Exciting New Developments in the Standard Cosmological Model

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- Title: Analyzing the Large-Scale Bulk Flow using CosmicFlows4: Increasing Tension with the Standard Cosmological Model
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The standard cosmological model is the best way physicists have come up with to explain the state of our universe and everything in it. The standard cosmological model is composed of three main parts: ordinary matter, dark matter, and dark energy [1]. Ordinary matter is all the things that we have come to know and love on our planet; things like protons, electrons, neutrons and more. Dark matter deals with a phenomena that has been observed in some cosmological objects. There exists objects that exert more gravitational force then their mass should generate, thus as a mass of particles that emitted no energy was theorized to compensate, and was later dubbed dark matter. Since it emits no energy, there is no way to observe it, and it just exists to add additional mass to the gravitational force of a cosmological object. Dark energy is used to explain the constant expansion of the universe. The big bang was the inception of the universe, and it is essentially treated as a massive explosion of energy and heat. But from our everyday lives we understand that an explosion should stop expanding eventually. Otherwise, when we turn the gas stove on, our house would burn down, then our city, then our country, then the world. But contrary to our assumptions physicists have observed that the expansion of the universe is actually accelerating. Therefore, they hypothesized that there must be some unseen energy that is adding to the expansion, and they dubbed it dark energy. Now, these may seem like wild guesses, but a lot of time and effort has gone into proving them. Most importantly these hypotheses are supported by measurements of cosmic background radiation. Since the big bang was just a massive explosion, there is remnant energy of the event. This energy exists in the microwave spectrum and allows physicists to compare hypotheses about the early universe with leftover energy from that time; this radiation allowed them to give some basis to these theories.

Bulk flow is the average velocity of all the different objects contained within some volume. This is an important cosmological tool for our understanding of the universe and the standard cosmological model. From the current understanding of the cosmological model, it is assumed that the universe is homogeneous and isotropic [2]. These mean that it essentially looks the same everywhere. Therefore it can be inferred that as the radii of bulk flow calculations get larger, the total bulk flow should start approaching zero. However, it is difficult to measure cosmological velocities and distances to find bulk flow. If someone asked you to measure yourself, that would not be a difficult job. But if someone asked you to measure the distances between galaxies the problem would become much more difficult. This is because of a phenomena called redshift. Redshift is the stretching of waves caused by the expansion of the universe and the Doppler effect.

The Doppler effect deals with waves and frames of reference. Light has wave properties, and so it has some frequency that we can see as a shade of color. However, if something is moving away from you (very quickly) while emitting light, this can change the shade that we see, since the waves are getting stretched out or squeezed together as they are travelling. Since everything is constantly expanding because of the expansion of the universe, the light that is emitted by the object is stretched out because of the Doppler effect. It is possible to measure the redshift of a galaxy, since we have estimates of the colors they should be. Once the redshift is acquired, physicists are able to do a quick and dirty estimation of the distance and velocity of the galaxy by using Hubble's constant, Hubble's constant being a value that approximates the expansion rate of the universe.

This paper [2] discusses the cutting edge strategies used to calculate bulk flow from a new cosmological data set Cosmic-Flows 4. Cosmic-Flows 4 contains estimated distances for 55,000 galaxies and other cosmological objects [3] and provides all the information of how these distances were found. The problem with having so much data is that there are various uncertainties contained within it. Cosmologists still debate which one of two rough approximations of Hubble's constant is more correct; and Hubble's constant is used to find the distances and velocities we care so much about here. The new calculation strategies used in this paper try to alleviate some of the uncertainty by calculating the distances and velocities in a way that allows the uncertainties to follow a Gaussian curve, which is a normal distribution function. The central limit theorem states that as more data is added to a set, the set of uncertainties should have a normal distribution. Since Cosmic-Flows 4 has approximately 55,000 galaxies, [3] the distribution of its uncertainties should have a Gaussian shape. Thus, using new methods to force the uncertainties into a Gaussian shape would imply that the data found in this paper has a better cosmological basis.

After these distances and uncertainties were calculated, the authors of the paper were able to compare the bulk flow of certain radii to the bulk flow that is expected by the standard cosmological model. As stated earlier, the standard model of cosmology assumes that at a large enough radius the universe is homogeneous and isotropic; implying that as the radii gets larger, the bulk flow should get smaller. These estimates and assumptions allow the authors to show that the bulk flow calculated from these measurements is far outside of the range expected from the standard cosmological model, which is a big discovery.

But why does this matter? Since the calculated data is so far removed from the bulk flow calculated from the standard cosmological model, this means that our universe is somehow fundamentally different than we had assumed. The standard model only has a slim 10^{-4} or 10^{-6} [2] probability for the situation we are observing to occur. The paper throws out a few hypothetical situations that would result in the errors seen, however they are all just hypotheses and will require more research in the future. In conclusion, this paper implies that we have a fundamental misunderstanding of our universe and that the standard cosmological model needs to be revamped.

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[1] H. A, The cosmological model: An overview and an outlook, Journal of Physics: Conference Series (2008).

[2] R. Watkins, T. Allen, C. J. Bradford, A. Ramon Jr, A. Walker, H. A. Feldman, R. Cionitti, Y. Al-Shorman, E. Kourkchi, and R. B. Tully, Analysing the large-scale bulk flow using cosmicflows4: increasing tension with the standard cosmological model, Monthly Notices of the Royal Astronomical Society **524**, 1885 (2023).

[3] R. B. Tully, E. Kourkchi, H. M. Courtois, G. S. Anand, J. P. Blakeslee, D. Brout, T. de Jaeger, A. Dupuy, D. Guinet, C. Howlett, *et al.*, Cosmicflows-4, The Astrophysical Journal **944**, 94 (2023).