High Angular Resolution and Extrasolar Planets: Beyond Basic Instrumental Performances

Jean Schneider CNRS - Paris Observatory, 92195 Meudon, France – Jean.Schneider@obspm.fr

Abstract
I review the characteristics of planetary systems accessible to imaging. I show that, beyond the basic angular resolution and dynamics performances of an optical “architecture”, other performances such as photometric precision, spectral range or timing are necessary to access some physical characteristics of the planets.

1 Introduction
The main problem faced by the imaging of planetary systems is to separate the planets from their parent star. This requires two equally important capabilities: a sufficient angular resolution to separate the planet from the star and a method of suppression of stellar light to fight the very high star to planet contrast (of the order of $10^6$ to $10^9$). But many characteristics of the planetary system require other capabilities and the present paper is intended to point out that the traditional couple “High angular resolution and contrast” is not the final response to all the scientific questions.
2 Characteristics of planets accessible to imaging

**Mass:** The most traditional quantity accessible beyond radial velocity measurements is the planet mass. The latter is measurable by astrometry. The astrometric precision forbids to measure mass below a few Earth masses. Another way to measure planet masses, with a much higher precision and down to fractions of Mars masses is to detect satellites of light planets and to infer the mass from the satellites revolution period and distance to the planet from Kepler laws (Schneider and Riaud 2001).

**Radius** $R_{pl}:$ It can in principle be deduced from the planet thermal flux $(F_{pl})_{th}$ given by

$$ (F_{pl})_{th} = 4\pi\sigma R_{pl}^2 \times T_{pl}^4 $$

The planet temperature $T_{pl}$ can be inferred from the matching of a Planckian function to the observed thermal spectrum (forgetting here complications due to absorption features).

**Albedo** $A:$ It can be measured from the reflected flux $(F_{pl})_{refl}$ given by

$$ (F_{pl})_{refl}(t) = F_* \times A \times \left(\frac{R_{pl}}{2a}\right)^2 \times \phi(t) $$

where $\phi(t)$ is an orbital phase factor. For a circular orbit with an “annual” period $P$, it is given by

$$ \phi(t) = (1 - \sin i \sin(2\pi t/P))/2 $$

The measurement of the albedo (generally in the visible) thus requires the measurement of the thermal flux (generally in the mid-infrared region).

But this scheme faces some complications which are *a priori* not exceptional. Indeed, formulae (2.1) to (2.3) are valid only for spherical bodies. There are at least two situations for which a planetary companion cannot be identified to a single spherical body: planetary rings and “binary planets”.

**Rings:** In that case:

1. part of the planet can be hidden by the ring (and vice versa)
2. The ring being not spherical, for half of the orbit the observer sees its back side which is not illuminated by the star and thus completely dark (Schneider 1999 [5]). The planet + ring total flux can then have an orbital
dependence completely different from (2.3), even in case of circular orbit. The solution is then to measure $\phi(t)$ along the orbit. That requires the capability to revisit the target several times (more then 10 along the orbit).

**Binary planets:** By “binary planet” I mean a planet with a large satellite companion which can eventually be as large as the planet itself. In the Solar System we do not know such binary planets. But since binary asteroids and brown dwarfs have been discovered these last years, it is not an unrealistic speculation that binary planets may exist in other planetary systems. They would not constitute just a curiosity, their existence would disturb the planet mass function deduced from dynamical (radial velocity, astrometric and timing) measurements.

How the separate a single from a binary planet? Even if the binary planet cannot be resolved, a straightforward way is to measure the position variations of the binary planet photocenter. Its amplitude $(\Delta x)_{ph}$ along a binary orbital period (“month”) is given by

$$\Delta x_{ph} = \frac{|F_1 a_1 - F_2 a_2|}{F_1 + F_2}$$

where $F_1,2$ and $a_1,2$ are the flux and the distance to the center of mass of the binary planet for each component. For the reflected stellar light and the thermal emission of the planets (assuming a rotation rate for each component sufficiently large to ensure a uniform temperature), $(\Delta x)_{ph}$ is of the order of 1 to $10 \times 10^{-3}$ AU (0.1 to 1 mas at 10 pc). A special mention must be made for tidally locked satellites. For that configuration, the satellite has, at any time, a cold and a warm face. In addition to the photocenter motion, there is a variation in the thermal flux as seen by the observer along the annual orbit (Woolf 2001). The corresponding annual variation of the effective temperature of the binary planet given by

$$T_{eff} = (1 + (R_1/R_2)^2)[T_{min}^4(1 + \cos \alpha)/2 + T_{max}^4(1 - \cos \alpha)/2]^{1/4}$$

where $\alpha$ is the angle between the line of sight and the star to planet direction. The induced monthly photocenter motion has an amplitude

$$\Delta x_{ph} = 2(a_1 + a_2) \frac{(M_1 T_1^4 R_1^2 - M_2 T_2^4 R_2^2)}{(M_1 + M_2)(T_1^4 R_1^2 + T_2^4 R_2^2)}$$

For instance, for an Earth with a large moon (half the Earth size), the photocenter amplitude is $3.3 \times 10^{-3}$ UA (= 0.3 mas 10 pc).
Variations of the planet temperature and albedo:

Annual: It can be due to the eccentricity of the orbit or to the inclination of the planet rotation axis with respect to the normal to the orbital plane (seasonal variation). For an orbit with an eccentricity $e$, one simply has $\Delta T/T = e$. In that case, the star to planet distance projected on the sky varies by an amount $2ea \sin \alpha$ ($= 0.1a$ in case of an eccentricity 0.1 and $\alpha = 30^\circ$) between two positions of extreme temperature variation.

Diurnal: The combination of the existence of surface albedo inhomegeneities (continents and oceans) with the diurnal rotation of the planet causes a periodic variation of its reflected flux. The period of this variation gives the duration of the day and its amplitude gives constraints on the surface features. For instance, on Earth, the albedo contrast continents/oceans is 200 to 300 %, giving rise to a relative flux variation of a few tenths for the whole planet.

Random: It is due to planet clouds or dust storms. On Earth, the global cloud coverage varies from 30% to 50%. For a mean surface albedo of 20% and a cloud albedo of 80%, the resulting random global albedo variation has an amplitude of 10-20%.

Some of these effects have been estimated quantitatively in the case of the Earth (Ford, Turner and Seager 2001). Nevertheless, it must be remarked that they will be difficult to disentangle from other effects (such as eccentric orbits or binary planets or planetary rings) without additional information on the planet position.

It is important to point out that several conditions must be fulfilled in order to make these effects measurable:

1. The angular resolution must be sufficient (a fraction of mas)
2. In order to detect both reflected light and thermal emission, both visible and mid infrared spectral domain must be accessible
3. The photometric precision must be sufficient to detect temperature variations (of the order of at most a few percent)
4. It must be possible to make separate exposures shorter than a planet rotation period at any time along the orbit. This excludes inertial scanning modes of the celestial sphere.
3 Conclusion: constraints on future space mission “architectures”

Imaging is scientifically more productive for optical architectures having, in addition to obvious angular resolution (large baseline) and stellar light rejection power

- Sufficiently flexible pointing capabilities
- Sufficient photometric precision
- Adequate spectral domain

Architectures fulfilling these conditions are feasible. For instance the “hypertelescope” concept (Labeyrie 1996) is now under study in the framework of the Terrestrial Planet Finder project (Ridgway 2000).

References

[1] Des Marais D., Harwit M., Jucks K., Kasting J., Lunine J., Lin D., Seager S., Schneider J., Traub W. and Woolf N., 2002, Biosignatures and Planetary Properties to be Investigated by the TPF Mission. JPL Publication 01-008

[2] Ford E., Seager S. and Turner E. 2001, Characterization of extrasolar terrestrial planets from diurnal photometric variability. Nature, 412, 885

[3] Labeyrie A., 1996, Resolved imaging of extra-solar planets with future 10-100km optical interferometric arrays. Astron. and Astrophys. Suppl., 118, 517

[4] Ridgway S. et al. 2001, Terrestrial Planet Finder: Architectures and Search Strategy. BAAS 32, No 4., 70.03

[5] Schneider J. 1999, The study of extrasolar planets: methods of detection, first discoveries and future perspectives. C.R. Acad. Sci. Paris, 327, Serie II b, 621

[6] Schneider J. and Riaud P., 2002, submitted
[7] Woolf, N. 2001 private communication; see also Des Marais et al 2002