Why are we so sure that Copernicus was right?

"Perhaps no discovery or opinion ever produced a greater effect on the human spirit than did the teaching of Copernicus. No sooner was the Earth recognized as being round and self-contained, than it was obliged to relinquish the colossal privilege of being the center of the Universe." – Johann Wolfgang von Goethe (author of "Faust")

No doubt, but **why are we so sure Copernicus was right**?

Well-educated people often know that Earth goes around the Sun and not the other way around. They know this mainly because their teacher said so.

What *evidence* makes us so sure?

(1) Copernicus's system is much simpler than the epicycles-on-epicycles nightmare into which Ptolemy's system had evolved. Still, this is only an aesthetic argument: it doesn't *prove* the Sun definitely *is* in the center.

(2) Galileo's discovery of the moons of Jupiter showed there were centers of motion other than Earth. This was in direct contradiction to Aristotle, who argued that Earth couldn't move, because it was the center of all motion. (Aristotle thought that things fell toward Earth because Earth was the center.)

However, this only showed that Earth was not necessarily stationary.
It didn't *prove* that Earth *is* moving.

(3) Galileo's discovery of the phases of Venus showed that Venus orbited the Sun. However, it didn't necessarily prove that *Earth* was moving. Again, it was an indirect argument. During Galileo's trial in 1633, Galileo tried to argue that the tides were the result of Earth's motion. We now know that this argument was quite wrong. (Nobody's perfect.)

(4) Tycho Brahe reasoned that if Earth moved around the Sun, then the stars should appear to move back and forth in the sky. This effect is called **parallax**: you can demonstrate it with your own two eyes. Try it: open one eye and close the other eye. Then switch eyes, and notice how objects near you appear to shift. Of course, they didn't move at all: they only appeared to. Parallax happens because your two eyes are looking in two different directions, because of the distance between your two eyes.

Surveyors use parallax to measure how tall mountains are, without having to climb them. (The mathematics involved is called *trigonometry*, and is often taught in high school.) Tycho tried to measure the distances to the stars by observing how they shift back and forth throughout the year, but he found no shifts. Tycho didn't know how far away the stars are: aside from the Sun, all known stars have parallaxes of less than 1 arcsecond (1"). With his unaided eyes, the smallest angles Tycho could measure were about 1 arcminute (1'), or 60 times larger. Tycho couldn't have seen the stellar parallax that we now know is there.

(5) **The aberration of starlight** was discovered by James Bradley. He published this discovery in 1728, the year after Newton died. It was *the first direct proof that Earth moves*, and that it travels around the Sun. The aberration of starlight is the same reason that raindrops appear to move sideways when one runs in the rain. As one runs, one's motion and the straight-downward motion of the raindrops add together. This makes the raindrops appear to deflect sideways, as one runs.

Bradley was using a telescope to search for stellar parallax, but he accidentally found that all stars move back and forth across the sky, by as much as 20.49 arcseconds near the ecliptic, and near zero near the ecliptic poles. Bradley correctly reasoned that this implies that Earth must move, making the stars' light appear to deflect.

(6) **The Coriolis effect**, explained by Gaspard Coriolis in 1835, shows that Earth spins. Coriolis realized that hurricanes have spiral shapes because Earth rotates under them. The Coriolis effect is also why it's hard to walk in a straight line on a Merry-Go-Round. As you take a step, the floor moves under your feet. It is a myth that one can see the Coriolis effect in water going down a toilet or a sink: they are rarely built precisely enough to show the effect.

(7) In 1838, Friedrich Bessel finally became the first astronomer to **measure stellar parallaxes**. This was partly because he used a telescope of unprecedented precision, which was built by Joseph von Fraunhofer. This happened just three years after the works of Galileo and Copernicus were taken off the *Index of Forbidden Books*.

(8) In 1851, over 200 years after Galileo and over 120 years after Newton, **the Foucault pendulum** was invented by French physicist, Jean Bernard Foucault. It is a long pendulum that hangs from a pivot, so it's free to move in any direction. As a Foucault pendulum swings throughout a 24-hour day, the pendulum appears to rotate around the pivot for no reason. The reason it appears to rotate is that it's really the floor beneath the pendulum that is rotating, as Earth spins.

(9) **Radar** is bouncing microwave signals off objects. By timing how long it takes for the signals to go out and return, radar measures the distances of objects. Radar has been used to locate airplanes since the 1940s. Since the 1960s, astronomers have tracked planets with Doppler radar, using instruments such as the radio telescope at Arecibo Observatory.

Radar can measure distances more accurately than using a tape measure, since the signals are guaranteed to measure in a straight line. By measuring the wavelengths of the returned signals also, Doppler radar can measure both distances and speeds of objects.

Astronomers can therefore directly observe the distances and speeds of the planets. They can also directly observe the distances and speeds of spacecraft, using signals made by the spacecraft. There have now also been spacecraft that have left the Solar System, and have looked back at Earth. It's not easy to think of evidence more direct than this.