DARK MATTER IN THE UNIVERSE

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UNSEEN MASS: Astronomers studying the motions of stars and galaxies throughout the universe have long noticed a strange discrepancy. Stars move around galaxies as if pulled by ten times the matter that we can see. Galaxies move around other galaxies in clusters at speeds implying up to 30 times the visible mass of the cluster. The force of gravity at many size scales seems to exceed the amount of visible matter by more than an order of magnitude. The curious implication of these results - that most matter in the universe is invisible to us - has taunted physicists and astronomers into a hunt for the so-called 'dark matter'. But how do you hunt an invisible animal? The difficulty of observing dark matter is perhaps a boon for theorists, who have proposed viable constituents ranging from black holes a million times more massive than the Sun to swarms of exotic subatomic particles one hundred millionth the weight of a hydrogen atom. Many such proposals, if verified, would offer further, testable predictions about the origin and fate of the universe.

Although, several independent lines of evidence have made the Big Bang a well-established theory of cosmogony, our knowledge of the fate of the universe awaits a measurement of its overall density. If there is insufficient matter to cause a reversal of the expansion initiated in the Big Bang, the universe will continue to expand, eventually (in about 100 billion years) cooling into blackness. But given a high enough density, the expansion will instead stop and the universe recollapse, ending finally in a Big Crunch. The 'critical density' is the value between these two destinies, where the expansion halts, but never quite reverses. Although to many such a finely-tuned cosmos seems unlikely, some very powerful theories (such as the so-called inflationary models) predict that the universe has exactly the critical density. Searches for dark matter are designed to help decide between these competing theories and their predictions.

GRAVITATIONAL LENSING: Since dark matter by definition cannot be directly observed, several recent searches have instead exploited the predicted gravitational effects of its mass on the observed light from nearby stars. The fundamental idea is not new - Einstein first predicted that mass can bend light. Experimental confirmation of this aspect of his general theory of relativity first came during a 1919 total solar eclipse when the images of distant stars passing near the limb of the Sun were displaced by the predicted amount. Extragalactic examples of this 'gravitational lensing' have also been seen. Lensing amplifies the apparent brightness of the distant light source by bending light rays towards our line of sight. Although the relative positions of the 3 elements of a gravitational lens (observer, lensing mass, and background lensed light source) critically affect the brightness amplification factor, the apparent relative motions of extragalactic objects like galaxies and quasars are so slow that observable changes in brightness are not expected in a human lifetime.

If the dark matter pervasive in galaxies is composed of normal atomic (baryonic) matter in 'clumps' such as planets, stars, or black holes, then these masses can also be expected to produce gravitational lensing locally. Since the motions of stars suggest large amounts of dark matter diffused in a halo around our galaxy, we should occasionally see a star in our own galaxy appear to brighten as a dark compact object crosses our line of sight to the star (see Figure 1). Since the mass of a typical star is at most a hundred billionth the mass of a typical galaxy, the strength and duration of the lensing is much smaller than for the extragalactic case. Lensing by compact objects such as stars and planets is thus called 'microlensing'. To produce detectable brightening, the alignment of observer, lensing mass, and lensed star must be less than a micro-arcsecond. That's about the angular size of a dime, a million miles distant. A wide variety of galactic models predict that such alignments in our galaxy should be extremely rare.

A TECHNOLOGICAL CHALLENGE: To detect these rare and often weak microlensing events, millions of stars must be repeatedly observed night after night. This in turn requires sensitive imaging that covers a wide area of sky, accurately measuring the brightness of hundreds of thousands of stars each night. Measurements of each star must be compared from night to night to search for brightness variability. Many types of stars are known to vary for reasons unrelated to microlensing, and are certain to populate the observed field. These include eclipsing binary star systems, pulsating giant stars, and rare episodic outbursts from more exotic systems like dwarf novae and X-ray binaries. A large number of variable stars are being discovered in ongoing searches for galactic microlensing, and these provide a valuable database for understanding these physically revealing phases in the lives of stars. But when the Holy Grail is the dark matter, other varying stars are primarily 'contaminants'. Fortunately, the brightness changes expected from microlensing can be distinguished with only a little extra effort.

Before a change in brightness of a star can be confidently identified as microlensing, it must pass a battery of tests. First, since an alignment only occurs in passing, the event must not repeat. Second, the brightening and subsequent dimming over time (the 'light curve') must follow a well-defined symmetric curve. By convention, the maximum change in brightness must exceed 30% for the event to be considered a detection. Third, the light curve must be achromatic; the shape and amplitude of the variations must be the same when observed through filters of different colors. This last test means a further requirement of the already beleaguered observer - every star must be monitored in two different colors throughout the event (see Figure 2).

EXPERIMENTS & RESULTS: Three teams of astronomers are now trying to acquire a large number of microlensing events to help understand dark matter in our galaxy. These experiments seem to be competing not only for detections of gravitational microlensing, but also for the most amusing acronym. MACHO is from the search for Massive Compact Halo Objects. OGLE is for the Optical Gravitational Lensing Experiment. EROS is the Experience de Recherche d'Objets Sombres (Research Experiment on Dark Objects).

The MACHO team consists of U.S. and Australian astronomers. They use an electronic camera called a CCD (for charge-coupled device), related to the light-sensitive imaging devices found in video cameras. The difference is that their camera is much larger and more sensitive. With 8 CCD arrays, each with 2048 picture elements on a side, more than 33 million separate numbers are generated for each image. This enormous camera is used with an Australian 1.3m telescope, and focused repeatedly on the Large and Small Magellanic Clouds (LMC and SMC), dwarf galaxies orbiting our own. Every clear night, several million stars in the LMC are observed, and their brightness compared to previous measurements. Two exposures, through blue and red filters, are used to ensure that every candidate lensing event is achromatic. When the LMC and SMC dwarf galaxies have swung low in the southern sky, the MACHO team also images the bulge, a spheroidal region of our galaxy toward its center. The nightly imaging of the MACHO experiment means that lensing objects heavier than Jupiter can be detected.

The EROS observations are performed two ways. One method uses computer analysis of large-area photographic plates. These are also most sensitive to dark bodies more massive than Jupiter. A second method points a camera with 16 CCDs toward the LMC, taking more rapid exposures. That data should be sensitive to lensing masses as small as the Earth's.

The OGLE team of Polish and American astronomers uses a single 2048x2048 CCD to image several fields toward the galactic bulge, also measuring several million stars each night.

As of this writing, all these groups have observed very strong candidates for microlensing events. There are now about a dozen seen toward the LMC, and nearly 100 towards the center of our own galaxy. The large number of lensing events toward the bulge was a big surprise, and perhaps indicates a larger stellar density there than was thought. This may be evidence that the Milky Way has a bar-like structure that has been seen in some external galaxies. Most predictions of the number of detectable lensing events had underestimated the effect of lensing stars far from the midpoint of the sight-line to the source star. Although a lensing mass is most effective halfway to the background source, somewhat heavier objects near to the source star can also amplify its light. The results so far suggest lens masses in the range of one to a few tenths the mass of our Sun. These typically represent objects much heavier than Jupiter, and are most likely to be small faint stars that are common throughout our galaxy. Although it now seems likely that microlensing is caused by ordinary low mass stars, much remains to be gleaned from these ongoing studies. Estimates of the amount of baryonic dark matter in compact form in our galaxy awaits more accurate determinations of the search efficiency, the percent of lensing events as a function of mass and distance that can be seen by these experiments. Many more lensing events along several sightlines are necessary to provide better statistics. Will the universe expand forever? How much of the dark matter is baryonic? How much is dispersed in compact masses throughout our galaxy? Time, and lots more data, will tell.