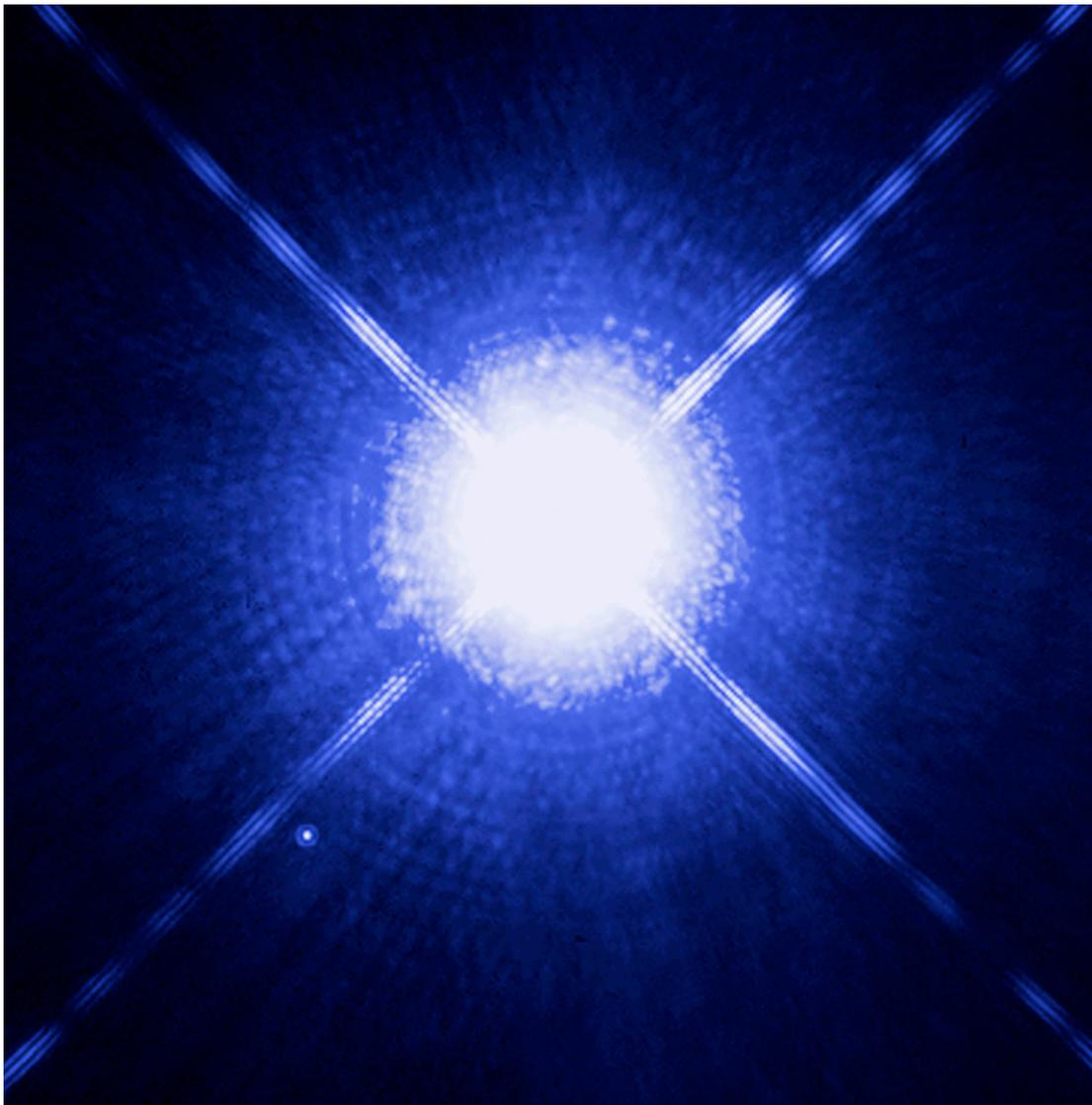


Astronomers uncover new way to measure the speed of stars

Ken Crowell, *Science Writer*

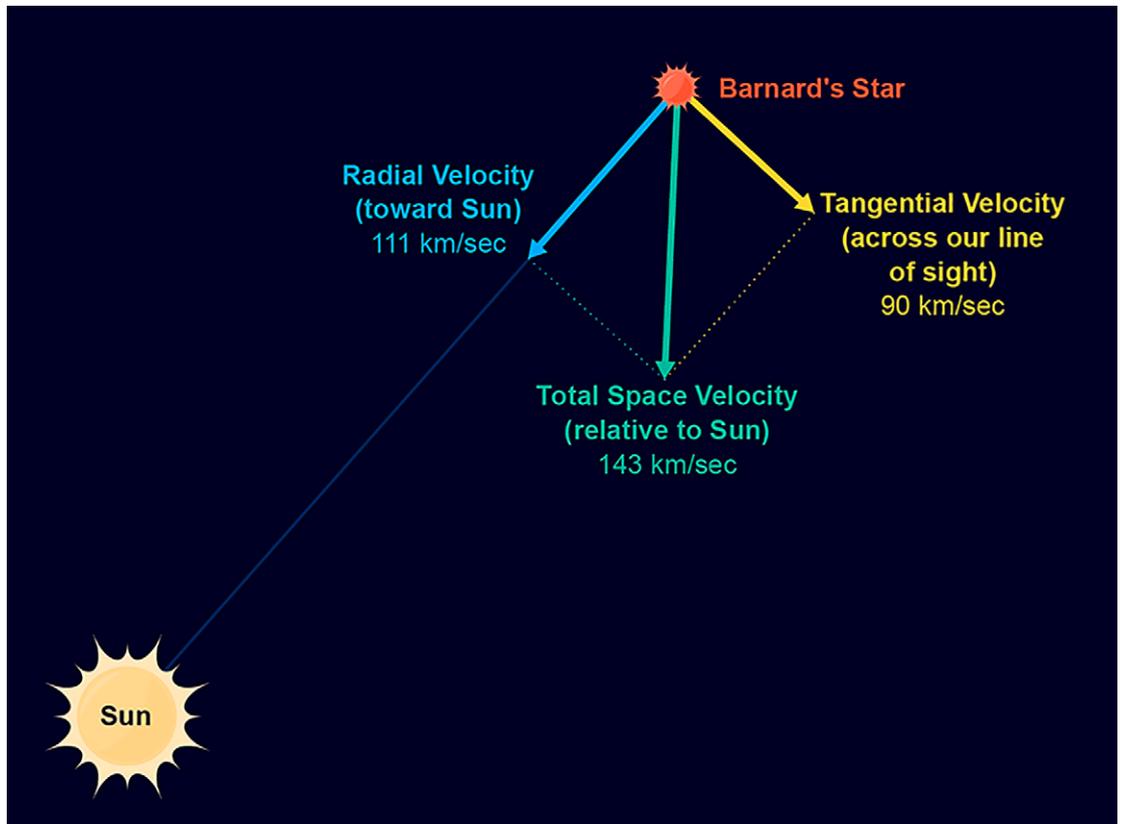
As an ambulance speeds toward you, its sirens scream at a high pitch. That pitch suddenly drops when the vehicle rushes by and races away. The

change in pitch arises from a well-known phenomenon called the Doppler shift. However, the effect is more than just an amusing oddity. For more than a



White dwarf stars have enormous gravitational redshifts that can make it hard to determine their velocities through space. This Hubble Space Telescope image shows Sirius A, 8.6 light-years from Earth; its white dwarf companion Sirius B is the tiny dot in the lower left. Image credit: NASA, H.E. Bond, and E. Nelan (Space Telescope Science Institute, Baltimore, MD); M. Barstow and M. Burleigh (University of Leicester, UK); and J.B. Holberg (University of Arizona, Tucson, AZ).

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The new velocity-detection technique works best for Barnard's Star. It is nearby and has both a large tangential velocity (yellow) and a large radial velocity toward Earth (blue). Together they give the total space velocity of the star (green) relative to the Sun. Image credit: Lucy Reading-Ikkanda (artist).

century, astronomers have exploited this same effect to measure how fast stars are moving toward or away from us. But that approach is set to change. New observations now allow the seemingly impossible: measuring the speeds of some stars along the line of sight without ascertaining their Doppler shifts.

"It's really cool," says Todd Henry, an astronomer at Georgia State University in Atlanta who was not involved with developing the new method, which works best for the nearest stars. "Humans have a natural curiosity to go explore things," he says, "and we always explore the nearest locales first."

Stellar velocities carry vital information about both the stars and our galaxy. The new technique for measuring these velocities promises to circumvent some drawbacks of the standard Doppler method and should prove especially useful for studying a breed of stars known as white dwarfs. Moreover, the new technique may even help in the hunt for life-bearing planets orbiting other suns.

Three Numbers

Determining the total velocity of a star through space has traditionally required measuring three quantities. The first is proper motion, which is how much a star moves across our line of sight rather than along our line of sight. Proper motion is expressed in fractions of a degree per year. French

astronomer Jacques Cassini discovered stellar proper motion in 1738, finding that the bright star Arcturus had moved from its position in earlier centuries (1).

The second quantity is distance, which Friedrich Wilhelm Bessel at Königsberg Observatory in Prussia first measured for a star beyond our solar system in 1838, exactly one century after the discovery of proper motion. Bessel observed the faint star 61 Cygni and successfully detected its parallax, a tiny change in the apparent position of the star that occurs because observers view it from different vantage points as Earth circles the Sun (2), and distance is inversely related to parallax. Distance lets astronomers convert proper motion into tangential velocity—how fast the star is moving across our line of sight in kilometers per second.

The third quantity is the Doppler shift, which gives the radial velocity—how fast the star is moving toward or away from us. Astronomers began detecting Doppler shifts of stars during the late 1800s, half a century after Austrian physicist Christian Doppler first described the phenomenon.

If a star is moving toward us, its light waves get scrunched up to shorter, or bluer, wavelengths, producing a blueshift. If a star is moving away, its light waves get stretched out to longer, redder, wavelengths, producing a redshift. The faster the star, the

greater this shift, so observers can measure the line-of-sight speed from the Doppler shift.

More than a century ago, though, far-sighted astronomers anticipated a day when they would measure the positions of stars so precisely that the change in proper motion would reveal the radial velocity, with no need for the Doppler shift. To most modern astronomers, who were taught that the Doppler shift is essential for measuring radial velocities, that's a radical claim.

But it came true this past spring. "For a small number of stars that are relatively close to the Sun, this method actually works very well," says Lennart Lindegren of Lund Observatory in Sweden. For seven nearby stars, he and Dainis Dravins, also at Lund Observatory, obtained radial velocities accurate to one kilometer per second, the standard for measuring useful radial velocities of stars from their Doppler shifts (3).

It's Just Geometry

The recent success wasn't the researchers' first attempt. In 1989 the European Space Agency (ESA) launched the Hipparcos satellite, which measured the positions and proper motions of more than 100,000 stars. Comparing these numbers with positions on old photographic plates yielded radial velocities of various nearby stars, but with typical uncertainties of dozens of kilometers per second (4).

Since then, however, ESA's Gaia spacecraft, launched in 2013, has observed more than a billion stars. Lindegren and Dravins relied on Gaia's precision and the quarter-century-long separation, or baseline, between the proper motions that Hipparcos and Gaia recorded to deduce accurate radial velocities of nearby stars. The achievement, Dravins says, has surprised some astronomers.

Yet the idea is simple. "It's just geometry," Dravins says. "There is nothing conceptually mysterious about this."

Suppose we measure the position of a star every January 1. After a year, we can draw an imaginary cosmic triangle, the first two sides of which extend from us to the star's position on January 1 of each year. The third side connects the star's starting and final positions over the course of that year. The two sides from us to the positions of the star form a tiny angle. This angle, divided by one year, is the star's annual proper motion. If the star is moving toward us, then that angle will increase with each passing year; conversely, if the star is moving away from us, that angle will instead steadily decrease. By measuring the increase or decrease in the proper motion from one year to the next, along with the star's distance and proper motion, you can determine how fast the star is moving toward or away from you. And you can do so without knowing its Doppler shift.

Success Stories

The new technique works best for stars that are not just nearby but also fast. The most suitable star turns out to be a well-known red dwarf—a cool, dim

star—named Barnard's Star, after astronomer Edward Emerson Barnard, who discovered the star in 1916 while he was at Yerkes Observatory in Williams Bay, WI (5). Among the stars in the night sky, Barnard's Star has the largest proper motion of all, more than half a lunar diameter every century. The large proper motion arises because the star is nearby, the second closest star system to the Sun, and swift. In 1916 it was 6.00 light-years away. Now it's only 5.96 light-years away.

"There is nothing conceptually mysterious about this."

— Dainis Dravins

As a result, Lindegren and Dravins easily detected the increase in proper motion of the star from the Hipparcos era to the Gaia era. From that, the researchers deduced the radial velocity of the star, good to within 0.4 kilometers per second. Moreover, their estimate—111 kilometers per second—agrees with the estimate made using the Doppler shift of the star to within just 0.6 kilometers per second.

Henry praises the work of Lindegren and Dravins. "I'm really glad they did it, and I'm glad they showed us how well the numbers turn out," he says. While acknowledging that the researchers achieved kilometer-per-second precision for only a handful of stars, he says a future Gaia-like mission, launched 50 years from now, could encompass far more stars because of the much longer baseline.

"It's always interesting to get a completely independent measurement of a quantity to stand next to another type of measurement," says astronomer Floor van Leeuwen of the University of Cambridge in England, who is a member of the Hipparcos and Gaia teams.

Another star that demonstrates the success of the new technique is Proxima Centauri. Located just 4.25 light-years from Earth, this red dwarf is the nearest stellar neighbor to our solar system and even has an Earth-mass planet (6). Lindegren and Dravins used the changing proper motion of the star to derive a radial velocity of 23 kilometers per second, accurate to within 0.7 kilometers per second and differing from the Doppler value by only 0.8 kilometers per second.

Proxima Centauri orbits two bright stars, Alpha Centauri A and B, every 550,000 years or so (7). Unfortunately, the new technique doesn't work on them, because bright stars overwhelm Gaia's detectors. The spacecraft makes the best measurements for stars dimmer than the naked eye can see.

Farther out, about 13 light-years from Earth, is another dim red star, Kapteyn's Star. The peculiar path of this star—it orbits the galaxy backward—gives the star both a large radial velocity and a large proper motion, yielding a radial-velocity measurement as good as Proxima Centauri's despite the larger distance.

Tailor-Made for White Dwarfs

The new technique is immune to some of the problems that afflict Doppler shifts. For example, the

outer layers of most stars are convective: Hot gas rises, radiates away its heat, cools, then sinks back down again. The hot rising gas moves toward us and the light from it is therefore blueshifted, whereas the cool sinking gas moves away and its light is redshifted. “They don’t cancel out,” Dravins says, because the hot, blueshifted gas is brighter. This induces a slight overall blueshift that muddles the measurements of the radial velocity of the star using the Doppler shift. In contrast, measuring the radial velocity from the proper motion does not suffer from this difficulty.

The ability to measure non-Doppler radial velocities is particularly helpful for astronomers studying white dwarfs, which account for six percent of all stars. White dwarfs are dense and compact, with surface gravities some 100,000 times greater than Earth’s. The immense gravity causes photons leaving the star to lose energy and get severely redshifted. The nearest white dwarf, Sirius B, has a gravitational redshift of 81 kilometers per second (8), vastly greater than the true speed of the star toward us of just 8 kilometers per second, which we know only because the star orbits a normal star whose velocity we can measure.

But many white dwarfs are loners. “For these single white dwarfs, we basically don’t know their space velocities very well,” Lindegren says. The nearest single white dwarf is Van Maanen’s Star, 14 light-years from us. It has a redshift, which would ordinarily mean that it is moving away. But by detecting an increase in

its proper motion, Lindegren and Dravins find that Van Maanen’s Star is actually moving toward us.

The new technique for measuring radial velocities may even help astronomers seeking Earth-like planets around other suns.

The gravity of an orbiting planet tugs its star toward and away from us, inducing periodic Doppler shifts in the star that reveal the presence of the planet. These Doppler searches have uncovered countless giant planets. But the low mass of an Earth-like planet barely changes the radial velocity of its sun; it’s a mere 0.00009 kilometers per second for the Sun and the Earth. So blueshifts and redshifts from stellar convection, flares, and other phenomena can swamp the tiny Doppler signal of a small planet. Consequently, Dravins says, Doppler searches for these possibly life-bearing worlds are “limited by the lack of understanding of stellar variability, which is intrinsically much greater than we expect from an exo-Earth.”

Although the new technique won’t help find any new Earths, it could enable Doppler searches to do just that. “How can we push the radial-velocity measurements in exoplanet searches to their highest precision?” asks Dravins. Measuring radial velocities independently of Doppler shifts could help astronomers understand how variable stellar phenomena such as convection and flares alter the measured blueshifts and redshifts of a star. In principle, this may allow Doppler-based planet hunters to mitigate errors, potentially helping to discover Earth’s twin as it orbits around a Sun-like star.

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