The quest for exoplanet direct imaging with ELT apertures:
A hunt for companions with the Large Binocular Telescope

ExoExplorer Science Series
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This is what a directly imaged planet looks like
Current RV planets

![Graph showing current RV planets with various Ks mag and Msini values.](image-url)
How do we break the mass/msin(i) degeneracy?
How do we break the mass/msin(i) degeneracy?

RV & DI \rightarrow m_P, formation scenarios
Resolution to probe the RV planet population

\[ \lambda/D \ (4 \text{ um}) \]
How do we do push the frontiers of exoplanet direct imaging with ELTs?
The Large Binocular Telescope (Mt. Graham, AZ)
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Largest apertures are from the ground

\[ B_{EE} = 22.7 \text{ m} \]

\[ B_{CC} = 14.4 \text{ m} \]

\[ D = 8.25 \text{ m} \]

LBT  GMT
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\[ D = 8.25 \text{ m} \]
Direct imaging

Stone+ 2018 AJ
Direct imaging
Stone+ 2018 AJ

Wall-eyed pointing
Spalding+ 2017 PASP
Direct imaging

Stone+ 2018 AJ

Wall-eyed pointing

Spalding+ 2017 PASP

Nulling interferometry

Ertel+ 2020 AJ & Physics Today (April 2022)
The LBT Interferometer
The LBT Interferometer
The LBT Interferometer
The LBT Interferometer

Infrared Instrument

Beam in 4.16 m Beam in

3.6 m

Phil Hinz
The LBT Interferometer

Phil Hinz
The LBT Interferometer

- Left adaptive secondary mirror
- Right adaptive secondary mirror
- Left primary and tertiary mirrors
- Right primary and tertiary mirrors
- LMIrcam
- NOMIC
- Phasecam
- NIC cryostat
The LBT Interferometer

- Left adaptive secondary mirror
- Right adaptive secondary mirror
- Left primary and tertiary mirrors
- Right primary and tertiary mirrors
- LMRcam
- NOMIC
- NIC cryostat
- Phasecam
- Phase
LBT: the first ELT aperture

8-m telescope
LBT: the first ELT aperture

8-m telescope

point spread function, "PSF"

\[ \sim \frac{\lambda}{D} \]
LBT: the first ELT aperture

22.7 m telescope

light pattern
LBT: the first ELT aperture

22.7 m telescope

"Fizeau" interferometry

\[ \sim \frac{\lambda}{B} \]
LBT: the first ELT aperture

8.4 m telescope

Adapt. from Fig. 4 in Patru+ 2017 MNRAS
LBT: the first ELT aperture

8.4 m telescope  
22.7 m telescope

Adapt. from Fig. 4 in Patru+ 2017 MNRAS
Gain in high-contrast imaging with Fizeau

Adapt. from Fig. 8 in Patru+ 2017 MNRAS
Gain in high-contrast imaging with Fizeau

\[ G(x, y) \propto \frac{\text{PSF}_{\text{One}}}{\text{PSF}_{\text{Fizeau}}} \]
Current RV planets

\[ \lambda/B \quad \lambda/D \quad (4 \text{ um}) \]

- DEC (degrees)
- Angle (arcsec)

- Ks mag
- Msin(i)
  - -3
  - 0
  - 3
  - 6
  - 9
  - 12
  - 10
  - 20
  - 30
  - 40
  - 50
Current RV planets

\[ \frac{\lambda}{B}, \frac{\lambda}{D} \text{ (4 um)} \]

JWST NIRCam, MIRI coronagraphs (approx.)

DEC (degrees)

Angle (arcsec)

s mag

Msin(i)

10
20
30
40
50
Current RV planets

\[ \lambda/B \quad \lambda/D \ (4 \text{ um}) \]

JWST NIRCam, MIRI coronagraphs (approx.)

JWST NIRISS
Altair: the first high-contrast Fizeau target
A PSF with additional degrees of freedom
The scale of the Altair system
The scale of the Altair system

Altair, 1AU

Habitable zone (Cantrell+ 2013)
The scale of the Altair system
Post-processing with Fizeau: the classical regime

\[ \rho > \frac{\lambda}{D} \]
Post-processing with Fizeau: the classical regime
Post-processing with Fizeau: the classical regime

angular differential imaging, "ADI"
Post-processing with Fizeau: the Fizeau regime

\[ \frac{\lambda}{D} \gtrsim \rho \gtrsim \frac{\lambda}{B} \]
Contrast curves in the classical angular regime
Fizeau baselines through the Altair HZ
Contrast curves: all together now
Contrast curves: all together now

Fizeau regime:
\[ \frac{\lambda}{D} \gtrsim \rho \gtrsim \frac{\lambda}{B} \]

Classical regime:
\[ \rho > \frac{\lambda}{D} \]
Gain in high-contrast imaging with Fizeau

\[ G(x, y) \propto \frac{\text{PSF}_{\text{One}}}{\text{PSF}_{\text{Fizeau}}} \]
What improvement does the gain suggest?
What improvement does the gain suggest?
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1 Gyr: $\sim 0.1 M_{\text{sol}}$

100 Myr: $\sim 60 M_J$
What improvement does the gain suggest?
What improvement does the gain suggest?
Areas for improvement (examples)
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DONE

Upgrade of detector readout electronics: \(~10\% \rightarrow \sim80\%\) integration time efficiency
Areas for improvement (examples)

DONE

Upgrade of detector readout electronics: \(~10\% \rightarrow \sim 80\%\) integration time efficiency

PARTIALLY DONE

Independent mirror feedback
Areas for improvement (examples)

DONE

Upgrade of detector readout electronics: ~10% -> ~80% integration time efficiency

PARTIALLY DONE

Independent mirror feedback

Site-specific atmospheric condition modeling
Areas for improvement (examples)

**DONE**

Upgrade of detector readout electronics: ~10% -> ~80% integration time efficiency

**PARTIALLY DONE**

Independent mirror feedback

Site-specific atmospheric condition modeling

**PLANNED**

Lower-noise wavefront sensor detector
Areas for improvement (examples)

DONE

Upgrade of detector readout electronics: ~10% -> ~80% integration time efficiency

PARTIALLY DONE

Independent mirror feedback

Site-specific atmospheric condition modeling

PLANNED

Lower-noise wavefront sensor detector

Future directions for LBTI in Fizeau mode:
Spalding+ 2022 AJ 163:62

Image: U Arizona
Take-away points

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Binocular observing can accommodate unique parts of search space.
Take-away points

Binocular observing can accommodate unique parts of search space

Fizeau variant of ADI can be used to look for companions

Image: U Arizona
Take-away points

- Bottlenecks to sensitivity include integration time and phase noise, but upgrades on the way.
- Binocular observing can accommodate unique parts of search space.
- Fizeau variant of ADI can be used to look for companions.