

Science@ESA vodcast series

Script for Episode 6 – Charting the Galaxy - from Hipparcos to Gaia

Available to download from <http://sci.esa.int/gaia/vodcast>

Hello, I'm Rebecca Barnes and welcome to the Science@ESA vodcast.

In this episode we'll discover the motions of the stars, learn how astronomers measure their distances and look at the new European mission that will really get to grips with our place in the Universe.

For thousands of years humankind has relied on the positions of the stars in the night sky; to develop calendars, to tell the time and to navigate the seas and oceans.

Astrometry - the measurement of the positions and motions of celestial objects – is one of the oldest branches of astronomy.

The stars in the night sky appear to be fixed in position and at an equal distance away from us. This is the concept of the celestial sphere on which stars have been grouped into constellations since ancient times. What is difficult to imagine when looking at the night sky is the immense depth of the sky; we do not get a 3-dimensional view.

From Earth each and every star seen with the unaided eye belongs to our Galaxy, the Milky Way. This spiral galaxy contains hundreds of billions of stars. If we could travel out of the Galaxy and look back, we would see that our Sun lies about two-thirds of the Galaxy's radius away from the centre.

Measuring the positions of the stars in the Galaxy and calculating their distance from Earth is complicated because all the objects in the sky are constantly in motion. The Earth rotates, about a slowly wobbling axis whilst it orbits the Sun. The Sun itself wobbles slowly about the centre of the Solar System as a result of the gravitational pull of the planets. The Sun, and all the other stars in the Milky Way, move around the centre of the Galaxy in different orbits and therefore at different speeds. Incredibly, the Sun takes more than 200 million years to orbit the centre of the Milky Way once.

So, to measure the position of a star and its movement, astronomers need to know its right ascension and declination, in other words its longitude and latitude on the celestial sphere. As well as these, three further parameters are required; one is distance and the other two are associated with the star's motion on the celestial sphere.

The three stars famously known as Orion's Belt, as these stars orbit the centre of the Galaxy, slowly, over time, their positions in the night sky change.

This movement is known as the proper motion and is a result of a star's motion through space relative to the Solar System. Due to the vast distances to the stars, the proper motion of a star measured over a period of one year is extremely small; it could take a star thousands of years to move through the apparent size of the Moon on the night sky.

Stars also move towards, or away, from an observer along their line of sight. This motion is known as a star's radial velocity and plays an important part in building a true picture of a star's movement in our Galaxy.

With everything constantly in motion how do astronomers measure the distance to the stars?

If the position of a star on the celestial sphere is observed over a period of one year, as the Earth orbits the Sun, the closest stars will appear to move against fixed, more distant background stars. This is the parallax; it is the only direct way to measure distances to celestial objects.

Astronomers measure the position of a star from two points in the Earth's orbit with a known separation. This distance and the measured angular displacement, with respect to the fixed background, can then be used to calculate the distance to the star.

Due to the concept of parallax, a star followed for a year appears to draw out a small circle against the background which is actually due to the Earth's orbit around the Sun – the further away the star, the smaller the circle. This means that at some distance this circle will appear to be a point and the parallax would be impossible to measure.

For stars which are more than a few thousand light-years away from Earth, the parallax angle becomes too small to be measured accurately by ground-based observatories. Therefore astronomers have developed other, indirect methods to find distances to celestial objects that depend heavily on theoretical models and assumptions.

The discipline of precisely measuring the positions of stars has a strong European heritage. Astrometry was pioneered long before the astronomical telescope existed. In ancient Greece, Hipparchus of Nicea painstakingly made naked-eye measurements of the positions of the stars and planets producing the first catalogue of just over one thousand stars. Over the centuries, many astronomers, including Tycho Brahe, John Flamsteed and Otto Struve continued this task with ever advancing technology.

Accurate measurement of star positions from the surface of the Earth is a difficult task. Positions can only be measured relative to other stars that can be seen and only within a small portion of the sky. In addition, the Earth's atmosphere distorts the stellar images to some degree, thereby limiting the accuracy with which their location can be defined. The biggest advancement in mapping the stars came late in the 20th Century, 40 years after the beginning of the space age.

In 1989, Europe launched the first spacecraft to chart the positions of the stars. During a mission lasting just over 3 years, Hipparcos mapped over one hundred thousand stars with very high accuracy. This provided astronomers with a 3-dimensional picture of the distances and movements of stars in the vicinity of the Sun. The wealth of data collected by Hipparcos is still being used by astronomers all over the world more than fifteen years after the satellite ceased to operate [Note 1].

When measuring the positions of the stars a huge amount of information is collected. This information is extremely important in all disciplines of astronomy, such as: studies of the Solar System, stellar structure and evolution, the Milky Way, cosmology and even General Relativity. Let's have a look at a few examples.

With information collected by the Hipparcos mission, astronomers were able to determine that the Milky Way is changing shape and identified that billions of years ago our Galaxy swallowed the small neighbouring galaxy as it passed too close.

Amongst other numerous results, data produced by this mission helped astronomers to predict when comet Shoemaker-Levy 9 would collide with Jupiter in 1994 and confirmed Einstein's prediction that gravity bends light. Catalogues of star positions are routinely used to point ground-based telescopes, navigate space missions and drive planetaria.

Information from Hipparcos has enabled astronomers to trace the Sun's passage through the Galaxy back in time. This has shown that over the last 500 million years the Sun has passed through four of the Milky Way's spiral arms. The times that these traverses occurred appear to coincide with extended cold periods on Earth. Perhaps the densely-filled star and gas environment of the spiral arms have an effect on the Earth's climate.

Mapping the positions and motions of stars allows astronomers to develop a frame of reference which in turn means that comparisons can be made between measurements of the same object taken at different times, at different locations and in different wavelengths.

Astrometry measurements are instrumental for time keeping. Universal Time is calculated by synchronizing atomic time to the Earth's rotation. Measuring star positions allows a frame of reference to be developed, so as more accurate positions can be achieved a better measure of the Earth's rotation can be determined.

In combination with other data, many other physical properties of a star can be determined from astrometric data, such as: the luminosity, radius, mass and age. This information is then used to understand the internal structure and can lead to even deeper explanations of stellar and galactic evolution.

Accurate data about the distances of stars, combined with models of stellar evolution are used to find stars that are like our Sun now. These solar twins are targets in the hunt for exoplanets which may harbour life.

This is just a small taster of the exciting and fundamental science to which astrometry data can be applied. Further examples are: tracking near-Earth objects, the discovery of new objects within the Solar System, and even the dynamical consequences and distribution of dark matter in our Galaxy and the Universe.

Despite the wealth of data delivered by Hipparcos fundamental questions about our Galaxy remain. In the night sky the Milky Way can be seen as a band of dust and gas that obscures the view of the Galactic Centre at visible wavelengths. Studies of other galaxies have shown that the structure of the Milky Way should be in the form of a disc, a central bulge and a halo. Astronomers are sure that our Galaxy's disc has a spiral shape but how the arms formed and exactly how many there are remains unclear.

To really see the structure of the Milky Way astronomers need to observe a much larger sample of stars that cover the entire spatial extent of the Galaxy. The Hipparcos mission only saw a tiny fraction of stars in the Milky Way and was limited to a region around the Solar System. Therefore not enough to lead astronomers to conclusive results; more stars at greater distances need to be mapped.

ESA is continuing to build upon the European heritage of astrometry and the legacy of Hipparcos with Gaia, a new European mission that is due to launch early in the next decade [Note 2]. Gaia will be able to detect much fainter stars and provide more accurate parallaxes than the Hipparcos mission. Gaia will therefore, over its five year lifespan, be able to study 1 billion stars in the Milky Way and beyond, to make the largest and most precise three-dimensional map of our Galaxy.

To make this colossal study the Gaia spacecraft will have two optical telescopes which will focus light onto one enormous focal plane feeding three instruments. The Astrometric instrument will detect stars as they cross the field of view giving astronomers the star position, proper motion and parallax. The Photometric instrument will collect information about the star's colour and brightness, and the Radial Velocity Spectrometer will provide astronomers with spectra of the star in order to determine how fast it is moving towards or away from us.

To achieve the precise and accurate measurements that will be needed the Gaia payload must remain mechanically and thermally ultra stable. This is achieved by using a special ceramic material to construct the payload and by shielding the payload with a large sunshield that will be unfolded after launch.

Gaia will collect an immense amount of data, in the order of a Petabyte, that's 1 million Gigabytes; this will all need to be stored and processed. To achieve this tremendous task hundreds of people from many disciplines, including, astronomers, software engineers, mathematicians and computer specialists, spread all over Europe, form the Data Processing and Analysis Consortium. This Consortium will work together throughout the lifetime of the mission to process the data and for three years afterwards, to then unite the data into a single entity – the Gaia catalogue, which is expected to be finalised around 2020 [Note 3]. This is a huge scientific and logistical challenge.

The enormous yield of data obtained by Gaia will have a revolutionary impact across astronomy.

As photons of light from celestial objects travel through our Solar System they are deflected by the gravitational influence of the Sun, planets, moons and minor bodies – this is the General Relativistic bending of light. How much photons are deflected depends on how closely they pass an object and the object's mass. Measuring and correcting for this effect is critical when determining accurate positions of stars. Gaia will follow the bending of light through the Solar System and therefore directly observe the structure of space-time with unprecedented precision.

Gaia's sensitive instruments have the ability to detect faint and fast-moving objects. This makes it possible to detect, and study the properties and motions of, hundreds of thousands of asteroids, comets and other minor bodies in the Solar System, including those that pass near to the Earth. Gaia will join Herschel and Planck at the second Lagrange point [Note 4] and from there will be ideally situated to probe the asteroid 'blind spot' between the Sun and Earth.

Further from home, Gaia will be able to detect tens of thousands of planets orbiting stars other than the Sun as well as measure the orbital characteristics of a significant number of known extra-solar planets.

Gaia will make accurate direct parallax measurements of indirect distance indicators, such as Cepheid variable stars, this information will have a major impact on knowledge of the distance scale of the Universe.

Globular clusters, which are among the oldest objects in the Milky Way and found typically in the halo of our Galaxy, will be extensively observed by Gaia. Measurement of their distance will enable astronomers to precisely determine their age and hence refine the lower age limit of the Universe.

Gaia will make a complete census of one billion stars across the entire sky, with the same suite of instruments. This doesn't mean that just a large number of stars are surveyed in detail, it means that all different types of stars will be studied, including those that are extremely short-lived or rare, and each star will be seen many times whilst the census is being made.

Another unique feature of Gaia will be the well-defined sampling of tens of millions of variable stars and tens of millions of binary star systems [Note 5].

Above all, Gaia's large survey of the stars will reach out to vast distances across, not only the disc of the Milky Way but also into the halo. For the first time, astronomers will be able to see the actual structure of our Galaxy and the distributions of the stars within, from which a 3-dimensional map of the Milky Way can be made.

With this crucial information about the shape of our Galaxy, and the precise positions, parallax distances, radial velocities and proper motions of 1 billion stars, Gaia will provide astronomers with enough data to reveal the history of our Galaxy. These data will be modelled to trace the paths of the stars back in time to learn more about the formation of the Milky Way and also to advance time to discover how our Galaxy will evolve over hundreds of millions of years in the future.

I'm Rebecca Barnes, thank you for watching the Science@ESA vodcast.

Script notes

The Science@ESA vodcast series was developed during the International Year of Astronomy 2009. The series explores the extraordinary Universe in which we live as it is seen through the "eyes" of ESA's fleet of science spacecraft.

This episode of the Science@ESA vodcast series was published in 2009. Aspects of the text that may have evolved or been updated in the meantime are indicated with clarification notes:

Note 1: ESA's Hipparcos mission ceased operations in August 1993.

Note 2: Gaia is scheduled to launch in 2013.

Note 3: The final Gaia catalogue is expected to be available about 3 years after the completion of the mission.

Note 4: Both Herschel and Planck were manoeuvred out of the L2 orbit, which is inherently unstable, into more distant long-term stable parking orbits around the Sun. Neither will be at L2 when Gaia arrives there.

Note 5: More recent reports suggest that Gaia will sample a few million variable stars and a few million binary star systems.