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The Exoplanet Opportunity: Top-Down Planetary Science

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What started as a trickle in the mid-1990s is now a torrent, with more than 1000 extrasolar planets currently known and thousands of candidates awaiting confirmation (see http://planetquest.jpl.nasa.gov). The study of exoplanets has already revolutionized scientific and public views of planet formation and will soon do the same for planetary atmospheres and interiors.

The diversity of exoplanets gives planetary scientists the leverage they need to crack hard problems. Pick any characteristic—mass, temperature, eccentricity, obliquity, gravity, winds—and odds are that the record holder is not in our solar system. Characterizing these distant worlds will bolster scientific understanding of planets and planetary processes, including those on Earth. As observations improve and measurements grow more detailed, exoplanetary research is likely to eventually reshape the geophysical sciences.

Seeing Distant Worlds

The fact that exoplanets orbit other stars causes two major observational challenges. First, they are extremely far away. Most discovered exoplanets are dozens to hundreds of light years away. By comparison, Jupiter is within a light hour of Earth. Second, with the exception of free-floating planets, exoplanets are always right next to an annoyingly bright star, as seen from Earth. Depending on the planet and observational wavelength in question, the planet can be anywhere from a thousand to 10 billion times fainter than its host star.

The large distance to exoplanets puts them squarely in the realm of Remote sensing, where the capital "R" stresses the fact that even in the best-case scenario, planetary scientists are inferring the properties of an unresolved dot. The great distances to these worlds ensure that researchers receive precious few photons from them, even if the light of the planet can be distinguished from that of its star.

In recent years, astronomers have worked out multiple ways of dealing with an exoplanet's host star.

Ideally, one can block the starlight without blocking out the planet in the process. This can be achieved by using interferometry to eliminate stellar photons or by physically blocking the stellar photons far from the telescope with an occulter or with a coronagraph inside the telescope.

In all three cases, the end result is that the planet can be seen as a dot in the diminished glare of the star; astronomers refer to this as spatially resolving or directly imaging the planet. Direct imaging is currently feasible only for nearby young Jupiter-like planets, which are still hot and therefore emit appreciable near-infrared radiation.

It is hoped that future ground- and space-based experiments will be able to directly image mature planetary systems similar to our own. Regardless of whether a planet is spatially resolved from its host star or not, it is possible to characterize the world by analyzing its reflected and emitted light.

Exoplanetary Remote Sensing: Reflection

Reflected starlight tells us what a planet looks like. Moreover, reflected light contains spectral and polarimetric signatures of absorption and scattering that help identify atmospheric constituents and surface features.

As a planet moves about its star, it exhibits phases, similar to what Venus does as seen from Earth. Astronomers cannot resolve the disk of an exoplanet with enough detail to see whether it is in a crescent, quarter, or gibbous phase (see Figure 1), yet the changing phases affect its overall brightness in a detectable way: When the planet is on the far side of its star, we see its dayside and measure more reflected light; when it is on the near side, we see its nightside and detect no reflected light. The detailed shape of a planet's reflected phase variations tells us about the spatial distribution and scattering phase function of clouds and surface elements.

In addition to phase variations, a planet's appearance also undergoes seasonal variations and rotational changes. From a distance, Earth looks somewhat bluer in austral summer than in boreal summer because of its lopsided continent distribution, and it looks unusually red when the Sahara desert is

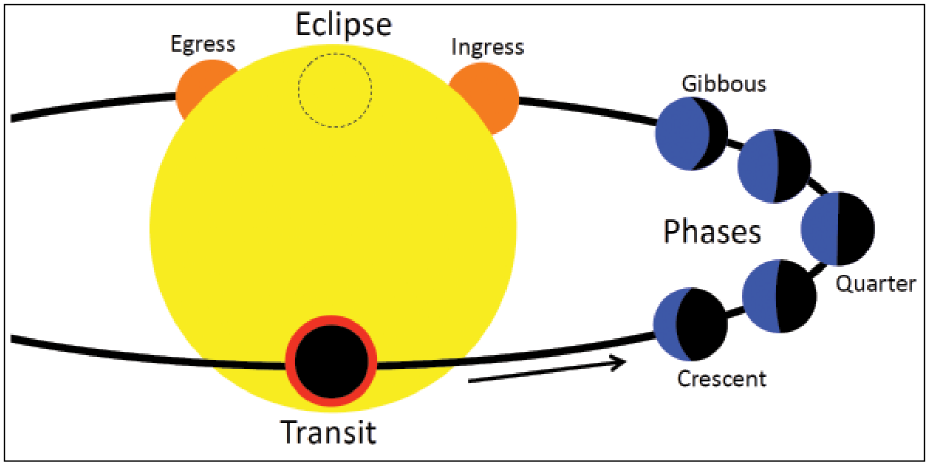

Fig. 1. A planet with an orbit that is nearly edge-on as seen from Earth will appear to transit in front of its star. This is more likely to occur for planets that orbit close to their star, so transiting planets are often synonymous with short-period planets. Measuring the light coming off the planet during the different stages of this orbit can give information about a range of properties, such as the planet's size, mass, temperature, and atmospheric composition.

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visible. The changing colors of the planet hint at the colors of various surface features coming in and out of view. It is possible to use inverse methods to extract reflectance spectra of component surfaces and to map their locations on the planet. When tested on single-pixel observations of Earth, these methods produce a coarse two-dimensional map of the continents and oceans; an estimate of planetary obliquity; and low-resolution spectra of clouds, land, and ocean [*Cowan and Strait,* 2013].

Emission

Starlight that is not reflected by the planet warms it up. In exoplanets with atmospheres, some of this heat is transported to cooler regions of the atmosphere and radiated away. Thermal radiation from the planet varies with its emitting temperature, which is usually cooler than its surface temperature because of the greenhouse effect. Insofar as different wavelengths probe different atmospheric pressures, the planet will not emit as a blackbody—absorption and emission features are imprinted by cool or hot upper layers. Emission spectroscopy is therefore sensitive to the atmospheric composition and vertical temperature profile of the planet but can be scuttled by clouds and vertically isothermal layers [*Burrows,* 2014].

By the same token, horizontal and temporal differences in planetary temperature produce time variations in thermal emission. For example, the dayside of a slowly rotating planet might appear brighter and warmer than its nightside. Most known exoplanets have curiously eccentric orbits and therefore experience significant seasons due to the changing star-planet separation (multiplanet systems tend to have more circular orbits, however). Rocky planets are expected to form with randomly oriented spin axes, which leads to the obliquity seasons familiar on Earth. Disentangling diurnal cycles, eccentricity seasons, and obliquity seasons based on thermal phase variations is a work in progress [*Cowan et al.,* 2012].

Transit

Planets that orbit close to their host stars cannot be spatially resolved without an impossibly large telescope—or array of telescopes—in space. For now, scientists analyze the combined light of both objects. This would be of merely academic interest except that the vast majority of temperate rocky planets huddle close to dim red dwarf stars [*Johnson,* 2014]. In principle, the reflected starlight and planetary emission of such “close-in” planets can be analyzed as described above, but in practice, this requires Herculean efforts in calibration because the host star contributes the vast majority of the light.

Fortunately, planets orbiting close to a star are more likely to transit in front of it, and transiting systems provide two unique means to characterize exoplanets: transits and eclipses (see Figure 1). These are the tools of the trade for characterizing short-period Jovian planets (“hot Jupiters”), and these techniques will soon be brought to bear on temperate rocky worlds.

When a planet passes in front of its host star, it blocks a fraction of the star’s light equal to the planet-to-star cross-sectional area ratio. The transit of a hot Jupiter in front of a Sun-like star typically lasts a couple of hours and produces a 1% dip in the overall brightness of the system, indicating that the radius of the transiting planet is about one tenth that of its host star. By inferring the stellar radius from its color or spectrum, one can convert this relative size into a planetary volume; this is how researchers know that hot Jupiters are, in fact, the size of Jupiter.

To determine a planet’s mean density and hence infer its bulk composition, it is necessary to weigh it. This is done by observing the reflex motion of the host star and making use of Newton’s laws. For planets in short orbits around nearby stars, the motion of the star can be teased out from the Doppler shift of stellar absorption lines in a high-resolution spectrum. Such measurements tell us that hot Jupiters are roughly the mass of Jupiter.

Surrounding a hot Jupiter’s opaque planetary disk is an annulus of partially transparent atmosphere that filters starlight. The measured spectrum of a planet in transit therefore contains an imprint of photon scattering and absorption that occurs in the upper atmosphere near the planet’s day-night terminator. Even if the bulk composition can be taken as a given (e.g., for hot Jupiters, an atmosphere consisting mostly of hydrogen and helium), it is still difficult to nail down the abundances of trace gases. High-altitude hazes can also wash out spectral features. Nonetheless, transmission spectroscopy is a powerful characterization tool that can only be applied to transiting planets [*Burrows,* 2014].

Eclipse

Eclipses of the planet by its star can be used to isolate planetary light. A planet that passes directly in front of its host star, as seen from Earth, must pass directly behind it half an orbit later (unless the planet is on a highly eccentric orbit). The brightness of the planetary system immediately before and after the eclipse is compared to the brightness during the eclipse, and the difference is a measure of the planet’s dayside brightness.

Astronomers may then convert the eclipse measurement into an estimate of the planet’s albedo or dayside temperature, depending on whether the instrument used to make the reading is sensitive to visible or thermal radiation. Spectrally resolved eclipse measurements can constrain estimates of atmospheric scattering, composition, and the vertical temperature profile [*Burrows,* 2014].

Although eclipses are primarily sensitive to the hemisphere-averaged properties of a planet, the very beginning and end of an eclipse offer a means of resolving the properties of the planet’s dayside. As the planet disappears behind its star (ingress) and reappears (egress), the star’s edge scans across the planet (see Figure 1). It is possible to invert these raster scans to construct a coarse two-dimensional map of the planet’s dayside [*Majeau et al.,* 2012].

To resolve the nightside of the planet, one needs to measure its thermal phase variations. On Earth, the hemispherically averaged day-night temperature contrast is much smaller than the seasonal contrast, but the story is completely different for short-period planets because of the strong tidal forces experienced in such an orbit. Tides damp obliquity, slow planetary rotation, and reduce orbital eccentricity. In other words, most short-period planets do not experience seasons but have permanent day and night hemispheres. The day-night temperature contrast is therefore an indirect measure of atmospheric and oceanic heat transport. High-precision thermal phase curves can be inverted to construct coarse longitudinal temperature maps of short-period exoplanets [*Cowan and Agol,* 2008].

Exoplanets as a Geophysical Laboratory

Much can be learned about exoplanets, even if they only ever appear as faint dots in astronomical images. Those keen to dig deeper into how exoplanets are characterized should peruse the volume *Exoplanets* edited by *Seager* [2011].

At the time of writing, there are a few hundred planets for which masses and radii (and hence bulk densities) have been measured. Roughly 50 of those have had their dayside thermal emissions measured via eclipses, fewer than a dozen have had their nightside thermal emissions measured, and about as many have reliable reflected-light measurements. In the realm of directly imaged planets, about 10 have thermal emissions measured in sufficient detail to extract radius estimates. All of these numbers are rapidly increasing.

On average, one temperate terrestrial planet exists for every one to two red dwarf stars, and such low-mass stars are many times more common than midsize stars. So the solar neighborhood must be teeming with warm rocky planets waiting to be discovered and characterized, something that could be done within the decade [*Johnson,* 2014]. The characterization of Earth-mass planets in the habitable zone of Sun-like stars, however, will have to wait for the dedicated space-based missions of future decades.

Exoplanet observations are necessarily coarse, and we observe them from the top down. When all you have is a single pixel, it is much easier to determine global mean temperature than to probe regional weather, much as it is easier to determine landmass distribution than local geology. When it comes to exoplanets, it is therefore most useful to think about processes that affect the global character of planets, especially their atmospheres and surfaces.

If Earth scientists and astronomers can overcome the nomenclatural barriers and the tendency to separate their disciplines, it should be possible to test geophysical theories that have so far resisted falsification: how cloud cover and wind speed depend on insolation and rotation, whether plate tectonics operate on planets of different mass, or how volatiles are cycled through planetary interiors, for example. Coarse measurements for a large number of planets are the perfect complement to the detailed measurements possible on Earth. That is the exoplanet opportunity.

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