Dark Matter

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The ultimate destiny of our expanding universe depends on how much matter it contains and whether or not the amount of matter will be enough to one day stop the expansion. When astronomers add up all the visible matter (matter that emits or reflects light) in the universe, the result is that there is clearly not enough to stop the expansion of the universe. However, they have discovered over the past several decades that there may be additional matter hidden from view.[1] This raises some important questions. What is this dark matter made of? How can it be detected?

Astronomers first found substantial observational evidence of unseen matter in the early twentieth century when studying the galaxy M31.[2] They discovered that the velocity curve for the outer limbs of the galaxy, which should drop off with increasing radius as mandated by Kepler's Laws and the Virial Theorem, leveled off at approximately 200 km/s. This observation was confirmed in the early 1970's when radio astronomers found that hydrogen gas at the edge of galaxies moved with roughly the same velocity as hydrogen gas at the center of galaxies. If the visible matter seen in galaxies is the only source of mass then the observed uniform velocity of hydrogen gas is a direct violation of Kepler's Laws and the conservation of angular momentum. Thus, the simplest explanation (which is usually the correct one) is that the visible matter in galaxies *doesn't* account for all of the mass! This claim suggests that *most* of the mass in the universe, as much as 90%[2], is contributed by unseen or "dark" matter. So, what is dark matter made of? There is no reason why dark matter has to be made of one single material. It is likely that there are different types of dark matter.

Dark matter candidates are generally divided into two categories: baryonic material, and non-baryonic material. Baryons are a subgroup of particles known as hadrons (particles that interact via the strong interaction) and are defined by having ½-integral spins (1/2, 3/2, 5/2, etc.). They comprise most of the matter that we deal with every day and ultimately decay into protons.[3] The suggestion that dark matter has the same rotational velocity as visible matter has led many to believe that dark matter is comprised of the same material as visible matter—baryonic particles.[2] The baryonic material emits only extremely weak blackbody radiation, and the best candidates are generally massive aggregates of particles rather than individual particles. These massive aggregates are often called Massive Astronomical Compact Halo Objects, or simply MACHOs.

The best candidate for baryonic dark matter is white dwarf stars.[2] White dwarfs are stars that have a mass up to 1.4 solar masses (the Chandrasekhar limit) but are only about the size of the earth. They are characterized by very high densities, high surface temperatures, but low luminosities. Because of the high density they would be able to contribute a significant amount of mass to the universe. However, with such low luminosities it is very difficult to see white dwarfs. With these characteristics combined with the likely abundance, white dwarfs appear to be a likely contributor to the dark matter in the universe.

Another possible contributor is brown dwarfs and Jupiter-sized objects (simply referred to as Jupiters).[2] Brown dwarfs are "aborted stars" whose cores never reached the threshold temperature to start the nuclear fusion process of turning hydrogen into helium. They typically have masses on the order of 1/10 the mass of our sun (or 10^{29} kg). Large objects such as Jupiter (10^{27} kg) also fall into this category. (In fact, there are many astronomers who argue that Jupiter should be classified as a brown dwarf). The only radiation they give off is due to gravitational contraction, which is why they are difficult to detect if not located near us. However, in order to be a significant contributor to the amount of dark matter in the universe it needs to be determined how many there are. If all of the dark matter is composed of brown dwarfs there would need to be one for every 30 ly^3 of space, many trillions over the entire Milky Way. However, the number of known brown dwarfs and brown dwarf candidates in our section of the galaxy is exceedingly slim, making it unlikely that the density of the galaxy's brown dwarf population accounts for all the dark matter.[2]

There are two types of massive baryonic objects that at first glance appear to be perfect candidates for baryonic dark matter: neutron stars and black holes. Neutron stars are very dense, 1.4 -3 solar masses with a radius of about 10 -15 km. Because neutron stars form from burnt-out stars they don't emit any light. High density and no luminosity should make them an ideal candidate for baryonic dark matter. However, the stars that eventually become neutron stars are on the order of 10 solar masses, which means that at least 7 solar masses of material is ejected during the supernova. If there is a significant number of neutron stars in a galaxy, then a majority of the galaxy's mass must have passed through a large number of early supernovae. This would have lead to a larger abundance of the heavier elements than what is currently observed, since so much material was recycled.[2]

The other seemingly good candidate, black holes, also has a high density and no luminosity. However, massive black holes are generally frowned upon by astronomers as a viable baryonic dark matter candidate, since they would cause velocities of any other objects in their vicinity to increase dramatically. Since the component of velocities normal to the galactic disk would also be amplified, spirals' disks would thicken. This is not observed.[2]

With the suspicion that still not all of the dark matter is accounted for, we turn to non-baryonic candidates for answers. The non-baryonic candidates are neutral individual particles, as opposed to the massive aggregates of the baryonic candidates. The lack of charge means there is no electromagnetic interaction with other charged matter, and so there is no radiation emitted from these particles.[2] Non-baryonic dark matter is divided into two generic categories: Cold Dark

Matter (CDM) and Hot Dark Matter (HDM). The “temperature” of dark matter is a reference to the speed of its particles. Hot refers to particles moving at relativistic speeds, and cold refers to more massive particles moving much slower than the speed of light.[4] CDM is also referred to as WIMPs (Weakly Interacting Massive Particles).

The best candidate for HDM is the neutrino, recently discovered to have mass.[2] Neutrinos are hypothetical particles predicted by the theorist Wolfgang Pauli in 1931. Pauli based his prediction on the fact that energy and momentum did not appear to be conserved in certain radioactive decays. He suggested that this missing energy might be carried off, unseen, by a neutral particle which was escaping detection. Three years later, Enrico Fermi named this theoretical particle the neutrino, meaning “little neutral one”. Scientists now believe there are six kinds of neutrinos, one associated with electrons (n_{e-}), one associated with muons (n_{μ}), one associated with the tau particle (n_t), and one associated with each of their antiparticles.[5] Currently, it is believed that there are 10^8 n_{e-}/m^3. If neutrinos do have a mass near its experimental upper limit ($1.8*10^{-5\ \mathrm{MeV}}/_{c}{}^{2}$), then it can contribute significantly to the overall mass of the universe.[2]

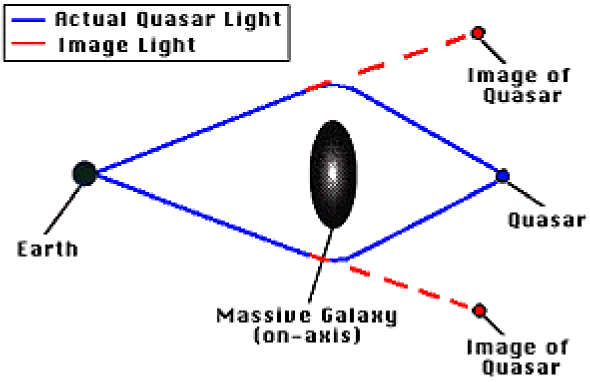
Another non-baryonic dark matter candidate is the axion, an extremely light hypothetical particle whose name was taken from an old brand of laundry detergent.[2] They were proposed independently in 1978 by Steven Weinberg of the University of Texas (who proposed the name) and Frank Wilczek of Princeton. Their belief was that axions were created through CP invariance:

> Axions were produced in the early universe during a violation of CP invariance. Three types of invariance apply to the laws of physics: Charge invariance (C), the conservation of overall charge; Parity invariance (P), which maintains that if the laws work for a certain system S, then they should hold for a system S' spatially reflected through the origin; and Time invariance (T), which maintains that the laws work when time is running either forwards or backwards. The laws of physics are governed by CPT invariance (all three operating simultaneously), but violations of P invariance and CP invariance exist. In the very early universe, symmetries began to break down at some point, leading to a violation of CP invariance. This CP invariance violation was accompanied by large-

scale production of axions; the number of axions produced is probably even more than the number of neutrinos produced.[2]

The typical assumed mass for the axion[6] is in the range of 10^{-6} eV to 10^{-4} eV. If axions exist there would be 10^8 for every cm^3 of space, which could account for a great deal of the dark matter in the universe. Their weak interaction with normal matter could potentially allow them to form dark matter clumps very early on.[2] Unfortunately, scientists have yet to detect axions, though several attempts have been made.

Detecting dark matter has proven to be quite difficult, but not impossible. The detection of baryonic dark matter, such as white dwarfs, can be accomplished through gravitational lensing. It is possible for light from a distant star (or quasar) to be deflected by the gravitational field of a massive object, such as a galaxy or MACHO, producing a twin image of the star (see figure 1).



(figure 1)[7]

Because non-baryonic dark matter interacts so weakly with regular matter, detection of HDM and CDM has proven to be much more difficult than detecting MACHOs. In May of 2000, however, Raymond Davis, Jr. and Masatoshi Koshiba shared the Wolf Prize in Physics for independently proving that it can be done.[8] Davis developed the first large-scale radiochemical neutrino detectors. He obtained the first measurement of the flux of neutrinos from the sun using a 400,000-liter tank of tetrachloroethylene in an abandoned gold mine. A handful of incoming neutrinos were captured by chlorine atoms, which were transformed into argon atoms through the process of inverse β decay. Davis also developed the technique for extracting the small number of Argon atoms from the tank – critical to the experiment's success.[8]

Koshiba led the design and construction of the Kamiokande and its successor, Superkamiokande. The approach used in these detectors was to record the Cerenkov radiation given off by electrons, positrons, and muons created when neutrinos scatter in the detector's large tanks of highly purified water.[8] The detectors provided the recording of the arrival time, energy, and direction of the incoming neutrinos.

Italian and Chinese experimenters from the DAMA (DArk MAtter search) collaboration have set out to find WIMPs of mass 50 times greater than the proton.[9] WIMPs have no charge and no strong interactions, but they do occasionally suffer from head-on elastic collisions with nuclei. The DAMA researchers are looking for such collisions in an array of sodium-iodide crystals of mass 100 kg. The scintillations from the nuclear recoils in the crystals are registered by a series of phototubes. Every effort is made to minimize the much larger effect of recoiling nuclei due to the unwanted background gamma radiation. The experiment is performed underground in chambers where only the most energetic cosmic rays can reach the crystals. The researchers look at the low energy recoils, assuming that those will be the ones resulting from interactions with WIMPs.

Because the earth moves with a periodic velocity with respect the presumed "halo" of dark matter enveloping the galaxy, DAMA researchers look for seasonal changes in the strength of the low-energy recoils. Over a period of four years a fluctuation of less than 1% was detected with the correct phase and period to be a seasonal variation. However, a seasonal effect can be produced by many factors: temperature, time-varying efficiencies, etc. DAMA has ruled out as many factors as possible and plans to continue to improve the experiment by increasing the detector mass to 250 kg.[9]

Another group trying to detect WIMPs is CDMS (Cryogenic Dark Matter Search). The CDMS experiment relies on a newer technology developed over the past decade for this and other astrophysical applications – cryogenic solid-state detectors.[9] Like the DAMA experiment, the CDMS experiment is designed to detect the recoil of nuclei from interactions with WIMPs. The setup contains two cryogenic detectors made of germanium. By using superconducting transition-edge thermometers the detectors measure heat deposited by the recoil of a single nucleus. To measure a temperature so small the apparatus must be cooled below 50mK. However, the experiment is suffering from the same difficulties of the DAMA experiment (background radiation) which has prevented any positive results. Currently, the CDMS detectors are a mere 10 meters below the surface, but plans to install detectors in the Soudan Mine in Minnesota are under way. In the mine, the thick overburden will virtually eliminate the flux of unwanted background radiation.[9]

However, with dark matter detection processes still in their infancy, scientists are left with inconclusive answers as to what dark matter is made of. The vast quantities of non-baryonic particles in the universe leads to the general consensus among theorists that over 90% of dark matter is non-baryonic particles.[8] Michael S. Turner of the department of Physics and Astronomy and Astrophysics at the University of Chicago concludes that, “The theorists’ prejudice of a flat Universe dominated by non-baryonic dark matter is at present just that! However… the theorists’ prejudice is well motivated by both theoretical and observational considerations; and most importantly, the particle dark matter hypothesis can and is being tested.”[6] So, as experiments get more sophisticated and theories become more refined, scientists are finding that most of the substance that makes up our universe is hidden from view. However, cosmologists and particle physicists alike are optimistic that we are well on our way to uncovering the mystery of dark matter.

Works Cited

1. Stephen Hawking's Universe, http://www.pbs.org/wnet/hawking/strange/html/dark.html (1997) by the Educational Broadcasting Corporation.
2. http://www.astro.ucla.edu/~agm/darkmtr.html#hist (1996-7) on dark matter candidates by Alex Gary Markowitz
3. P. Tipler, and R. Llewellyn, *Modern Physics,* 3rd ed. (W.H. Freeman and Company, New York, 1999) pp. 614-615.
4. Stephen Hawking's Universe, http://www.pbs.org/wnet/hawking/strange/html/hotcold.html (1997) by the Educational Broadcasting Corporation.
5. P. Tipler, and R. Llewellyn, *Modern Physics,* 3rd ed. (W.H. Freeman and Company, New York, 1999) pp. 526.
6. Michael S. Turner, "Dark Matter: Theoretical Perspectives", *Proceedings of the National Academy of Sciences of the United States of America*, (June 1993) Vol. 90, pp. 4827-34.
7. http://imagine.gsfc.nasa.gov/docs/features/news/grav_lens.html (on gravitational lensing)
8. Jim Dawson, "Pioneering Neutrino Astronomers to Share 2000 Wolf Prize in Physics", *Physics Today*, March 2000, pp. 91.
9. Barbara Goss Levi, "Explorers Focus More Sharply on Their Prey: Weakly Interacting Dark Matter", *Physics Today*, April 2000, pp. 17.