Are We Entering a Paradigm Shift for Dark Matter?

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Abstract

While the ΛCDM framework has been incredibly successful for modern cosmology, it requires the admission of two mysterious substances as a part of the paradigm, dark energy and dark matter. Although this framework adequately explains most of the large-scale properties of the Universe (i.e., existence and structure of the CMB, the large-scale structure of galaxies, the abundances of light elements and the accelerating expansion), it has failed to make significant predictions on smaller scale features such as the kinematics of galaxies and their formation. In particular, the rotation curves of disk galaxies (the original observational discovery of dark matter) are better represented by non-Newtonian models of gravity that challenge our understanding of motion in the low acceleration realm (much as general relativity provided an extension of gravity into the high acceleration realm e.g., blackholes). The tension between current cold dark matter scenarios and proposed new formulations of gravity in the low energy regime suggests an upcoming paradigm shift in cosmology. And, if history is a guide, observations will lead the way.

1. Introduction

It has often be argued that science moves forward through a series of leaps or revolutions (Kuhn 1962). An existing framework, or paradigm, which had been successful in the past in explaining a great deal of natural phenomenon, fails to explain some new observations, or is not providing a path forward in the face of new observations. The existing framework needs to be either modified to account for new observations or simply abandoned (although rarely is the process this simple). A new framework would then describe both past and new observations and, at the same time, lead to new insight and understanding of underlying processes. Sometimes new
paradigms even lead to new physics. These leaps forward are often referred to as paradigm shifts (Cohen 2015).

There have been numerous paradigm shifts with respect to motion (kinematics) in the history of astronomy. Based on ideas of the early Greeks, Ptolemy constructed a mechanical model of the Solar System using perfect circles. This was replaced by the Copernicus/Kepler formulation of heliocentric planetary motion, which in turn led to Newton and the introduction of gravity as the dynamic cause of celestial motion. Later Einstein, who introduced relativity to deal with motion in the high energy realm, led to a greater understanding of exotic astronomical systems, such as neutron stars and blackholes. The introduction of dark matter as the dominant source of gravity on galactic scales has extended this paradigm to cosmological realms. And, for over thirty years, the cold dark matter (CDM) paradigm has ruled our framework of cosmology and galaxy formation.

Here at the beginning of the 21st century, recent discoveries concerning the kinematics of rotating galaxies has drawn into question many of the basic assumptions about dark matter. For example, rotation curves of spiral galaxies strongly indicate a coupling between baryons and dark matter (Lelli, McGaugh & Schombert 2016), which is confusing as dark matter was originally proposed to only interact with matter by gravity, the weakest of the fundamental forces. The discovery of these new kinematic laws (see below) in the low energy, low acceleration region around galaxies may signal an end to the cold dark matter (CDM) paradigm but promises new physics on the horizon, if history is any guide.

It is deeply concerning that CDM models and simulations continue to be augmented, in an ad-hoc fashion, to reproduce new observations to the point of becoming non-falsifiable as a scientific theory. This type of behavior in our literature is one of the signals that we are at a crossroad for a new paradigm that seriously considers non-Newtonian aspects to motion on galactic scales. To better illuminate this issue of an ongoing paradigm shift, we consider the classical, historical story of one framework overtaking another, the geocentric to heliocentric paradigm shift, and compare this to the current CDM paradigm. This tale has the advantage of being extremely well studied by historians of science as well as being extensively taught to the younger members of the astronomical community.
2. The Copernican Paradigm Shift Lesson

The classic example of a paradigm shift is the transformation in medieval astronomy from the geocentric worldview to the heliocentric worldview. This shift, from the Ptolemaic to Copernican framework, is taught to astronomy students at all levels, and is drilled into the research community as the baseline example of how science works to progress forward in terms of understanding how the Universe operates. They are many nuances that have been discovered by historians of science concerning the heliocentric paradigm shift, but what we teach, regardless of complete historical accuracy, is along the following lines.

The early Greek philosopher’s were strongly influenced by the power of mathematics in understanding Nature, particularly geometry. The schools of thought surrounding Plato insisted on developing a cosmological model focused on perfect circles of motion for the heavens. This model connected the four primary elements (Air, Fire, Earth and Water) surrounding the Earth with the seven planetary sphere’s resulted in a framework where there was linear motion below the Moon’s sphere (resulting in “natural” motion being motion that returns to one’s sphere) plus perfect circular motion in the heaven’s (trans-Lunar).

This framework had the advantage of appealing to common sense (the sky sure looks like a half-sphere) while also providing a pure geometric view of the heavens, a clean spherical mechanism. The details of actual planetary motion are ignored, and the focus was on perfect shapes around an egocentric center (i.e., us). The later combination of Plato/Aristotle philosophies with Christian doctrine formed a complete cosmology/theology of planetary motion and human morality (so-called scholasticism, i.e., see Dante’s cosmology).

Of course, the devil is in the details (pun fully intended) and attempts to apply this geocentric framework quickly ran into difficulties with respect to planetary retrograde motion. As we teach our students, retrograde motion drives Ptolemy (c. 150 AD) to develop our first astronomical “kludge”, the ad-hoc addition of epicycles on deferents in order to “save the phenomenon” of perfect circles. The Ptolemy framework is horribly convoluted, (thus, violating Occum’s Razor), but became highly accurate (due to its computational flexibility). Lack of observed parallax, plus a poor understanding of inertia, meant the Ptolemy framework remained unchallenged for many, many years (about 1,500).

The Copernican framework is developed at the beginning of the Renai-
sance for primarily cultural reasons as there was nothing inherently inaccurate about Ptolemy’s model and there were no new observations that would have caused the Ptolemaic framework to be falsified (using modern terms). There was a general uneasiness concerning the orbital behavior of the inferior planets, (Mercury and Venus always being near the Sun, regardless of their orbital center being around the Earth), however there was no computational flaw to the geocentric model. While the Copernicus heliocentric framework is considered to be the standard example of a paradigm shift, it actually contained nothing superior as a computational tool since it also continued to use circles, rather than ellipses, and required similar epicycle kludges to correctly predict the positions of planets in the sky (in fact, the Ptolemy model continued to be used for centuries to construct almanacs). The heliocentric framework was accepted as a “mathematical fiction” in many scholarly circles at the time. Thus, we have two frameworks, both making predictions, many of these predictions (such as parallax) were outside the technology of that time.

As we teach, along comes Galileo with his new technology, the telescope. Simple observations falsify (in Popper’s words) the geocentric framework (but do not “prove” the heliocentric framework, which is also incorrect with its use of perfect circles). Kepler’s use of ellipses completes the kinematic description of Copernicus (removing the ad-hoc computational complexity of Ptolemy’s framework). Newton completes the dynamic framework with gravity, and his laws of motion, plus demonstrating that Kepler’s ellipses are required for an inverse squared force law (and giving us calculus as a new computational tool).

Again, there were many nuances to this story, but this is the way we teach it to our students:

Step 1. Two competing paradigms (geocentric vs heliocentric),
Step 2. dramatic observations (Galileo),
Step 3. one framework is falsified,
Step 4. a significant leap forward in our understanding of the Universe

This model of how science works is referenced in ways too numerous to count, even in circumstances where the exact details may not apply. The highly visible nature of this example is also due to the large number of changes in astronomy, physics, biology that were occurring at roughly the same time in Western Europe along with so many new technologies (e.g., the microscope and telescope). The result of many of these new ideas was a
decoupling with the concepts of Aristotle and other Greek thinkers, opening a path to novel interpretations of Nature. No one doubts this was a defining moment in the history of astronomy and the knowledge gained in later years can be traced back to this paradigm shift.

3. The Dark Matter Paradigm

The introduction of dark matter as the primary driver in galaxy kinematics has been well documented in many review articles (see Sanders 2010). Early work can be summarized as the discovery of excess motion (either cluster velocity dispersions or flat rotation curves) without corresponding luminous matter. Thus, the so-called “missing mass” problem is more correctly phrased as the “missing light” problem (Oemler 1988) and initial searches were focused on identifying the missing light as very faint, or even dark, matter as an obvious solution to the kinematic observations. And, in many ways, the assumption of dark matter “saves the phenomenon” of Newton-Einstein framework much like epicycles saved Plato’s framework.

However, this is not an accurate comparison. For epicycles, while perhaps mathematically necessary, do not carry the same weight as the scientific hypothesis of non-luminous matter to explain the deduced gravitational influence on and within galaxies. In addition, there have been many instances of “missing matter” being found through gravitational influence (the most famous, of course, is the discovery of Neptune). Epicycles, on the other hand, were a convenient mathematical tool with no history in astronomical calculations.

Despite this difference, the dark matter hypothesis has been particularly difficult for astronomers to work with as it is central to our frameworks that astronomical objects describe a reality distinct from the appearance of things. This is a form of instrumentalism, a view where frameworks are not necessarily true (in a mathematical sense) but are accurate and useful fictions to perform computations and make predictions about astronomical observations. This works well on phenomenon ranging from interstellar gas clouds made of atoms and molecules to galaxies made of point-like stars. However, dark matter, by definition being non-luminous, is not sampled directly by our telescopes. And scenarios using existing, but mostly non-luminous, astronomical objects (neutron stars, blackholes, black dwarfs) immediately ran into conflicts with other, well-established astronomical parameters (such as the age of the Universe). In other words, dark matter was a useful fiction with respect to known astronomy, but it’s framework
was outside known astronomical objects. And, unlike the debates of the reality of objects in the microscopic world (e.g., quantum fields), objects in cosmology are, by definition, macroscopic and must entail the same realism as known astronomical objects (i.e., stars). There were only a very limited number of speculative astronomical objects that satisfied the characteristics of dark matter (i.e., invisible) and did not violate existing, well established paradigms (such as the theory of stellar evolution).

The immediate solutions to a non-astronomical dark matter component is either 1) a known particle with surprising high mass or 2) an unknown particle with an unsurprisingly high mass. Attention immediately fell on the neutrino, with an early indeterminate mass. However, the family of neutrinos were soon shown to have insufficient mass to account for dark matter. Thus, research attention was directed to a new particle, assumed have a very high mass and a uniform distribution needed to account for motion in the halos of galaxies (cold dark matter, CDM, cold in order to gravitationally collapse early to form large scale structure). The loss of the Superconducting Super Collider in the mid-90’s released a large number of resources (i.e., people) resulting in a great deal of theoretical speculation about a new dark matter particle. However, decades of searching and speculation have produced no tangible object or working framework for a dark particle. While we are amazed at the ingenuity of our theoretical community, it is almost impossible to read recent work in this area without experiencing a sense of desperation.

As critical as astronomers have been to the dark particle enterprise (perhaps a little jealousy that dark matter had shifted from its astronomical focus and funding), there are many examples in the history of creative thinking where scientists certainly did not derive their theories from data. And one could argue that the discovery of “missing mass” is the kind of experimental push to framework building much like the photoelectric effect was to quantum physics.

Meanwhile, after it became increasingly obvious that dark matter was not going to be in the form of some astronomical object with an origin in baryonic material (brown dwarfs, neutron stars, blackholes, etc.), the main focus of astronomical investigations became to gathering more data in order to better outline the dark matter phenomenon. There was less an interest in explaining what dark matter was, and more an emphasis on how dark matter contributed to basic astronomical processes, such as galaxy formation. More data about events is the core of the philosophy of
empiricism, but empiricism by itself lacks predictive power. It did not seem fruitful to gather more observations of dark matter in the hope of building general correlations towards a new law of Nature. Attention was directed to defining the effects of dark matter on baryonic matter and its influence on cosmological models.

So, currently, one of the greatest challenges with the dark matter hypothesis is how do we formulate characteristics of things that are not observable? Being unobservable is not completely true, as we supposedly see the effect of dark matter on other matter, and some crude information can be extracted from those observations (e.g., lensing maps of galaxy clusters). And it is not uncommon in astronomy to investigate phenomenon through indirect observations (e.g., blackhole physics from accretion disk observations). But dark matter takes us into a very different realm of indirect observations, especially in that we have no information on the nature of dark matter itself to guide our investigations.

4. How does Dark Matter fit into Scientific Realism, is it Predictive?

Scientific realism is the view that we should believe in the unobservable objects postulated by our best theories. But, it also has a negative connotation in that it implies that common sense reality is an illusion, and that there are layers of reality that are remote from everyday experience. This view is not too difficult to embrace since, even in the laboratory, objects of scientific scrutiny have primary and secondary properties. Primary properties are things like mass and size, which are only altered by changing something fundamental about the object. Those properties that things only appear to have are secondary, such as color or taste. Secondary properties also have meaning in reality, but only through context (color is reflected light). Primary properties are what most scientists consider to be fundamental and mind-independent.

What we know about dark matter fits poorly into our current view of scientific realism. While motion is a primary property of matter, the cause of motion has a range of possibilities. Our failed dark matter searches have not even limited the characteristics of a hypothetical new particle as speculation moves the expected properties into new realms and often borders on untestable (a classical “moving the goalposts” fallacy). There does not appear to be any particular experiment which can falsify the dark particle hypothesis as the avenues for speculation are endless. In scientific
realism, objects exist independent of our minds and senses. Dark matter searches seem to presume objects that are not only independent of our senses, but are also outside our ability to sense them.

Ernst Mach, a late 19th century physicist who strongly influenced Einstein, argued that science should only concern itself with what was observable, and the function of natural laws is to systematize the correlations of our observations. Mach’s hope was to develop a functional system based on fundamental concepts (i.e., independent of observations) combined with practical correlations (determined in a deductive or inductive manner, so-called foundationalism). Dark matter searches seem to reverse this philosophy as there is very little in the Standard Model to suggest a dark particle. These searches also hope for new physics that depends on the discovery of such a particle to spur extension of the Standard Model into a new framework much like the many historical examples of new discoveries leading the way to Maxwell’s formulation of electromagnetism and Einstein’s development of relativity. Again, this seems very un-Mach-like. While one can never have absolute positive grounds to believe theoretical entities, like dark matter, no matter how empirically successful their theories, it still begs the question of whether they are real.

The state of dark matter research closely resembles the state of physics in the early 19th century concerning the caloric model versus the kinetic theory of heat transfer. The caloric model was extremely successful in many of its predictions, just as dark matter is a successful explainer of cosmological observations. The caloric model was also powerful in its use with developing new technology (e.g., steam engines). Mathematically elegant plus being precise guaranteed the popularity of the caloric model. And similar to dark matter framework, caloric theory required an invisible and immaterial substance at its core. Many of the same justifications were used to support the caloric research paradigm, in the sense that it was a great “explainer” of phenomenon and was “simple” in its formulation (invoking the short form of Occum’s Razor). It would evidentially fall in its inability to predict heat from friction in mechanical devices, such as drills, paving the way for a framework of atoms and motion, but for decades was the center of the new field of thermodynamics.

The dark matter paradigm has several positive characteristics. For example, it is very attractive for its promise of future new physics. The Standard Model seems incomplete to some, dark matter is a good excuse to test its boundaries. For cosmologists, dark matter is critical to explain the
details of the CMB and features in the large scale structure of the Universe as well as key elements to galaxy formation. Dark matter is so ingrained into the current cosmology framework that is is simple inconceivable that it does not exist for it is the “simplest explainer” of the observations. However, dark matter lacks any predictive power as a framework since its basic characteristics are unknown and its use in cosmology is mostly in what its does not do (i.e., interact with baryons except by gravity).

5. Is Dark Matter Testable?

The obvious answer to the question of whether dark matter can be tested as a scientific hypothesis is “of course”, once a dark matter particle is detected. Until that moment, it is a serious concern that dark matter, as it is framed for scenarios of galaxy formation, is untestable. This is due to the fact that with each failed experiment to identify a dark particle, or define a cross section, the “goalposts” for its characteristics are moved. The theoretical community is strongly committed to a new dark physics framework and, thus, is open to many avenues of formulation particularly when there are almost no constraints on the actual characteristics of dark matter.

The main question then becomes how do we reconcile our theoretical frameworks, particularly computer simulations, with our observations? Logical positivists struggled with how to separate the empirical content of theories, the synthetic part, from the theoretical, the analytic part. Certainly there is a history in astronomy that our theories and frameworks guide us in deciding what to observe. Many an observational program is designed to explore the predictions from a newly proposal theoretical concept. And key to that process was the well-known principle of falsification (Popper 1959) which was originally developed to define a demarcation between science and non-science, but has over time evolved as a basic principle underlying scientific exploration (even though philosophers still struggle with Popper’s ideas, see Gardner 2001).

In Popper’s scheme, there are many different kinds of predictions from frameworks, the most powerful ones being novel predictions (those which are predictions of new types of phenomenon). If these phenomenon are previously unobserved, then these frameworks contain bold conjectures and are especially attractive for observational investigation. How then does dark matter fit into our astronomical programs?

The greatest tension between astronomical observations and dark matter is our understanding of galaxy formation. Increasing telescope size and
wavelength coverage (i.e., new ground-based systems plus far-IR space telescopes) has made for deeper studies of galaxies to higher redshift. This has meant more information on the epochs associated with the first burst of star formation and the first epoch of galaxy evolution by mergers. This allows for detailed comparison between observations and our theoretical foundation on the physics behind galaxy formation plus predictions from computer simulations.

While this article is not a review, nor criticism, of how we test and refine our models of galaxy formation and evolution using computer simulations, it is instructive to examine how that process is perceived by the community. There is general agreement among observers that a good overview knowledge of the predictions from computer simulations makes for a healthy discussion section in a research article. This is perceived as a correctly processed scientific procedure that feeds back into our theoretical framework by isolating the processes that are important to the various galaxy formation scenarios.

The advent of advanced computer simulations, combined with comparison to high redshift observations (i.e., temporal or evolutionary information), has given us the ability to investigate extremely complex phenomenon and extract consistent predictions to be tested by observations. This has forced a change in our view of knowledge from an old system where frameworks must be certain, subject to proof and free of error (e.g., Newtons laws of motion) to a more modern view where we apply a critical and introspective analysis of our frameworks for their value in matching observed phenomena. Note that the interaction between computer simulations and observations is critical, the simulations are constrained by reality, and the observations can only be interpreted by reference to simulations, which model the underlying physics.

It should also be noted that the construction of computational frameworks is not a mechanical process, it is a process laced with creativity and rigorous testing. By their nature, computational models are unlike general frameworks. For example, frameworks can be falsified by just one negative observation, but most computational models are not of this type. Some unfalsifiable principles, like conservation of energy, are considered part of our knowledge and fundamental physics of a simulation. But, violation of fundamental physics in a simulation would reveal something else is wrong, not the principles themselves. When encountering new physics, the typical scientist will think up modifications to a theory, or extra assumptions, in order to save it.
Popper would consider computational models acceptable if they make further predictions for the framework (i.e., ad-hoc vs non-ad-hoc modifications). For example, the orbit of Uranus did not falsify Newton framework for it was assumed one of the input parameters was wrong (i.e., the influence of Neptune). If a computational model has lots of evidence in its favor, and it works, it would be crazy to abandon it without something better to replace it. This is how, in some sense, computational models gain an intellectual inertia as they provide some understanding to the underlying processes. However, theories can infect data to such an extent that there is no gathering of observations that can ever be theory-neutral and objective. Strong computational models differ from theory in that there is a disciplinary matrix (i.e., the education of a scientist) which includes skills that enable scientist to work within the paradigm. This restricts the avenues that can be used to modify computational models (individuals have limited tools in their mental toolbox).

Scientists adopt all manner of strategies to save theories from refutation. Especially if a framework 1) has had great deal of success, 2) has dealt with anomalies in the past, 3) has involved a massive investment in time and education and 4) has consumed extensive resources. In addition, a scientist who pauses to examine every anomaly seldom gets significant work done (Kuhn 1962). However, some anomalies will not go away and may produce conceptual paradoxes (Ladyman 2002). Kuhn-style revolutions involve change in the context which science questions are resolved and often evidence will never be enough to compel scientists to switch paradigms. Scientists are often thoroughly committed to their paradigm they are working within and refuting evidence is unlikely to locate the problem within the central assumptions that define the paradigm. The idea that a theory is supported by community because it is believed is called epistemic relativism and the dark matter paradigm seems deep in this well of logic.

Part of the problem for our computational models is that, in attempting to describe an objective reality, words mean different things in different paradigms. And, while scientific knowledge is fallible, partial and approximate, it is still the best method for making predictions. Computational models represent our most complex attempt at achieving this goal.

6. The Route Forward: Acceleration is the Key Parameter

History has a clear answer to the dark matter problem, more data. A particle detection would be a tremendous leap forward but, despite the par-
article community’s optimism, the odds are looking worst with each passing experiment. Dark matter is still an astronomy problem and astronomical observations have provided the only useful information on dark matter for the last 50 years.

Information on dark matter has historically been kinematic (although lensing maps have provided the first look at the distribution of dark matter in clusters). The most primary kinematic correlation concerning dark matter is the baryonic Tully-Fisher relation (bTF, McGaugh et al. 2000). The bTF demonstrates a correlation between the total baryonic mass of a galaxy and its total dynamical mass (presumably, dark matter plus baryonic matter). While some correlation is expected since baryons and dark matter arise from the same density fluctuations in the early Universe, the scatter in the bTF is completely observational, meaning that if one knows the total baryon mass of galaxy, you can deduce its total dark matter mass to within observational error. Given all the various physical processes involved in galaxy formation, that act differently on baryons compared to dark matter (e.g., gas cloud physics), this relationship is startling. In addition, the slope of the bTF contradicts most galaxy formation scenarios using dark matter.

An obvious extension to the bTF is to consider all the information contained spatial in the rotation curve, rather than a total mass value in a Tully-Fisher fashion. This is the recently discovered radial acceleration relation (RAR, McGaugh, Lelli, & Schombert 2016). This kinematic diagram relates the acceleration at a particular radius from the baryonic matter with the total acceleration deduced from the rotation curve (again, presumably dark plus baryonic matter). And, again surprisingly, the baryonic acceleration is very tightly correlated with the total acceleration, the scatter being completely within the observational errors. The meaning of this, new, kinematic law for rotating galaxies is that if one is given the baryonic value at a particular radius, you can then deduce the total mass value (dark plus baryonic) at that same radius. This is impossible given the dissipative processes needed to form a rotating disk from a dark matter halo.

While sounding esoteric, these relations are remarkably tight by astronomical standards and relate the baryon mass to the presumed dark matter mass (both on local and total scales). For example, the radial acceleration relation demonstrates that if one knows the baryonic mass at a particular point in a galaxy you immediately also know the dark matter mass, in other words the two substances are strongly coupled. In addition, these
correlations indicate the existence of an acceleration scale in a conceptually distinct manner and they return the same value, to within the errors, of about $10^{-10} \text{ m s}^{-2}$. This ubiquitous acceleration scale is a critical clue about the missing mass problem.

The conflict between these relationships and the dark matter hypothesis is that dark matter is presumed to only interact by gravity (the weakest force) with baryonic matter. Although there exists weakly interacting dark matter models, the coupling implied by observations exceeds any dark matter scenario, particular in the low density regime where gravity is also at its weakest. In other words, it is a baseline characteristic of dark matter that it cannot interact strongly with baryonic matter (this is required for the success of dark matter in cosmological models), and the indicated strong coupling is difficult to explain under any dark particle hypothesis. Perhaps more importantly, no dark matter framework predicted these kinematic relationships (although many have recovered this property after discovery with modifications to their frameworks, Kuhn and Popper would shame them).

The history of galaxy formation theory is laced with models to understand the structure of galaxies, and the evolution of structure. These models use parameters such as characteristic scale length, density and total mass to compare predictions to observations (then iterate on the input parameters). Thus, scaling relations, such as the ones discussed above, are critical to understanding galaxies. However, it is becoming increasing obvious that we are asking the wrong questions in attempting to understand the origin of these scaling relations. We tend to ask questions related to the effects of gravity (for example, scale length asks about the size of a galaxy under gravity as a function of mass or density). Instead, our new scaling relations indicate that acceleration is the controlling parameter. All the correlations are linked by a common acceleration scale, not a mass or density scale. Within the uncertainties of the data, all of them express the same acceleration scale which is not predicted in our current framework of galaxy dynamics. If this acceleration scale is unique and universal, then it represents a major change in our understanding of how galaxies work and explains the increasing popularity of modified gravity theories as the problem appears to be focused on how things move in galaxies rather than missing matter.
7. Is This a Paradigm Shift?

The evidence for a paradigm shift with respect to the dark matter framework is, as is expected from the history of science, driven by new observational correlations between baryons and dark matter. If the RAR is as important as we think, than we must reconsider our dark matter scenarios within these new observations and inspect our initial assumptions about dark matter as non-luminous and non-interacting (except by gravity). We appear to be forced to abandon this pathway as the strong coupling with baryons is exactly the opposite characteristic as originally proposed for dark matter. Thus, CDM paradigm appears to be underdetermined as a working framework. Underdetermination means that more than one theory is compatible with the evidence. Observations underdetermine a framework when they are insufficient to suspend judgement on theories. Often explanations require mere empirical adequacy (which is defined as simplicity, coherence, elegance), but also must give us more than just a description (like Ptolemy’s model) they need to tell us why in a causal way.

In this context, our computational models that use dark matter appear to be severely underdetermined. They simply have too many variables (i.e., feedback) that are proposed as “reasonable” corrections. This kind of modifying of the basic physics in simulations leads to a scenario of no or little progress and is reminiscent of what observers experienced during the “Hubble wars” in the 80’s. Two competing values for $H_0$’s were sustained for many years mostly by poor experimental design and a weak computational framework for understanding galaxies. Numerous “reasonable” corrections to distance scale data made the supporting of widely different values relatively easy. The feedback mechanisms in computational models has many of the same features as epicycles in Ptolemy’s framework; reasonable, justified by observations yet probably completely wrong.

Science is often defined as the process of rational inquiry produced by a cumulative growth of empirical knowledge. Growth is measured by the strength of our frameworks. Thus, a paradigm shift is characterized by 1) emphasis on novel observations, 2) abandonment of qualitative descriptions for quantitative ones, or 3) the appearance of novel interpretations. Adopting a new kinematic framework for rotating galaxies to explain the bTF and RAR, such as MOND (MOdified Newtonian Dynamics, Milgrom 1983), is very much like the adoption of the Lorentz contraction to explain the Michelson-Morley experiment. The original Lorentz contraction was presented as an ad-hoc fix to the Michelson-Morley results. It only became
a component to special relativity long after relativity was first proposed. MOND may not be correct or the finished product, but if history is any guide, our new path forward is something that is MOND-like. Much like a large jigsaw puzzle, MOND appears to be an edge piece to a larger framework. One thing that is clear is that our path forward lies in the low density, low acceleration realm of galaxies.

Our current frameworks will not exist in 100 years. While there are individuals who believe we closing on final theories that will explain everything, they have not been paying attention for the last few thousand years (definitely not in a Bayesian fashion). Certainly a framework that attempts to explain things is desired, but it is not a goal. Predictive power is the true goal of science and frameworks that lead us down new paths are what we really desire. Frameworks that fail to lead us in new directions need to be abandoned. Not because they are wrong in any real sense, but they simply have served their role in getting us ready for the next step. The CDM framework has reached this point.

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