Search for MACHOS

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Galactic rotation curves suggest dark matter halos in galaxies, constituting the vast majority of their mass. Some of this matter must be baryonic, and perhaps MACHOs make up a some or all of this part. To this end, the method of gravitational microlensing is put to use to detect massive compact objects in the halo of the galaxy, but observing microlensing events with the nearest extragalactic source, the Large Magellanic Cloud. Several large collaborations have invested large amounts of time and resources to this end, and though results are still controversial, it seems clear that MACHOs cannot account for more than ~30% of the dark mass in the halo.

Dark Matter

A variety of astrophysical data suggests that in order for the mean energy density of the universe to be equal to the critical energy density, a large amount of non-luminous "dark matter" must be invoked, some of which is baryonic[1]. A mean energy density which is equal to the critical energy density removes the sensitivity of the initial conditions and fits well with inflation theories, and is thus preferred for aesthetic and theoretical reasons. Galactic rotation speeds, as well as the effects of dark matter on the motions of gas, stars, galaxies, and clusters of galaxies also suggest that ~90% of the matter in the universe does not emit sufficient electromagnetic radiation to be detected on Earth (dark matter)[2]. From our own galactic rotation curve and the motions of other objects around our galaxy, it has been inferred that there is a dark matter halo with ~20 times the visible mass and with a different shape than the disk of the galaxy.

The need for baryonic dark matter in the galaxy suggests that the halos of spiral galaxies such as our own may be partly or wholly due to MACHOs (Massive Compact Halo Objects) and that these objects may consist of aborted stars like brown dwarfs, dim stars, and planets; or of star remnants like neutron stars, white dwarfs, and black holes.

Dark matter can take many forms, including WIMPs (Weakly Interacting Massive Particles) and supersymmetric particles, but the amount of baryonic matter needed to satisfy the nucleosynthesis theory, leading to a critical density of the universe, is nearly matched by the additional mass needed by galaxies to explain their rotation curves. Thus, it seems rational to search for baryonic dark matter, and specifically MACHOs, in the halos of galaxies.

Detecting MACHOs

Without the aid of electromagnetic radiation emission, the detection of MACHOs becomes very difficult. Standard astronomical methods like radio, optical, and X-ray telescopes cannot be used, at least not in a standard way. A method for observing MACHOs that utilizes a consequence of general relativity was first proposed by Paczynski[3] – gravitational microlensing.

Light rays from a source star are bent when they pass near to massive objects in the line of sight to the observer, and this bending causes the observer to see two distorted images of the source (see Figure 1). When the source, deflector, and observer are all in a line, the two images form a ring whose fadius is called the Einstein radius and is given by

$$R_E = \sqrt{\frac{4GM}{c^2}\frac{D_{OL}D_{LS}}{D_{OS}}} \qquad (1)$$

where G is the gravitational constant, M is the lens mass, c is the speed of light, and D_{OL}, D_{LS}, and D_{OS} are the distances between the observer and lens, lens and source, and observer and source, respectively. For many gravitational lensing experiments this leads to two images separated by several arcseconds that can be resolved, but in the search for MACHOs they cannot. The best stars to use as sources tend to be about 60 kpc away in one of the Magellanic Clouds (since they are far enough away to probe a significant amount of the galactic halo but close enough to resolve millions of stars), the lenses are in the Milky Way galactic halo, and the deflectors are typically less than a solar mass, and this leads to an angular separation on the order of milliarcseconds, which is not resolvable. When a microlensing event occurs, however, the brightness of the source star increases due to the combination of the intensities of the two images stacked upon each other, and a short-term increase in the luminosity of a source star can be observerd, and interpreted as a microlensing event and a detection of a MACHO.

A significant problem with microlensing comes in determining the mass of the deflector. Since distance from the Earth,

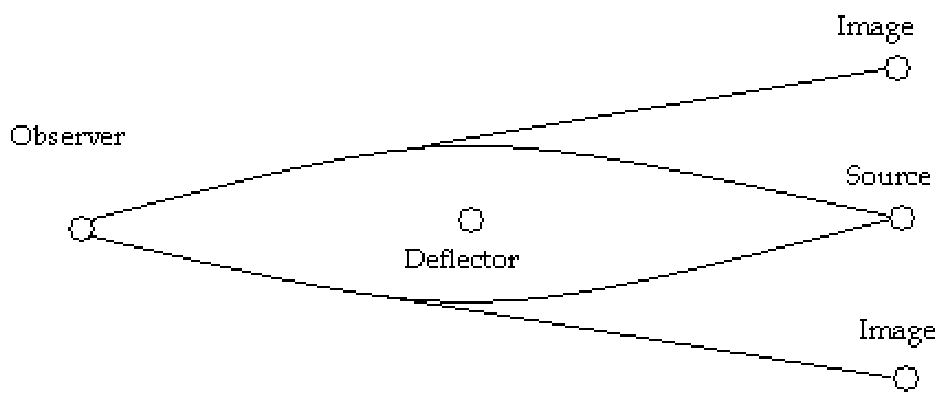

Figure 1 – Deflection of light by gravitational microlensing to create a change in source brightness.

mass, and transverse velocity of the lens all three affect the duration of the lensing event, it is nearly impossible to infer the mass of the lensing object without making other assumptions that may or may not be especially well founded. For example, a lens is usually presumed to be located in the galactic halo with a presumed density, perhaps spherical, and to be traveling mostly transverse to the line of sight. In some cases these presumptions are drawn into question and it is not possible to tell whether the deflector is indeed in the galactic halo, or whether it is located in the Large Magellanic Cloud, with the source. The reliance on assumptions about the shape and speed of the dark matter halo in the data interpretation has led to a variety of poorly understood events, which is real problem for an experiment with such a low event rate to begin with.

Even if we assume a spherical halo composed entirely of MACHOs, the optical depth toward the LMC will still be only on the order of $\tau \approx 5\times10^{-7}$,which still implies that in order to observe a reasonable number of microlensing events, an effort must be made to monitor the luminosities of several million stars for multiple years. Another problem is that the wide range (from 10^{-7} to a few solar masses) for MACHOs yields timescales for the events that range from a few hours to a few months. Thus, in order to monitor as many stars as possible, experiments must be tailored toward observing a specific size of deflector, namely toward either small or large mass deflectors.

Large Scale Collaborations

Several large scale experiments have arisen to survey stars in the Large and Small Magellanic Clouds, including MACHO, an American experiment observing in Australia; EROS 2, a French experiment observing in Chile; and OGLE 2, a Polish experiment observing in Chile. As an example of different experiment styles, EROS 1 monitored 150 thousand stars with very good time sampling, and did not measure any very short duration events, effectively ruling out any large contribution of mass from small mass objects to the overall dark mass of the galactic halo. Meanwhile, MACHO monitored 8.6 million stars but with very little time coverage, rendering them blind to short duration events, but increasing their ability to see long duration events. With the combination of the two datasets, any large contribution to the dark matter content by objects between 10^{-7} and 0.02 solar masses has been effectively ruled out. In fact, the most probable mass found for the lenses was approximately half a solar mass, which was much heavier than expected. This is above the limit for brown dwarfs and suggests white dwarfs or black holes. A limit on white dwarfs in the halo is set by the lack of He in the interstellar medium, however, and there is still disagreement about the interpretation of this data. The collaborations will continue to expand the number of stars monitored, and refine their techniques, minimizing other effects such as variable stars and blending.

Findings

The MACHO project, observing millions of stars in the galactic bulge from 1993-1999, found and cataloged 528 microlensing events[4], of which many were disregarded for reasons such as variable stars, binary events, duplicate events, cataclysmic events, and the like. Great care was taken to eliminate questionable events, and the MACHO group presents 450 of the events as high signal-to-noise and probable microlensing as modeled. Using this data, they have been able to calculate optical depth, and various other parameters.

The EROS 2 project, after the determination of EROS 1 that MACHOs could not be of the very low mass variety, monitored millions of stars in the LMC for a period of 6.7 years. To this end, they observed only one event[5], whereas if the halo had been entirely composed of MACHOs of 0.4 solar masses, they would have expected ~42 events. Using the spherical halo model, this corresponds to a mass fraction of MACHOs to the dark matter of only about 7%, ruling out MACHOs as the main contributor to the baryonic dark matter in our galaxy. This result is at variance with the MACHO collaboration, however, and several potential reasons for the differences have been proposed.

One interesting possibility is that there may be more MACHOs in the halo, but that they are clouds of gas that produce events which are not achromatic (that is, they produce a separation in colors that would not be measured using the current techniques). Another possibility considers an error in the assumption that the galactic halo of dark matter is spherical. N-body simulations have suggested that the halo may in fact be triaxial,[6] simply appearing spherical in certain conditions. This difference in the original distribution of dark matter would explain certain discrepancies in the current data.

Despite disagreements in the data and events observed, all collaborations seem to agree that the dark matter in the galactic halo cannot all be composed of MACHOs. Current estimates seem to range between 0% and 30%[7] for the fraction of the galactic halo composed of MACHOs. This suggests further efforts in the search for cold dark matter, namely the LSP (Lightest Supersymmetric Particle) and axions, and the data could even be consistent with a halo entirely void of MACHOs, with the correct initial conditions. Still, the data is weak enough that a halo composed of entirely MACHOs is not even totally ruled out. Generally, more results are needed, and as it is collected, the conclusions will become more convincing.

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[1] Spiro, M., Aubourg, E., and Palanque-Delabrouille, N., Nuclear Physics B (Proc. Suppl.) **80** 95-108 (2000)

[2] Mancini, L., Jetzer, P., Scarpetta, G, AIP Conf. Proc. 2003, Vol. 695, Issue 1, p339-347

[3] Paczynski B., Astroph. J. **301**, 503 (1986)

[4] Thomas, C.L. *et al*., Astrophys. JS. (2005) *http://wwwmacho.mcmaster.ca/Bulge/catalogPaper.pdf*

[5] Tisserand, P. *et al*., Astron. & Astrophys. (2006) *http://xxx.lanl.gov/PS_cache/astro-ph/pdf/0607/0607207.pdf*

[6] Holopainen, J,. *et al*., Mon. Not. R. Astron. Soc. **368**, 1209-1222 (2006)

[7] Gates, E., Gyuk, G., and Turner, M., Phys. Rev. D, **53**, 4138-4175