THE PARTICLE- AND ASTRO-PHYSICS OF DARK MATTER

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ABSTRACT

We review some recent determinations of the amount of dark matter on galactic, cluster, and large scales, noting some puzzles and their possible resolutions. We discuss the interpretation of big bang nucleosynthesis for dark matter, and then review the motivation for and basic physics of several dark matter candidates, including Machos, Wimps, axions, and neutrinos. Finally, we discuss how the uncertainty in the models of the Milky Way dark halo will affect the dark matter detection experiments.

1. Introduction

It is remarkable that here, at the end of the 20th Century, when science has produced the top quark, and measured tiny fluctuations in the microwave background, we still don’t know what the primary constituent of the Universe is. This is the stuff that dominates gravity on galactic scales, and determines the ultimate fate of the Universe, but we have almost no idea what it is. It doesn’t emit or absorb electromagnetic radiation at any known wavelength, but it is “seen” through its gravitational effects on scales from tiny dwarf galaxies, to large spirals like the Milky Way, to the largest scales yet observed. The next speaker (Caldwell, these proceedings) will describe exciting new developments in the possibility of detecting this dark matter; a topic which has progressed dramatically in the past few years. I will set the stage for his talk by reviewing recent developments in the amount and location of dark matter, mention some puzzles, and describe some of the more popular dark matter candidates.

2. Dark Matter Inventory

Evidence for dark matter (DM) exists on many scales, and it is important to keep in mind that the dark matter on different scales may be different – the dark matter in dwarf spirals may not be the dark matter which contributes \( \Omega = 1 \); in fact, the \( \Omega = 1 \) dark matter may not exist. This consideration is especially important when discussing dark matter detection, since detection is done in the Milky Way, and evidence for dark matter outside the Milky Way may not be relevant.

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So, let me start with an inventory of dark matter in the Universe. The quantity of dark matter on different scales is quoted using \( \Omega = \rho/\rho_{\text{crit}} \), where \( \rho \) is the density of some material averaged over the Universe, and \( \rho_{\text{crit}} \) is the critical density. Most determinations of \( \Omega \) are made by measuring the mass-to-light ratio \( \Upsilon \) of some system and then multiplying this by the average luminosity density of the Universe: 

\[
j_0 = 1.7 \pm 0.6 \times 10^8 h^{-1} L_\odot/M_\odot \text{ (Binney and Tremaine 1987; Davis & Huchra 1982; Kirshner et al. 1983).}
\]

Here \( h = 0.4 - 1 \) parameterizes our uncertainty of the Hubble constant. Note the factor of two uncertainty in this number, which implies that all determinations of \( \Omega \) which use this method will be uncertain by at least this amount. In fact, almost all determinations of \( \Omega \) do use this method; the exceptions being determination of \( \Omega_{\text{baryon}} \) from big bang nucleosynthesis, and the large scale determinations from bulk flows. For example, the mass-to-light ratio in the solar neighborhood is \( \Upsilon \approx 5 \), giving \( \Omega_{\text{lum}} = 0.003 h^{-1} = 0.003 - 0.007 \). If the solar neighborhood is typical, the amount of material in stars, dust and gas is far below the critical value.

### 2.1 Spiral Galaxies

The most robust evidence for dark matter comes from the rotation curves of spiral galaxies. Using 21 cm emission, the velocities of clouds of neutral hydrogen can be measured as a function of \( r \), the distance from the center of the galaxy. In almost all cases, after a rise near \( r = 0 \), the velocities remain constant out as far as can be measured. By Newton’s law for circular motion \( GM(r)/r^2 = v^2/r \), this implies that the density drops like \( r^{-2} \) at large radius and that the mass \( M(r) \propto r \) at large radii. Once \( r \) becomes greater than the extent of the mass, one expects the velocities to drop \( \propto r^{-1/2} \), but this is never seen, implying that we do not know how large the extended dark halos around spirals are. For example, the rotation curve of NGC3198 (Binney & Tremaine 1987) implies \( \Upsilon > 30h \), or \( \Omega_{\text{halo}} > 0.017 \). The large discrepancy between this number and \( \Omega_{\text{lum}} \) is seen in many external galaxies and is the most robust evidence for dark matter. This is fortunate since searches for dark matter can be made only in spiral galaxies; in fact only in our spiral, the Milky Way. Unfortunately, the rotation curve of the Milky Way is poorly constrained, which leads to uncertainty in the amount of dark matter in our Galaxy. However, there is less secure evidence for substantial dark matter in our Galaxy. By studying the motion of dwarf galaxies (especially Leo I at a distance of 230 kpc) Zaritsky, et al. (1989) find a mass of the Milky Way of \( M_{\text{MW}} = 1.25^{+0.8}_{-0.3} \times 10^{12} M_\odot \), for \( \Upsilon_{\text{MW}} \approx 90 \), and \( \Omega_{\text{MW}} \approx 0.054 h^{-1} \) (assuming the Universe is like the Milky Way). There are a limited number of small satellite galaxies around the Milky Way, so the uncertainty in this measurement is large. However, for external galaxies Zaritsky (1992) used a sample of 69 small satellite galaxies around 45 spirals similar to the Milky Way to estimate the total mass for a “typical” spiral. He found that \( M \approx 10^{12} M_\odot \) at 200 kpc from the center, implying \( \Omega_{\text{spirals}} \approx 0.087 h^{-1} \) out to this radius. Even in this case, there is not strong evidence that the rotation speeds drop, so there is no good upper limit to \( \Omega_{\text{spiral}} \). This number is similar to the number found by the Local Group Timing method (e.g. Binney & Tremaine 1987).
2.2 Clusters of Galaxies

Moving to larger scales, the methods of determining \( \Omega \) become less secure, but give larger values. There is a great deal of new evidence on dark matter in clusters of galaxies, coming from gravitational lensing which Tyson (these proceedings) will discuss, from X-ray gas temperatures, and from the motions of cluster member galaxies. For example, consider the Coma cluster of around a thousand galaxies; the cluster which Zwicky (1933) used to first hypothesize that dark matter existed. White et al. (1993) recently collated some of the data on the Coma cluster, reporting separate measurements of the amount of mass in stars, hot gas, and in total. Within a radius of \( 1.5 h^{-1} \) Mpc, they give

\[
M_{\text{star}} = 1.0 \pm 0.2 \times 10^{13} h^{-1} M_\odot \\
M_{\text{gas}} = 5.4 \pm 1 \times 10^{13} h^{-5/4} M_\odot \\
M_{\text{total}} = 5.7 - 11 \times 10^{14} h^{-1} M_\odot,
\]

where the total mass is estimated in two completely different ways. The first method is a refinement of Zwicky’s method of using the radial velocities of the member galaxies, and the assumption of virialization to gauge the depth of the gravitational potential well. The second method makes use of the ROSAT X-ray maps and the assumption of a constant temperature equilibrium to get the same information. Remarkably the two methods give the same mass within errors. Thus with a mass-to-light ratio of \( \Upsilon = 330 - 620 M_\odot / L_\odot \), one finds \( \Omega = 0.2 - 0.4 \), if the inner 1.5 Mpc of Coma is representative of the Universe as a whole.

There is, however, a very disconcerting fact about the above numbers. As pointed out by White, et al. (1993),

\[
\frac{M_{\text{baryon}}}{M_{\text{total}}} > 0.009 + 0.05 h^{-3/2}.
\]

Now the Coma cluster is large enough that one might expect its baryon to dark matter ratio to be the Universal value, \( (\Omega_{\text{baryon}}/\Omega_{\text{total}} = M_{\text{baryon}}/M_{\text{total}}) \), and in fact White, et al. argue that this is the case. Then the inequality above should apply to the entire Universe. But, as we discuss later, big bang nucleosynthesis limits \( \Omega_{\text{baryon}} < 0.015 h^{-2} \). If \( \Omega_{\text{total}} = 1 \), as many would like, the two inequalities are in quite strong disagreement for any value of \( h \)! So this is a big puzzle. The conclusions of White, et al., are that either \( \Omega \) is not unity, or that big bang nucleosynthesis is not working. As I think Joel Primack (these proceedings) and Tony Tyson (these proceedings) will discuss, there are other possible explanations. Notably that measurements of the the total mass in clusters by weak or strong gravitational lensing tend to give twice as much total mass as the X-ray and virial methods, and that mass and velocity bias may mean that clusters are not so representative of the Universe as a whole.
2.3 Large Scale Flows

Next, we turn to some of the most interesting new results on the amount of dark matter. One would really like to measure the amount of dark matter on the largest possible scales so that one can be sure the sample is representative of the entire Universe. Within the past several years a host of related methods have been tried, and while they initially gave uncertain results, the most recent determinations do impressively well. These methods have the advantage stated above, but the disadvantage that they depend upon assumptions about galaxy formation; which means they depend upon gravitational instability theory, biasing, etc. Also, the errors in these results are still large and the calculations are complicated, but they do have the promise to answer the fundamental question of how large \( \Omega \) is. They also tend to give values of \( \Omega_{\text{total}} \) near unity!

The simplest example comes from the observation that the local group of galaxies moves at \( 627 \pm 22 \) km/sec with respect to the Cosmic Microwave Background (CMB) (measured from the amplitude of the CMB dipole). If this motion comes from gravity, then the direction of the motion should line up with the direction where there is an excess of mass, and the velocity should be determined by the size of this excess. Thus, taking into account the expansion of the Universe, one has

\[
v \propto \Omega^{0.6} \frac{\delta \rho}{\rho} = \frac{\Omega^{0.6} \delta n}{b n},
\]

where the bias factor \( b \) has slipped in because observers use the excess in galaxy number counts \( \delta n/n \) to estimate the excess in mass density \( \delta \rho/\rho \). So, using galaxy counts from the IRAS satellite survey, Yahil et al. (1986) find that the direction of the \( \delta n/n \) excess agrees with the direction of the velocity vector to within \( \sim 20^0 \), and that

\[
\frac{\Omega^{0.6}}{b} = 0.9 \pm 0.2.
\]

Thus with the very conservative limit \( b > 0.5 \), one has \( \Omega > 0.2 \), and with the reasonable limit \( b > 1 \), one finds \( \Omega > 0.5 \). So there is now observational evidence that \( \Omega \) is near the theoretically favored value of unity. However, for the method above to be reliable, one must measure \( \delta n/n \) on very large scales to ensure that convergence has been reached. I don’t think this has yet been convincingly demonstrated.

The above technique is only one of a host of methods used to determine \( \Omega \) on large scales. Especially promising is the detailed comparison of the peculiar velocities of many galaxies to the detailed maps of \( \delta n/n \). This should not only determine \( \Omega \), but serve as a stringent test on the theory that large scale structure is formed by gravitational instability. The trick is to get the peculiar velocities, which means subtracting the much larger Hubble flow velocity. Since the redshift measurements gives only the radial component of velocity it seemed difficult to get complete information, but Bertshinger and Dekel (1989) proposed an ingenious method, in which one assumes that the velocity field is curl free, and proceeded to
reconstruct the entire three dimensional field. They use

\[ \nabla \cdot \mathbf{v} = -\frac{\Omega^{0.6} \delta n}{b}, \]

and solve for \( \Omega^{0.6}/b \). They find \( 0.3 < \Omega < 1 \) for reasonable choices of \( b \). Especially notable is that the detailed \( \delta n/n \) maps agree remarkably well with the reconstructed velocity fields, and I interpret this as evidence that gravitational instability is the most likely cause of the structure. In fact, this is now the story for most of the large scale flow methods. They find reasonable to excellent agreement with the theory, and predict a large value of \( \Omega \). A very nice table of values and a review of many of these methods can be found in Dekel (1994).

2.4 Big Bang Nucleosynthesis

Next, I turn to a very important and recently controversial ingredient in the dark matter story; namely the predictions of big bang nucleosynthesis. The standard story has been (Smith, Kawano, Malaney 1993; Walker, et al. 1991) that to get agreement with the measured abundances of helium, deuterium, and lithium, the baryonic content of the Universe had to be between \( 0.01 \leq \Omega_{\text{baryon}} h^2 \leq 0.015 \). Given the large uncertainty in \( h \) this meant \( 0.01 \leq \Omega_{\text{baryon}} \leq 0.1 \). This value is inconsistent with having a total \( \Omega = 1 \) in baryons, and so, together with the predilection for \( \Omega_{\text{total}} = 1 \), is the main motivation for postulating non-baryonic (elementary particle) dark matter. The majority of dark matter searches are targeted towards these non-baryonic particles. The lower limit of this range is actually above the abundance of known stars, gas, etc., and so there also seems to be evidence for substantial baryonic dark matter as well.

Much recent excitement was caused in this field when Songaila, et al. (1994) reported a possible detection of deuterium in a Lyman limit cloud at a redshift of 2.9 (via absorption of light emitted by an even more distant quasar). The controversy was caused by the extremely large value \( D/H \approx 2.4 \times 10^{-4} \), when measurements from the interstellar medium are in the range \( 1.9 \times 10^{-5} < D/H < 6.8 \times 10^{-5} \) (Steigman & Tosi 1992). If the new measurement is true, the limits from big bang nucleosynthesis would move to roughly \( 0.004 < \Omega h^2 < 0.0068 \), or \( 0.006 \leq \Omega \leq 0.035 \), substantially lower than the current limits. In this case, most of the baryonic material may well be known, and models of structure formation which require substantial baryonic content may be in trouble. However, it is too soon to tell whether the measurement will stand up. Several groups are making these measurements and hopefully soon there will be either confirmation or refutation of this result.

2.5 Distribution of Dark Matter in the Milky Way

While we don’t have a clue as to what the dark matter (DM) is, we have a reasonable idea as to how much of it there is in the Galaxy, how it is distributed, and how fast it is moving. This information comes from the rotation curve of the Milky Way, and is crucial to all the direct searches for dark matter. If we say
that the rotation curve of the Milky Way is constant at about $v_c = 220$ km/sec out to as far as it is measured, then we know that the density must drop as $r^{-2}$ at large distances. This velocity also sets the scale for the depth of the potential well and says that the dark matter must also move with velocities in this range. Assuming a spherical and isotropic velocity distribution is common, and a usual parameterization is

$$\rho(r) = \rho_0 \frac{a^2 + r_0^2}{a^2 + r^2},$$

where $r_0 \approx 8.5$ kpc is the distance of the Sun from the galactic center, $a$ is the core radius of the halo, and $\rho_0 \approx 0.3$ GeV cm$^{-3}$ is the density of dark matter near the Sun. Also, a typical velocity distribution is

$$f(v) d^3v = \frac{e^{-v^2/v_c^2}}{\pi^{3/2} v_c^3} d^3v.$$

It should be noted that the specifics of the above models are not very secure. For example, it is quite possible that the halo of our Galaxy is flattened into an ellipsoid, and there may be a component of the halo velocity which is rotational and not isotropic. Also, some (or even much) of the rotation curve of the Milky Way at the solar radius could be due to the stellar disk. Canonical models of the disk have the disk contributing about half the rotation velocity, but larger disks have been envisioned. Recent microlensing results may be indicative of a larger disk as well. I will talk about this later if there is time.

Finally, other important points about our Galaxy’s geography include the fact that the nearest two galaxies are the LMC and SMC, located at a distance of 50 kpc and 60kpc respectively, that the halo of the Milky Way is thought to extend out at least this far, and that the bulge of the Milky Way is a concentration of stars in the center of our Galaxy (8.5 kpc away) with a size of about 1 kpc.

### 3. Dark Matter Candidates

There is no shortage of ideas as to what the dark matter could be. In fact, the problem is the opposite. Serious candidates have been proposed with masses ranging from $10^{-5}$ eV = $1.8 \times 10^{-61}$ kg = $9 \times 10^{-72}M_\odot$ (axions) up to $10^4M_\odot$ black holes. That’s a range of masses of over 75 orders of magnitude! It should be clear that no one search technique could be used for all dark matter candidates.

Even finding a consistent categorization scheme is difficult, so we will try a few. First, as discussed above, is the baryonic vs non-baryonic distinction. The main baryonic candidates are the Massive Compact Halo Object (Macho) class of candidates. These include brown dwarf stars, jupiters, and 100 $M_\odot$ black holes. Brown dwarfs are balls of H and He with masses below 0.08 $M_\odot$, so they never begin nuclear fusion of hydrogen. Jupiters are similar but with masses near 0.001 $M_\odot$. Black holes with masses near 100 $M_\odot$ could be the remnants of an early generation of stars which were massive enough so that not many heavy elements were dispersed when they went supernova. Other, less popular, baryonic possibilities include fractal or specially conditioned clouds of neutral hydrogen. The non-baryonic
candidates are basically elementary particles which are either not yet discovered or have non-standard properties. Outside the baryonic/non-baryonic categories are two other possibilities which don’t get much attention, but which I think should be kept in mind until the nature of the dark matter is discovered. The first is non-Newtonian gravity. See Begeman et al. (1991) for a provocative discussion of this possibility; but watch for results from gravitational lensing which may place very strong constraints. I won’t talk about this possibility here. Second, we shouldn’t ignore the “none-of-the-above” possibility which has several times surprised the physics/astronomy community in the past.

Among the non-baryonic candidates there are several classes of particles which are distinguished by how they came to exist in large quantity during the Early Universe, and also how they are most easily detected. The axion (Section 3.6) is motivated as a possible solution to the strong CP problem and is in a class by itself. The largest class is the Weakly Interacting Massive Particle (Wimp) class (Section 3.4), which consists of literally hundreds of suggested particles. The most popular of these Wimps is the neutralino from supersymmetry (Section 3.5). Finally, if the tau or muon neutrino had a mass in the $5 \text{ eV}$ to $100 \text{ eV}$ range, it could make up all or much of the dark matter (Section 3.3).

Another important categorization scheme is the “hot” vs “cold” classification. A dark matter candidate is called “hot” if it was moving at relativistic speeds at the time galaxies could just start to form (when the horizon first contained about $10^{12} M_\odot$). It is called “cold” if it was moving non-relativistically at that time. This categorization has important ramifications for structure formation, and there is a chance of determining whether the dark matter is hot or cold from studies of galaxy formation. Hot dark matter cannot cluster on galaxy scales until it has cooled to non-relativistic speeds, and so gives rise to a considerably different primordial fluctuation spectrum. Of the above candidates only the light neutrinos would be hot; all the others would be cold.

3.2 Machos

Probably the most exciting development in the dark matter story is the detection of Machos by three separate groups (Alcock, et al. 1993; Aubourg, et al. 1993; Udalski, et al. 1993). All three groups monitored millions of stars, either in the LMC or in the galactic bulge, for signs of gravitational microlensing, and all three groups seem to have found it. It is still not clear whether the objects which are causing the microlensing are numerous enough to make up the Milky Way dark matter, or even whether they are in the galactic halo or disk. Whether they are light enough to qualify as bona fide brown dwarfs, or whether they are just faint stars is also not yet known. See David Caldwell’s talk (these proceedings) for a review of the current status of these important experiments.

However, from the more general point of view, I’d like to note that these experiments very well may have the capability to give a definitive answer to the question of whether the dark matter in our Galaxy is baryonic. The microlensing searches are probably sensitive to any objects in the range $\sim 10^{-8} M_\odot < m < 10^3 M_\odot$, just the range in which such objects are theoretically allowed to exist. Objects made purely of H and He with masses less than $\sim 10^{-9} - 10^{-7} M_\odot$ are expected to evaporate due to the microwave background in less than a Hubble time, while objects with masses greater than $\sim 10^3 M_\odot$ would have disrupted known globular clusters.
3.3 Light Neutrinos

Hot dark matter was out of favor for several years, but has come back into style in a big way. Neutrino dark matter was unpopular for two main reasons. First, by Jeans theorem, the current phase space density of any dissipationless particle should be less than or equal to its phase space density at decoupling. Tremaine & Gunn (1979), showed that this meant very light neutrinos could not be packed endlessly into dwarf galaxies. Gerhard & Spergel (1992) applied this result to the dwarf galaxy Ursa Minor, which is known to have a great deal of dark matter, and very conservatively found that if all the dark matter in Ursa Minor were neutrinos, the neutrinos would have to have masses greater than 81 eV. Since $\Omega_{\nu} h^2 = m_{\nu} / 90$ eV, and $\Omega_{\nu} h^2 < 1$, the maximum mass which neutrino dark matter could have is around 90 eV, with values of around 30 eV being favored. So the dark matter in dwarf galaxies such as Ursa Minor and Draco probably cannot be light neutrinos. Thus, one would need at least two types of dark matter to have hot dark matter play an important role. By simplicity, this led to neutrino dark matter being disfavored.

The other reason neutrino dark matter became less popular was that galaxy formation with pure hot dark matter and a Zeldovich perturbation spectrum just doesn’t match the observations.

While the arguments above are still valid, several recent developments have changed the attitude towards them. First, it is now known that galaxy formation with pure cold dark matter and a Zeldovich perturbation spectrum also doesn’t match the observations. So some additional ingredient is needed. Second, one of the few models which does match the observations is a mixed dark matter Universe with $\Omega_{\text{cold}} = 0.7$, $\Omega_{\nu} = 0.25$, and $\Omega_{\text{baryon}} = 0.05$. Thus, since it seems we may need two types of dark matter anyway, the objection that the dark matter in dwarf galaxies cannot all be neutrinos becomes less important. We may well have a tau or muon neutrino with a mass near 6 eV. In these mixed models, the cold dark matter dominates, and so the ongoing searches for the other dark matter candidates are hardly affected.

See talks by Joel Primack and David Caldwell (these proceedings) for more discussion of these models and attempts at detection of neutrino dark matter by measuring the neutrino mass.

3.4 Thermal Relics as Dark Matter (Wimps)

Among the particle dark matter candidates an important distinction is whether the particles were created thermally in the Early Universe, or whether they were created non-thermally in a phase transition. Thermal and non-thermal relics have a different relationship between their relic abundance $\Omega$ and their properties such as mass and couplings, so the distinction is especially important for dark matter detection efforts. For example, the Wimp class of particles can be defined as those particles which are created thermally, while dark matter axions come mostly from non-thermal processes.

In thermal creation one imagines that early on, when the Universe was at very high temperature, thermal equilibrium obtained, and the number density of Wimps (or any other particle species) was roughly equal to the number density of photons. As the Universe cooled the number of Wimps and photons would decrease together
as long as the temperature remained higher than the Wimp mass. When the temperature finally dropped below the Wimp mass, creation of Wimps would require being on the tail of the thermal distribution, so in equilibrium, the number density of Wimps would drop exponentially \( \propto \exp(-m_{Wimp}/T) \). If equilibrium were maintained until today there would be very few Wimps left, but at some point the Wimp density would drop low enough that the probability of one Wimp finding another to annihilate would become small. (Remember we must assume that an individual Wimp is stable if it is to become the dark matter.) The Wimp number density would “freeze-out” at this point and we would be left with a substantial number of Wimps today. Detailed evolution of the Boltzmann equation can be done for an accurate prediction, but roughly

\[
\Omega_{Wimp} \approx \frac{10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle},
\]

where \( \langle \sigma v \rangle \) is the thermally averaged cross section for two Wimps to annihilate into ordinary particles. The remarkable fact is that for \( \Omega \approx 1 \), as required by the dark matter problem, the annihilation cross section \( \langle \sigma v \rangle \) for any thermally created particle turns out to be just what would be predicted for particles with electroweak scale interactions. Thus the name “Wimp”. There are several theoretical problems with the Standard Model of particle physics which are solved by new electroweak scale physics such as supersymmetry. Thus these theoretical problems may be clues that the dark matter does indeed consist of Wimps. Said another way, any stable particle which annihilates with an electroweak scale cross section is bound to contribute to the dark matter of the Universe. It is interesting that theories such as supersymmetry, invented for entirely different reasons, typically predict just such a particle.

The fact that thermally created dark matter has weak scale interactions also means that it may be within reach of accelerators such as LEP at CERN, and CDF at Fermilab. After all these accelerators were built precisely to probe the electroweak scale. Thus many accelerator searches for exotic particles are also searches for the dark matter of the Universe. Also, due to the weak scale interactions, Wimp-nuclear interaction rates are within reach of many direct and indirect detection methods. Caldwell (these proceedings) will review these.

### 3.5 Example of the Neutralino

The most popular of the Wimp candidates is the neutralino from supersymmetry. Supersymmetry seems to be a necessary ingredient of any theory which which consistently combines general relativity with the Standard Model of particle physics.

When Dirac attempted to combine special relativity with quantum mechanics, he came up with the Dirac equation and discovered (to his chagrin) that it contained a new CPT symmetry which required the existence of a CPT partner, or anti-particle for every known particle. Dirac’s initial hopes that the electron might be the anti-particle of the proton were soon dashed, but the discovery of the positron vindicated Dirac’s theory. Today this “doubling” of the number of particles by CPT symmetry is taken for granted to such an extent that anti-particles are not listed in the particle data book.
It is interesting that attempts to combine general relativity with quantum field theory seem to require supersymmetry in a similar way. Here the symmetry relates integral spin particles to half integral spin superpartners and vice versa. Analogous initial hopes that the photon might be the superpartner of the neutrino were soon dashed, and now, if supersymmetry exists, it is known that there would be a doubling of the number of known particles. While there has been no quickly following discovery of supersymmetric particles, the hypothetical particles have been named and thoroughly studied. Intense searches for these particles are taking place at all the major accelerators. Examples of superpartners are the spin 1/2 photino, Higgsino, Z-ino, and W-ino (superpartners of the photon, Higgs, Z, and W), and the spin 0 squark and selectron (partners of the quark and electron).

There are actually several other strong motivations for the existence of supersymmetry, among which, the stabilization of the electroweak scale (hierarchy problem), and the remarkable coupling constant unification which occurs in supersymmetric grand unified models, stand out. The interest for dark matter, however, arises because typically there is a conserved multiplicative R-parity, which means that the lightest supersymmetric particle (LSP) is stable. The most likely LSP is the neutralino, which is a linear combination of the photino, Z-ino, and Higgsino. The precise components of the combination are determined by the parameters of the underlying supersymmetric model, and there are many of these parameters. Typically, the minimal supersymmetric model (MSSM) is considered, which is the supersymmetric extension of the Standard Model with the minimal number of new particles. While supersymmetry relates many couplings and masses, there are still dozens of free parameters in the most general MSSM, so many times a restricted set of these parameters is used which derives from assuming a simple grand unification scheme. The particle accelerators are searching this parameter space for supersymmetry, but have turned up no new particles. It is interesting is that in much of this parameter space calculation of the relic abundance predicts $\Omega \approx 1$ in neutralinos. For example a recent calculation by Drees and Nojiri (1993) (as programmed by Jungman, et al. 1994) shows this clearly.

These supersymmetric models are also within reach of the new generation of direct and indirect Wimp detection experiments as Caldwell (these proceedings) will review.

3.6 Axions

The best example of a non-thermal particle dark matter candidate is the axion. Actually thermal axions are produced in the standard way, but if such axions existed in such numbers as to make up the dark matter, they would have lifetimes too short to still be around in quantity. However, there is another, more important, production mechanism for axions in the early Universe.

The axion arises because the QCD Lagrangian contains a term

$$L \supset \frac{\theta g^2}{32\pi^2} G \tilde{G},$$

where $G$ is the gluon field strength. This term predicts an electric dipole moment of the neutron of $d_n \approx 5 \times 10^{-16} \theta$. Experimentally, however, the neutron dipole
moment $d_\alpha < 10^{-25}$, which means $\bar{\theta} < 10^{-10}$. The question becomes why does this $\bar{\theta}$ parameter have such a small value, when it naturally would have a value near unity? This is the strong CP problem, and one way to resolve this problem is to introduce a new Peccei-Quinn symmetry which predicts a new particle named the axion. The P-Q symmetry forces $\bar{\theta} = 0$ at low temperatures today, but in the early Universe, the axion field was free to roll around the bottom of its Mexican hat potential. The axion field motion in the angular direction is called $\theta$, and since the curvature of the potential in this direction is zero, the axion at high temperatures was massless. However, when the temperature of the Universe cooled below a few hundred MeV (QCD energy scale), the axion potential “tilts” due to QCD instanton effects, and the axion begins to oscillate around the minimum, like a marble in the rim of a tilted Mexican hat. The minimum of the potential forces the average $\bar{\theta}$ to zero, solving the strong CP problem, and the curvature of the potential means the axion now has a mass. There is no damping mechanism for the axion oscillations, so the energy density which goes into oscillation remains until today as a coherent axion field condensate filling the Universe. This is a zero momentum condensate and so constitutes cold dark matter. One can identify this energy density as a bunch of axion particles, which later can become the dark matter in halos of galaxies. The relic energy density $\Omega$ is thus related to the tilt of the potential, which in turn is related to the axion mass, a free parameter of the model. If the axion mass $m_a \approx 10^{-5} \text{ eV}$, then $\Omega_a \approx 1$. This rather unusual story is still probably the most elegant solution to the strong CP problem, and several groups are mounting laboratory searches for the coherent axions which may make up the major component of mass in the Galaxy. Again Caldwell (these proceedings) will review these experiments.

4. Uncertainties in the Milky Way Dark Matter

Finally, let me turn to a subject which has not received a lot of attention, but which I think will get increasing attention now that one of the dark matter searches (Macho) is returning positive results. That is, the uncertainties in the results of dark matter searches due to uncertainties in the model of Milky Way dark matter halo, where by model I mean the density and velocity distributions of the dark matter. This uncertainty affects Wimp, axion, and Macho searches, and so should be given some attention. For example, axion detection rates are proportional to the local density of dark matter, which can vary greatly in different galactic models, while Wimp rates are proportional to this as well as to the average Wimp velocity. Macho microlensing rates, being averages over the line-of-sight to the stellar source, are more complicated functions of all the parameters in the halo model.

Much of the model dependence comes because the parameters of Milky Way (and especially of the dark halo) are not well known. For example, the local circular velocity has been measured at values in the range $190 \text{ km/s} < v_c < 250 \text{ km/s}$. Estimates of the distance of the Sun from the galactic center range between $7 < r_0 < 9 \text{ kpc}$. And the halo core radius has been estimated at between $2 < a < 10 \text{ kpc}$. In addition, the halo may not be spherical, but may be flattened into an ellipsoidal configuration, and the rotation curve may be gently rising or falling (by about 15%).

To investigate this model dependence (Alcock, et al., 1994a) one can use some nice self consistent models of galactic halos due to Evans (1994). For example,
one can calculate the microlensing rate towards the LMC, SMC, and bulge using these models and see how the predicted rates change as the parameters vary within their observationally allowed ranges. Allowing the halo to be flattened up to a very reasonable axis ratio of three-to-one, one finds a variation in the predicted microlensing rate of more than a factor of ten. Since the purpose of the microlensing experiments is to measure the fraction of the dark halo made of Machos, and the connection between the measurement and fraction requires a model of the halo, one sees that this large model uncertainty will translate into an uncertainty in the dark matter fraction. Thus it may be difficult for the Macho searches to place strong constraints on the amount of non-baryonic dark matter in the halo.

However, there is an additional, and perhaps even larger, uncertainty which comes about because the mass of the stellar disk is not well known. In the above derivations of the allowed halo parameters a “canonical” exponential stellar disk was used. This says that about half the rotation curve of the Galaxy comes from the halo, and about half from the stellar disk (Evans & Jijina 1994). However, if, as has been suggested for many years, the disk is actually twice as massive (Oort 1960; Bahcall 1984), then very little need would exist for a dark halo component at the solar radius of 8.5 kpc. (At large r there would still be a need for halo dark matter). This might mean that the Wimp and axion searches would not have much dark matter locally to look for. The Macho searches are hoping to measure the amount of material in the disk and so resolve this part of the problem (Griest, et al. 1991; Paczyński, 1991; Alcock, et al. 1994b; Udalski, et al. 1994).

The hope is that the microlensing searches can also resolve the halo model uncertainties (if the halo consists of machos!). The idea is to look in several different lines-of-sight (LMC, SMC, M31, and bulge) and find quantities which differ enough among the different models to distinguish them.

5. Conclusions

Rapid progress is being made in the dark matter question, but as usual with new results, more questions are being opened than closed.

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