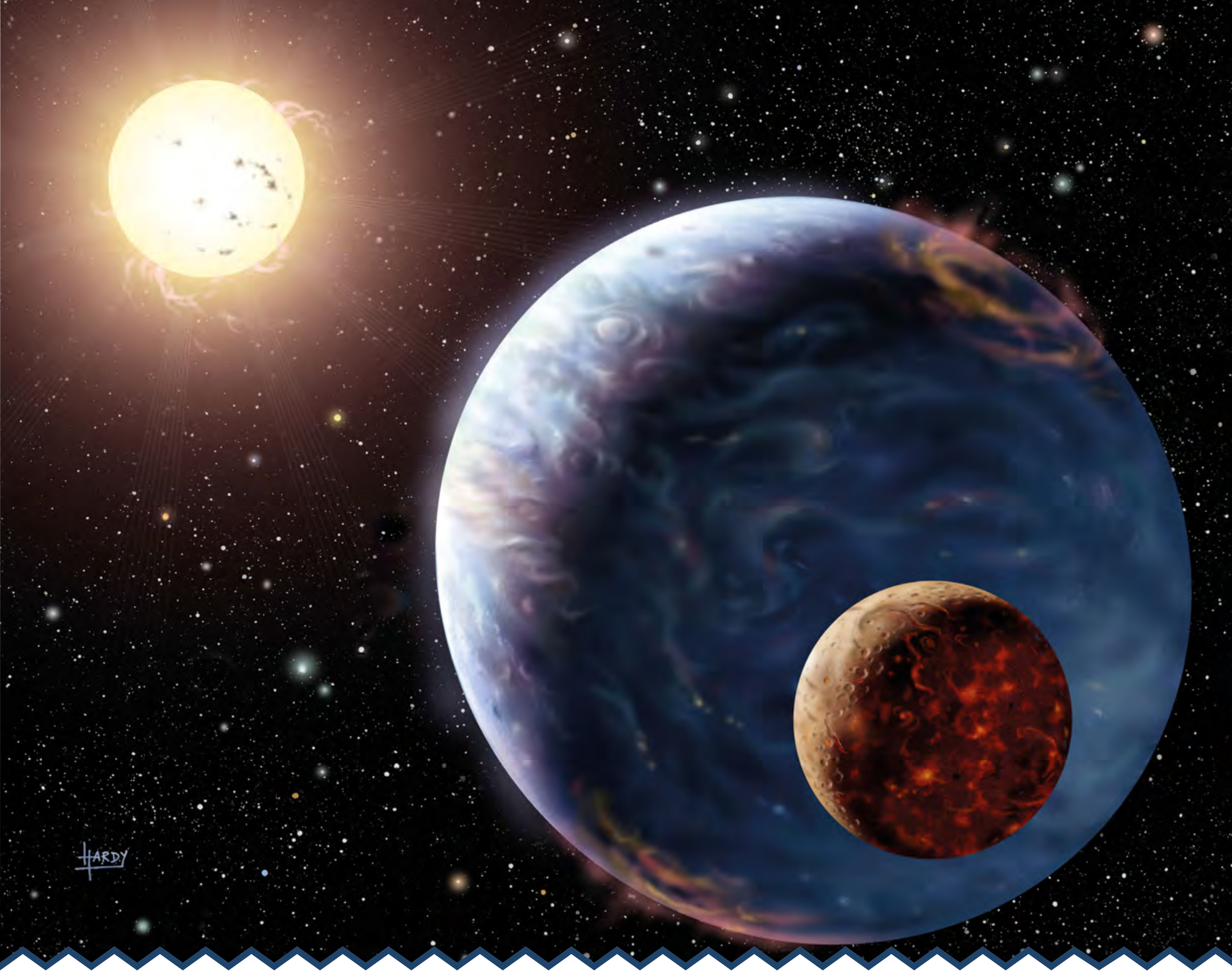

THE ATMOSPHERES OF EXTRASOLAR PLANETS

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The discovery of extrasolar planets, or "exoplanets" – *i.e.*, planets orbiting around other stars – may be seen as the major discovery of astronomy over the past two decades. About twenty years ago, in 1992, the first discovery of a couple of planets around a pulsar was announced by A. Wolszczan and D. Frail.

The discovery was based on an analysis of anomalies in the periodicity of the pulsar radio signal. Three years later, M. Mayor and D. Quéloz reported the first detection of an exoplanet around a solar-type star, 51 Peg. The method used this time was the so-called radial velocity technique, which consists of measuring the velocity of the star around the center of gravity of the star-planet system with high accuracy. This discovery, soon followed by many others, had an immense impact in the scientific community and beyond. While the idea of the plurality of worlds had been in the air for centuries and even

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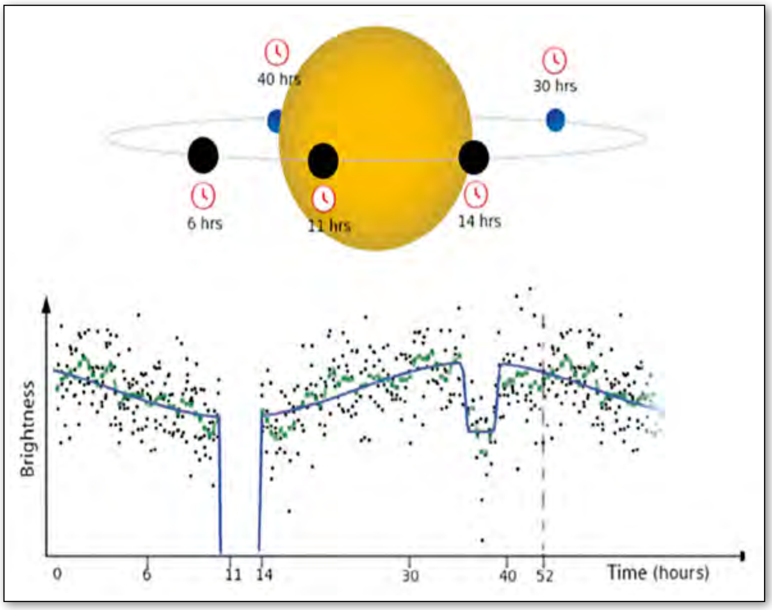

▲ **FIG. 1:** Upper part: Geometry of primary and secondary transits, which occur when the planet passes in front of the star and behind it. Lower part: light curve of the star during and between the two events. For a hot Jupiter, the depth of a primary transit may be about 1%. The depth of the secondary transit is significantly smaller. The light curve is maximal just before and after the secondary transit because the dayside of the planet (hotter than the nightside) is observed.

since Antiquity, the nature of the first observed exoplanets raised an immense surprise: the newly detected exoplanets were giant objects orbiting in the immediate vicinity of their host stars; they were thus very different from solar-system planets, and different scenarios had to be considered for their formation.

Since the beginning of the XXIst century, a new method has been successfully used. It consists of detecting transiting planets as they move across their host star: during the transit, the stellar flux is slightly reduced and this small decrease (about 1% for giant exoplanets) can be monitored by high-precision radiometry. This method, well adapted to giant planets orbiting close to their host stars, has proven to be very successful over the past ten years, thanks especially to the very successful *Kepler* mission, in operation between 2009 and 2013. Other techniques, including direct imaging, have also led to several tens of detections and are expected to be very promising in the near future.

As of today (December 2013), over a thousand exoplanets have been discovered in about 800 planetary systems. They show an incredible diversity in their masses, densities, and orbital properties. The masses range from several Jovian masses down to less than a terrestrial mass; their density range exceeds by far the one of solar system planets. The distribution of the mean distance to their host stars shows two maxima, one at close distance (about 0.04 au*) – this category includes the giant exoplanets first detected by velocimetry – and another one at a few au (but this might be an observational bias). Some exoplanets have highly eccentric orbits. From statistical studies based on *Kepler* data, it appears that nearly each star in the Galaxy might be surrounded by a planet.

How to form an exoplanet?

The huge diversity in the physical and orbital properties of exoplanets forces us to reconsider the model of planetary formation currently accepted for the solar system. This model is based upon the properties of planetary orbits, mostly coplanar, circular and concentric around the Sun. Following the early concepts developed by Kant and Laplace in the 18th century, it is now agreed that solar system planets formed within a disk, following the gravitational collapse of the fragment of an interstellar cloud in fast rotation. The Sun formed at the center and, within the disk, planets formed by accretion of solid particles. Near the Sun, the only available solid particles were made of rocks and metals. As heavy elements (formed by nucleosynthesis in stars) are relatively rare, the planets formed in this region – the "terrestrial", or "rocky" planets – were dense but small in size. In contrast, at larger distances from the Sun where the temperature was lower than about 200 K, the more abundant elements (oxygen, carbon and nitrogen) could be incorporated in solid nuclei in the form of ices (H_2O, CH_4, NH_3...), making it possible for nuclei to reach a mass of about ten to fifteen terrestrial masses. Beyond this critical mass, they were able to accrete the surrounding nebula – mostly made of hydrogen and helium – through gravitational collapse. This process explains the formation of giant planets, characterized by a large mass, a large volume and a low density, surrounded by a system of rings and satellites. The limit between the two kinds of planets is the distance of water condensation (at about 180 K) that defines the snow line.

This scenario naturally predicts that small rocky exoplanets are expected near their host stars, while giant exoplanets should be found at larger distances. How can this be reconciled with the discovery of many giant exoplanets near their stars? A new mechanism has been invoked to raise this apparent contradiction. According to current formation models of planetary systems, the first step of planetary formation takes place in a protoplanetary disk, with giant objects formed far from the star, as for the solar system; but a migration process soon takes place as a result of planet-disk interactions, and the giant exoplanet migrates toward its host star. For still unclear reasons (possibly a truncation of the disk's inner edge), the inward migration process often stops at about 0.03 - 0.05 au, before the planet is immerged in the star. From the observations of exoplanets' physical and orbital properties, this process appears to be relatively common in other planetary systems. By the way, recent numerical simulations suggest that solar system giant planets also encountered some migration effects, although less extreme than observed around other stars.

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* The astronomical unit (au) is the mean distance between the Earth and the Sun, *i.e.* about 150 million kilometers.

What are exoplanets made of?

The transit method allows us to retrieve the radius of an exoplanet and its distance to the host star; coupled with radial velocity measurements, its mass and density can also be inferred. However, knowing the density of a planet is not sufficient to determine its nature. An object of density close to 2 g/cm^3 may be an icy body or a mixture including a rocky/icy core and a hydrogen envelope. The only way to understand the nature of an exoplanet is to characterize its atmosphere. Over the past decade, a new method has emerged: the spectroscopy of transiting exoplanets. The idea is to measure the spectrum of the exoplanet as it transits in front of the star (primary transit) or behind it (secondary transit; Fig. 1). The planetary spectrum is obtained as the difference between the star's spectra recorded either during the transit or before/after the transit.

Transit spectroscopy of exoplanets' atmospheres

Primary transit spectroscopy was first performed with the *Hubble Space Telescope* in the visible range, where atoms (Na, K) and ions (C^+) were first detected, and later in the near infrared, where molecules (H_2O, CH_4) were found (Fig. 2). In the case of primary transits, the planetary atmosphere is observed at terminator, and the spectral signatures are seen in transmission in front of the stellar continuum. Secondary transit observations lead to a direct detection of the dayside emission of the planet. This emission can be either reflected or scattered stellar light (typically in the visible range) or thermal emission from the planet itself at longer wavelengths.

In the case of giant exoplanets very close to their host star ("hot Jupiters"), the thermal emission dominates the whole near infrared range above 1 μm. In this case, molecular signatures can appear in emission or in absorption, depending on the temperature gradient of the atmospheric region where the radiation comes from. The interpretation of the spectra is thus more ambiguous and depends upon the temperature gradient. On the other hand, the molecular detection becomes more favorable in the mid infrared as the flux ratio between the planet and the star increases with wavelength. Several molecules (H_2O, CH_4, CO_2 and CO) have been identified in a few hot Jupiters, from data obtained with the HST in the near infrared range and the *Spitzer* satellite at longer wavelengths (Fig. 3).

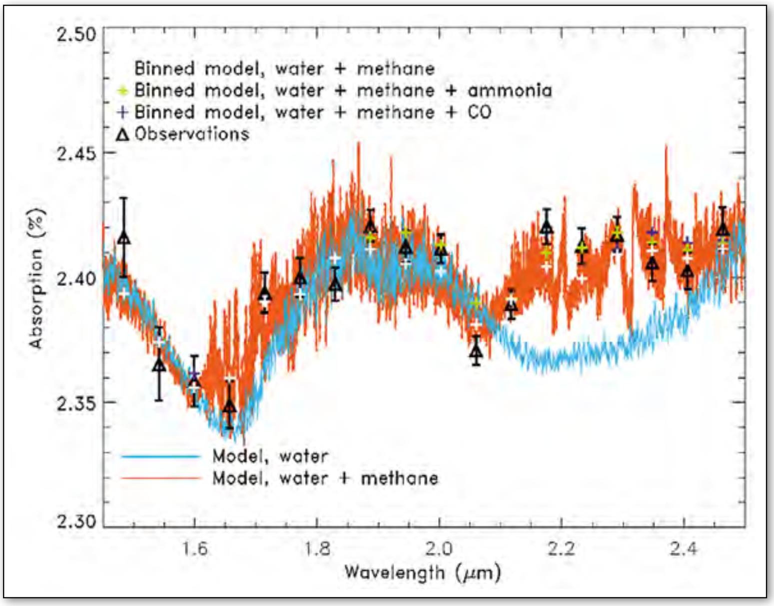
So far, spectroscopic observations of transiting exoplanets have been limited to bright targets, mostly hot Jupiters. This very promising technique, however, opens a new window in the exploration of exoplanets and should lead, within a couple of decades, to the atmospheric characterization of a large variety of objects.

Atmospheres of exoplanets: what can we expect?

Now that the characterization of exoplanets' atmospheres can be foreseen as technically feasible in a reasonable future, it is interesting to consider the problem from another point of view and try to infer the possible nature of an exoplanet's atmosphere, on the basis of its physical and orbital parameters. Knowing the mass of an exoplanet, its distance to the host star and the spectral type of this star, one can estimate its equilibrium temperature, *i.e.*, the temperature of a blackbody, which would receive the same amount of stellar flux. By analogy with solar system objects, the albedo of the planet (*i.e.* the fraction of stellar flux that is reflected by the planet) can be assumed to be in the range 0.03 to 0.3. Hot Jupiters (at distances of 0.03 - 0.05 au from their host stars) are found to have typical equilibrium temperatures in the range of 1000 K to 2000 K.

Assuming, as a first approximation, that the atmospheric composition of exoplanets is consistent with thermochemical equilibrium, one can estimate which molecule is expected to dominate under given temperature and pressure conditions. Regarding carbon and nitrogen, CO and N_2 are expected to dominate at high temperatures and low pressures, while CH_4 and NH_3 dominate under opposite conditions. This explains, to first order, why solar system giant planets are dominated by H_2, CH_4 and NH_3 while rocky planets (not massive enough to keep the hydrogen) are dominated by CO, CO_2 and N_2 (the Earth being an exception as the large abundance of oxygen results from the appearance of life). Water is also expected to be present in both kinds of planets, especially the giant ones, formed from big icy cores beyond the snow line.

▾**FIG. 2:** An example of primary transit observations of the hot Jupiter HD189733b. Data (black triangles) have been obtained with the Hubble Space Telescope. Models include absorption by water vapor (red curve) and by water vapor and methane (blue curve). Comparison with data shows that both water vapor and methane are present. The figure is taken from M. Swain *et al. Nature* **452**, 329 (2008).

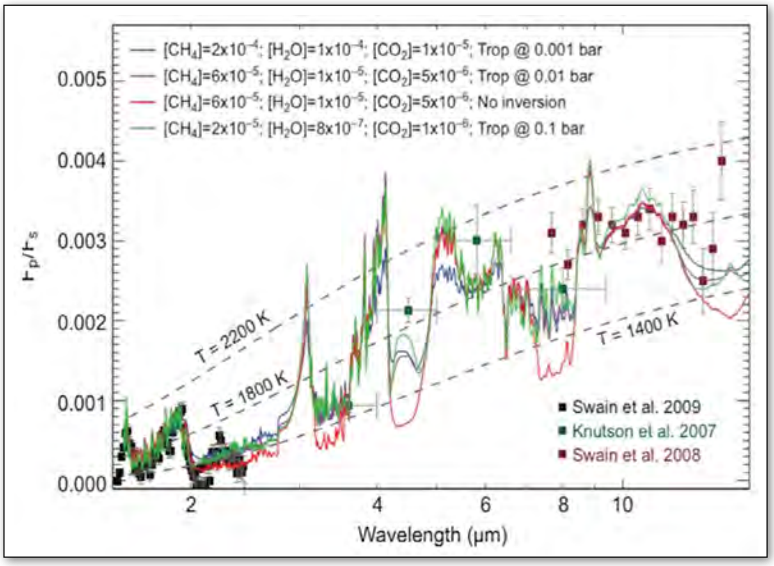


Following these remarks, a simple classification can be proposed for understanding the atmospheric composition of an exoplanet. Two parameters are important: its mass and its equilibrium temperature T_e. The value of T_e is to be compared with the temperature of the snow line, *i.e.*, 180 K.

1) If the exoplanet's mass is below ten terrestrial masses, the object can be considered as either a rocky planet (if $T_e > 180$ K) or a small icy planet (if $T_e < 180$ K). A proxy would be Mars or Venus in the first case (N_2, CO_2, CO, possibly H_2O atmosphere), Titan in the second case (N_2, CH_4 atmosphere).
2) If the exoplanet's mass is above about 15 terrestrial masses, the object is expected to have accreted the surrounding protostellar gas (mostly hydrogen and helium). Its atmosphere is thus expected to be dominated by these gases. In the case of hot Jupiters, one can expect a CO/N_2 composition very close to the star, and a CH_4/N_2 or CH_4/NH_3 composition at increasing distances from the star. For low values of T_e (< 180 K), we find the case of the solar system giant planets, dominated by H_2, CH_4 and NH_3.

It should be pointed out that this oversimplified model has strong limitations. First, no migration is assumed, while we know that this process is common in planetary systems. Migration is a likely mechanism, which could possibly explain two kinds of exotic hot exoplanets. Some are giant objects with a very low density, as HD209458b ($d = 0.36$ g/cm^3). These objects could be "inflated Jupiters" whose atmosphere is escaping due to very high exospheric temperatures. Other small and very hot objects exhibit a high density, much larger than the one of a rocky planet. It has been suggested that these objects might be the leftovers of big cores, formed far from the star and once surrounded by a massive gaseous envelope. They would have been subject to a strong compression factor, and they would later have migrated toward their host star – thus losing their gaseous envelopes through atmospheric escape processes – in a time short enough for their cores to keep their high density.

▾ FIG. 3: An example of secondary transit observations of the hot Jupiter HD209458b. Data (black points) have been obtained with NICMOS on the HST (short wavelengths) and Spitzer (long wavelengths). Different models include different molecular contents and different vertical temperature profiles. The "Trop" label refers to the level of the tropopause, *i.e.*, the level where the atmospheric temperature is minimum; the pressure of this level is indicated in the figure. In the red model, which has no temperature inversion, the strongest molecular signatures appear in absorption. In the three other models, which use a temperature inversion, they appear in emission. The figure is taken from G. Tinetti and C. Griffith (2010) in "Pathways toward Habitable Planets", *ASP Conference Series* 430, 115 (2010).



Other processes, known to be at work in solar system planets, may lead to departures from thermochemical equilibrium. The first one is transport-induced quenching which may bring disequilibrium species from the interior up to upper atmospheric levels by vertical motions, at a timescale shorter that the destruction lifetime of the species (this is the case, in particular, for PH_3 in Jupiter and Saturn). The second mechanism is photochemistry, which leads to the formation of new species, like the stratospheric hydrocarbons formed in the giant planets' stratospheres from photodissociation of methane. From the few measurements presently available on hot Jupiters, it already appears that departures from thermochemical equilibrium might occur. Most likely, new measurements will bring new surprises and will be diagnostics of other possible physicochemical processes.

A bright future

While the first spectroscopic observations of transiting exoplanets were mostly achieved from space, with the *HST* and *Spitzer*, more and more observations are now performed from the ground, using 3-m to 10-m class telescopes. In the near future, ongoing developments in the ground-based instrumental performances, the sizes of the telescopes and the data processing algorithms will allow us to characterize the atmospheres of more and more exoplanets. A key milestone will be the extremely large telescopes and, in particular the *E-ELT* of the European Southern Observatory, presently under development, whose first light is foreseen by the beginning of the next decade.

In parallel, the 6-meter *James Webb Space Telescope*, expected to be launched in 2018, will be of major interest for recording high-resolution spectra of bright targets. However, the best tool for characterizing the atmospheres of a large sample of exoplanets will be a dedicated space mission, capable of recording simultaneously the visible and infrared spectra of a large number of objects. The *EChO* (*Exoplanets Characterization Observatory*), submitted to the European Space Agency in the frame of the Cosmic Vision programme, is designed for this purpose. It includes a 1-m-class telescope to be located at Lagrange point L2, equipped with a spectrometer covering the wavelength range 0.4 μm to 16 μm, with the objective of measuring the spectra of a wide variety of objects, from hot to temperate, over a wide range of masses, from Jupiters to super-Earths. If selected, the *EChO* mission, planned for a launch in 2022 and a lifetime of at least 4 years, is expected to open a new window in our understanding of exoplanets' atmospheres, in the same way as the *Kepler* mission has revolutionized the inventory of extrasolar planets. ■

About the Author

Thérèse Encrenaz is Emeritus Scientist at Paris Observatory and a specialist of planetary atmospheres. Director of the Space Research Department of Paris Observatory (1992-2002) ; Vice-President of Paris Observatory (2007-2011). She has received the David Bates Medal of the European Geophysical Union in 2010.

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