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SEE-COAST: THE SUPER-EARTH EXPLORER

J. Schneider[1], P. Riaud[2, 3], G. Tinetti[4], H.M. Schmid[5], D. Stam[6], S. Udry[7], P. Baudoz [2], A. Boccaletti[2], O. Grasset[8], D. Mawet[3], J. Surdej[3] and the SEE-COAST Team

Abstract. The Super-Earth Explorer Coronagraphic Off Axis Space Telescope (SEE-COAST) is a space mission concept to be submitted to ESA call for proposals. It is devoted to the direct imaging, in the visible, of the stellar light reflected by its planetary companion. Here we present the type of planetary characterization we may accomplish with SEE-COAST, and we include a brief description of the spacecraft and mission strategy.

1 Scientific objectives

The main objective of the Super-Earth Explorer Coronagraphic Off Axis Space Telescope (SEE-COAST) is the characterization of a selected ensemble of exoplanets previously discovered by radial velocity and astrometric surveys. The project will be submitted to ESA call for proposals for small size missions to be launched in 2016.

Several questions can be raised about exoplanets' properties, some of them can be addressed by the detection of the stellar light reflected by the planet or of the thermal photons emitted by the planet. Both approaches are valid and may provide a complementary information. Of course, all questions may not be answered by a single mission. For some aspects we will have to wait for the second generation missions.

The planetary properties we are interested in observing and constraining are: the size (mass and radius), the atmosphere (chemical composition, clouds, seasonal variations, thermal inertia), the surface (type -rocks, ice, water, "vegetation"-, inhomogeneities), rotation (period, atmospheric dynamics) and environment (rings). Reflected light and/or thermal emission may be used to study these planetary characteristics. The former approach relies on the information that can be extracted from the stellar light reflected by the planet as a function of different parameters: wavelength λ, polarization $\vec{P}$, time t. The planetary reflected flux can be written as:

$$F_{pl}(\lambda, t, \vec{P}) = \frac{A(\lambda, t, \vec{P})F_*(\lambda, t)}{4}\left(\frac{R_{pl}}{r(t)}\right)^2 \times (1 - \sin i \cdot \phi(t)) \tag{1.1}$$

where A is the planetary albedo, $r(t)$ the distance to the star (constant in the case of circular orbits), i the inclination of the orbit and ϕ a phase function for the keplerian motion of the planet. The order of magnitude of the star-planet flux ratio can be estimated as:

$$F_{pl} = 6 \times 10^{-8} A \left(\frac{R_{pl}}{R_{Jup}}\right)^2 \left(\frac{1AU}{r(t)}\right)^2$$

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[1] LUTH - Paris Observatory, 92190 Meudon, France

[2] LESIA - Paris Observatory, 92190 Meudon, France

[3] U. of Liège, Belgium

[4] IAP, 75014 Paris, France

[5] ETH, Zurich, Switzerland)

[6] U. of Amsterdam, Netherland

[7] Geneva Observatory, Switzerland

[8] U. of Nantes, France

and is $\sim 3 \cdot 10^{-8}$ for a Jupiter at 1 AU with albedo $A = 0.5$. This high contrast ratio imposes an efficient stellar light suppression mechanism (see section 2).

The master Eq. 1.1 allows to derive only the product $A \times R_{pl}^2$ from the observed flux at a given time. Nevertheless the information embedded in Eq. 1.1 is very rich and can be used to disentangle the planetary albedo from the radius. The planetary characteristics may be retrieved from the dependence of the planetary flux to each of these parameters: λ (atmospheric composition, Rayleigh scattering, surface albedo, biosignatures) $\vec{P}$ (nature of the surface, Rayleigh scattering by a clear atmosphere) t (seasonal (climate), random (variation in cloud coverage), surface inhomogeneities, planetary rotation period, rings, thermal inertia...). Some of the planetary features, such as the albedo, can be constrained only using the combined information provided by the dependence on λ, $\vec{P}$ and t: a complete planetary characterization needs a 3-D fit of the function to the data. In addition, the cartography of the whole planetary system may give hints on the planet-disk connection. Further details on these topics are given in the next sections.

1.1 Wavelength dependence

A spectral resolution R $\sim$ 40 may provide information on essentially three aspects of the planetary atmosphere: chemical composition, pressure and optical properties:

Atmospheric species:

Table 1 shows the most important species accessible to the reflected light approach.

Table 1 List of the most important molecular species absorbing in the spectral range accessible to SEE-COAST. Successful detection of some of those lines will depend on molecular abundance, S/N obtainable for that particular target and planetary atmosphere's conditions.

Species	Spectral lines (nm)
CH_4	486, 543, 576, 595, 619, 668, 681, 703, 790, 840, 864, 727, 889
CO_2	1.05, 1.25
H_2O	514,575, 610, 650, 730, 830, 940, 1150
NH_3	552, 647, 929
O_3	Chappuis band centered at 602
O_2	626, 688, 762

Rayleigh scattering:

When clouds or aerosols are not present in the atmosphere, the planetary spectrum may show an increased reflectance in the blue due to Rayleigh scattering. Figure 1 shows simulations of the Rayleigh scattering for different atmospheric composition, pressures and surface reflectance properties. In the Solar System, we can observe Rayleigh scattering on six planets: Earth, Titan, Uranus, Neptune, Jupiter and Saturn.

Clouds:

We will observe the planet at different phases during its orbital period. The scattering properties of clouds, when averaged over the visible disk, are very sensitive to phases (Tinetti et al. 2006). This information, combined with the expected effects due to polarization (see sec. 1.3) will help to constrain the cloud coverage and the absolute albedo of the planet.

1.2 Time dependence

The planetary flux may vary on different time scales, for our purposes we are interested in monthly and daily variations. Periodic fluctuations on short time scales are possibly related to the rotation of the planet around its axis and might be detected using surface inhomogeneities and surface reflectance properties (Ford et al. 2001, Tinetti et al. 2006). If clouds do not entirely cover the surface, this method can be used to estimate the rotation period. Note that this modulation contrast and the period do not require the knowledge of the absolute value of the albedo; the ambiguity given by the product $A \times R_{pl}^2$ is not a problem here. Such investigation requires an extensive monitoring of the planet flux which can be limited to a few days or weeks.

Short term random variations may be explained by fluctuations in cloud coverage.

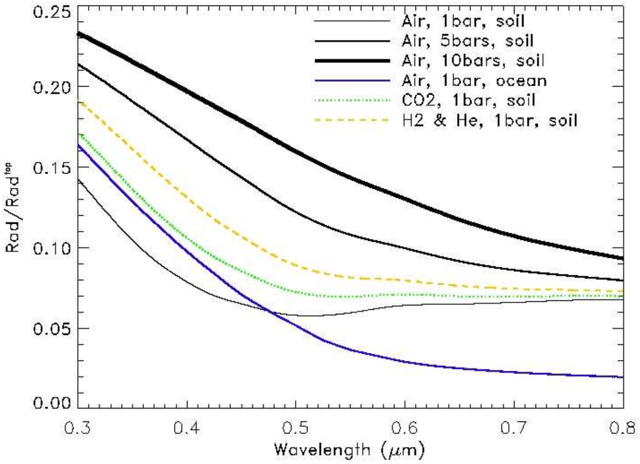

Fig. 1. Rayleigh scattering simulations for different planetary atmospheres.

Long term patterns might be correlated with the orbital motion, and might have different explanations: seasonal variability, due to a combination of tilt and orbital eccentricity effects (e.g. the case of Neptune (Sromovsky et al. 2003)), or effects induced by the planetary rings (Arnold & Schneider 2004).

Eccentric orbits:

Half of the planets detected have eccentricities larger than 0.35. The origin of this large eccentricity is unclear. It may or may not be the case for terrestrial planets. If it is related to the planets' migration and terrestrial planets are not affected by this process, they could have essentially circular orbits. But we must be prepared for this possibility: we expect in this case noticeable oscillations in the planetary temperature as a function of orbital parameters (Sertorio & Tinetti 2002). As a first order approximation, the temperature gradient between the periastron and the apoastron can be estimated (for a relatively small eccentricity e) by $\Delta T = e\,T$. For instance, if $e = 0.35$ and $T = 300$ K, $\Delta T = 100$ K. The effect is thus not negligible. Figure 2 shows the simulated spectrum of a giant planet for two extreme points of the trajectory.

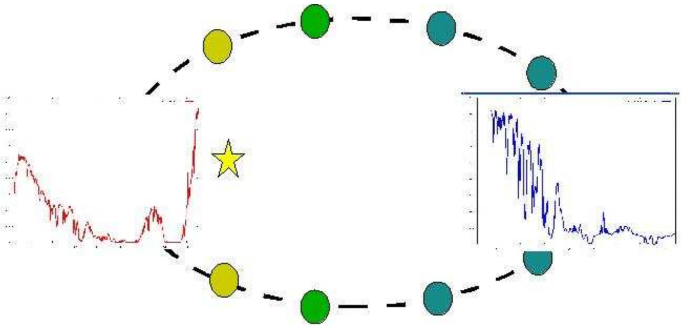

Fig. 2. Evolution of the spectrum of a giant planet along an eccentric orbit.

Rings:

Due to their negligible mass, we may suppose that rings are extremely difficult to detect. But this very small mass is compensated by a large area, as large as the planet itself in the case of Saturn. Since they may have a high albedo (∼0.5), rings can be as easy to detect by reflected light imaging as the planet itself. The master formula (Eq. 1.1) is valid only for spherical bodies and not for disk structures like rings. Planets with and without rings produce different light curves as a function of orbital angle, due to mutual shadow and occultation between the ring and the planet itself (Arnold & Schneider 2004). We can use this property to discriminate whether the planet is ringless or not. From a planetology point of view, rings are not only a curiosity. Their existence reveals the presence of satellites (which are continuous suppliers of dust by their collisions) and their radius R_R gives an indication on the density $\rho_R = M_{pl}/R_R^3$ of their building blocks.

1.3 Polarization

The degree of polarization of reflected light provides extra information about the scattering properties of the atmosphere under study. Polarization may help to estimate the degree of cloudiness of a planetary atmosphere, to retrieve the size of the scattering particles compared to the wavelength of the impinging light and to constrain the albedo because of its sensitivity to different phase angles (Schmid et al. 2006, Stam et al. 2005).

Multiple diffusion in fact destroys polarization. Therefore the degree of polarization is a measurement of the thickness of clouds. A high degree of polarization is a signature of single Rayleigh scattering (clear sky) or of a solid surface. The combination of the degree of polarization with a λ^{-4} dependence is a strong sign of Rayleigh scattering. Extrasolar planets may be observed at various angular phases (with respect to the parent star) from 0 to 90^o. The angular phase dependence is thus correlated with the orbital motion of the planet.

2 Spacecraft and mission strategy

These scientific objectives can be achieved with the 1.5 m coronagraphic telescope of the SEE-COAST mission. Its 2.2 m^2 collecting area is sufficient to detect $1R_{Jup}$ planets up to 15 pc and $3R_\oplus$ planets up to 5 pc. The high star to planet contrast of 10^8 - 10^9 imposes the use of a stellar light rejection mechanism. We have chosen a high performance coronagraphic phase mask with a suppression factor of 60,000 on the stellar peak, associated with a superpolished prime mirror. The focal instrument is a multiple coronagraphic device (Mawet et al. 2005) to attenuate the star and a spectropolarimeter with a low spectral resolution of R = 40 in the band 0.4 - 1.25 micron. An extension toward the UV is under study.

One possibility is to place the spacecraft on a L2 orbit (i.e. around the Earth-Sun Lagrange point L2), allowing a full accessibility of about half of the sky at any epoch. But other possibilities are considered.

The philosophy of the mission is not to search for new planets but to characterize planets already known by radial velocity or other techniques. At the end of 2006, about 220 planets were discovered: among them, already a sub-set of 30 can be detected with SEE-COAST We anticipate that by the time of launch in 2016 more planets will be accessible to SEE-COAST. As ancillary science, SEE-COAST will also observe circumstellar disks and AGNs.

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