Where can the speed of light change?

Richard Ward

The wave theory of light is firmly established, and consequently the path of light will usually bend where its speed changes because of its location. This restricts models of the universe to those in which the bending is so small that it cannot be observed from the earth.

Refraction

One hypothesis, among many, to solve the Distant Starlight Problem is that the speed of light is much higher in parts of the universe distant from the earth.[1] To test this hypothesis, we need to apply the wave theory of light, which was first propounded in the 17th century, but not widely accepted until two hundred years later.

Refraction had been observed and measured in the ancient world, but the relationship between the angles (figure 1) had not been found. In the figure, the dotted line is called the normal, and the angles are measured from it. The earliest known document stating the correct relationship is dated AD 985,[2] but this was not widely known, and several men independently rediscovered it over the following centuries. In the English-speaking world it is commonly known as Snell's Law (Willebrord Snell 1621).[3]

In general,

$$n_1 \sin i = n_2 \sin r$$

where n_1 is the refractive index of the first medium and n_2 is the refractive index of the second medium. The refractive index of a vacuum is defined to be 1.

Competing hypotheses

In the 17th century there were two hypotheses for the nature of light. Isaac Newton suggested that it was a stream of particles (or corpuscles),[4] but Christiaan Huygens thought it was a series of waves.[5]

Isaac Newton thought that the medium of higher refractive index attracted the corpuscles, so increasing their velocity perpendicular to the surface, and bending their path. Let u be their speed in medium 1, and v their speed in medium 2. The component of their velocities parallel to the surface does not change:

$$u \sin i = v \sin r$$

This matches Snell's Law if the ratio of the speeds is the same as the ratio of the refractive indices.

Huygens' model is shown in figure 2. In time t the wave travels from C to B at speed u, but a shorter distance from A to D at speed v.

$$CB = u\,t = AB \sin i$$
$$AD = v\,t = AB \sin r$$

Therefore

$$v\,t = AB \sin r$$
$$u\,t\ AB \sin i$$

So

$$v \sin i = u \sin r$$

This also matches Snell's Law, but the speed ratio is the inverse of the refractive indices.

Both hypotheses agree with the experimental observations, but Newton's requires a faster speed in the medium of higher refractive index, and Huygens' a slower speed. Both men were glad that Ole Roemer confirmed, in 1674, that the speed of light in the vacuum of space was finite, but there was no way to compare it with the speed in a dense medium. Because of Isaac Newton's brilliance in mechanics, most scientists supported his corpuscular hypothesis.

At the start of the 19th century Thomas Young performed an experiment using two slits very close to each other in which he observed *interference* which is characteristic of waves.[6] He published this is 1807, but many supporters of the corpuscular hypothesis remained sceptical.

The French Academy arranged a competition in 1818 which was won by a paper on *diffraction* by Augustin Fresnel, a strong supporter of the wave model. The eminent mathematician Siméon Poisson, one of the judges, used the argument in Fresnel's paper to show that there would be a bright spot in the centre of the shadow of a circular obstacle.[7] He thought this was ridiculous and concluded that Fresnel's treatment was absurd. Somewhat to his chagrin, the bright spot was verified by the astronomer François Arago. Figure 3 shows the bright spot in the centre of the shadow of a steel ball of diameter 0.66 mm.

As the corpuscular hypothesis could not explain this, it received its death wound. From that date onwards all physicists accepted that the wave model was the correct

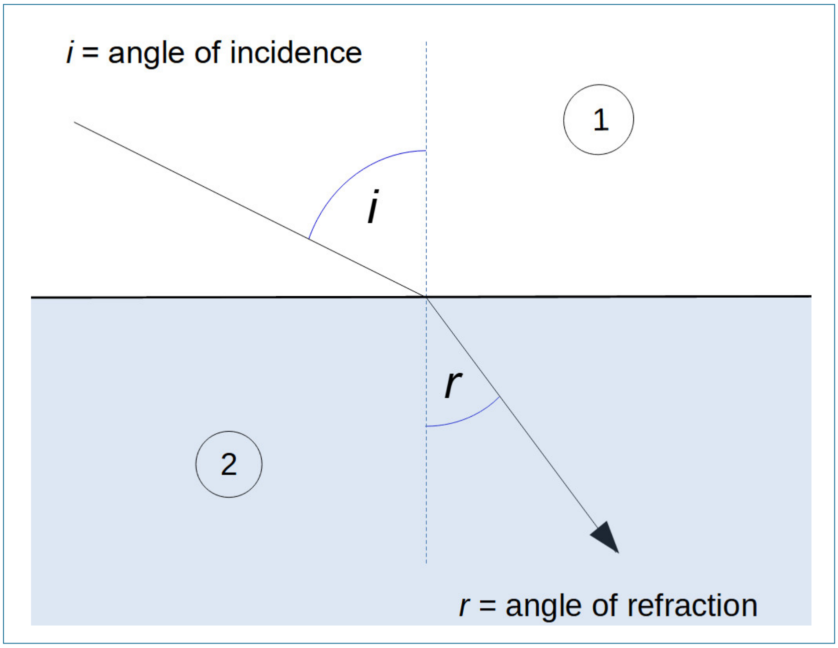

Figure 1. Angles

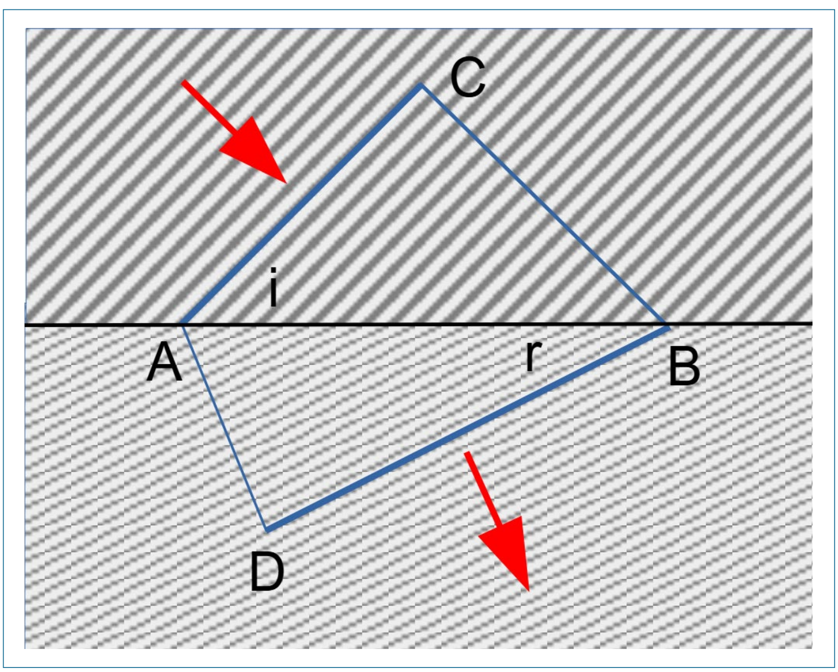

Figure 2. Refraction of waves

theory. It explains several other phenomena, such as how the iridescent colours of many birds, butterflies,[8] and soap bubbles are produced without using any pigments.

The wave theory requires that the higher the refractive index, the slower the light travels. Arago, in 1836, designed a method for measuring this directly, but practical difficulties and failing eyesight prevented him from achieving it.[9] A direct measurement was eventually made by Armand Fizeau and Léon Foucault in 1850, which agreed with the refractive indices.

Based on 19th-century experimental work by others, in 1862 the godly James Clerk Maxwell wrote: "We can scarcely avoid the conclusion that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena."[10] This led Heinrich Hertz to perform experiments which produced radio waves. Having a much longer wavelength, it is possible to demonstrate their reduction in speed on entering a transparent medium, with little experimental difficulty.

There can be no doubt that changing the speed of light causes refraction.

Critical angle

One issue of practical importance is illustrated in figure 4. The speed of light in medium 1 is 2.5 times that in medium 2. The light from any object in medium 1 will strike the boundary with an angle of incidence up to 90°. After passing through the boundary, the maximum angle of refraction, called the 'critical angle', is, in this instance, 24°. An observer in medium 2, looking directly upwards would see everything in medium 1 within 24° of the normal. There would appear to be a circular hole at the boundary, sometimes called 'Snell's Window'. No light from medium 1 would be seen around the window, but some objects in medium 2 would be visible.

If light from medium 2 is travelling upwards at an angle of incidence less than the critical angle, it refracts as in figure 2 with the arrows reversed. Note that the waves are continuous across the boundary. If the angle of incidence exceeds the critical angle, the crests of the waves in medium 2 are too far apart at the boundary to match those in medium 1. Instead of refracting, the waves are reflected back into medium 2. This is called 'total internal reflection'.[11] Referring to figure 2, for refraction:

$$CB < AB$$
$$u\,t < v\,t / \sin r$$
$$\sin r < v / u$$

So

$$\sin c = v / u = n_1 / n_2,\text{ where } c \text{ is the critical angle.}$$

In figure 5, the brown line indicates the path of light that is totally internally reflected. The diagram has been simplified by omitting the light that has been partially reflected.

Multimedia

If there are more than two media, the final angle of refraction is determined only by the initial and final refractive indices and the angle of incidence, if all the boundaries are parallel and total internal reflection does not occur. This follows from Snell's law.

At the first boundary,

$$n_1 \sin i_{12} = n_2 \sin r_{12}$$

At the second,

$$n_2 \sin i_{23} = n_3 \sin r_{23}$$

The angle of refraction at the first boundary, r_{12}, equals the angle of incidence at the second, i_{23}:

$$\sin r_{12} = \sin i_{23}$$

Therefore,

$$n_1 \sin i_{12} = n_3 \sin r_{23}$$

and in general

$$n \sin i \text{ is constant in all the media.}$$

In 1820, shortly after the corpuscular hypothesis had been rejected, Augustin Fresnel used the wave theory to derive formulas for how much light was partially reflected at the boundary between two layers at different angles of incidence.[12] These were confirmed by experiment and are somewhat cumbersome, but for light travelling along the normal the formula is simply:

Fraction of incident light reflected,

$$R = (n_2 - n_1)^2 / (n_2 + n_1)^2$$

Or in terms of the speeds,

$$R = (u - v)^2 / (u + v)^2$$

With a 2.5:1 ratio of speeds, as in figure 5, for a ray travelling up or down, the normal 18.4% of the energy would

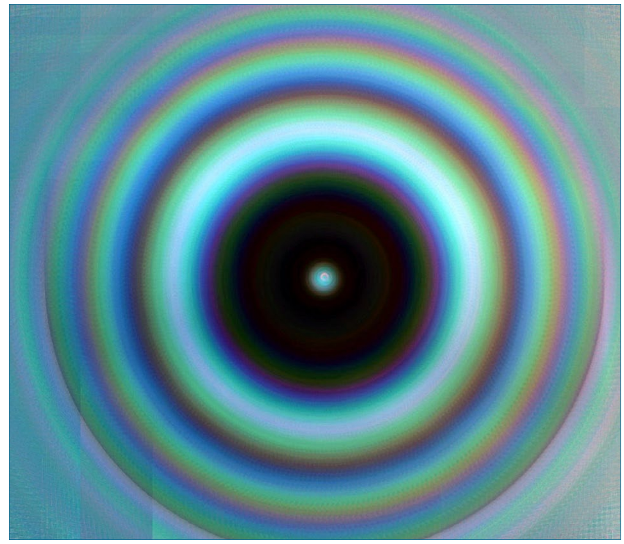

Figure 3. Poisson's bright spot

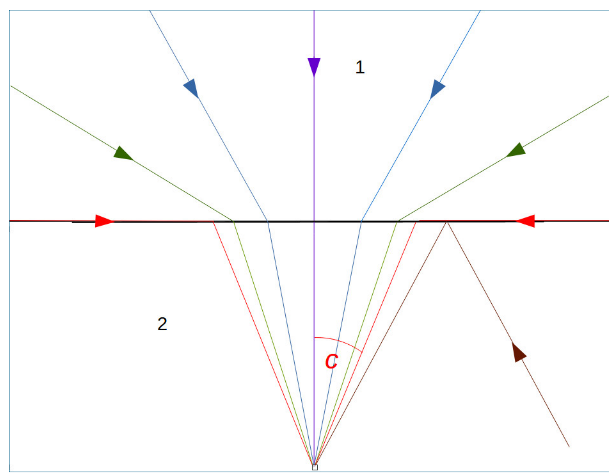

Figure 4. The Critical angle is labelled *c*.

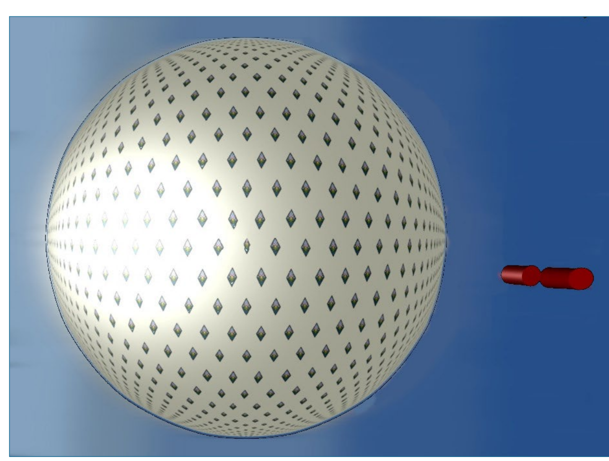

Figure 5. Flat boundary

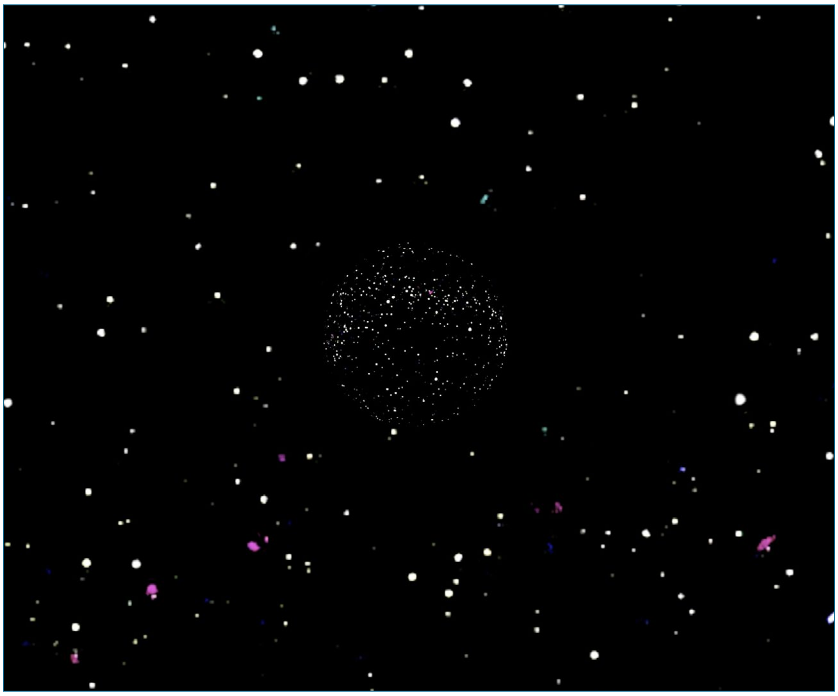

Figure 6. Southern view

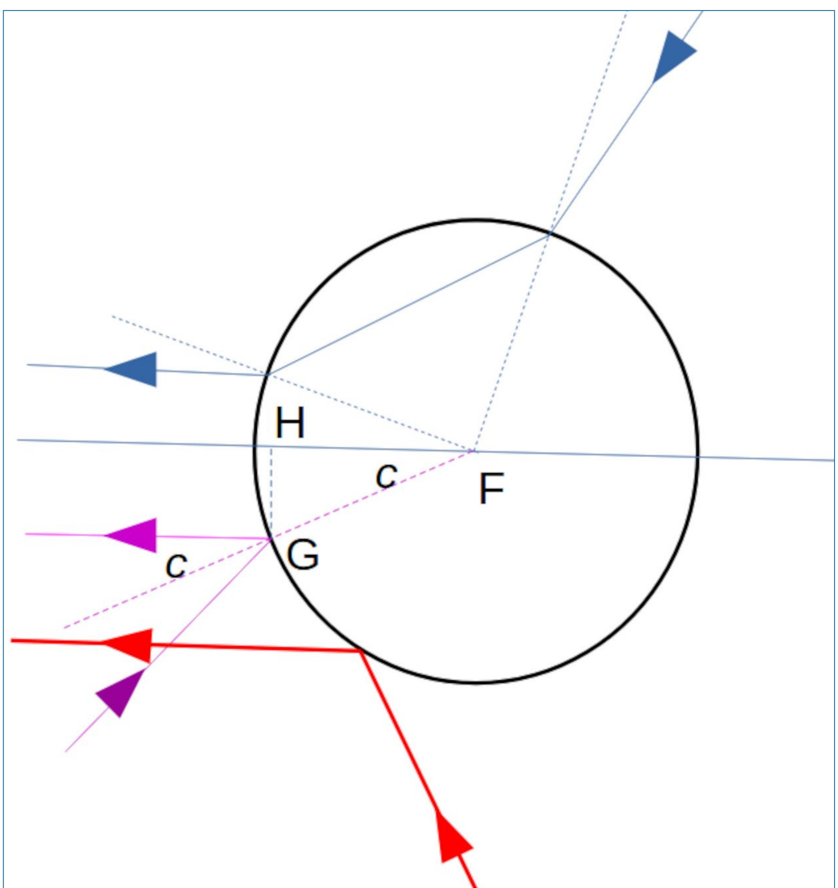

Figure 7. Rays across sphere

be reflected, and 81.6% transmitted. As the angle is increased, the proportion reflected increases and that transmitted decreases until at, and above, the critical angle, 100% is reflected and none transmitted.

Putting another medium between medium 1 and medium 2 will reduce the energy reflected if its thickness exceeds two micrometres (for white light). This is most effective if its index n is the geometric mean of the media either side of it. In this example, $n = 1.58n_1$, 9.6% would be reflected. For more than two boundaries, the exact calculation requires very advanced maths, but R is almost inversely proportional to the number of boundaries (the more boundaries, the closer the approximation).

In the limit as the number of boundaries tends to infinity, R tends to zero. The speed changes smoothly and no light is reflected. Many moths' eyes have a surface with a structure on the nanometre scale, which slows down the incoming light gradually so that none is reflected.[13] This was designed so that predators are not attracted by light reflected from the moths' eyes.

The speed of light at the surface of the earth at 0°C is about 0.03% slower than in a vacuum, and gradually increases with increasing altitude. This very small change is sufficient to refract light travelling almost horizontally by about 0.5° downwards, causing objects in space to appear higher than they are. This enables the setting (or rising) sun to be seen when it is actually below the horizon.

Incidentally, the critical angle at the surface of the earth is 88.6°, so if the earth were a flat disk, the edge of Snell's Window would be 1.4° above the horizon. In that 1.4° we would see inverted images of distant parts of the earth by total internal reflection!

The mirages seen on hot sand and roads occur because the air that is heated by contact with the hot surface is less dense than at eye level, so the speed of light is slightly higher, and light from the sky is totally internally reflected up to the eye.

Astronomy

I will now examine three hypothetical boundary shapes where the speed of light increases, on an astronomical scale.

A flat boundary beyond which the speed is considerably higher than on the observer's side

This is essentially that drawn in figure 4. All objects beyond the boundary would be seen at smaller angles from the normal, through a circular window. Figure 5 is a computer simulation[15] looking at a regular wallpaper pattern across a boundary with speed ratio 2.5:1. Note that the motifs on the wallpaper appear closer to each other as one looks further from the centre. Straight rows, except those which pass through the centre, appear as curves. Photographers call this *barrel distortion*. Outside the window, total internal reflection produces an image of the red rod which is just this side of the boundary, and an image of the blue background behind the observer.

Partial reflection will not occur if the speed reduces gradually across the boundary. The larger the speed ratio, the smaller the window. The refracted image, resembling a sphere, will shrink. The boundary will look like a mirror with a small hole in it. Counter-intuitively, the increase in speed is hindering vision.

Figure 6 shows the view, from the southern hemisphere looking parallel to the axis of the earth, if there were an 8:1 speed ratio across a boundary between the earth and the nearest stars. Most of the picture shows an inverted image of the northern sky with the Plough (aka Great Dipper) upper centre. In the centre is the window with a diminished and distorted view of all the stars beyond the boundary.

I am not aware that astronomers have observed anything like this.

A sphere where the speed inside is greater than outside

Figure 7 shows three rays, again with a speed ratio of 2.5:1. The blue one indicates the path typical of those that come from beyond the sphere and are refracted—away from the normal on entering and towards the normal on leaving. The purple line represents reflection at the critical angle c, and the red line shows how objects beyond the sphere can be seen by total reflection.

As

$$\sin c = v / u$$

and

$$GH = FG \sin c$$
$$GH = FG\, v / u$$

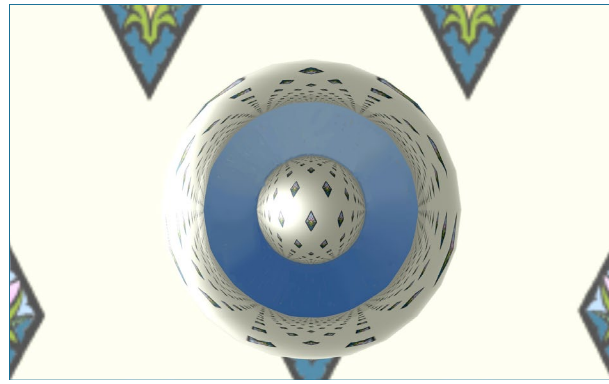

Figure 8. View of sphere

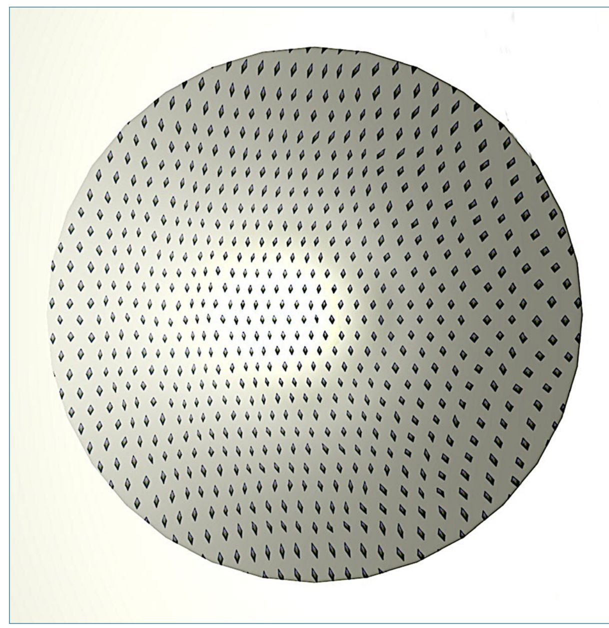

Figure 9. View from right of centre

In this case, $v / u = 1/2.5 = 0.4$. The refracted rays all come through a circular window, the radius of which is 0.4 of the radius of the sphere.

Figure 8 gives the appearance of the sphere as seen by a distant observer. The refracted rays form an image which looks like a ball; the outermost reflected rays show the true size of the sphere; the blue ring is light from the observer's side which has been reflected. Some of the motifs can be seen three times: by refraction, by reflection, and directly with correct size and spacing. Nothing which matches this, replacing the motifs with stars, has been observed.

An observer near the centre of a sphere where the speed inside is less than outside

If an observer is at the exact centre of a transparent sphere, all the light coming to him from outside will be at right angles

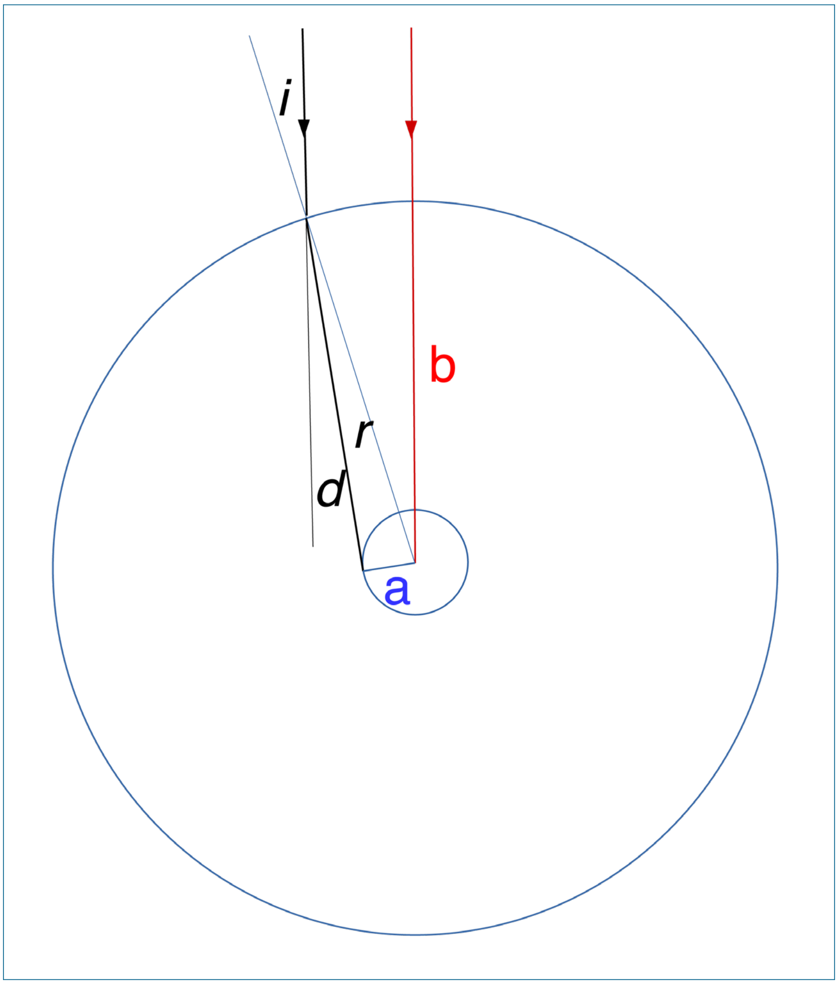

Figure 10. Sphere centred on the sun

to the boundary, so will not be refracted. He will have an undistorted view.

If the observer moves away from the centre, he will see a distorted image. Figure 9 is the image as seen from the right of the centre. The straight rows appear curved and further apart on the right.

Suppose the sun to be in the centre of such a sphere with radius b, larger than the orbit of Neptune, and the radius of the earth's orbit to be a, as shown in figure 10. Let the speed of light outside the sphere be u and the speed inside be v.

When the earth is directly above the sun, light from a distant star will be seen in its true direction as shown by the red ray; but, when left of the sun, the light's path is shown by the black ray, which has been deviated by the angle d. During the year it will appear to change its direction by $D = 2d$.

James Bradley looked for such a change, from a different cause and in the opposite direction[16] (c. 1728) and found that if there was a change it was less than one second of arc (or 5×10^{-6} radians). I will calculate how large b needs to be to make D so small.

$$i = d + r$$

From Snell's Law,

$$v \sin i = u \sin r$$

For very small angles,

$$v\, i = u\, r$$

$$v\,(d + r) = u\, r$$

Measuring the angles in radians,

$$r = a / b$$

Therefore

$$v\,(d + a / b) = u\, a / b$$

From which

$$b = a(u/v - 1)/d = 2a(u/v - 1)/D \text{ and the speed ratio } u/v = 1 + db/a = 1 + Db/2a$$

Where could such a spherical boundary be?

After it had completed its mission in the solar system, *Voyager 1* continued measuring the Solar Wind of very energetic charged particles emitted by the sun. In August 2012 a rapid forty-fold increase in the density of the plasma was observed, marking the edge of the Heliosphere.[17] This was at a distance of 120 Astronomical Units (au) from the sun. 1 au is the mean distance from the earth to the sun. Measured in Astronomical Units $a = 1$.

At this distance, $b/a = 120$. So

$$u/v = 1 + 5 \times 10^{-6} \times 120 / 2 = 1 + 3 \times 10^{-4} = 1.0003$$

Clearly 120 au is far too small.

The nearest star to the sun is Proxima Centauri, at a distance of 4.2 light-years (ly). Halfway there the gravitational attraction of the sun is no more than that from other nearby stars.

$$1 \text{ ly} = 63{,}240\text{au}$$ [18]

At 2 ly,

$$b/a = 2 \times 63{,}240$$

$$u/v = 1 + 5 \times 10^{-6} \times 2 \times 63{,}2400 / 2 = 1.32$$

To allow a speed ratio of 1,000,

$$b = 2a(u/v - 1)/D = 2a(1{,}000 - 1)/5 \times 10^{-6} = 4.00 \times 10^{8}\ a = 4.00 \times 10^{8}\ \text{au} = 6{,}325\ \text{ly}$$

This is about 9% of the radius of our galaxy (70,000 ly).

Finally, consider a boundary of radius 100,000 ly, which would give $D = 0.061$ seconds of arc. This looks possible if it is centred on the sun, but if its centre is the centre of mass of the galaxy some 20,000 ly from us, our view would be severely limited. The critical angle is 1/1,000 radians.

Geometry shows that multiplying by 100,000/20,000 yields the radius of Snell's window. This is 1/200 radians = 0.29 degrees, just over the angular radius of the moon as seen from Earth. Directly opposite to the galactic centre would be a window about the size of the moon through which other galaxies would be seen at 1/300 of true angular size. In all other directions we would see either stars or dust in our galaxy or images of them by total internal reflection.

The only observations which are anything like refraction are those attributed to *gravitational lensing*. These deviations from a straight line are typically a few seconds of arc.[19] If they are not due to gravity but to a change in the speed of light, a change of the order of 0.1% would be sufficient.

Conclusion

It is difficult to find any way in which the refraction caused by the current speed of light changing from one place to another would go unobserved. Where it changes, whatever its cause, the waves must be continuous across the region where it changes. This places severe limitations on any model in which the speed in different parts of the universe differs enough to solve the distant starlight problem.

Changing the speed with time rather than position, such as the cosmology posited in 2022 by Dr Russell Humphreys,[20] would not cause refraction if the speed changed simultaneously throughout the universe. He starts that article by stating that a rigorous creationist cosmology must

- have a firm biblical basis
- explain the increasing red shift of light with increasing distance
- explain the Cosmic Microwave Background Radiation
- explain the seemingly great age of the distant cosmos.

I would add to that list:

- avoid detectable refraction and other effects contrary to observations.

Ideally, it should permit straightforward explanations of currently puzzling discoveries such as the second large scale structure found recently by Alexia Lopez studying at the University of Central Lancashire,[21] and predict features which can be tested.

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