Stellar aberration

Posted on May 28, 2019August 28, 2020
This post is a bit more technical than usual and discusses stellar aberration, the apparent movement of stars as a result of the motion of the Earth. It is an interesting case of the application of the scientific method. Observations were made to test a scientific theory, but unexpected results were found, which in turn led to new discoveries.

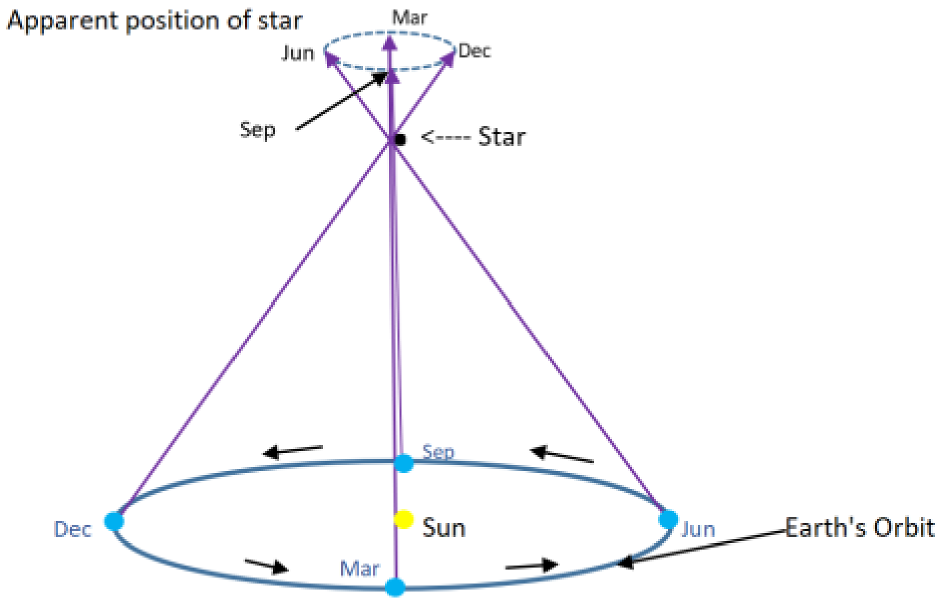
Discovery of stellar aberration

In 1727 the English astronomer James Bradley had been taking measurements of the position of *Eltanin***,** the brightest star in the constellation Draco.

(https://thesciencegeek01.files.wordpress.com/2019/05/aberation-bradley.png)

James Bradley (1693 – 1762) – image from Wikimedia Commons

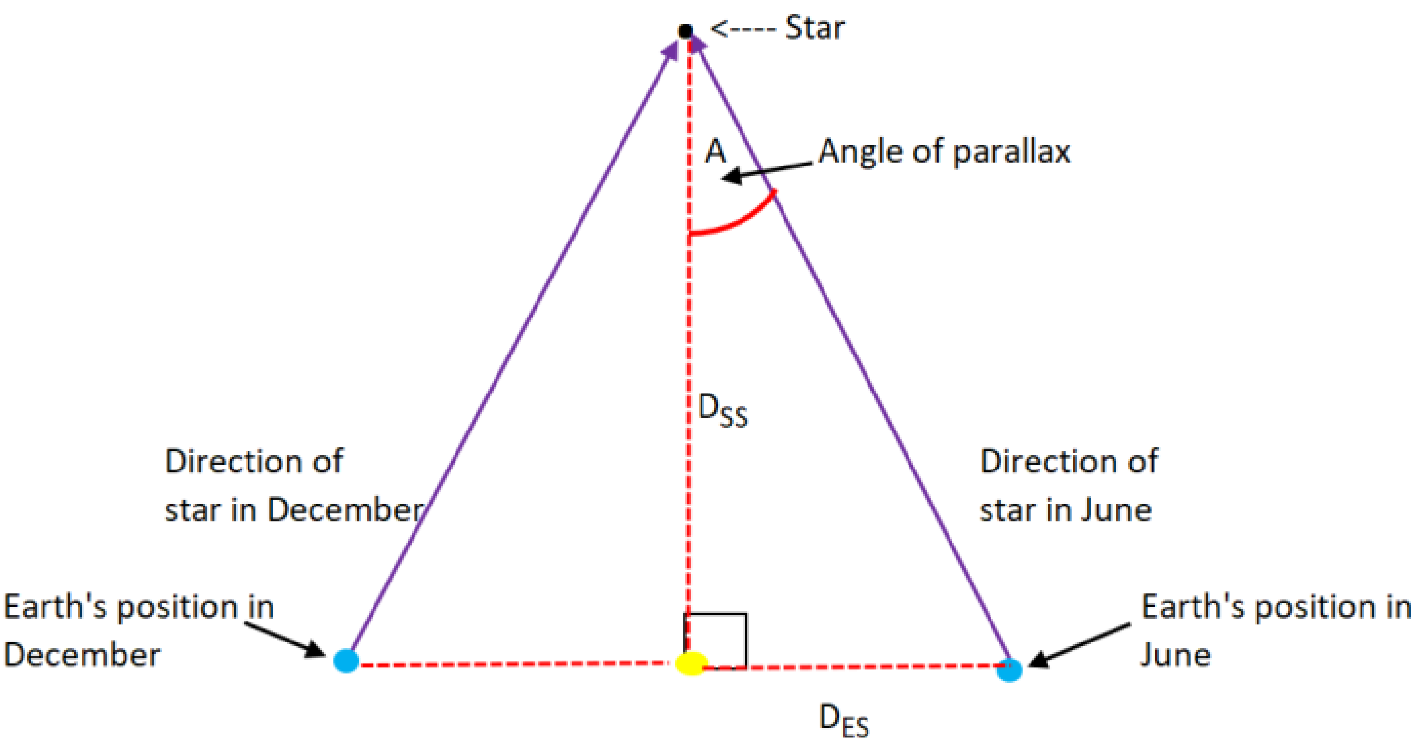
Bradley was looking for a small shift in the position of the star, known as the parallax.



(https://thesciencegeek01.files.wordpress.com/2019/05/aberation-exepected-parallax.png)

The expected shift in the position of a star during the year due to parallax

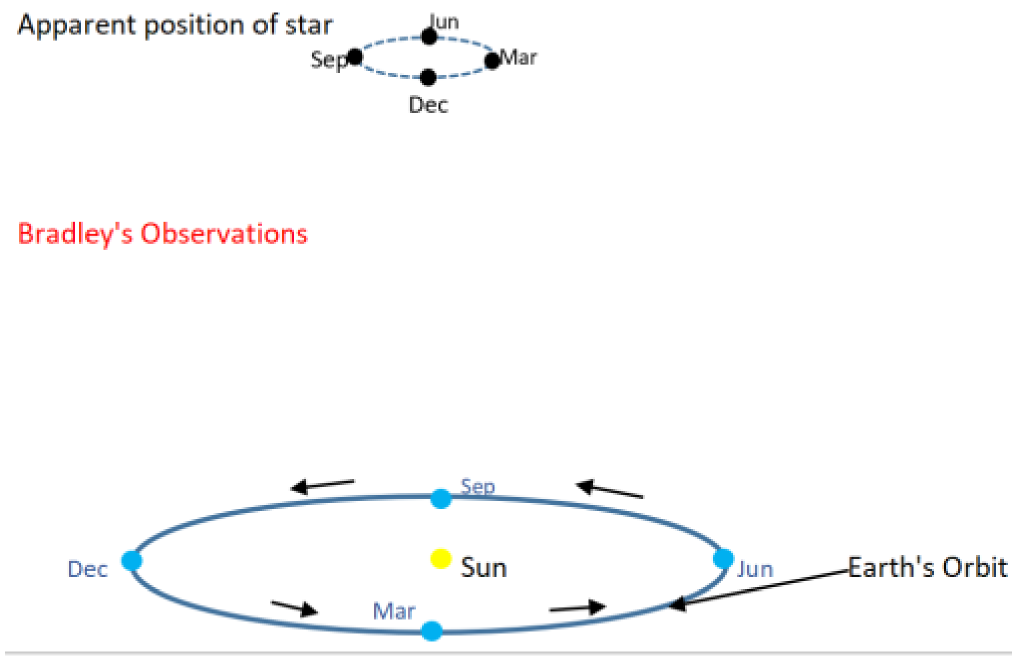
In Bradley's time the heliocentric theory, in which the Earth and all the planets orbit the Sun, was generally accepted by astronomers. However, it had not yet been accepted by the Catholic church and many thinkers outside the field of astronomy still believed the older geocentric theory (https://thesciencegeek.org/2017/11/10/geocentric-cosmology/). Finding the parallax of a star would confirm that the heliocentric theory was correct and would also allow the distance to the star to be calculated.



(https://thesciencegeek01.files.wordpress.com/2019/05/aberation-parallax.png)

The distance to star (Dss) is equal to the distance between the Earth and the Sun (Des) divided by the tangent of the parallax angle (A).

However, Bradley found that the position of Eltanin did not change as predicted. Although he found a small change in its position over the course of the year, the position shift was different from what it would have been if parallax were the cause.

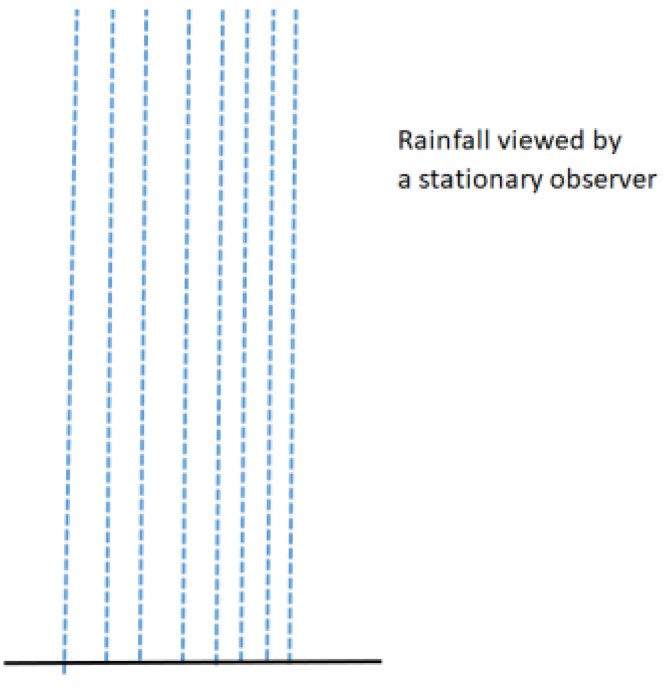


(https://thesciencegeek01.files.wordpress.com/2019/05/abberation-bradley-observations.png)

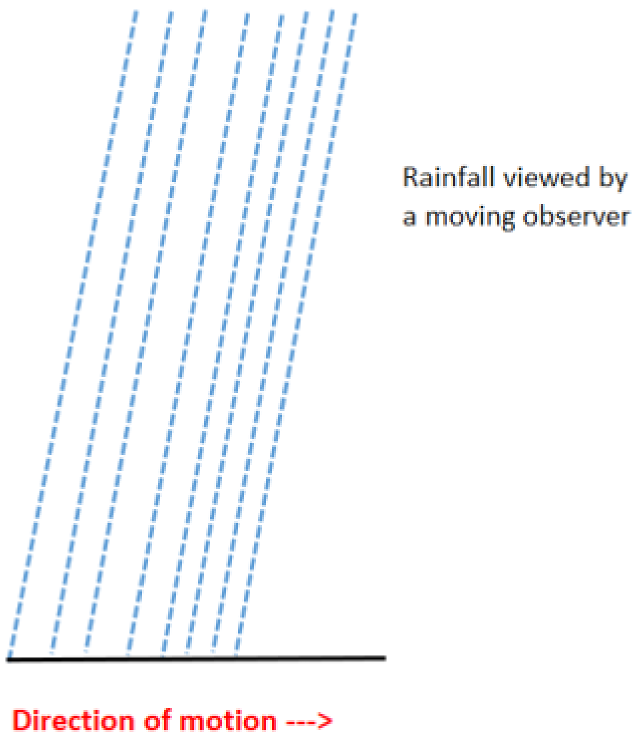
For clarity. the change in position has been greatly exaggerated. The maximum shift of Eltanin around its mean position is only 0.0056 of a degree, roughly 1% of the diameter of the Moon.

In trying to explain his observations Bradley discovered an entirely different effect which came to be known as stellar aberration. His discovery not only confirmed the heliocentric theory but allowed an accurate measurement of the speed of light.

To understand the cause of stellar aberration, first consider a rainy day where there is no wind – rain falls vertically from the sky. However, if you are moving, rain no longer falls vertically but is tilted in your direction of travel. Two common examples of this are: anyone carrying an umbrella and walking quickly will need to tilt their umbrella forward to shield from the rain and when a train is moving, rain appears to streak down its windows diagonally.

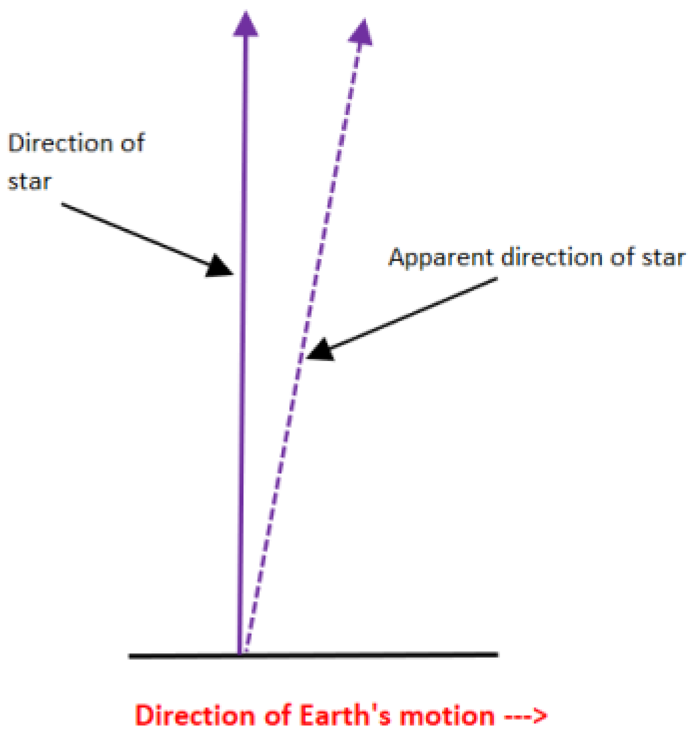


(https://thesciencegeek01.files.wordpress.com/2019/05/aberation-rain-stationary.png)



(https://thesciencegeek01.files.wordpress.com/2019/05/aberation-rain-moving.png)

Bradley reasoned that the change in the star's position which became known as stellar aberration was due to the Earth's motion around the Sun. Light consisted of small particles which travelled at a finite speed, and the light particles appear displaced in the direction the Earth was moving in the same way raindrops are.



(https://thesciencegeek01.files.wordpress.com/2019/05/abberation-earths-motion.png)

As the Earth goes around its orbit, the direction in which it is moving moves continually changes and so the displacement of the star from its mean position continually changes too.

(https://thesciencegeek01.files.wordpress.com/2019/05/aberation-bradley-explanation.png)

Bradley's explanation not only proved that the Earth revolved around the Sun, but he was able to work out the speed of light. To do this he showed that the maximum angle θ, by which any star is displaced from its mean position, is given by the formula:

$\theta = v/c$

where

- v is the Earth's velocity around the Sun
- c is the speed of light
- θ the angle the star is displaced, measured in radians (2π radians equals 360 degrees, so 1 radian is approximately 57.3 degrees).

From this we have

$c = v/\theta$

Using this, Bradley was able to estimate the speed of light as 301,000 km/s in modern units (Walker 2008). This is within 0.5% of the correct value.

Limitations of the classical theory

Bradley, like the majority of eighteenth-century physicists, believed in a particle theory of light. In the nineteenth century a wave theory of light became generally accepted. The wave theory was better able to explain phenomena such as diffraction and interference patterns. However, when this theory was used to try and explain stellar aberration, it ran into a couple of difficulties.

- Firstly, the aberration angle (v/*c*) varies with the speed of light (*c*). In the wave theory the speed of light depends on the medium through which light is passing. Light travels more slowly in air than it does in a vacuum, but the difference is small. In a denser medium, the slowing of light is more significant. For example, when light passes through water it travels 1.3 times more slowly than it does in a vacuum. So, if we filled a telescope with water, the aberration should be **3 times larger** than if it were filled with air. This experiment was first tried by the English astronomer George Airy in 1871 and no change in the aberration angle was detected,

- Secondly, the nineteenth-century wave theory of light required that it travelled in a medium called 'the ether'. This was an invisible material which had no interaction with physical objects. The speed of light is a constant when measured with respect to this mysterious ether. To explain the results of a historic experiment called the Michelson-Morley experiment, it was proposed that the ether was dragged along by the motion of the Earth when it goes around the Sun, i.e. the relative motion of the Earth against the background ether is zero. However, if this were the case stellar aberration would not exist

Today the generally accepted explanation of stellar aberration is by Einstein's theory of special relativity. In special relativity there is no absolute space and no absolute motion. As the Earth moves around the Sun in its near-circular orbit, we are observing a star in different reference frames, in which the relative direction of motion of the Earth when measured with respect to the star is different. Using the equations of special relativity the star has a different position when we transform its coordinates from one reference frame to another.

(https://thesciencegeek01.files.wordpress.com/2014/10/albert-einstein.jpg)

What about parallax?

The shift in position of a nearby star caused by parallax proved to be very much smaller than the position shift due to stellar aberration, which unlike parallax does not vary with a star's distance. Even for nearby stars the parallax is so small that it wasn't successfully measured until 1838, when the German astronomer Friedrich Wilhelm Bessel detected it for the star 61 Cygni. The parallax he measured was 0.314 arc seconds, which is around 65 times smaller than the shift due to stellar aberration. The shift in position of 61 Cygni due to parallax is equivalent to a width of a 2 cm at a distance of 12 km. Because parallax was so difficult to detect, by the year 1900 only 60 nearby stars had had their parallax measured. It wasn't until the development of machines to accurately measure the position of stars on photographic plates in the twentieth century that a large number of stellar parallaxes were calculated

The table below summarises the differences between parallax and stellar aberration.

	Stellar aberration	Stellar parallax
Cause	Change in the **direction** of the Earth's motion as it orbits the Sun	Change in the Earth's **position** as it orbits the Sun
First detected	Bradley, 1727*	Bessell, 1838
Varies with distance of star?	No	Varies inversely with distance. Nearer objects show larger parallax
Max shift in position	20.5 arcsec *(1 arcsec =1/3,600 of a degree)*	0.769 arcsec - Proxima Centauri (closest star to the Sun)

(https://thesciencegeek01.files.wordpress.com/2019/05/aberation-differences.png)

* Bradley was the first person to accurately measure and explain the cause of stellar aberration. A small shift in position of stars over the 12-month cycle been reported by earlier astronomers but it had not been accurately measured or accounted for.

I hope you have enjoyed this post, for those of you who want a little more detail I've put some further notes below.

Update 24 August 2020

(https://thesciencegeek01.files.wordpress.com/2020/07/youtube-logo.png)

A video containing some of the material in this post can be viewed on the Explaining Science YouTube channel. (https://www.youtube.com/channel/UCVNx4bGZXLhYx7X8PMKyltg) This channel is a new venture and over the next few months I plan to upload additional videos.

Technical notes

1. **How the amount of aberration varies with the position of a star**

In the Sun's frame of reference, consider a beam of light from a distant star, which lies at an angle A to the direction of the Earth's motion. The speed of light is c and the light beam has *x* and *y* velocity components ux and uy, where

- ux is its velocity in the direction of the Earth's motion.
- uy is its velocity in a direction perpendicular to x.

Therefore

- ux = cCOS(A)
- uy = cSIN(A)

(https://thesciencegeek01.files.wordpress.com/2019/05/aberation-suns-frame.png)

Because the star is at an angle A relative to the direction of the Earth's motion,

tan(A) = uy/ux = sin(A)/cos(A).

If the Earth is moving at velocity v in the x direction relative to the Sun, then in the ***Earth's frame of reference***:

- the x component of the beam's velocity is ux' = ux +v.
- the y component of the velocity is unchanged.

(https://thesciencegeek01.files.wordpress.com/2019/05/aberation-earthsframe.png)

From Earth the star appears at an angle A' to the direction of the Earth's motion.

tan A' = uy/ux'

= sin A / (cos A +v/c))

We want to find the displacement of the star due to the Earth's motion. If we give this the symbol θ, then θ = A' – A.

Using the standard formula for the tangent of the difference of two angles which many you will remember from high school mathematics lessons !

$$\tan(\theta) = \frac{\tan(A') - \tan(A)}{1 + \tan(A')\tan(A)} \qquad \textit{where } \theta = A' - A$$

$$\Longrightarrow \tan(\theta) = \frac{\dfrac{\sin(A)}{(\cos(A) + (v/c))} - \dfrac{\sin(A)}{\cos(A)}}{1 + \dfrac{\sin(A)}{\cos(A) + (v/c)} \dfrac{\sin(A)}{\cos(A)}}$$

$$\Longrightarrow \tan(\theta) = \frac{\sin(A)\cos(A) - \sin(A)(\cos(A) + (v/c))}{(\cos(A) + (v/c))\cos(A) + (\sin(A))^2}$$

$$\Longrightarrow \tan(\theta) = \frac{-(v/c)\sin(A)}{(\cos(A))^2 + (v/c)\cos(A) + (\sin(A))^2}$$

$$\Longrightarrow \tan(\theta) = \frac{-(v/c)\sin(A)}{1 + (v/c)\cos(A)} \qquad \textit{because } (\sin(A))^2 + (\cos(A))^2 = 1$$

$$\Longrightarrow \tan(\theta) \approx -(v/c)\sin(A) \qquad \textit{because } v/c \ll 1$$

(https://thesciencegeek01.files.wordpress.com/2019/05/aberation-calculation-1.png)

- If we take A as equal to 90 degrees, this means that the direction of the star is perpendicular to the direction in which the Earth is moving. So, sin(A) = 1 which means tan(θ) = – v/c

However, because the angle θ is so small, to a good approximation θ = tan(θ). So **θ = -v/c**

- If we take A as equal to 0 degrees, this means that the star lies in the same direction as the Earth is moving. So, sin(A) = 0, which means **θ = 0** and the star is unchanged in position.
- If we take A as equal to 180 degrees, this means that the star lies in the opposite direction from that in which the Earth is moving. So, sin(A) = 0, which means **θ = 0** and the star is unchanged in position.

2. Full relativistic calculation

The calculation of the angle of aberration θ shown above is an oversimplification. When we are adding velocities, we should really use the relativistic addition formula from Einstein's theory of special relativity to preserve the fact that nothing can travel faster than the speed of light. However, because the Earth's velocity around the Sun is so small compared to the speed of light, a more complicated relativistic formula gives virtually the same results as the simple formula derived above.

3. **Examples**

For simplicity, if we assume the Earth moves in a perfect circle around the Sun at a constant velocity of 29.8 km/s and the speed of light is 299,792 km/s then the table below gives the amount of aberration for different angles to the Earth's direction of motion:

Angle of star to Earth's motion degrees	Aberration arcsec
0	0.0
15	-5.3
30	-10.3
45	-14.5
60	-17.8
75	-19.8
90	-20.5

(https://thesciencegeek01.files.wordpress.com/2019/05/aberation-amount.png)

If we consider a star which is positioned at a right angle to the Earth's orbit, then as the Earth moves around its orbit the Earth would always be moving at 90 degrees to the direction of the star. The star would appear to move in a small circle of radius 20.5 arc seconds.

(https://thesciencegeek01.files.wordpress.com/2019/05/aberation-bradley-explanation.png)

In reality, the Earth moves in a slightly elliptical orbit. It travels at 30.3 km/s when it is closest to the Sun in January and 29.3 km/s when it is furthest away in July. This causes the aberration to vary between 20.2 arcsec in July and 20.8 arcsec in January and the star appears to move in an slightly elliptical path rather than in a perfect circle.

If we consider a star which in the same plane as the Earth's orbit then, assuming it lies directly opposite the Sun in June, its change in position during the year is shown in the diagram below.

(https://thesciencegeek01.files.wordpress.com/2019/05/aberation-ecliptic.png)

- In June the Earth is moving at 90 degrees to the direction of the star. So, the star is displaced an angle of v/c in the direction of the Earth's motion.
- In September the Earth is moving directly away from the star. Because the angle between the star and the direction of the earth's motion is zero the star is not displaced
- In December the Earth is moving at 90 degrees to the direction of the star (but in the opposition direction compared to June). So, the star is displaced an angle of v/c in the direction of the Earth's motion.
- In March the Earth is moving directly towards the star. So, the angle between the star and the direction of the earth's motion is zero and the star is not displaced.

As seen from Earth, over the course of the year a star in the plane of the Earth's orbit would appear to trace out a straight line centred around its mean position. Stars at angles between zero and 90 degrees to plane of the Earth's orbit would trace out ellipses centred around their mean position.

Reference

Walker B H (2008) *Optical engineering fundamentals, second edition,* Available at: *https://spie.org/publications/tt82_25_speed_of_light (https://spie.org/publications/tt82_25_speed_of_light)* (Accessed: 31 May 2019).

*Posted in General**Tagged aberration, Astronomy, latest, relativity, star, Sun, YouTube*

Published by Steve Hurley

Hi I am Steve Hurley. I work in the IT industry. I studied for a PhD in astronomy in the 1980s. Outside work my real passion is explaining scientific concepts to a non-scientific audience. My blog (explainingscience.org) covers various scientific topics, but primarily astronomy. It is written in a style that it is easily understandable to the non scientist. Publications and videos For links to my books and videos please visit www.explainingscience.org *View all posts by Steve Hurley*

15 thoughts on “Stellar aberration”

1. **Joe Nahhas** *April 21, 2022* *Reply*

   Greeting: Thank you for all the good presentations. The graphics is easy to understand. However, the reasoning by Bradley is contestable. The same results can be produced as observational errors because the 20.5 arc seconds is also can be found in a physics lab and without looking at the skies doing gravity experiments and electrostatics experiments and many other experiments suggesting something totally different and it’s not the light coming from the stars but a moving frame of reference or the sun’s motion. Id the sun is moving it produces the stellar aberration as error and produces all of relativity special and general as errors of a moving frame of reference of the sun. This fact I can prove and this fact the French mathematician Fourier worked on, and this fact was mentioned in 10th century and the fact is the moving stun as reference produces visual effects = 500 years of all wrong astronomy of a solar system.

2. **Mohammad** *April 20, 2021* *Reply*

   “So, if we filled a telescope with water, the aberration should be 3 times larger than if it were filled with air. This experiment was first tried by the English astronomer George Airy in 1871 and no change in the aberration angle was detected.” The question is Why? Why no change was detected?

3. **Uli Arndt** *January 10, 2021* *Reply*

   Thank you very much for your vivid, concise and understandable description of the situation of stellar parallax / stellar aberration.

   Steve Hurley *January 10, 2021* *Reply*

   Thank you and thank you your postive email about my video

BTW I am currently doing a video about special relativity,

4. **Matthew Agona** *July 10, 2020* *Reply*

   I was sort of curious about the algebra of the expressions for A – A' where you employ the difference of tangents. Is there any way you could show the steps for how you got the result? I have tried a few times now and am missing something

   Steve Hurley *July 11, 2020* *Reply*

   Thanks for your comment

   I assume that you mean that one or more of the steps under the phrase
   "We want to find the displacement of the star due to the Earth's motion. If we give this the symbol θ, then θ = A' – A".
   If you can indicate which of these steps are unclear I will add some additional explanation
   Steve

5. **Barbara** *June 2, 2019* *Reply*

   yes, indeed – and nearly 300 years on!
   I checked through the University notes I have and can't find it mentioned there either. I will post a note to them about it.

6. **Barbara** *June 1, 2019* *Reply*

   Although familiar with stellar parallax, I hadn't appreciated stellar aberration until I saw your article. The final section, with the last picture and 4 bullet points were very helpful; I then went back to the maths and it all "clicked".

   thesciencegeek *June 1, 2019* *Reply*

   Thank you for your comment Barbara,

   It is interesting that although stellar aberration causes a much larger moving in stars' positions than parallax, and was important in the development of modern astronomy, knowledge of it is much less common than parallax.

7. **Stellar aberration | SPACE FORCE** *May 30, 2019 Reply*
   […] Source link […]

thesciencegeek *May 29, 2019* *Reply*

Sounds great fun!
Do you happen to remember what value you got ?

8. **bitsanddragons** *May 29, 2019* *Reply*

   I remember calculating the speed of light using Bradley's method on Optics 101. The bonus points were for calculating the aberration, I believe…a lot of fun, indeed.

9. **Stellar aberration – The Science Geek – Dinezh.com** *May 29, 2019* *Reply*
   […] Source link […]

10. **Michael** *May 28, 2019* *Reply*

    Cool despite not really having a clue what you're on about 🙂

    thesciencegeek *May 31, 2019* *Reply*

    🙂

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