CESO: A concept for direct imaging of extra-solar Earth-like planets from the ground

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Concept

Cash and collaborators (2005, 2006) have recently presented work on the New Worlds Observer (NWO), which solves the problem of achieving planet-star contrasts of 10^{-10} without requiring major technological developments. The instrumental setup of NWO consists of a large occulter with a specific shape that minimizes diffraction, placed at a large separation from an optical telescope. An issue that is largely unspecified so far is the geometrical setup of NWO, but the general idea is to use the occulter in combination with a space-based telescope, such as the JWST. The feasibility of such a setup has been questioned. Here, we present a new geometrical setup with the capacity of solving all the geometrical problems of a free-flying occulter (fuel budget, scattered light etc.), and in addition, enables the use of ground-based telescopes for observations, which drastically reduces the cost and increases the efficiency of such a mission. For distinguishing the concept from similar ones, we provisionally name it CESO – Celestial Exoplanet Survey Occulter.

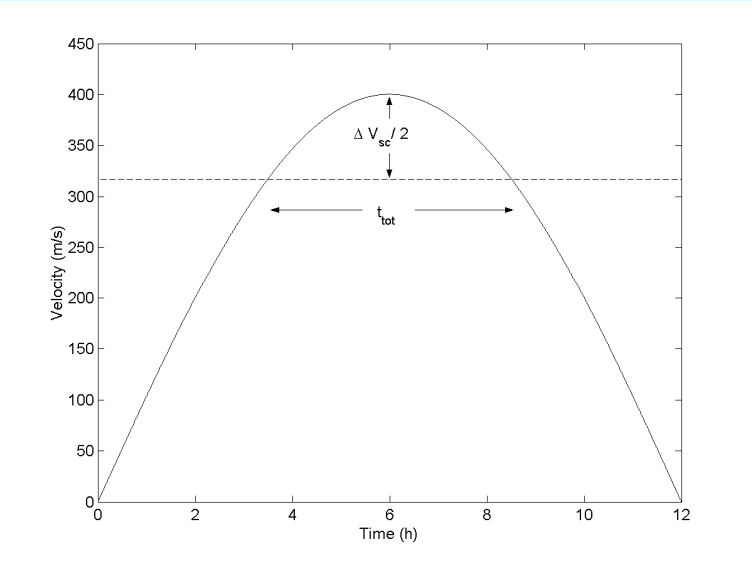

Fig. 1: Example of shadow control. The non-forced projected velocities of the occulter (dashed line) and a ground-based telescope (solid line) are plotted over a range of 12 hours around an observation. In the simplest case, the occulter simply starts to boost when the curves cross, first accelerating to keep up with the pace of the telescope until the point of maximum velocity, then decelerating until it reaches normal velocity, after which it is 'released' from shadow control. Observations can take place between the two crossings. The velocity correction required becomes a small fraction of what would be necessary in standard geometrical setups.

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Geometry

The occulter is placed in an Earth-leading (or -trailing) non-equilibrium orbit, slightly inclined to the ecliptic plane. The orbit is such that the occulter closely follows the celestial equator over the year. By making small velocity changes, the occulter can remain fixed with respect to a star as seen from the telescope during several hours, cover targets that are within +/-5 deg from its position at any point of the year, and make the necessary continuous orbit corrections. The great advantage of the orbit is the fact that it minimizes the necessary fuel consumption: the target-to-target motion is largely covered by the motion of the occulter relative to Earth, and the velocity correction during observations is largely canceled out by the rotation of Earth.

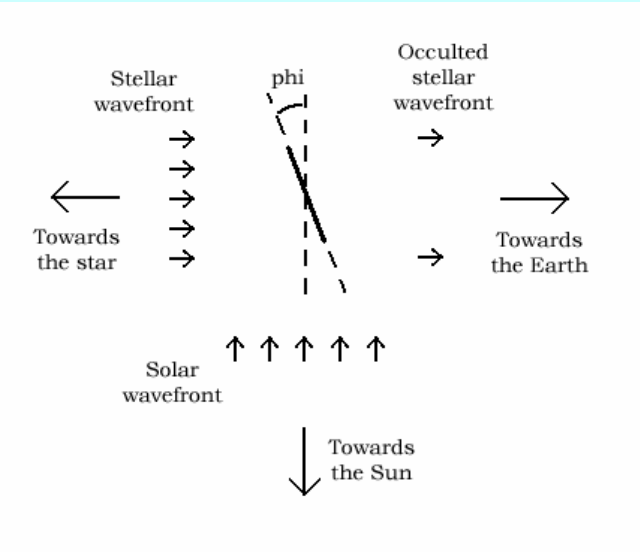

Fig. 2: Geometrical setup for the occulter with respect to the Earth, the sun and a distant star. The occulter receives sunlight on the far side of the occulter, such that it can power its propulsion system, yet not scatter any solar radiation towards Earth.

Propulsion

The large surface of the occulter can be used to generate large amounts (> 10 MW) of power by absorbing solar radiation. With an appropriate geometry, the occulter can provide the power required by MPD thrusters, while not scattering any solar radiation towards Earth. MPD thrusters can generate sufficient thrust for performing all the necessary maneuvers, and the high specific impulse offered means that a large amount of targets can be observed. Taking the full set of necessary corrections into account, it is found that more than 200 targets can be observed twice during more than 2 hours per visit.

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Observing from the ground

Any existing or future telescope on Earth can in principle be used for observing in the occulter shadow, but several parameters (regarding site specifics, telescope size etc.) affect the output is various ways, such that choice of telescope is in part an optimization issue. An AO system must necessarily be part of the instrumentation, though only to resolve planets in a system from each other, such that low Strehl ratios in the visible are sufficient. An IFU instrument with a modest spectral resolution would optimize the efficiency during the limited observation time per target. As an example which fulfills all the requirements, we use the 2nd generation VLT instrument MUSE (Bacon et al., 2006), which is under development. The estimated detection limits of MUSE give us a realistic view of what objects we can expect to detect with CESO.

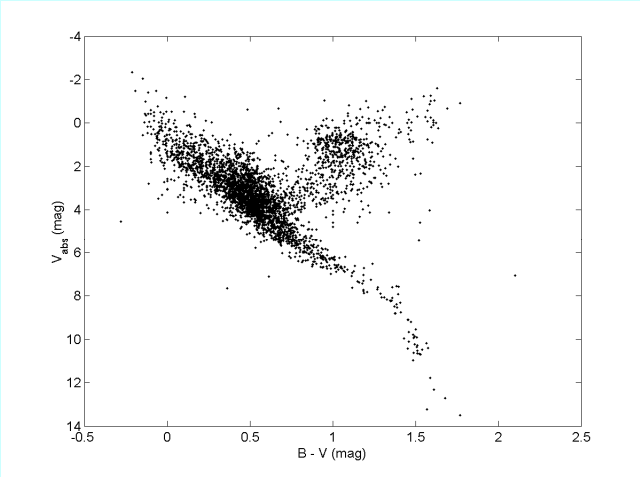

Fig. 3: Color-magnitude diagram of a brightness- and distance-limited HIPPARCOS sample within +/- 5 deg declination.

Targets

Due to the specifics of the orbit, only targets within +/-5 deg declination can be observed. An excellent target list is nonetheless attainable. We show this by selecting a distance-, brightness-, and declination-limited HIPPARCOS sample of more than 3500 stars. Based on the observed properties of each star, we derive a quantity thz for each star, which is the integration time required to detect an Earth-radius and Earth-albedo planet in the habitable zone (loosely defined as half to double the central HZ radius), based on the MUSE detection limits and including the requirement that the angular semi-major axis has to be larger than the IWA of CESO. A rejection of known binaries with inappropriate separations is also applied. Setting the requirement of thz < 2 hours, such that an Earth-like planet in the HZ can be detected in every case (if it exists there), gives more than 200 targets, matching the propulsion capacity of CESO.

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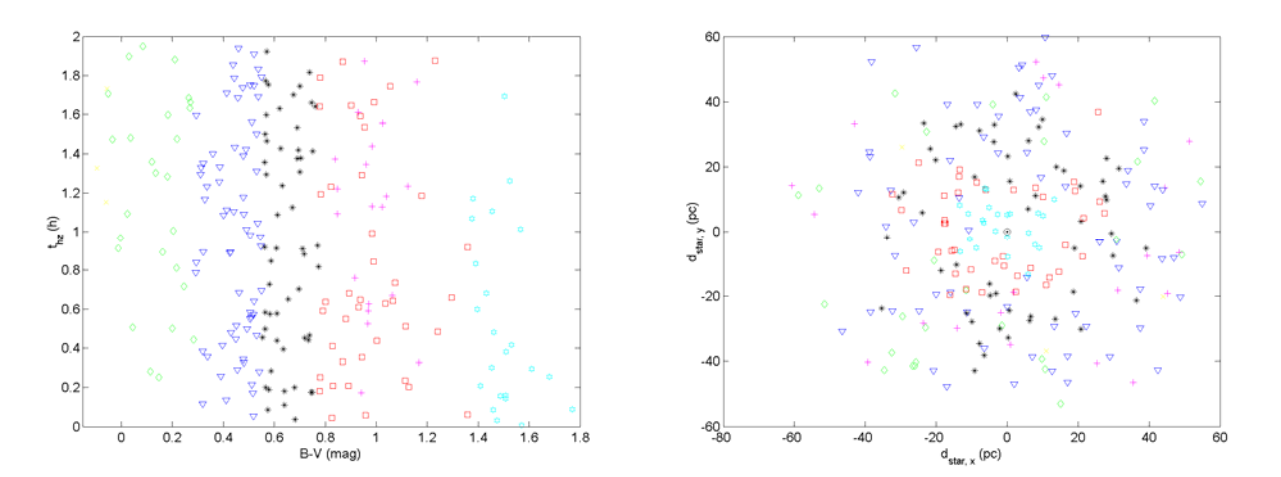

Fig. 4: Left: t_{hz} versus the B-V colors for the stars in our final example sample. The distribution of stars clearly peaks at the late-F/early-G boundary. Right: The distribution of the final sample of stars, projected on the plane of the celestial equator. Since all the stars have a declination of less than ± 5 deg, the plot gives a relevant view of their actual spatial distribution. B-stars are marked with yellow 'x' marks, A-stars with green diamonds, F-stars with blue triangles, G-stars with black stars, K-stars with red boxes, M-stars with cyan hexagrams, and giants with magenta '+' marks.

Conclusion

CESO offers a possibility to directly image Earth equivalents in the habitable zone of a wide range of stars. It is cheaper and more time-efficient than other concepts with similar science goals, and does not require any major technological development. In the upcoming era of exoplanet research, it can serve as a great complement to future missions such as Kepler, GAIA, SIM, and TPF/Darwin.

Questions or comments? I'm around during the workshop, find me or send me a mail at janson@mpia.de. --- Thanks to Webster Cash, Wolfgang Brandner, and Thomas Henning for useful comments and encouragement.