Characterization of Extra-Solar Planets with Direct-Imaging Techniques

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Primary Author: Giovanna Tinetti
University College London
g.tinetti@ucl.ac.uk
+44 7912509617

Primary US Contact: Webster Cash
University of Colorado, Boulder
webster.cash@colorado.edu
303-492-4056

Co-Authors: Tiffany Glassman, Northrop-Grumman Space Technologies
C. Keller, Astronomical Institute, University of Utrecht
Phil Oakley, University of Colorado, Boulder
F. Snik, Astronomical Institute, University of Utrecht
Daphne Stam, ESRON
Margret Turnbull, Global Sciences Institute

Planetary Characterization

In order to characterize the physical properties of an extra-solar planet one needs to detect planetary radiation, either visible (VIS) to near-infrared (NIR) reflected starlight or infrared (IR) thermal radiation. Both the reflected and thermal flux depend on the size of the planet, the distance between the planet and the star, the distance between the observer and the planet, and the planet's phase angle (i.e. the angle between the star and the observer as seen from the planet). Moreover, the planetary radiation also depends on the composition and structure of the planet's atmosphere and/ or surface, the wavelength of the observation, and other effects such as the presence and physical characteristics of planetary rings or moons. In this white paper, we describe the techniques needed to learn about the properties of the planet from various observations of its radiation. In a companion white paper, we discuss how planets might be found using direct-detection methods (Turnbull et al. 2009); here we focus on the more detailed photometry, spectroscopy, polarimetry, and time-variability that can reveal the true nature of these planets and the systems in which they were born.

Recently, transit techniques have been extremely successful in providing the first information about the atmospheric composition and structure of a selected number of Giant and Neptune-size planets orbiting very close to their parent stars. With the launch of JWST, these methods will have the ability to study large, hot, rocky planets, but they will still be unable to characterize Earth-like planets within the "habitable zone" of F, G, and K stars. Direct imaging of rocky Earth-size planets in the habitable zone requires subarcsecond angular resolution in order to remove the bulk of the signal originating from the central star.

In this paper, we discuss potential science that is primarily enabled by direct observation of visible and near infrared starlight reflected off of exoplanets. Such observations are not currently possible, but can become so in the coming decade with properly configured space missions. Coronagraphic techniques now exist that can efficiently separate the exoplanet light from the glare of the parent star. We discuss some of the key observations that can be made if the observatory provides the same capabilities for exoplanet studies that are routinely made now on faint stars. The authors believe that all of the observations described herein would be possible in the coming decade using an external occulter system such as the New Worlds Observer, which has just completed an Astrophysics Strategic Mission Concept Study.

Planetary albedo and mass

The reflected planetary radiation depends on clouds, aerosols, and surface types, all of which can highly influence the planetary reflectivity (albedo). Signatures of this influence will be detectable in broad-band photometric observations (Fig. 1). The planet's albedo will be derived from the reflected flux by assuming a planet radius. For massive (down to Saturn-mass) planets, all models agree that the radius is very close to one Jupiter radius. For lighter planets, we can make use, to first order, of mass-radius

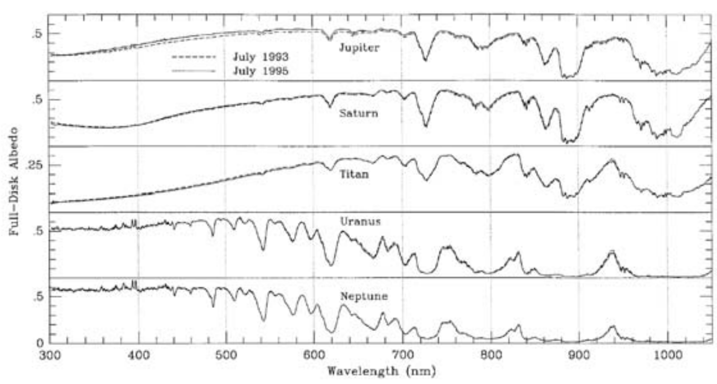

Figure 1: *Observed albedo for the gas giant planets and Titan in our Solar System (Karkoschka 1998)*

relations (Sotin et al. 2007; Valencia, O'Connell, & Sasselov 2006; Fortney et al. 2007). If a planet has been detected with radial velocity or astrometry measurements, its mass can be derived when combined with the observed orbital inclination angle. Depending on a planet's composition, its radius can vary by a factor of up to 20% for a given mass which translates into an uncertainty of 40% in the albedo. The value of the albedo can be further refined using flux and polarization spectra, time variability, and theoretical models as discussed below.

For all these reasons we argue that, while measuring the mass of the planet astrometrically is an important parameter for detailed modeling, the most important information is gained through direct observation. Measurement of mass should follow planet detection and classification, as opposed to being a necessary first step.

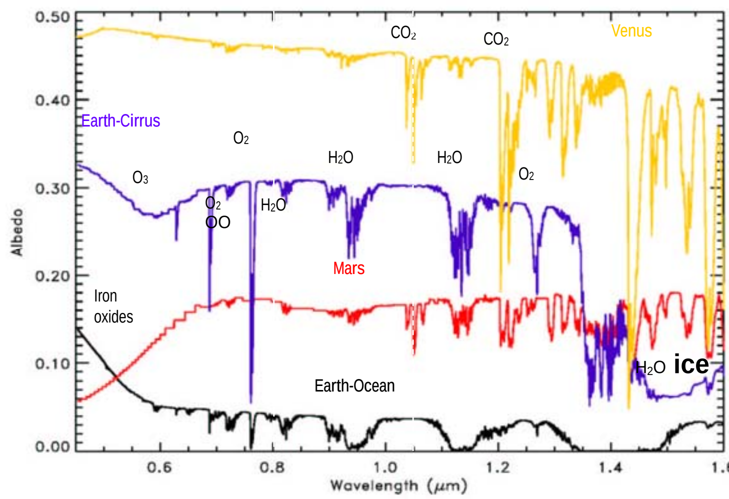

Fig. 2: *Albedo simulations of cloudy and cloud-free Earth (violet and black), Venus (yellow), and Mars (red).*

Spectroscopy and atmospheric species

Spectroscopy of the planetary radiation will provide very rich information, such as the species present in the atmosphere and the cloud coverage (Fig. 2). Table 1 lists the atmospheric gas molecules with absorption bands in the VIS/NIR bands.

Water is the necessary ingredient for the types of life found on Earth and it has played an intimate, if not fully understood, role in the origin and development of life on Earth. Water also contributes to the dynamic properties of terrestrial planets, permitting convection within the planetary crust that might be essential to supporting Earth-like life by creating local chemical disequilibria that provide energy. There are absorption bands from water though much of the VIS/NIR spectrum with a very distinctive spectral signature.

In addition to water, the search for carbon-dioxide is of special interest. Its presence would indicate (1) that carbon is available for the biosphere, (2) a (natural) greenhouse effect, and (3) a possible regulation by the hydro- and geosphere.

The greatest surprise in the composition of the planets in our solar system is the large amount of oxygen in the terrestrial atmosphere. This molecule is so reactive chemically that it must be continuously produced at enormous rates to persist. Thus the Earth's atmosphere can only be the result of a large input from the biosphere (Lovelock 1979). The challenge of remotely detecting life on a planet that has not developed a biogenic source of oxygen is fraught with unknowns. O_2 has its strongest spectral signature in the visible wavelength range.

Molecule	Absorption bands (μm)
H_2O	0.51, 0.57, 0.61, 0.65, 0.72, 0.82, 0.94, 1.13, 1.41
CH_4	0.48, 0.54, 0.57. 0.6, 0.67, 0.7, 0.79, 0.84, 0.86, 0.73, 0.89, 1.69
CO_2	1.21, 1.57, 1.6.
NH_3	0.55, 0.65, 0.93, 1.5
O_3	0.45-0.75 (the Chappuis band)
O_2	0.58, 0.69, 0.76, 1.27
CO	1.2, 1.7, 2.4

Table 1: *Absorption bands of the most important atmospheric molecules that can be detected and identified in the visible/near-infrared.*

Water, oxygen, methane, carbon dioxide and ammonia give the key signatures for characterizing atmospheres of exoplanets.

Time variability

Direct imaging of exoplanets may also reveal time-variability in the planet's flux and/or spectra. This variability could arise from daily rotation (with different parts of the planet rotating into view), from the orbital movement of the planet (which will generally change the phase angle), or from delayed impact of stellar activity. There might also be time-dependent changes on the planet itself due to weather and seasons.

A key indicator of the presence of liquid surface water is higher than expected reflectivity and variability at crescent phases when the system is observed at high inclination. This is due to the intensity of specular reflection off of the (somewhat) smooth ocean surface: the reflected light is concentrated at a reflected angle equal to the incident angle, much like a mirror (Williams & Gaidos 2008). Figure 3 shows that the behavior of the light curve at crescent phases may tell us if the planet has water-like features on the surface. The intensity of specular reflection causes the average daily brightness to be somewhat greater than for a land-only planet. Additionally, as clouds or land features temporarily obscure this specular reflection, the planet will significantly dim, causing potentially higher hourly variability (Oakley & Cash 2009).

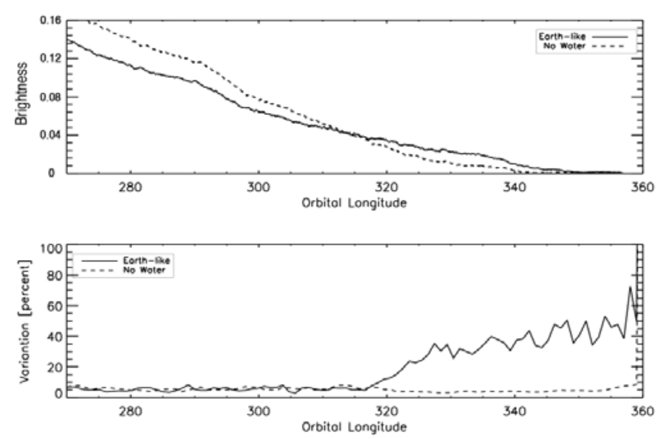

Fig. 3: *The detection of liquid surface water may be possible through studying the planet's photometric behavior at crescent phases. The top plot shows the average daily brightness of the planet, while the bottom planet shows the shorter-term variability that has been smoothed out in the top plot.*

These observations will be crucial in discovering oceans, however the crescent phase is the most difficult time to observe a planet, due to decreased signal strength, increased noise (due to stronger exo-zodiacal signal), and observational effects due to the planet approaching the inner working angle of the system. This should stress the importance of having an observing system with the smallest possible inner working angle.

It is also possible to measure diurnal flux changes for an Earth-like planet from long-term photometric monitoring (Ford et al. 2001; Tinetti et al. 2006; Hearty et al. 2008; Palle et al. 2008; Oakley et al. 2008). These effects were simulated and it was shown that, given several days of observation time, the periodic tendencies of the light curve can lead to an accurate determination of the rotation rate of the planet (Figure 4). A Fourier power analysis or an autocorrelation analysis typically indicates a 24-hour rotation rate for >50% of attempts with a broadband signal-to-noise range of 5-10 and has near perfect success for most geometries given a SNR of 20 or higher (Palle et al. 2008; Oakley et al. 2008). The analysis at lower SNR often returns a 12-hour rotation rate, which is not surprising given that the Earth consists of two main landforms interspersed by two main oceans. The changing cloud cover is the dominant source of confusion rather than noise introduced by external factors such as exozodiacal light.

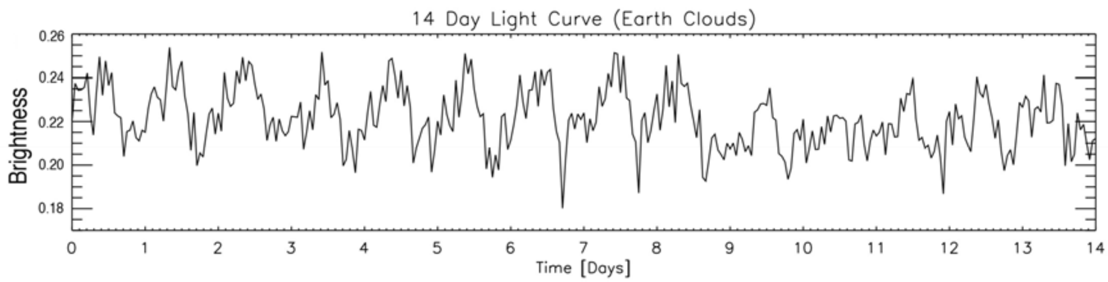

Fig. 4: *Sample data over 14 days of observation. The hourly variation is due to the changing disk-averaged albedo of the planet as clouds and surface features rotate into view. Given sufficient observation time, the rotation rate of the planet can be accurately determined.*

Time variability in spectra can also provide information about the distribution of surface types, aerosol, and clouds. For example, flux and polarization spectra of cloudy planets are expected to be very sensitive to phase, both in the total amount of light and in the shape of the spectra (the continuum shape and the absorption band depths) due to related changes in atmospheric path-length above the clouds and the changing position of the observer with respect to the star).

Polarimetry

With polarimetry, one measures the flux at a given polarization angle and determines the degree of polarization of the light (the fraction of polarized flux to the total flux). Polarimetry can help to distinguish (polarized) planetary light against the background of (unpolarized) direct starlight. It can help to quickly confirm that the dot of light that is detected in the vicinity of a star is indeed a planet and not e.g. a background star. Polarimetry can also be used to characterize the planet because the degree of polarization of the light scattered from a planet varies with the planetary phase angle and also depends strongly on the properties of the planetary atmosphere and/ or surface.

Starlight is virtually unpolarized, while the light that has been reflected by a planet orbiting the star will usually be polarized because it has been scattered within the planetary atmosphere or reflected by the planetary surface. The degree of polarization observed depends on the degree of polarization of the planet itself and on the background of residual, unpolarized starlight: the smaller the background flux, the closer the observed degree of polarization will be to the planet's degree of polarization. For exoplanets that can be spatially resolved from their star, the observable degree of polarization can reach several tens of percents in the extreme case of no background starlight (Stam et al. 2004).

Because the planet's light is significantly more polarized that the star's light, polarimetry observations can help to pull the signal of the planet from the background of unpolarized starlight. In addition, if the potential exoplanet is found to have a significant level of polarization, this can immediately confirm its nature as a planet rather than a background star. Such an instant confirmation eliminates having to wait to check whether the detected dot is actually in orbit around the star. There is even a relation between the direction of polarization and the imaginary line connecting the planet and its star: the direction of polarization of the reflected starlight will always be parallel or perpendicular to this line except for planets with strong horizontal inhomogeneities or very bright rings. This can help narrow down the possible orbits of the exoplanet in a single observation.

The degree of polarization of an exoplanet usually varies strongly with planetary phase angle because the scattering processes within the atmosphere depend strongly on the planet's illumination and viewing geometries (Fig. 5). In particular, the degree of polarization of an exoplanet will usually be highest for intermediate phase angles, when the angular separation between the planet and the star is largest and the planet should be easiest to detect. For phase angles near 0 and 180 degrees, the planet's degree of polarization will always be close to zero; however even a planet in a wide orbit cannot be spatially resolved from its star at these phases and is thus not observable with a direct-imaging technique.

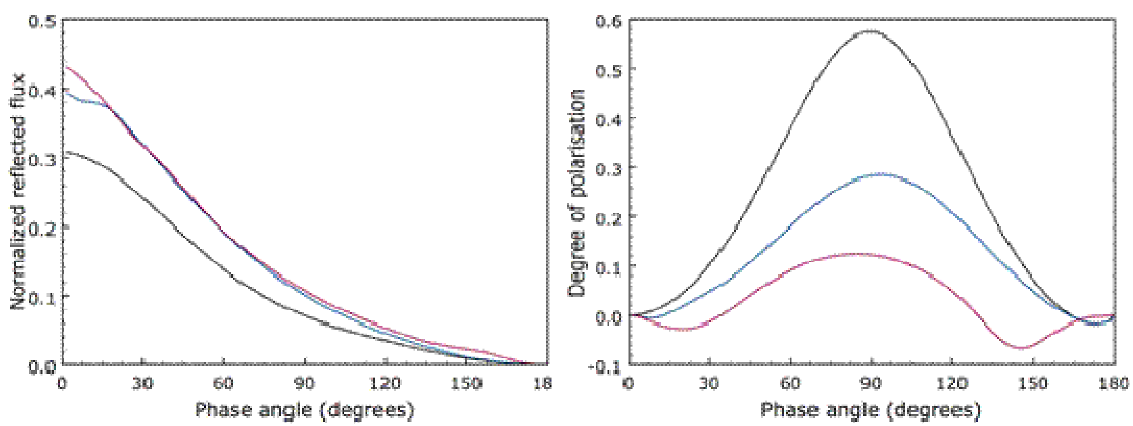

Fig. 5: *The flux (left) and degree of polarization (right) of starlight that is reflected by three model gaseous planets as functions of the planetary phase angle. The black line is a Jupiter-like planet with a pure molecular atmosphere, blue is the same planet except with an optically thick cloud layer in the troposphere, and purple is a cloudy planet with a thin stratospheric haze, each averaged over λ= 0.65 to 0.95 microns (Stam et al. 2004).*

Furthermore, polarimetry can be used to characterize the planet since the degree of polarization of a planet and its variation with phase angle depend strongly on the properties of the planet. Since the planet's reflection properties usually depend on the wavelength, the degree and direction of polarization also usually depend on the wavelength (Fig. 6). Indeed, the optical properties of the planetary atmosphere and surface have a larger influence on the degree of polarization of reflected starlight than on the flux (Hansen & Hovenier 1974).

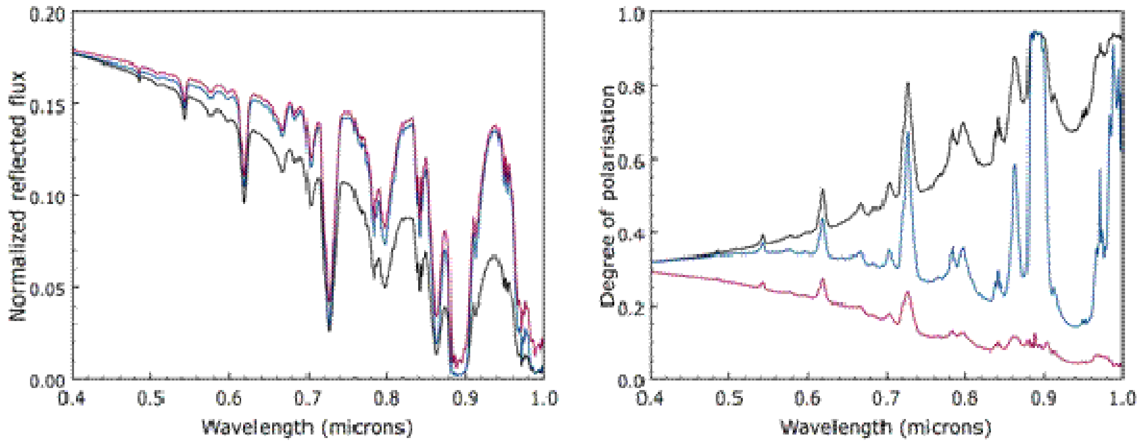

Fig. 6: *The flux (left) and degree of polarization (right) of starlight that is reflected by the three model gaseous planets described in Fig. 4 for planetary phase angles of 90 degrees. The fluxes have been normalized such that at a phase angle of 0 degrees, they equal the planet's geometric albedo (Stam et al. 2004).*

If the planet is embedded in a circumstellar disk, the dust particles in the disk will also scatter polarized starlight. However, because the microphysical properties of these particles will differ strongly from those in the planetary atmosphere, their polarization signatures will differ from that of the planet. Especially when the planet's polarization signature is measured across a range of wavelengths and at different planetary phase angles, we will be able to make a clear distinction between the planet and its environment. The polarimetry can also be used to characterize the circumstellar dust particles themselves.

The degree of polarization is a relative measure (the polarized flux divided by the total flux). As such, it is independent of the size of the planet and its distance to the star. Being able to characterize a planet without having precise information on these parameters is a strong advantage of polarimetry. Especially by combining flux with polarization measurements, planet characteristics can be retrieved that would be inaccessible by flux measurements alone. For example, the reflected flux is not sensitive to cloud-top altitudes, while the degree of polarization is. The flux, however, is sensitive to the optical thickness of the cloud, while the degree of polarization is less sensitive to this.

Thanks to the obvious advantages of polarimetry for exoplanet detection and characterization, several polarimeters are being used, built, or designed for this purpose, e.g. PlanetPol and ExPo on the William Herschel Telescope, SPHERE on the Very Large Telescope, GPI on the Gemini Telescopes, and EPICS on the European Extremely Large Telescope. It is critical to take polarimetry into account when designing and building a telescope and instrumentation, because the response of most optical components depends on the state of polarization of the incoming light: they are polarization sensitive. A polarization sensitive telescope and instrument can yield significant errors in the measured fluxes across the continuum and across absorption bands (which will influence the retrieval of gas mixing ratios).

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