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Investigating the Dark Sector: Attempting to Resolve the Hubble Tension with a Modified Model of the Universe

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Research Article

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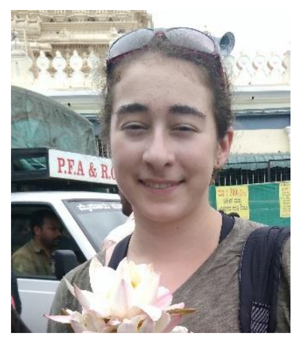
—Emma Clarke

How did the universe come into existence, and what is its fate? How did galaxies, stars, and planets form? What is the universe made of at the most fundamental level? These questions are at the heart of the field of cosmology. My endless fascination with these questions and curiosity about the universe on all scales, from the formation of galaxy superclusters down to the most fundamental constituents of matter, sparked my interest in physics—the branch of science that studies these topics. Cosmology, in particular, encompasses these interests and approaches these questions using mathematics, physics, numerical methods and computation, and astronomical observations.



The author, Emma Clarke

During the summer of 2018, I had the opportunity to exercise my interests in cosmology and particle physics while investigating a cosmological model—a mathematical description of the universe—at the Indian Institute of Astrophysics in Bangalore, India. My project, funded by an International Research Opportunities Program (IROP) award from the University of New Hampshire Hamel Center for Undergraduate Research, focused on a model of the universe in which dark matter has hidden interactions, thus providing insight into the composition and evolution of the universe.

Background

Cosmology is the study of the origin, evolution, and fate of the universe. Cosmology has been a subject of philosophic interest throughout human history, from ancient creation stories, such as the "cosmic egg" universe in the Hindu Vedic tradition, to models such as Aristotle's geocentric universe composed of the elements earth, air, fire, and water, to Copernicus's revolutionary heliocentric model of the solar system. Modern cosmology offers a scientific way of understanding the universe.

The cosmological model describing our universe that is most widely accepted by scientists is the big bang theory, which posits that the universe began with a "big bang" event in which a singularity (an infinitely small and dense point) started expanding in all directions. This theory is accepted because its predictions are well accounted for by observations made by astronomers. Astronomers observe the universe using telescopes that measure light at different frequencies.

Several kinds of observations are consistent with predictions made by big bang cosmology. For example, astronomers have observed that in general the recession velocities of distant galaxies (how fast they are moving away from us) are greater than those of closer galaxies, which implies the expansion of space. Measurements of cosmic microwave background radiation everywhere in the sky and the abundance of light elements (such as hydrogen and helium) are also consistent with predictions made from the big bang theory.

Incorporating Dark Matter and Dark Energy

Cosmologists have improved upon the big bang model by describing it mathematically by a chosen set of parameters called lambda cold dark matter, or ΛCDM, cosmology. The Greek letter lambda (Λ) represents dark energy, a mysterious (i.e., “dark”) repulsive force that opposes gravitation, which is this model’s mathematical explanation for observations that the universe is expanding and that the expansion rate is changing over time. “Cold dark matter” (CDM) is this model’s explanation for gravitational effects observed in large-scale structures, such as galaxies. For example, the pattern of rotational velocities of matter in galaxies can’t be accounted for by the amount of *visible* matter observed. Dark matter differs from ordinary visible matter in that it does not interact via the electromagnetic force. This means that it does not emit or scatter light, making it essentially “dark” to us.

How Fast Is the Universe Expanding?

The ΛCDM model has been very successful in accounting for our observations of the universe, but it does not completely explain all observations. One of the biggest issues in cosmology at present is the discrepancy between different measurements of the present expansion rate of the universe. The parameter that describes this expansion rate is known as the Hubble constant. Named after astronomer Edwin Hubble, who first calculated its value in 1929 (Hubble 1929), the Hubble constant can be determined by direct or indirect methods, but these two methods result in different values. This discrepancy, known as the Hubble tension, provided motivation for my research project.

The direct method, which is the classical way to calculate the value of the Hubble constant, uses measurements of distances to far objects (objects outside our solar system, such as other stars, other galaxies, and extragalactic stars) and the recession velocities associated with these objects (how fast they are moving away from each other). Scientists use observational and mathematical methods to calculate distances to increasingly distant objects. The succession of measurements used is called the “cosmic distance ladder,” because the measurements build upon one another. However, systematic errors are introduced, because the measurements between farther objects rely on measurements of distances to slightly closer objects, and so on. Any error in a measurement to closer objects will affect the accuracy of measurements to farther objects.

Improvements in measuring techniques, technology and equipment, and our understanding of astrophysical processes important to creating the distance ladder have decreased the number of errors and uncertainties in the direct measurement of the Hubble constant. To date, the best direct measurements place the value of the Hubble constant at 73.24±1.74 kilometers per second per megaparsec (km/sec/Mpc) (Riess et al. 2016). A megaparsec is about 3.3 million light-years, where one light-year is the distance light travels in one year.

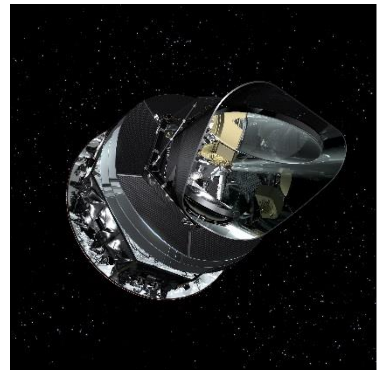


Figure 1. The European Space Agency's Planck satellite. *(Image courtesy of the ESA-AOES Medialab.)*

The value of the Hubble constant can also be determined indirectly through observations of photons (particles of light) traveling to us from when the universe (now 13.8 billion years old) was only 380,000 years old. These ancient remnants of the big bang are referred to as cosmic microwave background (CMB) radiation and are the farthest back in time we can see with light. The European Space Agency's Planck satellite (Figure 1), launched in 2009, scanned the whole sky for CMB photons (Figure 2) and "translated" the signal from the light collected into a temperature.

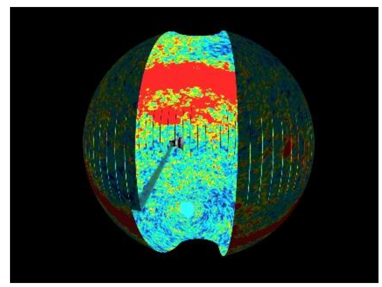


Figure 2. The Planck satellite scans the sky for CMB photons. *(Image by C. Carreau, courtesy of the ESA.)*

The average temperature of the CMB, measured by Planck to higher precision than ever before, is 2.7 Kelvin (corresponding to about -270˚C or -455˚F). Tiny fluctuations in this average temperature are hints of the seeds of structure formation, which evolved into the structures (such as galaxies and galaxy clusters) we observe in the universe today. The Planck satellite provides a detailed map of the tiny fluctuations in microwave frequency radiation in the sky (Figure 3). By fitting a cosmological model, such as ΛCDM, to measurements of the CMB, cosmologists can set constraints, or limits, on the possible values of parameters in the cosmological model, such as the expansion rate of the universe and density of matter in the universe, given the data.

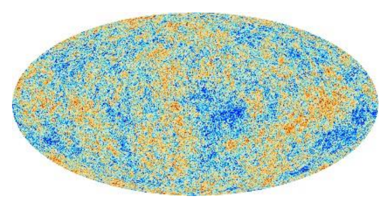


Figure 3. The CMB is a snapshot of the oldest light in our universe, imprinted on the sky when the universe was just 380,000 years old. Different colored dots show tiny variations in temperature that correspond to regions of slightly different densities, representing the seeds of all future structure: the stars and galaxies of today. *(Image courtesy of the CSA and the Planck Collaboration.)*

Applying the standard ΛCDM model to measurements of the CMB from the Planck experiment, the derived value of the Hubble constant is 67.27±0.60 km/sec/Mpc (Planck Collaboration 2018). The discrepancy between this value indirectly inferred from ΛCDM cosmology and the value determined directly by local measurements (73.24±1.74 km/sec/Mpc) is statistically significant (on the order of three standard deviations).

This discrepancy suggests errors in the methods used to calculate the value of the Hubble constant. One possible source is systematic error in distance measurements used in the direct method. Some unknown error may be present in the measuring devices or the distances determined via the cosmic distance ladder, as mentioned above. However, tests indicate that such errors are not likely to account fully for the current discrepancy (Riess et al. 2016).

Although such errors in the direct method are still being investigated and measurements are improved, my research investigated a more interesting possible source of error in the indirect method: the ΛCDM cosmological model. In the indirect method, if the cosmological model is incorrect or incomplete, then the predicted value of the Hubble constant based on CMB measurements will also be inaccurate. Thus, one way to address the discrepancy between the values of the Hubble constant from direct and indirect methods is to modify the cosmological model used in the indirect method. Because I am especially interested in the "dark" sector of the universe—components of the universe that are mysterious to us, such as dark matter—I joined a project that investigated the Hubble tension, the discrepancy in the indirect and direct Hubble constant values, by exploring physics in the dark sector.

Methods

My work on this project began at the Indian Institute of Astrophysics (IIA) in Bangalore, India. Located in the southern state of Karnataka, Bangalore is one of the largest cities in India and the center of India's high-tech industry. The IIA main campus, filled with a variety of trees and other greenery, is an escape from the bustle and noise of the traffic-clogged streets of Bangalore. IIA is a leading center for astrophysics and astronomy research in India, with a graduate program of approximately seventy students from across the country. Some undergraduates study at IIA for summer programs. Although on the other side of the world, IIA has a number of connections with the University of New Hampshire. For example, at the time of my visit, IIA's director was an alumnus of UNH. With these connections and the help of my research adviser at UNH, Jim Ryan, I was able to locate my ideal project at IIA.

With Drs. Subinoy Das and Kanhaiya Pandey, both cosmologists working at IIA, I investigated an extension of the standard ΛCDM model. We modified ΛCDM by adding an extra radiation component in the "dark sector." Here the term *radiation* refers to particles moving "relativistically," i.e., at velocities near the speed of light, such as standard model photons and neutrinos. Adding extra types of particles can cause significant changes to predictions made by the cosmological model about how the universe should look today. If these predictions differ significantly from what we actually observe in the universe, then the model is rejected.

The main campus of the Indian Institute of Astrophysics in Bangalore.

However, if the extra radiation component is "dark" and interacts only with visible matter via gravity, many complications can be minimized. This is why we started by adding only a *dark* radiation component to the standard ΛCDM cosmology. In this modified model, we proposed that the standard cold dark matter (CDM) in ΛCDM decays, and that the decay produces dark radiation. To test our modified model, we conducted numerical simulations and analyses on a supercomputer. The analyses incorporated measurements of the cosmic microwave background from the Planck mission to estimate the value of the Hubble constant.

Numerical simulations are important tools used to make predictions about the universe. A very complex set of equations is required to describe the many possible interactions of all the particles in the universe over billions of years. Because of the complexity, we use computers to do the work of solving the equations and running numerical simulations to test different cosmological models.

To prepare to run the numerical simulation incorporating decaying dark matter, I analyzed equations describing the standard cosmological model, ΛCDM, and then modified these equations to account for the addition of dark matter that decays into dark radiation. I then incorporated my modified equations into existing software often used by theorists for this purpose (Lewis, Challinor, and Lasenby 2000; Lewis and Bridle 2002).

I then began running the code describing the modified cosmological model on a supercomputer. The computer efficiently solves the equations and performs statistical analyses using cosmological data. Specifically, I used cosmic microwave background data from the Planck mission. As described above, cosmic microwave background temperature differences are important indicators of cosmic history. The results are predictions of what we can observe, such as the present value of the Hubble constant.

Results and Discussion

Figure 4 shows how the rate of dark matter decay affects the power spectrum of cosmic microwave background (CMB) radiation. Technically, the temperature power spectrum shows the power of CMB radiation at different length scales of fluctuations. Varying the value of the dark matter decay constant (which we refer to as "α"), which describes how fast dark matter is converted to dark radiation, has several observable effects on CMB. For example, a faster decay of dark matter into dark radiation shifts peaks in the spectra to smaller scales (see Figure 4). Faster decay also increases the suppression of the first and second peaks, and reduces the magnitude of peaks at small scales. In Figure 4, note that α=0 corresponds to the current standard cosmological model with noninteracting dark matter. As α increases, peaks shift to smaller scales, peaks are suppressed (purple arrow), and damping is reduced at small scales.

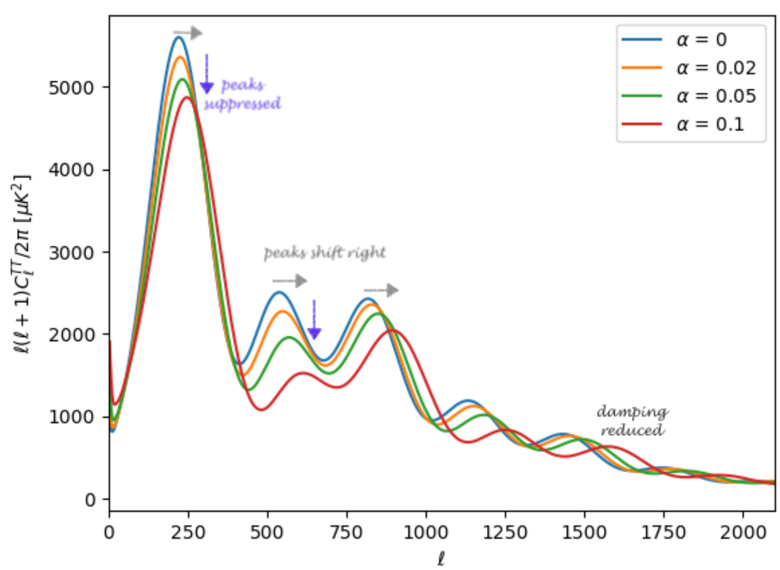


Figure 4. CMB temperature power spectra for several values of dark matter decay constant α.

Figure 5 shows constraints on the Hubble constant in the decaying dark matter model compared with those from the standard ΛCDM model. The most probable value of the Hubble constant is larger in the decaying dark matter model than in the ΛCDM model for the same data set. This demonstrates the decaying dark matter model's potential to at least partially resolve the discrepancies in the values of the Hubble constant determined by direct and indirect methods (i.e., the Hubble tension).

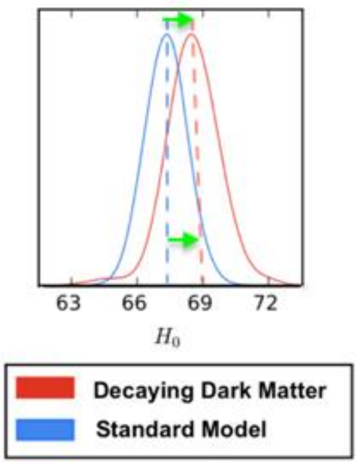


Figure 5. Constraints on the Hubble constant, H_0, in the standard ΛCDM model (blue) compared with the decaying dark matter extension (red) using Planck data released in 2015. The vertical dashed lines mark the most probable values in each model.

The finding that the decaying dark matter model resolves some of the discrepancies in direct and indirect measurements of the Hubble constant gives us reason to further investigate this model. Results of these investigations may help uncover new (particle) physics and be used in attempts to *detect* dark matter experimentally. In my honors thesis, I continued to investigate constraints on the value of the Hubble constant using additional combinations of data sets.

It will also be important to study the effects of the decaying dark matter model on cosmological structure formation. That is, how does the inclusion of decaying dark matter affect our understanding of the distribution of matter in the universe and the formation of structures, such as galaxies?

Additionally, the decaying dark matter model is general and does not specify a particular model for the particle physics phenomena responsible for the decay of the dark matter. This means that these results can apply to many different specific particle physics models related to the dark sector. Our numerical results can be used to constrain parameters in specific particle physics models. These constraints can then help guide particle physicists in the search for specific types of dark matter.

The author demonstrates a headstand at a UNESCO World Heritage Site in Hampi, India.

Concluding Thoughts

The IROP opportunity was an amazing experience in both research and travel. My project at IIA was my first foray into cosmology research, and the experience confirmed my interest in this field. Cosmology is an ideal combination of things I enjoy learning about: the universe, particle physics, general relativity, statistics, and computation.

While in India I made many new friends, mostly with PhD students with whom I lived at the IIA hostel. I also networked with scientists from around the world who came to visit and present their work at IIA. While taking breaks from research and academics, I explored Bangalore and other cities within the Indian state of Karnataka, making many memorable trips. These included a trip to historic Hampi and the UNESCO

World Heritage Site there; a day trip to Mysore, the birthplace of the Ashtanga yoga practice; and a monsoon trek in the Western Ghats mountain range. These invaluable experiences in both research and travel have motivated and prepared me to pursue both in my future career.

I would like to thank Dr. Subinoy Das for mentoring me during my time at IIA and continuing to offer support after my return to UNH. I would also like to thank Dr. Kanhaiya Pandey for providing guidance during this project. Thank you to IIA for hosting me during this project, as well as former IIA director Dr. P. Sreekumar for his part in coordinating this experience and welcoming me to IIA. Thank you to my adviser at UNH, Dr. James Ryan, for helping me set up this wonderful opportunity and supporting my journey toward a career in physics. A special thanks to the students at IIA, who were essential to helping me settle in and making my experience in India amazing. Last but not least, I would like to thank the Hamel Center for Undergraduate Research and my generous donors Frank and Patricia Noonan, Gerald and Jane Campbell Ellsworth, and Dana Hamel for making this opportunity possible.

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Author and Mentor Bios

Emma Clarke is from Rochester, New Hampshire. She is a University of New Hampshire (UNH) Hamel Scholar and is in the University Honors Program. Emma will graduate from UNH in May 2019 with a bachelor of science degree in physics. She relishes exploring and learning new things, which has motivated her to be involved with research since her first year at UNH. After her junior year, she participated in the International Research Opportunities Program. "For a very long time I have been obsessed with particles, statistics, and understanding the evolution of the universe," Emma said. She was able to focus on these topics at the Indian Institute of Astrophysics, where she worked with Dr. Subinoy Das. "I got to work through pencil-and-paper calculations as well as write code, which are two things I really enjoy doing." As a bonus, she got to visit India. Emma has been an editor of *Inquiry* for a couple of years, so she thought it was finally time to write about her own work and become an author. In fall 2019 she will attend Carnegie Mellon University to pursue a PhD in physics and continue working in theoretical and numerical/computational cosmology. This project confirmed for her that she is passionate about this area of research.

James M. Ryan is a professor in the physics department at the University of New Hampshire (UNH). He began working as a research scientist at UNH in 1978 and became a faculty member in 1986. High energy astrophysics and solar physics are his primary research areas. Dr. Ryan aided Emma in her attainment of a fellowship through the International Research Opportunities Program in the summer of 2018. Emma went to the Indian Institute of Astrophysics, which, at the time, was directed by one of Dr. Ryan's first graduate students. "The most interesting part of the experience was having my student work in a professional facility directed by one of my former students," said Dr. Ryan. Cosmology and dark matter are not Dr. Ryan's main areas of research, but he has enjoyed getting more involved in this area while mentoring Emma, especially since her return to the United States. Dr. Ryan believes that learning to write for *Inquiry*'s broader audience is useful for students in his discipline. To him, communication is an essential skill in any area of research or academic study.

Subinoy Das works at the Indian Institute of Astrophysics (IIA) as a reader. Dr. Das's areas of specialization are cosmology and particle physics. Emma, looking for a site for her International Research Opportunity Program (IROP) research, contacted him through a former University of New Hampshire (UNH) student who also worked at IIA. Dr. Das helped Emma design and propose her research project and guided her through reading many articles and lecture notes in preparation for her research during the summer of 2018. Dr. Das has mentored other undergraduates, but Emma is the first UNH mentee and *Inquiry* author he has worked with.