

How two planets likely acquired their backward orbits

It's challenging enough to figure out what exoplanetary systems look like today. Reconstructing their histories is more difficult still.

All eight planets in our solar system orbit the Sun in the same direction, and none of their orbits lie more than a few degrees outside the Sun's equatorial plane. That alignment makes sense: All of the solar system's angular momentum came from the same place—the gravitational collapse of a much larger cloud of gas and dust—so it should all point in the same direction, right?

For most of scientific history, our solar system has been the only planetary system that astronomers could study. It was easy to assume that alignment must be inevitable. But over the past quarter century, as researchers have collected more and more observations of extrasolar planets, it's become clear that not all planetary systems are like our own. In particular, many exoplanets orbit in a different, or even opposite, direction to their host stars' spins.

Several theories have been proposed to explain those orbital misalignments, but testing them has been a challenge. Now, through their observations of the exoplanet system K2-290 (illustrated in figure 1), Simon Albrecht of Aarhus University in Denmark, his recent PhD student Maria Hjorth, and an international team of collaborators have found a tidy confirmation¹ of one mechanism² that was proposed in 2012: Because of the gravitational influence of an orbiting companion star, the protoplanetary disk is pulled out of alignment with the primary star's spin before the planets even form.

Observing orbits

Exoplanets are generally too faint to image directly. For the most part, their existence is known only through the effects they have on their host stars' light. If a planet

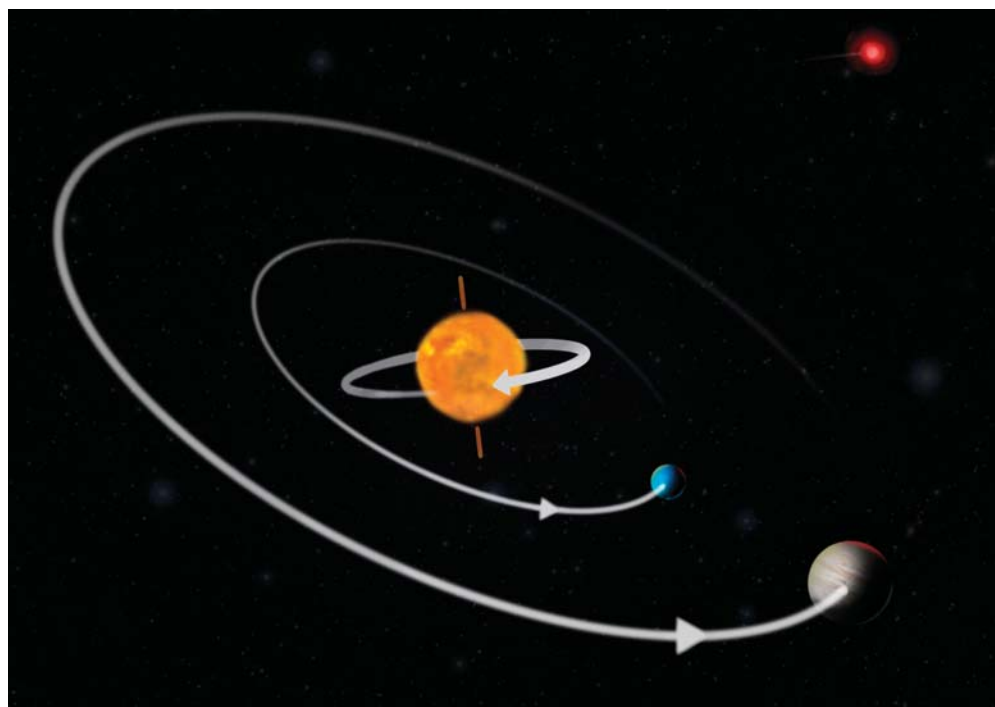


FIGURE 1. PLANETARY ORBITS in the K2-290 system are misaligned with their host star's spin, as illustrated in this artist's representation. The probable culprit is a companion red dwarf star, visible in the distance, whose gravitational influence disrupted the system before the planets emerged from the protoplanetary disk. (Image by Christoffer Grønne.)

has sufficient gravitational heft to pull its host star to and fro, it reveals itself through the periodic Doppler shifting of the star's spectral lines. That radial velocity method was responsible for most of the earliest exoplanet discoveries (see the article by Jonathan Lunine, Bruce Macintosh, and Stanton Peale, *PHYSICS TODAY*, May 2009, page 46), and it's most suitable for so-called hot Jupiters: giant gaseous planets that are so close to their host stars that they orbit every few days.

Most exoplanets discovered recently, on the other hand, are detected via the transit method—the periodic dimming of the host star by a planet passing directly across the line of sight (see *PHYSICS TODAY*, January 2014, page 10, and December 2019, page 17). That method, too, most readily detects hot Jupiters. But it's also suitable for spotting smaller, rocky planets with more Earthlike orbits.

With such indirect evidence of a planet's existence, it might seem impos-

sible to learn anything about the direction of its orbit. But transit detections, in particular, reveal a wealth of subtle information. When a star spins on an axis that's not parallel to the line of sight, part of it moves toward Earth and part moves away; its light is thus partly blueshifted and partly redshifted. A planet transiting the star in the same direction as the spin blocks the blueshifted part first and the redshifted part second. For a planet orbiting in the opposite direction, the reverse is true.

That spectroscopic trick is called the Rossiter–McLaughlin effect, named after two astronomers who studied it in binary stars almost a century ago. Exoplanets block much less of their stars' light than other stars do, but with sophisticated enough instrumentation, their Rossiter–McLaughlin effect can also be detected.

The first exoplanets to be spectroscopically studied in that way were all hot Jupiters.³ So when it came to light that

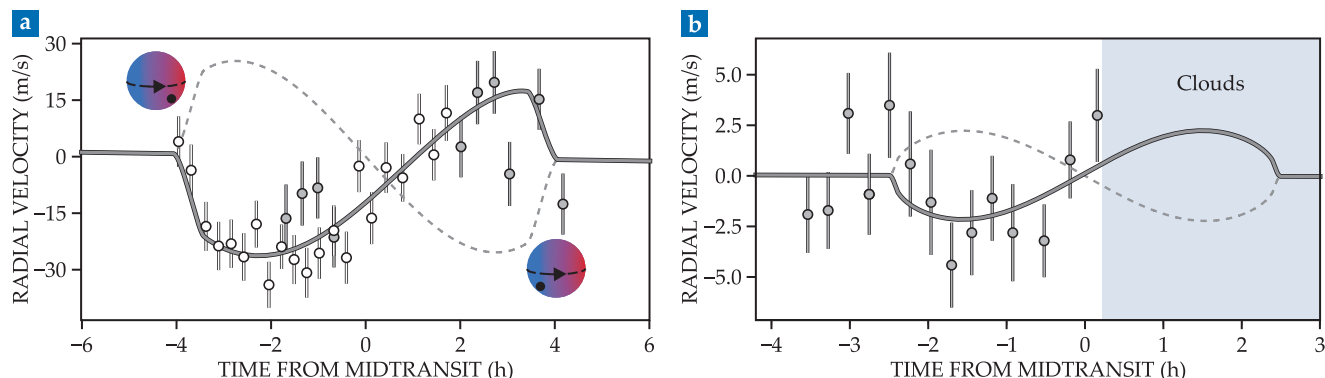


FIGURE 2. THE DIRECTION of a planet's orbit is revealed by the effective radial velocity—the redshift or blueshift—of the host star's spectral lines as the planet transits the star. **(a)** Two spectrographs recorded transits of the K2-290 system's larger planet (open and shaded circles). Both show redshifts followed by blueshifts, evidence that the planet orbits in the opposite direction of the star's spin. The solid curve is the best-fitting model, and the dashed curve is what would have been seen if the orbit and spin were aligned. **(b)** Only one transit of the smaller planet was recorded, and it was partially blocked by clouds. Still, that planet also appears to orbit backward. (Adapted from ref. 1.)

many of them were misaligned—by a few tens of degrees up to nearly a full 180° —researchers speculated that the mechanism responsible might be something specific to those planets' unusual sizes and orbits. “Hot Jupiters are already thought to be weird,” says Princeton University's Josh Winn, a coauthor of the new paper, “because giant planets shouldn't be able to form so close to a star. So maybe the same process that put the planet there also tilted its orbit.”

One theory is that the giant planets form in distant orbits—much like our own Jupiter—and then get kicked somehow into highly elliptical orbits.⁴ Notably, the dynamical processes that can form such orbits can also amplify any small misalignment into a large one. As the Jupiters approach and retreat from their host stars, tidal forces pull the planets like taffy and dissipate their orbital energy as internal friction. As they lose energy, the planets settle into circular orbits close to, but misaligned from, their stars.

Finding misalignment

But the K2-290 system has no hot Jupiters. Its planets are a warm Jupiter, 11 times the diameter of Earth and with a period of 48 days, and a hot sub-Neptune, 3 times Earth's diameter and with a period of 9 days. The system also contains a red dwarf in a binary configuration with the primary star at a close enough separation to have influenced the planets' orbits.

“Most of the time, if there's a companion star, it's harder to detect and confirm the planetary system because the additional light complicates the search and confirmation of the planetary signal,” says

Albrecht. But the red dwarf in K2-290 is sufficiently faint and distant from its primary to stay out of the way most of the time. “So I pitched to Maria that we should study this system,” he says.

Because both K2-290 planets transit the primary star, their orbital planes almost certainly coincide. (If they didn't, the intersection of the two planes would have to lie along the line of sight from Earth, which is unlikely.) But the researchers didn't yet know if the two planets orbit in the same direction, so they measured the Rossiter–McLaughlin effect for both.

For the larger planet, the measurement was straightforward. Many spectrographs around the world have the power to detect the subtle shifts in the stellar spectrum. The researchers observed two full transits of the planet with two different instruments: the High Accuracy Radial Velocity Planet Searcher–North in the Canary Islands and the High Dispersion Spectrograph in Hawaii. The data from both, plotted in figure 2a, clearly show the planet orbiting backward with respect to the star's spin.

The smaller planet posed a greater challenge. With less than $\frac{1}{10}$ the cross-sectional area of the larger planet, it blocks much less of the star's light, and its effect on the spectrum is so slight that only a few instruments in the world can measure it. One of those is ESPRESSO, the Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations, which came online in 2018 at the Very Large Telescope in Chile. As the instrument's name suggests, it is designed for the study of small planets. Demand for observing time is high, but the researchers

were able to fast-track an application to observe one transit of the smaller K2-290 planet.

“And it would have been great,” says Albrecht, “except that clouds blocked the star for half of our observing time.” Only with their precise knowledge of the orbital timing could the researchers conclude that the blueshift, shown in figure 2b, was from the first half of the transit, not the second, and that the smaller planet too was misaligned to the star's spin.

Resonance effect

The coplanar orbits rule out most proposed mechanisms, such as planet–planet scattering, that could have misaligned the system after the planets formed, because those processes would act differently on the two planets and give them different orbital planes.

But the discovery of the red dwarf companion allowed the researchers to test the postulated mechanism of primordial misalignment. As the planetary system is just beginning to coalesce, the theory goes, the protoplanetary disk is gravitationally torqued by both the binary companion star and the rotationally flattened primary star, and the disk in turn exerts a back-reaction torque on the star. The directions of those torques oscillate as the binary star orbits and the spin of the primary star precesses. As the disk disappears, the oscillation frequency due to the back-reaction torque slowly drifts.

When the frequencies come into resonance with one another, the two stars working together can tip the disk by a large angle in a short time. “The resonance can dramatically flip the disk even

when the binary companion's orbit is only modestly misaligned with the primary star's spin," explains coauthor Rebekah Dawson of the Pennsylvania State University. "When you drive the system at just the right frequency, you get a big response."

Once the frequencies drift back out of resonance, the disk settles into a new orbital plane that's widely misaligned from its original plane. Although the companion star is still there, it's no longer as influential on the planetary alignment as it once was.

The researchers can't be sure of the system's original configuration, but they guessed several values for the initial disk-star orbital parameters, and they modeled each one. In every one of their simulations, the system found its way within a few million years to a configuration consistent with what is observed today. "There are lots of misaligned systems,"

says Dawson, "but in the others, we don't have such a smoking gun."

What's out there

The evidence from K2-290 doesn't mean that the primordial mechanism is responsible for all planetary misalignments. "There's probably more than one way to mess up a system," says Winn, "and we're just beginning to explore what's possible."

It's far too soon to tell what the most common misalignment mechanism is—or even how prevalent misaligned systems are. Exoplanet studies are still overwhelmingly dominated by the systems that are easiest to observe, whose formation and dynamics may not be representative of planetary systems in general. Hot Jupiters remain by far the easiest planets to study by any method, although powerful new spectrographs like ESPRESSO are starting to bring smaller

planets under spectroscopic scrutiny. And multiplanet systems are rendered virtually invisible when the planets' orbits don't all lie in the same plane.

Still, the K2-290 observations pile on yet more evidence that planetary systems are diverse, and observations from our own well-studied solar system aren't necessarily universal or even typical. "We'd have developed a very different theory of solar-system formation," says Albrecht, "if, when Galileo looked at the Sun with his telescope, he'd seen the sunspots going the other way."

Johanna Miller

References

1. M. Hjorth et al., *Proc. Natl. Acad. Sci. USA* **118**, e2017418118 (2021).
2. K. Batygin, *Nature* **491**, 418 (2012).
3. J. N. Winn et al., *Astrophys. J. Lett.* **718**, L145 (2010).
4. R. I. Dawson, J. A. Johnson, *Annu. Rev. Astron. Astrophys.* **56**, 175 (2018).

A new look at the proton sea

The ensemble of particles that make up the proton manifests a puzzling asymmetry that continues to challenge theory and experiment alike.

Students of particle physics learn early that the proton is made of three quarks: two up and one down. But there must be more to the story than that. The proton's rest mass is 938 MeV. The three quarks, with masses of just a few MeV each, make up only a tiny fraction of that.

Where does the remaining mass come from? Much of it is the kinetic energy of the quarks—they're not at rest inside the proton, and special relativity dictates that their effective mass increases with speed. Most of the mass lies in the details of how the strong force holds the proton together.

Gluons, the carriers of the strong force, are themselves massless, but the energy of the gluon field contributes to the total proton mass. And the field can spawn fleeting pairs of quarks and antiquarks, known as the sea, as represented in figure 1.

At the energy scales encountered in everyday life, protons behave like self-contained particles, and the sea and the

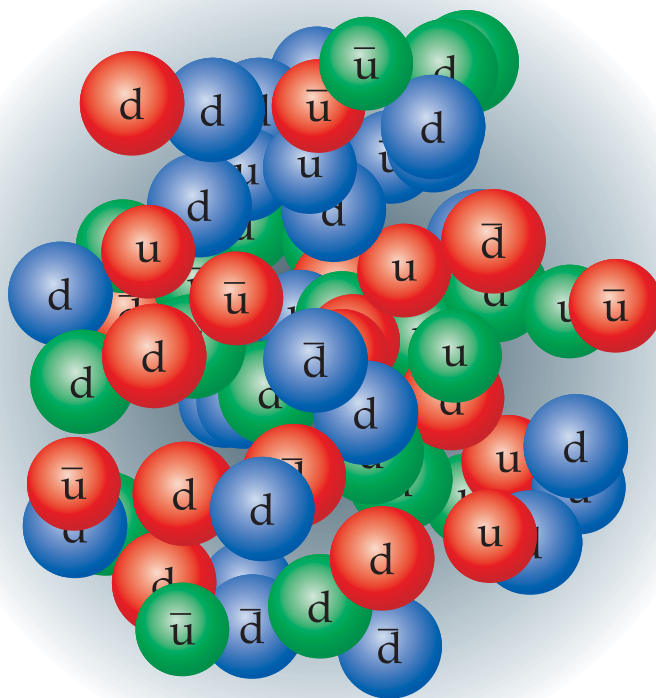


FIGURE 1. THE PROTON comprises not just two up quarks and a down quark but also a roiling sea of quark-antiquark pairs. The sea, which can't be accurately modeled by perturbative quantum chromodynamics, is an integral part of the proton's makeup and challenges theorists' understanding of how the strong force works. (Adapted by Donna Padian from an image by Paul Reimer.)