V–SHARK

System for coronagraphy with High order Adaptive optics from R to K band

Coronagraphy with Adaptive Optics @ LBT for high contrast and resolution imaging in the visual bands

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Outline:

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4. AO Control Loop System
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Research Goal

4826 Exoplanets observed with Indirect Methods
(1523 confirmed exoplanets with known orbital parameters)

web ref. ➔ http://exoplanets.org

Direct Imaging (reflected light)

Radial Velocity (RV)

Transit

MicroLensing (μL), Pulsar Timing (PT)

• Detection of face-on exoplanetary systems
• Comparison between orbital and physical parameters
• Observational time is reduced

Further possible applications for SHARK

• High-contrast images of circumstellar disks with optical/near-IR coronagraphy and polarimetric Differential Imaging
• Coronagraphic imaging of stellar jets
• 2D maps of Jets

28/05/2015
Exoplanets Direct Imaging problems

High contrast and detection

Typical case:
Sun-like star $R = 4.81$ mag
Jupiter-like planet @ 10 pc

High resolution

LBT: HIP76041 @ 750 nm

Adaptive Optics OFF
Exoplanets Direct Imaging problems

High contrast and detection

Typical case:
Sun-like star $R = 4.81$ mag
Jupiter-like planet @ 10 pc

High resolution

LBT: HIP76041 @ 750 nm

$\text{Separation}_{AB} = 70 \text{ mas}$

Adaptive Optics ON
High contrast required! (ideal case: the PSF is accurately known…)

Typical case:
Sun-like star R = 4.81 mag
Jupiter-like planet @ 10 pc

Upper limit
\[ \sqrt{N_{\text{Star}}} \]

Coronagraphy
AO: beating the atmosphere!!

**Airy Diffraction limited PSF**

- Plane waves from distant point source
- Turbulent layer in atmosphere
- Perturbed wavefronts

**Speckle distribution**

Atmospheric PSF: Large FWHM averaged profile

\[ \theta = 1.22 \frac{\lambda}{D} \]

\[ r_0 \propto \frac{\lambda^{6/5}}{\sec(z)^{5/3}} \]

\[ \tau_0 = 0.31 \frac{r_0}{v} \]

**Short exposure time** \((t < \tau_0)\)

**Long exposure time** \((t > \tau_0)\)

\[ \theta_{seeing} = 1.22 \frac{\lambda}{r_0} \]
**AO Control Loop System**

- Plane waves from distant point source
- Turbulent layer in atmosphere
- Perturbed wavefronts

Fitting, Servo-lag, Anisoplanatic Angle, WFS noise

AO Phase Residuals

$t_{exp} \sim 1\,ms$

LBT Primary Mirror

$\phi = 8.4\,m$

f/\# = 15 (gregorian)

LBT Secondary Adaptive Mirror

$\phi = 0.9\,m$

672 actuators
Laser Guide Stars (LGSs)

Sufficiently bright stars required for AO correction

Not always available in the star field

Laser Head
($\lambda = 589$ nm)

Launch Telescope

Rayleigh Scatter
Elastic scattering from atoms or molecules in lower atmosphere
$h \sim 30$ km (troposphere)

LGS
Radiation is absorbed and re-emitted
$h \sim 90$ km (mesosphere)
Wendelstein @ Teide Observatory

Launch Telescope

Receiver Telescope

Observatory Site

Control Room
Wendelstein @ Teide Observatory
Preliminary results

Laser Calibration:

- LGS and Standard Field Star Fluxes measurements
- Rayleigh Scatter Flux measurements
- LGS and Std star FWHM measurement on x and y axis
- 589 nm Sodium Laser Power Scan
- 589 nm Sodium D2B Scan
- Exposure Time 1 ÷ 20 s
- Filters: Johnson V and R
- Polarization: Vertical, Horizontal and Circular
Laser Pointing Camera (LPC) @ ESO-VLT

(Proc. SPIE 9147, Bonaccini Calia et al., 2014)
Simulations:

1) Rayleigh Scatter intensity up to an altitude of 30 km above ground;
2) Mesospheric Sodium fluorescence (LGS) from 80 to 120 km above ground;
3) Defocus effect on the Rayleigh scatter plume depending on the UT4 pointing altitude angle;
4) Decreasing brightness by using a second order power law due to the distance from LPC objective;
5) Air density profile depending on altitude;
6) Extra Rayleigh scatter from thin cloud layers (cirrus).
7) LGSs Asterism pattern configuration.
8) Laser uplink beams and LPC positions with respect to the VLT-UT4 telescope optical axis.
9) Integration time.
10) Lasers output power.
11) AZ and El angle of the VLT-UT4.
Laser Pointing Camera (LPC) @ ESO-VLT (Real Image)

LPC Image @ VLT UT4 with L3
April 29, 2015
The SHARK project: VIS channel

(V–SHARK)

- High resolution fast imager with FLAO @ LBT
- Binocular AO from 600 ÷ 900 nm and 900 ÷ 2200 nm
- Experimental focal plane for coronagraph and...
- Synchronous recording of wave-front residual

(Proc. SPIE 9147, Farinato J. et al., 2014)
SHARK VIS channel: V–SHARK
First design of V–SHARK

**SPECs:**

**Direct Imager**
- Field of view = (20x25)" or (8x10)"
- Sampling 4 ÷ 10 mas/pixel
- ADC bandwidth 600 ÷ 900 nm

**Coronagraph**
- Field of view = (5x5)"
- Sampling 4 ÷ 10 mas/pixel
- Focal plane 6 x occulter
- Pupil plane 6 x stops/apodizers

**Detector**
- Fast sCMOS imager 1 e⁻ r.o.n.
- Exposure 10⁻³ ÷ 30 s
SHARK VIS channel: V–SHARK

Functional block diagram of V–SHARK

**To LBTI WFS**

- f/15 beam
- Pick-up dichroic
- ADC
- Filter wheel 1 (direct imager)
  - Occulter wheel

**Camera**

- Dichroic
- Pupil wheel
- Filter wheel 2
- Collimator
  - 600÷750 nm imager
  - 750÷900 nm imager

**Direct Imager configuration**

- Active
- Movable
- Disabled
- Fix
**SHARK VIS channel: V–SHARK**

Functional block diagram of V–SHARK

- **f/# 15 beam**
- **Pick-up dichroic**
- **ADC**
- **Filter wheel 1**
- **Occulter wheel**
- **To LBTI WFS**

**Components:**
- **Camera**
- **Collimator**
- **Filter wheel 2**
- **Pupil wheel**
- **Dichroic**
- **600÷750 nm imager**
- **750÷900 nm imager**

**Configuration:**
- **Coronagraph active**
- **Coronagraph disabled**
- **Filter wheel 1 direct imager**
- **Moveable**
- **Fix**

**Relayed Focal Plane configuration**
SHARK VIS channel: V–SHARK
Andor Zyla fast sCMOS detector

Andor Zyla sCMOS specs (laboratory calibration):

- sCMOS detector with 2k x 2k squared pixels of 6.5 μm side
- Average Q.E. > 60% between 500 and 800 nm
- Read Out Noise ~ 1 e− at 280 Mpx/s
- Dark current < 0.1 e−/s
- 1000 frame per seconds on 200 x 200 pixel sub array
- Global and rolling shutter with ext. sync. (read out time 10 μs/line couple)
- Data and control interface USB 3.0 or Camera Link
- Binning up to 8x and subfield selectable with 1 pixel granularity
V–SHARK first test

February 13, 2015 INAF night:

a) Bad weather, seeing $1.2 \div 0.8$ arcsec (?)
b) Cloud layers dimming, 3 up to 5 mags
c) Target HIP 48455 $M_V = 3.85$, $M_R = 2.97$
d) Recorded 10 series of 10000 1 ms images
e) About 3 hours of test between clouds
f) Resolution: 3.9 mas/pixel of
g) Filter @ 630 nm, BW 40 nm no ADC
h) AO: 990 Hz, 300 modes only
V–SHARK first test

10 s integration time with RECENTERING:
PSF FWHM = 19.5 mas
SR = 25%
V–SHARK first test

10 s integration time with SORTING & RECENTERING:
PSF FWHM = 19.5 mas
SR = 32%
V–SHARK first test

10 s integration time with SORTING, RECENTERING & REFRACTION DECONVOLVED
PSF FWHM = 19 mas
SR = 33%
V–SHARK first test

Without image recentering

With image recentering
Conclusions

- Direct Imaging can be performed on Exoplanets for a deeper knowledge of both orbital and physical parameters with a reduced observational time;

- LGSs are very useful to study and sample the atmospheric turbulence especially when star fields are not crowded by bright stars;

- Wendelstein preliminary results establish a stable starting point for studying atmospheric Sodium density, but we are still calibrating the laser system;

- LPC simulations have been useful for LGSs astrometric offset calculations and photometric measurements @ VLT UT4;

- LBT–FLAO + V–SHARK
  - Good correction of wavefront distortions even in bad weather conditions (good PSF FWHM, good SR);
  - Versatile optical system (Direct Imaging/Coronagraphy);
  - Low Noise Andor Zyla fast sCMOS detector allows high S/N;
  - Off–line image analysis can improve the PSF FWHM significantly.