Studies in History and Philosophy of Modern Physics 47 (2014) 62–67

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

journal homepage: www.elsevier.com/locate/shpsb

On the interpretive role of theories of gravity and 'ugly' solutions to the total evidence for dark matter

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ARTICLE INFO

Article history:
Received 4 January 2014
Received in revised form
20 May 2014
Accepted 24 May 2014
Available online 19 June 2014

Keywords:
Dark matter
General relativity
Theory testing
Confirmation
Underdetermination

ABSTRACT

Peter Kosso (2013) discusses the weak gravitational lensing observations of the Bullet Cluster and argues that dark matter can be detected in this system solely through the equivalence principle without the need to specify a full theory of gravity. This paper argues that Kosso gets some of the details wrong in his analysis of the implications of the Bullet Cluster observations for the Dark Matter Double Bind and the possibility of constructing robust tests of theories of gravity at galactic and greater scales. Even the Bullet Cluster evidence is not sufficiently detailed to allow precision tests of General Relativity that would distinguish it from its rivals at galactic and greater scales. Taking into account the total evidence available, we cannot rule out "ugly" solutions to the dynamical discrepancy in astrophysics that involve *both* a large quantity of dark matter and a theory of gravity whose predictions differ significantly from those of General Relativity for interactions taking place at galactic and greater scales.

1. Introduction: Dark matter and philosophy of science

One of the most significant open problems in the contemporary physical sciences is commonly called "the dark matter problem" but can more accurately be referred to as "the dynamical discrepancy in astrophysics." Multiple lines of evidence point to the conclusion that the observed motions within galaxies, clusters of galaxies and larger systems cannot be adequately accounted for by the combination of the visible matter within those systems plus the most widely accepted theory of gravity, General Relativity (GR). Looking just to the dynamical evidence derived from the motions within galaxies and clusters of galaxies (neglecting for present purposes strictly cosmological or any other reasons to hypothesize large quantities of matter in the universe in addition to what can be optically detected), scientists are faced with a stark choice: Either there is 10–100 times more mass present than is visible in these systems and it is in some hitherto-unknown type of matter, or it must be that an otherwise highly confirmed theory, GR, needs to be significantly overhauled.

On the first option for resolving the dynamical discrepancy, the exotic matter in question is called "dark" because one of the only things we know about it is that it neither emits nor absorbs electromagnetic radiation. This means it cannot be the ordinary baryonic matter (composed of protons and neutrons) with which we are familiar from all of our ordinary experience. Candidates proposed to be the dark matter have ranged from black holes to new fundamental particles. Almost all such candidates have been ruled out on empirical or theoretical grounds, and those that are as yet not eliminated have almost no positive empirical support despite nearly 40 years of serious efforts to describe and detect dark matter. The most popular open matter solutions involve Weakly Interacting Massive Particles (WIMPs)—that is, particles that interact with other matter only through gravity and the weak nuclear force.

Although the vast majority of physicists and astronomers prefer a matter solution to the dynamical discrepancy in galaxies and larger structures, to some it has seemed methodologically and metaphysically undesirable that we should—in an *ad hoc* response to a very significant and unexpected empirical discrepancy—hypothesize vast quantities of matter of an exotic, unknown and more or less unobservable type without any other independent theoretical or empirical motivation to do so. For this reason a few attempts have been made to describe alternative theories of gravity that are predictively equivalent to GR at roughly solar system and shorter scales, but which are able to account for the

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http://dx.doi.org/10.1016/j.shpsb.2014.05.008
1355-2198/

observed motions in galaxies and clusters without the need for dark matter. Most notable among these attempts have been: the Modification of Newtonian Dynamics (MOND) developed by Milgrom (1983, 2010); MOND's relativistic version, namely Bekenstein's (2004, 2011) Tensor–Vector–Scalar gravity (TeVeS); and Mannheim's (2012) Conformal Theory of Gravity.

Since GR is highly confirmed for all systems about which we have detailed evidence, in order to be viable at all any alternative theory of gravity must be empirically indistinguishable from GR within the margin of error in the current observations for those systems. This is to say that possible deviations from GR's predictions are highly constrained within systems that are roughly the size of a solar system or smaller, since those are the systems for which we have detailed precision tests of GR. (Vanderburgh (2003, 814–815), makes this case in detail.)

To take one example of how an alternative theory of gravity fits within these evidential constraints, consider Milgrom's version of MOND. MOND holds that the action of gravity deviates from the predictions of GR below a certain threshold of acceleration. Although this empirical difference is predicted by MOND regardless of scale, in practical physical situations MOND only becomes observationally distinguishable from the Newtonian limit of GR at very large distances, much larger than a solar system. There is room for MOND at these scales both because such distances are required to get the very weak acceleration fields in which MONDian effects appear, and since the empirical constraints on the action of gravity are much looser at these scales since precision tests are not available. MOND's biggest empirical success is that it can reproduce the qualitative form of the observed rotation curves for spiral galaxies without the need for dark matter; similarly, it predicts motions within clusters that are similar to those observed, but requiring much less unseen mass than analyses that use the Newtonian limit of GR. Note that some attempts to devise viable comparative tests of MOND *versus* GR at less-than-galactic (but still incredibly large) scales have involved velocity dispersions within globular clusters, which are compact agglomerations of hundreds of thousands of stars that orbit parent galaxies. Scarpa, Marconi, Carraro, Falomo, and Villanova (2011), for example, find velocity dispersions in globular clusters that resemble those in elliptical galaxies. In both types of systems the velocity dispersions are constant beyond a given radius, contrary to what would be expected given the visible distribution of matter within them and the predictions of the Newtonian limit of GR. They speculate that this similarity might have a common origin, possibly a breakdown of Newtonian dynamics below the MOND acceleration threshold, but they acknowledge at the end of their paper that this would actually contradict MOND's original predictions for globular clusters, in which the acceleration field of the parent galaxy should be at or above the acceleration limit. If the observed velocity dispersions are in fact a result of an acceleration threshold effect, the standard explanation of elliptical galaxies' velocity dispersions in terms of dark matter haloes is incorrect. As of now this remains an unproven possibility.

Perhaps because of the sorts of sociological and institutional factors López-Corredoira (2014) identifies as operating in the discipline of cosmology—factors that over-emphasize the epistemological status of "received views" and function to effectively prevent non-standard theories from getting significant attention or being developed—gravitational alternatives to dark matter are generally not well-regarded in the community of physical scientists. In fact, however, as will be discussed below in more detail below, on the evidence available the standard "GR+DM" paradigm for addressing the dynamical discrepancy in galaxies and larger systems is observationally indistinguishable from non-standard models of "alternative gravity with only ordinary matter." In the current evidential situation, reasons for preferring one class of solutions over the other must be extra-empirical. It is plausible that this is due in part to the underdevelopment of both the evidence and the theoretical constructs: as scientists gather more evidence and find new ways to deploy it, and as they flesh out the details of the competing theories, it could well turn out that some of the current competitors will cease to be viable.

In the interests of full disclosure, let me remark that my own preference is for a matter solution to the dynamical discrepancy. However, it also seems to me that in order to eventually establish any such solution we will need to provide as objective an analysis of its epistemic status as possible. My own evaluation of the current evidential and theoretical context leads me to the conclusion that there is insufficient warrant to be confident in any particular class of solutions (let alone any particular solution). Opinions aside, what is of genuine general philosophical interest is that the dark matter case presents a very intriguing study of the nature of scientific reasoning.

Indeed, the study of dark matter is a very fertile ground for historians and philosophers of science in many ways. The subject is only just beginning to receive the attention it deserves. Dark matter raises a host of philosophical issues in new ways or in especially interesting contexts—evidential reasoning, scientific methodology, confirmation, explanation, unification, theory choice, underdetermination, limits to what is knowable, paradigm shifts, natural kinds, and unobservable entities are just a few of the sorts of issues that historians and philosophers of science could profitably approach through attention to dark matter. Among the works that have begun to give philosophical attention to dark matter are, for example, Hamilton (2013), Hudson (2007, 2013), Minasyan (2008), and Zinkernagel (2002). (Hamilton (2013, 7–10), includes a good summary of the current state of the evidence relating to dark matter. For an astronomer's perspective on the history of and evidence for dark matter, see Trimble (1987, 2013)).

Kosso (2013) is another entry in this burgeoning field of philosophical studies of dark matter. Kosso's main point is to extend the discussion of an apparent limitation on the empirical testability of gravitation theories that was raised in Vanderburgh (2003). In what follows I analyze Kosso's arguments and some related issues, ultimately concluding that Kosso's main point is uncontentious but not very contentful, and that the evidential status of theories of gravity at galactic and greater scales is changed very little by the observations of weak gravitational lensing in the Bullet Cluster that inspired Kosso's contribution. Sus (2014) also comments on Kosso (2013), and I critique various aspects of that piece along the way as well.

2. Implications of dark matter for testing alternative theories of gravity

Peter Kosso (2013) draws attention to the results of Clowe et al. (2006) regarding the Bullet Cluster. X-ray maps of the density of hot gas compared to density maps derived from weak gravitational lensing of background objects by the Bullet Cluster reveal that the two centers of mass of the baryons (hot gas) are not co-located with the two centers of mass of the cluster as a whole. This is interpreted as the consequence of a collision of two sub-clusters of galaxies in which the hot gas from the two interacted and slowed while their component galaxies and dark matter halos passed through each other without frictional braking. This result is widely taken to be a new *kind* of evidence for dark matter, and certainly the most direct proof available of the existence of dark matter. Since the other kinds of evidence for dark matter have already been discussed in detail in the other works cited above, in my comments below I will follow Kosso in focusing solely on the new