Optical and Infrared Spectro-Polarimetry with SPINOR: New Windows to the Sun

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NCAR Scientific Team

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1. Executive Summary

The measurement of solar (vector) magnetic fields demands quantitative spectro-polarimetry. HAO's pioneering work with the Advanced Stokes Polarimeter (ASP) has led the way during the past 12 years and has inspired the development of numerous ground and space based polarimeters. Unlike ASP, these new instruments are highly specialized because they have been designed to carry out specific, and often routine, tasks. A versatile research instrument like the ASP is still needed to undertake novel observations. However, due to its limited wavelength coverage, the ASP is incapable of tackling new research possibilities in the infrared, and its aging cameras and electronics are fast approaching the end of their maintainable lifetime. We propose the construction of a new spectro-polarimeter with truly unique capabilities. The Spectro-Polarimeter for INfrared and Optical Regions (SPINOR) will deliver fully achromatic spectro-polarimetry from 400 nm to 1.6 microns. The scientific possibilities offered by SPINOR, which are described in more detail below, will not be matched by any other instrument until the construction of the Advanced Technology Solar Telescope (ATST).

2. Introduction

HAO has held a worldwide leadership position in the observation and interpretation of solar vector magnetic fields for nearly three decades, owing in part to the development and operation of Stokes polarimeters: K-Corona Emission Line Polarimeter (Querfeld 1977), Stokes I and II Spectro-Polarimeters (Baur et al. 1981), and the Advanced Stokes Polarimeter (ASP, Elmore et al. 1992). Unlike most other instrumentation for measurement of solar magnetic fields during this period, the long-standing HAO program is founded upon the measurement of precise and complete polarization information as a detailed function of wavelength in solar spectral lines. This type of spectral and polarization analysis is a mandatory requirement for quantitative solar magnetometry (see, e.g., the discussion in Socas-Navarro 2002), and leads also to a more complete description that includes thermal and dynamic properties of the solar atmosphere.

The tremendous success of scientific results from the ASP has inspired the development of similar instruments that are intended to facilitate observations of the vector magnetic fields on a more regular and routine basis than has been possible with the ASP. Partnering with several other institutions, HAO is deeply involved in implementing new space and ground based spectro-polarimeters: the Sunrise and Solar-B space-based spectro-polarimeters, and DLSP (Diffraction-Limited Spectro-Polarimeter) and ATST ground-based spectro-polarimeters. Furthermore, HAO's expertise and heritage in this field has made major contributions to the development of similar instrumentation by other institutions: SOLIS, LPSP, TIP. These new instruments will make use of recent technological advances in detectors, adaptive optics, components, and computers. Except for ATST, all are far more specialized than the ASP, in the sense that they have been designed specifically for a given type of observations (as an example, Sunrise, Solar-B, DLSP and SOLIS will all observe the same spectral lines, namely the pair of Fe I lines at 630.2 nm). As these instruments are optimized for operation at specific, fixed wavelengths in order to facilitate routine observations, they are not suited for use as flexible research tools. They leave virtually no room for experimentation. One of the strengths of the ASP, that still today sets it apart from other similar instruments, is its versatility. The capability to carry out new types of observations provides the essential ingredient for groundbreaking discoveries. This is the reason why the ASP is one of the most frequently requested instruments by users of the National Solar Observatories (NSO) facilities. In the following section we summarize a few recent scientific gains that lead us toward devlopment of an even more flexible and capable new instrument, SPINOR.

3. Scientific Rationale

3.1. Photospheric magnetism

Recent investigations of photospheric fields in the infrared often reveal a different picture from conventional visible observations. A remarkable example is the finding of supersonic flows in the penumbrae of sunspots by del Toro Iniesta et al. (2001) in TIP data. Such strong flows had never been observed in the visible, with the exception of the peculiar δ-configuration sunspots (Martínez Pillet et al. 1994).

Perhaps the most puzzling observations of photospheric fields in the infrared are those of the quiet sun, particularly outside the magnetic network (the region sometimes referred to as the photospheric internetwork). Visible observations indicate that most of the fields in this region are strong ($\sim$1.3 kG), but concentrated into very small areas ($\sim$1% of the pixel; Socas-Navarro & Sánchez Almeida 2002 and references therein). However, recent infrared observations (Lin 1995; Lin & Rimmele 1999; Khomenko et al. 2003) show that most of the fields are weak ($\sim$400 G) and diffuse. These contradictory results have sparked a controversy on the true nature of quiet sun fields. This issue is an important one, since our current understanding indicates that most of the solar magnetic flux (even at solar maximum) is located in the quiet sun outside of active regions. A possible solution to the observational contradiction has been proposed by Socas-Navarro (2003) and Socas-Navarro & Sánchez Almeida (2003). It turns out that the observations may be explained easily by a small-scale distribution of fields, beyond the spatial resolution of the observations, having weak and strong fields mixed together. Moreover, these authors showed that the actual sub-pixel distribution of the field can be inferred from simultaneous visible and infrared observations (like those from SPINOR).

The results of Socas-Navarro & Sánchez Almeida (2003) can be extrapolated to other physical scenarios in which different field strengths coexist within the resolution element of the observations. Another example where this strategy would be very useful is the investigation of sunspot penumbrae. It is presently believed (see, e.g., Schlichenmaier 2002; Sánchez Almeida & Bonet 1998) that a penumbra is formed by a large number of thin radial filaments embedded in a magnetic environment, with the filaments having stronger and more inclined fields and channeling the cool siphon flows traditionally observed as the Evershed effect. The actual size, properties and origin of these filaments are still a subject of intense debate (Martínez Pillet 2000; Sánchez Almeida 2001; Martínez Pillet 2001), but it seems well established that they are not spatially resolved in the observations. The ability to infer spatially-unresolved distributions of the magnetic field from simultaneous visible and infrared observations would provide important clues on the structure of the penumbra.

Innovative new diagnostics of solar magnetic fields are emerging as a result of parallel theoretical and observational advances. In a recent effort to understand the anomalous polarization signals observed in some spectral lines, López Ariste et al. (2002) studied the hyperfine structure induced in the atomic energy levels by the nuclear spin, and its effects on the polarization transfer process. They demonstrated that the signature imprinted by the hyperfine structure on some spectral lines has an important potential for magnetic field diagnostics. Some of the most interesting lines lay in the wavelength domain between 800 nm and 1.5 microns. Examples are the Rb I D1 line at 794 nm, which shows a combination of hyperfine structure and isotopic mix, or the Mn I lines at 870 nm, and in the infrared at 1.29, 1.33 and 1.52 microns.

3.2. Chromospheric and coronal magnetism

Historically, HAO has been a leader in the investigation of both photospheric and coronal magnetism. A new global picture of solar magnetism is emerging from the seemingly disparate observational domains of photospheric small-scale magnetic fields and the diffuse, voluminous magnetic structure of the solar corona. The observation and interpretation techniques used for photospheric and coronal studies are markedly different, but the new global picture, ranging from the dynamo source deep in the solar interior to the solar wind and its interaction with the Earth, has engendered a close collaborative effort at HAO between the development of new coronal polarimeters (Mark IV, Coronal Multi-channel Polarimeter: CoMP) and the polarimeters mentioned in the previous section. To further the development of this global view, we identify a key missing ingredient: an in-depth investigation of the interface layer, the chromosphere. Observational capability for chromospheric magnetic fields and the associated dynamics has been lacking because most interesting and/or useful lines lay outside the wavelength coverage range of the ASP (it should be noted, however, that successful investigations of prominence fields have been carried out recently; e.g. Casini & López Ariste 2003). Observable lines either form too low in the chromosphere (e.g., the Mg I *b*-lines) or their polarization transfer is still not well understood (e.g., H_α).

SPINOR would open new perspectives for chromospheric investigations with its ability to observe the Ca II infrared triplet, around 854 nm. These lines are the best candidates for chromospheric diagnostics, at least in the Zeeman regime, due to their relatively simple formation physics, their long wavelengths (which results in stronger Zeeman signals), and the valuable information they carry on the thermal and magnetic conditions of the higher atmosphere (Socas-Navarro et al. 2000b; Socas-Navarro et al. 2000a). They are also sensitive to the Hanle effect, which provides complementary diagnostics on the weaker ($\sim$1 G) fields, and have been successfully modeled by Manso Sainz & Trujillo Bueno (2001).

Finally, the He I multiplet at 1083 nm is of great interest for chromospheric and coronal studies. This line is seen in emission in prominences and in absorption in filaments, with strong polarization signals arising from both Hanle and Zeeman effect. The CHIP instrument provides synoptic intensity images at this wavelength, which are used by the HAO coronal group as a proxy for the inner corona. SPINOR would be able to provide full spectro-polarimetry at 1083 nm, which implies the potential to investigate the magnetic and dynamic conditions of these structures. Other interesting coronal lines that may be accessible for observations are the two Fe XIII lines at 1074nm, although these may not be visible using a traditional solar telescope.

4. The proposed activity

SPINOR is not simply a modernized version of the ASP. By extending the observable wavelength range the solar community gains very important scientific benefits. Generally speaking, it is advantageous to observe at longer wavelengths because the Zeeman splitting is proportional to λ^2 (whereas, for instance, the Doppler width of a spectral line only increases as λ). It is then easier to resolve individual Zeeman components in the infrared, thus eliminating significant uncertainties, especially in the interpretation of weak magnetic fields. In the previous section we discussed a number of topics that can be addressed with SPINOR that are not possible with the current ASP. However, being that this a research instrument designed for maximum versatility, one must keep in mind that its most important applications may be some that we cannot envision at this time.

4.1. The SPINOR instrument

We propose to design and build a new instrument, the Spectro-Polarimeter for INfrared and Optical Regions (SPINOR), that will serve as a research instrument for the solar community. SPINOR has been conceived keeping versatility as the highest priority, to allow for a broad range of potential applications.

SPINOR will be installed at the Dunn Solar Telescope (DST, at Sunspot, NM, operated by the NSO). Eventually it will replace the ASP.

The project will be developed in a way to keep the ASP operational at all times until the new instrument is completed. The most important features are:

- Achromatic optics from 400 nm to 1.6 microns, coupled with visible and infrared detectors[1], offer the capability of simultaneous observations at diverse wavelengths simultaneously throughout the range of 400 nm to 1600 nm. This extended range represents a great improvement over that of the ASP (from 450 to 750 nm). Its potential scientific benefits, discussed in more detail in section 3, are enormous.

[1] Note that this proposal does not include the purchase of infrared detectors. For infrared observations SPINOR will rely on the CCD camera acquired by HAO for the CoMP project.

Table 1

Performance comparison between SPINOR and ASP

Parameter		ASP	SPINOR
Calibratable wavelength range (nm)		450-750	400-1600
Field of view along slit (arc seconds)		80	120
Quantum efficiency	400 nm	0.01	0.72
	700 nm	0.32	0.80
	1000 nm	0.02	0.10
	1600 nm	none	0.60
Read noise (electrons)		50	25

- Detectors with higher quantum efficiency and lower noise than those in ASP allowing for higher signal to noise observations.
- Use of state-of-the-art components, electronic systems, computers, detectors and software. Deployed 12 years ago, ASP's technology is now 15 or more years old, and it is starting to show its age. Both routine maintenance tasks and normal operation are compromised because many replacement parts are no longer available. The SPINOR system will be more stable and suffer significantly less downtime. Data products will also be easier to handle (e.g., using DVDs instead of magnetic tapes, simpler analysis procedures, etc), an improvement that will greatly facilitate the science and make the instrument more accessible to a broader user community.
- Open and modular design, with room on the optical bench to incorporate and/or replace components. SPINOR will be deployed at the DST as a set of instrument modules with "virtual" cameras, a concept that NSO has developed for the DLSP. This will allow diverse and complex observations, combining SPINOR with other DST instruments. The control software will be fully customizable for a broad variety of observing modes (although several pre-defined modes will exist for frequently used configurations).

4.2. Plan of work

The optical and electronic elements will be purchased as soon as funds become available and tested during the first year. Major components to be purchased for SPINOR are:

- 2 Visible Wavlength Camera Systems totaling \$99,900
- Achromatic polarization optics totaling \$70,748

The effort to integrate the various elements, develop software and demonstrate the capabilities of the new instrument will take place during the second year. The final design should be fully assembled and deployed by the end of the second year.

HAO effort now being applied to other projects can be directly applied to SPINOR, as follows:

- ATST: The VISP spectro-polarimeter, which HAO is building for the ATST, is required to operate simultaneously at visible and near-infrared wavelengths. Optical design efforts for ATST will be directly applied to SPINOR and those design concepts will be demonstrated by this instrument.

- SUNRISE: The visible detectors used by SPINOR will have the same architecture as those for Sunrise. The software to control the cameras and interface with the electronics will be a duplicate of that developed for SUNRISE.

- CoMP: SPINOR will share the infrared camera purchased for the CoMP project. The software required to control this camera will be developed using CoMP funds.

5. Summary and conclusions

The ASP has served the solar community as a unique research instrument for the past 12 years. Due in no small measure to the development and operation of the ASP, the volume and quality of literature produced since its inception on the structure and dynamics of photospheric magnetic fields is remarkable, and growing at an ever-increasing pace. The ASP has played a key role in placing HAO as a world leader in the investigation of solar magnetism. However, ASP is approaching the end of its maintainable lifetime. For this reason, and also driven by compelling needs to expand the simultaneous wavelength coverage of solar spectro-polarimetry, we propose the development of a new instrument.

5.1. Broader impacts

We perceive an urgent demand in the solar community for a new research (as opposed to specialized) spectro-polarimeter. We expect that SPINOR will fulfull this need and remain at the cutting-edge of solar research until the construction of the ATST. Its broad wavelength coverage will provide a uniquely connected view of photospheric, chromospheric and, to some extent, coronal magnetism.

As with the ASP, researchers from national and foreign institutions will be able to access the new instrument through the usual time allocation competition for the Dunn Telescope, operated by NSO.

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