Final report

International Cooperation for Innovations in Sensitive Polarimetry

Leibniz-Institute: Kiepenheuer Institut für Sonnenphysik
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Contact partner: Professor Dr. Svetlana Berdyugina

SAW-2011-KIS-7

Kiepenheuer Institut für Sonnenphysik Freiburg

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“International Cooperation for Innovations in Sensitive Polarimetry”

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1. Project Profile

1.1. Summary

Polarimetry is a powerful technique for revealing two- and three-dimensional structures in astrophysical objects beyond the spatial resolution provided by direct imaging at any telescope. The goals of this cooperation are (i) to explore novel physical mechanisms for polarized light, (ii) to develop an innovative polarimetric system with advanced modulation schemes and employ it on telescopes dedicated for polarimetric surveys, and (iii) to establish a lasting cooperation between two superior astronomical observatories on Canarias and Hawaii. The distinctive international partnership established in this project has enabled scientific and technological developments well beyond the current state-of-the-art.

1.2. Key questions

This project has brought together some of the world experts in theoretical and experimental polarimetry within an inter-disciplinary context of solar and night-time astrophysics. We have concentrated our effort on addressing the following fundamental questions:

- ☐ How magnetic fields are generated in objects having very deep convection zones or being fully convective? Cool dwarfs are known to show strong magnetic activity, and their dynamo is apparently different from that of more massive cool stars, such as the Sun. The process of generation of strong magnetic fields in such objects is not yet understood. Moreover, there exist no magnetic field measurements for brown dwarfs and hot Jupiters. Also, the role of a turbulent dynamo in the Sun is probably underestimated.
- ☐ How the circumstellar environment evolves during the dynamic process of star and planet formation? Over the course of a few million years, parts of the circumstellar gas and dust accrete onto the star, turn into planets, or dissipate in the form of winds and jets. Meantime the star also evolves from an active young star to a stable main-sequence star as the Sun. All these processes influence the environment of planet formation, habitable zone, and planetary atmosphere. Therefore, it is crucial to put direct constraints on these processes by revealing properties of circumstellar gas and planetesimals.
- ☐ What are the properties and inner structure of exoplanets? For majority of exoplanets true masses and densities are not known. This limits our knowledge on their internal structure, such as possible presence and size of a central solid core, which will enable us to distinguish between the core accretion and disk instability scenarios of planet formation. Also, the contents of the atmosphere, size of scattering particles, their distribution in the upper layers (weather pattern), and rotational periods of planets are still largely unknown.

1.3. Objectives

Our international team has fully employed advantages offered by polarimetry and pursued the following goals:

1. to develop and build innovative polarimetric systems achieving polarization sensitivity down to 10^{-6} on mid-size telescopes and employ it for polarimetric surveys,
2. to explore novel physical mechanisms for polarized light, employ them for studying stellar magnetic fields, circumstellar environment, and exoplanets, and disseminate the gained expertise to solar physics,
3. to establish lasting cooperation between two superior astronomical observatories on Canarias and Hawaii.

With our novel polarimetric systems we have routinely achieved the polarimetric sensitivity 10^{-5} and even better on very bright stars. Our polarimeters are now employed at dedicated telescopes at superior astronomical sites on Canarias and Hawaii, which are offered by this collaboration. This has opened new prospects and has allowed us to obtain unique polarimetric data for (i) cool dwarfs to detect their magnetic fields, (ii) protoplanetary disks to determine their geometry and structure, and (iii) exoplanets, including non-transiting systems, to obtain their radius, orbit inclination and atmosphere composition.

2. Report

2.1. Objective 1: Developing and building innovative polarimetric systems

DIPOL-2 polarimeter

Within this cooperation we have built a new broad-band polarimeter (DIPOL-2), capable of measuring polarization with the precision at the 10^{-5} level, and even better if photon statistics allows. The polarimeter and its principle scheme is shown in Figure 1.

The polarimeter utilizes two dichroic color-sensitive beam-splitters to measure polarization in *B, V* and *R*- passbands. Three CCDs: Apogee Alta U47 (thinned back-illuminated 1024x1024, pixel size = 13x13 μm) for the *B*-band and SBIG ST-402ME (765x510, pixel size = 9x9 μm) for *V* and *R*- bands are communicating with the computer via USB2 interface; read-out time is < 1s for each; peak quantum efficiency is > 90%.

The superachromatic $\lambda/2$ or $\lambda/4$ retarder rotated by a stepper motor is used as a polarization modulator. The use of a superachromatic $\lambda/2$ plate as the modulator enables us to carry out polarization measurements in a wide spectral region (400-800 nm), without a loss of modulation efficiency and tedious calibration procedures. A calcite analyzer provides separation of the two orthogonally polarized light beams by 1 mm in the telescope focal plane. Exposure duration can be set for the each passband independently.

The DIPOL-2 control system runs on a single PC equipped with three USB2 and one COM ports. Control software (VBScripts) sends commands to the CCD cameras and to the stepper motor. MaxImDL and CCDSoft packages are used for CCD control and ActiveComport for the RS232-line communication with the stepper motor. Actual position of the retarder is checked after each rotation and transmitted back to the control software which can correct the retarder position, if necessary. The CCD control software requires the system to run under Windows (XP and 7 have been tested). The control electromechanics for the retarder rotation is incorporated into the polarimeter head. The selection of the observing mode and the number of measurement sequences is done via graphical user interface of the control PC. Linear polarimetry mode sequence consists of 16 x 22.5° interval exposures, and circular polarimetry mode 4 x 90.0° interval exposures. Data reduction utilities include the standard calibration scheme: dark and bias subtraction + flat-fielding.

Automatic routines, executed via VBScripts, allow us to process many hundreds of CCD frames at once. Special algorithms were developed for pre-aligning images taken in long series of polarimetric sequences, to remove the image drift due to tracking errors. For observations of bright stars "defocusing technique" was developed which allows avoiding problems with saturation and yet collecting large number of ADUs during a single measurement (consisting normally of 4 exposures taken at the retarder positions of 0, 22.5, 45 and 67.5°, etc.). This is achieved by spreading the image over sufficient large number of pixels by intentional defocusing. After calibration, data reduction software processes the sub-frames with the stellar images in the center. All data reduction can be done remotely, on the host computer, thus avoiding transfer of huge amounts of data over the network.

Simple yet effective design with small number of optical elements and moving mechanical parts makes DIPOL-2 a highly versatile and reliable instrument with negligible instrumental polarization, very well suitable for observations with remotely controlled telescopes.

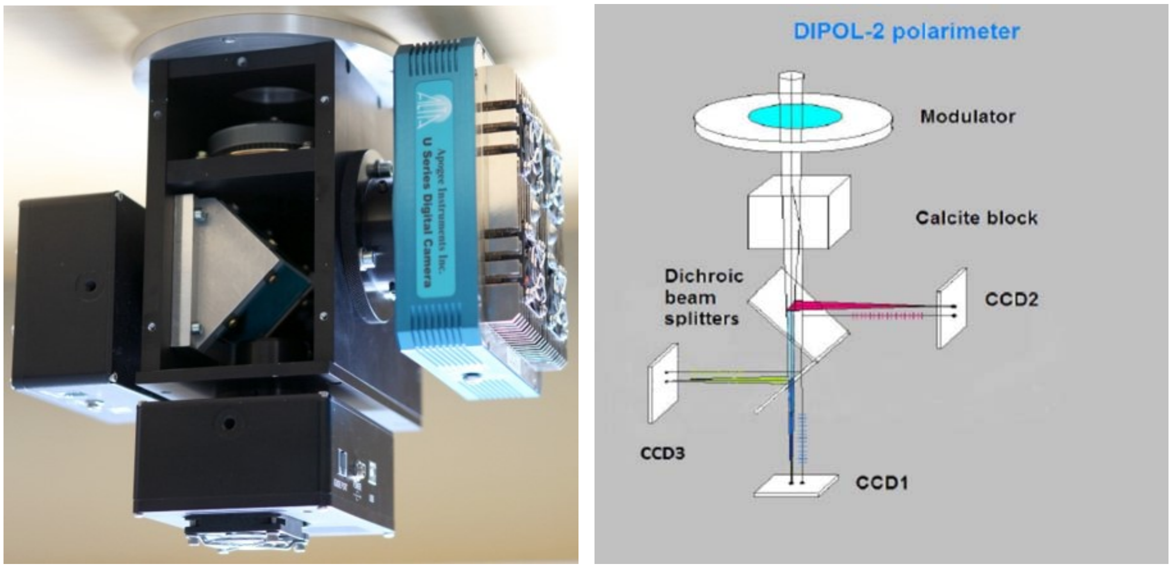

Figure 1. The DIPOL-2 polarimeter (on the left, front panel removed) and its scheme (on the right).

The separation between the two images with orthogonal polarization in the focal plane with the standard calcite (1 mm) has been optimized for the polarimeter to be used at telescopes with the mirror size 0.60 – 1.5 m and focal ratio f/8– f/15. To allow observations on telescopes with even larger mirror and longer focal length, we have provided two thicker calcite plates, yielding either 1.5 mm or 2 mm image separation in the focal plane of the telescope. With these calcites DIPOL-2 can be used even on the VLT at ESO (D = 8.115 m, F = 108.827 m, image scale in Cassegrain focal plane is 2"/mm).

To avoid large and variable telescope polarization, DIPOL-2 polarimeter has been deployed at telescopes with a Cassegrain focus and preferably at telescopes with equatorial mounts. We have built several copies of the DIPOL-2 polarimeter in order to deploy them at several observatories around the world and establish the first dedicated to polarimetry telescope network.

The DIPOL-2 design, test results and first observations were presented at the SPIE Conference on Astronomical Telescopes and Instrumentation, Montreal, 2014.

DIPOL-2 polarimeter has been (or is planned to be) deployed at the following telescopes (Fig. 2):

- Swedish Royal Academy (KVA) telescope, 0.6m, La Palma, Canarias, Spain (operating),
- Wilhelm Herschel Telescope (WHT), 4m, La Palma, Canarias, Spain (used as guest instr.),
- University of Hawaii UH88 telescope, 2.2m, Mauna Kea, Hawaii, USA (operating),
- Tohoku University T60 telescope, 0.6m, Haleakala, Hawaii, USA (commissioned 2014),
- Searchlight Observatory Network (SON) telescope H80, 0.8m, Haleakala, Hawaii, USA (planned),
- University of Tasmania and SON telescope, UTAS130, 1.3m, Bisdee Tier, Tasmania, Australia (planned),
- SON telescope H100, 1m, San Pedro de Atacama, Chile (planned).

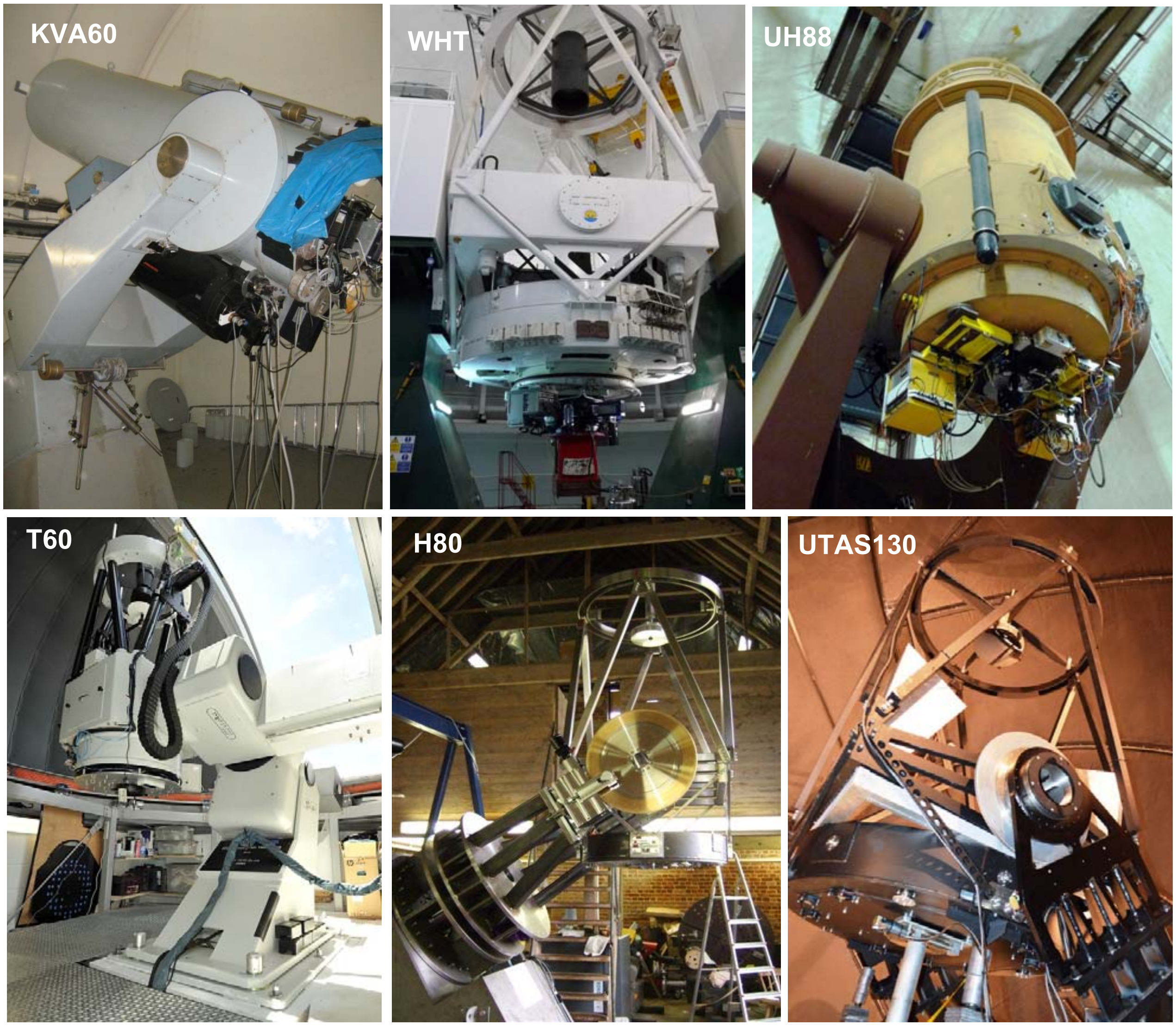

Figure 2. The telescopes on which the DIPOL-2 polarimeter has been deployed (top row, the polarimeter is shown attached to the telescopes during observing campaigns), and the telescopes where DIPOL-2 is commissioned or planned to be deployed (bottom row).

InnoPol polarimeter + Adaptive Optics system

We have designed and built a new EMCCD-based dual-beam imaging polarimeter called InnoPol combined with the Hokupa'a-85 curvature adaptive optics (AO) system components at the 3.67m Advanced Electro-Optical System (AEOS) telescope, Haleakala, Maui. This new instrument is placed behind the AO-corrected f/40 beam at the coude focus. The InnoPol system is a flexible platform for optimizing polarimetric performance using commercial solutions and for testing modulation strategies. The system is designed as a technology test and demonstration platform as the coude path is built using off-the-shelf components wherever possible.

Adaptive optics combined with novel polarimetric imaging technologies is a powerful combination for detecting faint objects in the presence of overwhelming backgrounds close to bright sources. The adaptive optics correction provides a high spatial resolution image in the presence of residual atmospheric and instrument-induced speckles. By suppressing speckles via differential techniques (polarization, color, psf subtraction), targets of interest can be imaged and characterized. The application for such techniques includes use cases for exoplanets and circumstellar material around bright stars, closely spaced objects and space situational awareness (SSA). Speckle evolution both in brightness and focal plane position cause major limiting systematic errors. Commercial EMCCDs, liquid crystals and electronics provide fast and flexible solutions to polarimetric modulation and imaging. Optimizing an instrument speed and performance depends critically on the scene dynamic range, field of view, atmospheric properties, and detector settings. Several other variables complicate the design choices.

The 3.67m AEOS telescope is owned and operated by the U.S. Air Force on Haleakala, Maui. The University of Hawaii (UH) has operated several instruments in the coude experiment room number 3, and KIS has a privilege to work at this facility through our well established collaboration with the UH. Our new instrument developments take advantage of this room, optical relays and associated laser alignment sources. We combine a rebuilt Hokupa'a 85-element curvature adaptive optics system (H85) and an EMCCD-based imaging polarimeter (InnoPol) to accomplish a few select science goals and technological developments. An optical layout for the AEOS telescope, H85 AO system, EMCCD polarimeter and associated systems is shown in Fig. 3.

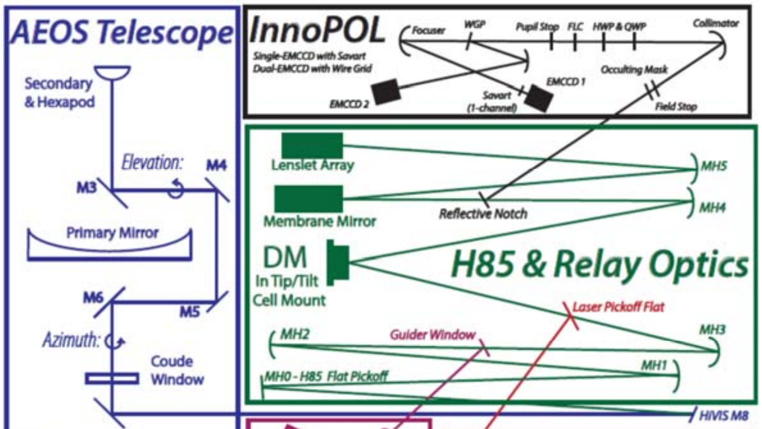

Figure 3: The system optical block diagram. Every optical element is shown and color coded according to functional group. The AEOS telescope optics in blue feed the coude room at f/200. The relay optics provide pathways for guiding and laser simulator injection (light & dark red). The adaptive optics system and associated relay optics are shown in green. The H85 AO compensated f/40 beam is reflected to the InnoPol science channel shown in black.

End-to-end simulations of the curvature AO system performance have been carried out taking into account atmospheric wind speed, turbulence strength, guide star brightness, AO system IMATs, gain and control system settings. The simulated image output was analyzed for optical performance, delivered Strehl ratio and other parameters. Figure 4 shows the model H85 delivered Strehl ratio under varying seeing conditions at an observing wavelength of 850nm.

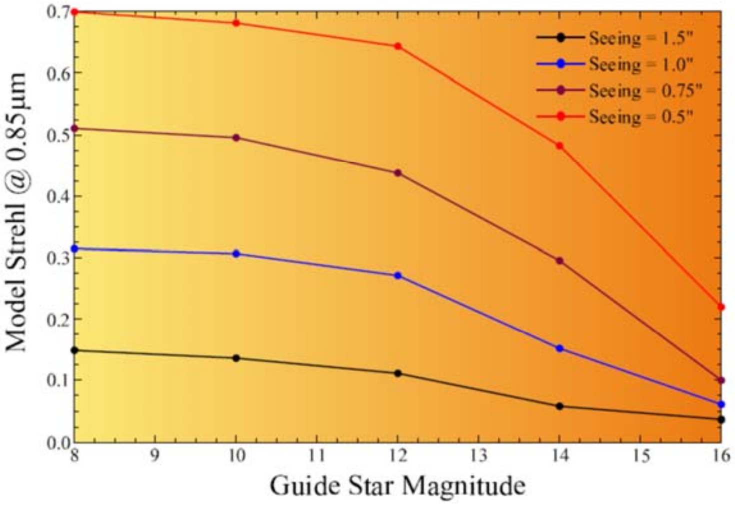

Figure 4: The predicted Strehl ratio at 850nm delivered by H85 to the scoring camera f/40 focus.

By making observations faster than the characteristic atmospheric time scale, we can freeze speckles from turbulence and can do our differential photometry with a pseudo-static optical system. Modern frame-transfer electron-multiplying detectors (EMCCDs) are becoming quite close to this ideal. We average many pairs of modulated images to improve statistics. CCD frame-transfer storage regions allow for the readout of one image to occur while the subsequent image is being exposed, giving a 100% duty-cycle with no time lost for readout. The newest generations of EMCCDs can continuously read 128x128 pixel frames at speeds over 500Hz allowing <2ms polarization modulation. Polarimetric modulation is also now possible with a range of components at high speeds. Several commercial options exist using liquid crystal technologies that switch faster than 0.2ms and have easily tunable optical properties. A schematic overview of this modulation plus fast-frame-rate readout polarimeter is shown in Figure 5.

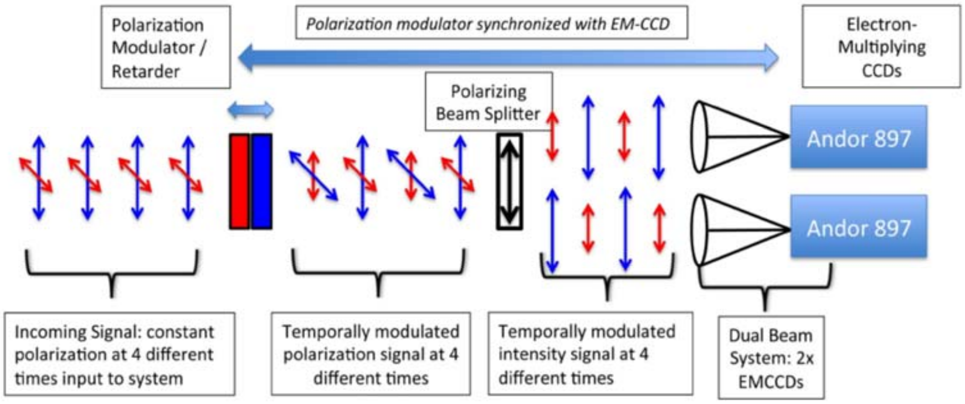

Figure 5: The conceptual model of the InnoPol polarimeter.

The incoming light is unpolarized with orthogonal incident polarizations represented as different colors. Each set of arrows corresponds to 4 different times separated by half the modulation frequency. The modulator acts to re-orient this input polarization as a function of time shown in the middle. The analyzer sends different modulated components in to two different beams. Each beam is recorded on it's own EMCCD with each frame readout synchronized with the modulator.

The only night-time instruments presently on-sky with this technology for AO-assisted imaging polarimetry is the VLT SPHERE. We note that the Gemini Planet Imager (GPI) and HiCIAO on Subaru have AO-assisted dual-beam polarimeters but not of the sophistication described here. EMCCDs and FLCs have been used without AO correction in ExPo at WHT. The technology we developed within this project here has not been used yet at night-time telescopes until 2014.

The EMCCD polarimeter was designed to be a flexible test bench for a dual beam system. We have acquired two Andor iXon Ultra 897 EMCCDs for use in a dual-channel polarimeter. Associated control electronics for liquid crystal drive signals, camera synchronization and triggering were purchased from Agilent and Tegam. Using ethernet-controllable function generators allows us to drive several liquid crystal types including ferro-electric and nematic.

We also purchased polarimetric components to allow dual-beam polarimetry in configurations using either one and two EMCCDs. Wire grid polarizers make effective polarizing beam splitters. The reflected beam when created by a cover-glass free wire grid polarizer shows good image quality and high degree of polarization in laboratory testing. Using both the reflected and transmitted beams creates two independent imaging channels. A 2-camera system provides the opportunity to double the pixel readout rate and possibly reduce systematic errors but with increased cost, system complexity. A calcite Savart plate was also purchased to allow testing in a dual-beam polarimeter with only a single EMCCD detector. This simplifies system complexity and operation but with a 2x reduction in the pixel readout rate capability. Given the fold mirror and open polarimeter optical bench space we can insert several modulator options as well as change camera mirror focal lengths and effective sampling. Expansion of the modulators to include achromatic liquid crystal designs is easily feasible following common techniques in solar and stellar applications.

The InnoPOL optics first collimate the f/40 AO corrected beam. This creates an 11mm diameter pupil image as well as provides a collimated beam for slow and fast polarimetric modulation. Space is also created for coronagraphic masks. In the wire-grid polarizer 2-channel setup, the wire grid then splits the two beams and two independent images are formed with two independent powered optics. In the single-channel system, a powered optic focuses the beam that is folded on to a single EMCCD. A Savart plate placed just in front of the converging beam creates a dual-beam polarimeter. A complete layout is shown in Figure 3.

As part of our project, we have evaluated several modulation strategies. These including rotating retarders, FLC and nematic liquid crystal type modulators. The polarization impact of several retarder errors were assessed both at a pupil plane and offset from the pupil to allow coronagraphy. We developed our own liquid crystal control electronics based on simple commercial Agilent function generators. These allow for remote control over ethernet, easy multi-channel synchronization and fast drive signal configuration changes. With this control setup, we drive several liquid crystal types with varying waveform speeds, shapes and amplitudes.

The InnoPol design and test results were presented at the international workshop “Polarimetry with Extremely Large Telescopes”, Utrecht, 2011, and at the SPIE Conference on Astronomical Telescopes and Instrumentation, Montreal, 2014.

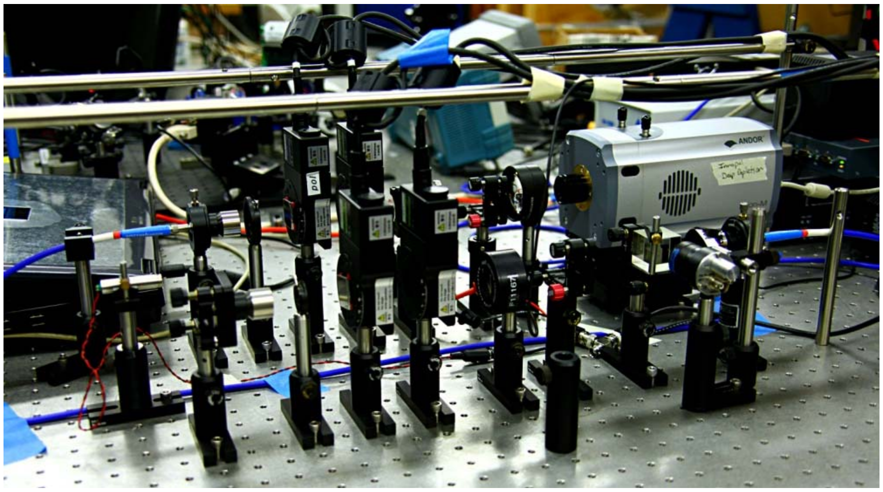

Figure 6: The blue channel of the InnoPol on the optical table. Basic components are the CCD detector, FLC modulator and motor-controlled polarization with a collimated broad-band input beam.

2.2. Objective 2: Polarimetric studies of stellar magnetic fields, circumstellar environment, and exoplanets and dissemination to solar physics

Theoretical studies

Among our goals were theoretical studies of diagnostic capabilities of novel physical mechanisms for polarized light based on the molecular PBE and optical pumping and elaborating observational strategies.

We have developed a quantum mechanical model of the CrH molecule in the presence of external magnetic field and calculated the Paschen-Back effect leading to strong polarization in the molecular bands. Also, we have incorporated a new grid of model atmospheres including Rayleigh and Mie scattering on molecules and dust particles. The results were presented at several international conferences and have been published as a refereed paper.

We have advanced the theory of resonance scattering in the presence of magnetic fields (Hanle effect) for atomic and molecular lines. Our primary goal was to apply this theory for planetary atmospheres. This is still under development, but this theory was disseminated to solar physics in order to measure weak magnetic fields in the solar corona. The results were presented at scientific conferences.

Observational studies

Another goal of this project was to carry out polarimetric surveys of cool dwarfs, protoplanetary disks and exoplanets using the facilities on La Palma and Haleakala.

Our theoretical study of the molecular magnetic interactions has served as a basis for the successful observations at the Keck with the LRISp polarimeter (Hawaii) and at the ESO/VLT with the FORS polarimeter (Chile). We were successful to obtain time on the Keck telescope, Mauna Kea, Hawaii, with the help of our UH collaborators. We have measured for the first time surface magnetic fields on a brown dwarf using various molecular and atomic lines. The results were presented at several international conferences and to be submitted for publication in 2014.

New polarimetric measurements of exoplanets have been obtained with polarimeters DiPol-2 and TurPol on La Palma with the help of our Finnish collaborators. The results were presented at scientific conferences (talks at “Stellar Polarimetry”, USA; “Extreme Solar Systems”, USA; 7th Potsdam Thinkshop, Germany; IAU Symp 293, Beijin; AG Annual meeting, Hamburg; Astrobiology

Science Conference, Atlanta, USA) and submitted for publication. All these observations are important for our future observing programs with the InnoPol system.

As a proxy for protoplanet observations we carried out spectropolarimetric observations of comets, dwarf planet Ceres and moons of Jupiter and Saturn using Mauna Kea telescopes Keck and CFHT through our UH collaborators. These data are being reduced and analyzed.

Carried out observing campaigns:

09-12/2011: Polarized reflected light from the hot Jupiter ups And b, KVA60 telescope, La Palma

12/04/2012: Revealing the nature of radio-pulsating brown dwarfs, VLT, ESO, Chile

04/06/2012: Venus transit observations, SOLARC, Haleakala

14/06/2012: Reflected light spectrum of the hot Jupiter HD189733b, Keck Telescope, Mauna Kea

21-22/08/2012: Revealing the nature of radio-pulsating brown dwarfs, Keck Telescope, Mauna Kea

21/09/2012: Reflected light spectrum of the hot Jupiter HD189733b, Keck Telescope, Mauna Kea

20-22/09/2012: Polarimetric probe of the atmosphere of a very hot Jupiter WASP-4b,VLT/ESO, Chile

01/03/2013: A sensitive search for an exosphere on Ceres, CFHT, Mauna Kea

05/03/2013: A sensitive search for an exosphere on Ceres, AEOS telescope, Maui

03-05/2013: Polarized reflected light from the hot Jupiter tau Boo b, KVA60 telescope, La Palma

21/10/2013: A Sensitive Search for outgassing from MBC Elst-Pizarro, Keck, Mauna Kea

16 & 19/11/2013: Coordinated comet ISON Campaign, CFHT, Mauna Kea

28/11/2013: Spectropolarimetry of comet ISON at its perihelion, SOLARC telescope, Haleakala

12/2013-01/2014: Revealing the nature of radio-pulsating brown dwarfs, VLT, ESO, Chile

Laboratory studies

The laboratory setup of the InnoPol polarimeter shown in Fig. 6 was also used to obtain polarized reflection spectra of various biological (plants) and non-biological (minerals) samples in order to use them for modeling reflection spectra of Earth-like exoplanets. This creates the basis for future remote searches for planets with photosynthetic life on their surface. The results were presented at several scientific conferences and submitted for publication.

2.3. Objective 3: Establishing lasting cooperation between two superior astronomical observatories on Canarias and Hawaii

Partner contributions

University of Hawaii (UH) has provided lab space, additional testing equipment, and 50% postdoc salary for experimental work. The AO system H85 was fully developed at UH and was combined with our InnoPol polarimeter. The UH has also allocated valuable observing time at the world-class telescopes for this collaboration:

- 6 nights at the 10m Keck telescope (Mauna Kea, in June, August, September 2012),
- 3 nights at the 3.7m AEOS telescope (Haleakala, November 2012),
- 1 night at 3.6m CFHT telescope (Mauna Kea, February 2013),
- 1 day at the SOLARC telescope (Haleakala, June 2012).

University of Turku (UTU) has provided polarimetric measurements of exoplanets with the new polarimeter DiPol-2 installed on La Palma (constructed together with KIS using its basic funding and the current project funding):

- about 100 nights in 2011-2013.

UTU has also contributed to tests of the InnoPol using the Tuorla 1m telescope, and 100% postdoc salary for scientific collaboration.

The fruitful cooperation between KIS, UH and UTU established within this project continues and expands well beyond it. In 2014 the DIPOL-2 polarimeter has been deployed at the UH 2.2m telescope (Mauna Kea), and UH has allocated 28 nights in June, July, October, November 2014 for a joint observing program of KIS, UH and UTU. Also in 2014 DIPOL-2 has been commissioned at the Tohoku University 60cm telescope (T60) on Haleakala and all partners have access to this facility. For the first time we are able to carry out continuous (24h around the clock) observations using the KVA telescope on La Palma and UH2.2m and T60 on Hawaii. This cooperation would be hard to achieve without this project.

A copy of the InnoPol imaging polarimeter supported by an AO system is being built at KIS using funding of the ERC Advanced Grant project. It will be deployed at the GREGOR solar telescope at night time. This will again allow continuous (24h around the clock) observations of extended objects such as protoplanetary disks and planets in the Solar system.

Thus, this project has created a solid foundation for the first world-wide polarimetric network which serves three original partners' science programs and also starts to attract new partners contributing their own facilities.

Cooperation Workshop

In July 2013 a cooperation workshop was organized in Alsace. The workshop included participants from KIS, UH, UTU as well as new partners willing to join our collaboration:

- Searchlight Observatory Network (SON) with their photometric telescopes in Chile, New Mexico and Tasmania to be equipped with our DIPOL-2,
- Tohoku University Planetary group (PPARC) with their spectroscopic telescopes at Haleakala to be equipped with our DIPOL-2,
- Lyon Observatory group with their technological developments for extreme AO systems (like on SPHERE/VLT) to be combined with our InnoPol system on future telescopes.

Figure 7: Participants of the first CONTRAST Workshop.

The six groups have decided to be organized into a broader cooperation CONTRAST: COoperative NeTwork for high-dynamic Range ASTrophysics. The main goal of this cooperation is to develop the first world-wide telescope network dedicated for polarization studies of exoplanets, protoplanets and solar system objects. The CONTRAST group will also work on advancing the telescope and instrument technology to achieve the 10^{-8} contrast (using imaging polarimetry) needed for detection of Earth-like planets in habitable zones of other stars with future extremely large telescopes. This is an important outcome of this project ensuring the deep, lasting and expanding cooperation of the original partners.

3. Publications

The following publications were submitted/published in the frame of the present project:

Refereed journal papers:

1. Berdyugina S.V., Berdyugin A.V., Fluri D.M., Piirola V. 2011, *Polarized reflected light from HD189733b: First multi-color measurements and confirmation of detection*, ApJ Lett., 728, L6–L10
2. Sennhauser C., Berdyugina S.V., 2011, *First detection of a weak magnetic field on the giant Arcturus. Remnants of a solar dynamo?* A&A, 529, A100
3. Kleint L., Berdyugina S.V., Shapiro A.I., Bianda M. 2011, *Solar turbulent magnetic fields: Non-LTE modeling of the Hanle effect in the* C_2 *molecule*, A&A, 536, A47
4. Shapiro A.G., Fluri D.M., Berdyugina S.V., Bianda M., Ramelli R. 2011, *NLTE modeling of Stokes vector center-to-limb variations in the CN violet system*, A&A, 529, A139
5. Strassmeier K.G., Ilyin I.V., Woche M., Granzer T., Weber M., Weingrill J., Bauer S.-M., Popow E., Denker C., Schmidt W., von der Lühe O., Berdyugina S., Collados M., Koubsky P., Hackman T., Mantere M.J. 2012, Gregor@Night: *The future high-resolution stellar spectrograph for the GREGOR solar telescope*, Astron. Nachr., 333, 901-910
6. Vornanen T., Berdyugina S.V., Berdyugin A.V. 2013, *Spectropolarimetric observations of Cool DQ White Dwarfs*, A&A, 557, id.A38
7. Kuzmychov O., Berdyugina S.V. 2013, *Paschen-Back effect in the CrH molecule and its application for magnetic field measurements on stars, brown dwarfs and hot exoplanets*, A&A, 558, id.A120
8. Riethmüller T.L., Solanki S.K., Berdyugina S.V., Schüssler M., Martínez Pillet V., Feller A., Gandorfer A., Hirzberger J. 2014, *Comparison of solar photospheric bright points between Sunrise observations and MHD simulations*, A&A, 568, id.A13, 23 pp.
9. Berdyugina S.V., Berdyugin A.V., Piirola V. 2014: *Upsilon Andromedae b in polarized light: New constraints on planet size, density, and albedo*, A&A, submitted
10. Hallinan, G., Littlefair, S., Cotter, G., Bourke, S., Harding, L., Pineda, S., Butler, R., Golden, A., Basri, G., Doyle, G., Kao, M., Berdyugina, S., Kuznetsov, A., Rupen, M., & Antonova, A. 2014, *A Transition from Coronal Activity to Auroral Activity at the End of the Main Sequence*, Nature, submitted
11. Järvinen S.P., Arlt R., Hackman T., Marsden S.C., Küker M., Ilyin I.V., Berdyugina S.V., Strassmeier K.G. 2014, *Do observations reveal the underlying dynamo? The case of AP Leo*, A&A, submitted

12. Berdyugina S.V., Harrington D.M., Kuhn J.R., Santl-Temkiv T., Messersmith, E.J. 2014, Remote Sensing of Life: Photosynthetic Pigments as New Biomarkers, Int. J. Astrobiology, submitted
13. Prokhorov A., Bruls J.H.M.J., Berdyugina S.V. 2014, *Molecular band diagnostics: Synthetic spectra of molecular bands in the UV and visible from a 3D MHD simulation snapshot of the solar photosphere*, A&A, under revision

Conference papers:

14. Berdyugina S.V.: *Polarimetry of cool atmospheres: From the Sun to Exoplanets*, in Solar Polarization 6, eds. J.R. Kuhn et al., ASP Conf. Ser., 437, 219–235 (2011)
15. Berdyugina S.V., Berdyugin A., Piirola V.: *Exoplanets as blue as Neptune*, American Geophysical Union, Fall Meeting 2011, abstract #P11F-1634 (2011)
16. Helling Ch., Pedretti E., Berdyugina S.V., Vidotto A., Beeck B., Baron E., Showman A., Agol E., Homeier D.: *Aspects on multi-dimensional modelling of substellar atmospheres, in 16th Cambridge Workshop on Cool Stars, Stellar systems and the Sun*, eds. C. Johns-Krull et al., ASP Conf. Ser., 448, 403 (2011)
17. Sennhauser C., Berdyugina S.V.: *Magnetic field detection on late-type giants from Zeeman Component Decomposition*, in 16th Cambridge Workshop on Cool Stars, Stellar systems and the Sun, eds. C. Johns-Krull et al., ASP Conf. Ser., 448, 1255 (2011)
18. Sennhauser C., Berdyugina S.V.: *Zeeman Component Decomposition (ZCD): Common line profile and magnetic field reconstruction from polarized spectra*, in Solar Polarization Workshop 6, eds. J. Kuhn et al., ASP Conf. Ser., 437, 173-179 (2011)
19. Berdyugina S.V.: *Polarimetric Signatures of Habitable Planets*, AbSciCon2012, #1351741 (2012)
20. Berdyugina S.V.: *Sunspots and Starspots: Cut from the same cloth?* General Assembly International Astronomical Union, Special Session 10, abstract (2012)
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