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COSMIC CONCEPTS: FASTER THAN LIGHT?

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How do we learn about the cosmos?
Prior to a few years ago, the only way that humankind could glean information from the cosmos was via the detection of light. Light of all different colours and wavelengths propagates across the Universe encoding information about the physical properties of different phenomena. For the last few years, gravitational radiation is becoming a new way of learning about the Universe outside of Earth.

How much faster is the speed of light than the speed of sound?
In a thunder and lightning storm, we are used to hearing thunder a notable delay after seeing a fork of lightning. This is because light from the lightning travels faster than sound from the same event. In fact, light travels about one million times faster than sound.

How is speed defined?
Speed is defined as the ratio of the distance taken to travel and the time taken to travel that distance. Fast speeds are difficult to measure, especially when small distances (and short transit times) are involved. Making a measurement outside of planet Earth, and scaling up in size, for example to the solar system helps greatly.

What's orbiting around Jupiter?
Although planet Earth has only one satellite, our Moon, orbiting around it, the planet Jupiter has very many moons orbiting around it. The number currently known is 79! The first four of these were discovered by Galileo Galilei in 1610. These first four, known as the Galilean moons, are the brightest of all the moons. Their names are Io, Europa, Callisto and Ganymede.

How could Jupiter and its satellites be used to measure the speed of light?
In 1676, the Danish scientist Ole Romer used the orbits of the innermost moon of Jupiter, known as Io, to measure the speed of light. The moments when Io goes into, or comes out of, Jupiter's shadow provide a precise timing signal, and this means that Io can be used as a clock. These timing signals are recorded on Earth at very slightly different times, depending on the distance of Earth from Jupiter, because light travels at a finite speed. In particular, the interval between two subsequently received timing signals are shorter when Earth is moving in its orbit around the Sun in a direction that is towards Jupiter than when it is moving away from Jupiter. (This is essentially the Doppler effect.) Rømer was able to analyse this effect and make a very good estimate of the speed of light.

Who was the first person to measure the speed of light?
Ole Rømer (1644-1710): Born in Århus, Denmark. He made many scientific contributions, including inventing a thermometer with two fixed points. This was then improved by Daniel Fahrenheit, which led to the Fahrenheit scale, an improvement on the original Rømer scale. His measurements of the speed of light based on observations of the Galilean satellites of Jupiter were performed in 1676.

The speed of light could be predicted...?
James Clerk Maxwell made a prediction of the speed of light two centuries after Ole Rømer's measurements. His prediction was remarkable for three reasons: (i) the value of the speed he predicted was similar to measured values and (ii) the value depends only on two physical quantities (the rate at which electric field propagates [known as

"permittivity"] and the rate at which magnetic field propagates [known as "permeability"] (thus he had showed that light was a electromagnetic wave) and (iii) his prediction, if true, implied that the speed of light was independent of how fast the source of light was moving or how fast what was detecting the light was moving.

Who was Albert Einstein and what did he say about the speed of light?
Albert Einstein (1879-1955): Born in Ulm (Germany), but the family then moved to Munich in 1880 and then to Milan and then Pavia in Italy in the 1890s. He failed to get into ETH (then the Swiss Federal Polytechnic) in Zurich in 1895 and so completed schooling in Aarau in Switzerland for a year, before being admitted to ETH, graduating with a teaching diploma in 1900. He then spent time fruitlessly looking for a teaching post, before finding a job in in the Federal Office for Intellectual Property (patent office) in Bern as an assistant examiner, starting in 1901. The work in the patent office was sufficiently undemanding that he had enough time to develop his revolutionary ideas, including the four papers published in his "miraculous year" of 1905:

1. A paper explaining Brownian motion (which was foundational in statistical thermodynamics).

2. A paper explaining the photoelectric effect (which was foundational in quantum mechanics), and for which he won his Nobel prize.

3. and 4. Two papers which launched special relativity, the first of which proposed the universal speed limit considered in this lecture.

Didn't people claim a few years back that some neutrinos travelled faster than the speed of light?
Yes, this was claimed in 2011 by the OPERA experiment working at Gran Sasso in Italy, timing the passage of flight of neutrinos from CERN. This announcement was greeted with much scepticism, including by the scientists who made the measurements. Had this result have been true, it would have turned upside down our understanding of space-time and causality. But it wasn't correct! Much careful checking followed, and eventually a timing mishap was identified due to a problematic cable contributing to the wrong measurement of the time-of-flight of the neutrinos. The scientific endeavour is characterised by being willing to be surprised, by being willing to think new thoughts. Scientists follow the maxim of the economist John Maynard Keynes who pointed out "in the light of new information, I change my mind"; this is a crucial part of intellectual integrity, every bit as important as honesty itself. The scientific endeavour is also self-correcting, as evinced by the fact that within a few months this surprising result being announced, it was investigated, carefully checked and refuted.

Can we make images of the cosmos in different colours?
Yes! By imaging in different wavelengths, be they optical wavelengths (that our human eyes are sensitive to) or radio wavelengths or X-rays or Gamma-rays, we see a different picture. Multi-wavelength imaging therefore helps us discern the full story about a particular physical phenomenon.

Why do astrophysicists talk about superluminal motion?
Because some black hole systems known as quasars eject jets of energetic plasma at speeds comparable with the speed of light. Geometric effects can give rise to measurements of speeds that are apparently greater than the speed of light. When the geometry of the situation is factored in, the corrected speeds at which the plasma is moving can be deduced and while fast, it doesn't exceed the speed of light.

Further reading and references:

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"Subtle Is the Lord: The Science and the Life of Albert Einstein", Abraham Pais, Oxford University Press, 2005

"The man who changed everything: the life of James Clerk Maxwell", Basil Mahon, Wiley, 2004

"M87 at 90cm: a different picture", Owen, Eilek & Kassim, *Astrophysical Journal*, 2000, 543, 611

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