Investigating Planetary Environments with the LBT Interferometer

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The LBT: A unique platform for IR direct imaging and interferometry

The Large Binocular Telescope is a facility on Mt. Graham in southern Arizona, administered by a consortium of American, Italian, and German institutions. The LBT has twin 8.4-m diameter primary mirrors, and corrects atmospheric distortions in the wavefront using deformable secondary mirrors. This allows the number of “warm" mirror surfaces to be minimized, thus optimizing the facility for thermal infrared observations, where planet-to-star ratios are most favorable.

The interferometer LBTI can work in a variety of modes, including directing imaging using the two individual apertures, or in interferometric modes by coherently combining the two beams.

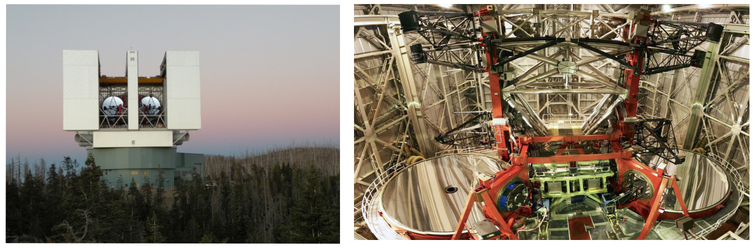

Fig. 1: Left: The LBT on Mt. Graham, Arizona. (Image credit: J. Hill / LBTO.) Right: The chamber of the LBT, showing the twin setup of primary mirrors, adaptive secondaries (on the uppermost swing arms), and LBTI (the green structure between the primary mirrors). (Fig. 1 in Böhm+ 2016 *SPIE Proc* 99062R.)

As adaptive optics systems improve and 30-m-class telescopes come on-line in the coming decade, sensitivity levels and inner working angles will greatly improve. The nature of direct imaging data also allows us to

- constrain the wide-orbit orbital architectures of systems (see Stone+ 2018 *AJ* 156:286)
- characterize atmospheres of non-transiting planets. For example, a band-head signature of methane (which in combination with other gases could provide a biosignature) is observable at 3.3 μm (see Skemer+ 2014 *ApJ* 792:17).

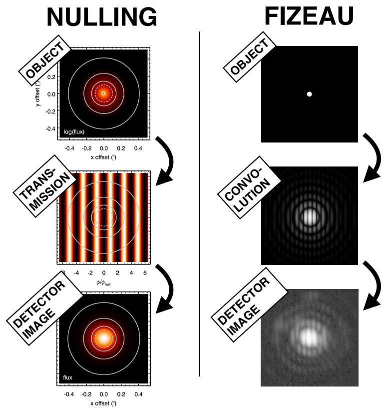

Fig. 2: The LBTI’s two interferometric modes transform the targets in different ways, and are applicable to different science cases. Some images adapted from Ertel+ 2018. *AJ* 155:194 and Spalding+ 2018 *SPIE Proc* 107010J.

The unique interferometric capabilities of LBTI, however, provide truly one-of-a-kind probes of exoplanet environments. Data from these modes constrain the physio-chemical conditions available for planet formation and, ultimately, the emergence of life.

One observing mode, nulling, allows one to sieve an observed target through a transmission pattern projected onto the sky, and obtain an image which is (to first order) a standard Airy function, but composed of flux from material immediately around the star. Another mode, Fizeau, preserves and maximizes spatial detail. The sensitivity of interferometric observations can also be improved by controlling the optical path length (against rapid changes induced by the atmosphere and telescope vibrations) between both beams. A phase-sensing camera can currently do so with bright (*Ks*<4.7) objects, with possible future upgrades.

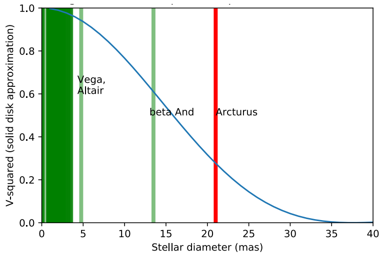

Fig. 3: Extended objects exhibit fringes with reduced visibility. For phase control (either in nulling or Fizeau mode), the *Ks*-band object on which the phase is being controlled has to be as point-like as a ~15 mas circle or smaller. Here, green lines represent stars on which the phase-sensing detector has been able to close the phase loop, and the red line respresents the star Arcturus, on which the phase loop cannot close.

Nulling interferometry: to detect faint exozodiacal disks

Nulling interferometry involves the combination of the beams from both LBT sub-telescopes paraxially, or by overlapping the pupils like pancakes. This provides a total resolution of a 14.4 m baseline, which is the center-to-center distance between the primary mirrors. LBTI is particularly sensitive for these observations due to the combination of an IR-optimized telescope and twin apertures on a common mount without the need for delay lines.

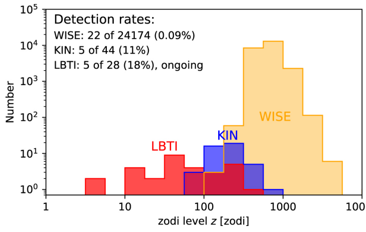

Fig. 4: Exozodi sensitivity and target sample of the HOSTS survey (LBTI) compared to other facilities. LBTI is a factor of 5 to 10 more sensitive. (Fig. 6 in Ertel+ 2018. *AJ* 155:194.)

This mode does not allow the detailed reconstruction of an image, but is relevant for detecting the small, 11 μm luminosity offset of exozodiacal dust disks in the habitable zones around nearby FGK stars. This quantity represents the biggest unknown in expected noise calculations relevant to the design of future space-based imaging missions which seek low-mass exo-Earths.

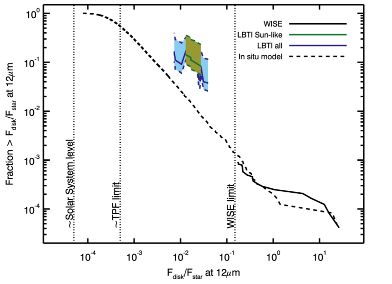

Fig. 5: Constraints on the exozodiacal luminosity function, in terms of the ratio of disk to star luminosities. The LBTI “Sun-like” sample refers to stars with types no later than F5. Some bright, early-type stars with HZs at larger angles were also observed. All stars are underplotted as blue. (Fig. 7 in Ertel+ 2018. *AJ* 155:194; see also Weinberger+ 2015 *ApJSS* 216:24)

The LBTI HOSTS nulling survey took science observations 2014-2018, which are the most sensitive nulling observations ever taken. These have constrained the exozodiacal luminosity function at at the level of $4.5^{+7.3}_{-1.5}$ zodi* (Ertel et al. in prep.) brightnesses, and have revealed exoplanet systems to be reassuringly dust-poor. This bodes well for the future contribution of direct imaging to the search for habitable planets, and for constraining their atmospheric compositions.

Fizeau interferometry: to map bright, extended sources (like protoplanetary disks)

Fizeau interferometry is the combination of the two beams *multi*-axially, where every point in the LBT aperture interferes with every other point in the aperture. This provides baselines out to the 22.7 m distance from one edge of one of the primary mirrors to the other. This also provides a field-of-view over the entire detector (approx. 20x20 asec^2).

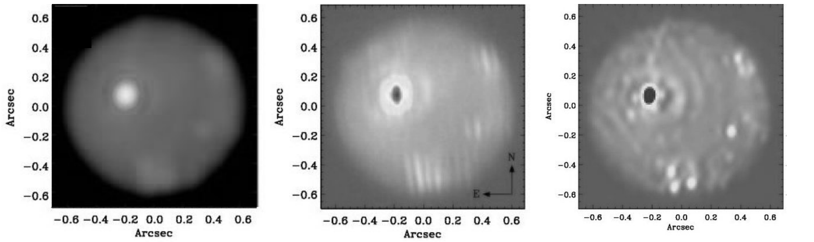

Fig. 6: Left: The Jovian moon Io as seen in *M*-band through a single aperture (Adapted from Fig. 1b in Conrad 2016 *SPIE Proc* 99070L). Middle: An example of what the two-aperture data looks like, with different color scaling. Right: An image of Io as reconstructed from Fizeau imaging. (Middle and right images adapted from Figs. 2 and 4 in Leisenring+ 2014 SPIE Proc 91462S.)

The Fizeau mode is in an ongoing process of commissioning, but has been used to

- map the volcanically active surface of Io (e.g., Conrad+ 2015 *AJ* 149.5:175)
- probe for low-mass companions around a nearby star (with phase control) (in prep.)
- image circumbinary and protoplanetary disks (in prep.)

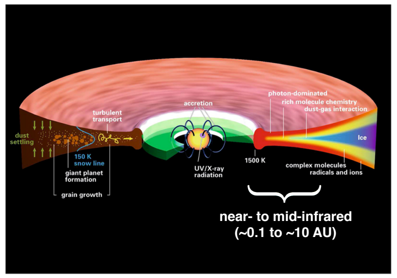

Fig. 7: An illustration of a protoplanetary disk (not to scale) showing the radial dependence of dominant physical processes and the region most relevant to infrared observations. (Adapted from Fig. 2 in Henning+ 2013.)

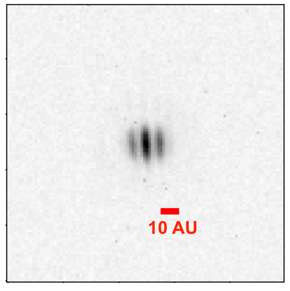

Fig. 8: A frame of a protoplanetary disk (before deconvolution), captured using Fizeau interferometry with LBTI on UT January 8, 2019. Greyscale is reversed. A PSF from a single-aperture image would look much like an Airy function, but the PSF here is an Airy function multiplied by a vertical fringe pattern resulting from the baseline between the two LBT apertures. This kind of PSF is unique, and allows the reconstruction of detail smaller than that imposed by the diffraction limit of a single aperture.

In the protoplanetary disk case, we are endeavoring to map the distribution of water ice. The water ice distribution within protoplanetary disks remains *very* poorly constrained, even though it is critical for a number of processes. Water ice can provide ‘sticky’ ice surfaces which can allow μm- and mm-sized dust to coagulate, and will influence the final compositions of planets. It will ultimately determine the water budget available for emerging biospheres. Observations of the water ice distribution in protoplanetary disks will thus help determine the feasibility that life may emerge elsewhere in the universe.

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* Multiples of the Solar system's HZ dust surface density.