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REVIEW

The Dark Halo of the Milky Way

Charles Alcock

Most of the matter in the Milky Way is invisible to astronomers. Precise numbers are elusive, but it appears that the dark component is 20 times as massive as the visible disk of stars and gas. This dark matter is distributed in space differently than the stars, forming a vast, diffuse halo, more spherical than disklike, which occupies more than 1000 times the volume of the disk of stars. The composition of this dark halo is unknown, but it may comprise a mixture of ancient, degenerate dwarf stars and exotic, hypothetical elementary particles.

The Milky Way galaxy is visually very striking (*1*). The spectacular rotating disk of stars and gas is a familiar feature of the night sky. The large central bulge is a spectacular sight from the Southern Hemisphere in the southern winter. The Milky Way must be a stunning apparition from the viewpoint of astronomers in the Andromeda galaxy, our nearest large neighbor, just as we have long admired the Andromeda galaxy.

Astronomers have discovered that, in addition to the visible structures, there is an invisible halo of material that envelopes galaxies like the Milky Way (*2*). The dark halo of the Milky Way is much more difficult to investigate than the stars and gas, for the obvious reason that it seems inaccessible to direct observation. Astronomers have discerned, nevertheless, that this dark halo is larger, more massive, and differently shaped than this disk of stars and gas (*3*).

We know little about the physical composition of the dark halo, and this is surely one of the most important unresolved issues confronting astrophysics and cosmology at the turn of this century. Summed over all of the galaxies in the universe, the dark material contained in the halos of galaxies is at least 20 times as massive as the visible material.

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Furthermore, there is evidence that the universe as a whole contains even more dark matter between the galaxies. Arguments based on models of the nuclear processes that occurred when the universe was only minutes old suggest that only a small portion of this dark component can be made of ordinary material (such as protons, neutrons, and electrons) (*4*).

The description of the dark halo is primarily a discussion of our ignorance. The questions that arise include the following: (i) What is its physical extent? (ii) How much does it weigh? (iii) What is its shape? (iv) How did it form? (v) How does it interact with the visible component? (vi) What is it made of? Our approach to these questions is limited by what we can detect. Progress on questions (i) through (v) has come through the study of the motions of tracers, low-mass objects such as small galaxies that orbit the Milky Way.

The approach to question (vi) is more complex, and only preliminary information is available. Resolution of this mystery will involve astronomical observation, terrestrial experimentation, and theoretical insights drawn from elementary particle physics and theoretical cosmology.

The Dark Halos of Other Large Spiral Galaxies

Observations of hundreds of other spiral galaxies reveal many that are similar to the Milky Way (*5*). These similarities include the apparent sizes and luminosities of the galaxies, the mixtures of stars and gas, and morphological characteristics such as the central bulge and the disk of stars and gas that shows spiral structure.

External galaxies are usually simpler to study than the Milky Way because we are outside these systems. This allows us to measure the rotation curves (the rotation speed of the material in the disk versus distance from the center) for hundreds of galaxies. Most of these measurements were made with the 21-cm emission line of atomic hydrogen, a spectral line that is observed with radio telescopes. These rotation curves reveal a stunning regularity: The speed of rotation does not decline at large distance from the center as would be expected if the mass in these systems was distributed in space in proportion to the light. In general, these curves show little or no decline at large distance, and in many cases, slow rises are apparent.

This is in direct contrast to what is seen in the solar system, in which most of the mass is in the sun, around which the planets orbit. The speed of rotation of the planets declines with distance from the sun as the inverse square of the distance. The laws of gravity and motion elucidated by Newton are expected to apply on galactic scales, and in the outer parts of galaxies, well outside the visible material, one might reasonably expect to see a declining rotation curve, as in the solar system. The difference between the expectation based on the distribution of visible matter and the measured rotation curves suggests the presence of a massive, unseen component: the dark matter.

Dark matter is a pervasive feature of disk galaxies. There have been many studies of the rotation of external galaxies, perhaps the most comprehensive of which was done by Persic *et al.* (*5*), who derived a universal rotation curve based on a sample of about 1100 spiral galaxies. There is clear evidence for dark matter because, for disk galaxies of all sizes, the rotation curves cannot be reconciled with models in which the mass is distributed in proportion to the light.

The Mass of the Dark Halo of the Milky Way

The investigation of our dark halo is complicated first by its invisibility and second by our immersion deep inside it and its gravitational potential well. Nevertheless, much has been learned from the study of the motions of gas clouds, single stars, globular clusters of stars, and eight small, satellite galaxies that orbit within the dark halo. This subject has been reviewed many times, prominently by Fich and Tremaine (*3*) and more recently by Zaritsky (*6*). Kochanek (*7*) showed that the estimation of the total mass of the halo of the Milky Way depends sensitively on the sample of objects that is used. Much is known about the mass distribution in the inner 10 kpc, which is the visible component, and progressively less is known as we move away from the center. This discussion will start, then, in the inner region of the halo.

The rotation curve of the Milky Way can be measured with some confidence for radii (distance to the center) less than that of the sun. The sun is about 8 kpc from the center of the Milky Way. The tangent point method (*1*) assumes that the motions are circular. Observations of all the material along a line of sight (usually this is done with the 21-cm line of atomic hydrogen) will show a wide range of radial velocities. The highest velocity picks out the circle that is tangent to the line of sight. The tangent point method does not work for material outside the solar circle (lines of sight have no tangent points). The rotation curve thus depends on determining not only a radial velocity for some stars or gas but also the distance to the objects. Distances are notoriously difficult to estimate with confidence (*8*), and astronomers have usually resorted to indirect techniques.

One successful indirect technique is based on the variation of the thickness of the disk of atomic hydrogen (*9*, *10*) (Fig. 1). There is no evidence for a decline in rotation speed at large radii. The contributions to the rotation curve from the disk of stars and the central bulge account for a decreasing fraction of the total as one moves away from the center. The rotation speed due to the invisible, dark halo (corona) is also shown.

The rotation curve of the Milky Way may be approximated by $v(r) = \Theta_o$, where Θ_o is the rotation speed at the solar circle and $v(r)$ is the rotation speed at radius r. This is a good approximation for $r > 20$ kpc, which for our purposes can be termed the outer halo, and explicitly assumes that the rotation curve is flat in this region. With the additional assumption that the matter distribution is spherically symmetric, the density of matter becomes $\rho = \Theta_o^2/(4\pi G r^2)$, and the total mass interior to radius r becomes

$$M(r) = r\Theta_o^2/G \qquad (1)$$

where G is Newton's constant. The mass interior to radius r is proportional to r. This cannot extend indefinitely because the Milky Way must have an outer edge somewhere, and thus the simple flat rotation curve also cannot extend indefinitely. The model shows that estimating the total mass of the Milky Way is dependent on analysis of the outer regions of the Galaxy.

A modification of this model rotation curve is to terminate the Galaxy abruptly at some maximum radius R_{max}. The rotation curve for $r > R_{max}$ is given by Kepler's law, as in the solar system, and the total mass of the Milky Way is $M_{total} = R_{max}\Theta_o^2/G$. More sophisticated models have been constructed, for example, by Jaffe (*11*) and Wilkinson and Evans (*12*). These models have no discontinuity in density at R_{max} and allow detailed analyses of the motions of the small galaxies that orbit the Milky Way. The simple model

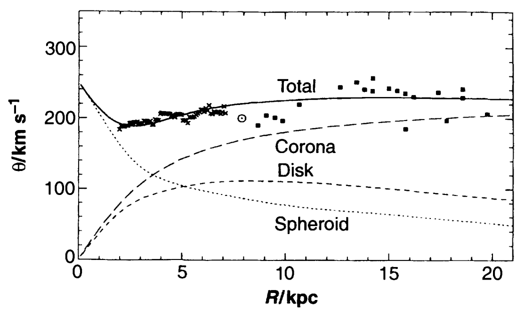

Fig. 1. Rotation curve for the Milky Way derived from 21-cm measurements [from Merrifield (9)].

described above mimics these sophisticated models closely enough for our discussion.

The region between 20 kpc and R_{max} can be investigated with the velocities of exceptionally fast nearby stars (stars moving more than twice as fast as the sun, which are within a few hundred parsecs of the sun), with the orbits of small galaxies in the outer regions, and by examining the dynamical history of the Milky Way and Andromeda. The first method is based on the hypothesis that nearby stars are gravitationally bound to the Galaxy. Stars that move faster than the escape speed v_e will leave the Galaxy. For our simple model, $v_e^2 = \Theta_o^2\{\ln[(GM_{total})/(\Theta_o^2 R_o)] + 1\}$, where R_o is the radius of the solar circle. This expression shows that v_e is only weakly dependent on M_{total}. Additionally, Little and Tremaine (*13*) and Kochanek (*7*) have shown that this technique is sensitive to assumptions made about the distribution function of velocities close to v_e. Kochanek's application of this technique to data from Carney *et al.* (*14*) yielded $M_{total} > 3.8 \times 10^{11}$ solar masses ($M_\odot$).

The study of the motions of globular clusters and small galaxies in principle should allow us to estimate the mass of the dark halo. These objects are found out to a radius of ~250 kpc (a small galaxy named Leo I) and are distributed usefully across the sky (that is, they are not confined to the plane). Their usefulness is compromised in part because full, three-dimensional velocities are known only for a few of them (*7*) and because there is no direct relation between their velocities and locations and the mass of the Milky Way. These difficulties are addressed by making models of the Milky Way and models of the distribution of velocities of the tracer objects and then using Bayesian statistical analysis to determine bounds to M_{total}. This approach was introduced by Little and Tremaine (*13*), developed by Kochanek (*7*), and most recently applied by Wilkinson and Evans (*12*). The latter authors had the most data at their disposal. They concluded that $M_{total} \sim 2 \times 10^{12}$ $M_\odot$, that with high confidence $M_{total} < 6 \times 10^{12}$ $M_\odot$, and that the halo extended out beyond 200 kpc from the center of the galaxy. Uncertainty in the mass determination results primarily from systematic errors due to the small number of tracers used.

There is an additional, very interesting technique. The Andromeda galaxy is falling toward us, and this is due to the gravitational attraction of the Milky Way, which draws it away from the Hubble expansion of galaxies. The masses of the two galaxies must exert sufficiently strong gravitational pull to accomplish this during the time available. The estimate depends on of the age of the universe and the ratio of the masses of the two systems, but not on the distribution of matter within each galaxy (*15*). Zaritsky (*6*) obtained $M_{total} > 1.4 \times 10^{12}$ $M_\odot$ with this technique. The similarity between this result and that obtained from the analysis of satellite orbits is reassuring.

Thus, the Milky Way is dominated by a large, dark halo. This halo extends far beyond the visible disk, plausibly beyond 200 kpc, and its mass is $\sim 2 \times 10^{12}$ $M_\odot$ (certainly $> 1.4 \times 10^{12}$ $M_\odot$, and possibly as high as 6×10^{12} $M_\odot$).

The Shape of the Dark Halo

The determinations of the mass of the Milky Way described above all assumed that the Galaxy is spherically symmetric. This is a reasonable guess for the dark halo, which dominates the mass, but there is little observational evidence to support it. All of the data for the inner portions of the halo are derived from the plane of the disk and have no direct bearing on the distribution of material far from this plane. The techniques that are applied to the outer halo, where most of the material is found, do involve tracers that are more usefully distributed around the Galaxy and are not confined to the plane. However, the information that can be gleaned from the high-velocity stars and from the satellite galaxies presently is insufficient to place strong bounds upon the shape of the dark halo.

The situation with external galaxies is not much better. The many external galaxies described above have been investigated primarily with the use of tracers that are confined to the plane of each galaxy. This is certainly true for the rotation curve data. There are a few interesting exceptions, known as the polar ring galaxies. These are spiral galaxies that are encircled by perpendicular rings of material. Sackett and Sparke (*16*) concluded from detailed analyses of the galaxy NGC 4650 that the dark halo of this galaxy is moderately flattened, with an axis ratio of about 2:1. In the absence of data, we can turn to theory for guidance. Computational models of the formation of galaxies suggest that the dark halos are more or less spherical (*17*). This is a general consequence of the hypothesis that the halo is made up of dissipationless material, which does not radiate away its internal energy during gravitational collapse the way gaseous material does.

The Composition of the Dark Halo

Dark matter dominates the Milky Way. The investigations that lead to this conclusion rest entirely on studies of motions of tracers within the Milky Way. It is necessary, however, to discuss contemporary cosmology and elementary particle physics to develop an understanding of the possible constituents of this dark matter. The points that are germane to this discussion are best summarized with the cosmic density parameter Ω_c, which is the mean density in the universe of component *c*, in units of the mean density that would just allow the universe to expand forever (*18*). First, the present-day mean density in stars appears to be $\Omega_* \sim 0.003$ (*18*). Stars make up a small fraction of the material in the universe.

Second, the mean density in baryonic matter (made up of the atoms and molecules familiar to us all) is $\Omega_B \sim 0.04$ (*4*). This result is based on calculations of the production of the isotopes of the elements hydrogen, helium, and lithium in the first minutes after the Big Bang and the comparison of these calculated yields to observation. The concordance is one of the most successful in all of cosmology. Because $\Omega_B > \Omega_*$, we can conclude that most of the baryons in the present-day universe are in some dark form (*18*).

There are two additional conclusions from cosmology that we need. First, the mean density in all of the dark halos of galaxies (Ω_H) is estimated by measuring the total luminosity per unit volume and multiplying by a mass-to-light ratio for galaxies. The key assumption is that mass-to-light ratios are universal, which has not been demonstrated. This procedure yields $0.05 < \Omega_H < 0.1$ (*18*). Finally, the total density of matter appears to be larger still: $\Omega_M > 0.2$ (*19*).

$\Omega_M > \Omega_B$ is a robust conclusion, which leads to the remarkable hypothesis that most of the matter in the universe is not baryonic (*18–20*). This nonbaryonic dark matter is a rich source of speculation, which has focused on two favored candidates, the neutralino and the invisible axion, which are discussed below.

Thus, there are at least two types of dark matter: baryonic and nonbaryonic. There is no known mechanism that would preferentially make galaxy halos out of one or the other type (*21*), so we are left to conclude that dark halos are mixtures of at least two flavors of dark matter: baryonic and either neutralinos or axions.

Experimental Searches for Baryonic Dark Matter

Baryonic material can exist in several dark forms, including planets, brown dwarfs, very old degenerate dwarf stars, and neutron stars. (Black holes are frequently added to this list, but strictly speaking a black hole is not made up of matter.) These objects, most of which emit some light but at levels below present-day detection thresholds, are collectively known as massive compact halo objects (MACHOs). Paczynski (*22*) suggested that MACHOs could be detected by their gravitational microlensing of background stars. This indirect technique does not depend on light emitted by the MACHOs. Good reviews of this area of research are available (*23*).

The simple gravitational lens comprises a pointlike source of light (typically a star), a pointlike massive deflector (the MACHO), and an observer. It is characterized by an angular size θ_E, called the Einstein radius. If the target star lies directly behind the MACHO, its image will be a ring of light of this angular radius. If the MACHO is separated from the line of sight to the source by some finite angle, $\theta = b/D_d$ (where b is the physical distance of the MACHO from the line of sight and D_d is the distance from observer to the MACHO), the ring splits into two arcs. The combined light from the two images produced by the gravitational lens causes a net magnification of the light from the star of

$$A(u) = (u^2 + 2)/u\sqrt{u^2 + 4} \quad (2)$$

that depends only on $u = \theta/\theta_E$. Large magnification occurs when $u \ll 1$. The Einstein radius is related to the underlying physical parameters by

$$\theta_E = \sqrt{\frac{4GMD_{ds}}{c^2 D_d D_s}} \quad (3)$$

where M is the MACHO mass and D_d, D_s, and D_{ds} are the observer-lens, observer-source, and lens-source distances, respectively. The term microlensing is used when θ_E is so small that the two images cannot be separated with current observing equipment and the image doubling cannot be seen. Frequently, the related quantity $R_E = \theta_E D_d$ is referred to as the radius of the Einstein ring, where R_E is the physical size of the ring described above, measured at the location of the MACHO. For a source distance of 50 kpc and a deflector distance of 10 kpc, the Einstein radius is $R_E \sim 8\sqrt{M/M_\odot}$ astronomical units.

The observable phenomenon, as the MACHO moves at constant relative projected velocity **v**, is the varying magnification of the light from the star (Fig. 2). Note the substantial magnification. This phenomenon is distinctive, and with high-quality data, it is straightforward to separate gravitational microlensing from other forms of variation in stars.

The frequency of gravitational microlensing by MACHOs in the halo of the Milky Way is low (*22*). At most, one star in 2×10^6 is expected to be magnified at any instant. The surveys for this phenomenon thus follow millions of stars in the hope of detecting such events. Target stars are drawn from the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC). These are two satellite galaxies that orbit within the halo of the Milky Way, but at sufficient distance that one samples a large chord through the halo. Four groups have reported detections of microlensing events: the MACHO Project (*24*), the EROS Project (*25*), the OGLE Project (*26*), and the DUO Project (*27*). Of these groups, only the MACHO and EROS projects have reported survey results toward the Magellanic clouds.

When no detections of microlensing events are made in a microlensing survey, the interpretation is unambiguous. The MACHO and EROS projects have detected no evidence for microlensing toward the LMC with event durations between a few hours and 20 days. The experiments have good sensitivity to events over much of this range, and the absence of detections is statistically significant. A combined analysis of the data from MACHO and EROS has shown that objects in the mass range $10^{-7} < M/M_\odot < 10^{-3}$ contribute less than 10% to the dark matter in the Milky Way (*28*). Planets and brown dwarfs fall into this mass range, so these promising objects are not major contributors to the mass budget of the dark halo.

The MACHO Project has detected over 20 microlensing events toward the LMC and SMC. A comprehensive analysis (*29*) concludes that MACHOs are a substantial constituent of the halo, but not the dominant component (Fig. 3). Furthermore, the maximum likelihood estimate of the mass of the lensing objects is $\sim 0.5\ M_\odot$. There is controversy regarding the quantitative interpretation of these data. It has been suggested that some or all of the lenses are in the LMC itself (*30*), that there may be a small galaxy between us and the LMC (*31*), that debris torn from the LMC by tidal gravitational forces may have supplied the lenses (*32*), and even that a severe warp of the disk of the Milky Way has placed disk material into the line of sight (*33*). No one of these suggestions is really satisfactory in explaining the data, and none have the elegance of the dark halo interpretation. But they do greatly complicate the interpretation, and the microlensing community is designing new programs to address these ambiguities. The most promising approach is to collect a much larger set of events and to estimate directly the locations of these events (*34*). Should one or more of these suggested nonhalo explanations for the microlensing events turn out to be correct, the inferred MACHO fraction in the dark halo will have to be revised downward.

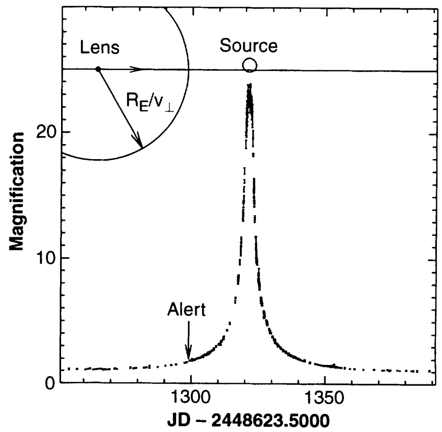

Fig. 2. Light curve for a well-sampled microlensing event from the MACHO Project. The date this event was detected by the MACHO Alert system is indicated with an arrow. The schematic relates the Einstein radius θ_E to the angular size of the source star and indicates transit of the lens across the source face (*24*).

There is exciting new evidence that suggests the MACHOs are ancient degenerate dwarf stars. Hansen (*35*) showed that these objects would have bluer colors than naively expected from the cool surface temperatures such old objects would have. Ibata *et al.* (*36*) found four objects in the Hubble Deep Field (HDF) with these colors. The HDF is a very deep exposure of the sky taken with the Hubble Space Telescope (*37*), and Ibata *et al.* compared that exposure with another taken 2 years afterward. They claim to have detected proper motion in two of these objects. Proper motion is angular movement on the sky, which in this case is consistent with these being halo degenerate dwarf stars. Follow-up data will confirm (or refute) this interpretation, and new data should find many such objects, if ancient degenerate dwarfs stars make up much of the dark halo.

Experimental Searches for Nonbaryonic Dark Matter

The experimental search for nonbaryonic dark matter is very challenging. The objects in question are hypothetical, so their properties and their densities are not known. Theory does offer some guidance, and the experiments have focused on two plausible candidates, the neutralino and the axion. Both are examples of cold dark matter (*18*).

The neutralino is an object that arises in theories of elementary particles involving supersymmetry (*20*). The neutralino weighs as much as a large atom or small molecule (between ~30 and ~10^4 times as much as a proton) and interacts with normal matter only

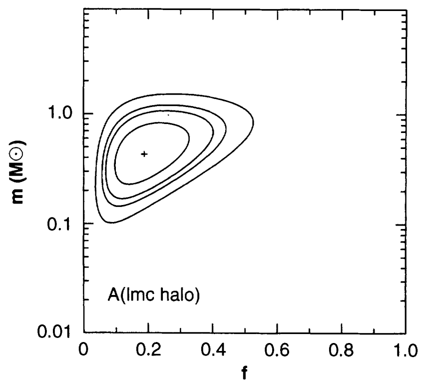

Fig. 3. Likelihood contours for MACHO mass *m* and halo fraction *f* for a typical halo model. The plus sign shows the maximum likelihood estimate, and the contours enclose regions of 68%, 90%, 95%, and 99% probability.

through the weak interaction (similar to the neutrino-matter interaction). The neutralino is a specific example of a weakly interacting massive particle (WIMP).

The neutralino, if it exists, would have been copiously produced in the early universe. If we assume that neutralinos make up most of the matter in the universe, we may further assume that most of the dark matter in the Milky Way is made up of neutralinos. Thus, their density in the solar neighborhood is given by the expression $\rho = \Theta_o^2/(4\pi G r^2)$ derived above. Additionally, modeling the production of neutralinos in the early universe places restrictions on the possible choices of interactions and masses of the neutralinos.

Estimated interaction rates of halo neutralinos with normal matter are low, of order one interaction per kilogram of matter per day. This interaction would impart momentum and energy to one nucleus in the detector. Exquisite experiments have been devised to look for these rare interactions in materials as diverse as silicon, germanium, sodium iodide, and alumina (*20*). To date, none of these experiments have sufficient sensitivity to place strong constraints on the neutralino (Fig. 4), but improvements in the coming decade will enable the neutralino to be either discovered, or largely ruled out, as a major constituent of the dark matter.

The axion is different from the neutralino. It was hypothesized in an attempt to solve a problem in quantum chromodynamics (*38*), and later it was realized that axions might be produced copiously in the early universe (*39*). The axion is a very light object, with mass between 10^{-6} and 10^{-3} eV (this makes it $<2 \times 10^{-9}$ times as massive as the electron and $<3 \times 10^{-14}$ times as massive as the neutralino). The axion does interact with photons, and a sensitive experiment is searching for this very rare, low-energy interaction (*40*). Preliminary results are beginning to place constraints on the properties and abundance of cosmic axions (Fig. 5).

Looking Forward

Much remains to be learned about the dark halo of the Milky Way, but in all likelihood the next two decades will see the resolution of some of the mysteries described above. Two important new astrometric space missions, NASA's Space Interferometry Mission (SIM) and the European Space Agency's GAIA, will provide distances to and proper motions for a large number of stars that trace the gravitational field of the dark halo. Wilkinson and Evans (*12*) claim that data from SIM and GAIA will allow the mass of the dark halo to be determined to within 20%.

New microlensing programs (*34*) will allow the contribution of MACHOs to the dark matter to be determined. Improvements will include greater sensitivity to the microlensing of very faint stars and the ability to routinely determine the locations of the microlenses. In addition, the tentative detection of ancient degenerate dwarf stars in the dark halo will be confirmed or refuted with new data, primarily from new ground-based instruments such as the wide field-of-view camera on the Subaru telescope.

The experimental searches for neutralinos and axions will mature in the coming decade. The detectors should achieve the sensitivity needed to detect these hypothetical particles if one or both of them contribute substantially to the dark matter. In summary, the prospects are bright that most of the important parameters of the dark halo of the Milky Way will be determined in the course of the next two decades.

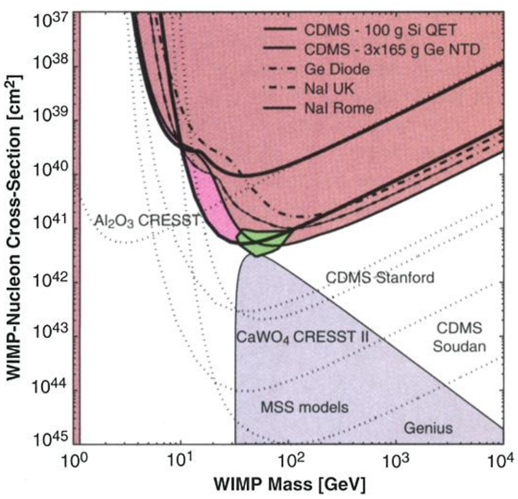

Fig. 4. Current limits on WIMP (neutralino) cross sections as a function of the WIMP mass. The region at the top is excluded by experiments. The blue shaded region at the bottom is the rates predicted by minimal supersymmetric models, including constraints from accelerator experiments (*20*). Extrapolation of various projects is shown as dashed lines (figure supplied by B. Sadoulet).

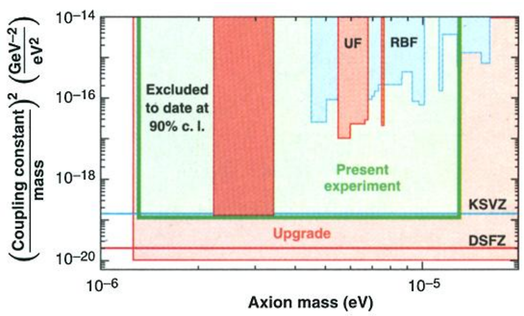

Fig. 5. Regions of axion mass and coupling to photons excluded by Sikivie-type microwave-cavity experiments. RBF, Rochester-Brookhaven-Fermilab; UF, University of Florida; Red, LLNL-MIT-UF-FNAL-LBNL-INR (Moscow). Shown also are predicted couplings from two different axion models and the projected reach for an experiment based on superconducting quantum interference device (SQUID) amplifiers. As all axion couplings are proportional to mass, the presentation has been flattened by displaying the coupling divided by the axion mass (figure supplied by K. van Bibber).

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REVIEW

The Baryon Halo of the Milky Way: A Fossil Record of Its Formation

Joss Bland-Hawthorn[1] and Ken Freeman[2]

Astronomers believe that the baryon (stellar) halo of the Milky Way retains a fossil imprint of how it was formed. But a vast literature shows that the struggle to interpret the observations within a consistent framework continues. The evidence indicates that the halo has built up through a process of accretion and merging over billions of years, which is still going on at a low level. Future satellite missions to derive three-dimensional space motions and heavy element (metal) abundances for a billion stars will disentangle the existing web and elucidate how galaxies like our own came into existence.

In recent years, we have passed an interesting landmark. With the most powerful telescopes, we can now reach as many galaxies as there are stars in our Galaxy: about 100 billion sources. The oldest stars in our Galaxy are of an age similar to the light travel (look back) time of the most distant galaxies in the Hubble Deep Field (*1*). For these galaxies, the cosmological redshift (*2*) measured from galaxy spectra presently takes us to within 5% of the origin of cosmic time—the Big Bang. For the stars, their upper atmospheres provide fossil evidence of the available metals at the time of formation, and astronomers use a variety of techniques for dating a star from its spectrum (*3*). The old Galactic stars and the distant galaxies provide a record of conditions at early times in cosmic history, and both harbor clues to the sequence of events which led to the formation of galaxies like the Milky Way. But the oldest stars, like the most distant galaxies, are exceedingly faint and lie at the limit of modern observing techniques.

Galaxies as we see them now, at low redshift, can be divided into two classes: 80% are gas-rich (mostly disk spiral and irregular galaxies) and 20% are gas-poor [including the elliptical, earliest-type (S0) and dwarf spheroidal galaxies]. In the special environment of dense galaxy clusters, only about 40% of the galaxies are gas-rich. But in the early universe, the Hubble Deep Field has shown us that galaxies are mostly irregular. Broadly speaking, disk spirals and small spheroids are supported by rotation, whereas large spheroids are supported by random stellar motions and have little or no rotation. To confuse matters, some spheroidal galaxies have a disk component, and most disk galaxies like the Milky Way have spheroidal components. While the various galaxy types pose a challenge to any formation theory, the relative importance of the disk and the spheroid accounts for much of the variety in galaxy morphologies (*4*).

When the early universe was cool enough to form atoms, dark matter and baryons were thought to have co-existed in small clumps (*5*). As time progressed, gravity caused the clumps to cluster together. This picture forms the basis for the hierarchical cold dark matter (CDM) model, which places galaxy formation within a cosmological context. Sophisticated N-body CDM simulations of the growth of structures in the early Universe have been successful at reproducing some observational properties of galaxies (*5*). Current models include gas pressure, metal production, radiative cooling and heating, and prescriptions for star formation. The models predict that lower mass clumps are denser, which is borne out by theory (*6*) and observation (*7*). Moreover, the outer parts of galaxies are expected to be accreting low mass (10^7 to 10^8 $M_\odot$) objects even to the present day (*8*, *9*).

The orbital time scales of stars in the outer parts of galaxies are several billion years and it is here we would expect to find surviving remnants of accretion. Observational studies of the Galactic halo attempt to find stars of a given type within a localized region of six-dimensional phase space where each star has a velocity (v_x,v_y,v_z) and a location (x,y,z) within the Galaxy. Most stellar types can exist over a range of metal abundances. The heavy element abundance can provide information on when in the Galaxy's history the star was formed (*3*). The published literature on the baryon halo is very extensive and, for the most part, in a state of flux. However, most astronomers agree that tantalizing clues are beginning to emerge of how the Galaxy materialized out of the hot, dense, early universe. In this review, we focus on the fossil evidence from the baryon halo of the Milky Way (near-field cosmology) with occasional reference to the high redshift universe (far-field cosmology).

The Milky Way

Our Galaxy, the Milky Way, can be divided into three parts: a baryon halo (which includes the stellar halo and globular clusters), a baryon disk with the associated stellar bulge, and an unseen dark (non-baryonic) halo, which accounts for about 95% of the mass of the Galaxy (*10*) (Fig. 1). The disk and the dark halo are addressed in other review articles in this special issue (*11*). While the gravitational influence of dark ha-

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