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MEMORANDUM

To: L. Rafael Reif

From: Peter Fisher

Subject: The expansion of the universe

Date: Thursday, March 24, 2016

The astronomer Edwin Hubble first observed the expansion of the universe in 1927 and many later observations have established it as an empirical fact. Einstein's theory of gravity, the General Theory of Relativity, applied to a universe of uniform density, predicts the expansion and serves as the primary means of interpreting astronomical observations in terms of the density and composition of the matter in the universe. This memo[1] describes just what is meant by, "the expansion of the universe."

Einstein's Special Theory of Relativity is built around the finite velocity of light, c, in relatively inertial frames. Energy and hence information can travel no faster than c.

The universe either has a finiate age, t_o, is infinitely old.

If the universe has a finite age, then our knowledge of the universe is confined sphere of radius ct_o centered on the Earth. The Cosmological Principle assumes every point in the universe is just like every other point and there is no preferred direction in the universe. Any observer anywhere in the universe can only know what is happening within a sphere of radius ct_o centered on the Earth.

If the universe is infinitely old, then light from the infinite past would be arriving at the Earth now. The night sky would be infinitely bright: the light reaching us from a galaxy at distance d grows dimmer like $1/d^2$, but the number of galaxies grows as d^2. The same amount of light from galaxies at each distance interval falls on Earth, the universe is infinite, so an infinite amount of light would reach Earth.

Interstellar matter may scatter the light, making the light from more distant galaxies appear to diminish and solving the problem of the infinitely bright night sky. However, the scattering of light leads back to the notion that we can only have knowledge of the universe out to a certain distance. Since the night sky appears quite dark, we know we can only have knowledge of a finite portion of the universe.

Hubble was able to measure the redshift and distance of galaxies out to about a million light years. Redshift is the Doppler effect for light from a receding star or galaxy and says that a receding white light source would appear reddish as the wavelengths of light emitted by that source

[1] The picture in this memo is the best picture we have that has an empirical foundation. There is a great deal of very interesting and provocative theoretical speculations about multiverses and parallel universes, but these have no observational basis.

lengthens in proportion to its recession velocity. Hubble showed the redshift of a galaxy was, on average, linearly dependent on its distance from Earth, implying that the galaxies are all moving away from each other.

If all the galaxies in the universe are moving away from each other, there must have been a time, the start of the universe, when they were all in the same place. That time is just the reciprocal of the Hubble Constant, the proportionality constant between velocity and distance, and works out to be 13.7 billion years. The Cosmic Microwave Background (CMB) is light from the formation of neutral hydrogen 400,000 years after the universe started. Someday, we may observe neutrinos that were emitted two seconds after the start of the universe or gravitational waves from even earlier in the universe. However, our knowledge of the universe will always be confined to a sphere centered on the Earth 13.7 billion light years in radius.

Quite literally, everyone one of us sits at the exact center of their own universe. What lies beyond? The Cosmological Principle assumes the universe is spatially infinite, has the same mass density everywhere and no preferred direction – beyond the shell of our known universe lies more of the same.