Characterizing Habitable Exoplanets with Interferometry

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1. Observing Habitable Worlds

The in-depth characterization of the physical and chemical properties of terrestrial exoplanets is an important long-term goal of exoplanet research. This will require spectroscopy with sufficient resolving power and SNR at both thermal and scattered wavelengths. A broad spectral coverage from visible to mid-IR is necessary to assess the radiative budget of the planet, which is the key to understanding its climate. In addition, it also enhances the number of observable spectral molecular signatures, making the identification of molecules more robust and minimizing the uncertainty on their abundances. Observations will also have to be spread over several orbital periods, with different sampling frequencies, in order to characterize the signal variability associated with climate, rotation, seasons, phases and variations in the stellar luminosity. Polarimetry combined with visible spectroscopy would also constitute an additional way to derive the atmospheric gaseous/particle content. Techniques to constrain the mass and radius of the planet will not only contribute to understanding the nature of the planets but will also strongly increase the information content of the spectra whose interpretation depends on both the gravity and the radius. The radius, in particular, allows converting observed fluxes into albedos (scattered light) and brightness temperatures (thermal emission). The radii and masses of non-transiting planets can be constrained from spectra, although at reduced accuracy and with reliance on suitable models.

2. Why Mid-Infrared?

With a low-resolution spectrum of the thermal emission, the mean effective temperature and the radius of the planet can be obtained. Furthermore, the mid-infrared spectral region (~6–20µm) contains a number of important spectral features that can be used to diagnose the presence of H_2O, CO_2, and O_3, which serves as a proxy for O_2 (Angel et al. 1986, Léger et al. 1996). Methane also has a strong absorption band in this spectral region, but it would be extremely difficult to detect in an Earth-like atmosphere. In the past, however, before the rise of oxygen, biogenic CH_4 may have been more abundant in the Earth's atmosphere by a factor 100–1000 (Catling et al. 2001); at this level it would also be detectable and serve as an indicator of bacterial life. One cautionary remark is in order, however: the detection and interpretation of infrared absorption bands could be complicated by the presence of cirrus clouds, which tend to reduce the depth of these features (Smith et al. 1993).

3. Mid-Infrared Means Interferometry

An instrument that aims at spatially resolving the planet from its host stars needs to provide sufficient angular resolution, i.e. of order 0.1" for a habitable-zone planet at a distance of 10pc. At visible wavelengths, this corresponds roughly to the resolution limit of a meter-sized telescope; in the thermal infrared an interferometer is needed to keep the unit telescope size reasonable. Working at very high contrast means that the starlight has to be rejected efficiently, and this in turn requires extremely precise control of the wavefront.

A space-based interferometer with starlight rejection capabilities – i.e. nulling (Bracewell 1978, Angel & Woolf 1997) – offers simultaneously the sensitivity, angular resolution and dynamic range needed to isolate and spectroscopically characterize the light of an exo-Earth in the ~6–20µm mid-infrared spectral domain. This technique is able to spatially resolve and discern the faint planetary photons from the 10^6 times brighter stellar flux, as well as from spurious sources like stellar leaks (due to resolved stellar disk), our own local Zodiacal cloud, the exozodiacal light, and the thermal emission produced by the instrument. Luckily, the mid-IR range is also where the otherwise huge flux contrast of the system is reduced.

A 10-year long activity on both sides of the Atlantic to select the optimal array geometry converged to the so-called Emma X-array configuration (Cockell et al. 2009). The baseline concept is an X-shape configuration of four 2-m collectors flying in formation at L2 over a 5-year duration. The beams are combined within an additional centrally positioned spacecraft, where destructive interference cancels out the light from the central star. The long and short baselines of the rectangular configuration are tunable from tens to hundreds of meters in order to uniquely optimize the transmission map of the interferometer to the size of the habitable zone, which directly depends on a given stellar spectral type. In the X-array arrangement, the respective destructive outputs of the two short-baseline Bracewell interferometers are combined with opposite phase shifts (±90°). This results in an internal "phase chopping" process (Mennesson 2005), which efficiently removes the thermal background and any emission from centro-symmetric sources around the nulled star.

The key enabling technologies (formation flying and starlight suppression by nulling) have been advanced substantially in recent years.

4. Conclusions

During the past few years, most efforts to develop mission concepts and technologies for habitable planet characterization have focused on the visible and near-infrared wavelength range, with coronographs and external occulters considered for the technical realization. However, our knowledge will remain incomplete without access to the thermal infrared, where most of the planetary flux is emitted. Nulling interferometry is the natural mission architecture in this wavelength range, driven by basic resolution requirements. Implementing such a mission appears entirely feasible with technologies whose foundations are well-understood and that could be brought to flight readiness within one decade.

5. References

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Short Summary

Invited talk on interferometry