A matter of universal interest

A research psychologist friend of mine recently asked me about dark matter. Is that conjecture really on solid ground? He expressed worry that physicists may, in this case, have invoked the invisible and undetectable a little too readily. When faced with a puzzle, isn't it rather unscientific to explain it away by assuming the existence of some strange and invisible substance of just the right kind, distributed through the Universe in just the right way? Couldn't it be, he went on, that the apparent need for dark matter just reflects a gap in our understanding of something fundamental about cosmology, including the workings of gravity?

Not at all expert on the topic, I didn't know how to reply. So I started reading and fortunately came across a recent, beautifully written history of the idea of dark matter that explores how and why most physicists have come to believe in it (G. Bertone and D. Hooper, preprint at http://arxiv.org/abs/1605.04909; 2016). The story is reassuring — the idea of dark matter doesn't seem any more dubious than earlier hypotheses about as-yet-unobserved things such as atoms or black holes or microorganisms. Even so, it turns out that my friend's intuition is also sound — there is still room for doubts over the reality of dark matter. A fundamental lack of understanding of gravity is still legitimately in play.

As astrophysicists Gianfranco Bertone and Dan Hooper relate, the philosophically simple idea that some things may be hidden from us has been present in science for centuries. In modern times, the mathematician Friedrich Bessel argued in 1844 that the presence of unseen companion stars would naturally account for oddities in the observed motions of the stars Sirius and Procyon; he was right. Many scientists have convinced themselves through logical argument that most of the astronomical Universe is unobservable at present. Lord Kelvin pioneered the use of the kinetic theory of gases in the analysis of galaxies, and on its basis came to the conclusion that "many of our stars, perhaps a great majority of them, may be dark bodies".

There's nothing at all strange in this and the modern idea of dark matter isn't a lot different. In the 1930s, Fritz Zwicky identified a notable scatter in the apparent velocities of eight galaxies within the Coma Cluster. The velocity dispersion ought to reflect both the gravitational forces acting between the bodies and the overall mass of the cluster.

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Zwicky sought to check the consistency of the observation by using the virial theorem of classical mechanics, which relates the average potential energy among some gravitating bodies to their average kinetic energy, which is linked to the velocity dispersion. His calculation led to an expected velocity dispersion of 80 km s^{-1}, some ten times smaller than observed. "If this would be confirmed", he concluded, "we would get the surprising result that dark matter is present in much greater amounts than luminous matter" (*Helv. Phys. Acta* **6,** 110; 1933).

This was anything but a decisive result. As Bertone and Hooper note, astronomers and astrophysicists mostly kept open minds over the next few decades, neither strongly believing or disbelieving in dark matter. They awaited further evidence, which arrived in the 1970s with technological advances that enabled more accurate measurements of the velocities of stars within different parts of galaxies.

This made it possible to test with increasing precision expectations of how the rotational speed of stars should change as one moves outwards from the galactic centre. According to well-accepted calculations of stellar motions under gravity, if the luminous stars in a spiral galaxy contain most of the mass, then this galactic rotation curve should increase with radius, reach a peak and then fall off outside the zone that contains most of the mass. In the early 1970s a study that compared the observed and expected radii of the rotation curve peaks for two galaxies, M33 and NGC 300, found that the observed peaks were substantially larger. The author Ken Freeman concluded that "there must be in these galaxies additional matter which is undetected. Its mass must be at least as large as the mass of the detected galaxy" (*Astrophys. J.* **160,** 811; 1970).

Other astronomers soon found similar results for a host of other galaxies. By 1980, observations on dozens of galaxies confirmed that all had increasing rotation curves out to the largest observed radius, indicating that galactic mass kept growing out beyond the luminous stars and gas. By this time, Bertone and Hooper's history concludes, the idea of dark matter was becoming broadly accepted — and for pretty normal reasons. Physicists since then have mostly turned their attention to finding plausible candidates for it, and trying to detect them. Today, the front-runner is a class of non-baryonic weakly interacting particles of various possible kinds; a wide variety of other exotic possibilities — including primordial black holes — having been more or less ruled out.

So dark matter does seem to be a fairly sensible hypothesis, suggested directly by the available evidence. And yet the idea that dark matter may actually be a grand illusion still persists.

In the early 1980s, astrophysicist Mordehai Milgrom suggested that it might be possible to explain the observed motions of stars and gases within galaxies without invoking any hidden matter, but by instead looking to variations in the behaviour of gravity. In particular, all would seem natural if for very small accelerations the force of gravity on a mass followed not Newton's second law, $F = ma$, but a slightly different law. Milgrom's idea — now known as modified Newtonian dynamics — didn't conserve energy or momentum, nor was it consistent with general relativity, but the concept has been taken further since then.

According to Bertone and Hooper, the most advanced project to date goes under the name TeVeS theory — the acronym stands for tensor–vector–scalar gravity. Developed by physicist Jacob Bekenstein, it is consistent with general relativity, and offers a generalization of it with two additional fields and some free parameters. It is also apparently consistent with a variety of cosmological data as well as the observed rotation curves of hundreds of spiral galaxies. Pretty impressive, although it does still have some problems fitting the data for galaxy clusters.

This story, presumably, will end as previous searches for hypothetical entities have: either with an eventual definitive detection of the stuff that makes up dark matter, and a pleasing resolution of the various puzzles surrounding the behaviour of galaxies, or with the ultimate abandonment of the hypothesis if an exhaustive search over decades finds nothing. For now, it looks like an eminently reasonable scientific speculation. ❐

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