High-Contrast Imaging with Starshades

Aki Roberge

Starshades are a relatively newer idea for providing the extreme high-contrast needed for exoplanet direct observations. They have strengths and weaknesses that are complementary to those of coronagraphs. A starshade is an independent spacecraft flying in formation with the telescope (Figure 1). The goal is to keep the telescope in the shadow cast by the starshade, and keep both spacecraft aligned with the target star. The larger the telescope, the larger the starshade needs to be. The edges of a starshade have a very particular shape to control diffraction and deepen the shadow at the location of the telescope. An example of a small starshade mission concept can be seen in this video: https://exoplanets.nasa.gov/resources/1015/. A lecture on the Theory and Development of Starshades given at the 2014 Sagan Summer Workshop is available here: https://www.youtube.com/watch?feature=player_detailpage&v=h5w6z0jow1Q#t=0.

A starshade blocks the unwanted bright light from an exoplanet host star before it enters the telescope, while allowing light from nearby planets to pass nearly unattenuated. Since the starlight is blocked outside the telescope before it can be diffracted and scattered by the telescope optics, several advantages compared with internal coronagraphs are realized:

- Internally diffracted and scattered light reaching the detector is minimized. Telescope segments and obstructions do not need to be masked out and the wavefront does not need to be corrected with deformable mirrors.
- The contrast and inner working angle (IWA) no longer depend on the telescope diameter but rather the starshade size and separation from the telescope. For planets in habitable zones of nearby sun-like stars, the separations are tens to hundreds of thousands of km depending on the size of the starshade, which can be several tens to greater than 100 meters in diameter. For example, a 10-meter-class telescope would require a starshade diameter of 100 m when operating at a wavelength of 1 μm and an IWA of 40 mas.
- Starshades have no intrinsic outer working angle because no internal optical elements limit the region of high contrast.
- They can be designed to operate over large bandpasses (several times larger than coronagraph bandpasses) and to provide small IWAs at virtually any wavelength. For a fixed IWA and contrast level, the required starshade size increases with wavelength.
- Total throughput is high since the starshade does not require any internal masking of the optical beam. This makes a starshade an excellent option for deep spectroscopy, especially in the NIR where coronagraphs struggle to provide small IWAs.

The disadvantages of a starshade relate to the logistics of testing and operating two spacecraft in a optical configuration separated by large distances:

- The need to slew the starshade over huge arcs to realign it with different target stars means there are long intervals (days to weeks) between the high-contrast observations. The telescope can do other kinds of astronomical observations in the intervals, but starshades are relatively inefficient for high-contrast surveys.
- The total number of observations with a single starshade is limited by the amount of fuel that can be carried by the starshade spacecraft. This puts significant limitations on large-scale searches for planets, especially since the discovery and confirmation of a planet may require multiple observations of a single target. This can be mitigated by using multiple starshades or by refueling a single starshade, increasing cost and complexity.

- To avoid scattering sunlight off the starshade and into the telescope, the angle of the starshade-telescope configuration compared with the sum is limited; therefore a specific target can only be observed at specific periods during the year. This makes scheduling of repeat observations for orbit determination difficult.
- The starshade and telescope must be precisely aligned during observations to maintain high contrast. Keeping the telescope in the darkest part of the starshade shadow generally translates to lateral position precision of about a meter (the separation precision is hundreds of kilometers).
- Full-scale end-to-end system tests on the ground are not possible. Sub-scale tests are being be done in the lab and in the field (Figure 2); however without full-scale tests in realistic conditions, there will always remain a certain level of risk in determining performance.
- The large sizes of starshades means that they must be folded up for launch and deployed in space. Launching the starshade with the telescope increases volume constraints on both spacecraft, while launching the starshade separately leads to increased launch costs.
- The exact shape of the optical edge must be accurate (on the order of 100 μm tolerance for contrast in the 10^{-10} range) after deployment. Further, the thin edge of the starshade must be engineered to minimize sunlight scattering back into the telescope. The fabrication of high-precision starshade edges is an area of active work.

More information on starshade technology development may be found at https://exoplanets.nasa.gov/exep/technology/technology-overview/.

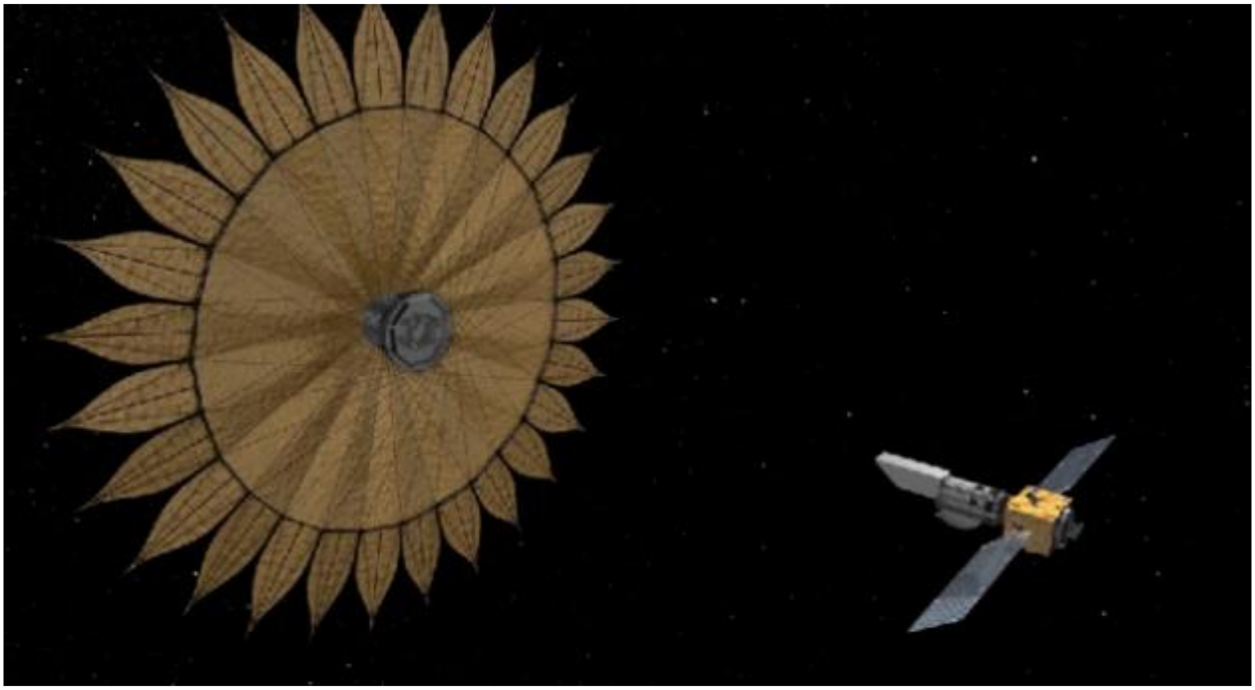

Figure 1: Artist's conception of the Exo-S mission concept, a starshade paired with a small telescope. The image captures a moment just after starshade deployment. Credit: NASA / JPL / Caltech.

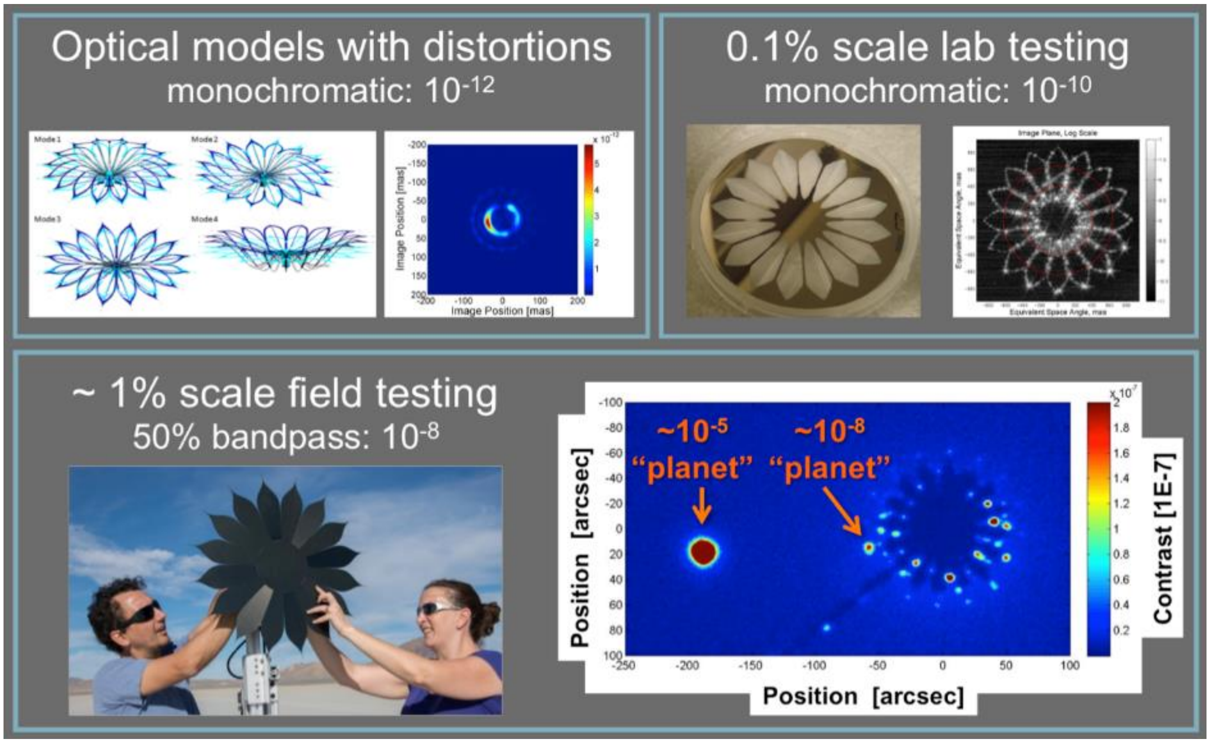

Figure 2: Summary of recent starshade contrast performance testing: modeling done at JPL (upper left panel), sub-scale lab demonstrations in the Princeton University testbed (upper right) panel, and sub-scale field demonstrations executed by Northrop Grumman (lower panel).