Chapter 6

Hot Jupiters

Gas giant exoplanets

Ever since the first planets around stars other than the Sun were discovered in the 1990s, we have learned quite a lot about exoplanets, with more than a thousand of all types and sizes now detected.

It turns out that planets are a very common by-product of the formation of stars from interstellar gas. When a new star is formed, more often than not it is accompanied by a host of planets, comets and asteroids. The best current estimates, by the NASA Kepler space planet-search mission, is that planets of the size of Earth are common, and number in the billions in our galaxy.

For the largest and most amenable to observation among the exoplanets, we have a chance to become personal, collecting not only their names and addresses, but also some of their intimate details and life history. One category of planets in particular has been the subject of intense scrutiny since the early 2000s, the *hot Jupiters*.

Hot Jupiters are similar in mass and composition to our Jupiter and Saturn. Like stars, they are mostly made up of hydrogen and helium, with a few percent of heavier materials such as water, rocks and metals. The difference is that they orbit much closer to their star than any planet in the Solar System, so close that they complete one orbit – their "year" – in only a few days, whereas Jupiter takes 11 years to circle the Sun.

Surveys suggest that about one in every 100 stars have a hot Jupiter close to them. This is surprisingly common, because before hot Jupiters were discovered, no planetary scientist predicted that gas giants would be found so close to their host star – the typical orbital distance of hot Jupiters is 1/20th of the Earth-Sun distance.

Hot planets

The proximity of the star is a crucial factor for a planetary atmosphere, as the differences between Venus, Earth and Titan illustrate. Venus is a scorching inferno, Earth a pleasant paradise (well, some of it), and Titan a frozen tangle of methane lakes, mostly because of their distance to the Sun.

Fig. 6.1 Size of the star 51 Pegasi seen from its hot Jupiter companion, and the Sun from Venus, Earth, Mars and Titan (from left to right).

Hot Jupiters receive enormous amounts of starlight, hundreds of times more than the Earth, which brings their atmospheric temperature above one thousand degrees Celsius.

Moreover, because their rotation is locked to their orbit, this heat is received only on one side of the planet, the "day side". The other side faces the dark cold of space.

The main problem for hot Jupiters' atmospheres is therefore dealing with this very simple issue: how to transport these massive amounts of heat around the planet, away from the infernal day-side towards the dark side.

Hot Jupiters cannot do that simply by spinning on themselves like the planets in the Solar System, their stars would not allow it.

When a gas planet orbits close to its much heavier star, it is welded into a teardrop shape by the gravitational pull of the star. If the planet spins faster on itself than it orbits around the star, the tip and bulge of the teardrop experience a strong pull that tends to bring them back towards synchronised rotation. In the same way, the Earth's

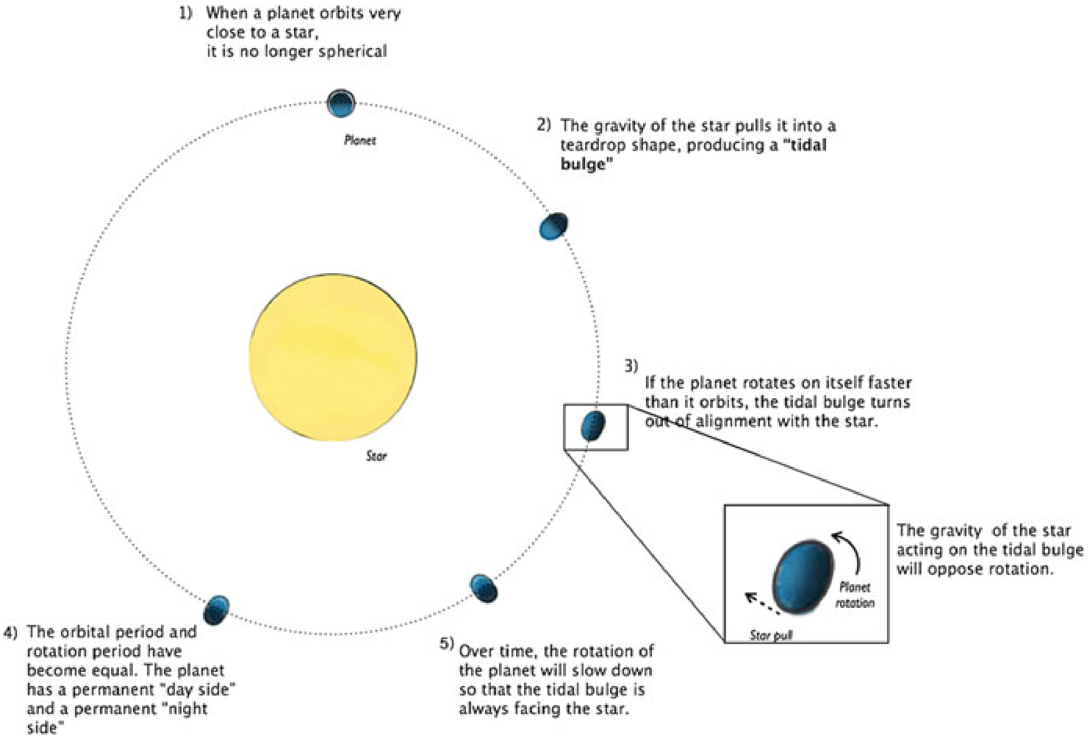

Fig. 6.2 Tidal synchronisation: when planets orbit close to their parent star, the pull of the tides on the planet synchronises the orbit with the rotation, so that the planet always presents the same side to the star.

Moon pulls the oceans out of shape and towards it twice every day on Earth, which is why this process is called *tidal* for exoplanets as well. Over time, the pull of the star wins over the spin of the planet, and the planet is forced into synching its spin with its orbit, and forever lining up its teardrop shape towards the star.

This is what happened to our Moon: it used to spin rapidly on itself, but over a few million years the gravitational pull of the Earth has slowed it down so that its heavier side now always faces towards us. Its orbital and rotation period have become identical, at 28 days. This is why we always see the same face of the Moon. An observer on the Moon, by contrast, sees the Earth spin on itself every day, because the gravitational pull of the Moon has not been enough to slow down the Earth sufficiently[12].

The temperature difference between the day side and the night side of hot Jupiters can be so strong that, in order to bring the heat from one side to the other, jet streams are pushed to velocities higher than the speed of sound (which is around 5,000 kilometres per hour in a hot Jupiter atmosphere, because sound travels faster in a lighter, hotter gas). When an atmospheric jet breaks the sound barrier it can create a shockwave. As the supersonic wind blasts into more slowly moving currents it cannot push them out of the way fast enough (the speed of sound is the speed at which "pushes" propagate through an atmosphere), causing the shockwave. In other words, the star's heat makes the atmosphere blast away from the day side!

What pattern do these jets follow? One could imagine a petal-shaped circulation, with the winds moving out in all directions from the centre of the day side (the point directly under the starlight), by the shortest path towards the night side. But although

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[12] Although it did slow it down quite a lot. We now know that the Earth was rotating faster in the past. Geologists have found out that the duration of days has lengthened over the eras. For instance, a day was about 21 hours long in the Cambrian era. This is inferred from measuring how many days there were in a year from sea shells that grow a bit every day, and faster in the summer than in the winter.

the planet is always presenting the same face to the star, it is still spinning on itself – with a period equal to its orbital period. The rotation of the planet will, as on other types of planets, make polewards motion of currents more difficult than motions along latitude lines, so the atmospheric circulation will generally settle into global eastward jets, like on Venus.

These eastwards currents have been observed on one hot Jupiter, "Isis"[13], that we mentioned in the Preface.

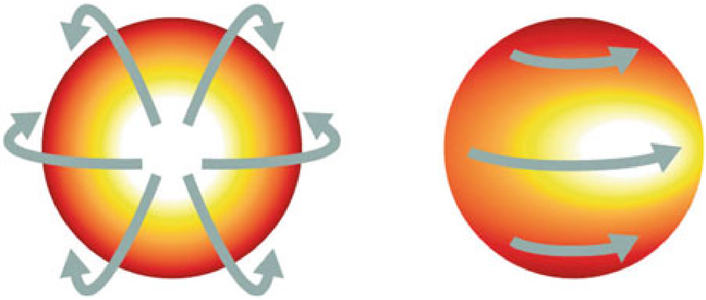

Fig. 6.3 Petal-like circulation versus super-rotation – two possible ways to bring the heat from the day side to the night side of a hot Jupiter. Free-for-all winds rushing away from the hottest point, or global eastward currents.

Because of their high temperatures and the constant swirling of their atmospheres that whip up the planetary interiors by injecting heat into them, hot Jupiters can expand to sizes much larger than our own Jupiter, sometimes even to the point of slowly leaking gas into space. Osiris in the Pegasus constellation is surrounded like a comet by a gigantic tail of gas lost from its atmosphere. It is 1.3 times the size of Jupiter. The largest exoplanets we know reach twice the size of Jupiter, which is about eight times the volume, and larger than some diminutive stars.

A hot Jupiter tour

Let us embark on a spaceship and travel to the two nearby hot Jupiters that we know best, the ones that I have been calling Osiris and Isis, with official names HD 209458b and HD 189733b.

To travel to Osiris, we head for the constellation Pegasus in the northern sky, then straight ahead for 150 light-years or so, with occasional corrections to keep the star in our sights. On the scale of our galaxy, we are still in the solar neighbourhood. Not only have we not left the block, we are just in another room of the same building. As we draw nearer to the star, we notice a tiny speck of light glistening on its side. A mere ten star-diameters away from it, Osiris displays its splendid crescent, a dark, purplish glow basking in its host's glaring light.

Aspects of Osiris

The parent star of Osiris is a common sort of star, similar to the Sun except for a slightly higher temperature. Osiris is one of the "bloated" gas giant exoplanets, even larger than Jupiter. It orbits twice a week around its star, twenty times closer than the Earth is to its Sun. Its peculiar dark purple colour is due to the absorption of light by sodium – which swallows most of the incoming starlight, starting with orange.

The atmosphere of Osiris does not show the banded structure of Jupiter and the

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[13] On the topic of planet naming, see notes at the end of the book.

other outer planets of the Solar System. Because of tidal locking its rotation period has to be identical to its orbital period, about three and a half days. In Chapter 5 we saw how a slow rotation implied wide-scale, planet-embracing weather patterns, and this is what we expect on Osiris.

The atmosphere of hot Jupiters is so hot that none of the molecules that we have encountered before in planetary clouds will be able to condense. Methane, ammonia, water, sulphuric acid, carbon dioxide, all these are far above their evaporation point, so they cannot condense into droplets or crystals to form clouds. All these molecules dissolve in a hot, transparent gas.

Could the whole atmosphere remain transparent, or could the whole planet be like a gigantic drop of water hovering in the sky, with the stars in the background showing through? This does not happen because forming clouds is not the only way for gases to absorb light.

The other way, that we know from measurements but for which we do not have a good intuitive grasp, is direct absorption of light by atoms. This is how ozone intercepts the harmful ultraviolet light from the Sun in the stratosphere, or how chlorophyll in plants captures sunlight to store energy.

In the hot gas atmosphere of Osiris, most of the incoming sunlight is captured by sodium and potassium.

Atoms capture photons by using their outer electrons as fishing nets. The more loosely their electrons are connected to the nucleus, the easier for them it will be to catch photons. In most atoms the electrons are too tightly attached to the nucleus to allow them to absorb photons of visible light. Only higher-energy photons, in the ultraviolet part of the spectrum, have sufficient energy to reach the inside of the atom. The exception is the *alkali* elements. These are the atoms in the first row of the Periodic Table of the elements, the first two being sodium and potassium. Their inner electron layers are full, and they have just one solitary electron in the outermost layer. This is the most favourable configuration for the absorption of light by an atom: the last

Fig. 6.4 Sodium gloom.

electron will be only loosely bound, available for other functions such as catching light or hooking to another atom.

In fact, the alkali elements are known chemically for their propensity to share their solitary electron very easily, which makes them chemically very active. They are eager to react with elements at the other extreme of the table, which lack only one or two electrons to complete their outer layer, like oxygen or chlorine. Such a reaction readily occurs between sodium and chlorine, yielding NaCl, table salt.

Another use of sodium that is related to the looseness of its outer electron is its use in city street lighting, the source of the slightly gloomy orange glow of modern suburbs. Sodium atoms can absorb visible light, and according to the laws of quantum physics that means they can also emit it. In a sodium lamp, sodium vapour is heated electrically until the outer electrons produce photons at the specific wavelength of sodium, orange.

In elemental form, sodium and potassium are light metals that look light grey, a bit like aluminium, except that they are soft as clay and easy to cut with a knife. Both elements are extremely reactive with water. Put into contact with H_2O, they steal the water's oxygen in a fast reaction. Pieces of sodium dropped in water burn and fizz until there is nothing left; potassium explodes instantly.

In the hot, transparent atmosphere of Osiris, sodium and potassium atoms capture most of the incoming light from the star. Paradoxically, this means that transparent-air hot Jupiters are very dark when viewed from space, because very little of the starlight will make its way back into space. Osiris is about as reflective as a piece of coal.

Also, somewhat paradoxically, the planet's colour will be "anti-orange". Since the atmosphere will catch orange light first, the planet will glow in the complementary colour, an ambiguous purple tinge.

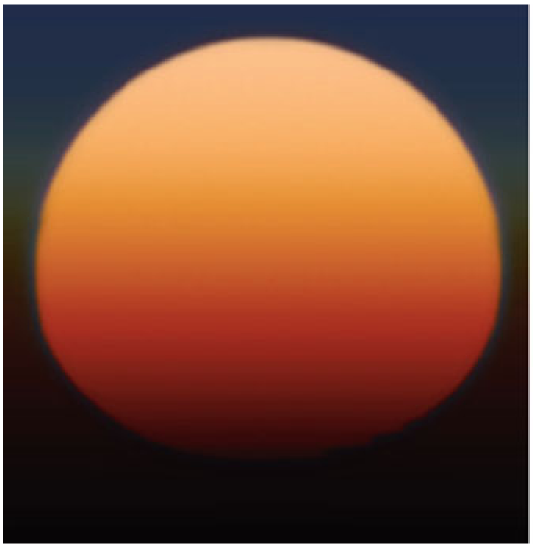

Fig. 6.5 Sunset on Isis.

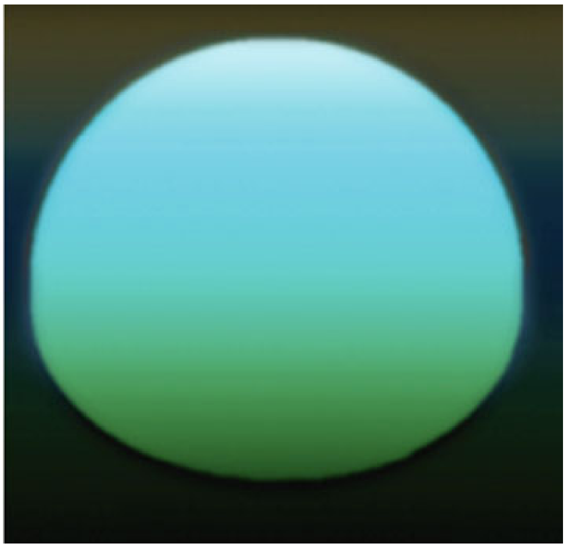

Fig. 6.6 Sunset on Osiris.

Alien sunsets

We also know quite accurately what sunsets look like on Isis and Osiris. The colours of the setting star in the sky of the planet are exactly what is measured when collecting the spectrum during a transit, which was done for both planets with the Hubble Space Telescope, and the precision of the data is sufficient for a translation into colours as perceived by the human eye.

I have attempted this translation for these two planets. On Isis the sunset looks like a glorious sunset on Earth, on a very clear day with some dust in the air. This is because in both cases, Rayleigh scattering is the dominant mechanism. On Earth the scattering is caused by molecules and air-borne dust in the air. On Isis the Rayleigh scattering is thought to be caused by silicate dust. One key difference with a sunset on Earth is that the "Sun" appears much larger from Isis, because the planet is so much closer.

Osiris by contrast has a sunset that looks truly alien. The star is white outside the atmosphere since its temperature is close to that of the Sun. It then acquires a bluish tinge as it sinks deeper, because the absorption by sodium removes the red and orange from the starlight. Deeper down, Rayleigh scattering by the molecules in the atmosphere starts scattering the blue part of the spectrum as well, so that the only frequencies that are able to squeeze past are green, then murky brown. Outside the star's disc the atmosphere has a faint glow in its upper parts due to re-emission in the sodium lines; then it become bluer because of the Rayleigh scattering.

Rock and iron clouds

At 1,000 degrees Celsius and above, the temperature on hot Jupiters is much too high for carbon dioxide, water or methane to exist in liquid or solid form, but other substances can resist such temperatures. As a rule of thumb, heavier molecules evaporate at higher temperatures, so to find these refractory compounds we have to move down the Periodic Table into the realm of rocks and metals.

The most abundant of those are silicate rocks and iron, which will form tiny droplets when the temperature of the gas in a hot Jupiter cools, for instance when currents enter the obscure side of the planet. These droplets of glass (amorphous silicate) and metal can form clouds. On hot Jupiters, lava just rains out of the air, and glass storms lash out at sunset.

After Osiris, the next destination of our imaginary spaceship is Isis, a planet slightly cooler and shrouded in such glass clouds. We will approach this new giant planet and send a smaller capsule into its atmosphere, just like the gallant Galileo probe plunged into the clouds of Jupiter in 1995.

Travel to Isis

We now head towards the star HD 189733, 63 light-years from the Sun. Seen from Earth, the parent star of Isis is close to the spectacular Dumbbell Nebula, and we could take it as a landmark (skymark?) in our trip; but seen from Osiris the star appears in the direction of an entirely different region of the sky.

As we come closer, it becomes apparent that the host star of Isis is very different from the Sun, it emits a deep orange light. Eclipse shades reveal that its surface is sprinkled with dark star spots, which slowly drift across its face every few days.

Star spots

Stars have atmospheres too! Boiling, violently turbulent mixtures that bubble and burst from the inside to evacuate the intense heat of the nuclear reactions taking place in the core. One key difference with planetary atmospheres is that the intense heat – five or six thousand degrees Celsius – has stripped many atoms of one electron. As a result, the gas is a hot plasma that carries electric charges and responds to magnetic fields. On the intense boiling surface of the star, the magnetic field is tweaked and twisted in complex and ever-changing patterns, that channel the flow of plasma. In some regions the magnetic field becomes strong enough to prevent the hotter, lower layers from bubbling up to the surface. This produces temporary regions with lower temperatures – the star spots. Seen from the side, star spots are also regions where the stellar atmosphere is shallower.

Fig. 6.7 The atmosphere of the Sun. Image credit: NASA

Aspects of Isis

As on Osiris, powerful eastward jets transport the heat from the day side to the night side of the planet, whizzing past at 2,000 kilometres per hour. The temperature map of the atmosphere of Isis, measured with the Spitzer infrared space telescope, shows that the night side is heated to 700 degrees Celsius, proving that a large amount of heat is blown from the day side.

Because Isis spins slowly (its rotation is locked by tides), the weather features in the atmosphere are swirling across the whole planet. None of the tight banding and eddies of Jupiter here, more like the steady, obstinate flow around Venus.

Our spaceship edges closer to the planet and settles into orbit around it. Unlike the gas giant planets in our Solar System, Isis has no rings or moons to embellish it. The gravitational perturbation from the nearby star would rip them away in a short time.

Let us now complete one orbit around the planet. The day side is blindingly bright. Because the star is so close, the planet is a hundred times brighter than the full moon and eclipse shades are essential to look at it. Most of it is a deep featureless expanse, but some denser dust clouds occasionally trace the eastward currents. An oval hurricane can faintly be seen near the North Pole.

As we plunge towards the night side the star sets behind the planet, and everything is abruptly plunged into darkness. We can remove our shades and as we let our eyes adapt, one by one the outer stars appear in front of us. As we turn back to look at the planet a ghostly vision greets us. The night side is glowing with a deep, vibrating red hue, with swirls and tentacles tracing the paths of the hot currents flowing in from the day side. The raging wind is so hot that it produces the characteristic red glow of cinder and hot metal, a thermal emission that all bodies produce with a wavelength corresponding to their temperature. The Earth's thermal emission is completely in the infrared, and without special infrared goggles it is impossible to perceive even on the darkest of nights. Around 700 degrees Celsius most of the radiation is still in the infrared, but some spills into the visible red so the glow becomes perceptible to the naked eye.

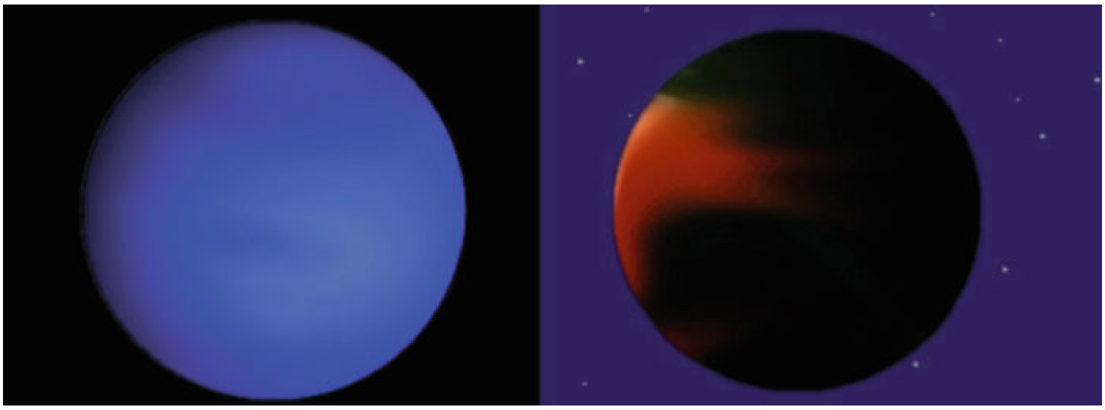

Fig. 6.8 The bright side (left) and dark side (right) of Isis. The bright side is dark blue, possibly because a haze of glass droplets reflects blue light from the star and sodium gas absorbs red light. On the dark side, the hot currents blowing eastwards from the day side emit a red glow because of their high temperature.

The beauty and majesty of the night side of Isis at close range rivals that of Jupiter, in a different category. It has none of the elaborate bands, swirls, eddies and colours of our giant companion, but a single majestic broad-brush spectral theme.

And suddenly, as we approach the edge of the night side, the host star HD 189733, rises again and floods everything with intense light. The star is red in colour because it is markedly cooler than the Sun (merely 4,800 degrees Celsius compared to the Sun's 5,500 degrees Celsius). HD 189733 is also fainter than the Sun, but in our story we are so close that the brightness at this distance is many times stronger than the Sun seen from Earth. Another amazing view, never seen on Earth: a flood of red light many times brighter than sunlight at noon, a stunning view that may remain imprinted forever in our blinded retina if we don't put our eclipse shades back on very fast.

Taking the plunge

What we can learn about the atmosphere while remaining in orbit is limited. What is the haze made of? What lies underneath? Let us send a brave little probe covered with instruments to do this work for us. It seems safer to stay in the orbiter and record the results; the pressure and temperature conditions down there are not welcoming, and with the gravity of the planet it would be nearly impossible to crawl back out again.

Dropping from orbit, the probe falls towards the planet at such speed that it will cross the whole upper atmosphere in less than a minute, until friction slows it down. As it flashes by like a shooting star, the instruments quickly record the colour of the sky – light blue, no surprise there – and gathers spectroscopic snapshots that measure the composition of the atmosphere.

Compared to the previous hot Jupiter that we have visited, the colour of Isis is strikingly different. No more sodium anti-orange here, the planet is profoundly blue, as blue as the deep blue sea. This is not due to oceans, but to a cover of haze and dust that scatter the incoming starlight. An atmosphere that scatters light will acquire a deep blue colour, whatever the source of the scatter, provided the particles doing the scattering are very small – like atoms and molecules in the air and sea. That is why the clear sky is the same blue as a clean sea.

Deeper down, as the probe sheds the thermal shield which protected it during the initial slow-down and opens its Kevlar parachute, it enters the zone of the haze or cloud of glass. The instruments work frantically to gather as many recordings as possible in the shortest time and send them back to orbit. Is the haze made of enstatite, a magnesium-rich silicate that produces shiny, sparkly grains? Or is it olivine, a dark silicate, common in Earth basalt, that would produce blacker clouds? Or could it be iron droplets? The droplets slowly rain down (if that is the correct term) but as they reach even warmer layers inside the planet they evaporate again.

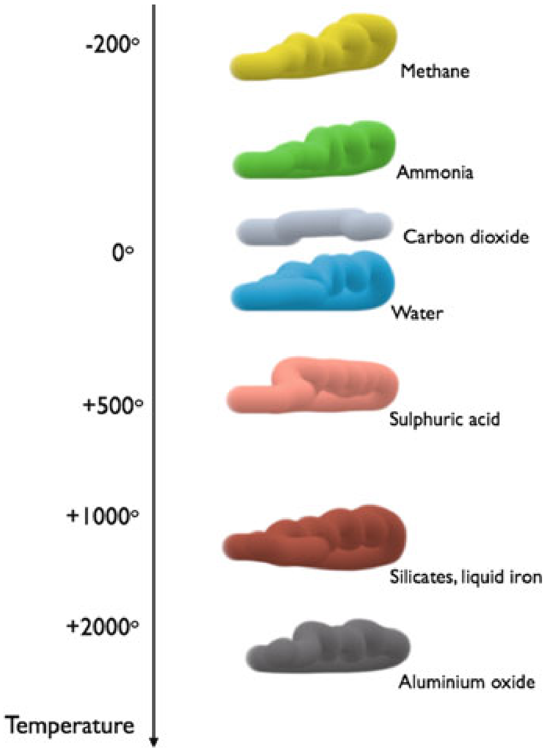

Fig. 6.9 Cloud-forming substances in planetary atmospheres for different temperatures. This is an extension of Fig. 5.10 to higher temperatures. Above 1,000 Kelvin, droplets and grains of rocks, salts and metals can form clouds.

The probe has now reached a level where the pressure is equal to one atmosphere, like at sea level on Earth. The temperature is close to 1,000 degrees Celsius however, and the searing heat starts creeping through the probe's thermal insulation.

How hot?

Temperatures above forty degrees Celsius are unpleasant for humans. In the dry air of a sauna people can endure temperatures up to 100 degrees for short periods of time. Kitchen ovens usually reach 220 to 250 degrees, and the temperature around an ordinary flame is around 300 degrees.

Intense fires – for instance when a whole room is on fire and reaches what is called the flashover point at which everything burnable spontaneously ignites – reach around +1,000 degrees Celsius. Temperatures in this range are the maximum possible for combustion of carbon compounds (wood, houses, oil, natural gas) with oxygen.

Fire-fighters use *proximity suits* to resist an ambient heat of 260 degrees Celsius. The tougher category of *entry suit*, designed to step straight into the flames, provides protection up to 1,000 degrees Celsius for short periods.

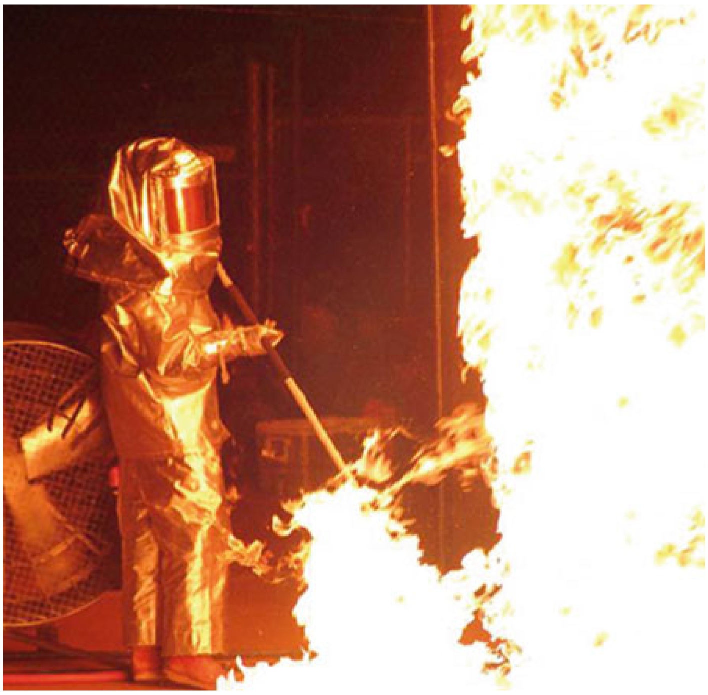

Fig. 6.10 A “fire entry suit” designed to spend short moments in contact with fires up to 1,000 degrees Celsius. Image credit: Meikangco.com

The thermal tiles coating the bottom and front of the Space Shuttle resist temperatures of up to 1,600 degrees Celsius for the duration of the re-entry, just a few minutes.

Most metals start melting at temperatures between 1,200 and 1,500 degrees Celsius, with the exception of a few soft metals like mercury, lead and tin which have much lower melting points, and some hardy metals like tungsten which can withstand more heat.

Thus, relatively cool hot Jupiters like Isis have atmospheric temperatures which a fire-fighter in the best protection suit would resist for only a few moments, and in which copper or gold would soften rapidly. In the atmosphere of even hotter hot Jupiters, the suit would fry in an instant, and iron and steel would evaporate.

Time for a glass of water…

…and time for our probe to let go of its parachute, and drop faster before the instruments melt down. It is now becoming very dark around the probe, and the star, a very deep red, has almost vanished in the murky sky. That is where compounds like water, carbon dioxide and methane should be most clearly detectable in the infrared. Quick, robot, take a few spectra and send them back to the base! Also fire off a few Kevlar balloons, floaters equipped with transducers, to measure the wind speed, the eddies and the turbulence in this chaotic and stifling atmosphere.

The temperature and pressure have now exceeded the resistance of the probe, and its metallic carcass slowly sinks down into the dark, deeper levels of the atmosphere of the planet, until it reaches temperatures that will melt and vaporise any metal.

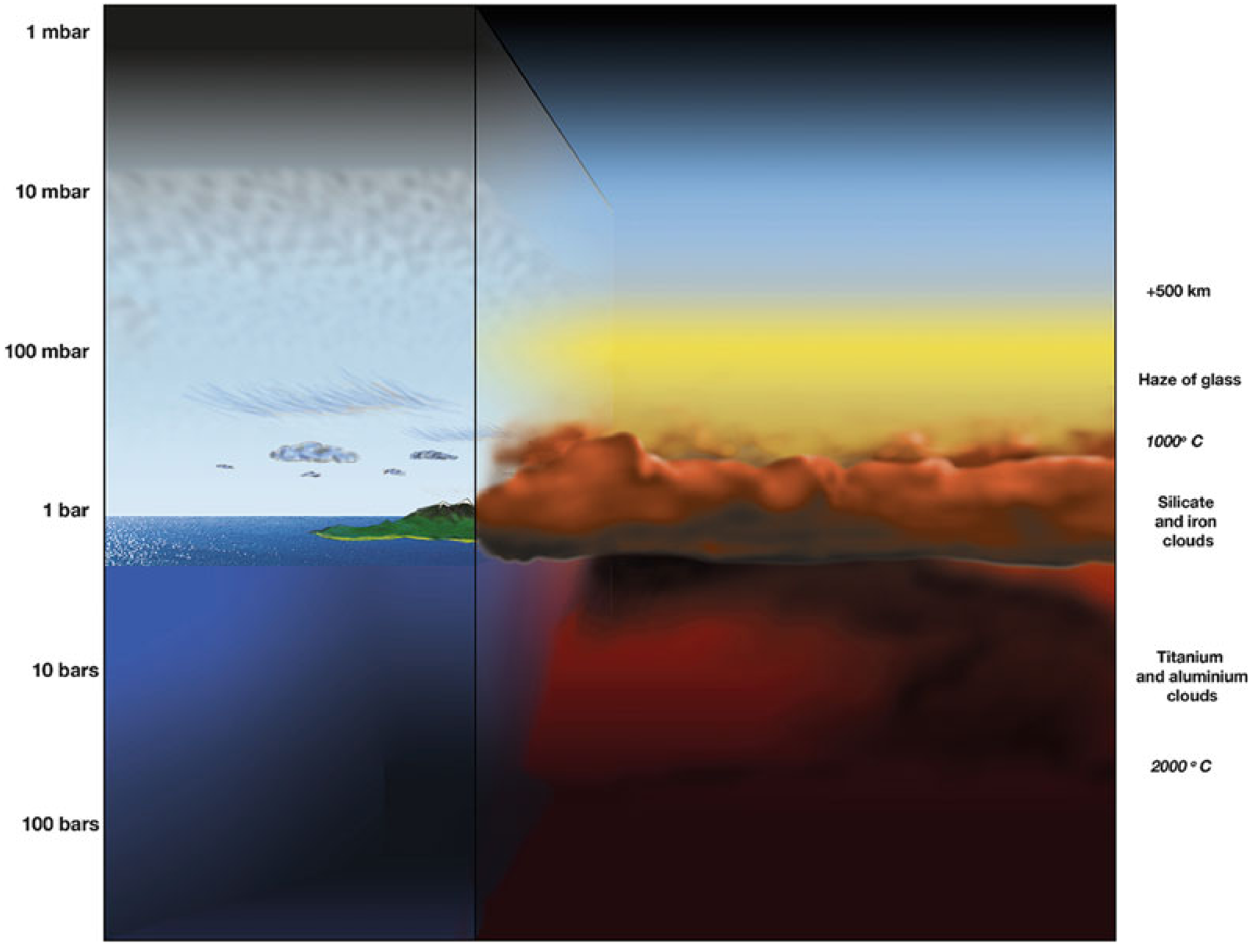

Fig. 6.11 Profile of the atmosphere of a hot Jupiter (based on present understanding of HD 189733b, “Isis”) compared to Earth on the same pressure scale.

Interlude

Observations

Of course, dropping a descent probe into the atmosphere of a hot Jupiter is a planetary scientist's fantasy, and will certainly not happen any time in the foreseeable future. Nonetheless, the details described in our imaginary journey to Osiris and Isis are based on observations made in the past decade from our distant vantage point back here in the Solar System. The direction and speed of the winds, the trail of escaping gas, the light of sodium, all have been measured with telescopes. But when we can't even see the surface of Pluto from Earth with the Space Telescope, it seems difficult to imagine how we could observe the atmospheres of distant exoplanets. If it is such a challenge merely to detect them, how can we be studying their atmospheres from so far away?

Exoplanets are indeed vastly more distant than the outer planets in the Solar System. Saturn is a bit more than one light-hour away from us, Neptune is four light-hours away. The distance to the closest star is three light-years, and the nearest gas giant exoplanets that we know of are dozens of light-years from us. At that kind of distance they appear no larger than a coin lying on the surface of the Moon, and their glow is fainter than a distant galaxy.

This is not the only problem. Space telescopes and giant telescopes on the ground can now detect and resolve extremely faint galaxies at the other end of the Universe. The real problem that astronomers face when investigating exoplanets is the proximity of their stars, which are obviously so much larger and brighter than any planets they might have. Clever tricks are needed either to avoid the glare of the host star to get a glimpse of the planet, or, like in martial arts, to use the strength of the host star against itself in order to reveal the planet.

Among the methods used to detect extra-solar planets, one of the most powerful techniques is to look for *transits* – this is when a planet happens to cross the disc of its host star. Two such events were observable from Earth in 2004 and 2012 when Venus passed in front of the Sun.

About twice per century, Venus crosses the disc of the Sun as seen from Earth. The event has played a key role in the history of astronomy. It has permitted us to measure the scale of the Solar System, therefore the size of the Sun and its distance from Earth, as well as the size of the other planets. The trick is to observe the transit of Venus

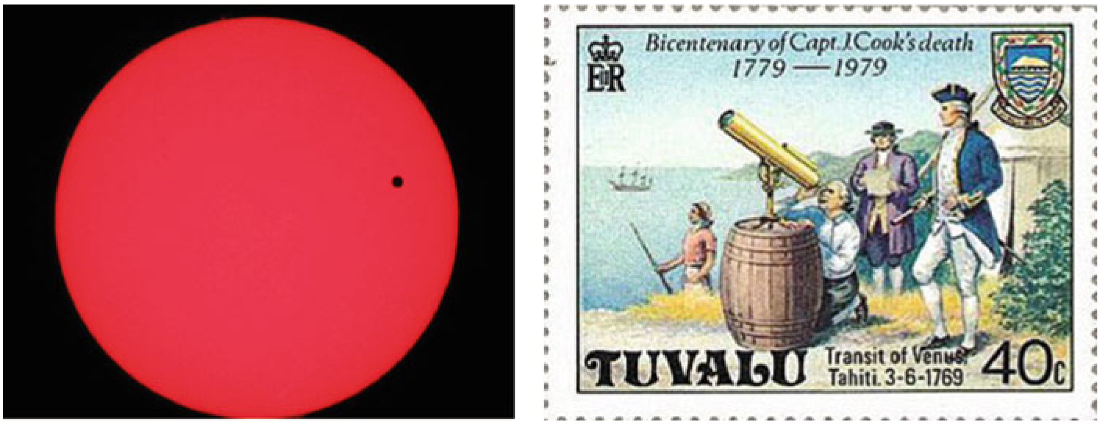

Fig. 6.12 and **6.13** The transit of Venus. Left: a photo of the 2008 transit. Image credit: Christine Wheeler. Right: commemorative stamp of Captain Cook's expedition to Tahiti for the 1769 transit.

from very different locations on Earth. The difference in the local time of the transit allows a measurement of the angle of the Earth as seen from the Sun, which provides the missing measurement to translate other observations like the apparent size of the Sun into real distances. Several expeditions were sent across the Earth to accomplish this key measurement for the two transits of 1761 and 1769, including the memorable expedition of Captain Cook to Tahiti.

In 2004 I was in Marseille on a bright summer day, using a small telescope to see our sister planet slowly crawl across the solar disc. Seeing an Earth-sized planet as such a puny dot on the Sun makes one realise the true scale of the Solar System. Early on a damp morning in June 2012, I found myself on a hilltop near Geneva trying to observe this again. It was a beautiful enough sight as the Sun slowly emerged over the lake, but low-lying clouds got in the way. This was rather a shame because the next transit of Venus is only due in 2117.

In the case of an exoplanet transit the stars are far too distant to be seen as discs. The trick to detecting transiting exoplanets is to monitor the total light of a large number of stars, and look for regular dips in the luminosity of some of them, which may be due to the transit of a planet.

For instance, in 2001 a telescope in the Chilean desert monitored a crowded patch of stars in the Milky Way to hunt for transits. One of the stars showed periodic dips that might have been due to a transiting exoplanet. But these measurements are difficult because the movements of air in the Earth's atmosphere blur the images and make it easy to confuse the light emitted by one star with that emitted by a neighbouring one.

With French colleagues we then used one of the European Southern Observatory's Very Large Telescopes in Chile – a behemoth with a primary mirror eight metres (26 feet) in diameter – to catch the transit with a higher precision. We also measured the motion of the star with enough precision to detect the tiny wobble induced by a planet orbiting around it. In that way we confirmed the presence of a transiting hot Jupiter

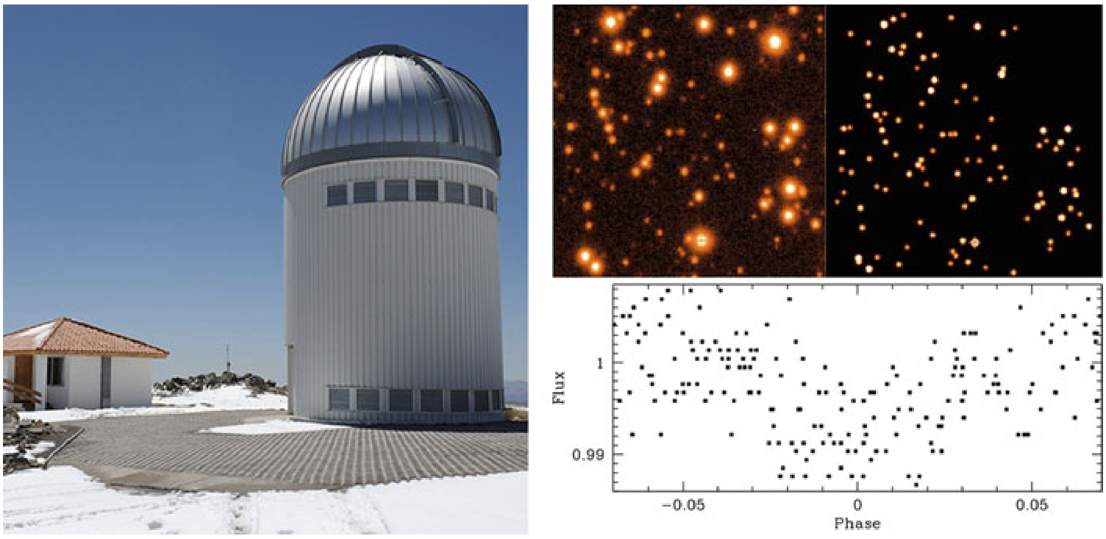

Fig. 6.14 The transit of OGLE-TR-132 with the Polish telescope (left) detected from the temporary dip in brightness (right). Image credit: Warsaw University Observatory at La Campanas

around the star, now called OGLE-TR-132b.

When a planet is detected by its transits, its size can be measured directly. The exact amount by which the stellar light dips when the planet crosses its disc is proportional to the surface of the planet. When combined with a mass measurement from the wobbles of the star due to the tug of the planet, we can get an idea of the density of the planet, and whether it is made primarily of gas or solid substances.

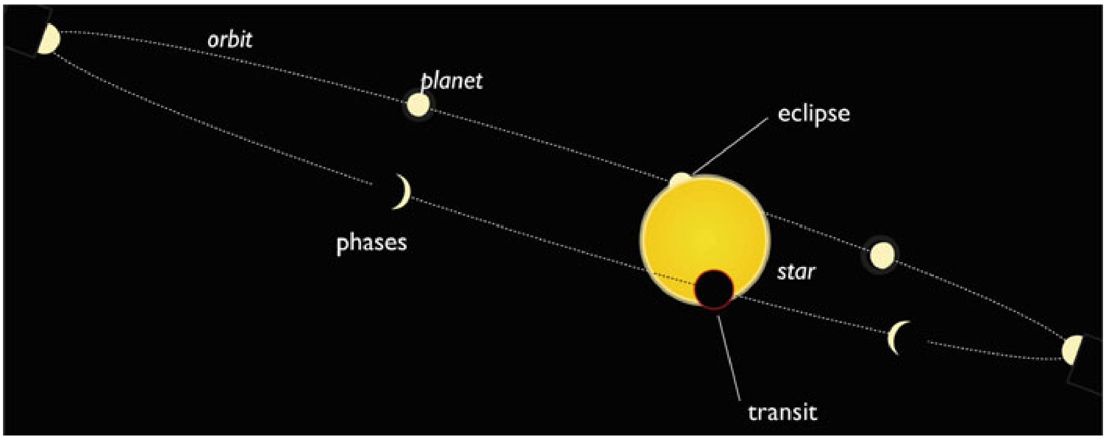

Fig. 6.15 The orbit and phases of a transiting planet.

It gets better: even if the transiting planet cannot be observed directly, with very sensitive measurements it is possible to measure its atmosphere. This is done in several ways. During the transit, if the planet has an atmosphere, some of the light from the star will filter through it before reaching the telescopes on Earth. This will make the planet look bigger in wavelengths where the atmosphere is more opaque, and smaller where it is more transparent. Which wavelengths of light an atmosphere absorbs or not reflects its composition and structure.

A second way to measure the atmosphere of transiting planets is to catch the

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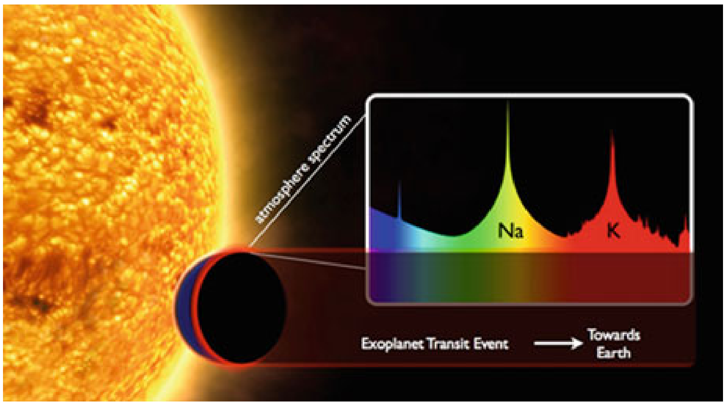

Fig. 6.16 Transmission spectroscopy: the spectrum of the atmosphere of a transiting planet can be reconstructed, because part of the starlight is filtered through the atmosphere during the transit. The spectrum of the planet in this sketch is dominated by sodium and potassium absorption, as expected for hot Jupiters without clouds. Image credit: David Sing

system at the other side of the orbit, when the planet disappears behind its star. The tiny resulting drop in total light will tell us how bright the surface of the planet was. Again, doing this at several different wavelengths yields a spectrum of the planetary atmosphere on the side facing the star. This difference in brightness is small: around 0.1 percent if it is a Jupiter-sized planet, to as little as 0.0001 percent for an Earth-like planet circling a Sun-like star.

A third piece of information is given by the phases of an exoplanet. This is the slight change in total light as the planet moves around its orbit, and presents different sides to us (like the phases of the Moon). Measuring the amplitude of the phases shows how hot the night side is compared to the day side, and, in the best of cases, enables the reconstruction of a temperature map of the whole atmosphere of the planet.

These three methods are at the source of most of what we know about the atmospheres of exoplanets. They have been applied mainly using two space telescopes, *Hubble* for visible light, and *Spitzer* for infrared light. They could help us to understand the atmosphere of an Earth-like exoplanet.

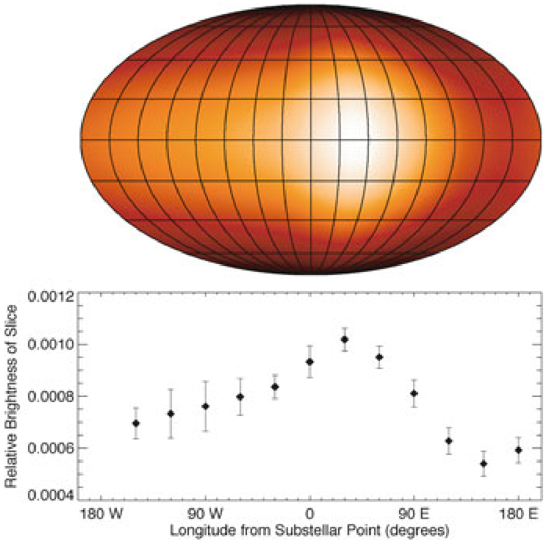

Fig. 6.17 Brightness map of the hot Jupiter Isis in the infrared, as inferred from measurements by the Spitzer Space Satellite. In the absence of winds or currents in the atmosphere the hottest point should be facing the star, on the Equator at zero longitude. Fast eastward winds shift the hottest points around 20 degrees in longitude. Image **c**redit: Knutson *et al.*

On Earth, red light crosses the air more easily than blue light, which is why the setting Sun is red, and the sky blue. Infrared light is almost entirely blocked out by the water vapour present in the atmosphere, while ultraviolet light is intercepted by the ozone layer. To an alien astronomer, the Earth in transit would appear smallest in red, larger in blue, even larger in infrared (by about ten kilometres, the height of the troposphere), and largest of all in the UV (by 30–50 kilometres, the size of the ozone layer). From these values our alien observer could venture some informed guesses on the composition and structure of our atmosphere.

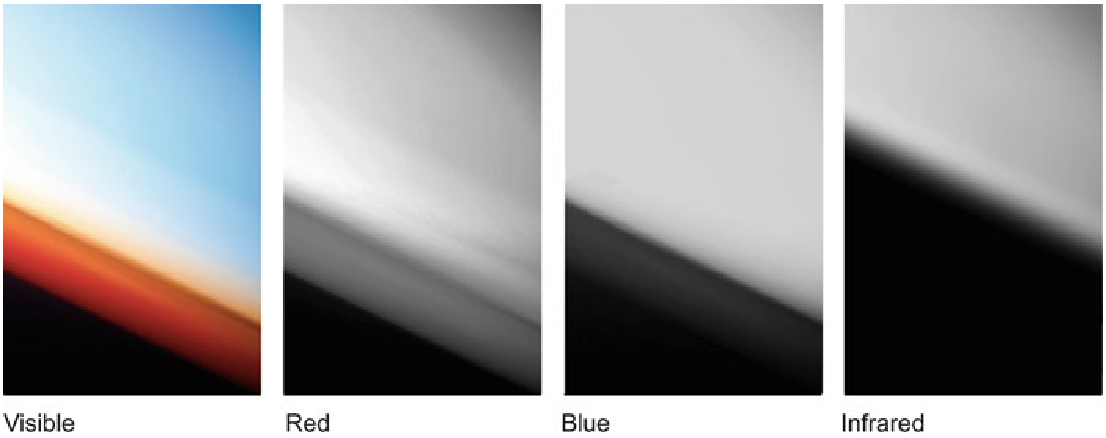

Fig. 6.18 Transmission spectroscopy of Earth's atmosphere from space. The Earth looks larger through a blue filter than a red one, because the atmosphere scatters blue light. It looks even larger in the infrared, because water vapour and CO_2 absorb infrared light. An alien astronomer could measure these features of our atmosphere during an Earth transit, even without seeing the planet, just by measuring the change in size in different wavelengths of light. Image credit: NASA/ISS

The transit methods work best for planets close to their host star, because the probability that a planet on a close orbit crosses the disc of its host star is much higher, and also because close-in planets are hotter, and therefore contribute a larger fraction to the light of the whole system.

As to the other end of the scale of orbital distances, for planets which are far enough from their host star (from five Astronomical Units like Jupiter to the edge of planetary systems at around 100 Astronomical Units), it is possible to conceal the intense stellar light and try to pick out the faint glow of the planet itself. Conceptually this is the simplest method, but it is technically demanding. Sophisticated tricks, like *interferometry*, are required to separate the firefly from the lighthouse, and this method is still in its infancy. Once the planet is identified in this way, however, it can be directly imaged and its spectrum measured without resorting to indirect methods.

These patchy and uncertain measurements are all we have today to ground our knowledge of exoplanet atmospheres. Just as it was a century ago for Solar System planets, some caution is due about our inferences and conclusions. The large brush strokes are probably correct but it is likely that many details will be revised as we gather better observations.

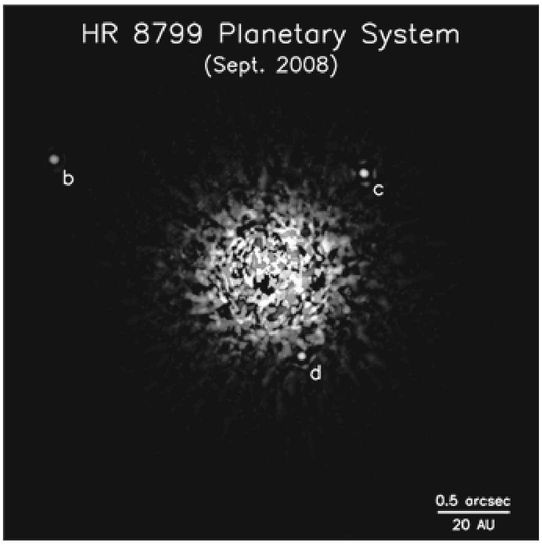

Fig. 6.19 An image of the HR8799 planetary system. The blinding light of the host star is suppressed, three planets are barely visible ("b" to "d"). Credit: C.Marois et al., NRC Canda

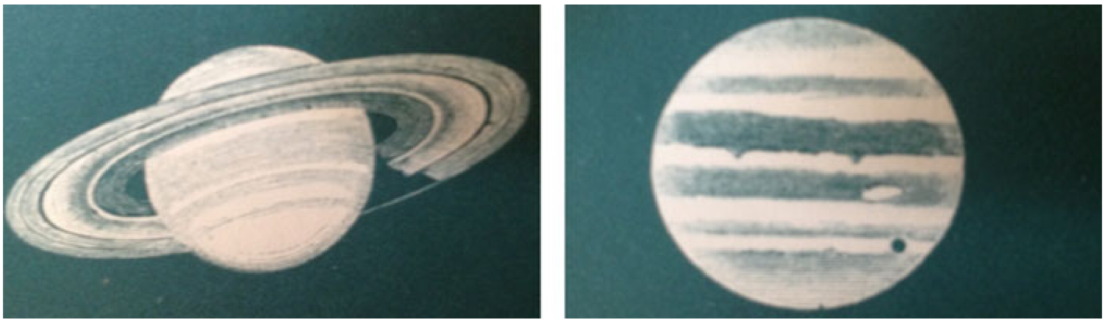

Fig. 6.20 Historical sketches of Jupiter and Saturn. Image credit: Agnes Giberne: Sun, Moon and Stars (1881)

Caution: observation-free zone ahead

The story is different for the next chapter. At this point, observations of the atmosphere of planets smaller than hot Jupiters are virtually nonexistent. What we can infer is entirely based on models, speculations and extrapolations. I have striven as much as possible to stick to inferences solidly grounded in known physics and astronomy, but if the past is any guide, some of the expectations presented in the next chapter will turn out to be completely incorrect, and the reality will be even more interesting and surprising than we thought.