
32. Aberration and Galactic rotation

STELLAR ABERRATION is the term used to describe the apparent displacement of celestial objects from their ‘true’ positions, as a simple consequence of the velocity of the observer.

To picture the phenomenon, let us start with a very simple analogy from daily life. Imagine that we are standing in the rain, with rain falling straight down on us from above. If we walk briskly, in any direction, the rain will appear to be coming from ahead of us. This is a simple example of the ‘vectorial addition of velocities’, and is experienced in many everyday situations. For example, riding a bicycle on a windless day, an ‘apparent’ wind will always be blowing in our face.

THE SAME EFFECT is well-known in astronomy, and is considered here only in its non-relativistic form. For an observer on Earth, moving through space with velocity v , then a star’s position will *appear* to be displaced in the direction of the observer’s motion by an angle v/c , where c is the speed of light.

There is an important point to make at the outset. If the observer’s motion through space was constant, unchanging over time, then the position of all stars would be shifted by the same amount. And we would not be able to differentiate between their ‘true’ positions, and their apparent positions.

But the Earth’s velocity does change, over months, as it moves in its annual orbit around the Sun. Knowing the Earth’s orbital radius we can calculate the speed of the Earth, around the Sun, to

be about $v = 30 \text{ km s}^{-1}$. The speed of light is around $c = 300\,000 \text{ km s}^{-1}$, so we find that v/c is about 0.0001. This quantifies the angular displacement in radians, which is about 20 arcsec. A star’s apparent position can therefore be displaced by up to 20 arcsec from its ‘true’ position, depending on its location on the sky.

We can easily measure the effect because the 20 arcsec shift is in one direction when the Earth is at one point in its orbit, but in the opposite direction 6 months later. The effect is large compared to star positional measurements of an arcsec or better, let alone at the level of the milli- or micro-arcsec accuracies of Hipparcos or Gaia.

The aberration due to the Earth’s orbital motion around the Sun is referred to as ‘annual aberration’.

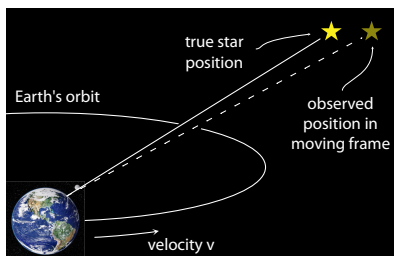
There is also a similar effect, albeit smaller in amplitude and on a shorter time-scale, due to the Earth’s spinning motion about its rotation axis. This contribution is referred to as ‘diurnal aberration’. We will see that there are others!

STELLAR ABERRATION, due to the observer’s *velocity* through space, is distinct from the effect of parallax, which is due to the observer’s changing *position*. But the two are entwined in the history of astronomy, specifically in the protracted efforts to measure the first stellar parallax during the 17th, 18th and 19th centuries.

Even before 1600, astronomers were in agreement that the crucial evidence needed to detect the Earth’s motion around the Sun, and so to confirm the Copernican hypothesis of a Sun-centred solar system, was the measurement of trigonometric parallax. A major breakthrough came with Edmond Halley’s discovery of the first stellar proper motions in 1718. And as instrumental accuracies reached the levels of a few arcseconds, the Reverend James Bradley, England’s third Astronomer Royal, was immersed in his own efforts to measure parallax, targeting the bright star Gamma Draconis.

While Bradley failed to measure parallax, he did detect a small systematic shift in his star positions, which he eventually correctly attributed as resulting from the addition of the velocity of light to the Earth’s velocity in its orbit around the Sun. From his angular shifts, he estimate the speed of light at $295\,000 \text{ km s}^{-1}$. Announced in 1729, it has been described as one of the most significant discoveries in the history of astronomy.

Fast forward to the present day, and the effects of the observer’s motion, whether on Earth or from a space platform like Hipparcos and Gaia, are well understood.



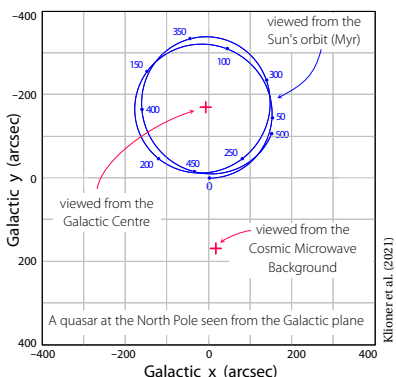
Even at it's L2 orbit location, 1.5 million km from Earth, Gaia's position and velocity in space are determined to better than 1 km, and some 0.2 m s^{-1} respectively. With this knowledge, and in the framework of special relativity, the effects of stellar aberration can be accurately predicted. And they are fully accounted for in the data analysis as part of the Gaia star catalogue preparation.

BUT ANOTHER COMPLICATION now raises its head. If the velocity of the observer is changing with time, i.e. if the observer is accelerating, the star displacements also change with time. If the measurements are accurate enough, and if the changes with time are fast enough, a systematic pattern of apparent proper motions, in the direction of the acceleration, would become apparent.

Such a possibility was already noted almost two centuries ago by John Pond, UK's sixth Astronomer Royal. But in the context of the structure of the Universe as it was known at the time, there was no particular reason to postulate an acceleration. And the idea was essentially discarded as being unmeasurable in any case.

WHAT EFFECTS could cause an acceleration of the solar system? One is the fact that, in the enormity of space and time, the Sun is moving in a (roughly) circular orbit around the Galaxy, with an orbital period of 250 million years. On an even more epic scale, our Galaxy itself is in motion within the Local Group of galaxies, and with respect to the cosmological reference frame defined by the Cosmic Microwave Background.

If stars in our Galaxy provided the only reference frame available, an acceleration term would probably be impossible to separate from other effects. But with its inertial reference frame materialised by 500 000 distant quasars, it turns out that the Gaia data are indeed accurate enough to discern the *acceleration* of the solar system due to its 250 million year orbit around the Galaxy.



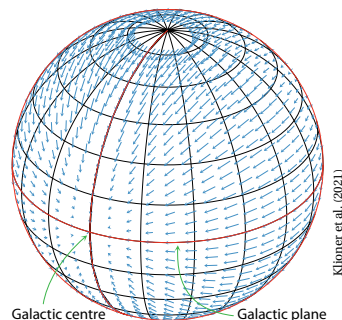
Group of galaxies. For the latter, positional shifts are predicted to be around 200 arcsec. But in the absence of its variation over time, the effect is unmeasurable.

THE POSSIBILITY of discerning the first of these, viz. the effects of Galactic rotation, or 'secular aberration', has been pursued since the early 1980s in the framework of high-accuracy radio VLBI observations. But with the systematic displacement of the best-placed quasars being only around $100 \mu\text{as}$, the effect is not much above the error of individual VLBI positions.

The latest studies, based on 39 radio sources from almost 40 years of VLBI observations, give an acceleration of $5.83 \pm 0.23 \mu\text{as yr}^{-1}$ in the direction $\alpha = 270.2^\circ$, $\delta = -20.2^\circ$ (Charlot et al., 2020).

IN THE CONTEXT of Gaia, the problem was first recognised as being of relevance by Bastian (1995), and it was duly included as one of the targeted mission goals (Perryman et al., 1995). A quarter of a century later, a detailed assessment has been made with Gaia EDR3 by Klioner et al. (2021).

For the acceleration due the Sun's orbit, they used the distance and motion of Sagittarius A*, the black hole at its centre, to predict an acceleration of $6.98 \text{ km s}^{-1} \text{ Myr}^{-1}$ towards the Galactic centre, and an *expected* pattern of quasar motions shown here.



And they estimated the contributions from other terms, such as our Galaxy's central bar, the Sun's motion with respect to the Galactic plane, and the contribution of individual extragalactic objects in the Local Group.

TO DERIVE THEIR observed acceleration, Klioner et al. (2021) started with 1 614 173 sources identified in EDR3 as 'quasar-like', teasing out the acceleration from a detailed examination of the proper motion vector field.

They found a Galactocentric acceleration of $5.05 \pm 0.35 \mu\text{as yr}^{-1}$ in the proper motions. This is a thousand times smaller than the Galactic rotation and shear effects of our Galaxy's stellar population, which is around $5\text{--}10 \text{ mas yr}^{-1}$. In units of more relevance to the scale size of the Galaxy, this corresponds to $7.33 \pm 0.51 \text{ km s}^{-1} \text{ Myr}^{-1}$. And in units more recognisable in terms of the acceleration due to gravity at the Earth's surface, it amounts to $2.32 \pm 0.16 \times 10^{-10} \text{ m s}^{-2}$.

THIS FIRST DETECTION of secular aberration in the optical agrees with the theoretical expectations from Galactic dynamics. Further improvements will be possible with future Gaia data releases. It is even possible that the 'secular extragalactic parallax', caused by the motion of the solar system with respect to the rest frame of the Cosmic Microwave Background, could be discerned.