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quick study

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Twenty years ago planets orbiting faraway stars were the stuff of science fiction. Now their atmospheric composition and even their weather are being revealed by sensitive spectral measurements.

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For centuries astronomers had expected that planetary systems around other stars would echo our own, with small, rocky planets orbiting close to the star and more massive gas-giant planets farther out. It therefore came as a surprise when the first planets discovered around nearby stars turned out to be massive gas giants similar to Jupiter, orbiting extremely close to their parent stars. Fifteen years later those hot Jupiters are viewed as merely the tip of the iceberg; astronomers currently know of more than 3000 extrasolar planets or planet candidates whose diverse properties continue to defy our expectations of what should be out there.

For most of those planets, we know little more than their approximate size and orbital period. Many unanswered questions remain. Is the planet a gas giant, or is it rocky? What is its temperature? Does it have an atmosphere, and if so, what is the atmospheric composition? What is the weather like? To answer those and other questions, some planetary astronomers are studying eclipsing systems in which the planet periodically passes in front of its host star. Figure 1 summarizes the key techniques discussed below.

Unfortunately, space precludes my presenting in detail a complementary approach known as direct imaging, in which astronomers use adaptive optics and other sophisticated techniques to obtain images in which the planet can be seen as a separate point of light next to the much brighter host star. Unlike methods for eclipsing systems, which are most sensitive to planets that orbit very close to their host stars, direct imaging works best for more distant gas-giant planets that are still young enough to retain some of the heat generated by their initial formation. Although only two such gas-giant systems have been studied to date, several new dedicated adaptive-optics systems that will come on line next year should produce an avalanche of new discoveries.

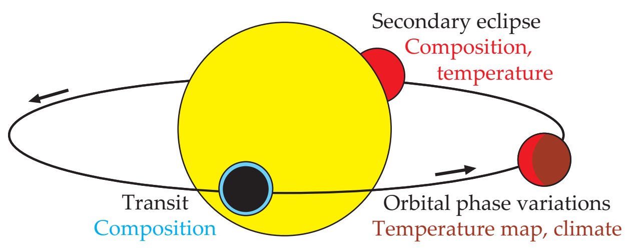

Figure 1. Three techniques for studying the properties of exoplanet atmospheres. When a planet passes in front of its host star, the wavelength dependence of the fraction of starlight absorbed gives information about atmospheric composition. When the planet passes behind the star, the decrease in IR light gives information about composition and temperature. Variations in the IR brightness of the planet as it revolves around the star reveal the day–night temperature difference. (Adapted from D. Deming, S. Seager, *Nature* **462**, 301, 2009.)

Together, the two approaches enable planetary astronomers to study a large sample of extrasolar planets with diverse characteristics (figure 2 illustrates a few of them) in order to constrain models for planet formation and evolution and to explore the atmospheric physics and chemistry of entirely new classes of planets.

Atmospheric composition of hot Jupiters

From our viewpoint here on Earth, it is difficult to imagine a class of planets more alien than the close-in, gas-giant hot Jupiters. Those distant worlds are much closer to their host stars than Mercury is to our sun. As a result, their temperatures can approach those of cool stars and their atmospheric properties are correspondingly exotic.

From measurements of the amount of light blocked by the planet when it transits its star, we can determine the planet's radius. We can estimate its mass by measuring the Doppler shift of the light the star emits as it is gravitationally tugged to and fro by the orbiting planet. Together, radius and mass measurements give density. The observations confirm that, as expected, hot Jupiters are primarily composed of hydrogen and helium, and have at most a small core of rock- or water-rich material.

The massive atmospheres of hot Jupiters are transparent at some wavelengths and opaque at others, so the amount of light blocked by the planet during a transit varies with wavelength. The wavelength-dependence of the transit depth (the fraction of light absorbed) is very tiny—typically only a few parts in 10 000—but it has been successfully measured with both ground- and space-based telescopes for approximately a dozen planets. Those spectra indicate that hot-Jupiter atmospheres contain water, methane, carbon monoxide, and possibly carbon dioxide in addition to hydrogen and helium. The abundances of those molecules relative to H appear to vary from planet to planet for reasons that are not yet fully understood. One possible explanation is that gas giants form with different amounts of H, C, and O depending on their location in the protoplanetary disk, the dense gas that orbits a young star and provides the raw materials for planet building. Another is that the close proximity of hot Jupiters to their host stars results in the selective destruction of some molecules via photoionization or other processes.

Exoplanets also pass behind their host stars in events known as secondary eclipses. By measuring the wavelength-dependent decrease in IR radiation during those secondary eclipses, astrophysicists learn about the shape of the planet's emission spectrum, which, in turn, provides information about the planet's atmospheric composition and how temperature varies as a function of altitude. In hydrostatic equilib-

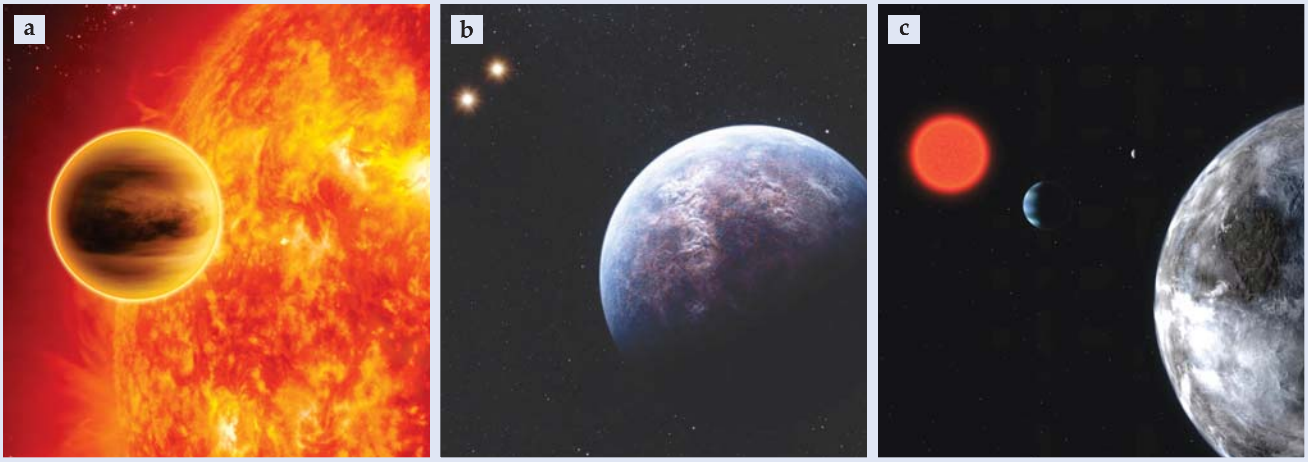

Figure 2. Exoplanets in artists' renditions. **(a)** The gas giant HD 189733b (courtesy of the European Space Agency). **(b)** Gliese 667 Cb (courtesy of the European Southern Observatory). This super-Earth is smaller than a gas giant like Jupiter. **(c)** The planetary system orbiting the red dwarf Gliese 581 (courtesy of ESO). Planets orbiting cool, low-mass stars like Gliese 581 are the best targets of study for detailed characterization of Earth-like exoplanets.

rium—that is, when pressure and gravity forces balance—the temperature decreases with increasing height; the contrary case is called a temperature inversion.

Infrared secondary-eclipse measurements published for nearly 50 hot Jupiters reveal that some of those planets appear to have strong temperature inversions, whereas others do not. Possibly, high UV fluxes received by planets orbiting magnetically active stars destroy the high-altitude atmospheric absorber responsible for the formation of the temperature inversion. Or perhaps some planets simply lack the raw materials to make the absorber in the first place. Both hypotheses yield clear predictions that will be tested within the next couple of years.

As a result of their short orbital periods, hot Jupiters should be tidally locked, meaning that the same side of the planet always faces the host star. One open question is whether heat absorbed on the dayside of those planets is efficiently transported around to the nightside. By obtaining a phase curve—that is, by monitoring changes in the brightness of the planet as it orbits its host star—astrophysicists can determine the amplitude of the day–night temperature gradient in the planet's atmosphere. Infrared phase curves obtained by the *Spitzer Space Telescope* for a handful of hot Jupiters indicate that most appear to have strong winds and correspondingly warm nightsides. However, the data also hint that planets with temperatures above 2500 K may have larger day–night temperature gradients. The relatively high gradients may simply reflect the heat-carrying capacity of those hotter atmospheres. But they could also be due to more exotic phenomena—for example, planetary winds containing partially ionized gas can be slowed down via interactions with the planet's magnetic field. The weather on hot Jupiters appears to be relatively unchanging, as repeated observations of the dayside brightness of two representative planets over several years rule out significant variability.

Smaller, more Earth-like exoplanets

The studies of eclipsing hot Jupiters described above rely primarily on observations with the *Hubble* and *Spitzer* telescopes. Neither of those telescopes was designed with transiting planets in mind, and the exoplanet observations frequently push them to their limits. How, then, can we hope to study much smaller planets with the same instruments? The answer is simple in principle: We look for planets around smaller stars. Because the transit depth scales as the square of the ratio of planetary and stellar radii, small planets orbiting small stars can have transit depths equal to those of their more massive hot-Jupiter counterparts.

The current poster child for that approach is a planet known as GJ 1214b, which has a mass approximately six times that of Earth and orbits a bright, nearby star with a mass less than one-fifth that of the Sun. Planets, like GJ 1214b, that have masses greater than Earth's but much less than Neptune's are known as super-Earths. They can have compositions ranging from primarily rocky (making them truly super Earths) to a mixture of gas and ice (more like a mini-Neptune); GJ 1214b has a low mean density that suggests it is closer to the latter type. Other extrasolar planets with comparable masses have much higher densities consistent with rocky compositions. Measurements indicate that GJ 1214b's wavelength-dependent transit depth is very nearly constant. That could be due either to a high cloud layer overwhelming the delicate signals that indicate atmospheric composition or to a compact water-rich atmosphere.

Studies of exoplanet atmospheres are now at a pivotal stage. Although we currently know of only a handful of low-mass transiting planets orbiting bright, nearby stars, we expect ongoing surveys such as MEarth and future missions such as the *Transiting Exoplanet Survey Satellite* to dramatically expand the sample over the next five years. The *James Webb Space Telescope*, slated for launch in 2018, will far surpass the capabilities of *Hubble* and *Spitzer* for characterizing exoplanet atmospheres. It is likely that within the current decade we will be able to carry out the first studies of the atmospheres of terrestrial and potentially habitable worlds. We have very little idea what we will find, but past experience indicates that whatever it is, it will surprise us.

Additional resources

▶ H. A. Knutson, A. W. Howard, H. Isaacson, "A correlation between stellar activity and hot Jupiter emission spectra," *Astrophys. J.* **720**, 1569 (2010).

▶ J. N. Winn, "Exoplanet transits and occultations," in *Exoplanets*, S. Seager, ed., U. Arizona Press, Tucson (2010), p. 55.

▶ Exoplanets.org, http://www.exoplanets.org.

▶ *Kepler* mission, http://kepler.nasa.gov.