DiPol-UF: simultaneous three-color (BVR) polarimeter with EM CCDs

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CCD Polarimetry: errors vs photon counts (or S/N)

Error of normalized Stokes parameters: $\sigma_{q,u} = k\, N^{-1/2}$

$N = No + Ne$, k – analyzer's efficiency

If one wants to have $\sigma = 0.001\%$ (10 ppm, or 10^{-5}), 10^{10} photo electrons must be recorded(!)

Polarimetry is photon-hungry technique: to reduce error in n times, n^2 more ADUs must be collected

The necessary S/N ratio in combined o and e images for the desired error $\sigma(P)$ is given by:

$(S/N)_{(fo\ +fe)} = 1 / (\mathrm{sqrt}\ (n/2) * \sigma(P))$ where n is the number of half-wave plate positions

(from *Patat & Ramaniello, 2006, PASP, 118, 146*)

In case of n = 4 this ratio converts to: $S/N \approx 0.7 / \sigma(P)$ $\Rightarrow$ for $\sigma(P) = 0.1\%$ the $S/N \approx 700$ is required in each dual images in each of the four CCD exposures (!)

Definition of 'high accuracy' in polarimetry is vague (!)

For AGN people: $\sigma(P) \sim 0.1\%$ is small / high accuracy

For HIPPIs: $\sigma(P) \sim 0.01\%$ is large / low accuracy

CCD Polarimetry: Maximum Accuracy

CCD camera – best detector in the optical and near-IR

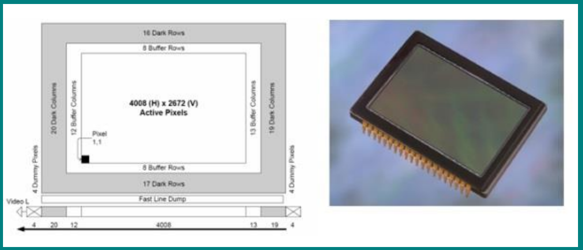
For faint stars, S/N is the main factor limiting accuracy

Early pixel saturation is the CCD ”bottleneck” and main factor limiting accuracy for the bright stars:

To avoid saturation, short exposures (≤1 sec) must be used ⇒

many hundreds of images must be taken ..

(image download time) >> (total exposure time) ⇒ low efficiency (!)



CCD – pixel well depth < 200000 e$^-$

*PMT – up to **10^6** e/sec*

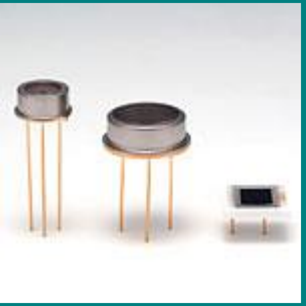
TurPol (Piirola) → PMT (10^{-5})

‘Photo-elastic’ polarimeter (Kemp) → PMT (10^{-5})

PlanetPol (Hough et al.) → APD (10^{-6}) WHT (4.2 m), stars with $m_V < 4$ mag

POLISH1-2 (Wiktorowicz) → APD, then PMT (up to 10^{-6})

HIPPI (Baley et al.) → PMT (10^{-6})



*APD – up to **10^8** e/sec*

Typical maximum precision of the CCD polarimetry is ~10^{-4} only (0.02 – 0.05%)

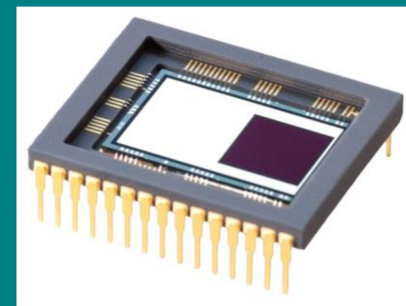
Polarimetry with EM CCD: Andor iXon 897 Ultra

Teledyne e2v EM CCD97-00 sensor:

- 512 x 512 pixel; 16 x 16 μm pixel size
- Full well depth: 180000 e^-
- EM and conventional amplifiers
- Masked temporary storage area on chip
- QE: ~ 96% (various coating options)

Andor iXon 897 Ultra EM CCD Camera:

- TE cooling down to -80^{o} C below ambient
- Readout rate up to 56 / 10 full frames/sec
- Connection via USB 2 port
- Multiple readout modes (FVB, FT, accumulative..)
- Window readout possible
- Full image vertical shift time < 0.002 seconds
- Can be used with permanently open shutter
- External shutter, external trigger options



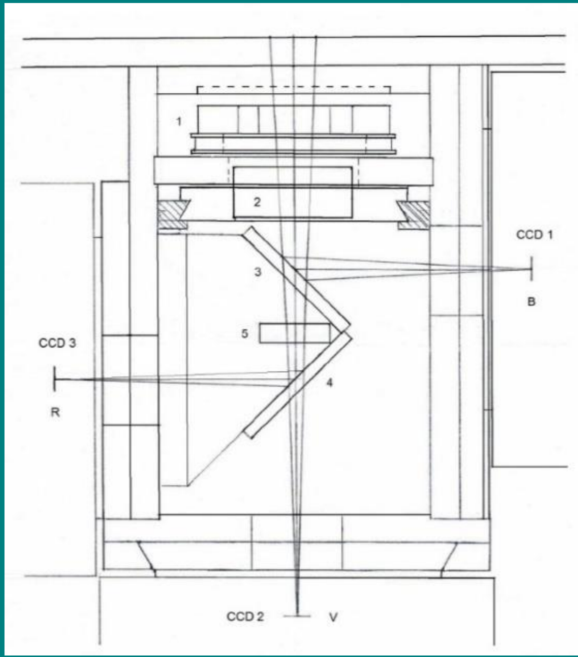
e2v EM CCD97-00 sensor

Andor iXon 897 Ultra EM CCD camera

DiPol-UF: High-Precision Three-Band CCD Polarimeter

DiPol-UF design requirements:

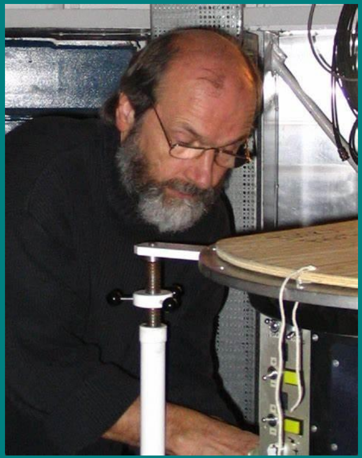
- Free of systematic errors (at the level of 10^{-6})
- Simultaneous observations in the three pass-bands
- High sensitivity in the B – band (Rayleigh scattering!)
- High throughput (minimum light losses)
- Suitable for mounting on various telescopes
- Reliable, service-free
- Easy to use (simple calibration and data reduction)
- No image saturation problem



TurPol → Dipol → Dipol-2 → DiPol-UF

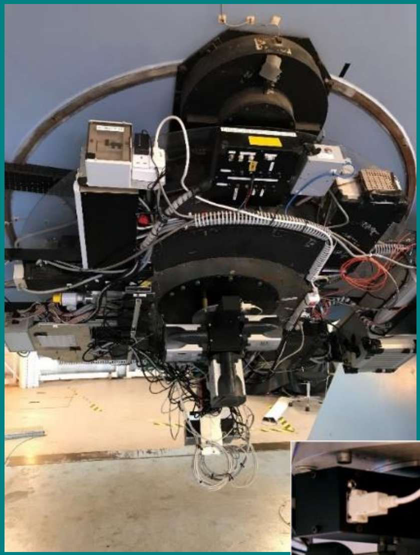
DiPol-UF is a joint project: University of Turku (Finland) and KIS (Germany)

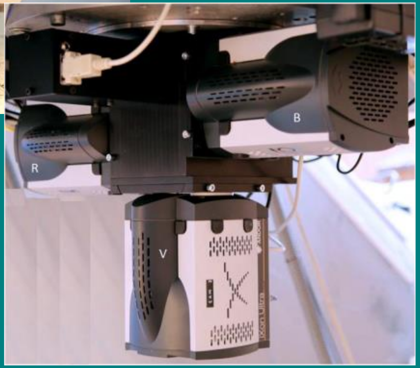
DiPol-UF is designed and built in Tuorla Observatory by V. Piirola



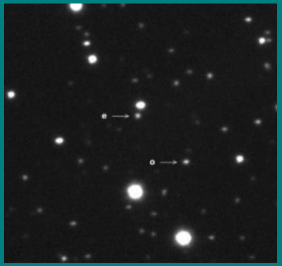
DiPol-UF: High-Precision Three-Band CCD Polarimeter

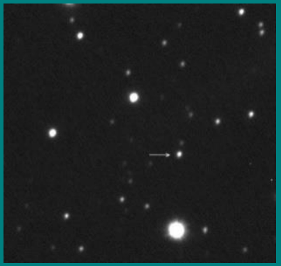
- *Super-achromatic λ/2 or λ/4 retarder discretely rotated by TRINAMIC stepper motor*
- *Analyser: plane-parallel calcite, beams separation in the focal plane: 1.8 mm (14.6 arcsec)*
- *Two thin (1mm) dichroic color-sensitive beam-splitters, B, V and R pass-bands*
- *3 CCDs: Andor iXon Ultra 897*
- *3 industrial-grade Axiomtek eBox 560-500FL mini-PCs for cameras control*
- *Optimized for remotely controlled observations*
- *Retractable calcite unit: can be used as a high speed three-bands photometer*





Officially commissioned at the NOT in July 2019
Link: www.not.iac.es/instruments/dipol-uf/





Paper: Piirola, Kosenkov, Berdyugin, et al. 2021, AJ, 161, 20

Dipol-2: High-Precision Three-Band Polarimeter

- Two orthogonally polarized images are recorded simultaneously:

no errors due to variations in transparency and seeing

- Single measuring cycle consists of 16 / 8 waveplate rotations:

rotationally induced internal errors, arising from dust particles on retarder, etc. are minimized / eliminated (full 360 degrees rotation)

❖ *Defocusing Technique:*

✓ *avoiding saturation problem*

✓ *collecting up to $10^{7} e^{-1}$ per single exposure*

✓ *avoiding errors due to imperfect flat-fielding*

❖ *Elimination of Sky Polarization*

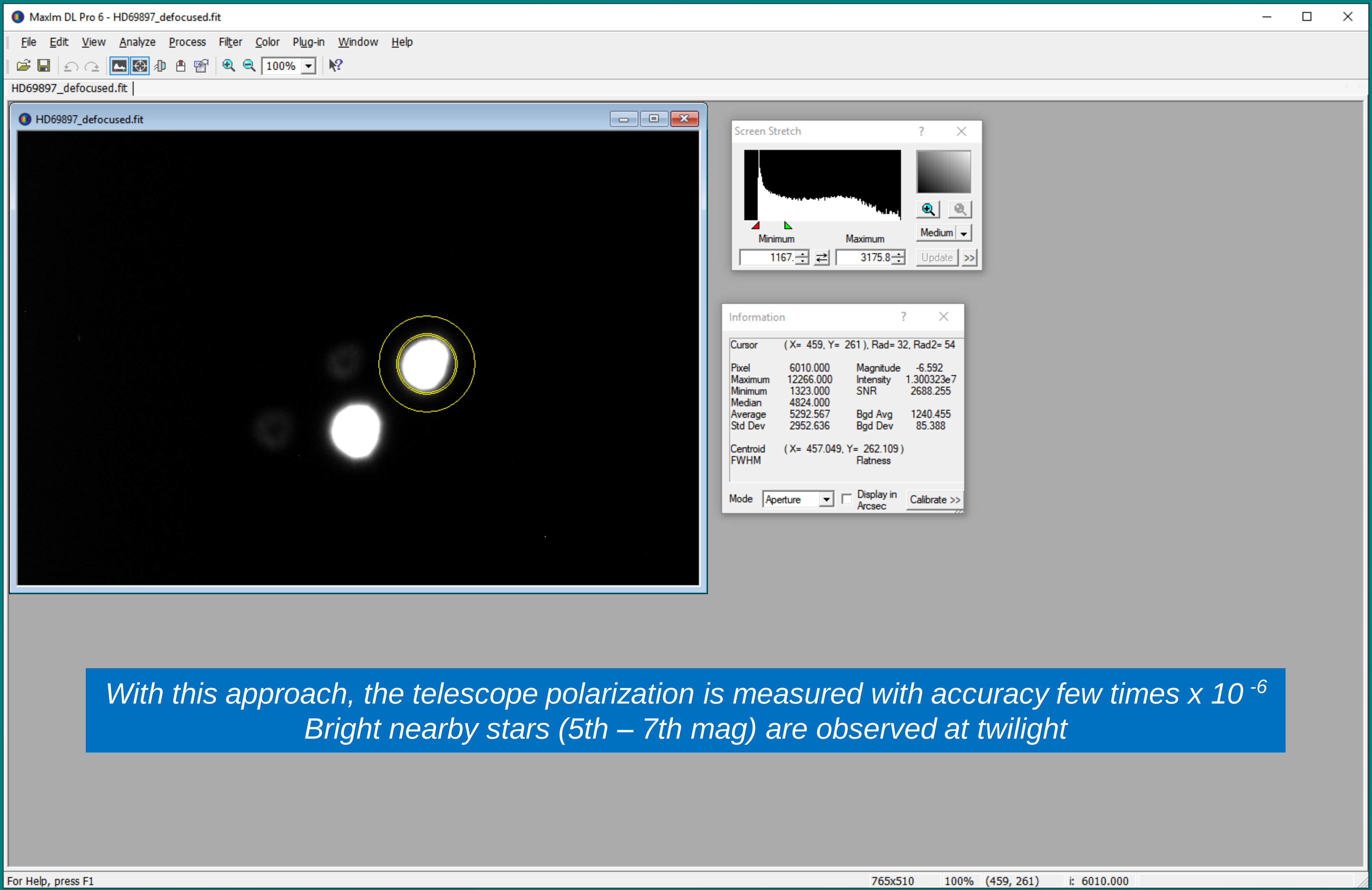
Orthogonally polarized sky images are overlapped: sky polarization is eliminated automatically

⇩ ⇩

Accuracy is only photon-limited: up to 10^{-6} (ppm)

Precision at the level of 10^{-5} (0.001%) is routinely achieved for sufficiently bright stars

DiPol-UF: Defocusing Explained

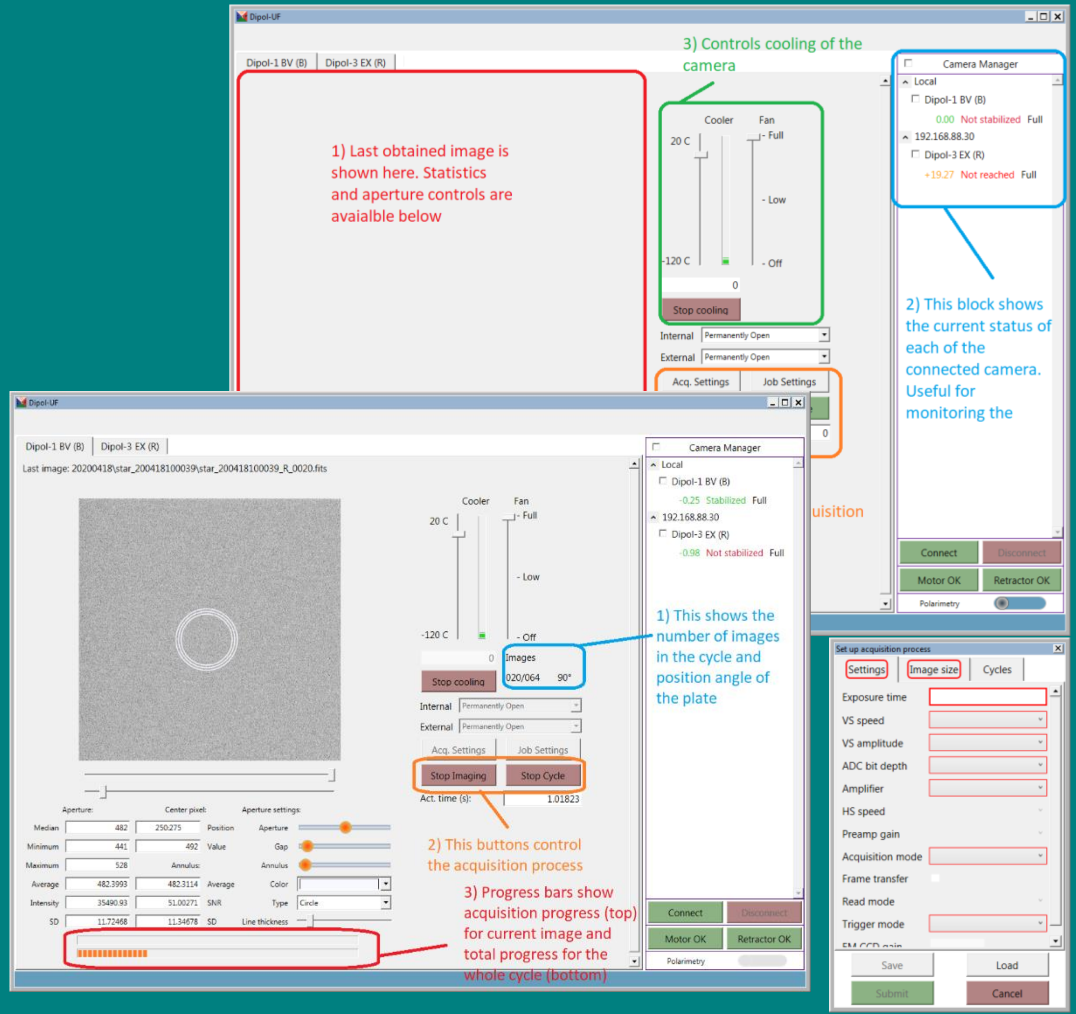


With this approach, the telescope polarization is measured with accuracy few times x 10^{-6}
Bright nearby stars (5th – 7th mag) are observed at twilight

DiPol-UF: Control Software

Custom-made control software

- Three PCs are linked via high-speed local network
- Accessed via VPN connection (VNC)
- Displays image acquisition for all three CCD cameras in real time
- Provides control over all camera settings
- Video mode for object centering and focusing
- Linear, circular and photometry modes
- Automatic acquisition of calibrating images
- Images are saved in standard FITS format



Instrumental polarization control: up to 5 – 10 zero-polarized + 2 highly polarized stars per run (can be very bright and observed in twilight)

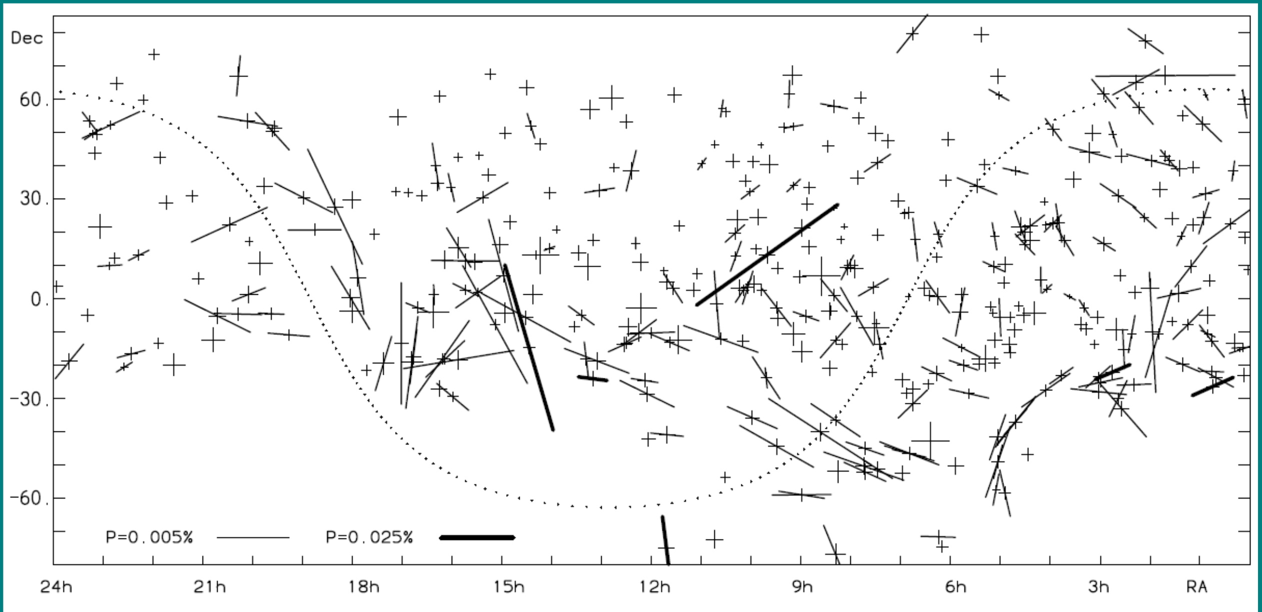
Images calibration: standard calibration (bias and dark subtraction + optional flatfielding)
Data reduction: standard aperture photometry software → o and e intensity ratios Q_i are measured and converted to Stokes parameters

Part II. DiPol-UF at the NOT: Science Cases

Interstellar Polarization in the Vicinity of the Sun

Even nearby stars can be polarized up to 10^{-4} by local ISM (!)

Dipol-2 and DiPol-UF can effectively "convert" high flux to high accuracy: 10^{10} e^{-} $\rightarrow \sigma(P) = 10^{-5}$ (0.001%)



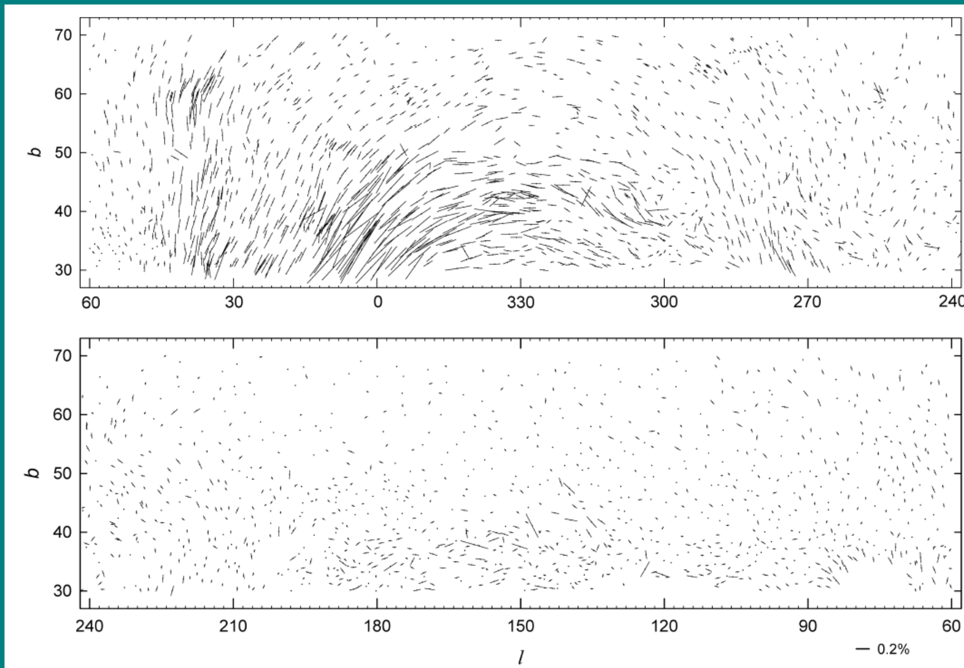
Telescope	JD interval	Stars	Mag range
UH88	2456818–7678	125	6.1–9.1
T60	2456994–8508	205	3.9–6.5
H127	2457775–8183	31	4.1–6.9
	Additional data:		
WHT	2457206–7407	12	7.2–8.4
NOT	2458687–8688	15	3.8–5.8

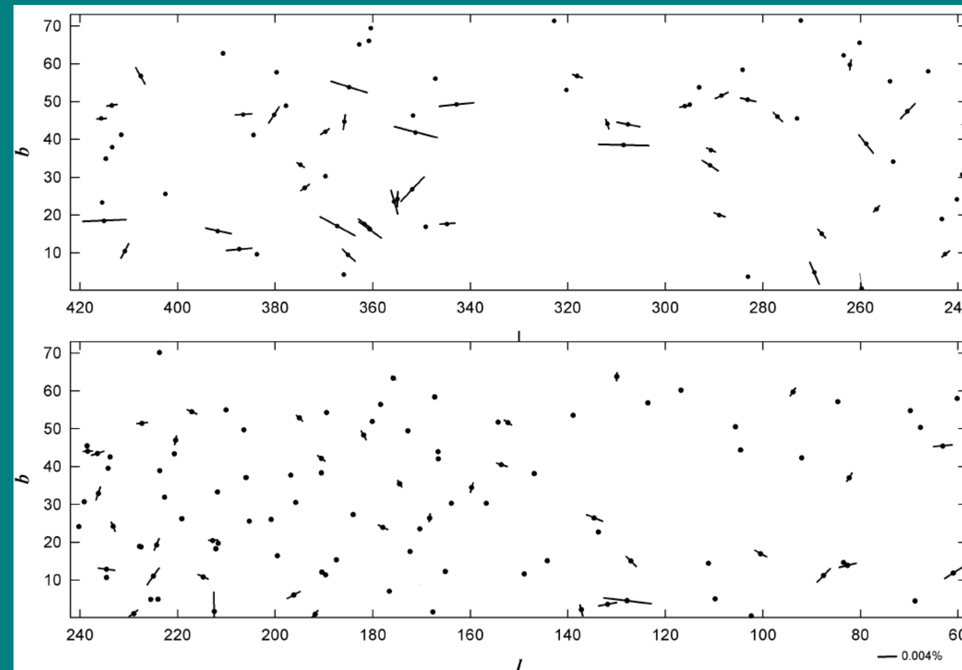
Sample of nearby stars has been observed at the NOT during DiPol-UF commissioning run

Polarization map of the nearby stars (< 50 pc) in equatorial coordinates. The length of bar corresponds to degree of polarization and direction gives direction of polarization. For low degrees of polarization, $p < 2\sigma$ (no detection), only a cross with bar lengths, σ, are plotted. Dotted line shows Galactic equator.

Paper: *Piirola, Berdyugin, Frisch, et al. 2020, A&A, 635, 46*

Interstellar Polarization in the Vicinity of the Sun





Comparison of polarization maps of northern galactic latitudes (b > 0º)for the distant (100pc < d < 500pc, Left) and nearby (d < 50pc, Right) stars. Polarization scale on the left plot is compressed by a factor of ~70 in comparison from that on the right and only the stars with b > 30º are shown.

Comparison of two maps reveals the presence of similar polarization patterns, that is, the ISMF structures seen at large distances also extent to and appear at close distances, near the Sun.

Broad-band Circular Polarization in Magnetic WDs

Zeeman effect:

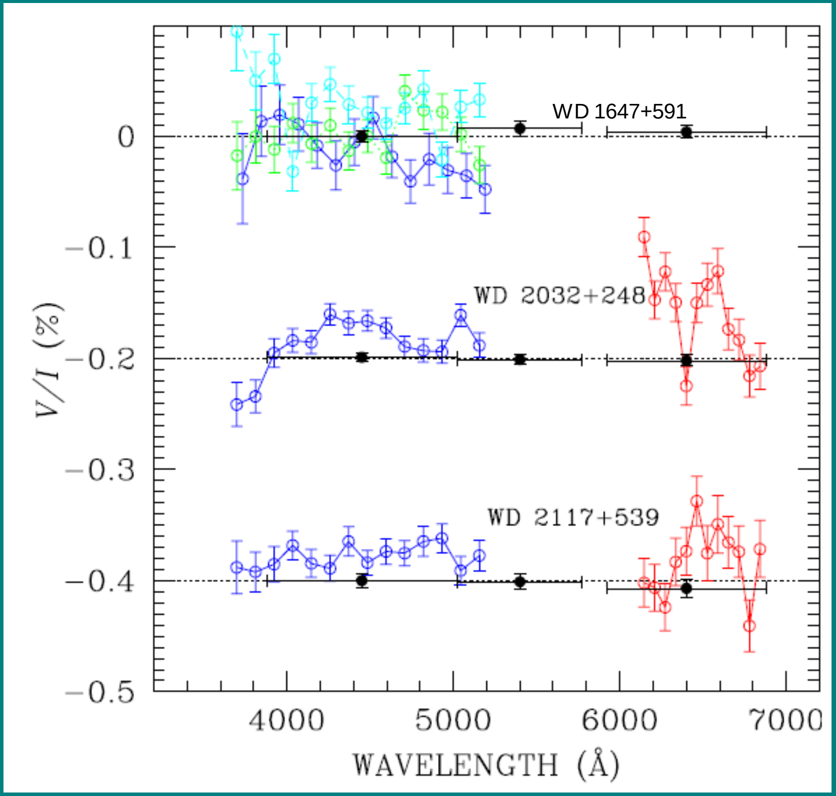
Zeeman spectropolarimetry has been extensively used for studying magnetic fields in WDs last three decades

- Lack of spectral lines in the cool (old) H and He DC type WDs
- Magnetic field with ≥ 1 MG strength results in continuum circular polarization ≥ 0.1%
- Spurious background polarization prevents to measure continuum polarization with most spectropolarimeters (FORS2, ISIS) at the level of < 0.1% (Bagnulo & Landstreet, 2020)

DiPol-UF is the optimal instrument for the broad-band continuum polarimetry of cool and old WDs (!) ⇒

✓ free of systematic errors

✓ sensitivity is only photon-limited.



ISIS vs Dipol-UF continuum circular polarimetry of known non-magnetic WDs. Data for different stars are offset along the vertical axis by 0, -0.2 and -0.4%

Broad-band Circular Polarization in Magnetic WDs

Survey of magnetic fields in the very oldest white dwarfs with the DiPol-UF at the NOT

The aim: to study the incidence of magnetic field in the coolest and oldest WDs

- *A lack* of field in the oldest stars would confirm the action of Ohmic decay of a fossil field
- Finding that *fields are common* even among the oldest WDs could support the hypothesis that magnetism originates and is sustained by some dynamo effect

We will measure polarization in the complete sample of ~70 old WDs in the local 30 pc volume.

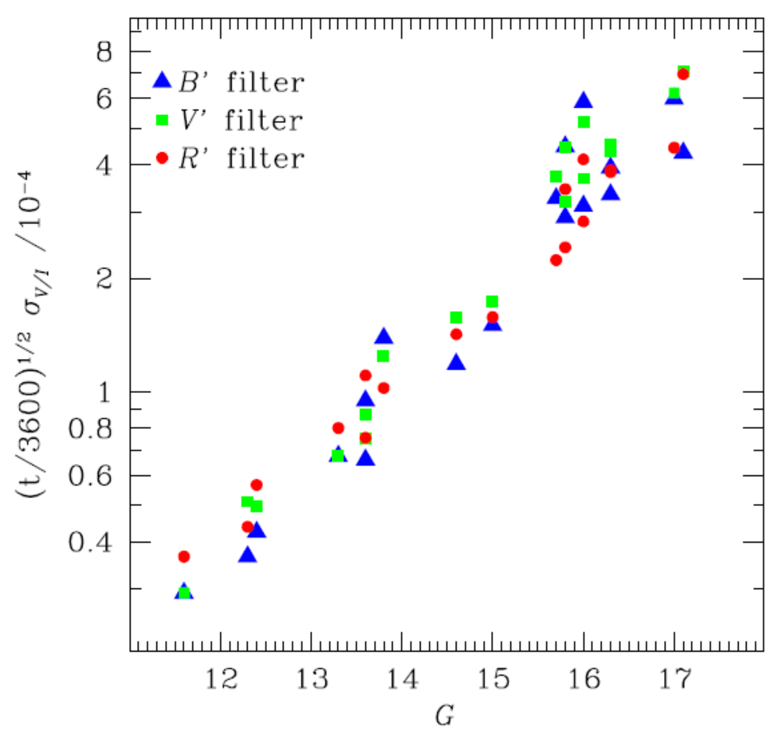


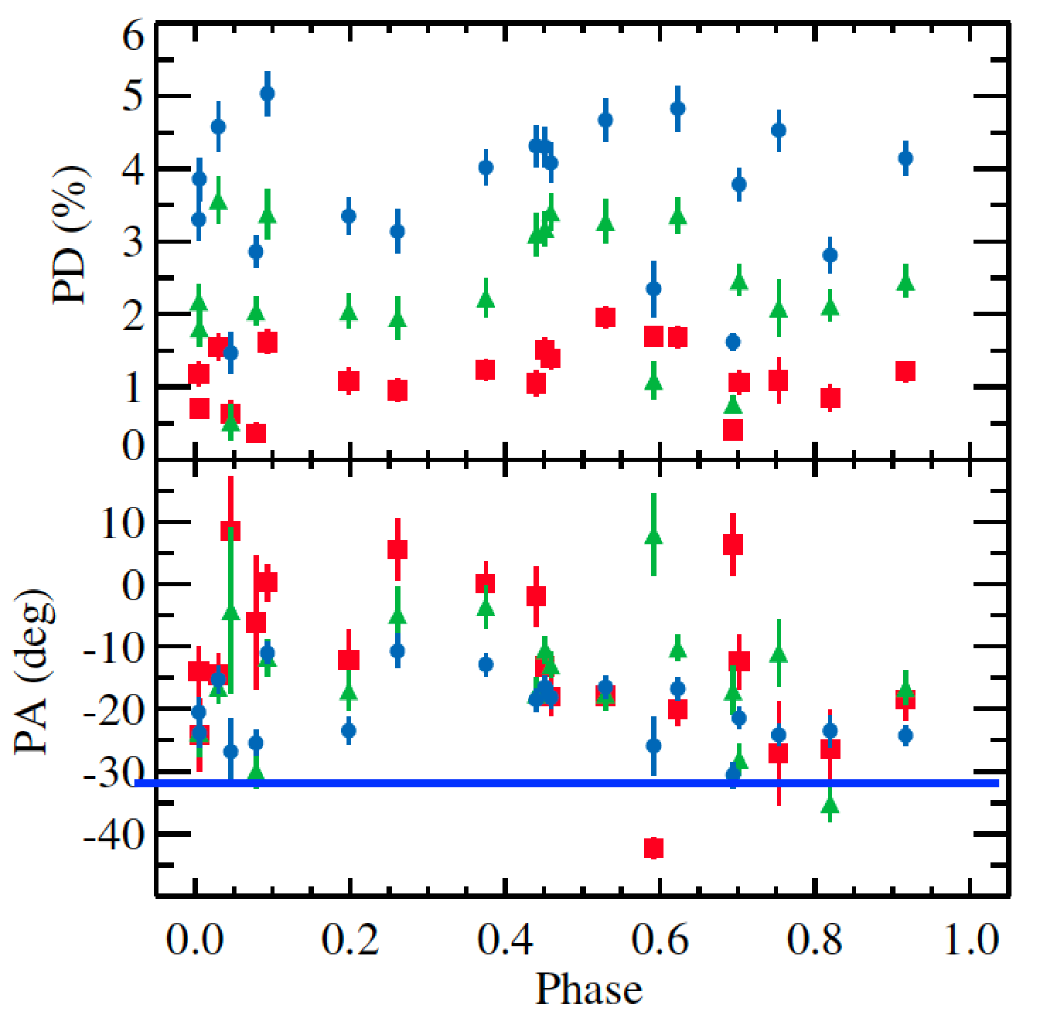
Fig. 4. Relation between magnitude and uncertainty of our measurements of Table 3 as a function of Gaia G magnitude, normalised to 1 h exposure time.

Pilot circular polarimetry with DiPol-UF (July 2021, 3 nights) resulted in discovery of two new magnetic DC WDs: WD 1556+044 and WD 2049-222 →→

V/I(%) = 0.095 ± 0.019 – the weakest non-zero polarization detected in WDs (!)

Paper: *Berdyugin, Piirola, Bagnulo, et al. 2022, A&A, 657, 105*

Low-mass X-ray binary MAXI J1820+070 in quiescence



Variability of polarization degree and polarization angle vs. orbital period 0.685 days

Went to outburst in 2018

Was observed with DIPol-UF at the NOT in July 2019, April 2020, July 2020, and July 2021 → Polarization in quiescence is larger than that in the outburst (!)

- PD is 1 − 5%, very blue
- PD is variable, no obvious orbital dependence
- $\langle PA_B \rangle = -19.7^o \pm 1.2^o$

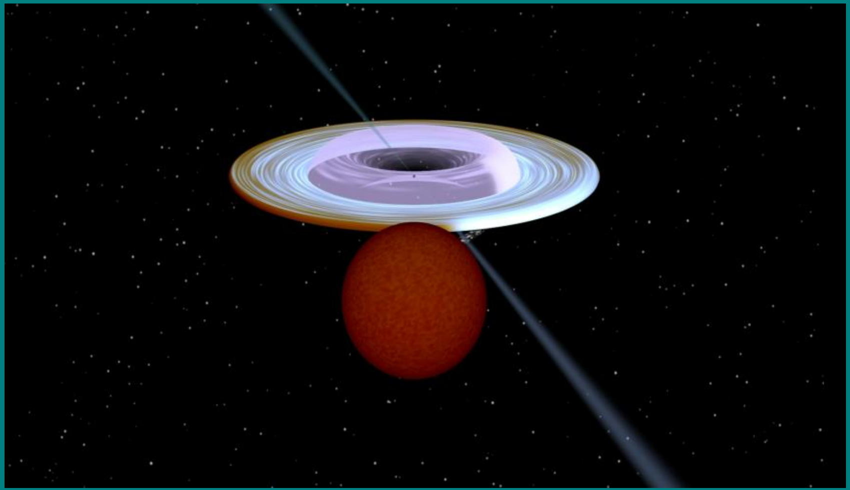
Direction of Polarization PA ≈ -20º is related to the orbit direction

Jet direction is related to BH spin: $PA_{jet} = \theta_{bh} = 25.1^o \pm 1.4^o$ (Espinasse et al. 2020)

Low-mass X-ray binary MAXI J1820+070 in quiescence

- The polarized UV excess can be produced by scattering of the disc radiation in the hot inner accretion flow.
- Polarization angle is rather stable, differs from the jet position angle by about 45°.
- The misalignment between the jet (BH spin) and the disc is >40°.

Large misalignment has profound implications for the models of black hole formation, models of X-ray and optical QPOs, reliability of BH spin measurements from iron lines, BH mass measurements, etc.

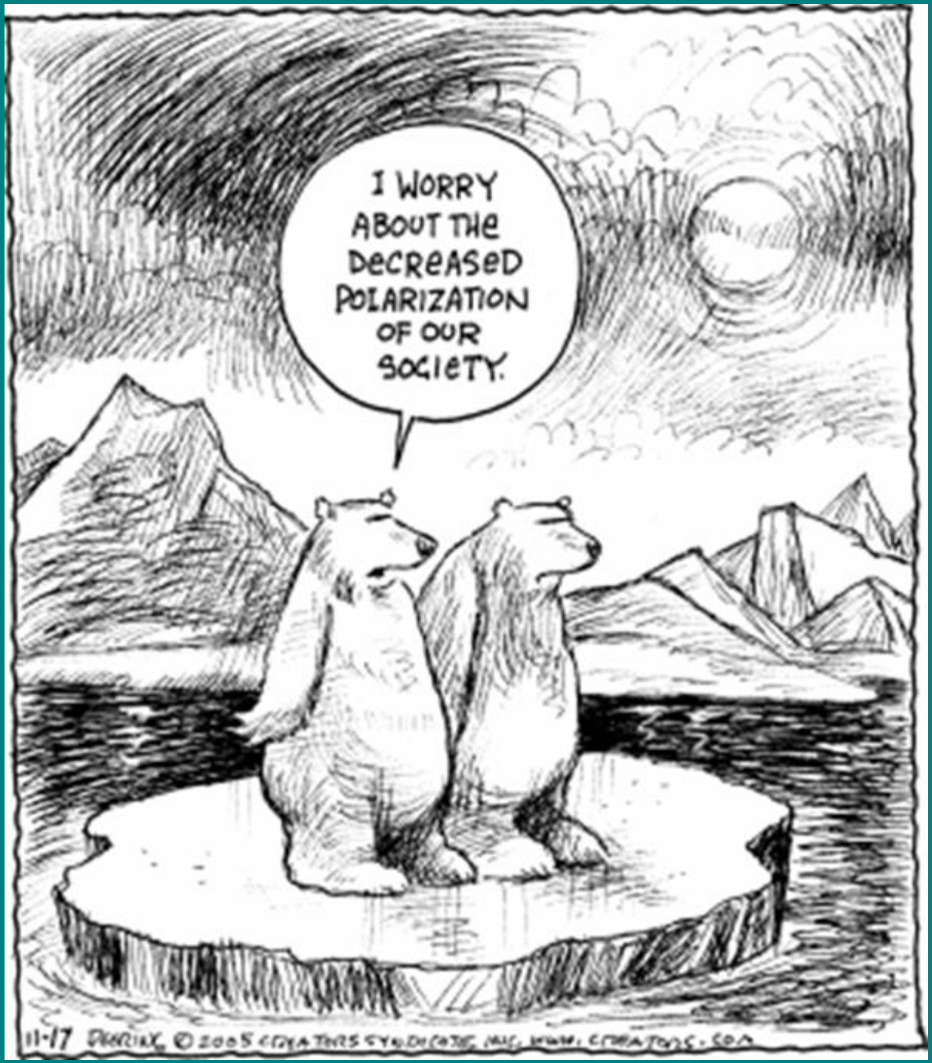


Artistic representation of MAXI J1820+070 binary system

Paper: *Poutanen, J., Veledina, A., Berdyugin, A., et al. 2022, Science, 375, 874*

DiPol-UF highlights

- Simple and easy to observe / reduce data
- Reliable / service-free design
- Simultaneous B, V and R polarimetry + option for high-speed photometry
- Accuracy is photon limited only (up to 10^{-6})
- Suitable for bright and faint targets
- Available to NOT community as the instrument with the limited access



Thank you!