Long-Distance Partners

Two stars can maintain a long-term relationship over surprisingly large distances.

Double stars exemplify the stunning diversity of the heavens: A red giant pairs up with a white dwarf; a yellow main-sequence star circles a blue giant; an orange dwarf whirls around a ravenous black hole.

But binaries also exhibit another kind of diversity. At one extreme, two stars can be so intimate they touch, the pair resembling a glowing peanut. At the other extreme, the stars can be so far apart they take millions of years to swing around each other.

Extremely wide binaries involve some of the brightest stars in the sky and probe a diverse array of astronomical issues. After an extremely wide binary forms, the pair must navigate a galaxy that's trying to split the duo apart. Furthermore, because the only thing holding one star to the other is gravity, and because gravity is so weak over such a great distance, the stars' orbital motion tests the validity of Newton's law of gravity at that limit.

Binary Basics

There's no official definition of an extremely wide binary. For binaries whose brighter member resembles the Sun, the most common separation between the two stars is about 50 times the Sun-Earth distance, or 50 astronomical units. But the most extreme few percent of all stellar pairs have members that lie some 10,000 au apart or more. This enormous distance is nearly one-sixth of a light-year and about 250 times

▲ **ALPHA CENTAURI** The nearby binary Alpha Centauri AB and its tag-along companion, Proxima Centauri, lie so far apart that their separation is clearly visible on the sky. The overlaid ellipse shows Proxima's most likely orbit, and the dot its location (the star is invisible in the image).

SKY IMAGE: E. SLAWIK / NOIRLAB / NSF / AURA / M. ZAMANI; ORBIT: PIERRE KERVELLA greater than the vast expanse from the Sun to frigid and far-off Pluto.

For a brilliant example, gaze at Capella in the constellation Auriga, the Charioteer. What you see with the naked eye is a pair of yellow *G* giants. At least 9,300 au away from the giants is a 10th-magnitude red dwarf binary that slowly revolves around them.

The study of extremely wide binaries received an enormous boost after the European Space Agency launched the Gaia spacecraft, which measured precise stellar distances and motions. If two stars truly constitute a binary, then their distances from us should be nearly identical, as should their velocities through space.

"It's been really transformative," says Kareem El-Badry (Caltech), "because before Gaia, if you saw two stars that were close to each other on the sky and might be a wide binary, it was very hard to tell whether they were actually physically bound or just two stars that are passing past each other at totally different distances."

Thanks to Gaia, we now know that most stars in extremely wide binaries have highly elliptical orbits around each other. As a result, the minimum distance between the two stars, known as *periastron*, is much smaller than their greatest distance, called *apastron*. Astronomers define the *mean separation* of the two stars as the average of the periastron and apastron distances.

The stars spend most of their lives farther apart than their mean separation, though, because they speed around each other fastest when closest together and most slowly when farthest apart. They therefore race through periastron and linger at apastron. In like fashion, Halley's Comet spends a lot more time near Neptune's orbit than Venus's. So two stars with a mean separation of 10,000 au can have nearly twice that separation for hundreds of thousands of years.

The greater the mean separation between the two stars and the less massive they are, the greater their orbital period, according to Kepler's third law. Thus, while no human being lives long enough to track a complete orbit for the widest binaries, it's straightforward to estimate their orbital period (see box at right).

To explore a star with a far-off partner, we don't need to travel far at all. The nearest example is right next door.

Alpha Centauri: Our Extreme Neighbor

Because of its proximity, we know Alpha Centauri's properties better than those of any other extremely wide binary. The system is triple, with two bright stars and a faint one currently located 12,000 au from them (*S&T:* Apr. 2019, p. 34). The bright stars are a yellow *G* and an orange *K* sun that orbit each other every 80 years. Their amber light blends together, making them the third-brightest nighttime star, after Sirius and Canopus.

Then there is little Proxima Centauri, a dim red dwarf also known as Alpha Centauri C. It is 4.25 light-years from Earth. That's slightly closer than the bright stars Alpha Centauri A and B, which are 4.34 light-years from Earth. All three stars are some 6 billion years old, which means they have plied the Milky Way together for longer than the Sun has shone.

Over the past decade, Pierre Kervella (Paris Observatory) and his colleagues have removed any doubt that Proxima Centauri orbits its bright partners by measuring the three stars' precise velocities through space. Because Proxima is so far from its mates, its escape velocity from them is a mere 550 meters per second (1,240 mph) — 1/20 of the escape velocity from Earth's surface. As a result, when evaluating the red- and blueshifts in the stars' light due to the stars' motions, Kervella's team had to worry about subtle effects astronomers usually ignore. For example, light climbing away from a star's surface suffers a slight redshift due to the star's gravitational pull. Proxima's estimated gravitational redshift is 500 m/s — nearly as great as its escape velocity from Alpha Centauri A and B.

Also, stellar convection induces a slight blueshift. Hot gas rises, gives off its heat at the star's surface, then sinks back down again. Because the rising gas moves toward us, the light it emits is blueshifted; because the sinking gas moves away from us, its light is redshifted. The two don't cancel out, though, because the hot, blueshifted gas outshines the cool.

In 2021, after taking all of these factors into account, the astronomers reported their latest results: Proxima Centauri's velocity through space differs from that of Alpha Centauri A and B by just 280 m/s, which is less than the system's escape velocity. Thus, Proxima Centauri is indeed gravitationally bound to Alpha Centauri A and B. Proxima Centauri revolves around them every 510,000 years, with a mean distance from the pair of 8,200 au.

Kepler's Third Law

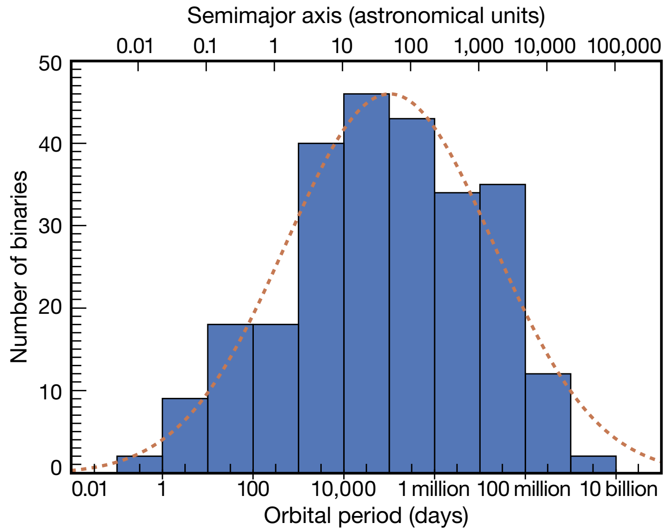
Kepler's third law relates a binary's mass, period, and mean separation. The equation is simple:

$$MP^2 = a^3,$$

where M is the total mass of all the stars in the system in solar masses, P is the orbital period in Earth years, and a is the mean separation in astronomical units. If you know two of these quantities, you can therefore calculate the third.

An extremely wide binary has such a long orbital period that you can't possibly observe it. But thanks to Kepler's third law, you can calculate this number from the masses of the two stars — estimated from their spectral types — and from their mean separation.

Ah, but what is the mean separation of stars that take thousands of human lifetimes to go from periastron to apastron? Fortunately, astronomers have calculated that this quantity is typically about equal to the *projected* separation — that is, the distance between the two stars if both are exactly the same distance from Earth.



▲ **BINARY PERIODS** This plot shows the distribution of orbital periods and separations for the companions of more than 250 Sun-like stars. The most common period is about 100,000 days, or 270 years, with an average separation of roughly 50 au. But a few percent of systems have companions that take at least hundreds of thousands of years to complete an orbit and lie many thousands of au apart.

D. RAGHAVAN ET AL. / *ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES* 2010

Questions of Origin

But how does such an extremely wide system form? Stars are born with other stars in groups and clusters, and the cores of newborn star clusters are typically no more than 10,000 au across — smaller than the widest binaries. How do you bake a loaf of bread that's larger than the oven?

The answer lies in the clusters' evolution. The clouds of gas and dust in which clusters originate have their own gravity, which helps bind the newborn stars to one another. But as stellar winds and supernova explosions expel the gas and dust, most clusters break up. When this happens, two departing stars, though separated by an immense distance, may by chance be going the same way and link up via their gravitational attraction to each other, thereby creating an extremely wide binary. This process occurs most readily in sparse star-forming regions, such as the clouds of Taurus and Auriga, where other stars won't interfere. By contrast, in a dense region, such as the Orion Nebula Cluster, the gravitational tugs of other stars would quickly split a wide pair apart.

Another possibility is that some extremely wide binaries start out as compact triple stars. Two of the stars gang up on the third — usually but not always the lightest — and kick it away. In most cases, the ejected star escapes altogether, but in some cases, it remains loosely bound at a large distance. That sounds a lot like the Alpha Centauri system.

But this idea may not actually apply there. If Proxima Centauri was born close to Alpha Centauri A and B, the small star should be on an extremely elliptical orbit, one that carries the little red star from close to far, with an eccentricity exceeding 0.9. (Learn more about eccentricity on page 24.) But Kervella finds that Proxima Centauri's orbital eccentricity is only 0.5. This result suggests that Proxima Centauri was not born right next to its bright mates but instead latched onto them as the star cluster that spawned them all was disintegrating.

Far-off Friends for Fomalhaut

Six times farther from Earth than Alpha Centauri lies what is often called the loneliest star: white *A*-type Fomalhaut, a fixture of the southern sky in the constellation Piscis Austrinus, the Southern Fish. No other bright star shines near Fomalhaut.

But Fomalhaut does have company — of the long-distance sort. In 1938, American astronomer Willem Luyten discovered that an orange dwarf shares its motion through space. This star, Fomalhaut B, is 57,000 au from the main star, almost one full light-year away.

But that's nothing compared with a recent discovery. In 2010 Eric Mamajek (now Jet Propulsion Laboratory) found that a fainter star, a red dwarf on the other side of Fomalhaut A, also shares the bright star's motion. The red dwarf, named LP 876–10, is located a whopping 158,000 au away — 2.5 light-years, more than half the distance between the Sun and Alpha Centauri. It lies 5.7° from Fomalhaut A in our sky and even shines in a different constellation: Whereas Fomalhaut A is the beacon of Piscis Austrinus, Fomalhaut C (as Mamajek calls it) lies just over the border in dim Aquarius, the Water Bearer. All three Fomalhaut stars are almost exactly the same distance from Earth, 25 light-years.

If the red dwarf is orbiting Fomalhaut A, then one full revolution takes some 20 million years. Mamajek thinks a true pairing is likely because, if the two stars are not gravitationally bound, then even a slight difference in speed would have carried them far away from each other during the 440 million years they've been shining.

Nor is it likely that Fomalhaut C is just now escaping from the bright star. "It would be like meeting somebody for the first time, and you're meeting them on the day of their divorce," he says.

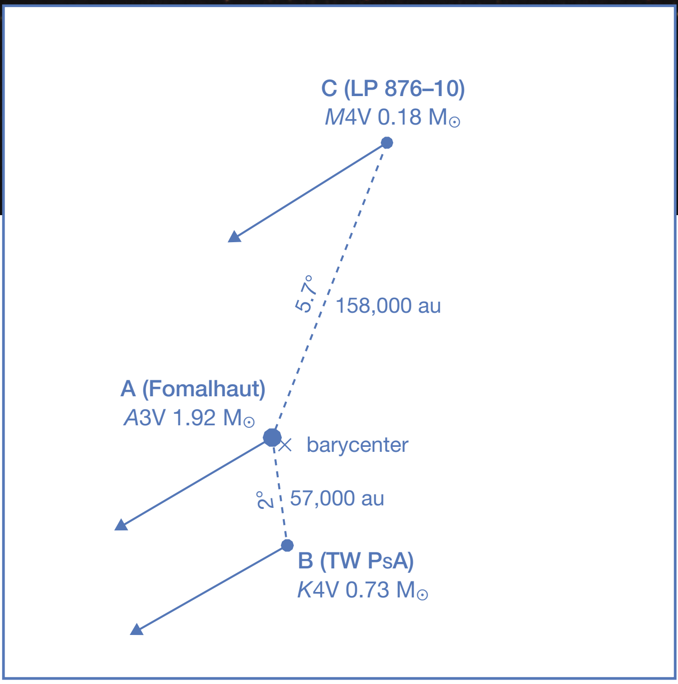
But not everyone accepts this conclusion. "It's not a binary," says Andrei Tokovinin (Cerro Tololo Inter-American Observatory, Chile). "This is a young star. It's normal that it is accompanied by some smaller brothers that were born together." He thinks the three stars constitute what's known as a *moving group*. Like the five central stars of the Big Dipper, they move through space together — but only because they were born together, not because they are gravitationally bound to one another.

Kervella, for his part, says the velocities of the Fomalhaut stars are too uncertain to make a definite statement one way or the other.

Surviving the Milky Way

An extremely wide binary faces several challenges as it sails through the galaxy. "The main threats are passing stars and passing giant molecular clouds — that is, dense concentrations of gas in the interstellar medium," says Scott Tremaine (Institute for Advanced Study). "Either of those can create

▲ **NOT SO LONELY** The only bright star in its region of the sky, Fomalhaut is accompanied by two fellow travelers, which both lie at significant distances from the primary. The image spans roughly 30°. Star C is invisible here; the line points to its location.



▲ **IN A PACK?** The proper motions (arrows) of the stars LP 876–10 and Fomalhaut A and B suggest that the three form a gravitationally bound system. The barycenter is the trio's estimated gravitational center. The angular distances are on the plane of the sky, but the separation distances are in three dimensions.

FOMALHAUT: AKIRA FUJII; FOMALHAUT TRIO'S MOVEMENT: BEATRIZ INGLESSIS / *S&T*, SOURCE: E. E. MAMAJEK ET AL. / *ASTRONOMICAL JOURNAL* 2013

gravitational pulls on the wide binaries that are sufficient to change the orbit from bound to unbound and thereby disrupt the binary."

A passing star can gravitationally entice one member of an extremely wide binary away, since the two stars in the binary are so weakly bound to each other. Furthermore, the wider the binary, the greater the chance another star will slip between the two, rupturing their marriage.

Molecular clouds, meanwhile, can possess millions of solar masses of gas and dust, which exert their own gravitational pull. "The most dangerous encounters would be the ones where the binary passes through the molecular cloud," Tremaine says. Because the cloud is clumpy, its gravity can pull more on one star than the other, splitting the pair apart.

▲ **TAURUS MOLECULAR CLOUD** Stars form in clumpy filaments, as revealed in this infrared mosaic from the Herschel Space Observatory. The bright, reddish regions are the densest environments, with the most intense star formation.

An extremely wide binary also feels the galaxy's tide. Just as the Moon's gravity tugs harder on seas facing moonward than on those facing the other way, so the galaxy's gravity yanks more on whichever star in a binary is closer to the galactic plane, luring the star away from its distant mate.

Even a star's evolution can dissolve a long-distance stellar marriage. When a red giant sheds its atmosphere and becomes a white dwarf, the loss of mass can unbind an extremely wide binary. For this reason, extreme binaries rarely have white dwarf stars — as El-Badry and Hans-Walter Rix (Max Planck Institute for Astronomy) discovered after analyzing Gaia data.

Remarkably, despite all the dangers, extreme binaries can endure for more than 10 billion years. We know this because they exist in the Milky Way's halo, the population of ancient stars around the galactic disk (*S&T:* Aug. 2023, p. 34). For example, two 9th-magnitude orange *K* stars in Libra go around the galaxy backward, opposite the way our galaxy spins — a testament to their halo bona fides. The stars are 96 light-years from Earth, with the brighter, HD 134439, located 5 arcminutes north of the fainter, HD 134440. If both stars are equally distant from Earth, they are 8,800 au apart — and even farther apart if their distances from us differ.

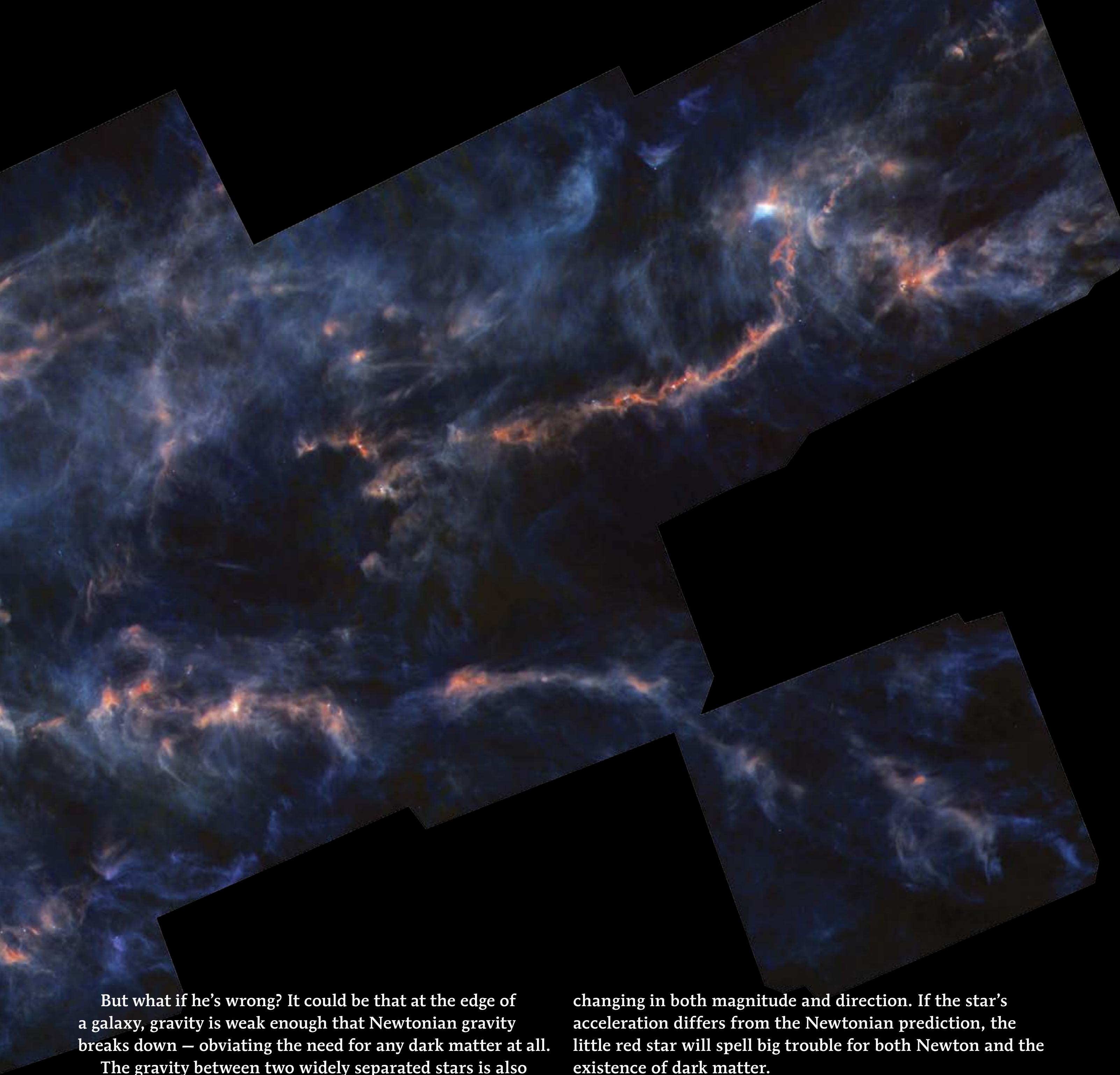
Given the hazards posed by passing stars and the galactic tide, Yan-Fei Jiang (Flatiron Institute) and Tremaine have calculated how far out a star can hold on to its partners. The answer: surprisingly far. For a system with 3 solar masses — the approximate total of Fomalhaut A, B, and C — that distance is 6 light-years. All three Fomalhaut stars are safely within that limit.

For that matter, the Sun and Alpha Centauri also add up to about 3 solar masses, and we are less than 6 light-years from our neighbor. So if the Sun's velocity through space changed to match Alpha Centauri's, we would all become bound together, thanks to the gravitational attraction of the member stars on one another. In that case, our solar system would revolve around Alpha Centauri every 80 million years.

Weighing the Law of Gravity

Extremely wide binaries could even threaten a cornerstone of physics: Newton's law of gravity. Thanks to Einstein, we already know that Newton's venerable law is incorrect when gravity is extremely strong. What if it's also wrong when gravity is extremely weak?

This question is more than idle speculation. Astronomers deduced decades ago that the Milky Way abounds with dark matter because of how fast our galaxy's stars revolve around the galactic center. In the solar system, planets move around the Sun more slowly the farther out they are: Pluto is 10 times slower than Mercury because it's 100 times farther out. Why? Nearly all the solar system's mass is in the central object, the Sun. By contrast, in a spiral galaxy, stars at the galaxy's visible edge move nearly as fast around the galactic center as those closer in. That means the galaxy possesses a huge halo of dark matter that exerts gravitational force — if Newton is right.



But what if he's wrong? It could be that at the edge of a galaxy, gravity is weak enough that Newtonian gravity breaks down — obviating the need for any dark matter at all.

The gravity between two widely separated stars is also weak. If Newton is wrong, the stars might revolve faster than Kepler's laws predict. By using Gaia data on extremely wide binaries, some astronomers have actually claimed to see this deviation, while others dispute it.

"I'm not that concerned for Newton," El-Badry says. "Newton has done pretty well for himself in the last 360 years, so the evidence needs to be pretty strong before you start to get worried."

Alpha Centauri could hold the key, Kervella says. Because we can measure its properties precisely, we might be able to see whether Proxima Centauri's velocity is changing in both magnitude and direction. If the star's acceleration differs from the Newtonian prediction, the little red star will spell big trouble for both Newton and the existence of dark matter.

Extremely wide binaries therefore do more than just demonstrate how gravity can tether two stars together over immense distances. These remarkable star systems could also lead to new discoveries about one of the fundamental forces of physics, a force that holds us to Earth, Earth to the Sun, and the entire solar system to the Milky Way Galaxy.

■ Contributing Editor KEN CROSWELL earned his PhD for studying the Milky Way. He is the author of *The Alchemy of the Heavens*, *Planet Quest*, and *Magnificent Universe*.