Physics 200-04

Notes on Aether

**Aberration** While Copernicus has convincingly showed that strange correlations in Ptolemy's description of the motion of the planets could be explained by assuming that they were the reflection in the sky of the orbit of the earth around the sun, Tycho Brahe's model, in which all planets orbit the sun, which itself orbits a stationary earth, was an equally good explanation of those coincidences. (Eg that the orbits of the outer planets in their minor circular orbits were all of the same phase, and that the equants and deferents of the minor orbits all point to the sun). Newton's theoretical work on the motion of the planets suggested very strongly that it was the planets, including the earth, which orbits the sun, strong experimental evidence was missing.

In the early 1700 Bradley, the third Astronomer Royal in the Greenwich Observatory found that the star delta Draconis ( the fourth brightest star in the constellation Draco) was changing its North-South position regularly over the course of the year (this north-south angle was all he could measure). He finally realized that this is the same effect as that in which rain always seems to be coming at you from in front as you run through it.

Based on the corpuscular theory of light dominant at the time, this is easy to understand. Consider diagram 1 in which a star is located at an angle $\theta$ above the direction of motion of the earth. Its velocity components coming to the observer on the earth are $-c\cos(\theta)$ along the direction of motions and $-c\sin(\theta)$ in the perpendicular direction. But for the observer on the earth, the velocity of the earth is subtracted from the horizontal velocity (at least according to conventional Galilean relativity), giving an effective horizontal velocity at the earth of $= c\cos(\theta) - v$. Thus for the earth observer, the angle at which the light appears to be striking the earth is

$$tan(\theta') = \frac{c\sin(\theta)}{c\cos(\theta) + v} = \frac{\sin(\theta)}{\cos(\theta) + \frac{v}{c}} \qquad (1)$$

Ie, the angle is smaller and the light appears to be coming from more ahead. Since for the earth $v \approx 30km/sec$ while $c = 3\ 1\ -^{5}\ km/sec$, the maximum deflection angle is about 20 seconds of arc. Bradley measured this to about 1%, from which knowing the velocity of the earth, he could calculate the velocity of light.

One puzzle was the velocity of light. As a particle one would expect its velocity to vary. In particular if the source was moving, one would expect that the velocity might be some value in the rest frame of the source, but that the velocity of the source would add (vectorially) to the velocity of light. Thus the aberration angle should be source dependent. No such dependence was ever found.

However, what Bradley's observations convincingly demonstrated was that it must be that the earth is in motion with just the figures Newton ascribed to

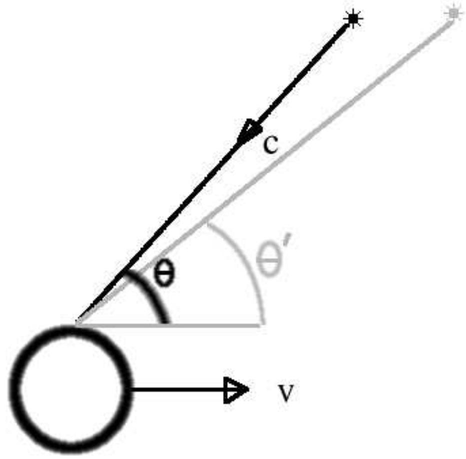


Figure 1: The setup of Bradley's measurement of the aberration of light from a star. The earth has velocity v, the star is at angle $\theta$ from that direction if the earth were at rest. With the earth moving the star appears to be at a smaller angle $\theta'$ with respect to that velocity direction. Since the velocity direction changes over the year as the earth orbits the sun, the deflection direction and angle change as well.

it. Otherwise there was really no way of explaining the fact that all of the stars uniformly participated in this dance, describing little circles or ellipses in the sky depending on the relation of their direction to the orbital plane of the earth. (stars in the perpendicular direction to the orbit would describe circles, while stars in the plane would move back and forth along a line. Others would describe tiny ellipses). That these regular motions could be due to actual synchronized motions of the distant stars, rather than due to the motion of the earth was (and is) just too far fetched a notion.

**Wave theory of light** In 1801 Young showed with his double slits that light behaved as a wave, rather than as a particle. The light going through a pair of very closely spaced slits showed interference beyond the fringes. Over the next twenty years many more experiments showed that light behaved as a wave. This cleared up one problem. Many waves (eg, sound waves in air, although not ocean waves on the water surface) propagate with one fixed velocity with respect to the medium in which they travel. It became very natural to ascribe the apparent independence of the velocity of light from the source to this constancy of velocity of a wave in a medium. A key problem was then what the properties of the medium were, and in which frame the medium was at rest. It raised the possibility that Galilean relativity was wrong, and that there was a universal frame, the rest frame of the aether (the medium carrying light waves) which was special. Furthermore, one could contemplate experiments which could determine the velocity of the earth with respect to this rest frame.

**Aether Drag**:Even the aberration experiments had to be reinterpreted in the light of the wave nature of light. and the explanation became more difficult. If one used the group velocity of the light as the defining velocity in determining the direction of the observed star, the phase velocity gave completely different results. Fresnel suggested that if one assumed that the earth did not simply pass through the aether without affecting it, but rather that the earth partially dragged the aether along with it (by an amount corresponding to the index of refraction), then the aberration results could be simply explained in a wave theory. He predicted that in a moving fluid, with index of refraction $n$ (such that the rest velocity of light in the medium at rest was $c/n$) , the velocity of the light in the moving medium would be $\frac{c}{n} + v(1 - \frac{1}{n^2}$. This is in contrast to no change in the velocity of light of all, or in a complete-drag theory, in which one would have expected the velocity to be $c/n$ in the frame of the moving fluid and thus be $\frac{c}{n} + v$ in the moving fluid. (if the light was propagating the opposite direction as the fluid, the $v$ would go to $-v$ in the above expressions).

This theory was a bit silly, since it implied that the amount by which the aether had to be dragged would depend on frequency, since $n$ changes with frequency. How could one fluid, the aether, be dragged with different velocities depending on what waves were being observed?

In 1851, Fizeau carried out an experiment in which he tried to differentiate between Fresnel's ideas, Stoke's idea that the aether should be completely dragged by a flowing fluid, of that there was no aether drag at all.

He shone light in two directions along a path through flowing water, and looked to find a difference in how long it took the light to go around the two loops in opposite directions. He used the oscillations of the light as the clock to time this difference, interfering the two beams at the end of their path to see what that time difference was. His result agreed with the Fresnel result, and with neither the complete aether drag, or no aether drag hypotheses.

The key lesson of this experiment was that the aether was not completely dragged along by a flowing fluid, and thus by implication not by the earth either. There should be an aether wind as the earth moved around the sun, and the value of the wind (ie the velocity of the earth with respect to the aether at the earth) should be measurable.

Michaelson-Morley Following suggestions by Maxwell and others, Michaelson and then Michaelson and Morley devised and experiment to determine the velocity of the earth with respect to the aether. They did this by using an interferometer to time the difference in time for light to travel back and forth along a path parallel to the earth's motion, and one perpendicular to the earth's motion. Both arms were assumed to be of equal length, and the apparatus was rotated to exchange the parallel and perpendicular arms to check for any inequality.

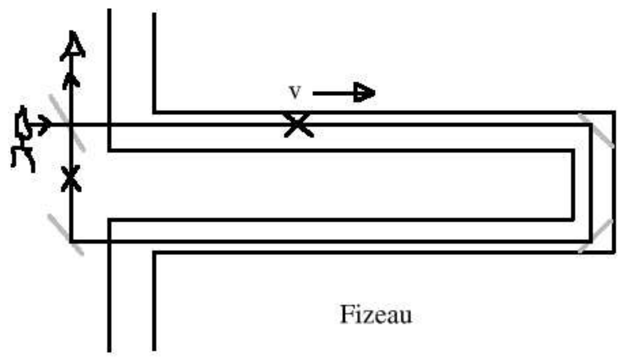


Figure 2: Setup of the Fizeau experiment to measure the difference in velocity of light travelling with and against a flowing fluid. The incident light is split by the half silvered mirror, making sure that the crests of the light on the two paths start out together. By measuring the interference when they are recombined again at that mirror, one can determine the difference in time for the two paths.

In the perpendicular arm, the velocity of light in the perpendicular direction is $\sqrt{c^2 - v^2}$ (since the light must have a velocity of v in the parallel direction to make up for the aether flow). In the parallel direction, on the outgoing path, the light is bucking the flow of the aether and its velocity is $c - v$ while on the return path it is $c + v$.

The difference in time was thus predicted to be

$$\Delta t = \frac{2cL_{par}}{c^2 - v^2} - \frac{2L_{perp}}{\sqrt{c^2 - v^2}} \tag{2}$$

which, if $L_{par} = L_{perp} = L$, is approximately (to lowest order in $v/c$)

$$\Delta t = \frac{Lv^2}{c^2} \tag{3}$$

Instead they found a value of 0. Their experimental accuracy was such that they could have detected a velocity as small as 30m/sec (vs the actual orbital velocity of the earth of 30km/sec). Thus the aether if it exists must be dragged completely with the earth, in contradiction to the Fizeau experiment.

**Fitzgerald** Fitzgerald suggested that one way you could get a null experiment was if there was some interaction between the arms of the interferometer and the aether wind rushing past, which shortened the parallel arm to $L\sqrt{1 - \frac{v^2}{c^2}}$. However, this contraction would have to be independent of the material of which the arms of the interferometer was made, an unlikely behaviour for matter interacting with the aether wind.

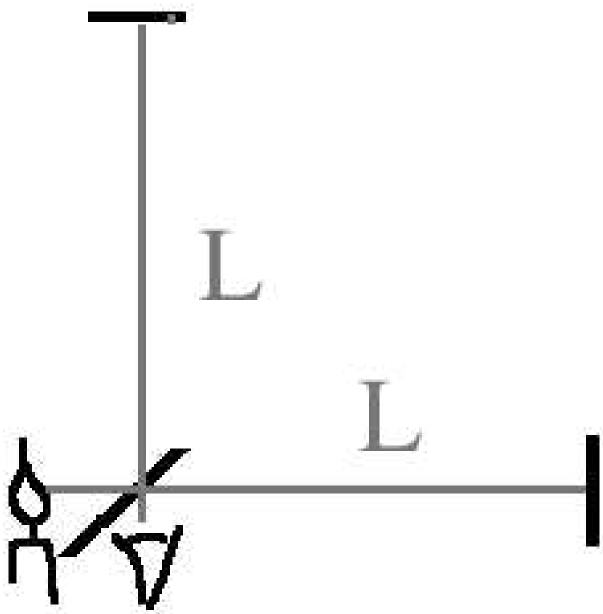


Figure 3: The Michaelson Morley experiment to measure the difference in time that it takes light to travel along arms parallel and perpendicular to the velocity of the earth. Using usual Newtonian concepts, the perpendicular component of velocity in the perpendicular arm is $\sqrt{c^2 - v^2}$ while in the parallel arm it is c-v going out and c+v coming back.