SCIENCE CASE FOR AN INTERFEROMETER IN THE VISIBLE TO CHARACTERIZE EXOPLANETS AND CONSOLIDATE BIOSIGNATURES

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Abstract

The characterization of exoplanets will be rather poor in the thermal infrared. Here we describe the benefits from their detection in visible reflected light at high angular resolution. We give the main characteristics of an interferometer which would be required to achive these science objectives.

Key words: Exoplanets – Biosignatures – Interferometer

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1. Introduction

Exoplanets do constitute a vast territory for exo-life. While in the Solar System there are at most 2 or 3 possible sites for life, from the significant fraction of at least 7/of stars harbouring giant planets, it is reasonable to expect that several tens of habitable Earth-like planets will be detected in the coming decades. In addition, while we already know that there is at best only very primitive or fossilized life in the Solar System, the possibility for (very) evolved (if not "intelligent") life on exoplanets is still open, giving a promising perspective.

One can reasonnably be anticipate that in 2015+ some few Earth mass planets will detected, by radial velocity and astrometry (SIM and GAIA), in the Habitable Zone of K or G stars in the solar neighborhood. The challenge will thus more be to characterize these planets than to find them.

2. The benefits of reflected light

2.1. Characterization of planets

There are two possible approaches, which differ both in their scientific and instrumental aspects: : visible (0.3 - 4 microns) or thermal infrared.

The visible approach offers several benefits:

1. Reflected light.
   At visible wavelengths, where most of the stars emit their light, planets reflect their parent star-light. This reflected light makes possible several aspects of planet characterization::
   - *Atmopsheric composition.*
   Different atmospheric species, H_2O, CO_2, CO, CH_4, NH_3 or sulfuric molecules, have spectral features in the 0.3 - 4 micron range. A special mention must be made for 0_2 (at 760 nm) and the ozone Chapuis bands in the 450 - 600 nm region because of their exobiological significance (as discussed in section 2.2).
   - *Atmospheric density*
   It can be derived, for sufficiently transparent atmospheres, from Rayleigh scattering by molecules in the atmopshere.
   - *Rings of planets*
   A planet being a spherical object, its reflected light flux is modulated along the orbital revolution by a Keplerian phase factor $\phi(t)$, which is, for a circular orbit with a period P and an inlination i, $\phi(t) = 1 - \sin i.\cos(2\pi t/P)$. But if the planet is surrounded by rings, the latter being planar and not spherical, the orbital modulation if the reflected flux is complicated, including mutual ring-planet shadow effects, and depends on the ring inclination. Figure 1 gives an example from Arnold & Schneider 2004
   Rings do not just constitute an entomological curiosity. They have two consequences:
   - The very existence of rings around a planet is an indirect proof of the presence of satellites in the same system, as rings are expected to have a short lifetime and to survive they must be replenished by dust or ice generated by the collision of small bodies. The size and optical thickness (derived from the ring+planet light curve) constrain the density of the ring material, while the orientation gives a direct determination of the orientation the planet, since from dynamical considerations, the rings necessarily lie in the equatorial plane of the planet (or, equivalently, perpendicular to its rotation axis).
   - If rings are present in a system, they can lead to an incorrect determination of the planet radius inferred from its thermal emission, as envisaged by thermal infrared space missions such as Darwin/TPF-I. As described here, the ring and planet contributions cane be separated in the reflected light regime at optical and near-infrared wavelengths.
   - *Surface albedo and color*
   For a planet with a wavelength-dependent albedo $A(\lambda)$, the reflected flux $F_{refl}(\lambda) = A(\lambda){R_{pl}}^2/a^2$ (after sub-

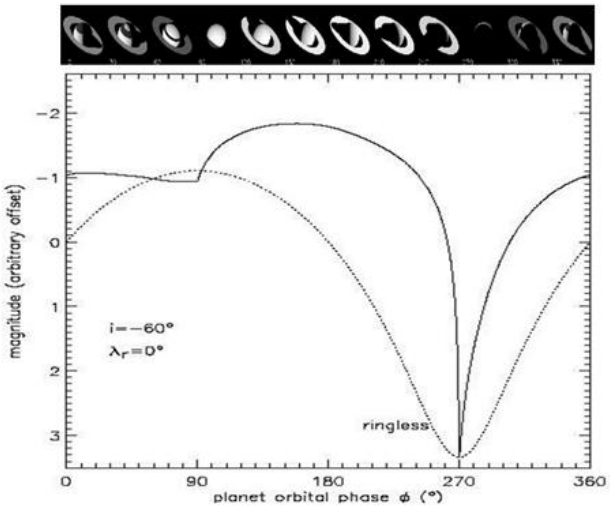

Figure 1. Orbital modulation of the reflected light flux for a planet alone (dashed line) and and a planet+ring (full line) (Arnold & Schneider 2004).

straction of the orbital phase factor) gives only the product $A(\lambda) \times R_{pl}^2$. It is nevertheless possible to discriminate, on the single basis of the reflected flux, between a giant and a telluric planet since it is unlikely that a giant planet can have an albedo suffiently low (~ 0.005) to mimic an Earth-sized planet. The albedo color gives access to the contribution of soils since most of the rocks have an increasing reflexivity toward the red.

- *Surface morphology*

The albedo of snow, rocks and liquid water is respectively about 95%, 45% and 6%. Therefore, if these materials are distributed in an heterogeneous manner on the planet surface ("continents" and "oceans"), the planet rotation will modulate the reflected light flux. It will thus be possible to derive from the diurnal lightcurve monitoring the duration of the planet day (given by the modulation period) and the size of oceans and continents. An annual modulation of the color and normalized value of the albedo (after substraction of Keplerian phase) gives access to seasonal effects.

2. High angular resolution.

The latter of course results from the shorter wavelength than for thermal infrared emission. It has several benefits (listed in order of increasing resolution):

- *Detection satellites*

Satellites can be detected without resolving them from the planet by varations in the planet flux due to mutual planet-satellite shadow and eclipse effects.

If in addition the angular resolution is sufficient to resolve the satellite, it will be possible to derive the planet mass from is orbital period and distance to the planet and from the Kepler law. This will be useful for instance for planets at very large orbital distance, but more particularly for low-mass (down to Mars) planets for which radial velocities and astrometry fail.

Another outcome from resolving a planet-satellite (or binary planet (Schneider 2005)) system is the determination of the planet size (or albedo) and mass. Indeed if a planet is binary, one infers from the unresolved system with a given flux a wrong albedo for a given radius (or equivalently a wrong radius for a given albedo: for instance for two components with the same radius and albedo the global flux of the unresolved system is $2A(\lambda) \times R_{pl}^2$, leading (for a given albedo) to an effective radius $R_{eff} = \sqrt{2}R_{pl}$ or to (for a given radius) to an effective albedo $2A(\lambda$ Similarly the true mass of each compenent is (in case of equal masses) half of the value derived from radial velocity or astrometric measurements.

- *Spectroscopic investigation of transiting planets*

Transiting planets have already provided an investigation of their atmosphere by absorption spectra of the parent star during the transit. This approach is limited by the very small planet atmopshere/star surface ratio. It will be improved by a factor N^2 for a spectral imaging of the transit with a resolution of N pixels on the stelar surface (Schneider 1999).

-*Star-planet interaction*

Magnetized close-in planets ("hot Jupiters") can induce active spots on the stellar surface. These planet-induced spots lead to an activity modulation with a period identical to the planet orbital period, while the modulation by normal spot are in phase with the stellar rotation. This phenomenon has been observed spectroscopically for the planet HD 179949 b (Shkolnik et-al 2003. An interesting aspect is the relative geometry of the planet location on its orbit and the location (latitude and longitude) of the planet-induced spot. All these phenomena can be investigated in detail with a stellar surface imaging.

- *Cartography of the closest planets*

Ultimately, the benefit of very high angular reolution will be to provide a cartography of the planet surface ("oceans", "continents" and even "forests"). Of course this will be possible only for planets for which the cloud coverage is not dominant. Maping the planet will be important to consolidate and investigate the surface, vegetation-like, biosignatures for instance by the seasonal variations of "forests".

2.2. BIOSIGNATURES

The first steps of the search for Life on exoplanets will rely on spectral biosignatures. Other approaches like polarimetry are at present unclear. One can see two types of spectral biosignatures:

- *Atmospheric*

They are inorganic molecules produced by bio-chemical processes and rejected into the atmosphere. These are for instance O_2 (and its by-product O_3), CH_4 and possibly sulfuric molecules. On Earth, the only significant source of O_2 is photosynthesis (for which molecular oxygene is a by-product). If this circumstance would be the case on an habitable exoplanet, oxygen would be a promising indication of some kind of bio-chemical photodissociation of water.

- *Surface*

These are spectral characteristics of the biological material iteslf, *e.g.* "vegetation". On Earth, vegetation has a universal and very characteristic spectral shoulder at 725 nm in the reflectance spectrum (the "red edge" VRE). It is a consequence of the fact that the stellar light below 725 nm is absorbed by vegetation and is converted into bio-chemical energy. The detectability of the VRE in the global Earth spectrum, as if Earth were detected from infinity, has been demonstrated observtaionally from the Earthshine spectrum (Arnold et-al 2002).

On an habitable exoplanet, there is no reason why such an biological capture of light should lead to an VRE at exactly 725 nm, but, whatever the bio-chemical details, there must be some broad absorption feature due to a biological capture of light. It is an empirical fact that such features are very rare in minerals. This approach is complementary to the atmospheric dejecta biosignatures approach in the sense that it gives some hints on the biological mechanisms at work: if the VRE is not at 725 nm, photosynthesis on the concerned exoplanet cannot be due to the chlorophyll molecule.

In both cases, another important molecule is water insofar one accepts that water is essential for life.

We will not open here a general discussion of questions and problems raised by these approaches (importance of plate tectonics, possible confusion between ozone and rare silicates at low spectral resolution etc). Owing to the philosophical importance of this issue, we will only point out that oxygen and ozone biosignatures can perhaps be mimicked by abiotic reactions. Advocators of these biosignatures generally argue (correctly) that there is apparently no atmoepheric photochemistry that can account for a large amount of oxygen and ozone in presence of water (*e.g.* Selsis 2002). But one should not forget the possibility of oxygen-producing reactions provided by catalytic surface chemistry. It is therefore essential to consolidate the two types of biosignature, atmospheric gases and surfacic "vegetation", by each other.

3. CHARACTERISTICS OF A VISIBLE INTERFEROMETER

The three main characteristics of the interferometre architecture are the baseline, the number of pupils and the size of apertures. The physics of the planet characterization imposes the wavelength range.

- *Baseline B*

The baseline is imposed by the angular resolution. To resolve a planet-satellite analog to the Earth-Moon or Jupiter-Io system at 10 pc, an angular resolution of 0.2 mas is needed, corresponding to a baseline of 1 km at 1 micron. To make a 10×10 pixel image of a stellar surface (for the imaging of transits and of planet-induced spots) at 10 pc, a 5 km interferometer is required at 500 nm. To make the 10×10 pixel cartography at 500 nm of an Earth-like planet at 5 pc, a 250 km interferometer will be necessary. The example of the LISA project shows that the limitations will come more from beam divergence than from metrology and spacecraft control.

Rapid pointing can be made by translating the focal recombiner. Slow pointing is made by rotationg the interferometer. Short stroke delay lines compensate for high frequency OPD variations (piston).

- *Number of pupils*

The examples of science objectives discussed abov point toward a snapshot imaging capability of the interferometer. It would require an hyptertelescope (Labeyrie 1996), an Interferometric Remapped Array Nuller (IRAN) (Vakili et-al 2004) or a "pupil replication"-like configuration (Greenaway 2005, Riaud et-al 2005). A sufficient snapshot imaging capability requires at least 6 and preferably 37 apertures (Riaud et-al 2002).

An interferometer with a large number of apertures can be implemented in successive steps with increasing capabilities and science objectives as the number of apertures increases. The baseline can also be flexible and adaptable to different targets (*e.g.* for surface imaging of stars with different brightness and angular diameter).

- *Total area and aperture size*

Neglecting here speckle noise, the size of aperture is driven by the photon noise of the targets. The high star-to-planet contrast (6.10^9 for an Earth-like planet with an albedo of 0.3 at 1 AU of a star) imposes a coronagraphic attenuation of the star light. The condition for detectability with an SNR of $k\sigma$ is that the planet signal is k times the residual star light (after attenuation) at the planet location.

If the objective is to detect an Earth at $3\lambda/D$ from the star in 10 h with a SNR = 7 in a 10 nm spectral band near a V = 5 star, the required total collecting area is (for an end-to-end efficiency of 0.1 and a global starlight attenuation factor of 10^4) 20 m^2, equivalent to area of the TPF-C project. For 6 apertures, their diameter must be 1.8 m.

For the 10×10 pixel cartography of an Earth, the total collecting area under the same conditions must be 2000 m^2. For 37 apertures, their diameter must be 7.4 m. For an interferometer with 12 apertures of 7.4 m, the same 10×10 pixel cartography would require, under the same conditions, an exposure time of 100 h. One can anticipate that the number of promising targets (for instance Earths with potential biosignatures) will be small. Long exposure times (up to weeks) will not be prohibiting. A total exposure time of 100 h is presumably larger than the planet rotation period. To investigate the planet rotation and surface morphology as discused in section 2.1, it will be neccessary to fragmentate the total exposure into 1 h sub-exposures.

Note that for stellar surface imaging of planetary transits and planet-induced spots, no coronagraphy is required and a moderate collecting area (a few meter square) is sufficient.

- *Vawelength range*

The vawelength range should start at 300 nm (to allow possibly for oxygen band in the UV) and extend up tu 4 - 5 micron where the thermal emission becomes dominant. Note that this wavelength range is difficult to reach from the ground since adaptive optics is limited to the near infrared.

4. ADDITIONAL SCIENCE

An interterometer like this would have many astronomical applications. For instance, a 1 km baseline at 1 micron can map the Galactic center with a resolution of 0.8 AU. It can map a quasar, and in particular resolve multiple images of lensed quasars, or galactic nuclei at 1 Gpc, with a 1 pc resolution. A 50×50 pixel stellar surface imaging, for general stellar physics purposes, can be made at 0.5 micron for the nearest stars at 1 pc. Among the many surroundings of stars (disks etc), let us mention the neighborhood of optical pulsars. With a high speed camera (frequency of 100 Hz), one can investigate the reflection of the rotating pulse on the environment with a resolution of $3R_{\odot}$.

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