Characterising Extrasolar Planets in Reflected Light and Thermal Emission

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Abstract
The physical bases of the detection and characterisation of extrasolar planets in the reflected light and thermal emission regimes are reviewed. They both have their advantages and disadvantages, including artefacts, in the determination of planet physical parameters (mass, size, albedo, surface and atmospheric conditions etc. A special attention is paid for Earth-like planets and new perspectives for these different aspects are also presented.

1 Introduction
The first discoveries of extrasolar planets have triggered a renewal of the permanent question on the possible presence of life outside the Solar System. This question can now be addressed in scientific terms. Before detecting life on exoplanets, it is necessary to detect and characterize these planets. I do here focus on the reflected light and thermal emission approaches of the direct imaging of planets.

2 Detection of exoplanets by imaging
Although the most difficult, it is the most promising method for the characterization of planets. I will therefore remind its essential aspects. There are two kinds of emissions by a planet:

1. Reflected light:
The planet reflects the stellar light with a flux ratio given by

$$\frac{F_{\text{refl}}(t)}{F_*} = \frac{A_{pl}}{4} \times \left(\frac{R_{pl}}{a}\right)^2 \times \phi(t) \quad (1)$$

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where $\phi(P, i, e, \omega, t)$ is an orbital phase factor (sinusoidal in case of a circular orbit) and $A_{pl}$ the planet albedo. This ratio peaks at the same visible spectral range than the star itself and is typically $10^{-9} - 10^{-10}$.

2. Thermal emission:

The planet, heated by the star at a temperature $T_{pl} = T_\ast \times (R_\ast/2a)^{1/2}(1 - A_{pl})^{1/4}$, emits a thermal flux given by

$$\frac{F_{th}}{F_\ast} = \left(\frac{R_{pl}}{2a}\right)^2$$

This ratio peaks at the mid-infrared and is typically $10^{-7} - 10^{-7}$, i.e. about $10^3$ larger than in the visible range. There is no orbital phase factor here.

Note that the above formulae do not hold for non spherical objects, i.e. planets with large Moons and planets with rings.

3. Application of imaging to the characterization of exoplanets

Let us look with more details into the planet characteristics accessible by imaging.

1. Orbit:

If an object is detected close to the star, one wants to determine its orbit. Two orbital positions, together with the observation epochs, i.e. 6 observables $t_1$, $t_2$, $x(t_1)$, $x(t_2)$, $y(t_1)$, $x(t_2)$, are in principle sufficient to determine the 6 orbital parameters $a$, $i$, $\omega$, $\Omega$, $T_0$ and $e$. But one has to verify that the object is not a close background star. This requires a third position measurement $(x(t_3)$, $y(t_3))$ at a third epoch $t_3$.

This minimum number at least holds for the thermal emission which is independent from the orbital phase. For the reflected flux, one can take advantage of the phase dependence given by (1) to reduce this number to 2 orbital positions to deduce the orbit parameters. In that case it would indeed by unlikely that a background star had, by coincidence, a flux variation precisely given by (1). This reduction from 3 to 2 of the number of observations of a star required to assess the existence of a planet is important for missions scenarii and represents a significant advantage of observations in the visible.

2. Mass:

In principle it can be determined only from the dynamical perturbation of the star’s motion by the planet. Nevertheless, from a low spectral resolution spectrum ($R=5$) in the visible, one can infer whether there is a high, medium
or low density atmosphere. From the latter, one can deduce, up to a factor 2-5 (Brown et al 2002), the mass of the planet (low mass planets do not retain their atmosphere, while high mass planets retain thick atmospheres). The thermal infrared is not suited for this type of studies.

3. **Radius:**

From formula (1) and from the fact that the albedo has an upper limit of 1, the visible flux gives an lower limit for the planet radius; unless a giant planet would have an albedo of 1%, it cannot be confused with an Earth-sized planet. The thermal emission gives, thanks to the formula (2) a safer value for the radius (unless the planet is surrounded by Moons (DesMarais et al 2001) or by rings (Schneider 1999).

4. **Temperature:**

For reflected light, it can be inferred from the star-planet distance and from the albedo through the relation $T_{pl} = T_* \times (R_*/2a)^{1/2}(1 - A_{pl})^{1/4}$. But then one has in principle to know the planet albedo. Nevertheless, the latter formula shows that the temperature is not very sensitive to the albedo: a variation of $A_{pl}$ from 0.3 to 0.7 gives an decrease of 20% for $T_{pl}$. Here again, the thermal infrared gives a direct (and independent) measurement of $T_{pl}$, safer than from the reflected flux.

5. **Albedo colour $A(\lambda)$:**

The albedo can only be given by the reflected flux. But, as seen on formula (1), only the product $A_{pl} \times R_{pl}^2$ can be directly measured. Nevertheless, the measurement at different wavelengths gives the albedo colour, regardless of its absolute value. By itself this already constitutes a precious indication on the nature of the planet surface, as shown by Brown et al. (2002).

7. **Environment:**

- **Atmosphere:**

As already mentioned, the albedo colour gives the amount of Rayleigh scattering, and thus the density of the atmosphere (Brown et al. 2002).

- **Clouds:**

The most natural explanation of chaotic variations of the albedo would be a variable cloud coverage. Let us note that a similar chaotic variation can also be due to dust storms, like on Mars. In this case, the confusion with clouds can be removed by the colour characteristics of the albedo fluctuations: clouds have a white albedo, while dust is red.

- **Rings:**

Their existence would be inferred from a non Keplarian variation of the phase factor $\phi(t)$. Indeed, its standard mathematical expression ($\phi(t) = (1 - \sin i \sin(2\pi t/P))/2$ in case of circular orbits) holds only
for spherical bodies. In presence of rings, for half of the orbit, the observer sees only their backside, which is black, giving to \( \phi(t) \) a more complicated expression depending on the detailed configuration of the rings (Schneider 1999). This case is not an exception, as shown by the Solar System planets; it is quantitatively not negligeable since for instance the reflected solar flux from Saturn rings is as large as the planet reflected flux itself.

- **Moons**:
  
  They will most likely be first detected by the transit method (Sartoretti and Schneider 1999). For the coming generation of imaging space missions (e.g. Darwin/TPF), the angular resolution will not be sufficient to separate them angularly from their parent planet. It will nevertheless be possible to detect them by a photometric monitoring of the planet:
  
  a) **Planet-satellite mutual transits** (Schneider 2003). A planet brightness drop with an amplitude \( (R_{sat}/R_{pl})^2 \) should appear with a period half the satellite revolution period. The geometric probability of this event nevertheless does not exceed \( \approx 10\% \). The event is detectable in both reflected and thermal emission regimes.
  
  b) **Planet-satellite mutual shadows** (Schneider 2003). It is most likely that the satellite orbits lies close the planet orbital plane. In that case, the satellite throws, once per orbit, a shadow on the illuminated part of the planet and, once per orbit, disappears in the planet shadow. An interesting feature of this event is that the satellite+planet flux drop has a very characteristic shape. In case of a satellite orbit lying exactly in the planet orbital plane, this shape is, for \( \phi = \pi/2 \), \( \Delta F_{pl}/F_{pl}(\phi_{sat}) = \tan \phi_{sat} \), varying from 0 (when the satellite orbital phase \( \phi_{sat} = 0 \)) up to a maximum \( (R_{sat}/R_{pl})^{3/2}/\sqrt{2} \) which is larger by a factor \( \sqrt{R_{pl}/(2R_{sat})} \) than the drop due to mutual transits. For satellite orbits not lying exactly in the planet orbital plane, the evolution of the function \( \Delta F_{pl}(\phi_{sat})/F_{pl} \) along the planet orbital revolution gives the two angular parameters characterizing the relative inclination of the planet and satellite orbital planes. In addition to being larger than mutual transits, mutual shadows have a geometric probability close to 1. This event can be seen only for reflected light, i.e. in the visible.

8. Surface properties:

- **Structures**:

  The formula (1) only gives the product \( A_{pl} \times R_{pl}^2 \). It thus does not enable to give the absolute value of the planet albedo. But from the
time variation of $F_{refl}(t)$ one can, after correction of orbital effects, deduce the time variation $A_{pl}(t)$ of the albedo (since the planet radius is constant). A short term (hours to days) periodic variation would reveal the presence of surface inhomogeneities of the albedo by the modulation of $F_{refl}(t)$ due to the planet rotation. The period of the modulation gives the duration of the planet day, its amplitude gives the albedo contrast between different parts of the planet surface (“continents”) and the shape of the modulation gives the spatial extension of “continents” (Schneider 1999, Ford, Seager and Turner 2001). In principle the modulation of the thermal emission by oceans and continents could also be detected during the diurnal planet rotation. But, while the continent/ocean contrast is about a factor 5 in reflected light, it is only $4|T_{ocean} − T_{cont.}|/T_{mean} ≈ 10\%$ for thermal emission.

- **Internal heat vs/ stellar heating:**
  Depending on the orbital phase, the observer sees the illuminated side or dark side of the planet. There may exist a temperature contrast $\Delta T_{pl} = T_{pl,day} − T_{pl,night}$ between these two sides. Along the orbital revolution it will provide an annual modulation of the effective planet temperature $T_{pl,eff}(t) \approx (T_{pl,day}^4(1 − \sin i \cos(2\pi t/P))/2 + T_{pl,night}^4(1 − \sin i \sin(2\pi t/P))/2)^{1/4}$ (for $e = 0$). A low $\Delta T_{pl}$ would mean a high atmospheric or oceanic circulation, while a high $\Delta T_{pl}$ would mean a low lithospheric heat conductivity. For instance, for the Earth the day/night temperature difference is about 10 K leading to a relative thermal flux variation $4(T_{pl,day} − T_{pl,night})/T_{mean} \approx 10\%$. For the Moon and Mars the temperature difference is $\approx 100$ K, giving a relative flux variation of a factor 2. The contrast $\Delta T_{pl}$ can be due to several factors: surface (lithospheric and oceanic) thermal conductivity, oceanic and atmospheric circulation, and depends on the planet rotation rate. An additional source of thermal emission can be purely internal, due to tectonic activity and to rocks radioactivity. It could in principle produce a temperature in excess of the equilibrium temperature $T_{pl} = T_e \times (R_e/2a)^{1/2}(1 − A_{pl})^{1/4}$. But the example of the Earth, for which the the tectonic and the radiogenic heat flow is only $100$ mW/m², compared to the $\approx 1$ kW/m² heat flow produced by stellar heating, shows that this effect can be appreciable only for planets far away from their star, where the stellar heating is small. That is e.g. the case of Io where the thermal heating causes about 12 one day volcanic outbursts per year doubling the total 5 micron flux (Spencer and Schneider 1996). Together with the planet radius, mass (and thus the density), age, albedo, the measurement of the effective tempera-
ture and its modulation will provide precious constraints on the planet atmospheric, surfacic and internal structure. Of course, this measurement is possible only in the infrared regime.

9. Life?
A traditional prerequisite is the presence of liquid water, imposing a planet temperature of about 300 K. The planet must therefore lie in the “habitable zone”, i.e. at a distance of \( \approx \left( \frac{T_e}{T_\odot} \right)^2 \left( \frac{R_e}{R_\odot} \right) \) AU from the star (\( \approx \) from 0.1 to 1.5 AU, for M to F stars).

The detection of signatures of Life (“biosignatures”) makes use of two approaches:

- **“Dejecta”:**
  These are by-products of biological activity on the planet. The latter are mainly atmospheric gases such as \( \mathrm{O}_2 \) (and its by-product \( \mathrm{O}_3 \)), \( \mathrm{CH}_4 \).
  The key argument here is that on Earth all the molecular oxygen content of the atmosphere (20%) comes from the photosynthetic activity of vegetation and bacteria. This argument is enforced by the fact that on Mars and Venus there is no oxygen or ozone. Since the main source of carbon for organics is the atmospheric \( \mathrm{CO}_2 \), the latter must also be present in the planet atmosphere. The detection of \( \mathrm{O}_2 \) is a priority in the sense that it gives an access to the degree of biological evolution on the planet (DesMarais et al. 2001, 2002). \( \mathrm{O}_2 \) is detectable only in the visible, all the other gases are detectable in both visible and infrared regimes (DesMarais et al. 2002).

- **“Vegetation”:**
  Whatever the detailed photosynthetic mechanisms are, they must subtract energy from some part of the stellar spectrum reflected by the planet, leading to absorption features in this spectrum. This mechanism is responsible for the “red edge” at 750 nm in the terrestrial vegetation spectrum. The latter has been observed globally, for the first time, for the whole Earth seen as an unresolved source in the Earthsine spectrum (Arnold et al. 2002). The shape of this spectral feature gives some indication on the energy conversion mechanism, but the possible confusion with mineral absorption features has to be investigated further. It cannot be a safe biosignature by itself, it is useful only in association with other ones.

The Table 1 summarizes the best wavelength regime for different planet characteristics.

| Table 1 |
| Parameter          | Visible | Infrared |
|-------------------|---------|----------|
| Radius            |         | yes      |
| Mass              | yes     |          |
| Temperature       | yes     | yes      |
| Albedo            | yes     |          |
| Day               | yes     |          |
| Seasons           | yes     | yes      |
| Clouds            | yes     |          |
| Rings             | yes     |          |
| Moons             |         | yes      |
| $O_2$             | yes     |          |
| $O_3$, CH$_4$, CO$_2$, H$_2$O | yes | yes |
| Vegetation        | yes     |          |
| Intern. heat      |         | yes      |

It seems that more science can be done with reflected light observations, but it cannot do all of it and thermal infrared regime will provide important complements.

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