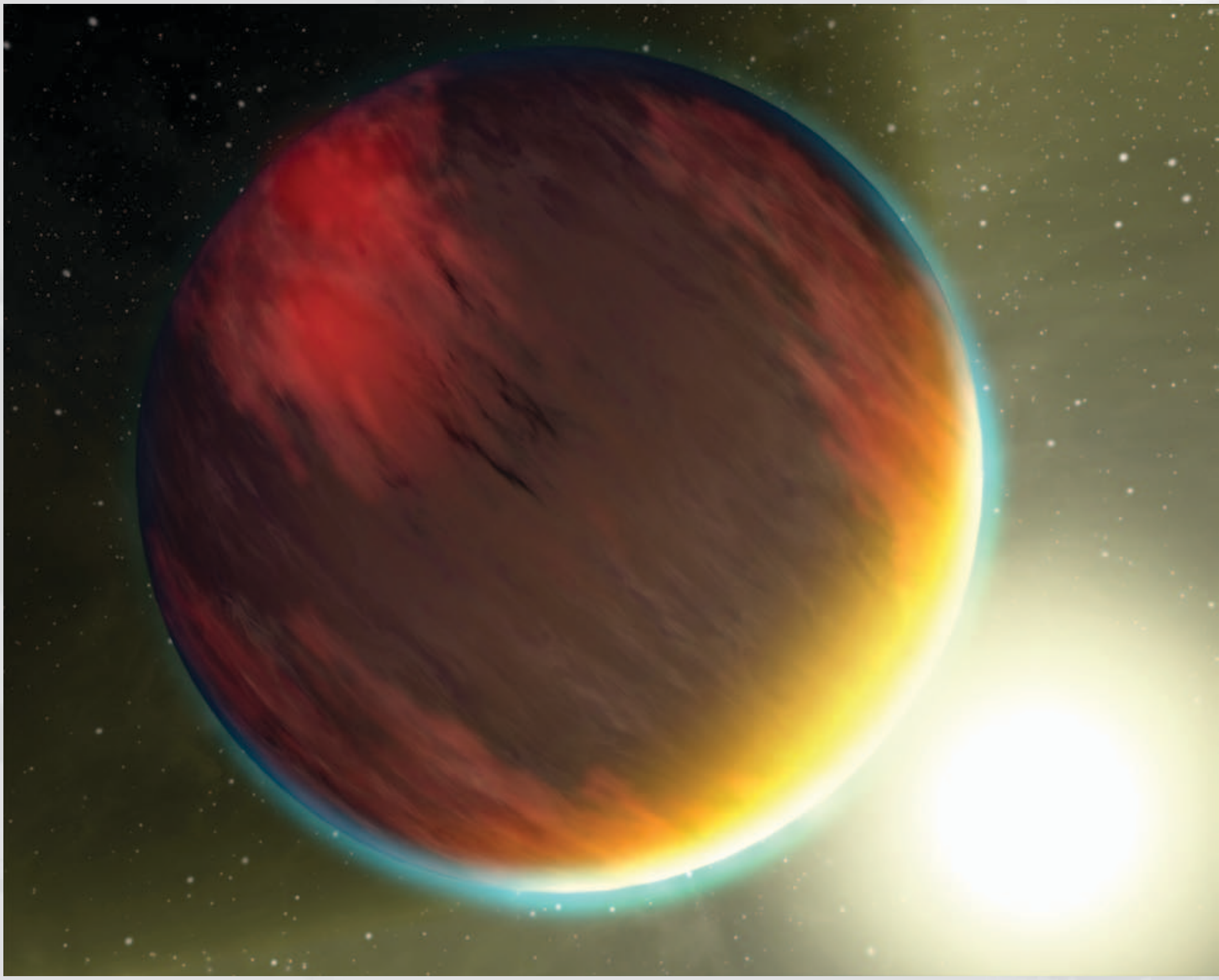
Strange

FIGURE 1

***Artist's conception of a hot Jupiter**, seen against the bright glare of its nearby parent star. Hot Jupiters revolve around their stars in only a few days and are found around 1% of Sun-like stars.* [NASA-JPL/Caltech]



New Worlds

by Joshua Winn

At some point in your life, you may have looked up at the stars and wondered: is there anyone out there on some distant planet, looking back at me? This universal curiosity helps to explain why the field of EXOPLANETARY SCIENCE—the study of planets *outside* of the solar system—has attracted so much attention.

FOR THIS REASON, EXOPLANETARY SCIENCE is often portrayed as a single-minded quest for potentially inhabited Earth-like planets. However, the most remarkable discoveries have been planets with unanticipated properties, many of which make them extremely *unsuitable* for life. These strange new worlds are fascinating to contemplate and give important clues about the formation and evolution of planets in general. As in any area of science, the extreme cases are often the most revealing.

Impossible planets

In this article I will focus on HOT JUPITERS: giant planets with atmospheres hotter than the inside of a furnace *(Figure 1)*. They are hot because they are extremely close to their stars, with a typical separation of 3% of the distance from Earth to the Sun. Viewed from Earth, the Sun looks about as large as a blueberry held at arm's length. In the sky of a hot Jupiter, the star would loom as large as a dinner plate.

As another consequence of its tiny orbit, a typical hot Jupiter completes a full revolution in only a few days. By comparison, even fleet-footed Mercury is a slow-poke, taking 88 days to circle the Sun.

The discovery of hot Jupiters was a surprise not only because the solar system lacks such a planet, but also because the prevailing theory of planet formation forbade

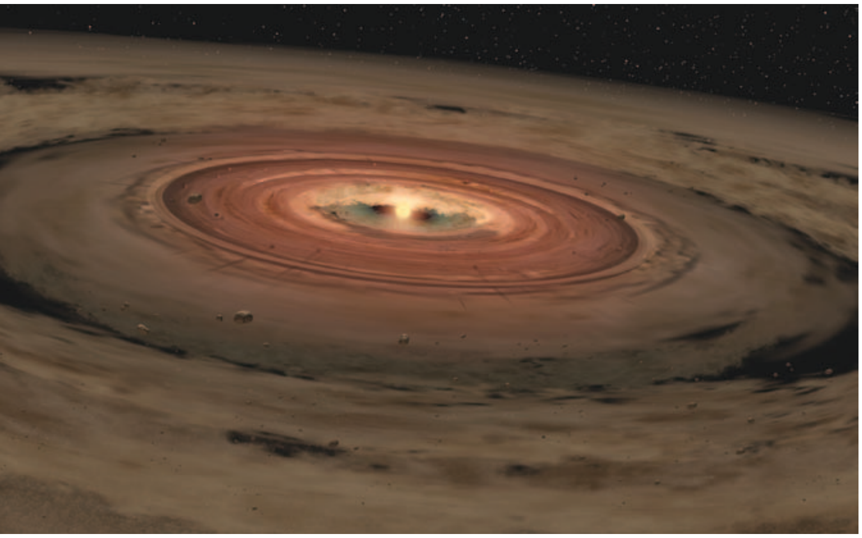


FIGURE 2

Artist's conception of a protoplanetary disk. *They are composed of gas and dust left over from star formation, which is the raw material for planet formation.* [NASA-JPL/Caltech]

their existence. In this theory, known as CORE ACCRETION, planets begin as dust grains within the disk of hydrogen and helium gas that surrounds every young star *(Figure 2)*. The grains stick together into pebbles, which cluster into rocks, boulders, and eventually planets, over millions of years. If the growing planet manages to exceed ten Earth masses, its gravity becomes strong enough to capture the surrounding gas, and it swells up to become a gas giant. However, this threshold mass can only be achieved in distant, colder regions of the disk, where the supply of solid materials is enhanced by ices of water, methane, and ammonia. In other words, giant planets only form beyond the star system's "snow line," where there is enough solid material to pack onto the growing planet.

This theory works in the solar system, where the snow line is between Mars and Jupiter. The rocky planets (Mercury, Venus, Earth, and Mars) are all within the snow line, while the gas giants (Jupiter, Saturn, Uranus, and Neptune) are more distant. It was therefore quite a shock in 1995 when the first hot Jupiter was discovered, well within the snow line of its parent star. Now we know of hundreds of hot Jupiters; about 1% of Sun-like stars have one.

Does the existence of hot Jupiters mean that the core accretion theory is wrong? Not exactly. Nobody has found any fault in the argument that gas giants must form beyond the snow line. The current consensus is that hot Jupiters were once ordinary Jupiters that were transported inward. However, the transportation mechanism is murky and theoreticians have thought of many ways a planet might shrink its orbit.

Close encounters

One scenario requires two or more planets. For a long time, the planets all revolve around the star in what seems like a harmonious arrangement, but over billions of years the configuration proves unstable. The planets exert gravitational forces on one another, altering their orbits and eventually leading to close encounters that slingshot the planets around the star system. One planet may be thrown outward or even ejected; another may be thrown onto a highly elongated elliptical orbit, with one end of the ellipse very close to the star *(Figure 3)*.

If the latter planet approaches the star closely enough, its orbit will shrink and become circular due to tides. Tides occur whenever two astronomical bodies are close to one another; they are a consequence of the weakening of gravitational attraction with distance. For example, the familiar ocean tides arise because the Moon's gravity exerts a greater force on the near side of the Earth than the far side. Less well-known is that these same tides are gradually enlarging the Moon's orbit and slowing the Earth's spin rate, over billions of years. These changes are the result of the conversion of gravitational energy into heat by ocean currents and crashing waves. Going back to the case of exoplanets, the tidal force on a planet from a nearby star eventually causes the planet's orbit to shrink and become circular.

Theorists have come up with variations on this theme. For example, the gravitational perturbations can accumulate gradually, without close encounters. Or a companion star can provide the perturbation, rather than a second planet. I will lump these variations together under the name FEW-BODY DYNAMICS. One might also call it the "MIT hypothesis," since an influential paper on this topic was written in 1995 by Frederic Rasio and Eric Ford, while both were members of the MIT Physics department. In fact, one could also call it the "freshman physics" hypothesis because it is relatively simple, and because Ford was a freshman at that time.

Disk migration

That same year, a different idea was proposed for shrinking the orbit of a giant planet. The idea relies on the gaseous disk from which planets form. Over millions of years, the material in the disk gradually spirals inward and accretes onto the star, which is why the five-billion-year old Sun no longer has a disk. But early in a star's history, when the disk is still present, it can exert an effective frictional force on a giant planet and cause the planet to spiral inward with the gas. The planet is said to "migrate" from its initial location, beyond the snow line, to a closer and hotter orbit.

The planet–disk interaction is subtle, and an "effective frictional force" stands for an intricate calculation involving gravitational and fluid dynamics—definitely not "freshman physics." But as calculations were performed with increasing accuracy, disk migration seemed ever more powerful and even inevitable as a way to shrink orbits. Indeed the problem became how to *stop* it: why does the giant planet not spiral all the way onto the star? And what prevented our own Jupiter from becoming a hot Jupiter?

The rival hypothesis of few-body dynamics had its problems, too. Arranging for just the right interactions to fling a giant planet onto an appropriate orbit—close enough for tides to be important, yet not so close that the planet is destroyed—seemed contrived. Could this really happen frequently enough?

Original spin

For about 10 years not much progress was made on these questions. It looked increasingly like a stalemate, with no way to tell whether either theory was correct. Beginning around 2005, our group began pursuing a method that could potentially distinguish between these theories. The method relies on measuring the *orientation* of the hot Jupiter's orbit. In both theories, the planet forms within the gaseous disk, and therefore its orbit is aligned with the disk. But the theories disagree about whether the orbit of the hot Jupiter would still be aligned with the disk.

Few-body dynamics would tend to tilt the orbit away from its initial plane. This is because close encounters tend to amplify any initial misalignments between the planets' orbits. The perturbation from a neighboring star can even flip a planet's

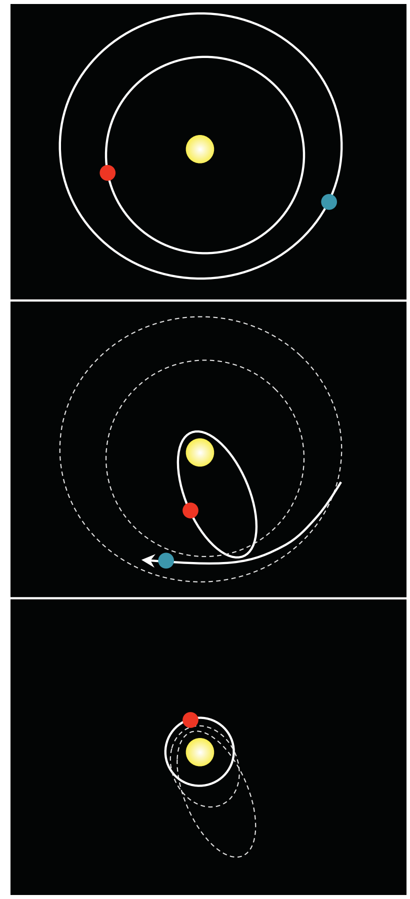


FIGURE 3

Planet scattering as the possible origin of hot Jupiters. (Top) *Two giant planets orbit a star.* (Middle) *A close encounter ejects one planet and sends the other planet onto a highly elliptical orbit.* (Bottom) *The orbit is shrunk and made circular by tidal forces between the star and planet.* [Joshua Winn]

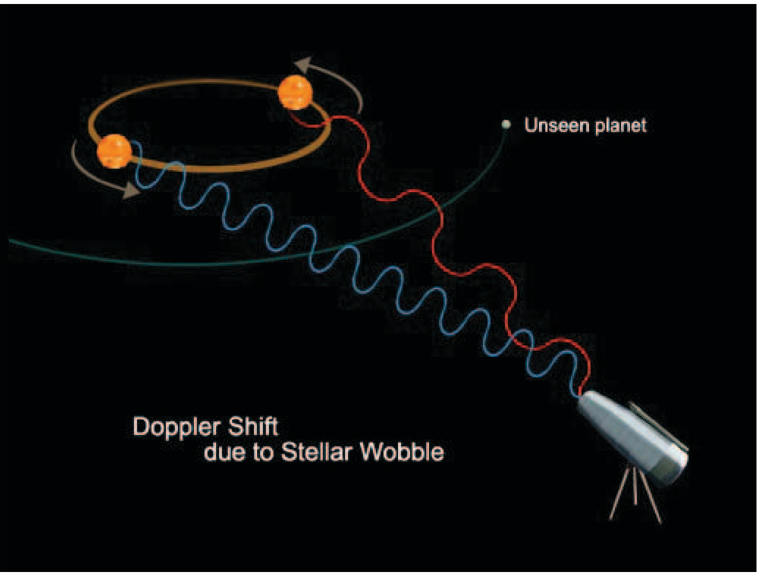


FIGURE 4

Detecting a planet using the Doppler shift. *The planet pulls on the star, causing it to move. When the star moves toward Earth, its light is shifted toward the blue end of the spectrum (shorter wavelengths). When the star is receding from Earth, its light is shifted toward the red end of the spectrum.* [NASA/JPL-Caltech]

orbit over completely, reversing the direction of revolution. In contrast, disk migration would cause a planet to spiral inward without changing its orbital plane. Therefore, if we could tell whether the planet's orbit had been tilted we could distinguish between the two theories. This may sound straightforward, but there were two major obstacles to performing this test.

One obstacle is that all of the known hot Jupiters are around mature stars, billions of years old, and the gaseous disks are no longer present. So how can we measure the orientation of the orbits relative to the plane that was once defined by the disk?

Our approach was to take advantage of the parent star's *rotation*. Presumably, the star's rotation was aligned with the gaseous disk, since the star was formed within the disk. This is supported by the observation that the Sun's equatorial plane is tipped by only 6° from the plane defined by all the planets' orbits. For hot Jupiters, then, we can use the star's equatorial plane as a proxy for the initial plane of the planet's orbit.

The other obstacle is the difficulty in measuring the angle between the planet's orbit and the stellar equator, an angle known as the STELLAR OBLIQUITY. Until this point, I have deferred the description of how we detect exoplanets and measure their characteristics; the methods are indirect. With very few exceptions, we cannot simply use our telescopes to make an image of an exoplanetary system, because the planets would be lost in the much brighter glare of the parent star. Instead, we sense the planet by tracking the motion or the brightness of the star.

Planet detection methods

Just as the planet is kept in its orbit by the gravitational pull of the star, the star too is pulled around in an orbit by the planet. The star's orbit is smaller than the planet's orbit, and its orbital speed is comparatively slow; for example, the Sun's orbital motion is only about one-thousandth that of Jupiter. But the stellar motion can be detected as a change in the star's spectrum of emitted radiation, thanks to the DOPPLER SHIFT *(Figure 4)*.

You may remember the Doppler shift as the explanation for why the pitch of a siren is higher as an ambulance approaches, and then lower as the ambulance passes by and drives away. When any sort of wave—sound and light waves included—is emitted by a moving source, an observer detects a shift in wavelength. Waves are compressed for motion toward the observer, and stretched for receding motion. Changing wavelength corresponds to changing pitch for sound, and changing color for light. Approaching light waves are shifted to the blue, while receding light waves are made redder. These slight redshifts and blueshifts can be detected with specialized spectrographs on large telescopes.

In addition, if the planet's orbit happens to carry it directly in front of the star, as viewed from Earth, then the planet will periodically block a small fraction of the star's surface from view. These miniature eclipses, or "transits," can be registered as slight reductions in starlight received with our telescopes *(Figure 5)*.

Measuring obliquities

Our technique for measuring the stellar obliquity—and our hope for unraveling the mystery of hot Jupiters—relies on both the Doppler shift and transit methods. We track the Doppler shift of the star throughout a transit. In addition to the shifts due to the star's orbital motion, there are additional shifts due to its rotation. One-half of the star is approaching the Earth, and is blueshifted, while the other half of the star is receding and is redshifted. Ordinarily these two effects cancel each other out and produce no net Doppler shift. But when a planet is transiting, the balance is destroyed. While the planet is hiding part of the redshifted half of the star, the net starlight appears slightly blueshifted, and vice versa.

By tracking this anomalous Doppler shift throughout a transit, we can measure the angle on the sky between the planet's trajectory and the star's equator. This is illustrated in *Figure 6*. A well-aligned planet will produce an anomalous redshift, then a blueshift. Whereas a misaligned planet may spend the entire transit on the blue side of the star, producing an anomalous redshift throughout the transit.

We did not invent this measurement technique. In fact, it was dreamed up in 1893 and is known as the Rossiter-McLaughlin effect, after the two astronomers who measured it definitively in 1924. But those measurements pertained to eclipses of one star by another star—binary stars—rather than transiting exoplanets.

For exoplanets the measurements are painstaking, and require substantial time using the world's largest telescopes. After a few years, we and our colleagues managed to perform these measurements for about 10 hot Jupiters, finding them all to be well-aligned with their parent stars. This finding was compatible with disk migration, which does not tilt orbits, and in opposition to few-body dynamics, which predicts a large range of orbital orientations.

It seemed like case closed. In fact, it became difficult to raise funds or gain access to telescope time to continue this work. Why invest further in studying a problem that was

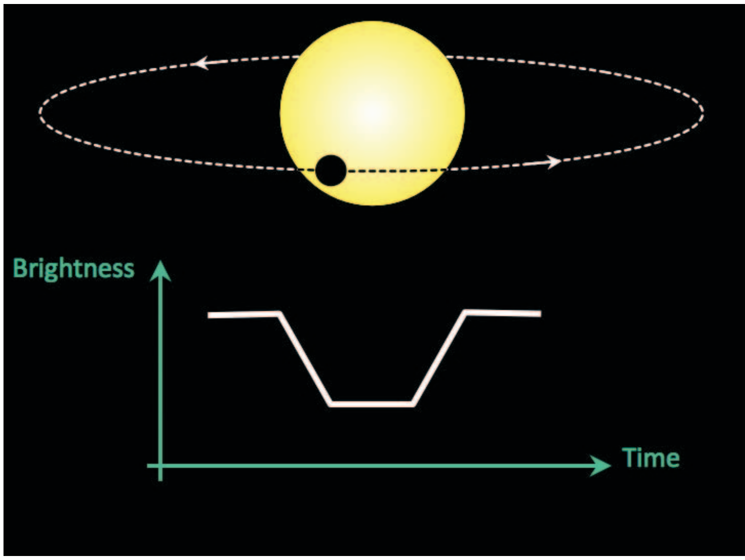


FIGURE 5

Detecting a planet using transits. *The planet's orbit carries it in front of the star, causing a miniature eclipse or "transit". Telescopes on Earth can detect the diminution of starlight.* [Joshua Winn]

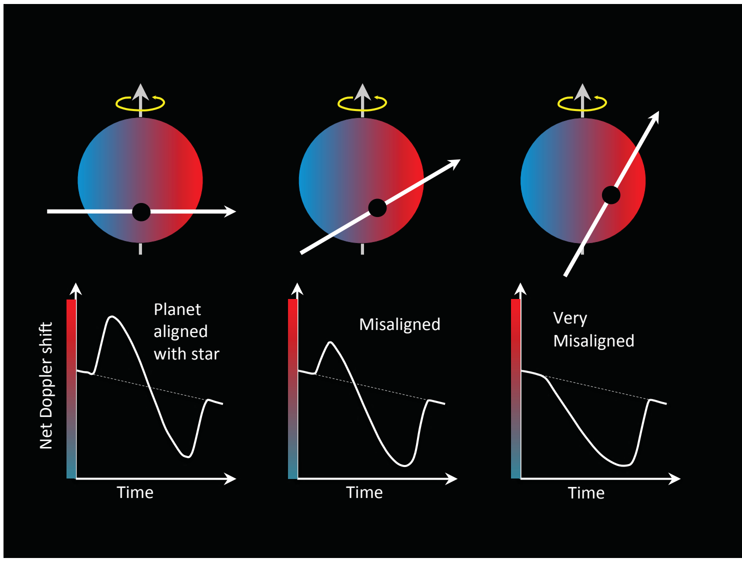
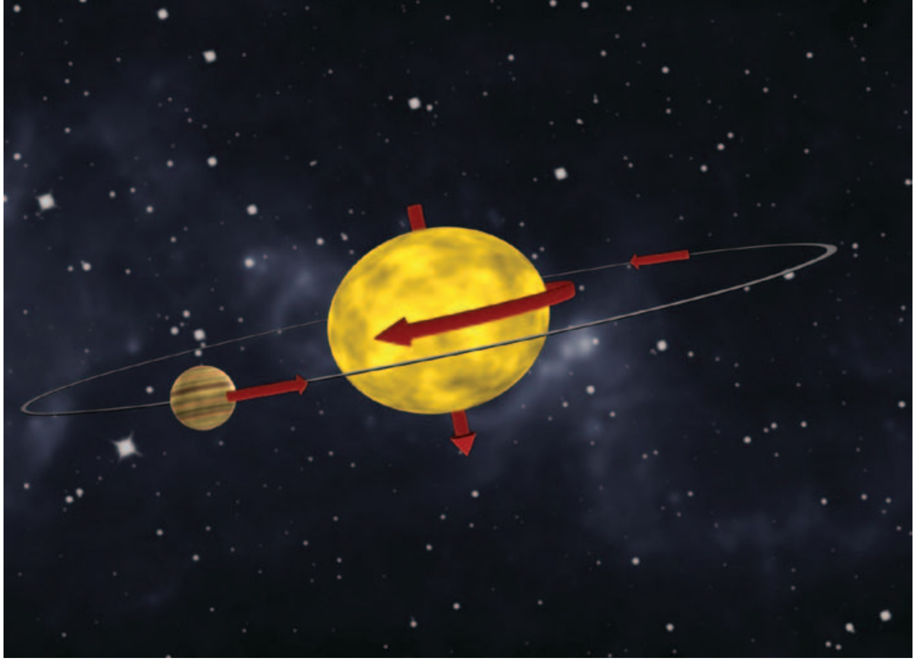


FIGURE 6

Measuring the star's obliquity, using the Rossiter-McLaughlin effect. (Left) *A planet for which the stellar equator is aligned with the planetary orbit. During a transit, an observer measures a redshift, followed by a blueshift.* (Middle) *A misaligned planet. The duration of the redshift is shorter than that of the blueshift.* (Bottom) *A very misaligned planet, which produces a blueshift throughout the entire transit.* [Joshua Winn]

FIGURE 7

Artist's conception of a retrograde planet. *The planet's revolution and the star's rotation are in opposite directions. Many such planets are now known.* [Simon Albrecht/MIT.]



already solved? However, in such situations there is always a danger of "premature curiosity satisfaction," to borrow a phrase from philosopher Daniel Dennett. We suspected that we had not yet sampled the full diversity of exoplanetary systems.

This suspicion was soon confirmed. The next 20 exoplanets that were observed showed an essentially *random* distribution of obliquities, including planets with moderately tilted orbits, planets on "polar" orbits carrying them over the north and south poles of their parent stars, and several "retrograde" planets for which the orbital revolution is *opposite* to the stellar rotation *(Figure 7)*.

In retrospect, we have found evidence that the first 10 planets were not appropriate for this project. In those systems, tidal forces between the star and planet were too strong. Even if the planet's orbit had once been tilted, the tidal forces would have reoriented the star and the orbit into alignment. This erases the information we seek. The next 20 systems involved a broader mixture of planet masses, orbital separations, and stellar types, for which tidal forces were not as dominant.

Case closed again?

These findings led to a reversal, giving a decisive advantage to the "MIT hypothesis" of few-body dynamics—previously a dark horse—in the effort to explain hot Jupiters. This conclusion has since been supported by other studies. For example, we have found that stars with hot Jupiters are *less likely* to have additional planets further out, compared to stars without hot Jupiters. This "loneliness" of hot Jupiters is interpreted as a consequence of the formerly elongated orbit of the giant planet, and the chaotic gravitational interactions that produced it. These factors would have scattered or ejected any smaller planets in the vicinity. Indeed, one implication of this work is that if we want to find Earth-like planets, the *worst* place to look would be around a star with a hot Jupiter.

Some of my colleagues are again prepared to declare the case closed, though I do not yet agree. One more task remains: we must check on our assumption that the stellar equator is indeed a faithful indicator of the initial orbital plane of the giant planet. We have been assuming this is the case: when we observe a high obliquity we have been assigning the blame for the misalignment on the process that created the hot Jupiter. But what if the star is to blame? What if stars and their disks become misaligned for reasons having nothing to do with hot Jupiters?

The types of systems we would like to check are those for which there is *no* evidence of any dramatic planetary rearrangements. The stars in such systems should always have low obliquities, if our story for hot Jupiters is correct. Our group is pursuing this task by targeting planetary systems more like the Solar system, with multiple transiting planets in orbits that are aligned with each other, and without any hot Jupiters.

The problem is that such systems are much more difficult to identify and study. They are less common, and as a result the stars are usually too distant and faint to observe the Rossiter-McLaughlin effect. My PhD student Roberto Sanchis Ojeda is pioneering a new technique for measuring obliquities, which relies on tracking the effects of "star spots," the analogs of the dark spots that are seen on the Sun. In July 2012, he reported his first results in the journal *Nature*: a low-obliquity star with three planets in coplanar orbits. Once we have a larger sample of such results we may be able to settle the matter, decisively testing whether hot Jupiters arise from few-body dynamics or disk migration and thereby solving one of the longest-standing problems in exoplanetary science.

Other oddities

For this article, I focused on hot Jupiters and one of the insights we have gained by studying them. But I could have chosen from among a dozen other types of strange new worlds, each of which has been illuminating in a different way. For example, my MIT colleague Saul Rappaport recently found a rocky planet so strongly irradiated by its parent star that it appears to be disintegrating. Another example is Kepler-36, a two-planet system that MIT student Katherine Deck has shown to have chaotic orbits; it is impossible to predict where the planets will be in a hundred years. Finally, in 2011 we discovered a planet with *two* parent stars. The existence of such planets was long a subject of speculation in the scientific literature as well as in science fiction (think of Star Wars, and the twin suns of Tatooine). Now it is known that such planets are common.

The lessons from the discovery of these qualitatively new types of planetary systems are that the planet formation process is bountiful, and there is much yet to be learned about the full range of possibilities.

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