8.6: Possible Explanations for the Missing Mass in Galaxies and Clusters

What Do You Think: Missing Mass

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If we take the observations of the motions of stars and gas in galaxies, and the motions of galaxies in galaxy clusters, at face value, then they imply the existence of additional mass that is unseen: dark matter. The unseen mass could take several forms. Some are fairly simple, others quite exotic. We will consider several possibilities and explore what evidence exists for and against them. Keep in mind that astronomers still do not know the exact nature of the dark matter. While they have made progress in ruling out some of the following possibilities, its composition remains unknown.

8.6.1: Faint Astronomical Objects

The simplest explanation for dark matter would be that it is composed of normal matter that is too faint to see. This matter could take the form of dim, low-mass but otherwise normal stars, for example. Or it could be made up of other very dim objects like planets, white dwarfs that have cooled down, neutron stars, or black holes. If there were many of these sorts of objects floating around in galaxies and galaxy clusters, then they could easily explain the amount of mass we measure. However, they would be extremely difficult, or even impossible, to detect directly with current technology.

One of the early popular ideas to explain the “missing mass,” as dark matter used to be called, was to attribute it to a population of very faint stars. This was an obvious idea for astronomers to consider. They already knew that faint stars vastly outnumber bright stars— the fact that the sky seems to be filled with bright stars is an illusion, the result of bright stars being much easier to see. With moderately large telescopes it is possible to see the brightest stars anywhere in our Galaxy (discounting that they might be behind thick dust clouds). It is even possible to see the very brightest stars in nearby external galaxies. Contrast this with the faintest stars, which are only visible out to a few dozen parsecs, even with fairly large telescopes. Because faint stars are so difficult to see, it is natural to assume that many of them have been missed. As a result, they are a natural candidate for the “dark matter.”

Unfortunately, this idea does not turn out to be viable. When scientists made careful studies looking for faint stars in our galaxy, even with the Hubble Space Telescope, they did not find them, at least not in the numbers required to explain the dark matter. When sensitive cameras using CCDs (charge-coupled devices) first became available in the early 1980s, one of the first ways astronomers used them was to look for faint red stars. Because of their higher sensitivity to light, CCD detectors were much better suited for these kinds of projects than the older photographic films in use until then. The low numbers of faint red stars found in these studies ruled out the most natural and simple explanation for dark matter - faint stars. Instead, it implied that a more exotic explanation was needed.

The next most obvious candidate for dark matter is the burned out remnants of dead stars. These include white dwarfs, neutron stars, and black holes. Because these are all the compact remains of former stars, they have been given (somewhat in jest) the name **MAssive Compact Halo Objects** or MACHOs. Some other objects that are not stellar remnants, like brown dwarfs, are also included in this category. These objects are even more difficult to detect than faint red main sequence stars. In fact, they generally cannot be seen at all from our perch here on Earth. White dwarfs and brown dwarfs are visible if they are not too distant, but neutron stars and black holes are usually invisible. The only way we see them is if they are in particular systems in which they might emit x-rays or radio signatures. Any black holes or neutron stars not in such systems are essentially undetectable. The same is true of most white dwarfs and brown dwarfs, which are too far away to be seen.

So, is there no hope of detecting MACHOs at all? We certainly cannot detect them via their own light, at least not with currently available telescopes and cameras. But there is another way: gravitational lensing. When these compact objects pass in front of a distant background of stars, occasionally one will align exactly with a background star. The background star is magnified by the gravity of the compact object, which acts like a lens (see Figure 8.21). When that happens the background star's brightness appears to increase, and we can detect that increased brightness if we monitor many stars.

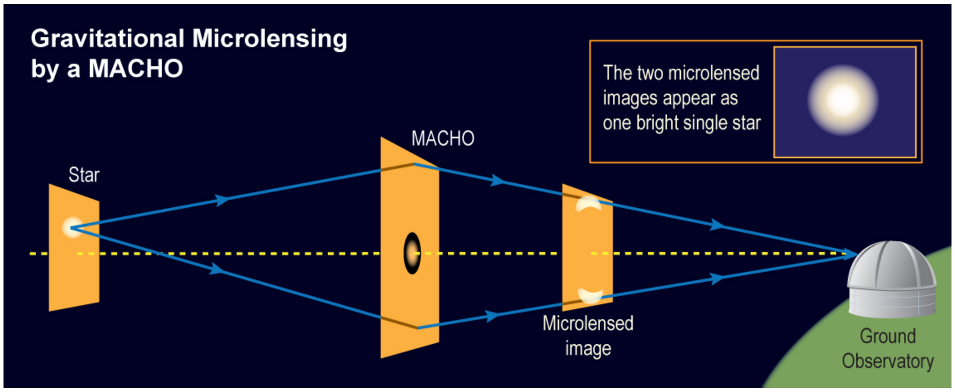

Figure 8.21: Gravitational microlensing. The intense gravitational field of the MACHO acts like a lens to smear and distort the image of the background star. The starlight is bent around the MACHO into two banana-like shapes that are larger than the original stellar image. The telescope cannot resolve the microlensed images, instead seeing a single resulting image that appears brighter than the original star. Credit: NASA/SSU/Aurore Simonnet

You might already have deduced that there are not enough of these compact objects to explain the amount of dark matter in galaxies. Many were detected, and they could comprise some of the dark matter, but only up to half of it. That still leaves a lot of unseen, and unexplained, material in the Galaxy.

✓ White Dwarfs and Brown Dwarfs as Dark Matter?

We will do a couple of calculations to determine the number of undetected white dwarfs or brown dwarfs that would be needed to make up the Milky Way's entire unseen mass, which is about 1.8 x 10^{42} kg.

Worked Example

How many white dwarfs would it take to account for all of the Milky Way's unseen mass? Assume that a typical white dwarf has a mass of 2 x 10^{30} kg.

- Given: unseen mass in Milky Way of 1.8e42 kg, mass of white dwarf is 2e30 kg
- Concept: divide the unseen mass by the mass of a white dwarf to find out how many white dwarfs it would take to make up the unseen mass:

  (1.8e42 kg)/(2e30 kg) = 9e11 white dwarfs

This would be 900 billion white dwarfs, which is not realistic given what we know about the Milky Way and its stars.

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8.6.2: Dark Matter Particles

Observational searches for faint stars and MACHOS have found that, for the most part, dark matter is not composed of these objects. MACHO surveys would have found non-luminous objects, and surveys for faint red stars would have found the very faint luminous ones. The only possibility that remains is that the dark matter is made of even smaller objects that cannot be easily detected, such as very small particles.

If the dark matter is composed of particles, the particles must have some special properties. First, of course, they must be massive. After all, their combined mass is causing the gravitational effects seen in galaxy rotation curves and the motions of galaxies and hot gas in galaxy clusters. Second, they cannot interact with (absorb, emit, or reflect) light. If they did we would have seen the particles already. This means the dark matter is not made up of atoms or molecules or particles of dust or gas. Nor can it be made up of common sub-atomic particles, like electrons or protons, for example. All of those things interact strongly with light of various wavelengths. Dark matter's lack of interaction with light is the property that makes dark matter dark.

The dark matter particles also must not interact strongly with other kinds of particles. Presumably, if dark matter did interact strongly with known particles, electrons for example, then we would have seen the results of these interactions in particle physics experiments. We have not. Some experiments claim results that *might* be caused by the interaction of dark matter particles within their detectors, but these results are still extremely tentative. Current data simply are not good enough to say that dark matter has absolutely been detected.

Furthermore, if the dark matter particles interacted strongly with each other, then we should have seen the production of known particles like photons, electrons, etc., that would be produced by these interactions. For example, we might expect to detect gamma rays from two massive dark matter particles annihilating each other. The process would be analogous to the annihilation of an electron and positron pair, in which we see x-ray photons with energies of 511 keV , the rest energy of an electron or positron. For the case of dark matter particles annihilating, the energy of the photons would be much larger because of the hypothetically larger mass of the particles involved. These hypothetical particles are often called WIMPs (again, in jest), for **Weakly Interacting Massive Particles**, a term coined in 1985 by physicists Gary Steigman at The Ohio State University and Michael Turner at the University of Chicago.

The Fermi Gamma-ray Space Telescope is being used to search for such gamma rays, but so far nothing conclusive has been found. This could be because the particles are too massive to be detected within the energy range of Fermi, which has a top energy sensitivity of 300 GeV. Or it could be because we have not looked through the data carefully enough, or because the signal is just too weak. Of course, we also might not be seeing a signal from dark matter annihilation because the hypothesized gamma-ray emitting dark matter particles are not there in the first place— perhaps dark matter is made of something else entirely, something that does not annihilate.

What about neutrinos? Neutrinos are well known to interact very weakly. However, they also have extremely small masses, near zero, which makes it difficult to account for so much missing mass. For a while some scientists thought that neutrinos were a good candidate for dark matter. However, as we will see in the chapter on structure formation, they are not suitable to explain the bulk of the dark matter. So far, scientists have seen lots of MACHOs, though not enough to explain the dark matter. No one has ever seen any WIMPs, but particle physicists have several candidates for what these particles might be.

Many scientists were hoping to simply create WIMPs in collisions at the **Large Hadron Collider** (LHC) at CERN, a particle physics laboratory located at the Swiss/French border near Geneva. (CERN is also known as the European Organization for Nuclear Research, or in French, Organisation Européenne pour la Recherche Nucléaire— formerly Conseil Européenne pour la Recherche Nucléaire.) In the collider, protons and antiprotons (the anti-matter counterparts of protons) are accelerated to high energies, as high as 7 TeV (7×10^{12} eV). Since the proton and anti-proton beams travel in opposite directions, when they collide there will be 14 TeV of energy available to create new particles.

Each collision creates a tiny fireball at the collision site, and out of that fireball emerge new particles. Most of them by far are the commonplace photons, electrons, positrons, neutrinos, etc., that we are familiar with already. But scientists have been hoping that WIMPs will be produced from time to time, and that their instruments will record this. At the time of this writing this has not happened. The LHC has been operating at full energy of 14 TeV for more than half a decade. It takes up to two years for scientists to sift through the enormous amount of data produced during each season. Thus far, despite some tantalizing false alarms, nothing convincing has been seen. The search continues.

8.6.3: MOND

If you are like some scientists, you might be questioning the conclusions we have reached so far in this chapter, as well as the assumptions we used to reach them. First, we applied Newton's laws of gravity and motion to stars and gas orbiting in galaxies and galaxy clusters. Those laws make a definite prediction regarding how these objects should move under the influence of a certain amount of gravitating mass. We compared those predictions to the amount of mass we can see and realized that the two do not match. In fact, they are not even close. From this we conclude that there must be mass present that we cannot see— dark matter.

There is an alternative conclusion that we could make instead: perhaps we are seeing all the mass present, but our reliance on Newton's laws is misguided. When we apply Newton's laws to the motions within galaxies and galaxy clusters, we are assuming that the laws are valid there. But does that really have to be the case? Newton developed his laws to describe motions that he could observe on Earth and in its near vicinity. Newton's laws have since been tested within the confines of our Solar System, and they work exceedingly well. For example, we are able to send spacecraft to other planets and planetary systems, insert those spacecraft into orbit and de-orbit them if we wish, land on the surface, etc. But does that mean our physical laws will work when we go outside the Solar System? Here we explore this idea for a moment.

We learned in Chapter 6 that the acceleration experienced by objects traveling in circular orbits, called centripetal acceleration, is provided by gravity. We saw that the general expression for centripetal acceleration is given as

$$a_c = \frac{v^2}{r}$$

where v is the speed of the orbiting object and r is the orbit's radius. We can compare the values of this acceleration for several different physical systems.

The following table shows values for several planets, the Sun as it orbits in the Milky Way galaxy, and a typical galaxy in a cluster. The first column for each object gives the relevant orbital speed, the second column gives the size of its orbit, and the last column gives the resulting centripetal acceleration.

Table 8.2 Comparing Objects in the Solar System, Galaxy, and Galaxy Clusters

OBJECT	V (KM/S)	R (M)	A_C (M/S^2)
Earth	29.79	1.49×10^{11}	5.96×10^{-3}
Neptune	5.43	4.50×10^{12}	6.58×10^{-6}
Sun	220	2.50×10^{20}	1.96×10^{-10}
Cluster galaxy	1000	3.10×10^{23}	3.24×10^{-12}

The accelerations of Solar System objects are clearly much larger than those for stars in galaxies or for galaxies in clusters. (This statement is not true for the Oort Cloud comets, but they are not relevant currently to the arguments presented here because we cannot track them when they are not close to the Sun.) And of course, accelerations are much, much larger for falling bodies near the surface of Earth. Since the sizes of these accelerations are so different, some scientists wonder if the same laws of motion and gravitation can be used to describe the motion of all of them. If the laws of gravity are not the same everywhere, say if gravity works differently at low accelerations than it does at high accelerations, then perhaps our conclusions about the dark matter are in error.

The first papers published that follow this sort of thinking appeared in the early 1980s. They argued that, by replacing Newton's second law with a slightly modified form, the need for dark matter to explain galaxy rotation curves and the motions of galaxies in galaxy clusters could be avoided. The modification was a simple one: change Newton's second law by multiplying it by a function, which we label *f*, as follows:

$$F = ma \rightarrow F = ma \cdot f(a/a_0)$$

In this expression, the function *f* depends on the acceleration, a; a_0 is a parameter that we can use to help match the model to the data. The function is defined such that $f = 1$ when $a >> a_0$. Otherwise $f = a$. This modification is similar to the models we created in

Section 8.1 for mass distribution. However, in this case we are not modeling how mass is distributed in a galaxy, we are modeling how the force on a particle depends on its acceleration. The value of the parameter a_0 must be about 10^{-10} m/s^2 if the model is to match galaxy rotation curves.

With this definition, when the accelerations are large compared to a_0, as they are in the Solar System, then the usual set of equations devised by Newton is valid and the motions behave in the manner we expect. However, when the accelerations are small, comparable to or less than a_0 (as they are for, e.g., stars orbiting a galaxy) then we must use a modified version of Newton's second law:

$$F = m\frac{a^2}{a_0}$$

Because we have modified Newton's second law, this procedure is referred to as MOdified Newtonian Dynamics, or MOND. If we now set this equal to the force of gravity, assumed to be in the standard form, then we have

$$m\frac{a^2}{a_0} = \frac{GMm}{r^2}$$

We can rewrite this further (after canceling the common factor of m from both sides) using the expression for centripetal acceleration to replace a:

$$\frac{\left(\frac{v^2}{r}\right)^2}{a_0} = \frac{GM}{r^2}$$

or...

$$\frac{v^4}{a_0 r^2} = \frac{GM}{r^2}$$

Now we can cancel the common factor of r^2 and rearrange to get

$$v = (GMa_0)^{1/4}$$

This is very different from what we got before. It depends only on physical constants (G and a_0) and the mass inside the orbit, M. If we assume that light traces mass, then we expect the rotation velocity to become constant at some point because the light (and under these assumptions, the mass) drops off rapidly as we move away from the center of the galaxy (as in Figure 8.22).

So under the assumptions of MOND, we find that the rotation velocity is independent of distance from the center of the galaxy, at least for stars orbiting at large distances. That is exactly what is observed for real galaxies. No amount of "hidden," "missing," or "dark" matter is required.

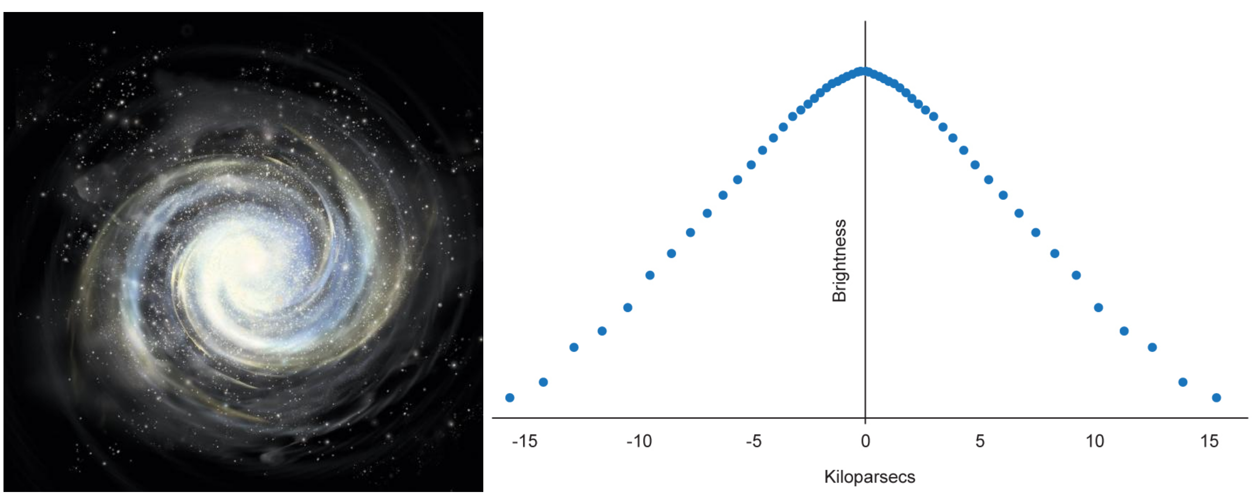

Figure 8.22: Spiral galaxy surface brightness profile. This figure shows (a) an illustration of a spiral galaxy, and (b) a graph of the galaxy's brightness profile. Credit: NASA/SSU/Aurore Simonnet

So, is this result believable? Can we truly avoid the need for a new kind of matter by making a small modification to the laws of physics, a modification that would go completely unnoticed in any laboratory experiment we could devise? How can we tell whether this or our previous treatment, if either, is the correct one? Have we learned something new about the laws that describe motions of objects in the Universe?

These questions are not easy to answer. Yet, they are the kinds of questions that face scientists every day. How do we decide between two competing ideas when both are able to explain the same data equally well? Given only the information discussed in this chapter it is not possible to refute the ideas of MOND. We tend to have a bias against making modifications to existing physical laws, a bias born of our familiarity with the laws as we first learned them and our many successful applications of those laws, even in a regime far removed from the one that is relevant here. These successes can give us a certain amount of confidence that the laws are valid in all circumstances. But are such confidences warranted? As we will see in the next chapter, they are not, but they are not given up easily either.

The only way that scientists are able to decide among competing ideas is to collect more information about the Universe. At some point, we hope, one of the ideas will no longer be compatible with the improved view revealed by our new measurements. This has occurred with MOND over and over again, at least as we have described it here.

We shall see that other gravitational effects, from Einstein's general relativity, not just from the Newtonian viewpoint, can be used to distinguish between the ideas of MOND and the need for dark matter. To jump ahead, the results have always been consistent with the dark matter idea, not with MOND… However, MOND continues to evolve; each time an old version is shown to be inconsistent with observations, its supporters modify its equations in such a way that the inconsistencies are removed. We will revisit these ideas in the next couple of chapters and hopefully develop some ideas of our own about whether the MOND approach is reasonable.

Throughout our explorations, you should keep in mind that Newton, when he devised his laws of motion and gravitation, was also searching for ways to express experimental results as simply as possible using mathematics. His method was exactly the one employed by the champions of MOND now.
