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Solid Exoplanet Surfaces and Relief

Jean-Loup Bertaux

Contents

Introduction

Characterizing the solid surface of an exoplanet will be difficult. Detecting mountains and reliefs in rocky exoplanets is certainly even more challenging. In this

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chapter, we try to investigate which techniques could be used for these purposes. A good starting point is to list a number of techniques that have been used in our own solar system and to check if their extrapolation to the great distances that are involved for exoplanets is possible or not. The use of the atmospheric column above a particular region is a good proxy for its altitude. We examine the case of transiting planets and non-transiting planets, and we conclude by advocating for a systematic search of small planets from ground-based radial velocity measurements in the vicinity of the Sun.

Of course gaseous planets like our giant planets Jupiter and Saturn are excluded. The "ocean" exoplanets, which would have a solid core but a thick ocean, so thick that no solid terrain would be emergent, are de facto considered: the presence of liquid water together with the total absence of relief in an observed exoplanet could be an indication that this is indeed the case.

Reflected Light, Thermal Emission, and Orbital Phase

We will restrict our discussion to two types of light emission process from an exoplanet. There is the host starlight which is scattered by the surface of the planet (and/or by clouds), and there is the black-body (or thermal) radiation emitted by the surface–atmosphere combination. While the scattered starlight is located only on the illuminated hemisphere of the planet (the day side), the thermal radiation is emitted by the whole body. If the exoplanet has been detected by the radial velocity method or by the transit method, the orbital period is well known, and the phase of the planet also. In particular, we know when the planet is beyond the host star, well illuminated (superior conjunction), or between us and the host star (inferior conjunction), where the night side is prominent. The inclination angle $\pi/2 - i$ of the orbital plane to the line of sight (where i is the inclination of the orbital pole to the line of sight, LOS) is not known (except for transiting planets), but monitoring the exoplanet lights (scattered and thermal) as a function of orbital phase would allow in principle to determine both the inclination and the relative contributions of scattered and thermal radiation. Of course, the detection with direct imaging, followed by a monitoring, would yield also the information on the period, the orbital phase, and the inclination.

Spectroscopy as a Major Tool to Characterize the Surface and the Atmosphere

The spectrum of the starlight scattered by the planet B(λ) is the product of the starlight spectrum S(λ) by the area of the planet and its reflectance Rf(λ):

$$B(\lambda) = \pi\ R_{pl}{}^{2} S(\lambda)\, Rf(\lambda) \qquad (1)$$

with both S(λ) and the reflectance Rf(λ) being functions of the wavelength λ. Since the star spectrum S(λ) is known, it is the reflectance spectrum Rf(λ) which carries information on both the solid surface on which the starlight was scattered and the atmosphere which was crossed twice by the planetary light observed from outside. This is why this reflectance is often referred as TOA reflectance, for "top of atmosphere." The thermal radiation is also modified by the emissivity of the surface material and by the absorption/emission processes in the whole atmosphere.

The atmospheric composition may be retrieved from the distinct spectral signature of the various gaseous species. Rare gases (monoatomic) cannot be detected, as well as nitrogen N_2. Triatomic molecules have a variety of well-known spectral signatures (e.g., HITRAN spectroscopic database, and Fig. 2) which allow to identify them, and the depth of gaseous absorption features in the reflectance spectrum Rf(λ) allows to determine the column abundance of the various species.

The spectral signatures of the solid surface are much more diverse than gaseous absorption, because of the great quantity of the various minerals that could be present. Large databases of laboratory measurements on pure samples do exist, but even on Mars some identifications are sometimes difficult. The comparison of Martian soil spectral signatures obtained from orbit and the in situ mineralogical identification from rovers (Curiosity, Mars 2020, Exomars) will provide precious catalogues of mineral signatures for further use in exoplanets. The signatures of water ice and CO_2 ice are relatively easy to identify, but their details depend on the size of the icy grains, a complication but also a source of information.

Characterization of the Surface of a Solid Planet: Solid, Liquid, or Clouds?

Identifying the Presence of Liquid Water by Spectroscopy

The reflectance of liquid water is very low (a few %) and is also spectrally featureless. One may however infer indirectly the presence of liquid water, by measuring both the temperature of the surface (from thermal emission) and the column abundance of water vapor. Because of H_2O vapor pressure saturation, if there is liquid water, the column abundance above this liquid cannot exceed the saturation maximum value but should not be much lower than this maximum value (high relative humidity). This is typically the case of Earth's oceans, but the same should apply to other species, as CO_2 or methane/ethane (the case of Titan). A quiet liquid surface may be also inferred by detecting the glint emission: when the liquid surface acts as a mirror reflecting the star light to the observer. Indeed, the glint of the Sun has been observed by Cassini on Titan's lakes, as proposed by Christophe Sotin. As discussed in Visser and van de Bult (2015) and references therein, a time series of disc-integrated measurements could be analyzed and reveal the presence of a glint. However, a similar signature would come from a flat icy surface or flat icy particles floating high in the atmosphere.

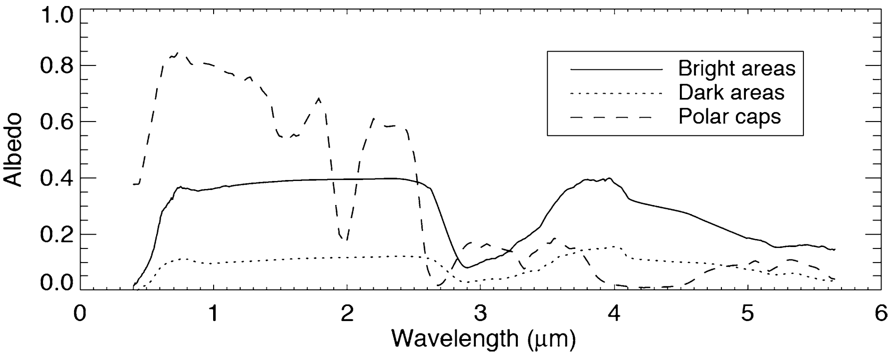

Fig. 1 Three typical spectra of the albedo (same as reflectance) of Mars. The Polar caps spectrum is a composite of North and South solar caps, showing both H_2O and CO_2 ice absorptions. The two soil spectra are different in level but not in shape. The main absorption around 3 μm is quite conspicuous (From Erard 2001)

The Case of Mars

Typical CO_2 absorptions in the reflectance spectrum of Mars revealed the presence of CO_2, with a column abundance providing a surface pressure of 6 mbar. The high (visible) reflectance of the North and South polar regions revealed the presence of ice. While the North polar cap shows the typical signature of water ice in the near IR, the South polar cap spectrum indicated the presence of CO_2 ice. However, with high spatial and spectral resolution observations from Mars Express, it was discovered that CO_2 ice represents only a thin layer ($\approx$10–20 m), on top of a massive H_2O ice layer, like in the North. Only in small regions of the South polar cap the CO_2 ice layer is absent, revealing the H_2O ice underneath (Bibring et al. 2004; Bertaux et al. 2006). In the case of exoplanets, in most cases only one polar region can be observed because of the orbit inclination to the line of sight (LOS).

Figure 1 represents the three major types of reflectance spectra of planet Mars in the visible and near IR. These spectra have been corrected from the atmospheric absorption. In fact, the dark areas and the bright areas display almost the same shape but are distinct from the H_2O ice spectrum of the polar cap. The severe drop in the blue may be assigned to many things (not very discriminating), while there is a conspicuous absorption around 3 μm which is assigned to the presence of OH bonds, revealing the presence of water in the rocks, either adsorbed or as an intimate part of the chemical formula of the mineral.

The Case of the Earth

In 1990, the Galileo spacecraft en route to Jupiter made a fly-by of the Earth and conducted a series of measurements which were analyzed by Carl Sagan et al. (1993), with the purpose to detect signs of life (bio-signatures) and signs of

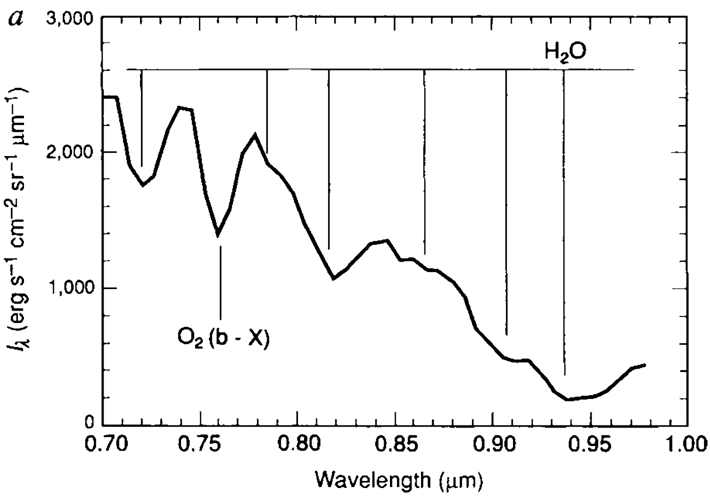

Fig. 2 Spectrum of Earth reflected solar radiation collected by Galileo during its Earth fly-by over ocean. Within this small spectrum range, H_2O has several bands, and O_2 shows the conspicuous A band (also noted (b−X) (From Sagan et al. 1993)

intelligent life (techno-signatures) on Earth, as a test case for future observations of exoplanets (well before the first detection in 1995). The presence and mean abundance in the atmosphere of water vapor, dioxygen (O_2), ozone (O_3), CO_2, and methane (CH_4) can be easily detected from the TOA reflectance spectra of the Earth (Fig. 2). The UV reflectance drops severely to 0 below ≈300 nm, because of ozone absorption in the Hartley band (protecting life at the surface). With atmospheric transmission models (e.g., TAPAS on-line, Bertaux et al. 2014), the reflectance of the surface may be retrieved for further analysis. The remaining spectral signature is complex, diverse, and variable. Partial cloud cover is another difficulty. With our criteria of relative humidity, an external observer would deduce that there are large areas covered with liquid water. The most interesting surface signature is probably the one of chlorophyll. Leaves are green because the red light of the illuminating sun is absorbed by the chlorophyll. But in the near infrared, near 0.72 μm, chlorophyll ceases to absorb and vegetation is quite reflective (the naked eye cannot see it, but CCD cameras can): this is the so-called chlorophyll edge that will constitute a major target to identify in exoplanets as bio-signatures (Fig. 3) – in principle, it cannot be confused with any soil spectral signature (Sagan et al. 1993).

Ozone is present in the atmosphere of the Earth since 500 million years, allowing life (vegetation first) to invade all continents which were desertic before. It means that the fact that there is life on Earth is known in the whole Galaxy, and even on many other galaxies. On the contrary, techno-signatures are emitted since only ≈100 years; the "sphere of knowledge" (that there is intelligent life on Earth) is small, but growing at the speed of light, encompassing more and more exoplanets in the habitable zone (HZ).

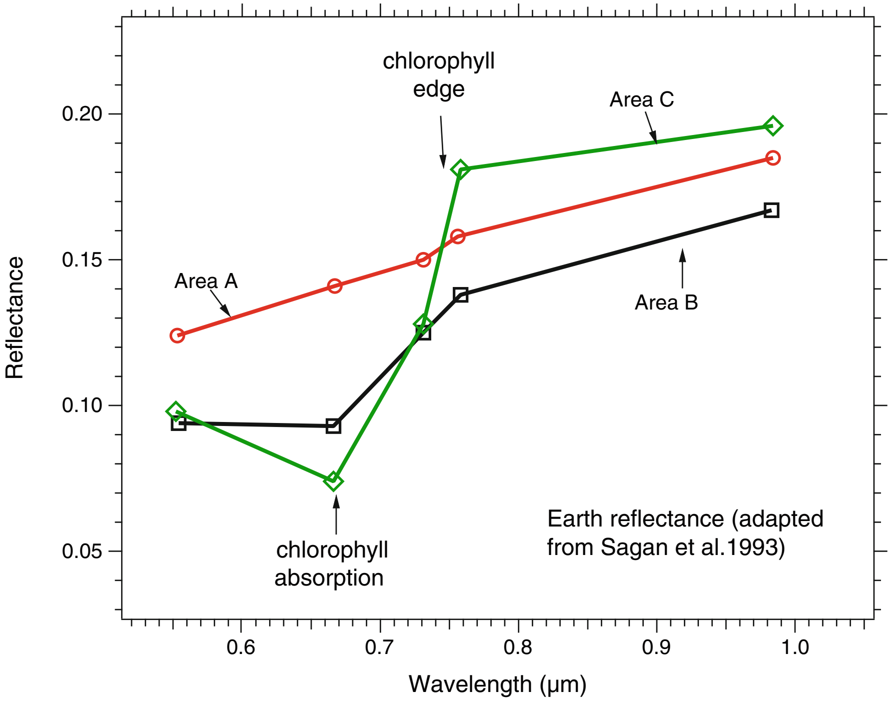

Fig. 3 The reflectance spectrum recorded in three areas of Earth during Galileo fly-by. Area C is over extended forest in the northern part of South America; the chlorophyll red absorption (0.6–0.7 μm) and the sudden increase at 0.72 μm, the chlorophyll edge, are quite conspicuous and constitute major candidates as a bio-signature to search for in exoplanets. Area A (desert of Atacama) shows almost no sign of the chlorophyll signature, while Area B is intermediate: partial vegetation cover (Adapted from Sagan et al. 1993)

The Case of Venus

Venus is often quoted as a test case for exoplanets' investigations. It is totally covered by clouds of small droplets of sulfuric acid (H_2SO_4) at 85% concentration. This was determined by combining spectroscopy and polarimetry as a function of phase angle and may be achieved without spatial resolution. To go one step further requires spectroscopic observations of the night side only of Venus: there are strong emissions in the near infrared (Fig. 4) in narrow spectral "windows" revealing both the very high temperature of the surface and the massive abundance of CO_2, the presence of water vapor in small abundance (30 ppmv), and also the presence of deuterated water HDO. Further analysis is complicated by the presence of the clouds which have a variable thickness, blocking more or less the radiation coming from the surface. The solid surface composition is difficult to determine from orbit. One particularly bright ground feature was assigned to "recent" lava flows (some 100,000 years old). However, the brightness (emissivity) could be determined only

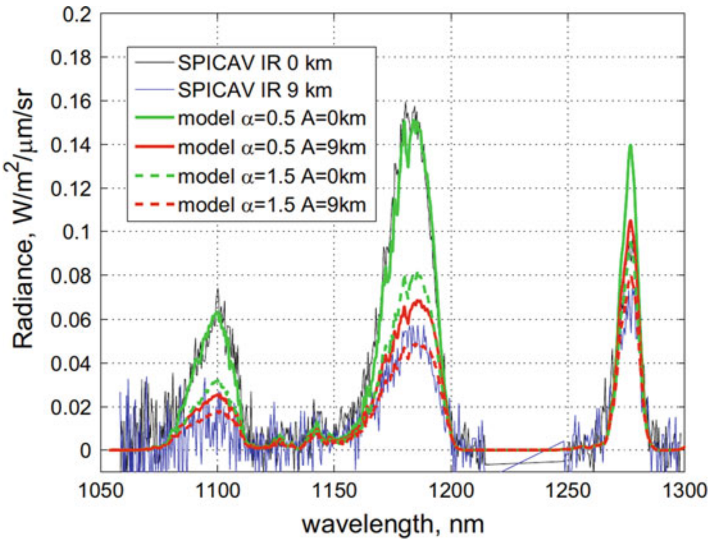

Fig. 4 Spectrum of the night side emission recorded by SPICAV-IR instrument on board Venus Express, in three spectral windows (not fully absorbed by CO_2 or H_2O), compared to various models. The *black* and *blue* curves are the measurements obtained respectively over a terrain at 0 and 9 km altitude. In spite of the increased atmospheric absorption, the signal is stronger at 0 km because the surface is hotter and the black-body radiation more intense. The coefficient α represents here the uncertain continuous absorption of CO_2, which could be determined from such observations, using the atmosphere of Venus as a laboratory of spectroscopy (From Fedorova et al. 2015)

relatively to the expected temperature at the particular altitude of that terrain known from radar observations, and this cannot be extrapolated to an exoplanet (unless the altitude is known independently from the column of gas above a given point, see below).

Finding Mountains and Relief on Exoplanets

The determination of the altitude distribution of a solid surface is different if the body to be investigated is an airless body (in which there are no clouds), or if the body has an atmosphere, in which case it may be cloud-free, partially (Earth) or totally cloud-covered (Venus). In the case of Venus, the best altitude measurements come from radar investigations, whose wavelength may propagate through the clouds without being affected (i.e., Magellan radar). However, this technique cannot be used for exoplanets, because of the r^{-4} dependence of the return radar signal with the distance r to the target. Similarly, the laser altimetry technique which was very successfully operated on planet Mars to get the best altitude model so far (the MOLA model) cannot be used for exoplanets.

The Effect of Diffraction by the Aperture of a Telescope

Exoplanets are and will be observed with telescopes. The angular resolution R_a of a telescope is limited by diffraction. The smallest beam R_a is related to the diameter of the telescope A and to the wavelength λ of observation:

$$R_a \approx 1.22 \ \lambda/A \tag{2}$$

where λ and A must be in the same length unit, and R_a comes in radians. The spatial resolution R achieved on an exoplanet at distance D from the sun is therefore

$$R = R_a D \approx 1.22 \ D \ \lambda/A \tag{3}$$

It is useful to have in mind the size of a telescope necessary to achieve a desired spatial resolution at a given distance. Let us consider exoplanets at a distance of 10 parsec (a sphere of 10 parsec centered on the sun contains more than 100 stars, and probably at least the same number of exoplanets). Knowing that 1 parsec $\approx 3 \times 10^{13}$ km, and for a desired resolution of 1,000 km, the diameter of the telescope comes to

$$A\,(\text{meter}) \approx 3.6 \times 10^5 \ \lambda\,(\text{micron}) \tag{4}$$

For a wavelength of 1 μm, it calls for a telescope of 360 km in diameter. However, as is shown in the chapter "Multipixel Imaging of Exoplanets," one may achieve the same spatial resolution with a swarm of small telescopes placed on a parabolic surface of the same size: this is the concept of the "diluted pupil." At a distance of ≈3 parsec, a diluted pupil mirror of 100 km would achieve the desired 1,000 km resolution and could be conceivably set up on the Moon, constituted of a network of small telescopes linked together by an optical fibers bundle.

We will discuss the application of all techniques described above with the assumption that R ≈ 1,000 km is achieved. But we will also discuss resolution-less observations, where the light of the exoplanet is integrated over the whole disc: a case more relevant to the nearer future.

Getting Spatial Resolution on the Planetary Disc Without Imaging

Some exoplanets have the good taste to transit in front of their host star, as seen by us. This opens the possibility to study its atmosphere by the spectral transmission, the star providing the light on which is measured the transmission, as discussed in the chapter ► "Exoplanet Atmosphere Measurements from Transmission Spectroscopy and Other Planet Star Combined Light Observations". Here we consider rather the so-called secondary transit (or eclipse), when the planet passes behind the star. The light of the planet is progressively masked by the edge of the star, acting as a "knife-edge." In this configuration, there is no masking of the host star. The time variation of the total signal carries some information about the planet light distribution across its disc which might reveal some spatial inhomogeneities. Indeed this method has been already used successfully by *Spitzer* space observatory on the star HD189733 and its hot Jupiter planet, on which a "hot spot" has been located by fitting the nonsymmetrical eclipse light curve as sketched in Fig. 11 (Agol et al. 2010).

Similarly, the terminator of the planet acts also as a "knife-edge," separating the day side and the night side of the planet. This situation occurs also for a nontransiting planet, in which case the star light may be reduced by a proper coronagraph (internal or external). In this case, the information is coming from the variation of the signal as a function of the orbital phase of the planet; the variation of the phase angle (w.r.t. the host star illumination) as seen from the Earth is larger when the inclination of the orbital plane on the line of sight $\pi/2-i$ is small. When mountains are around the terminator, it will result in some irregularities in the light curve of the planet, because their elongated shadows are "eating" a part of the illuminated hemisphere. They add also some light to the night side hemisphere when they are beyond the terminator but their top still illuminated by the star.

Beating the diffraction limit of a telescope aperture by using the secondary eclipse or the terminator limit as a spatial discriminator might remain for a long time the only way to record spatial variations on an exoplanetary disc. However, the interpretation of irregularities in the light curve is not unambiguous, because surface variations of the reflectance could also produce irregularities. With multipixel images around the terminator, the irregular shape of the terminator (like the fuzzy terminator of the Moon) could be more safely interpreted as revealing mountains (or craters).

Some Basics of Atmospheric Physics Relevant to Surface Altitude

In the atmosphere of rocky planets, the role of convection is essential in controlling the vertical profile of the atmosphere, which in turn partially or totally controls the ground surface temperature, provided that the atmosphere is sufficiently abundant. Convection is triggered by heating of the atmosphere by the surface, with ascending motions and of course descending motions at other places to compensate. Because of the adiabatic cooling of ascending air (and adiabatic heating of descending air), the resulting vertical temperature profile reaches a so-called adiabatic equilibrium profile (no exchange of energy with outside), within which an air parcel may go up and down adiabatically while remaining at the same temperature as the rest of the surrounding atmosphere. As a result, the atmospheric temperature decreases with altitude in a known way. Horizontally, this adiabatic vertical profile is maintained identical over large areas.

Imaging: Morphology and Shadows

Direct imaging of an exoplanet with good spatial resolution may be interpreted in terms of relief. For instance, a roundish structure may be interpreted as the dome of a large volcano, culminating at high altitude. However, there are also calderas, which are also roundish but are strong depressions due to the collapse of ground surface inside the evacuated magma chamber below.

The shadow of mountains has been historically the first way to determine the existence of mountains on another world: the moon. The projected shadow of a given mountain is larger when being near the terminator (the line separating the day side and the night side of the planet). Looking at the terminator on the moon with binoculars shows that the terminator is not always a smooth line, but rather a wiggly line, revealing the presence of mountains. The most recent example comes from images of Pluto collected with the New Horizon mission.

Measuring the Surface Temperature as a Proxy to the Altitude

The equilibrium temperature of the surface is therefore linked to the atmospheric temperature, in addition to the radiation from the local star. On Mars, the atmosphere is too thin to have a strong influence on the surface temperature, mainly controlled by radiation from the star and black-body radiation escaping to space. On Earth, the atmosphere is thick enough, but the presence of changing cloud cover is a complication.

Venus, with its thick CO_2 atmosphere (93 bar) and total cloud cover, is an interesting case which must have its counterpart in some exoplanets. The surface temperature is very high (740 K) and the black-body radiation peaks around 1 μm wavelength. The atmosphere is adiabatic, and its temperature is decreasing with altitude and is controlling the surface temperature. Therefore, the absolute radiance emitted by the surface around 1 μm is directly linked to its altitude (Fig. 4). And this thermal radiation propagates outside, even through the clouds (by multiple scattering), and can be mapped from outside (Fig. 5). Because the clouds are at 50 km of altitude, there is some blurring of the map, by an amount of about 50 km, therefore not a problem for exoplanets (and even for present Venus studies). An example of a partial map of the 1 μm radiance is given on Fig. 5, obtained by the VMC camera on board the ESA Venus Express mission.

Measuring the Column of an Absorbing Gas

Any atmosphere will be in hydrostatic equilibrium to first order. Therefore, the column of a well-mixed gas will be related to the altitude of the terrain below. Unfortunately, a cloud will mimic the same behavior as a relief. One may discriminate both with numerous observations: clouds move with respect to the solid body,

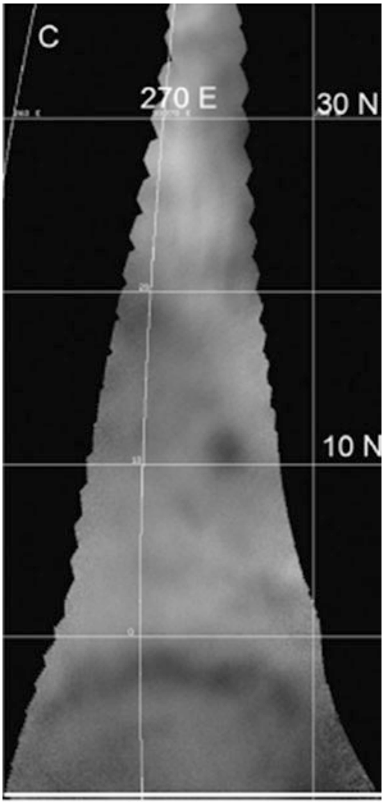

Fig. 5 A series of VMC images of the surface taken with a 1.01 μm filter along one orbit are combined into a mosaic (orbit #470 of Venus Express on 4 August 2007). There is about 2,000 km between the two parallels marked 10 N and 30 N. The size of the image (constant VMC field-of-view) increases while the distance to the planet increases along the eccentric orbit (Extracted from Basilevsky et al. 2012)

while mountains are not. A strictly periodic signal might be more safely assigned to a mountain.

UV Rayleigh Scattering (0.2–0.5 μm)

For moderate atmospheres (like Mars, 6 mbar ground pressure), an obvious candidate to measure the column of air is Rayleigh scattering by gas, valid whatever is the composition. In Fig. 6 the quantity of UV light recorded at 210, 250, and 300 nm in nadir viewing from Mars Express with SPICAM instrument along one orbit passing over the huge volcano Olympus Mons, together with the known elevation of the surface, is plotted. The highest altitude is the nadir point, the lower is the UV signal through Rayleigh scattering. Knowing the gravity of the planet and the temperature of the atmosphere allows relating the measured absolute UV radiance to the column of gas and to the mean altitude of the observed spot. The contribution of aerosols is also decreasing with altitude. Complications may arise from the presence of clouds. Also, it is difficult to distinguish such a signal from a geographical variation of the surface albedo.

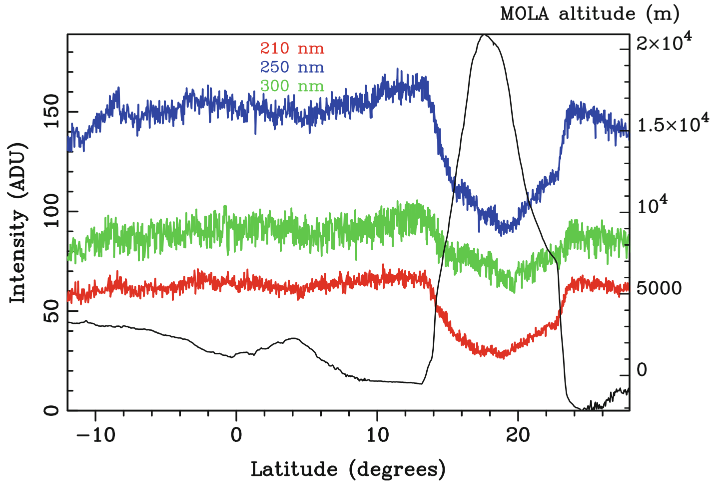

Fig. 6 Along one day side polar orbit of Mars Express passing over the large volcano Olympus Mons on planet Mars (22 December 2005), the altitude of the nadir point is changing vastly by about 20 km (*black curve*, right scale). The UV light recorded by SPICAM instrument is the sum of the surface albedo and the Rayleigh scattering of the atmosphere. This contribution is decreasing (*colored curves*, left scale) when high altitude terrains are observed, at the three UV wavelengths 210, 250, and 300 nm (Courtesy of Franck Lefèvre 2017)

The Case of Dioxygen (O_2)

Dioxygen may be a privileged target gas to be observed on exoplanets, since on Earth it is a by-product of biological activity. Due to its very low condensation temperature, this gas is expected to be well mixed within the atmosphere and therefore is a good candidate for altitude retrieval. The strongest absorption bands are the famous A band at 760 nm (Fig. 7) and the near IR band at 1.27 μm. It may be noted that CO_2 monitoring spacecrafts on Earth (e.g., GOSAT and OCO-2) are also measuring systematically the column abundance of O_2 in the A band in order to derive the CO_2 mixing ratio, which is now above 400 ppmv and still increasing with disastrous effects on the climate as we know.

In Fig. 8 (left) is an example of a geographic map of the pressure retrieved by the imaging spectrometer Meris on board ENVISAT Earth observation spacecraft. It is compared to an altimetry map of the same region (Tunisia, Lybia) in Fig. 8 (right).

The Case of H_2O

While H_2O is of major interest in the question of habitability of the observed exoplanet, it must be used with precaution to relate its column abundance to the relief, because its abundance is mainly dictated by the temperature at ground level and its condensation pressure/temperature curve. In the atmosphere of the Earth, the H_2O column is highly variable. Indirectly though, if it is not possible to measure the temperature from the thermal emission, the H_2O column could serve as a proxy to the temperature. As revealed by meteorology monitoring spacecraft, it is clear

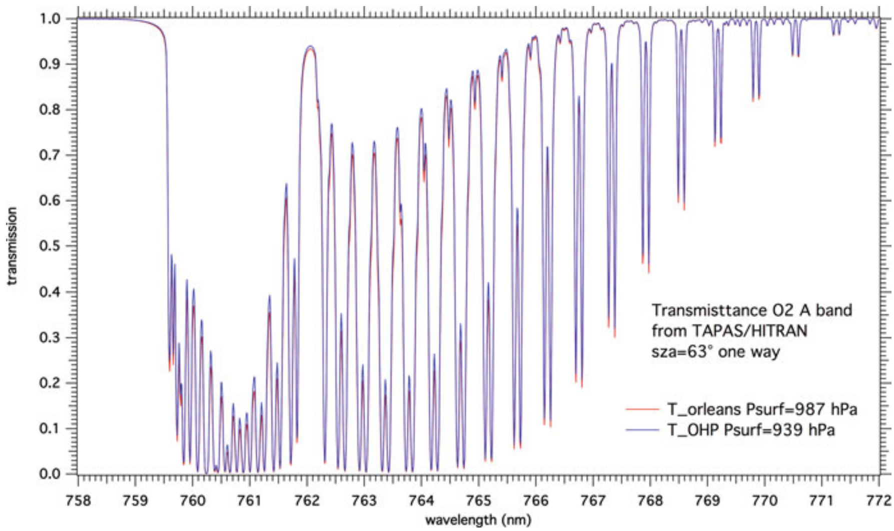

Fig. 7 Atmospheric transmission of O_2 in the famous A band, computed from TAPAS web site and HITRAN database for two sites with different ground pressures. The shape of this band is so conspicuous that even an extraterrestrial astronomer would recognize it immediately

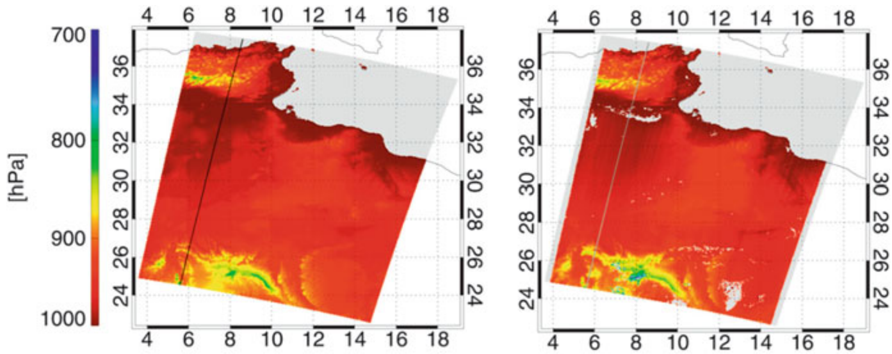

Fig. 8 (Left) A map of surface pressure on North Africa (*color coded* in hPa, 1 hectoPascal = 1 mbar), derived from a topographic altitude map and assuming a constant atmospheric vertical profile over the area. (Right) Map of surface pressure retrieved by Meris instrument on board ENVISAT from the depth of absorption of the O_2 band at 760 nm (From Lindstrot et al. 2009). Both maps coincide very well, illustrating the potential of gas column abundance to estimate the terrain altitude

that the H_2O column is much smaller above Himalaya than over the seas. And in the case of Venus where there is no condensation at all (H_2O is even supercritical in the lower atmosphere, no distinction between liquid and vapor), it could be determined at 1.1 µm (e.g., Bézard et al. 2011) that H_2O is a well-mixed gas with a constant mixing ratio of 30 ppmv. Therefore, all column abundances of H_2O may be

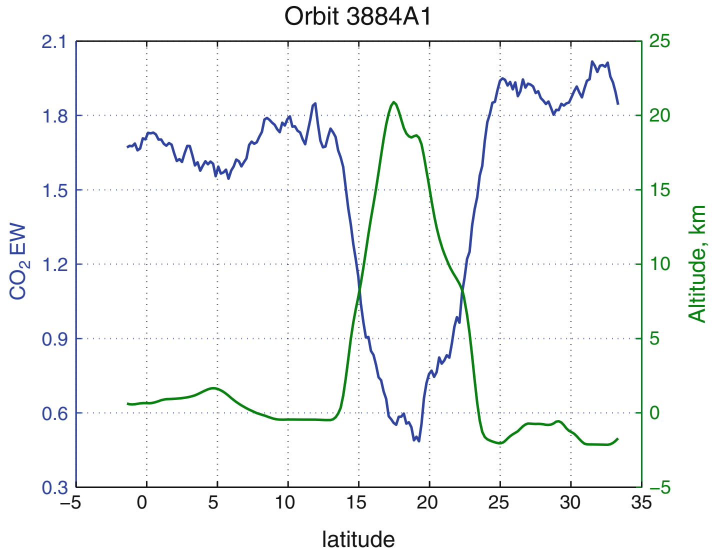

Fig. 9 The depth of a CO_2 absorption band recorded by SPICAM-IR instrument at 1.4 μm (*blue line*, left scale, EW = equivalent width in nm units related to the column abundance of CO_2) is compared to the altitude of the point observed at nadir, along one orbit of Mars Express flying over Olympus Mons (*green line*, right scale). The higher is the altitude, the smaller is the column abundance and the 1.4 μm CO_2 band depth measured by its EW. This indicator is more precise than the UV of Fig. 6, because it is less sensitive to the presence of aerosols (Courtesy of Anna Fedorova 2017)

translated into an altitude of the relief. Actually, the inverse situation happened: on Venus the column abundances were measured, and relating with the altitude known from radar observations through the clouds, the mixing ratio could be determined and revealed to be constant in the lower atmosphere of Venus.

The Case of CO_2

CO_2 is a relatively inert gas and should be well mixed, even if it is not the main gaseous constituent (as it is on Mars and Venus). It presents both weak and strong absorption features, allowing to cover a wide range of atmosphere thickness, from the UV (below 190 nm), to the near IR, and up to the very strong 15 μm absorption band currently used to retrieve temperature altitude profiles in the Earth's atmosphere for meteorological purposes. Therefore, it is a good candidate for topography retrieval but will suffer, like other gases, from the possible confusion with the clouds. Figure 9 shows the depth of the 1.4 μm CO_2 band in the scattered radiation from Mars along one orbit of Mars Express flying over Olympus Mons, looking nadir. It is directly related to the altitude.

Methane (CH_4) would be also adequate. Nitrogen (N_2) is not adequate because it does not absorb properly; ozone (O_3) is not adequate because it is chemically controlled and not at all a well-mixed gas.

The Case of an Exoplanet as a Point Source

Solid Surface and Relief

Here we discuss the questions of the solid surface characterization and the relief when the exoplanet is not spatially resolved. There are already interesting observations of transiting exoplanet, in particular during the secondary eclipse. In Fig. 10 the observed light curve (around 8 μm) of the star HD189733 by *Spitzer* spacecraft (Knutson et al. 2009) is reproduced. The light of the giant exoplanet is disappearing abruptly when passing behind the host star, with a decrease of the total light star + planet = 0.3%. Let us assume that a very high signal-to-noise ratio (SNR) could be achieved for a number of wavelength intervals suchlike the ones which have been suggested above. In principle, the planet-only light curve (obtained by subtraction of the star light observed during the secondary eclipse) should present a minimum when transiting and a maximum just around the time of secondary eclipse, for geometrical reasons. And if the surface of the planet is homogeneous (constant albedo, no relief), then the shape of the light curve during eclipse can be calculated a priori.

As described in Fig. 11, *Spitzer* has already detected a "hot spot" on the giant planet HD189733b. If there is one region with high relief (a mountain), then the CO_2 column above the mountain will be smaller (Fig. 9), which might be detected exactly in the same way as the "hot spot," during a secondary eclipse, without the need of imaging.

If there is one feature in the planet-only light curve which makes it depart from the homogeneous model ("hot spot," UV spot, CO_2 column, chlorophyll spot, etc.), this feature could be observed during many successive orbital periods. If it occurs always at the same orbital position, then it would mean that the rotation of the planet is locked to the host star by tidal forces, like the Moon that presents always the same face to the Earth (it seems to be the case for HD189733b). Otherwise, the tracking of this feature will allow determining the rotation period of the planet. And the feature, if connected to one altitude indicator as the ones suggested above, could be analyzed in terms of altitude distribution on the planet.

Even in the case of no feature at all, there is still one possibility to detect the presence of a mountain, when the signal is not linear with altitude. This is the case of the 15 μm CO_2 line profile, which detailed shape could be an indicator that the surface temperature is not homogeneous, due to the presence of a mountain for instance.

Everything which is said above is still valid if there is no transit, no eclipse, and some inclination of the orbital plane. Also, the light of the star may be drastically reduced by an occulter (internal or external). In such a case, some part of the orbit might be lost by the masking but not its entirety.

When the star is eclipsing a transiting planet, the spectrum of the star-only S_0 is recorded. Therefore, it may be subtracted for any other part of the orbit (except the transit) to get the planet-only spectrum, as a function of the orbital phase. A

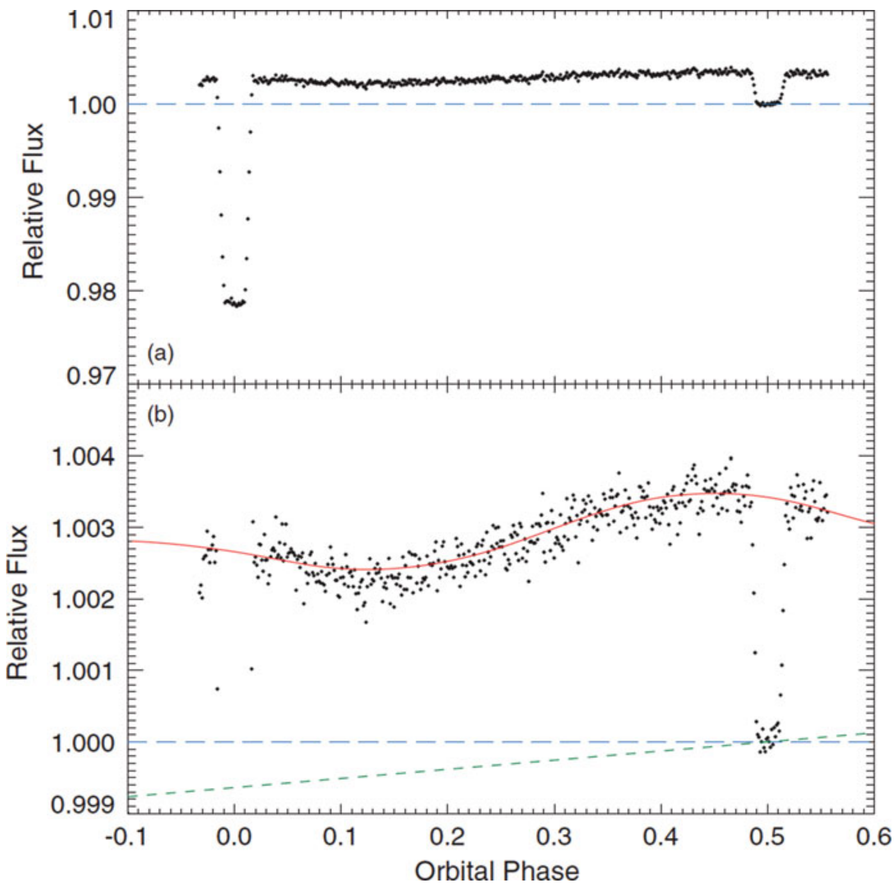

Fig. 10 The light curve of the star HD189733 and its orbiting planet HD189733b is displayed (at 8 μm from *Spitzer*) as a function of the orbital phase. On the upper panel, the light of the star is dimmed (by 2%) during the transit of the planet in front of the star disc. The secondary transit, or eclipse, is also clearly seen at phase 0.5; the star light-only is the bottom level reached at this time and may be extrapolated at all phases to get the planet-only light curve as a function of orbital phase (bottom panel, signal above *dashed line* to account for some star spots) (From Knutson et al. 2009)

limitation of the method is the variability of the star luminosity S_0 itself. However, the star-only spectrum S_0 may be scaled before subtraction to other star + planet measurements, hoping that the *shape* of the star spectrum will be more stable than its absolute brightness. The resulting planet-only spectrum would depend on only one parameter, the scaling factor, adjusted to each observation to get a planet-only spectrum which makes sense: for instance, no negative values. This method could be called the *differential spectroscopy method*. It may be extrapolated to the case of nontransiting planets, either with or without an occulter to decrease the stellar light.

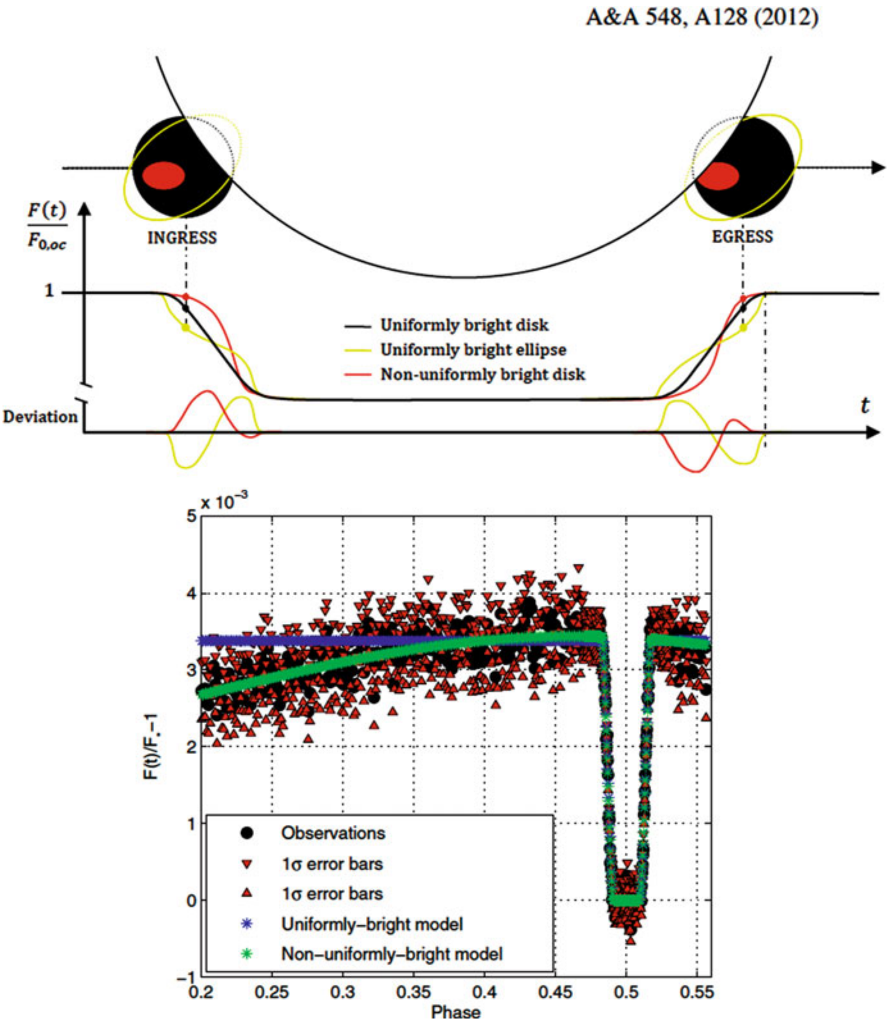

Fig. 11 (Right) The light curve during secondary eclipse of exoplanet HD179833b passing behind its host star, as recorded by *Spitzer* (Agol et al. 2010). The *blue curve* is a model of uniformly bright planet disc, while the *green curve* models the behavior of a hot spot on the disc

Transiting Planets Versus Nontransiting Planets

The advantages of studying exoplanets which transit across the disc of the host star are:

(i) The atmosphere may be studied by absorption spectroscopy. (ii) The secondary transit (eclipse) is also a great source of information for atmosphere, surface characterization, and relief. (iii) There is no need of an occultation system (coronagraph) to dim the star light.

However, only a small fraction of all exoplanets have the appropriate geometry to be observed in transit, since the observer (in the solar system) must be near the orbital plane of the exoplanet. As a consequence, transiting exoplanets are statistically further out than nontransiting planets, by a factor F_g. For instance, when considering the special case of planets in the habitable zone (HZ) of their host star (which dictates their distance to the star, and therefore the probability of transit), it was calculated that HZ-nontransiting planets are three to nine times nearer than HZ transiting planets, the "gain" factor F_g depending on the spectral type of the star dictating its total radiation (Bertaux 2014): $F_g = 6.2$ for solar type stars. It translates into a telescope three to nine times smaller in diameter to achieve the same SNR on the star and its planet than for a transiting one. Also, an occulter may be used, reducing the contaminating signal of the star.

Conclusions

The discovery of the first exoplanet in 1995 opened a new era of discoveries. It seems that never in the history of astronomy, a particular field has grown as fast as the field of exoplanet research is growing now. We may expect for the next century that this will continue to grow, with new telescopes on Earth and in space. This is probably because this field of research is connected to a philosophical question, touching everybody: are we alone in the universe? This used to be a science-fiction question, but now it is in the realm of reality.

In the recent past, telescopes in space (except transit dedicated missions like Corot, Kepler, future Plato) have been designed as general-purpose instruments, optimized for a certain wavelength domain, within some programmatic and budget constraints. Their scientific objectives have been general astronomy and not designed primarily for the study of exoplanets. The James Webb Space Telescope (6.2 m) is one example of such a case. Given the increasing interest for exoplanets, it seems that future large telescopes in space will be primarily designed for the study of exoplanets. Their capabilities will be used for other astronomical purposes, as secondary objectives. This is the case for the projects WFIRST (2.4 m), HABEX (4 m), and LUVOIR (8–12 m depending on launcher existence) that are under study as possible successors of JWST in the USA. LUVOIR would reach UV wavelengths at 0.1 μm (as HST). The polishing should be much better, in order to decrease the contamination of the host star light at the position of the targeted exoplanet.

In this respect, we might foresee some evolution in the conception of future telescopes in space. In the past era, the in situ exploration of the solar system required a different space system for the various objects that were visited. The orbiters, fly-bys, rendez-vous, descending probes, and sample-return missions were tailored and designed to the particular target object. Similarly, we will target first the nearest exoplanets from the sun (like Proxima Centauri b at 1.3 parsec) lying in the habitable zone of its host star. The requirements for a space system able to study this exoplanet are easily defined, since we know the distance of the star and the distance between the host star and its exoplanet. This reasoning may be extended to other nearby stars, once we know the existence of their exoplanets.

It was suggested (Bertaux 2014) that the technique of radial velocity measurements for detecting exoplanets may be able to make an exhaustive search of all exoplanets in the habitable zone (and many others), for stars up to 10 parsec (to begin with). The best illustration is the discovery of Proxima Centauri b with radial velocity measurements performed by ESO Harps spectrometer at La Silla (Anglada-Escudé et al. 2016), in the habitable zone. It is worth to note that, because of the Galactic motions of all stars, the star Proxima Centauri happens to be the nearest to our Sun nowadays just by chance. Picking a star at random and finding that it hosts a planet in its habitable zone shows that the occurrence of a rocky planet in the habitable zone of any star is indeed very high.

A rough calculation indicates that an ensemble of 33 sets (telescope + spectrometer) would be able to make an exhaustive search of exoplanets around all the stars (about 3,000) within 100 light years from the sun, each set monitoring 90 stars during 10 years. A lower number of sets would just have to concentrate on nearer stars. The exact number of sets is not at all critical: the more, the faster we explore exhaustively our neighborhood. It is our conviction that a systematic search for such HZ planets around all stars (by increasing distances from the sun) would be achieved faster and cheaper by an ensemble of dedicated telescope + spectrometer. The size of the telescope may be of the order of 2 m diameter, automated to reduce operation costs.

A rough estimate of the cost of one setup is about 15 M$. This is based on the cost of "off-the shelf" 2 m automated telescopes and the estimate of HARPS-like spectrometers building. The operation cost is about 10% per year of the hardware cost. A small step for the tax payer, a gigantic step for humanity and exoplanets.

Cross-References

- ▶ The Solar System: A Panorama
- ▶ Composition and Chemistry of the Atmospheres of Terrestrial Planets: Venus, the Earth, Mars and Titan
- ▶ The Solar System as an Observation Tool for Exoplanets
- ▶ Future Space Missions for Exoplanet Science
- ▶ Characterization of Exoplanets: Secondary Eclipses
- ▶ Exoplanet Atmosphere Measurements from Direct Imaging (Ground and Space)
- ▶ Atmospheric Retrieval for Exoplanet Atmospheres
- ▶ Formation of Terrestrial Planets
- ▶ Surface and Temporal Biosignatures

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References

Agol E et al (2010) The Climate of HD 189733b from fourteen Transits And Eclipses measured by Spitzer. The Astrophysical Journal 721:1861–1877

Anglada-Escudé G et al (2016) A terrestrial planet candidate in a temperate orbit around Proxima Centauri. Nature 536(7617):437–440

Basilevsky AT et al (2012) Geologic interpretation of the near-infrared images of the surface taken by the Venus Monitoring Camera, Venus Express. Icarus 217(2):434–450. https://doi.org/10.1016/j.icarus.2011.11.003

Bertaux JL (2014) A Road Map to the New Frontier: finding ETI. EPSC Abstracts Vol. 9, EPSC2014-864

Bertaux JL et al (2006) SPICAM on Mars Express: Observing modes and overview of UV spectrometer data and scientific results. J Geophys Res 111(E10):CiteID E10S90

Bertaux JL, Lallement R, Ferron S, Boonne C, Bodichon R (2014) TAPAS, a web-based service of atmospheric transmission computation for astronomy. Astron Astrophys 564:A46

Bézard B, Fedorova A, Bertaux JL, Rodin A, Korablev O (2011) The 1.10- and 1.18-μm nightside windows of Venus observed by SPICAV-IR aboard Venus Express Icarus 216:173–183

Bibring JP et al (2004) Perennial water ice identified in the south polar cap of Mars. Nature 428(6983):627–630

Erard S (2001) A spectro-photometric model of Mars in the near-infrared. Geophys Res Lett 28(7):1291–1294

Fedorova A, Bézard B, Bertaux JL, Korablev O, Wilson C (2015) The CO_2 continuum absorption in the1.10- and 1.18-μm windows on Venus from Maxwell Montes transits by SPICAV IR onboard Venus Express. Planet Space Sci 113–114: 66–77

Knutson HA et al (2009) Multiwavelength constraints on the day-night circulation patterns of HD 189733b. Astrophys J 690:822–836

Lindstrot R, Preusker R, Fischer J (2009) The retrieval of land surface pressure from MERIS measurements in the oxygen A band. J Atmos Ocean Technol 26(7):1367. https://doi.org/10.1175/2009JTECHA1212.1

Sagan C, Thompson WR, Carlson R, Gurnett D, Hord C (1993) A search fro Life on Earth from the Galileo spacecraft. Nature 365:715

Visser PM, van de Bult FJ (2015) Fourier spectra from exoplanets with polar caps and ocean glint. Astron Astrophys 579:A21