ALBERT EINSTEIN

Slow start

Independent, proud

Patent office in Bern, 1902-1909

Miracle year, 1905

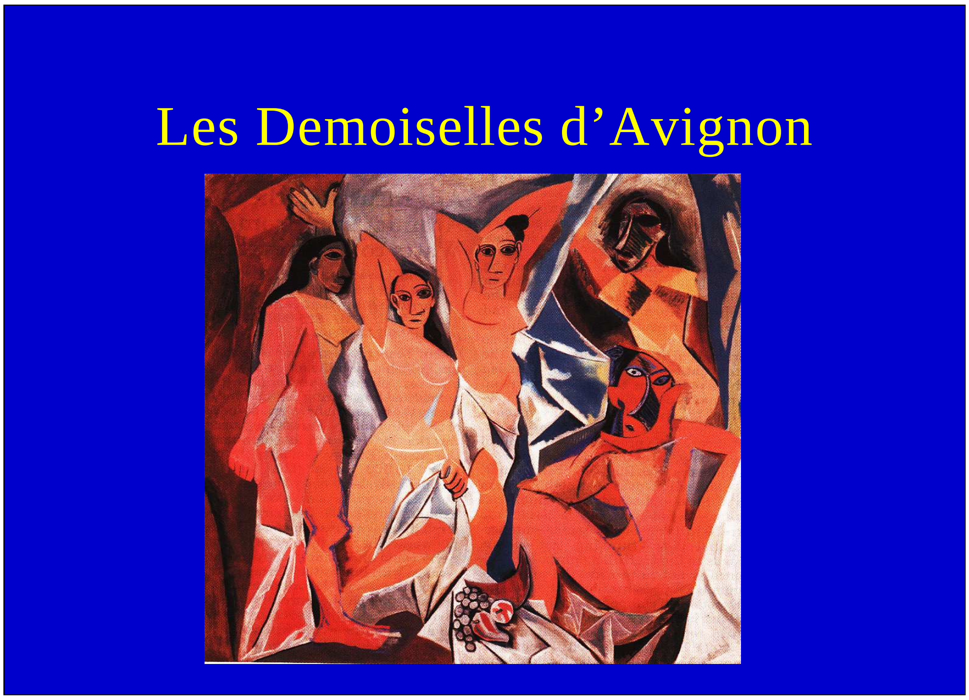
Director of Physics Institute, Berlin, 1914

Came to US, 1933

See toolkit file “Einstein.doc”

Einstein has long had a very high public profile. His most famous equation, $E = mc^2$ appears everywhere. People associate him with four dimensional space and with time travel. SHOW SNL tape of “The Einstein Express”.

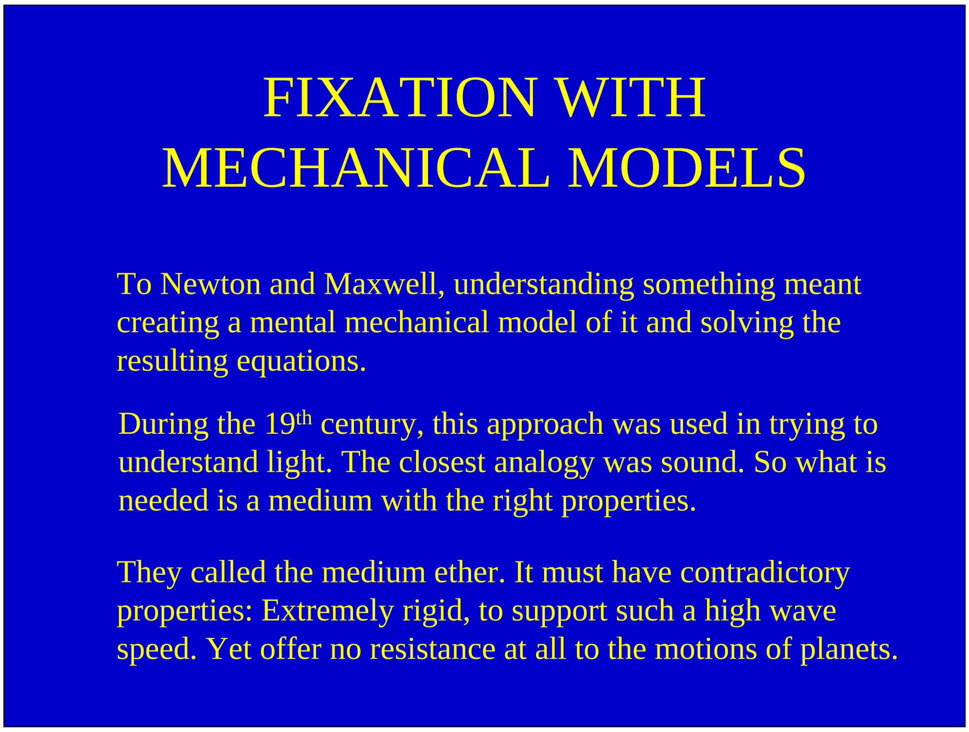
Another element in the public imagination is an association of modern physics and modern art. In particular, Einstein and Picasso.



Picasso’s painting of 1907 is said to be the first four dimensional painting. Einstein and Picasso became famous at about the same time, one for helping create modern physics, the other modern art. Did these two creations have something to do with each other? People have written and thought about this for decades, recently ranging from Steve Martin’s “Picasso at le Lapin Agile”, to Arthur Miller’s “Einstein and Picasso”.

During the early years of the 20th century, both men were trying to find themselves, and were doing so with the help of a small group of intimate friends, of which they were each the center. At that time, Henri Poincare, an influential French polymath had just written a book on possible geometries in our world. Einstein had read a German translation of it, and one of Picasso’s group had read it and told the group about it. Poincare was particularly interested in a fourth spatial dimension, not a fourth time dimension as in H. G. Wells’ “The Time Traveler” of 1895.

Ideas like these were in the air and discussed all over Europe by intense groups like those of Einstein and Picasso. Picasso may have put ideas like this into the above painting. If one can step into the fourth dimension, (“the Astral Plane”) then one perhaps could see all three dimensions of ordinary objects at once instead of only two. The woman on the lower right above is perhaps Picasso’s example of what this would look like.



Building models of objects and processes we observe in nature is one of the major activities of scientists. The model needs to include the most important influences acting on the situation, and be simple enough that quantitative predictions can be made using it.

Sound was the wave phenomenon that seemed to most closely resemble light. Sound is a compression wave in a mechanical medium such as air, water, or steel. The wave speed increases with the rigidity of the medium, and decreases with its mass density. So to obtain such a high speed of light, the medium, called ether, must have an extremely low density, yet be very rigid. It must fill all space out to the stars, since we see them.

At the same time, the ether must allow planets to drift through it without any offering detectable resistance. Otherwise they would not move repeatedly in their elliptical orbits obtained from Newton's laws using only the gravity force, with no contribution from the ether.

If the earth is drifting through the ether, can we detect the motion? If light propagates relative to the ether, like sound does relative to its mechanical media, then the ether's velocity, measured by us on earth, would be added to that of light. So light will have different speeds in different directions as measured by us.

THE ETHER

Whenever energy is transmitted from one body to another in time, there must be a medium or substance in which the energy exists after it leaves one body and before it reaches the other.

J. C. Maxwell (1873)

I came to the opinion quite some time ago that Fresnel's idea, hypothesizing a motionless ether, is on the right track.

H. A. Lorentz (1895)

The introduction of a "luminiferous ether" will prove to be superfluous inasmuch as the view here developed will not require an "absolute stationary space"..

A. Einstein (1905)

Here we see quotations from three luminous theoretical physicists from different times. Maxwell was the outstanding theorist of the 19th century who had developed electromagnetism as we know it today. It is ironic that he was so wedded to mechanical models, yet his electromagnetism serves as the model for the field theory approach used today.

Lorentz expresses the consensus belief of his time. At about the same time another prominent physicist speculated that one day it would be shown that lightning consists of cracks in the ether.

Einstein made ether superfluous as he says here. Before we look into how he did so, let's pursue further the ether idea since historically it played such a major role.

THREE POSSIBILITIES

There is an ether. A relativity principle exists for mechanics but not for light, for which there is a preferred inertial frame, the ether frame. Then we should be able to locate it experimentally.

Maxwell was wrong. A relativity principle exists for both mechanics and light but Maxwell's equations for light are not correct. In this case we should be able to perform experiments to show deviations from Maxwell's equations and reformulate them.

Newton was wrong. A relativity principle exists for both mechanics and light but Newton's equations are not correct. In that case we should be able to perform experiments to show deviations from Newton's laws and reformulate them.

Looking back on the period 1880-1900 we can summarize the state of affairs with the three possibilities above. This is not historically accurate in that nobody during that period expressed the situation this way. But from our viewpoint today this is a concise summary statement.

If the ether exists and the speed of light exists relative to that medium, then the only coordinate system in which Maxwell's equations are valid is the one at rest with respect to the ether. Maxwell's equations say the speed of light is c. This is the only coordinate system for which that would be true. In that case a relativity principle exists for mechanics (no preferred inertial system, as Galileo argued), but not for light.

If a relativity principle exists for both mechanics and light, then either Maxwell's equations are wrong, or Newton's laws are wrong. If Maxwell is wrong, then velocities might still add in the usual way. If Newton is wrong, then a new way of adding velocities is needed since the way Galileo and Newton did this is not consistent with Maxwell's equations.

MICHELSON’S SWIM RACE

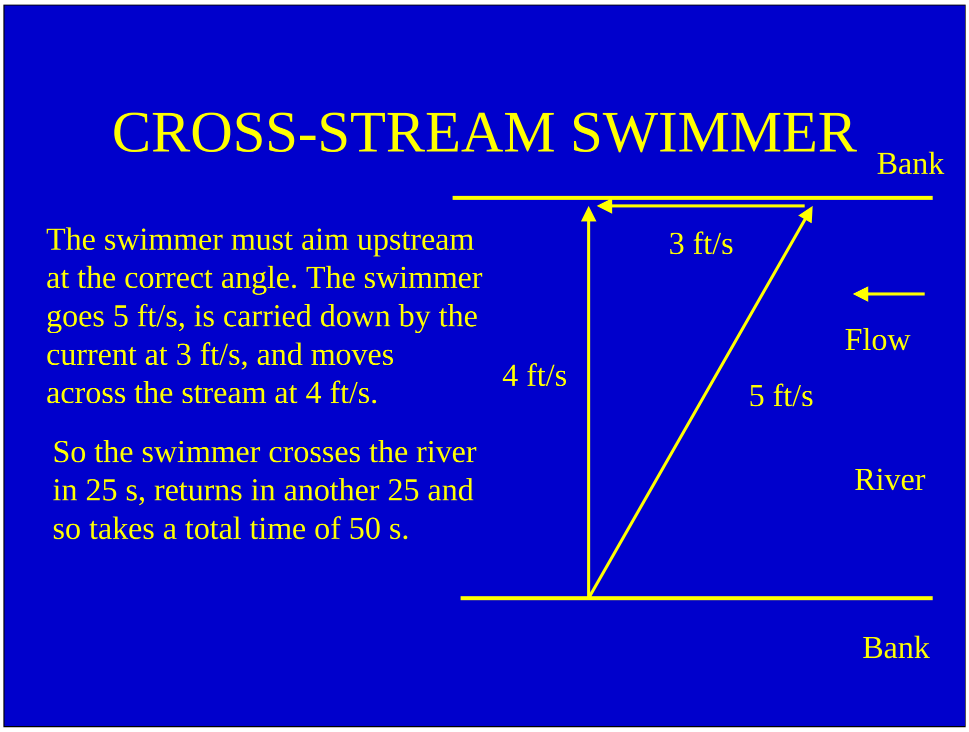
Two swimmers, each of whom can swim at 5 ft/s, have a race. The race takes place in a river 100 ft wide flowing at 3 ft/s. One swimmer goes upstream 100 ft (measured along the bank), then returns. The other swims across to the opposite bank and returns. Who wins?

The swimmer going upstream moves at 2 ft/s relative to the bank, taking 50 s to go 100 ft. Coming back, the speed is 8 ft/s, so it takes 12.5 s for a total time of 62.5 s.

Albert Michelson was an instructor at the US Naval academy when he measured the speed of light so well, got an idea for how to measure the “ether wind”. He explained it to his children (according to his daughter) in the following way.

The race is set up as described above. The time taken by the swimmer going up and down stream is easy to calculate. Here we are using the same way we have previously used to evaluate relative velocities. They simply add or subtract. This is referred to as Galilean velocity addition.

To calculate the travel time for the swimmer going across stream we need a diagram, shown on the next slide.

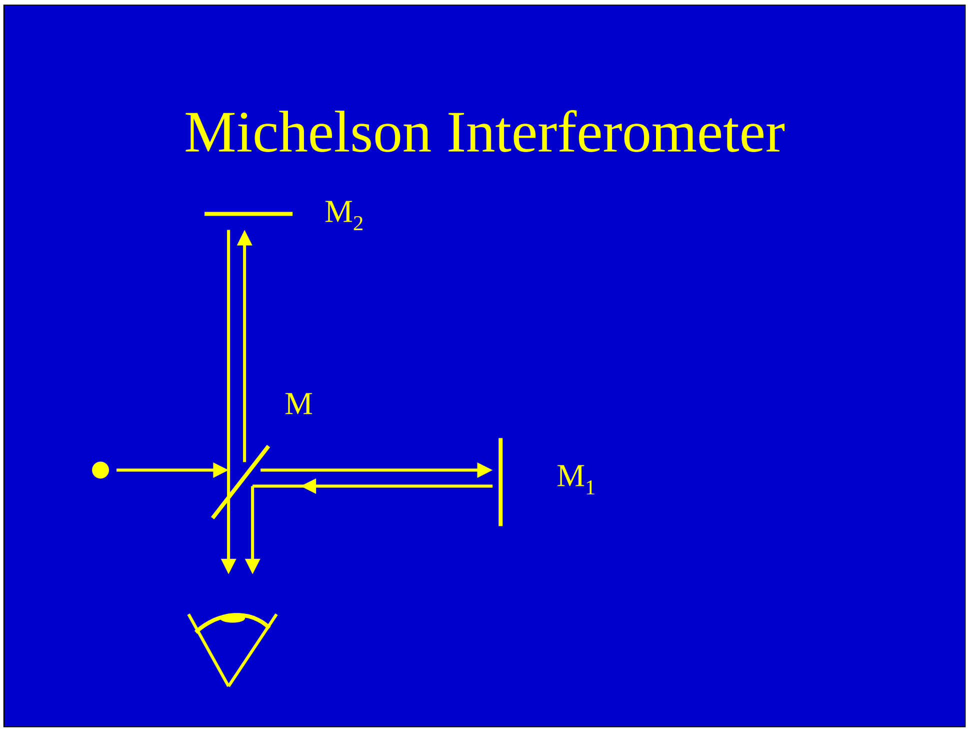


The swimmer must aim upstream at the correct angle to counteract the flow of the river. A real swimmer would do this automatically by judging their position as they go.

In each second, the swimmer moves 5 ft through the water while the current moves 3 ft downstream. This forms a 3,4,5 right triangle, and we see that the swimmer moves across the stream at 4 ft/s.

So the cross-stream swimmer wins the race, taking 50 s for the round trip.

Michelson invented an interferometer based on this swim race with which he thought he could detect the motion of the Earth through the ether. At the time he started this work, 1880, he and everyone else expected the ether was real, and Earth must be moving through it.



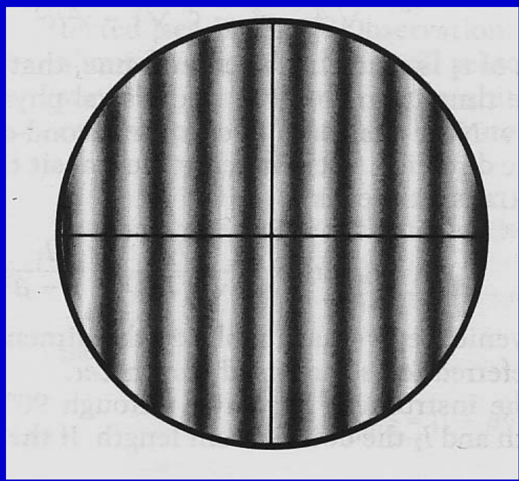
Michelson won the 1907 Nobel Prize in Physics for his invention of this interferometer and the various measurements he made with it. Here is the idea. We want to use the interference properties of light. As we have seen, one way to do this is to split a beam into two parts that travel different paths, then bring them back together. Michelson did this in a radically different way than Young or the soap film.

A source of light on the left sends light horizontally to a mirror M at 45^0. This is a half-silvered mirror that transmits half of the beam through and reflects the other half. The transmitted half goes on to mirror M_1, is reflected back, and half of it is reflected again by M downwards towards the viewer. This is ¼ of the original beam – much more than for the Young experiment (~ 10^{-3}) or a soap film (0.02).

The half of the beam reflected at M goes up to mirror M_2, is reflected back, and half of it is transmitted by M to the eye of the observer.

So now, two beams that traveled out and back perpendicular to each other are recombined to be seen. If the two path lengths are precisely the same length, the two beams will interfere constructively. If the two paths differ by half a wavelength, they will interfere destructively. The actual pattern seen in the eyepiece can be complex depending on how well the mirrors are adjusted.

Michelson Interference Pattern



Shown above is an interference pattern seen in a Michelson interferometer. The bright stripes indicate constructive interference, and the dark stripes destructive interference. The mirrors have been deliberately aligned to be not exactly perpendicular. This is the interference pattern of a wedge. The optical path length is changing on going from left to right. Going from one bright stripe to the next corresponds to changing the difference in path length between the two beams by one wavelength of light.

It is clear that very precise length comparisons can be made with the interferometer. At one point the length of the standard meter was calibrated in terms of the wavelength of light from a particular atomic transition. In addition the index of refraction of gases can be measured.

Of course the first application of the interferometer was to the attempted observation of the “ether wind”.

SHOW Michelson interferometer with microwaves, and with light.

Michelson-Morley Experiment

Assume the light going to M_1 moves parallel to the ether wind of speed v. Then the round trip time is:

$t_1 = l/(c - v) + l/(c + v) = [2l/c][1/(1 - v^2/c^2)]$

Assume the light going to M_2 moves perpendicular to the ether wind. Then its round trip time is:

$t_2 = [2l/c][1/(1 - v^2/c^2)^{1/2}]$

When the whole apparatus is rotated by 90^0 the paths are interchanged. The time difference for the two paths when simplified, is $\Delta t = (2l/c)(v^2/c^2)$

This corresponds to a fringe shift of $\Delta N = 2l/\lambda(v^2/c^2)$

Assume the earth is moving through the ether with speed v. This speed was usually taken to be the speed of earth in its orbit about the Sun, which is 30 km/s. If the experiment is done repeatedly throughout the year, this is the speed change likely to be observed.

We have done the calculations for the swimmers in the river. The calculation for light beams in the ether wind is just the same. The beam going across the current takes a little less time. The time difference can be expressed as a fringe shift expected in the interferometer using delta N = delta t/T where T is the period of the light equal to T = λ/c.

Using the path lengths in the 1887 experiment, the predicted shift is 0.4 of a fringe. The smallest detectable shift in that experiment was 0.01 fringe.

Michelson-Morley Numbers

Earth's orbital speed about the Sun = 30 km/s.
If a stationary ether exists, our speed through it must change by this amount during the year.

This means $v/c = 10^{-4}$ and $v^2/c^2 = 10^{-8}$
For the 1887 experiment, $2l/\lambda = 0.4*10^{8}$
So the predicted fringe shift is $\Delta N = 0.4$

If a stationary ether exists, we do not know our speed through it. Is the Sun stationary in the ether? Is our Galaxy?

What we do know is that during the year, the Earth must change its speed relative to the ether by an amount equal to twice the Earth's orbital speed around the sun.

It became standard practice to use the earth's orbital speed of 30 km/s to predict the "expected" fringe shift due to the ether.

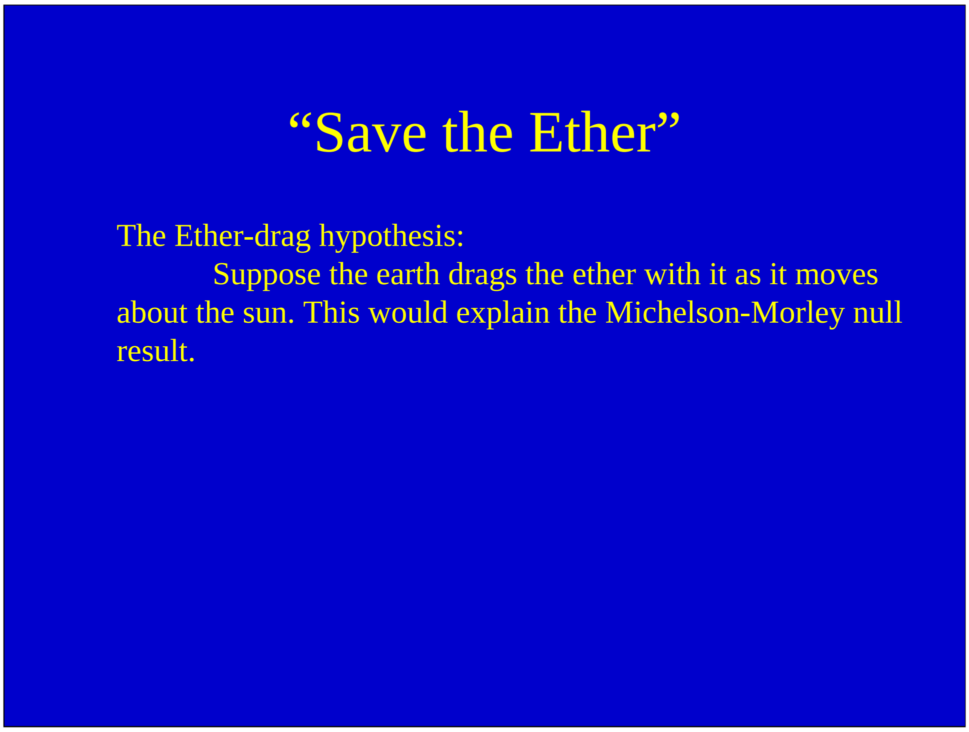
Michelson-Morley Summary

Observer	Year	Predicted Shift	Upper Limit
Michelson	1881	0.04	0.02
Michelson-Morley	1887	0.4	0.01
Morley-Miller	1903	1.1	0.015
Illingworth	1927	0.07	0.0004
Michelson et al	1929	0.9	0.01
Joos	1930	0.75	0.002

The number of times this experiment was repeated bears testimony to how deeply felt was the belief in an ether. The predicted shift is based on a speed through the ether equal to the earth's orbital speed about the sun. The result however does not depend on an assumed ether stationary with respect to the sun. The earth's velocity through the ether could be zero at a given time. It should change however as the earth rotates, and as it moves about the sun in its orbit. So the expected changes in v are this magnitude or larger.

The ratio between the predicted shift and the upper limit varies between 40 and 375 after 1887. The experimental result is certainly convincing – no ether drift is seen. It is also testimony to how difficult the experiment was. An improvement of barely a factor of 10 in the ratio of expected to upper limit fringe shift indicates how good a job Michelson and Morley did.

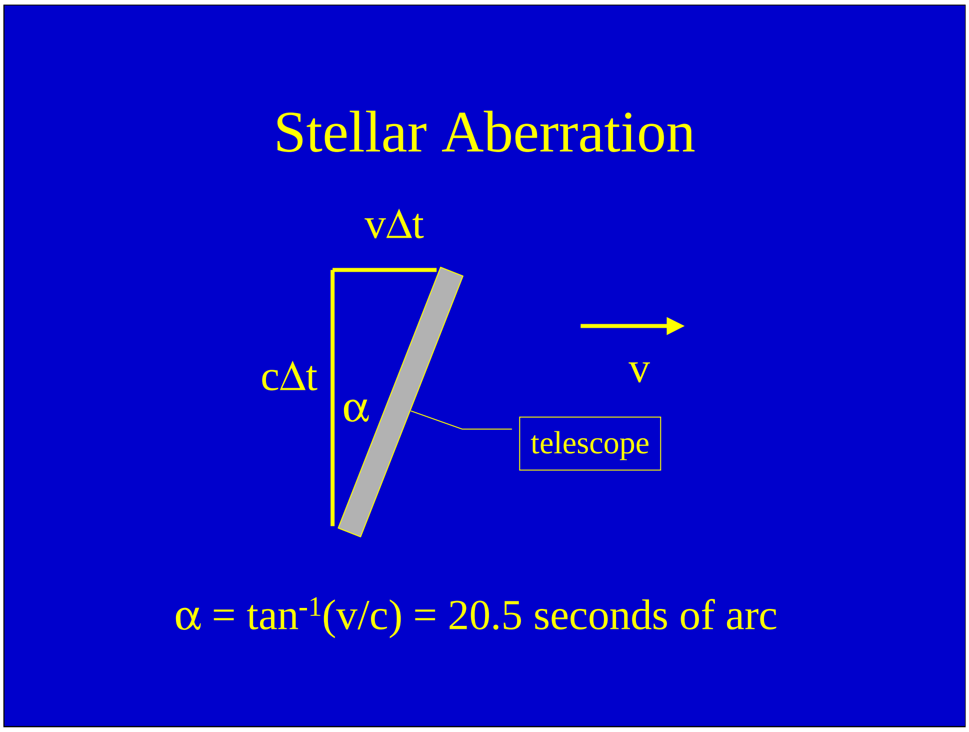
In 1958 the experiment was repeated using microwaves with an improvement of about 50 over the results shown above. Today it could be done even better with a laser source.



Suppose the earth drags the ether with it as it moves about the sun. This would produce a local stationary ether, and would then explain the Michelson-Morley null result. Admittedly this adds another unusual property to the already bizarre ether, but it has the advantage that neither our theories of mechanics or of light would need modification.

Presumably each of the planets would drag ether with them, and it would be stationary with respect to the sun at its location as well. The ether would need to be very elastic over large distances, with negligible restoring force for these large strains.

This hypothesis was not however consistent with the observed stellar aberration.

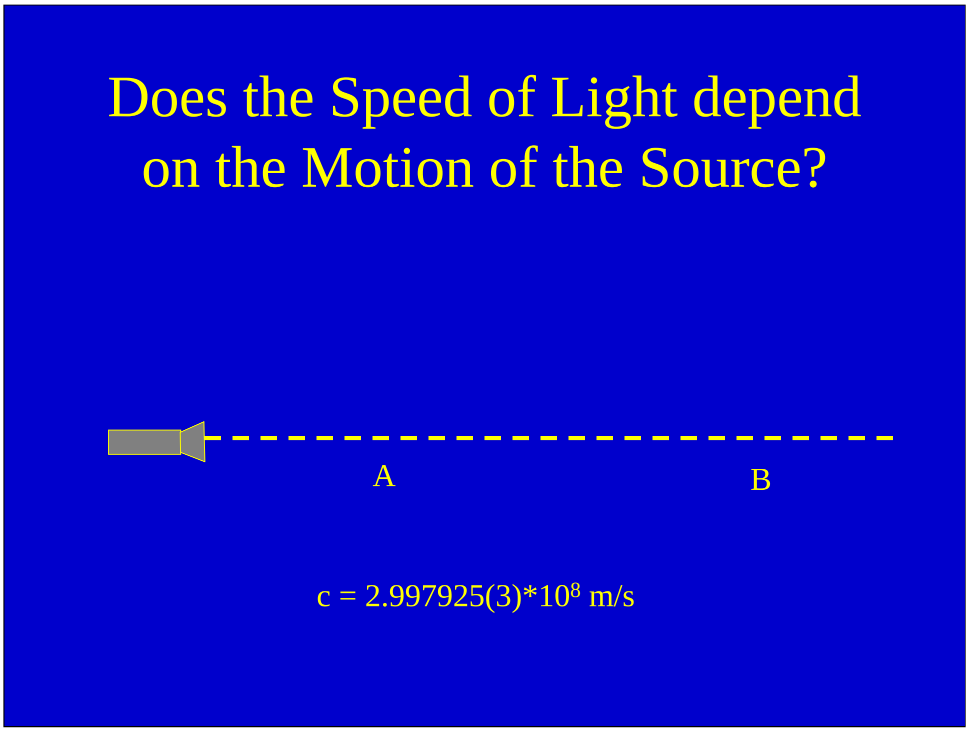


Stellar aberration was first observed in 1727 by Bradley. He observed that stars appear to move in circles with a diameter of 41 seconds of arc. This is much too small to be seen by naked eye which is why its discovery had to wait for the availability of good telescopes.

Stellar aberration can be accounted for by assuming a stationary ether through which the earth moves. In the diagram above, a star is directly overhead and not shown in the picture. Its light moves straight down. The earth is assumed to be moving to the right through the stationary ether with speed v.

Then to see the star, a telescope must be tilted through a small angle towards the right. As the light moves downward through the telescope, it moves to the right by virtue of earth's motion. Using the earth's orbital speed about the sun of 30 km/s, we obtain an angle of 20.5 seconds of arc. As the earth moves about the sun, the star will move around in a cone with half angle equal to 20.5 seconds, in excellent agreement with observations.

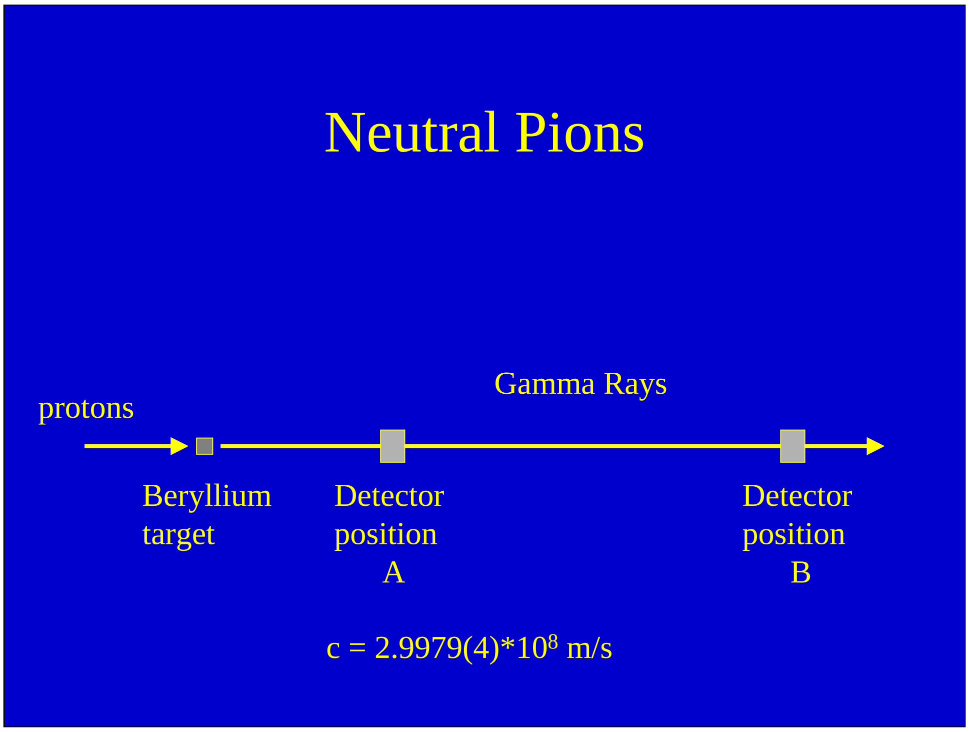
Our immediate conclusion is that the ether is not dragged along by the earth. If it were, no stellar aberration would be seen. This also means that if the ether does not exist, we will need to find another explanation of the observed stellar aberration.



Certainly a basic property of light is this aspect of its speed. Does the speed depend on the motion of the source? The speed of a baseball certainly does depend on the motion of the pitcher throwing it. If he throws a 90 mph fastball while running towards home plate with a speed of 10 mph, then we expect the batter to try to hit a 100 mph fastball.

Does a light beam behave like a baseball in this way? Above we see a sketch of a flashlight creating a beam of light. To measure its speed, we would need to turn the flashlight on and back off quickly, then record the time when the flash arrived at point A and at point B. The distance between A and B divided by the time for the light pulse to travel between them is the speed of light for a stationary source. By 1964 that speed had been established to be $c = 2.997925 \times 10^8$ m/s in vacuum, with an uncertainty of plus or minus three units in the last figure shown.

Now we want to do the same thing with the flashlight moving. The faster we can move it, the more convincing will be the result. To find a light source moving at nearly the speed of light, we need to look at some of the elementary particles produced at accelerators.



In 1964 the following experiment was carried out by Alvager et al in Geneva, Switzerland. High energy protons come out of an accelerator and strike a Be target. The protons collide with protons in the Be nuclei of the target. Among the reaction products are neutral pions. These are mesons with masses intermediate between that of electrons and protons.

Neutral pions are unstable, and decay very quickly into two gamma rays. Gamma rays are high energy light. They are electromagnetic waves with lots of energy, and they travel at the speed of light. In this experiment the pions were moving with speed $v = 0.99c$ as they emerged from the Be nucleus. So we can regard the pions as simply rapidly moving flashlights.

What was done then was to place gamma ray detectors at two different distances from the Be target, and measure the arrival time of the gamma rays. The arrival time difference for the two detectors divided by the distance between them gave a value for c of $c = 2.9979 \times 10^8$ m/s. The uncertainty in this value is plus or minus four units in the last figure shown. The two speeds are the same within 0.01%.

Within experimental error, the speed of light is shown to be the same as for a stationary source. The usual way of adding velocities does not work at all for light. When we add 0.99c to c we get c.