Detection of dark matter in the galactic halo

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More than ninety per cent of the material content of the universe is in the form of dark matter – matter that emits no significant detectable radiation and is, therefore, unseen. Experiments to detect the dark matter by direct as well as indirect means are currently being performed by various groups in the world. This article discusses the recent announcements by two groups of possible detection of dark matter in the dark 'halo' of our galaxy by the gravitational microlensing method.

Two different groups of astronomers have recently reported[1,2] the detection of a total of three 'events' providing what may be called the first 'direct' evidence for the existence of *dark* (i.e., non-luminous) compact objects (of mass less than $1M_\odot$, $M_\odot$ being the solar mass) in the 'halo' of our galaxy. Such dark 'massive astrophysical compact halo objects' (MACHOs) have for long been considered to be a very likely candidate for the composition of (at least a part of) the *dark matter* in the halo of our galaxy. The two independent experiments were in effect searching for signals of a phenomenon called gravitational microlensing. According to this, any MACHO, passing by close to the line of sight from an earth-borne observer to a distant star, would act as a gravitational *lens* that would magnify the light intensity of the image (actually two unresolvable images, see below) of the distant star in a characteristic time-dependent manner that depends on the velocity of the MACHO. The events mentioned above correspond to gravitational microlensing of three different stars in the Large Magellanic Cloud (LMC) (which lies about 50 kpc from the centre of our galaxy; $1\ \text{kpc} \sim 3 \times 10^{21}$ cm) by individual MACHOs in the halo of our galaxy.

A variety of astronomical observations indicate the presence of a large amount of non-luminous matter in the universe, i.e., there is more stuff in the universe than is accounted for by the luminous objects like stars that can be 'seen'. The presence of the dark matter (DM) is betrayed by its gravitational effect on the observed stars, gas, galaxies, etc. The contribution of DM to the total mass density of the universe is, however, not precisely known. Even more uncertain is the nature (i.e., composition) of this DM. Is DM also fundamentally made of baryons (protons and neutrons) as the stars are? If yes, is it in the form of compact objects like stars (that for some reason are non-luminous), or in the form of a diffuse gas? There are arguments and supporting evidence that the DM in the universe cannot be entirely made of baryonic matter. So some amount of non-baryonic DM must also be present. The non-baryonic DM could be in the form of some kind of weakly interacting massive particles (WIMPs), for example, a small-mass neutrino species, or, axions, or perhaps some completely unknown variety of particles. Indeed, a host of new (hypothetical) elementary particles have been suggested as possible candidates for the non-baryonic DM.

Actually, there is a hierarchy of dark matter 'problems' associated with the hierarchy of scales of various astronomical objects in the universe. On the scale of galaxies, for example, measurements of the rotational speed of the material in the outer parts of individual galaxies yield values for the rotational speed so high that the visible matter in the galaxy by itself would be insufficient to explain the observed gravitational binding of the material to the galaxy, and so one must postulate the existence of a certain amount of invisible matter in the galaxy in addition to the visible matter. This and other observations have given rise to the widely held view that the visible 'disk' of a galaxy (like our own Milky Way) is embedded in a roughly spherical dark *halo* whose mass, though not known precisely (it depends on the unknown size of the halo), can be as large as six to seven (or perhaps even ten) times the mass associated with the visible disk. Similarly, on the scale of clusters of galaxies, the dynamics of individual galaxies in the cluster indicates the presence of a large amount of DM in the cluster. There is evidence for the presence of DM on even larger scales. In general, the contribution of DM to the overall mass density seems to be larger on larger scales. While the issues involved in the various DM problems on different scales in the universe are interrelated, the present discussion focusses mainly on the issue of the DM problem on the galactic scale.

By convention, the total mass density of matter (ρ) in the universe is measured in units of what is called the 'critical density', $\rho_c = 1.88 \times 10^{-29} h^2\ \text{g cm}^{-3}$, where

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h is a factor that parametrizes the uncertainty in the value of the Hubble constant H_0 which gives the rate of expansion of the universe in the current epoch ($H_0 = 100\ h$ km s^{-1} Mpc^{-1}, with h thought to be in the range 0.5 to 0.8). The visible matter ('stars') in the universe gives a contribution, $\Omega_{vis} \approx 0.003\ h^{-1}$ to the mass density of the universe, where $\Omega \equiv \rho/\rho_c$. On the other hand, the successful theory of primordial nucleosynthesis in the standard 'Hot Big Bang' model of the universe, which explains the abundance of various light elements in the universe in a natural way, pins down the value of Ω_B, the total (i.e., dark plus visible) contribution of baryonic matter to Ω in a fairly restricted range, giving a mean value of $\Omega_B \approx 0.015\ h^{-2}$. Since $\Omega_B > \Omega_{vis}$, the implication is clear: There must be *some* amount of dark baryons (i.e., baryons not residing in luminous stars) in the universe. Even apart from this argument based on primordial nucleosynthesis, it is only natural to expect that there should be some amount of dark baryonic matter present in the universe. After all, luminous stars are only one possible form of existence of baryonic matter, and there are more ways in which baryonic matter can turn 'dark' than luminous! In particular, there is no *a priori* reason why the basic star formation process itself should not give rise to some stars whose masses are less than $\sim 0.08\ M_\odot$ – such low-mass 'stars' would not have a central temperature high enough to ignite the nuclear reactions at the core, and so, such 'stars' would not shine. Indeed, one possible type of such low-mass stars called *brown dwarfs* are thought to be a good candidate for the baryonic DM in the halos of galaxies. (A brown dwarf is supported against its own gravity by the degeneracy pressure of cold electrons, not by radiation pressure as in 'normal' stars). Among the other possible candidates for the baryonic DM in the galactic halo are neutron stars and white dwarfs too 'cold' to emit any detectable radiation, and stellar-mass black holes. However, a variety of arguments seem to favour brown dwarfs as a very likely candidate for the baryonic DM in the galactic halos. (We remind the reader that here we are talking only about the *baryonic* part of the DM in the galactic halo. It is indeed possible that WIMPs like massive neutrinos or axions also contribute to the total DM in the galactic halo, and laboratory experiments to search for WIMPs are also being performed by various groups; for a recent review of these experiments and a review of DM in general, see, e.g., ref. 3). The recent gravitational microlensing experiments[1,2], the subject of the present discussion, are designed to search for only the *compact* objects as candidates for DM in the galactic halo.

That the phenomenon of gravitational microlensing can be used to detect dark compact objects in our galaxy was first pointed out by Paczyński[4] in 1986. Deflection of the trajectory of any light ray towards a massive body lying close to the light trajectory is one of the classic, experimentally verified predictions of Einstein's theory of gravitation. One specific consequence of this gravitational deflection of light is that a foreground massive point object, lying close to the line of sight from an observer to a distant object (e.g., a star or a quasar), can act as a gravitational *lens* such that two images of the same distant object are seen by the observer. Just as in the case of more familiar optical lens, the light intensity of each of the images is magnified by a calculable amount that depends on the geometry of the lensing configuration and the mass of the gravitational 'lens'. For a source star in the LMC, and taking $1 M_\odot$ as the mass of the deflector (MACHO), the angular separation of the two images of the star is ~ few milli-arcseconds, and so the two images are not resolvable. This is perhaps a blessing in disguise because the magnified light intensities of the two images get combined making the lensing event easier to detect. If the observer, the deflector and the source star all lie in one line then the observer would actually see not just two images but rather a whole continuum of images in the form of a ring, called the 'Einstein Ring'. For a given lens geometry, the radius of the Einstein ring, R_E is proportional to $M^{1/2}$, M being the mass of the deflector. For a $1 M_\odot$ deflector at a distance ~10 Kpc from the observer and for a source star in the LMC, say, R_E is $\sim 1.3 \times 10^{14}$ cm. In a real situation, the observer, the deflector and the source star may not be collinear. Nevertheless, the value of the quantity R_E serves as a useful length scale in the problem. If r is the (perpendicular) distance from the deflector to the line-of-sight joining the observer and the star at any instant of time, then the combined magnification, A, of the two images of the star is a monotonically decreasing function of increasing r; it turns out that detectable amplification occurs only if $r \leq R_E$, in which case $A \geq 1.34$. In a typical situation, as a MACHO approaches and then passes by close to the line-of-sight between the observer and the source star, the light intensity of the star would vary in such a way that the intensity would first increase, reach a maximum (whose value depends on the distance of closest approach to the line of sight), and then decrease. The duration of a typical microlensing event is given by the time scale in the problem, namely, $\tau \equiv R_E/v_T$, v_T being the velocity of the MACHO transverse to the line-of-sight. For typical models of galactic dark halos, $\tau \sim 100(M/M_\odot)^{1/2}$ days, where M denotes the mass of the MACHO. So depending on the mass of the MACHOs, size of the halo, etc., the duration of a microlensing event can be anything from a few days to roughly a year. The probability that at any instant of time a source star in the LMC is microlensed (with a 'detectable' intensity amplification $A > 1.34$) by a MACHO in the halo of our galaxy is roughly 5×10^{-7}. This, together with the fact that the duration of the 'event' can be as long as a year, means that roughly two million stars in the LMC must be monitored (for any intensity variation) for about a year, to detect one microlensing event! The specific features that would distinguish microlensing events from intrinsically variable stars (such stars exist, of course!) are (i) the symmetric nature of the light curve about the time of maximum amplification, (ii) its achromacity (i.e. the intensity variation is independent of the light wavelength), and (iii) the uniqueness of the event (i.e. a given star should be microlensed only once – the probability of a given star being microlensed more than once is essentially nil!).

The USA–Australian MACHO collaboration[1] used a dedicated 1.27-m telescope at the Mount Stromlo Observatory in Australia to monitor about 1.8 million stars near the centre of LMC for about a year. (Actually they also monitor stars in the central 'bulge' of our galaxy and stars in the Small Magellanic Cloud. However, detailed analysis has been done only for the LMC stars). About 250 observations have been made for each of the LMC stars during this one year period. The imaging has been done by using two CCD cameras and the stars are imaged simultaneously in two colours, namely, red and blue, by using a dichroic beam splitter. (For more details of the observational procedure, see the original paper[1].) The MACHO collaboration has reported one microlensing event in which a metal rich helium-core-burning ('clump giant') star in the LMC brightened up by a factor ~ 6.8 over a characteristic time interval of ~ 34 days. Assuming that this is a genuine microlensing event, the most likely mass of the lensing MACHO *estimated* from the duration of the event is ~ 0.1 $M_\odot$. (The duration of the event depends not only on the lensing mass but also on its transverse velocity to the line-of-sight and on the distance from the observer to the lens. All these are unknown *a priori*, which means a *unique* determination of the lensing mass from the duration of the event is not possible, although one may estimate the lensing mass by using a reasonable model for the mass and velocity distributions of the halo dark matter). With only one microlensing event, the MACHO collaboration has made no statement about the fraction of mass density of the halo in lensing objects.

The French EROS collaboration[2] has been monitoring the brightness of about three million stars in the LMC for over three years, and has reported two candidate microlensing events. The reported events are from the digitized data collected from 5° × 5° Schmidt plates of the LMC obtained at the European Southern Observatory at La Silla, Chile. To study the achromacity property of the possible microlensing events the plates were taken with two filters, red and blue. (Actually, the EROS collaboration also has an ongoing programme of imaging the LMC stars by using CCD cameras as in the MACHO collaboration; but the part of the CCD data that has been analysed has not yielded any candidate events so far). The two EROS microlensing events consist of one LMC star that brightened by a factor of ~2.5 over a period of ~54 days, and another star that brightened by a factor of ~3.3 over a period of ~60 days. (The 'duration' of the events as defined by the EROS group is roughly a factor 1/2 of the 'duration' defined by the MACHO group[5]. The above numbers for the event durations of the EROS events are obtained when we use the MACHO definition of the event duration). From the characteristics of these two events, the EROS group infers that the masses of the lensing objects lie between a few times $10^{-2}M_\odot$ and about $1M_\odot$. The EROS group also claims that the 'number of events observed is consistent with the number expected if the halo is dominated by objects with masses in this range'.

With a total of only three events, the case for microlensing cannot be said to have been proved with absolute certainty. To rule out the possibility that the two groups have detected a new class of variable stars and not microlensing events, a large number of microlensing events with lensed stars spread throughout the colour-magnitude diagram will be required (because the gravitational microlensing phenomenon is predicted to be independent of the type of the lensed stars). Also, the range of masses of the lensing dark halo objects and the fraction of the halo mass density in these objects can be estimated reliably only by means of various kinds of statistical tests on a large sample of events. In any case, the MACHO/EROS results by no means prove that baryonic dark matter in the form of compact objects is the full story as far as the galactic halo DM is concerned. In particular, the prospects for directly detecting the non-baryonic component of the DM in the ongoing laboratory experiments are not affected significantly although more microlensing events will help in restricting the possible contribution of any non-baryonic DM to the overall DM density in the galactic halo. The confirmation of a MACHO-dominated picture of the baryonic component of the galactic halo DM will, however, have a lot of implications for our understanding of the basic star formation process which will have to explain how such a large fraction of the baryonic matter ends up in relatively low-mass 'stars'.

For the present, while we wait for more gravitational microlensing events to be accumulated, what can be said with certainty is that gravitational microlensing has proved to be a powerful tool for 'seeing' the dark objects that are believed to constitute a large fraction of the material content of the universe.

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