Dark Matter and Dark Energy

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For *The Routledge Companion to Philosophy of Physics*
Edited by Eleanor Knox and Alistair Wilson
Submitted April 2017

Introduction

The current best current cosmological model poses an intriguing puzzle. According to this model, a vast majority of the mass-energy content of our universe is currently unobservable, except through indirect means. All of the observable luminous matter—including stars, galaxies, interstellar dust and gas—makes up only a small fraction of the mass-energy in the universe. While this sounds like an incredible claim, it is almost universally accepted by astrophysicists and cosmologists.

Contemporary understanding of the universe is based fundamentally on astronomical observations and the current best theory of gravity. From observations, cosmologists have proposed a model for the history and structure of the universe. This model is commonly referred to as the concordance, or "Standard Model" of cosmology, and includes elements such as big bang theory, inflation, nucleosynthesis, and reionization.[1] This Standard Model is considered to be in agreement will all available observational data. It originates from our current best theory of gravity, general relativity (GR), as described by Einstein's Field Equations (see section 3 of this volume for discussions of GR). By accounting for various initial assumptions and observational evidence, the Field Equations become the Friedmann–Lemaître–Robertson–Walker (FLRW) models.[2] More specifically, the Lambda Cold Dark Matter (ΛCDM) model is the current best parameterization of one of the FLRW models to describe the large-scale structure formation in the universe. None of the parameter values in the model are fixed by the theory; instead their values are determined based our observational evidence. According to this model, the total mass–energy of the universe contains only about 4% baryonic matter (ordinary visible matter

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[1] Cosmologists use "concordance model" to refer to the currently accepted cosmological model, the Standard Model of cosmology with the specified contributions of different types of matter that are in agreement with current best observations. This Standard Model of cosmology is distinct from the Standard Model of partial physics.

[2] The cosmology literature often refers to FLRW models as a class of *exact solutions* (rather than class of models) to Einstein's field equations specified by the FLRW metric. That is, any specification of parameter values, such as curvature (Ω_k) and mass-energy density (Ω_m), which is consistent with the field equations, is referred to as a solution to the model. In this context, the ΛCDM model is a parameterization of the perturbed FLRW models. The reader should understand the FLRW solution as a set of models; any specification of parameters yields a particular model, such as the ΛCDM model. For a detailed discussion of the construction of the ΛCDM model from the FLRW models and Einstein's Field Equations, including its initial assumptions, observational evidence, and tests, see Hamilton (2014), Smeenk (2013).

such as stars and gas). The rest of the universe is made up of 24% dark matter and 72% dark energy.

These new mysterious entities, dark matter (DM) and dark energy (DE), are accepted by most cosmologists as a well-established part of our universe (Hinshaw 2009). However, some see the inclusion of these strange elements to be an *ad hoc* addition to the model in order to ensure fit with the empirical data (Lopez-Corredoira 2014; 2017). Why should the mass directly observed in stars and gas account for such a small part of the universe's content? From observations, cosmologists have seemed to infer the existence of DM and DE, yet they know very little about their nature since they can only be observed indirectly.

The logical structure of these observational inferences are of great concern both to cosmologists and to philosophers. If the Standard Model of cosmology is correct, and there is this strange mass and energy, where is it, and what is its nature? How can we be confident DM and DE exist, and were not simply invented to ensure observations are in agreement with GR? Should one take DM and DE as an indicator that GR is wrong? Given that belief in the existence of DM and DE stems from empirical observations, I begin with a review of the observational evidence. Much of the philosophical debate takes issue with this empirical evidence and what one is warranted to conclude regarding the nature of DM and DE. I then examine some of the other philosophical issues surrounding the discovery of DM and DE, including underdetermination of theory, theory change & theory choice, and role of computer simulations in modern astrophysics and cosmology.

Observational Evidence

Claims about the existence of DM and DE are primarily motivated by observational evidence. In astrophysics and cosmology, there are two relevant notions of observational evidence: direct and indirect (see Anderl in this volume for further discussion of the nature of evidence in astrophysics more generally). There is direct observational evidence for many kinds of entities—stars and galaxies can be seen in optical wavelengths using telescopes, and x-ray telescopes can be used to directly observe interstellar gas via its emissions. The devices used to make these observations rely for their operation on physical theories (such as electromagnetic theory) that are remote from the theory being tested (that is, the theory of gravity). In the context of the search for DM and DE, what would count as direct evidence would be the detection of DM or DE particles (e.g., using something like a photodetector), or testing for them through a means independent from GR. However, thus far there has only been indirect observational evidence. Indirect observations involve predicting the interactions of the entity in question with other systems by using the relevant physical theory, and directly observing the effects of those interactions. This inferential process relies on a more substantive assumption of the truth of the theory being tested, therefore confidence in the evidence depends on the degree of confidence in the underlying theory. Indirect evidence is often considered to be secondary, or less powerful, when compared to direct evidence. Thus far however, there has been no direct detection of DM and DE; their existence is inferred only from indirect observations. Nevertheless, most cosmologists consider there to be enough indirect evidence to establish that DM and DE exist.[3]

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[3] See Spekel (2015), Matarrese (2011), and Gates (2010).

Observational Evidence for Dark Matter

DM is currently unobservable at any electromagnetic wavelength, and has only been detected via its gravitational interactions (hence, "dark" matter). There are five observations that are considered to be the strongest indicators of the existence of DM.[4]

Beginning with observations of smaller scale phenomena, one line of evidence comes from observations of single disc galaxies, and their rotation curves. A galaxy rotation curve is a plot of the orbital speeds of stars or gas in a galaxy against their radial distance from that galaxy's center. The amount of matter in a given galaxy determines the curve for rotational speed as a function of the distance from the galactic center. In calculating a theoretically expected rotation curve (using GR), astronomers initially based their calculations off the visible mass—stars and gas—in a galaxy. They expected the velocity to decrease when moving from the center of mass of a galaxy to its outer edges, with the outer edges of the galaxies having a slower rotation, since not as much mass is present. However, in the 1960s when astronomers began to collect and plot actual observational data, they found it did not match their calculated expected curve. The galaxies in fact had a relatively constant, high velocity rotation curve to their outer edges where few stars are visible. For galaxies to rotate in the way the observations indicated (and maintain consistency with GR), there must be significantly more mass in the outer edges of galaxy than the mass they were able to see. To account for this discrepancy between observations and theory, it was postulated that there must be a halo of DM surrounding every disc galaxy.

This mass discrepancy is also present in larger structures in the universe, such as clusters of hundreds of galaxies that are bound together gravitationally. While studying the Coma Cluster in 1933, Fritz Zwicky wanted to determine its gravitational mass using the virial theorem, an equation relating the average kinetic energy of a system to its total potential energy. He then compared the inferred gravitational mass to the mass of the luminous matter in the galaxies. Based on his calculations however, there was not enough luminous matter present to hold the Coma Cluster together gravitationally. He concluded that there must be more mass there that he could not see holding the galaxy together (Zwicky 1933). On even larger scales still, such as the large-scale structure formation surveys of the Sloan Digital Sky Survey, astronomers observe structural patterns that could not be held together gravitationally (at least according to GR) by the amount of visible matter alone. The observed structure formations also support DM being "cold" (i.e. slow with respect to the speed of light), rather than "hot" or "warm", as only CDM obtains structural properties in agreement with the observations.[5]

In addition to these three structural lines of evidence, a fourth, and perhaps most compelling, line of evidence for DM comes from 2006 observations of the Bullet Cluster (Clowe et al. 2006). The Bullet Cluster is actually two clusters of galaxies that have undergone a collision. In between galaxies in galaxy clusters, there is a vast amount of gas. During the collision, the gas particles in the clusters heat up from the collision, and cause an increase

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[4] See Trimble (1987) for complete history of the observational evidence and constraints on DM, as well as de Swart (2017).

[5] See Bertone et al. 2005 for further discussion.

brightness in x-ray emissions. From the observations of x-ray emissions, astronomers can determine where the gas is located, as well as how energetic it is. However, the visible matter in the galaxies in the clusters are not significantly affected by the collision, and essentially pass through, forming in two separated regions (with the gas in between).

Astronomers can map the matter distribution in this collision through the effects of gravitational lensing.[6] The matter in the Bullet Cluster distorts background galaxy images, and by measuring that distortion astronomers can measure the location of the cluster's mass. Given that the gas accounts for the vast majority of the baryonic (visible) matter, the lensing would be expected to follow the gas. However, the gravitational lensing effects are strongest in two regions near the visible galaxies. This evidence that most of the matter in the cluster is near the galaxies. Since DM is considered to interact even less frequently than baryonic matter, during the collision the DM from one cluster would pass by the other objects in the cluster. By including DM in the calculations, astronomers obtain the mass in the right distribution to predict the gravitational lensing they see in the observations.[7] The dynamical interaction found in the bullet cluster is some of the clearest evidence that DM of some form exists (Gates 2010).

The final line of evidence comes from the observations of the Cosmic Microwave Background (CMB), the electromagnetic radiation left over from the epoch of recombination. The observation of the CMB is a landmark discovery in cosmology as it provides evidence in favor of many features including a Big Bang origin of the universe, and a very nearly flat geometry of the universe. The observed patterns in the CMB also offer evidence for the existence of DM. Fluctuations in the CMB are typically explained as the result of two competing forces acting on matter. The first is an attractive gravitational force, and the second is an outward pressure caused by photons. This competition results in variations, or oscillations, of dense regions in the CMB. These oscillations can be presented in the form of a power spectrum of the CMB. The peaks in the power spectrum in particular are sensitive to the matter density of the universe, and are consistent with predictions that include DM, as well as those that do not. Data from the COBE (Cosmic Background Explorer), WMAP (Wilkinson Microwave Anisotropy Probe), and Planck satellite measured the CMB power spectrum through the first peak oscillation, and suggested that the measured peaks match predications made with DM included in the model (Natarajan 2016).

Observational Evidence for Dark Energy

Cosmologists have inferred from the empirical data that the universe is pervaded by a relativistic energy density that carries negative pressure, driving the expansion of the universe at an accelerated rate. This energy field is smoothly distributed (in that it is everywhere throughout the universe) and persistent (in that the density remains approximately constant as the universe expands). It is referred to as "energy" because energy fields exhibit a similar nature (i.e., smoothly distributed and persistent). It is "dark" in that it is not directly detectable; rather, its

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[6] It is worth noting that gravitational lensing is a consequence of GR, and thus contributes to the indirect nature of the resulting evidence for DM.

[7] This observation also is in agreement with DM being a weakly interacting massive particle (WIMP) rather than a massive astrophysical compact halo object (MACHO).

existence has been inferred through indirect observational means. DE appears in the Standard Model as the cosmological constant, Λ, representing the value of the energy density of the vacuum of space.[8]

Observations from CMB are taken to be a line of evidence for the existence of DE as well as being evidence for DM. Cosmologists use the CMB to measure the shape of the universe (flat, no curvature; open, negative curvature; or closed, positive curvature), because the shape affects the magnitude of the slight variations seen in the CMB. By measuring these variations, they concluded that the universe is very nearly flat. However, the exact shape of the universe depends on the total mass-energy content; to have a flat universe, the mass-energy density of the universe must be equal to the critical density. Mass-energy content calculations based on baryonic matter made up only a small portion of the mass-energy needed to have a flat universe. Even when estimates of DM are included, in order for observations to match what is seen in the CMB, there is still about 72% of the required mass-energy unaccounted for.

The second key line of evidence for DE comes from observations of Type Ia supernovae (SNIa). While cosmologists had determined the universe is expanding (Hubble 1929; Freeman 2001), 1998 observations of these supernovae led to claims that the expansion is taking place at an accelerated rate (Riess et al 1998). SNIa begin as white dwarf stars and accrete matter until they reach the Chandrasekhar limit (a mass 1.4 times the mass of the Sun) and explode. Since the Chandrasekhar limit is the same value everywhere in the universe, the supernovae explode with roughly the same amount of energy, and therefore have similar luminosities.[9] Distant SNIa were investigated by cosmologists because of their relationship between intrinsic luminosity and the length of time it takes for a supernova's brightness to decline after reaching peak luminosity. By measuring the brightness of SNIa, one can determine how far away the object is. From the relationship between the distance to an object and its redshift, one can determine how fast an object is receding. Observations showed that the distant supernovae were dimmer than expected, which meant that the supernovae were actually further away than what would be predicted if the universe were expanding at a constant rate.[10] This led most cosmologists to conclude that the luminosity distance is dominated at low redshift by an accelerating component, and in order to account for the observed acceleration of the expansion rate of the universe, cosmologists appealed to DE having the property of a strong negative pressure (acting repulsively).

Finally, the third line of evidence comes from baryon acoustic oscillations (BAO), very large scale oscillations in the density of baryonic matter, whose magnitude helps measure the expansion history of the universe. The overdensities in the distribution of matter in the universe occur at regular intervals, and therefore provide a means to measure distance. The BAO measurements allow for comparison between the observation of current acoustic waves to that of

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[8] The cosmological constant, Λ was originally included by Einstein in his field equations to maintain a static universe (however later considered a mistake). Contemporary cosmology has reintroduced the idea of the cosmological constant, now with a positive value, to account for the observed accelerated expansion of the universe.

[9] These astronomical objects with a known absolute magnitude are called "standard candles".

[10] In fact, these SNIa observations suggested that the expansion of the universe has been accelerating since around a redshift of $z \sim 0.5$.

the acoustic waves at the time of recombination from the CMB. Drawing on Doppler effect, BAO observations provide another way to measure distance between objects.[11] These observations also point to the universe expanding at an accelerated rate (Seo 2003).

While these are considered the cornerstone observations in support of DE, recent work in cosmology attempts to find other means by which to support the existence of DE. The 2011 WiggleZ survey from the Australian Astronomical Observatory (Blake et al. 2011) attempts to measure galaxy redshifts, and analyze the galaxy distributions in order to learn more about the nature of DM, as well as support the hypothesis of the universe's accelerated expansion independently of the SNIa data. Another approach is to look for late-time Integrated Sachs–Wolfe effect (ISW) in the CMB, as it would be a direct signal of DE in a flat universe (Crittenden & Turok 1995). Others still are attempting to test evidence of DE through observational Hubble constant data (Ma & Zhang 2011).

Realism about Dark Matter and Dark Energy

Given the nature of the observational evidence described above, it does not seem unreasonable for astronomers to infer the existence of DM. The observations seem to indicate that there is something that behaves like baryonic matter by interacting gravitationally, yet is not directly observable. The mystery, then, is determining DM's basic physical properties. In principle, it is not necessary that DM be composed of some heretofore unknown kind of matter—it could be partially composed of standard baryonic matter, which for some reason cannot be observed. However, there are strong reasons to believe that DM is composed of a new fundamental particle since otherwise the laws governing behavior of baryonic matter would seemingly have to be complex and disunified. Candidates include axions, sterile neutrinos, WIMPs, and self-interacting dark matter.[12] While the exact constitution and properties of DM are undetermined, most astronomers are nonetheless committed to its existence. This raises classical philosophical questions connected to scientific realism, and whether this positive epistemic attitude towards DM is justified.

Scientific realism is a commitment to the truth or approximate truth of scientific theories, and the entities posited by the theory. Scientific realism with respect to DM amounts to the belief that DM is *as real* as the stars and gas we can observe. However, no matter how much observational techniques improve, DM may turn out to never be directly observed. Realists do not tie their belief in the existence of a theoretical entity to its observability. Antirealists, on the other hand, are skeptical of the existence of DM, considering it to be an important part of the ΛCDM theoretical understanding of our observations, without any further metaphysical commitment. In general, antirealists do not hold realist commitments to entities they cannot directly observe. DM may pose a special problem for realists, since they are committed to the existence of an unobservable entity that makes up a significant portion of the universe's matter content (Shapere 1993).

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[11] Given their capacity to measure distances, BAO act as "standard rulers", see Bassett & Hlozek 2010.

[12] See Spergel (2000); and Bertone et al (2004) for review of these candidates, their evidence, and constraints

An intermediary position is *entity realism* (Cartwright 1983 & 1989; Hacking 1983; 1989). On this view, we should be realists about entities about which we have significant causal knowledge, for example, those things that can be routinely manipulated in the laboratory. This has the benefit of allowing one to be a realist about entities such as subatomic particles, without committing to realism about DM, at least until more is known regarding its constitution and properties. Since we know little about DM's causal properties beyond its gravitational interaction, it is not yet the kind of entity that we could, hypothetically, reliably manipulate in the laboratory, and therefore falls outside the scope of entity realism.

The same issues regarding scientific realism apply to DE. However, the nature of DE is even more mysterious. While DE is posited as an explanation for the evidence that the universe is expanding at an accelerated rate, we know little else about its composition and properties. DE is represented in the Standard Model by the cosmological constant, Λ. However, there are issues connected to determining the value of this constant, as well as specifying what physical feature, entity, or force the constant represents, which are addressed in the next section.

The Cosmological Constant Problem

Minimally, the empirical evidence seems to require that there be some element included in the FLRW equation to account for the accelerated expansion of the universe. This element is a non-zero Λ, or cosmological constant term, which is taken to represent DE. There are two major research goals surrounding DE. One aims to refine the value of the DE constant, and obtain the most precise equation to describe the data. The other attempts to answer the question of what the nature of DE is such that it *causes* the acceleration.

The main candidate for how to understand DE is as a true cosmological constant, or a vacuum energy—a fixed amount of energy associated to every region of space, which remains constant in time (i.e., does not dilute with expansion, and so is unlike other types of energy and matter). The vacuum energy is perfectly smooth and constant throughout the universe, and has a pressure and stress-energy density such that it has a negative value in the equation. On this view, the cosmological constant Λ is considered to represent this vacuum energy in the FLRW models.[13] Another candidate option for understanding DE is as ‘‘quintessence’’, a scalar field that fills the universe, and changes very slowly as time passes. On the quintessence view, the universe is filled with a new kind of dynamical energy fluid or field, leading to the accelerated expansion effects. In principle, quintessence does not directly rely on the FLRW model, however it has been primarily studied within this context.[14] On both these models, DE has a uniform, extremely low density everywhere in space. Therefore, it may be possible to directly detect DE, since it would be present in local regions of the universe.

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[13] When Einstein first introduced Λ, he didn't think of it as "energy". Rather, he thought of it as a modification of the way spacetime curvature interacted with energy. However, this turns out to be the same thing as vacuum energy. For a detailed history of the cosmological constant in modern physics, see Earman (2001).

[14] See Uzan 2010 for extended discussion of DE candidates.

The value of the cosmological constant was first measured in 1998 through the supernovae data described above, indicating Λ to be very small. Some physicists note the similarity between the Λ vacuum energy and the vacuum energy predicted by quantum field theory (QFT). However, this small value of Λ conflicts with the value of the vacuum energy predicted by QFT (see Wallace (this volume) section 10.2, for more details). As a result, the disagreement between the cosmological constant vacuum energy density and the predictions suggested by QFT (zero-point energy) may be problematic. This is referred to as the Cosmological Constant Problem (CCP). In light of the empirical evidence for a positive cosmological constant, CCP concerns understanding why the cosmological constant is so small relative to the vacuum energy density calculated in QFT, but not exactly zero, as indicated by the accelerating expansion (Smeenk 2014).[15]

Philosophers have attempted to contribute to solving the CCP by analyzing the different possible interpretations of Λ consistent with the evidence for it. Earman (2003) argues that much of the problem with Λ stems from the fact that most cosmologists are strongly committed to interpreting the empirical data within the context of the FLRW cosmological models, which requires either a positive cosmological constant ($\Lambda > 0$) or else something standing in for a positive Λ mimicking this behavior (such as quintessence). As such, there are two senses in which the cosmological constant can be a constant. While different interpretations of the Λ may be empirically indistinguishable, the theories that embody different Λ may not be. Another approach examines the relations between different fundamental physical theories (GR and QFT). Rugh and Zinkernagel (2002) consider the way in which a commitment to a physically real vacuum energy may influence the way in which the problem is defined. Others attempt to understand the assumptions at play in different proposals to address the CCP. Nobbenhuis (2006) distinguishes three different ways to understand the CCP: as a question about 1) why is the cosmological constant so small, 2) why is it not exactly equal to zero, and 3) why is its energy density today of the same order of magnitude as the matter energy density. These questions offer a schema in which to categorize proposals in hopes of gaining insight to advantages or drawbacks to different approaches to solve the problems. Bianchi & Rovelli (2010) on the other hand, find the arguments that the nature of DE is mysterious to be unconvincing, or ill-founded. They take the phenomena of an accelerated expanding universe to be clearly predicted and well-described by GR. They also argue that identifying the cosmological constant with the QFT vacuum energy density is a mistake.

Underdetermination of Theory by Evidence

Underdetermination of theory by evidence is the problem that, for any body of evidence supporting a theory, there will be other theories that are logically compatible with the same body of evidence. As such, there may not be good empirical grounds for choosing one theory over another. In order to select one theory over another, other considerations need to be brought in—

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[15] Prior to the 1998 supernovae observations, there was a different version of the CCP, now called the "old" CCP. Namely, why isn't there a cancellation mechanism that leads to $\Lambda=0$? See Weinberg 1988 for detailed discussion of the old CCP.

such as simplicity or explanatory power.[16] As a result of the limitations of empirical observations, the correct cosmological model of our universe can be considered to be underdetermined by the evidence as well. Certain extra-theoretic considerations, such as consistency with our best theory of gravity, led to the inclusion of the previously unknown entities DM and DE in the FLRW models. In order to have a model consistent with empirical data, previously unknown entities like DM and DE were posited. However, some philosophers argue that the inclusion of DM and DE in the FLRW models is too *ad hoc* a theoretical posit, which indicates that one should favor a different theory of gravity. The question is, are cosmologists warranted in preferring general relativity over rival gravitation theories?

Vanderburgh (2003) argues that DM in fact highlights a weakness of GR. Thus far, DM has been indirectly detected by its gravitational effects. However, in order to claim its detection, one needs to assume a theory of gravity. Evaluating the empirical adequacy of a gravitational theory (on scales of a single galaxy or larger) the mass disruption in the dynamical system must be known. However, because of the astrophysical dynamical discrepancy (i.e., our observational data of single galaxy rotation curves not matching our original expected, non-DM, rotation curve), we do not know with the actual mass distribution. In order for astronomers to infer that mass distribution from observations, they must already assume some gravitational law. (i.e., if assuming GR, then the only way to obtain the observed dynamics is that there must be other unobserved matter). However, that law of gravity cannot legitimately be assumed, as which gravitational law ought to be taken to apply is the very issue under consideration. This is referred to as the "dark matter double bind". On these larger scales there is not currently, and perhaps cannot be, an empirical basis on which to decide among rival gravitational theories. The evidential status of GR is thus, according to Vanderburgh, considerably weaker than is usually supposed. The only way to pick between competing theories of gravity is by appeal to methodological criteria of theory choice. Even when considering the other lines of evidence (rotation curves, velocity dispersions, X-ray temperatures, and gravitational lensing), Vanderburgh (2005) argues that, while the different methods give roughly agreeing results, they still measure the mass discrepancy by assuming GR applies to the systems.

Kosso (2013), on the other hand, argues that the Bullet Cluster will not fall prey to the dark matter double bind, since gravitational lensing is a direct consequence of Einstein's Equivalence Principle (EEP); a complete gravitational theory is not needed in order to derive the gravitational lensing effects. Thus, though it may still be indirect evidence, the gravitational lensing seen in the Bullet Cluster can offer an independent reason to believe that DM exists. Sus (2014), however, argues that on a careful analysis of the empirical evidence, the EEP alone cannot support the claim that gravitational lensing in the Bullet Cluster constitutes evidence for DM. Likewise, Vanderburgh (2014) argues that even in the case of the Bullet Cluster, there is still the need to assume GR (or some theory of gravity) in order to infer the precise mass distributions from the observations.

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[16] Issues related to the underdetermination of general relativity include the underdetermination of global properties of spacetime geometry (Manchak 2009; 2011) and the role of the cosmological principle in deriving general relativity (Ellis 2007; Beisbart 2009; Butterfield 2012).

There are alternative gravitational theories that aim to account for the empirical evidence without the introduction of DM and DE. One of these views proposes modifying Newtonian dynamics so that the missing mass is not required to account for the evidence. However, the Modified Newtonian Dynamics (MOND) approach is viewed as contentious, given many astrophysicists consider GR to be well established as the theory of gravity (Dodelson 2011). They therefore regard the adoption of MOND as unjustified. Yet the advocates of MOND claim that their model is as good (if not better) as ΛCDM for describing observed galaxy dynamics (Milgrom 1983; Famaey & McGaugh 2013; McGaugh 2014). By and large, the astrophysical community has favored maintaining GR and ΛCDM, rather than abandoning them for alternatives.

Theory Change and Theory Choice

Given the underdetermination problem and existence of possible alternatives to ΛCDM, why do astrophysicists accept the model that posits DM and DE? One way of understanding this is analyze the issue by examining the role theory choice plays in contemporary astrophysics. Regardless of underdetermination, in order for research to proceed a theory must be selected. A solution, then, might consist in focusing on how each theory is empirically supported, which may resolve the appearance of empirical equivalence. This can be achieved through understanding the broader theoretical framework within each theory is embedded, allowing analysis of how each receives indirect empirical support (Massimi and Peacock 2015). Additionally, it may be useful to compare this case of DM and DE to other historical cases, such as the irregularity of Uranus' orbit or precession of Mercury's perihelion to determine what lessons can be learned about theory change and theory choice (Lahav & Massimi 2014).

Alternatively, the conflict between ΛCDM and MOND might be best understood as two incommensurate paradigms, indicative of an approach to a Kuhnian scientific crisis, and a matter of acquiring enough anomalies to induce a paradigm shift (McGaugh 2014). In the meantime, we might appeal to seemingly objective criteria of theory choice (accuracy, consistency, scope, simplicity, and fruitfulness) (Kuhn 1977). However, these criteria are criticized as being imprecise and in conflict with each other. They are not sufficient to determine theory choice, and depend on sociological considerations. Regardless, in order to continue to conduct research, the scientific community may see the theory as the best choice to make right now. This has led some philosophers and physicists (Ruphie 2011; López-Corredoira 2014) to offer a social hypothesis as the real justification for the prevalent use of the ΛCDM model in cosmology. It is not that the ΛCDM model is empirically well justified. Rather, cosmologists favor it due to the sheer amount of time and allocation resources (both financial and intellectual) that have already been invested.

Acceptance of ΛCDM can also depend on the characterization of empirical success. For instance, the Newtonian ideal of empirical success of a theory involves agreeing measurements from diverse phenomena. Harper (2012) argues that this kind of reasoning is appealed to in support of DE. By tracing these dependences, one can assess the extent to which different measurements depend on independent assumptions. The success of a theory, then, is related to the degree to which a variety of independent lines of evidence constrain the parameters (such quantity and distribution of DM and DE) in the theory. In the case of DE, there is a convergence of accurate measurements of parameters by diverse phenomena. Given the variety in observations and assumptions behind those observations, there is surer footing regarding DE not as an ad hoc auxiliary hypothesis, but rather as an accepted background assumption.

In the background of these discussions is the issue of testability of scientific theories. While philosophers have raised numerous concerns regarding Popperian falsification criterion, falsifiability is taken very seriously as a good criterion for scientific research by a majority of cosmologists. As such, there is concern regarding the testability of the ΛCDM model, and if tests aim at confirmation or falsification.[17] Rather than thinking of DM and DE as a response to falsifying observations of a gravitational theory, cosmologists interpret the observations as the discovery of DM and DE. As such, Popperian "conventionalist stratagems" may be at play in favoring the ΛCDM model (Merritt 2017). Alternatively, while testability may be preferred, it may not be required as it may not be feasible in practice given the lack of experimental access and large scales of cosmology. As such, there may be a need for a shift in the methodological and accepted epistemic standards (Kragh 2014).

Models and Computer Simulations

Models and computer simulations serve as investigative tools to provide further insight into the nature of DM and DE. As computational power has increased, cosmologists have produced complex simulations of galaxy collisions, cluster interactions, and of the structural history of the entire universe. These models and simulations play a critical role in the justificatory reasoning process in astrophysics. Yet their use has also led to three standout problems for ΛCDM, particularly in the context of DM. First, the Millennium Run simulations quite closely match the observed large scale structure of the universe, which is taken to support for the ΛCDM model (Boylan-Kolchin et al. 2009). However, there are cases where the simulations and observations disagree. MOND-based computer simulations have highlighted a discrepancy between the ΛCDM-predicted structure properties of galaxies, and actual astronomical observations. This discrepancy is between the observed DM density profiles of low-mass galaxies, and the density profiles predicted by ΛCDM-based cosmological N-body simulations (referred to as the Cusp/Core Problem) (Weinberg et al. 2015).

While some of the DM is accounted for in DM halos surrounding galaxies, this is only accounts for a portion if it. The second problem is referred to as the missing satellites problem. The computer simulations based on cold DM models predict large numbers of subhalos (~100-1000 for a galaxy the size of our Milky Way). However, the Milky Way only has 23 known satellites. If the models are correct, there are a significant number of satellites yet to be observed. One possibility is that the galaxies are undetectable because they are composed entirely of DM. Analyzing this in the context of modeling and simulation, one can assess the problem in terms of whether the models offer robust predictions. Some cosmologists cast the problem in these terms (Bullock 2013), and drawing on the philosophical work of robustness analysis may be beneficial. Finally, ΛCDM simulations predict not only how many galaxies there should be, but also their masses. Even if some of the missing satellites are composed entirely of DM, the model still predicts satellites that are simply too massive to lack any visible matter, and "too big to fail" to form.

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[17] See López-Corredoira (2017) for details on the tests for and problems of the ΛCDM Model.

There is a question of how to understand this conflict between observations, and computer simulations. By their very nature, models and computer simulations are necessarily incomplete representations—they contain idealizations, approximations, and simplify the features in the system being modeled. Given this, there is a need to understand what justifies their use to make claims about the nature of the real systems (Jacquart 2016). Given their critical role, there is much work to be done examining the role of computer simulations in modern methodology of astrophysics, determining what we can and cannot learn from them, as well as how we validate or verify our cosmological models.

Acknowledgements

I thank Lucas Dunlap for helpful comments on an earlier draft of this essay. This work was supported by the National Science Foundation award no. SES-1557138.

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