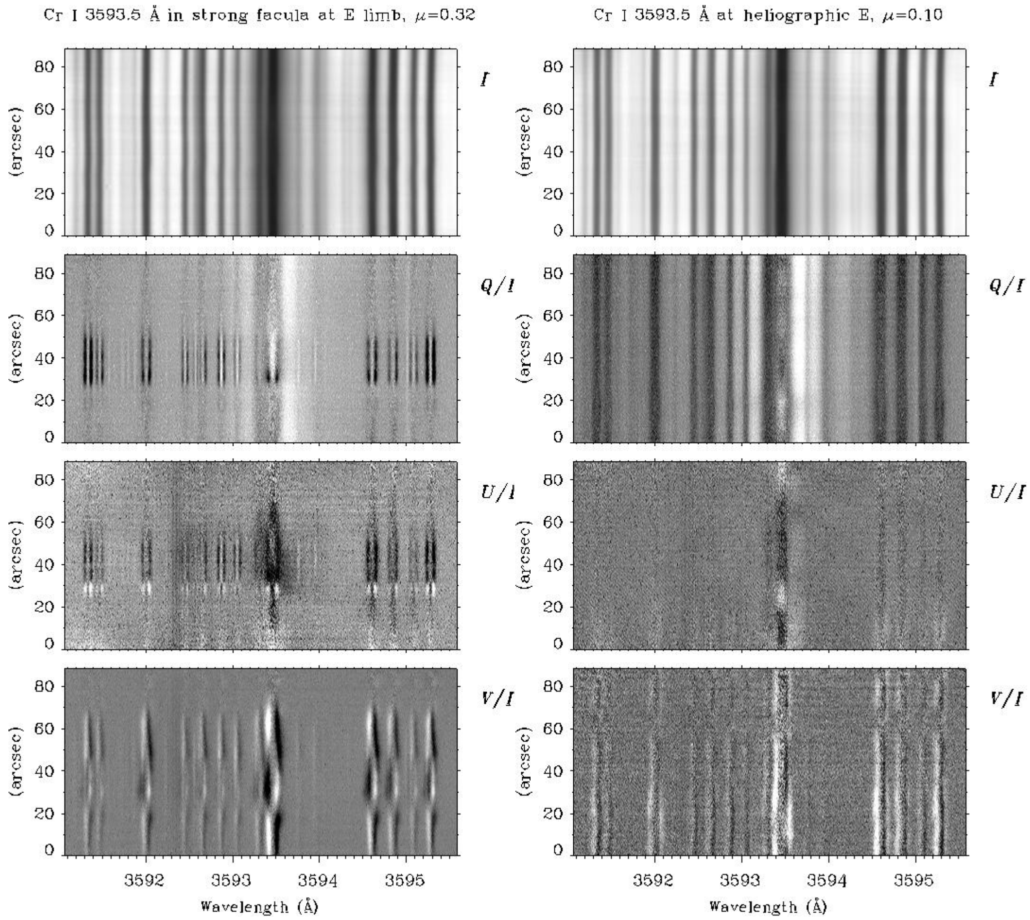

Fig. 4. Stokes vector images of the Cr I 3593.5 Å line, showing how it responds to the Hanle effect, and, in the left panels, its behavior in the mixed Hanle-Zeeman regime, surrounded by lines that are governed by the Zeeman effect. Of all lines in the whole solar spectrum above 300 nm, Cr I 3593.5 Å has the largest scattering polarization amplitude.

developed for use at external telescopes (and was used in an observing campaign at the SST on La Palma in October 2006), a collimated version has been installed for use at IRSOL. Previous work with ZIMPOL has focused on the spectral properties of the Second Solar Spectrum, while the spatial variations have played a secondary role. With the narrowband filter system, which may be applied to any wavelength between 395 and 660 nm, we are in a position to embark on a focused exploration of the spatial variations of the Second Solar Spectrum, in particular for the exploration of the small-scale and largely "hidden" properties of solar magnetism. These efforts will be aided by an adaptive optics system, which is being implemented at IRSOL for use with ZIMPOL.

Although the future is thus full of scientific opportunities, it also has uncertainties. The ZIMPOL developments have been done under my Chair at ETH Zurich, which is the only Chair in Switzerland that covers the field of solar physics. I will retire from this position end of November 2007, and the succession will not be known for a long time. As long as the situation remains undefined, it is hardly possible to invest in new projects, the focus will unfortunately rather be on survival.

IRSOL will however remain a home base for the ZIMPOL systems, and the observing programs there will continue to be complemented with special observing campaigns at external telescopes. THEMIS is considered for the next external campaign. It would be the first time that ZIMPOL would be combined with THEMIS. In spite of severe technical constraints for placing the ZIMPOL modulation system in the THEMIS Cassegrain focus, the current plan is to use an FLC-type modulation system with THEMIS to record all four Stokes parameters simultaneously.

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