Inventory of the Universe

The European space observatory *Gaia* has surveyed approximately two billion stars with unprecedented precision – a treasure trove of data that has already changed our view of the Milky Way. **Coryn Bailer-Jones** from the **Max Planck Institute for Astronomy** in Heidelberg has been involved in the project since its inception. He compiled one section of the star catalog and, among other things, searched it for stars that have approached close to our solar system, or will do so in the future.

Graphic: ESA/ATG medialab; background image: ESO/S. Brunier

Viewing the Milky Way: the *Gaia* space observatory surveys the sky with unprecedented precision in three dimensions. The mission focuses on the stars of our galaxy.

TEXT **THOMAS BÜHRKE**

"I sort of slipped into the *Gaia* project," says Coryn Bailer-Jones, recounting how the *Gaia* success story began. At the University of Cambridge, he had been working on how to effectively classify stars using large datasets: "The process I developed there was based on neural networks." After receiving his doctorate, the British-born scientist came to the Max Planck Institute for Astronomy in Heidelberg in 1998, where he initially researched brown dwarfs. It was a hot topic at the time, as celestial bodies of this kind had only been discovered a few years previously.

But then Bailer-Jones heard about the *Gaia* project and went to a meeting organized by the European Space Agency, ESA. There he caught the attention of one of the founders of the project, Michael Perryman, who immediately recognized his potential. "He convinced me to join *Gaia*," recalls Bailer-Jones, a decision that was to shape his future career.

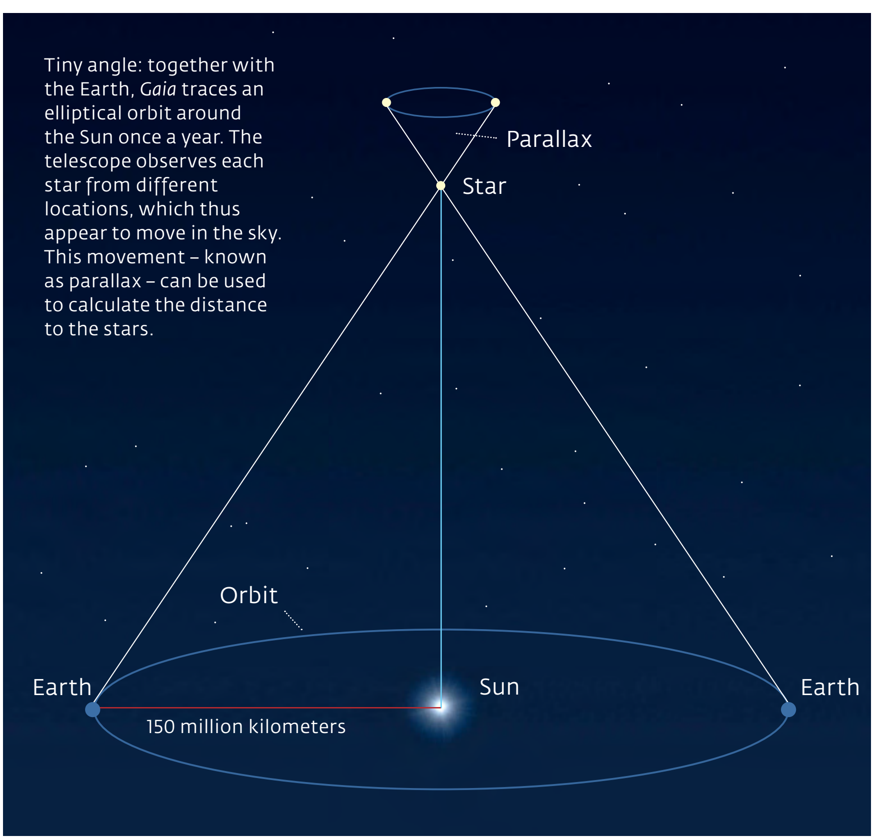
THE TELESCOPE THAT DOESN'T TAKE PICTURES

Launched at the end of 2013, the observatory has the largest camera ever deployed in space. But, unlike the *Hubble Space Telescope*, it doesn't take normal images of the sky. Instead, *Gaia's* task is to measure the positions, motions, luminosities, and colors of more than a billion stars in our Milky Way – a cosmic census of unprecedented magnitude and precision.

Gaia is so precise that, theoretically, it could detect the movement of a beetle on the Moon. It slowly rotates around its axis and provides images of the area of the sky currently in its field of view on a gigapixel camera. This consists of 106 CCD chips and measures around half a meter by one meter. At the end of the mission, each celestial body will have been measured about a hundred times.

The analysis of the *Gaia* data depends only on geometry, without making astrophysical assumptions about its targets. This makes use of *Gaia's* orbit around the Sun: the telescope orbits the Sun at a distance of approximately 300 million kilometers, staying close to the Earth, mapping the positions of the stars continuously. As it observes celestial objects from different locations during its orbit, their positions in the sky vary, describing a minute ellipse that reflects *Gaia's* movement around the Sun.

It's easy to visually demonstrate the effect. Hold your finger up in front of your face and look at it first with your left eye and then with your right. Your finger looks like it's jumping back and forth against the background. Your eyes correspond to two positions of *Gaia* on its orbit and your finger to a star. The closer the star is, the greater the perspective shift, which is referred to as "parallax". If you know the diameter of the orbit and have recorded the parallax of a star, you can calculate its distance.



Tiny angle: together with the Earth, *Gaia* traces an elliptical orbit around the Sun once a year. The telescope observes each star from different locations, which thus appear to move in the sky. This movement – known as parallax – can be used to calculate the distance to the stars.

Graphic: designergold after Mario Lehwald

In September 2016, the *Gaia* Consortium published the first catalog with about two million stars. As incomplete as this data set was, it was cause for celebration in the world of astronomy. But the second catalog from April 2018 surpassed expectations: it detailed the positions, brightness, parallaxes and movements of 1.3 billion objects. This treasure trove of data was made available by the *Gaia* Consortium and ESA to all researchers worldwide – an unprecedented act of generosity.

Within ten months of this data release, scientists had published more than a thousand scientific papers based on the data, the first appearing on preprint servers just a few hours after access was granted to the data archive. This was only possible thanks to extensive preparation.

Change of subject: originally, Coryn Bailer-Jones studied a particular type of star known as brown dwarfs. But then he found out about the *Gaia* satellite – and eventually joined the project.

Photo: Wolfram Scheible

In 2006, long before *Gaia's* launch, the ESA founded eight so-called Coordination Units (CUs). Astronomers and software specialists in these units prepare the data so it can be used for research without further processing. Two of these CUs are run from Heidelberg. The Astronomisches Rechen-Institute (ARI) at the Centre for Astronomy of Heidelberg University oversees CU3. Around a trillion individual measurements are processed and calibrated to yield astrometric values such as the positions, distances, and velocities of the stars.

RENDEZVOUS WITH A DWARF

In the 1970s, the space probes *Pioneer 10* and *11* and *Voyager 1* and *2* left Earth for the outer solar system. They are currently more than a hundred times further away from the Sun than the Earth and will continue into interstellar space. We are still in radio contact with the two *Voyagers*.

Should aliens ever spot one of the probes, they'll find messages on board. Recently Coryn Bailer-Jones together with a colleague from the Jet Propulsion Laboratory of the U.S. space agency NASA calculated when the probes will approach a known star in the next millions of years. The result: none of the probes will come closer than 0.6 light-years to any of the 7 million stars in *Gaia* for which we have the required data. The closest will be for *Pioneer 11* in 920 000 years, with a flyby of a dwarf star called TYC 992-192-1.

CU8 was headed until mid-2018 by Coryn Bailer-Jones (he now concentrates more on the scientific and technical work within CU8). CU8's task is to distill astrophysical parameters from the *Gaia* data. "We work on the processed data results, so we have to wait for our colleagues," explains Bailer-Jones. "But of course, we started planning our approach long before launch." They used their expertise to develop software packages that would be compatible with each other, and tested this software using simulated data.

Astronomers with an interest in *Gaia* had long known in what form the data would appear. They had written their programs in advance and, to a greater or lesser degree, could start working with the data immediately after their release. The spectrum covers almost all areas of astronomy – from discovering asteroids in our solar system to identifying the motions of stars

» The team around Coryn Bailer-Jones has used *Gaia's* photometric and parallax data to determine the temperature of more than 160 million distant suns.

in streams through the Milky Way and surveying dark matter.

Coryn Bailer-Jones and his team have used *Gaia's* photometry and distances to determine the temperature of more than 160 million stars as well as the absolute luminosity and radius of 77 million stars. "We have produced the largest ever standardized dataset of the physical properties of stars," says the Max Planck astronomer. In addition to data on stars, the catalog contains asteroids, galaxies, and half a million quasars. The latter are extremely bright central regions of galaxies, each of which harbors a black hole. This draws in matter from its surroundings, which heats up and shines brightly.

Finding asteroids – small bodies within our planetary system – requires a very specific strategy, as, unlike stars, they move relatively quickly across the sky. To date, some 14,000 of these objects have gone online.

A CLOUD OF BILLIONS OF CHUNKS OF RUBBLE

While Bailer-Jones provides material for other scientists to make discoveries, he has also developed his own particular areas of interest over the years. One of these is the question of whether other stars have passed close to the Sun, going on to trigger comet showers.

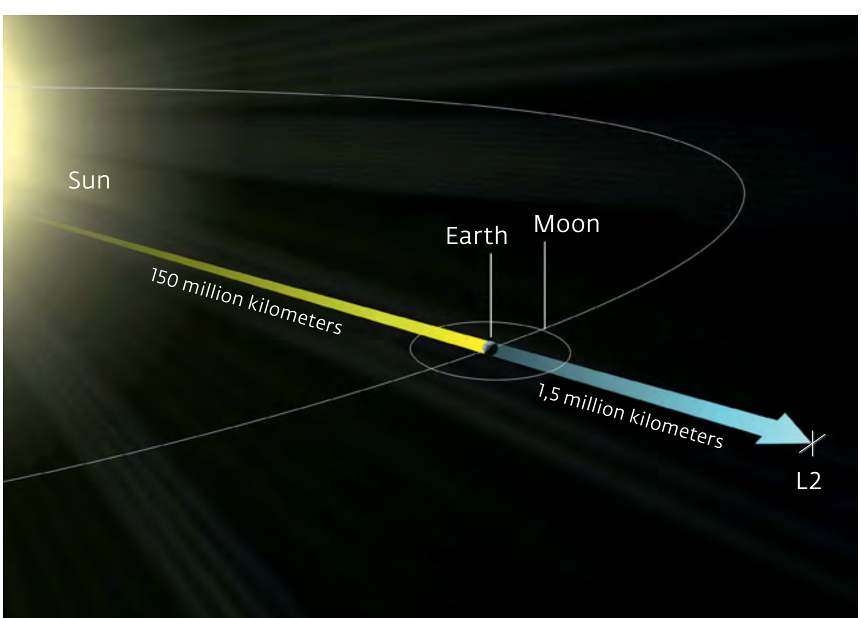
The idea has been around for a long time. Our solar system is surrounded by a sphere of billions of lumps of rock and ice. Astronomers call this the Oort Cloud. Normally, these objects orbit without being disturbed. However, if a star passes close to this cloud, its gravity can eject some of them from their orbits. If these pass close to the Sun, they heat up. Ice within them vaporizes, drawing dust with it. A comet is born.

As fascinating as we find their passage across the night sky, they can also have a devastating effect, for instance when a kilometer-sized lump collides with the Earth. Events of this kind have influenced the evolution of life on our planet. The extinction of the dinosaurs 65 million years ago has been attributed, at least in part, to the impact of such a cosmic body. We don't know, however, whether the visitor at that time was a comet from the Oort cloud or an asteroid from the inner solar system.

The *Gaia* data are uniquely suited to identifying stars that might have triggered such comet showers – or those that could do so in the future. The data can be extrapolated into the past as well as into the future. Astronomers suspect that the Oort cloud extends to 100,000 times the distance of the Earth to the Sun. That corresponds to one and a half light-years and, thus, about one third of the distance of Alpha Centauri, the nearest star to Earth.

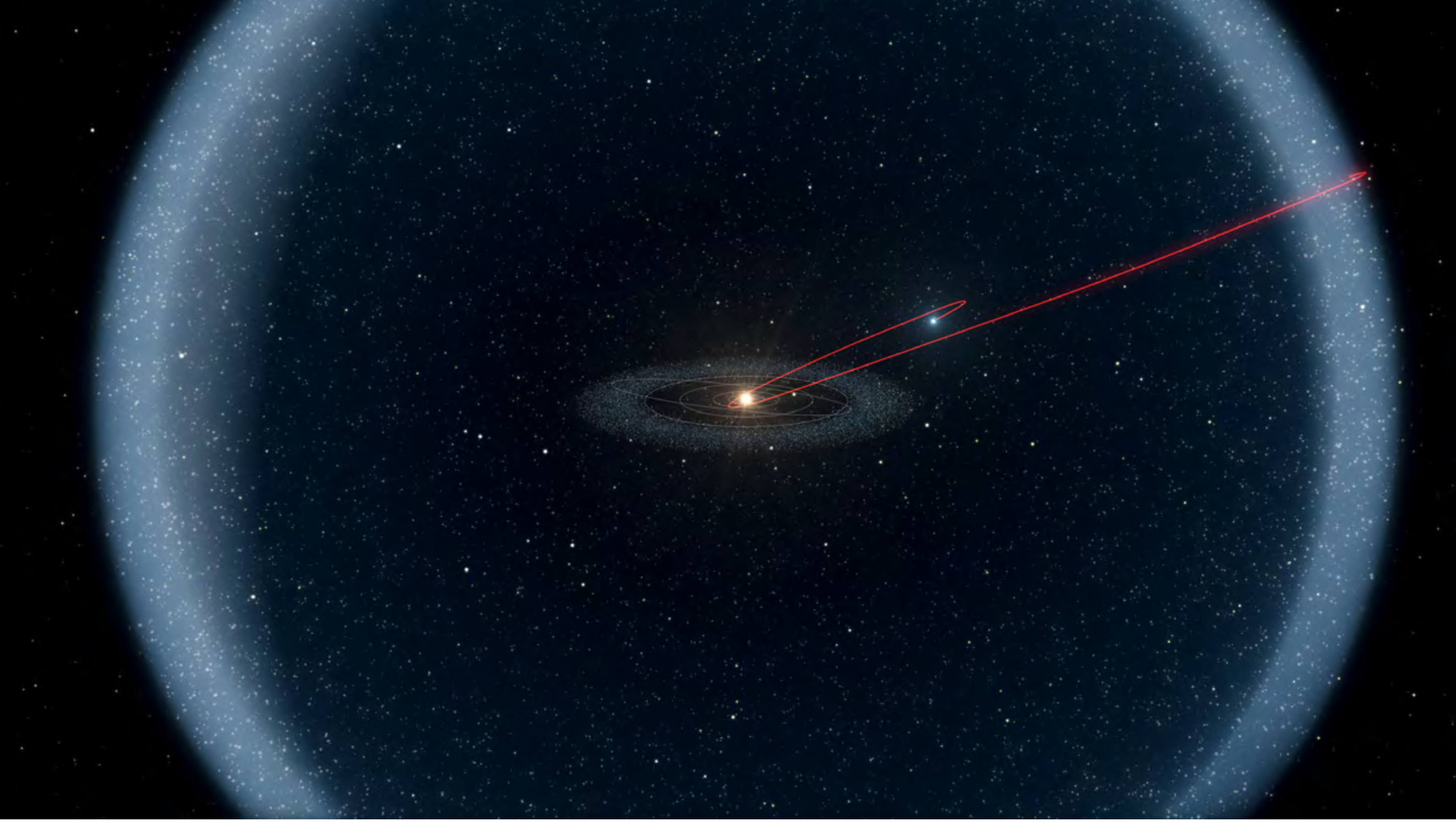
STELLAR STRANGERS PASSING OUR SUN

Coryn Bailer-Jones, therefore, searched the *Gaia* catalog for stars that had passed through this region of space, allowing him to systematically specify for



In outer space: a large number of science satellites are circling Earth. However, *Gaia* moves around Lagrange point 2 (L2). This is about 1.5 kilometers away from our planet, and permits observations that are largely free of interruption.

Graphic: ESA/NASA



Cosmic rubble field: about 70 years ago, the Dutch astronomer Jan Hendrik Oort theorized the existence of a spherical cloud of innumerable blocks of ice and rock. This Oort cloud is thought to extend up to one and a half light-years into space.

Graphic: ESO/L. Calçada

the first time how often this might occur. From a set of more than seven million stars that had the required data, he identified seven plausible intruders. The most interesting is a star called Gliese 710. "This is an old acquaintance of ours from previous research, but now we have much more accurate data on it," says Bailer-Jones.

According to his calculations, Gliese 710 will pass the Sun in 1.3 million years with a separation of only 14,000 Earth orbital radii. "It is also the star with the largest known impulse transfer to the Oort cloud," says the astronomer. Gliese 710 has only about 70 percent the mass of the Sun, but it moves relatively slowly, giving it enough time to eject cometary nuclei from their orbits.

It would, naturally, be a sensation if astronomers were to identify the star that caused the impact 65 million years ago. "But that's essentially impossible for several reasons," explains Bailer-Jones, as we can only calculate the orbits of stars accurately up to five to ten million years into the past or future.

Over longer periods of time, the associated errors of the calculations become too large. The accuracy of the orbits are limited both by the accuracy of the measurements, especially the radial velocities of stars, and by the gravitational field of the Milky Way, through which all of its stars travel. This gravitational field is generated not only by stars but also by large clouds of molecules and dust, and the enigmatic dark matter.

Moreover, *Gaia* only observes stars in a particular luminosity range: too bright and the detector is saturated, too faint and the telescope can't see them. However, we can estimate the number of these missing stars from other observations. With this method, Coryn Bailer-Jones has arrived at a statistical estimate according to which every 200,000 years one star on average travels past the Sun at a distance of no more than one and a half light-years. Many of these are dwarf stars, which, due to their low masses, barely disturb the Oort Cloud.

Given that several million years can elapse between the disruption of a comet's orbit and the arrival of a comet near to the Earth, his results indicate that the Oort Cloud is actually in constant turmoil. Even though Bailer-Jones will probably never catch the destroyer of the dinosaurs, he has made the first concrete estimate of how often stellar invaders penetrate the comet reservoir.

Another way that *Gaia's* treasure trove of data can be exploited for scientific analysis was demonstrated by the recent arrival of a mysterious messenger from the stars. On 19th October 2017, astronomers employing a telescope in Hawaii discovered a faint point of light moving across the sky. Initially, they classified it as just one more of the known 800,000 asteroids. But when they calculated the trajectory of the object, they were astonished.

It wasn't moving around the Sun in the same way as asteroids, but was flying out of our solar system at an extremely high speed of 95,000 kilometers per hour, almost perpendicular to the planetary orbital plane. It must have arrived from a distant star, and after briefly visiting the solar system, was already heading out on its interstellar journey. It was named 'Oumuamua, which in Hawaiian means 'messenger from the distant past'. >

Unknown messenger: in October 2017, researchers on Hawaii discovered an unusual celestial body that flew through our planetary system. Was it an asteroid or a comet? What is certain is that this object, 'Oumuamua, came to us from a distant star.

After the astronomers had identified 'Oumuamua as an interstellar traveler, they immediately alerted observatories around the world to examine it in detail while it was still visible. The scientists discovered that it must have an unusual shape, resembling either a cigar or a pancake around 400 to 800 meters in length or diameter. It also wasn't rotating around one specific axis, but was tumbling through space.

DID THE INTRUDER COME FROM VEGA?

Immediately, astronomers wondered where the intruder might have come from. The first orbital calculations pointed in the direction of the bright star Vega in the constellation of Lyra. However, over the course of a journey of about 300,000 years the stars have shifted considerably relative to each other, meaning that when 'Oumuamua set out it didn't do so from near Vega. Naturally, this was a perfect case for *Gaia*, as the observatory measures the positions and motions of stars with great accuracy.

"When I first heard about 'Oumuamua, I thought that one of my colleagues would already be working on it and would publish something within the next few days or weeks," recalls Bailer-Jones. The first attempts in the fall of 2017 were still based on the first *Gaia* catalog, which had too few stars for a comprehensive analysis. However, the situation didn't change quickly with the publication of the second catalog.

"In mid-July 2018, I received an e-mail from Karen Meech asking me whether I wanted to tackle the question of 'Oumuamua's origin," he recounts. Meech, from the Institute for Astronomy at the University of Hawaii, had led the 'Oumuamua research from the beginning.

Bailer-Jones quickly set to work, and within four weeks, together with colleagues, he wrote a paper in which he cited four candidate stars where 'Oumuamua's journey might have started more than a million years ago. This required another important observation: in June 2018, astronomers had discovered that 'Oumuamua apparently hadn't moved through the solar system solely under the influence of gravity. Near the Sun there must have been an additional force. Comets consist partly of ice, some of which is vaporized by solar radiation. Like a rocket, this provides them with propulsion. Although 'Oumuamua lacked some of the tell-tale signs of cometary activity, this remained the most plausible explanation for the additional force.

FOUR CANDIDATES LEFT STANDING

Only once Bailer-Jones and his colleagues had taken this effect into account could they correctly calculate its course and trace its journey back into the past. To do this, they also needed to

Graphic: ESO/M. Kornmesser

consider whether 'Oumuamua had been diverted on its journey to us by the gravity of other stars.

In their analysis, the team initially selected 7.2 million stars, 4500 of which were top candidates. The researchers calculated their motions over the past few million years, and further took into account all the uncertainties using a so-called "Monte Carlo" simulation. The procedure is a little like clay pigeon shooting in that each star is replaced by a swarm of stars differing slightly in trajectory.

In the end, Bailer-Jones and his colleagues settled on four distant stars as plausible origins for 'Oumuamua. One is the reddish dwarf star HIP 3757. 'Oumuamua passed close to it just over a million years ago. 'Oumuamua approached the Sun-like star HD 292249 even closer, 3.8 million years ago. It passed by two further candidates, about which little is currently known, 1.1 and 6.3 million years ago. In all cases, 'Oumuamua's trajectory was within a distance of two light-years or less.

Unfortunately we cannot prove that one of these candidates was 'Oumuamua's home star, not least because many other possibilities were not included in the analysis due to lack of a radial velocity measurement. It is also unclear by which mechanism 'Oumuamua was ejected out of its parent star system. "It could have been in a binary system and was flung into space by the gravity of one star when it came too close," explains Coryn Bailer-Jones. However, none of the four candidates is yet known to have a companion star. "It is also conceivable that a giant planet like Jupiter threw out 'Oumuamua."

But if the cosmic wanderer initially set off much more than five million years ago, all this speculation is moot. "If it was ejected a hundred million years ago, it has by now already traveled halfway around the center of the Milky Way, and retracing its route would be impossible," says Bailer-Jones.

Gaia's third data release will be in two years' time. The new catalog should contain the radial velocities of ten times more stars, as well as more accurate parallaxes and proper motions. This could lead to the identification of further candidates. So the search for 'Oumuamua's home country will continue, as will the many other investigations involving *Gaia's* data. "We've only just begun to sift through the immense treasure trove of data," says Bailer-Jones. "We'll be at it for decades to come." ◂

SUMMARY

- **The European astrometry satellite *Gaia* measures positions, magnitudes, parallaxes, and motions of more than one billion celestial bodies with unprecedented accuracy.**
- **This treasure trove of data enables in-depth insights into the structure and development of the Milky Way.**
- **Scientists can calculate the paths of stars through the Galaxy for millions of years into the past and the future.**
- **One project was to discover the origin of 'Oumuamua. The celestial body came from the vastness of space and recently entered – and left – our solar system.**

GLOSSARY

Asteroids, also known as minor planets or planetoids, are astronomical small bodies that orbit the Sun. They have diameters ranging from a few meters to about a thousand kilometers.

Astrometry is a branch of astronomy that involves precise measurement and calculation of the positions of the stars in the sky. This branch, also referred to as positional astronomy, is the basis of much research in astronomy, especially into celestial mechanics. From the astrometric measurements one can infer the parallax, or distance, to a star, as well as transverse velocity.

Radial velocity is the movement of a star directly towards or away from the observer. This velocity can be measured using the Doppler effect, which shifts the wavelength of light approaching an observer into the shorter wavelength blue region of the spectrum and into the longer wavelength red region of the spectrum when moving away from an observer.