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BARYONS AS DARK MATTER[a]

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Dark matter may reside in galactic disks, galactic halos, clusters of galaxies and the background Universe. Cosmological nucleosynthesis arguments suggest that only some fraction of the baryons in the Universe are in visible form, so at least some of the dark matter problems could be baryonic. The dark matter in galactic disks (if real) is almost certainly baryonic and, in this case, it is either in white dwarfs or brown dwarfs. The dark matter in galactic halos could be at least partly baryonic and, in this case, it is likely to be contained in the remnants of a first generation of pregalactic or protogalactic stars. The various constraints on the nature of such remnants suggest that brown dwarfs are the most plausible candidates, although (rather perplexingly) microlensing searches currently favour white dwarfs. The dark matter in clusters or intergalactic space could be baryonic only if one gives up the standard cosmological nucleosynthesis scenario or assumes that the dark objects are primordial black holes which formed before nucleosynthesis. If it is non-baryonic and in the form of "cold" WIMPs, then such particles should also provide some of the halo dark matter.

1 Evidence for Dark Matter

A gravitationally bound system of mass M, radius R and density ρ has a characteristic potential $\Phi \sim GM/R \sim G\rho R^2$ which may be probed by studying the dynamics of its components (velocity $V \sim \Phi^{1/2}$), the emission of its gas (temperature $T \sim \Phi$) or its gravitational lensing effects (light deflection $\delta \sim \Phi/c^2$). A dark matter problem arises whenever the values of M or ρ inferred from measurements of Φ and R exceeds the mass or density in visible form. Evidence for dark matter has been claimed in four different contexts - the Galactic disk, galactic halos, clusters of galaxies and the background Universe - and the different methods of probing the potential are summarized in Table (1). The form of the dark matter need not be the same in all these contexts and this should be born in mind when discussing the candidates.

Local Dark Matter

There may be local dark matter in the Galactic disk, with a density comparable to the visible density; in this case, R is associated with the thickness of the disk $\sim 300\,\mathrm{pc}$ and measurements of the stellar velocities perpendicular to the

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disk provide an estimate of the total disk density. Although it has long been suspected that this exceeds the density in visible stars, the evidence is very controversial. In their most recent analysis Bahcall et al.[5] obtain a dark fraction of 60%, whereas Flynn & Fuchs [29] get an upper limit of 10% and Kuijken & Gilmore [48] claim there is no dark matter at all. Dark disk objects in the mass range $10^{-6} - 1 M_{\odot}$ may also be sought through their microlensing effects on stars in the Galactic bulge.

Galactic Halos

There may be dark matter in the halos of galaxies with a mass $M_{dark} \sim 10 M_{vis}(R_h/100\text{kpc})$ which depends upon the (uncertain) halo radius R_h. The best evidence for dark halos in spiral galaxies comes from rotation curve measurements, the dependence of the rotation speed V upon galactocentric distance R being a measure of the mass within that radius $M(R)$. An important feature of the typical spiral rotation curve [66] is that it is approximately constant at large R and this implies that $M(R)$ increases like R, which is faster than the increase of visible mass. Indeed neutral hydrogen observations suggest that V continues to remain constant well beyond the visible stars [70]. There also seems to be a correlation between the form of the rotation curve and the galaxy luminosity. Persic et al. [59] claim that there is a "universal" rotation curve, characterized by a single parameter, and this has the feature that the dark fraction goes up as the luminosity decreases. The mass distribution in ellipticals is best studied using X-ray observations of the hot gas and this again indicates the presence of dark matter, in many cases with the same $M \sim R$ law which characterizes spirals [71]. There is also evidence for dark matter in dwarf galaxies - indeed stellar velocity measurements [1,50] indicate that they have even higher dark mass fractions than bright spirals. Microlensing effects on stars in the Large Magellanic Cloud provide a direct probe of dark objects in our own halo with mass in the range $10^{-7} - 10 M_{\odot}$ and may have already met with success.

Clusters of Galaxies

There may be dark matter associated with clusters of galaxies; in this case, R characterizes the size of the cluster $\sim$ 10Mpc and the velocity dispersion indicates that the dynamical mass exceeds the visible mass by at least a factor of 10. This is confirmed by X-ray data on the gas emission, with the gas itself containing more mass than the galaxies [8]. Further evidence for dark matter in clusters comes from lensing: distant galaxies behind the cluster may

	Dynamics	X-rays	Lensing
Local	√	X	?
Spirals	√	X	√
Ellipticals	?	√	?
Dwarfs	√	X	X
Clusters	√	√	√
Background	√	X	√

Table 1: *Evidence for dark matter*

be distorted into arclets by the cluster potential and the properties of these arclets can be used to infer the dark matter distribution[74,79].

Background Dark Matter

None of the forms of matter discussed above can have the critical density required for the Universe to recollapse: $\rho_{crit} = 3H_o^2/8\pi G$. However, according to the currently popular inflation theory[34], in which the Universe undergoes an exponential expansion phase at some early time, the total density should have almost exactly the critical value ($\Omega \equiv \rho/\rho_{crit} = 1$), corresponding to $M_{dark} \sim 100 M_{vis}$. This would have two possible implications: either there is another dark component which is distinct from the clustered dark matter or galaxy formation is biased[27,45], in the sense that galaxies form preferentially in a small fraction of the volume of the Universe. In either case, one would expect the mass-to-light ratio to increase as one goes to larger scales and there is some indication of this from dynamical studies. A variety of other methods can be used to probe the background density. Measurements of the deceleration parameter using supernovae as distance indicators[57] suggest that Ω is close to 1 and the fact that the fraction of clusters with substructure is high implies that Ω is at least 0.5[31]. Gravitational lensing effects may also provide evidence for intergalactic dark matter in the form of compact objects.

2 Baryonic Versus Non-Baryonic Dark Matter

The main argument for both baryonic and non-baryonic dark matter comes from Big Bang nucleosynthesis. This is because the success of the standard picture in explaining the primordial light element abundances [81] only applies if the baryon density parameter Ω_b lies in the range $0.010h^{-2} < \Omega_b < 0.015h^{-2}$ where $h \equiv H_o/(100\,km\,s^{-1}Mpc^{-1})$. The upper and lower limits come from the upper bounds on the helium abundance and the sum of the deuterium and helium-3 abundances, respectively. Although more recent estimates by Copi et al.[21] allow a wider range of values, $0.007h^{-2} < \Omega_b < 0.022h^{-2}$, the upper limit implies that Ω_b is well below 1, which suggests that no baryonic candidate could provide the critical density required in the inflationary scenario. This conclusion also applies if one invokes inhomogeneous nucleosynthesis since one requires $\Omega_b < 0.09h^{-2}$ even in this case [52]. The standard scenario therefore assumes that the total density parameter is 1, with only 1-10% being baryonic.

On the other hand, the value of Ω_b allowed almost certainly exceeds the density of visible baryons Ω_v. A careful inventory by Persic & Salucci [58] shows that the contributions to Ω_v are 0.0007 from spirals, 0.0015 from ellipticals and spheroidals, $0.00035h^{-1.5}$ from hot gas within an Abell radius for rich clusters, and $0.00026h^{-1.5}$ from hot gas out to a virialization radius in groups and poor clusters. This gives a total of $(2.2 + 0.6h^{-1.5}) \times 10^{-3}$. For reasonable values of h, they infer $\Omega_v \approx 0.003$, which is well below the baryon density inferred from nucleosynthesis.

Which of the dark matter problems mentioned in 1 could be baryonic? Baryons would certainly suffice to explain the dark matter in galactic disks: even if all disks have the 60% dark component envisaged for our Galaxy by Bahcall et al. [5], this only corresponds to $\Omega_d \approx 0.001$ - well below the nucleosynthesis value for Ω_b. On the other hand, the cluster dark matter has a density $\Omega_c \approx 0.1 - 0.2$ and this cannot be baryonic unless one invokes inhomogeneous nucleosynthesis. Whether dark baryons could explain galactic halos depends on the typical halo radius: if our own galaxy is typical, the density associated with halos would be $\Omega_h \approx 0.02h^{-1}(R_h/70kpc)$ and, for reasonable values of R_h, this could be either less or more than Ω_b. The various values of Ω required by these arguments are summarized in Figure (1). This emphasizes that there are four distinct issues:

$\Omega_b = \Omega_v$? Do we really need dark baryons? Recent measurements of the deuterium abundance in quasar absorption systems gives $X(D) \approx 2 \times 10^{-4}$, which is about an order of magnitude larger than the standard interstellar abundance [17,67,76]. In this case, the upper limit on Ω_b is reduced to $0.005h^{-2}$, which is only marginally larger than the Persic- Salucci estimate of Ω_v. How-

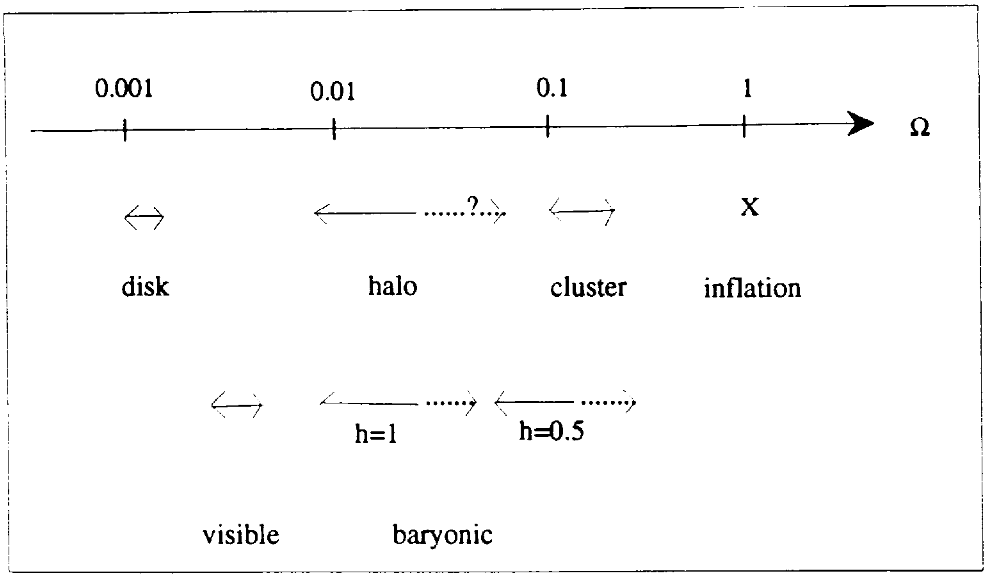

Figure 1: *This compares the density associated with the various dark matter problems to the density in visible form and the baryonic density required by cosmological nucleosynthesis (with the inhomogeneous case shown dotted).*

ever, other groups find the standard deuterium abundance in quasar absorption systems[80], so the evidence for such a high value of X(D) is inconclusive.

$\Omega_b = \Omega_h$? Could dark baryons suffice to explain galactic halos? The estimate $\Omega_h \approx 0.02h^{-1}(R_h/70kpc)$ is compatible with the Copi et al. limit of $\Omega_b < 0.022h^{-2}$ only for $R_h < 70h^{-1}kpc$. For the Milky Way, the minimum halo radius consistent with rotation curve measurements, the local escape speed, the kinematics of globular clusters and the dynamics of the Local Group is about 70 kpc[28], which would just be compatible with this. However, Zaritsky et al. [89] argue from observations of the satellite systems of other galaxies that spirals typically have 200 kpc halos, which would not be.

$\Omega_c = \Omega_h$? Could all the dark matter in clusters derive from halos? Although the cluster dark mass cannot all be associated with individual galaxies now - else dynamical friction would result in the most massive galaxies being dragged into the cluster centre[84] - it may still have derived from the galaxies originally. Indeed, in the hierarchical clustering picture, one would expect the galaxies inside a cluster to be stripped of much of their individual halos, thereby forming a collective halo[85]. Bahcall et al.[6] advocate this possibility: in their scenario both elliptical and spiral galaxies have halo radii of $200h^{-1}kpc$. However, unless one invokes a rather exotic cosmological nucleosynthesis scenario[32], this scenario could only account for all the cluster dark matter if the original galactic halos were non-baryonic.

$\Omega = 1$? We have seen that the background dark matter can be identified with the cluster dark matter providing one invokes biased galaxy formation. However, it must be emphasized that the direct evidence for $\Omega = 1$ is poor. Indeed Bahcall et al. [6] argue that there is no need for Ω to exceed Ω_c. One problem with the standard scenario with $\Omega_b \sim 0.01 - 0.1$ and $\Omega = 1$ is that X-ray data suggest that the ratio of visible baryon mass (in stars and hot gas) to total mass in clusters is anomalously high compared to the mean cosmic ratio. For example, ROSAT observations [86] suggest that the baryon fraction within the central 3 Mpc of the Coma cluster is about 25% and there is now evidence that this is a fairly widespread phenomena [87]. It is hard to understand how the extra baryon concentration would come about, since dissipation should be unimportant on these scales, so this has been referred to as the "baryon catastrophe". Unless one invokes a cosmological constant, it suggests that either Ω is well below 1 or Ω_b is higher than allowed by the homogeneous nucleosynthesis scenario.

3 Possible Sites for Dark Baryons

Henceforth most of the emphasis will be on baryonic dark matter, so we must address the question of where the dark baryons are located and what form they may take. Apart from the dark baryons in galactic disks, which anyway have a negligible cosmological density, there are various possibilities and these are summarized in Table (2).

The discrepancy between Ω_b and Ω_v could be resolved if the missing baryons were in a hot intergalactic medium and evidence for such a medium may come from the recent detection of helium absorption [24,43]. However, the temperature would need to be finely tuned in view of the Gunn-Peterson test and the COBE limit on the Compton distortion of the microwave background. A second possibility is Lyman-α clouds. Although the density parameter associated with "damped" clouds [49] is probably around $0.003h^{-2}$, comparable to the density in galaxies and therefore consistent with the idea that these are protogalactic disks, the density associated with undamped systems is unknown and, depending on the ionized fraction and geometry, could be much larger [62]. However, by the present epoch the undamped clouds could have fragmented into stars, so this does not exclude the other possibilities discussed below.

The usual estimate of Ω_v does not include the contribution from a population of dark intergalactic objects, such as dwarf galaxies [13] or low surface brightness galaxies [54]. Indeed it has recently been claimed that dwarf galaxies may provide all of the missing baryons [41]. There could also be intergalactic

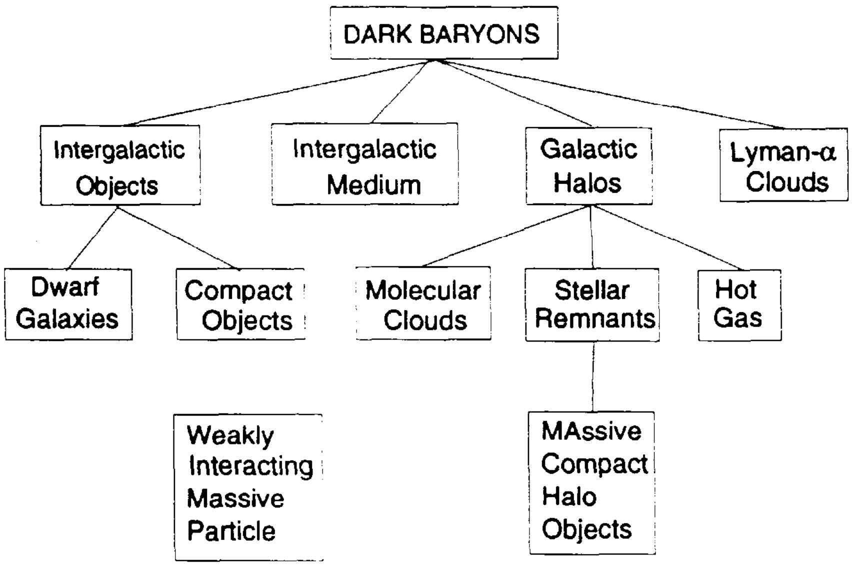

Table 2: *Summary of possible locations for dark baryons*

dark matter in the form of compact objects [16]: either the remnants of a first generation of pregalactic stars or primordial black holes which formed before cosmological nucleosynthesis. Only the latter could have the critical density required by inflation. Otherwise most of the intergalactic dark matter would have to be in the form of "Weakly Interacting Massive Particles" or "WIMPs".

We have seen that galactic halos could contain all the dark baryons if the typical halo radius R_h is less than $70h^{-1}kpc$. In this case, one might consider three possible forms for the dark baryons: hot gas, cold molecular clouds or "Population III" remnants. The first possibility would appear to be inconsistent with X-ray observations since the gas would need to have the virial temperature of $10^6 K$. The second possibility has been discussed by Pfenniger et al.[60] but will not be considered further here. The third possibility corresponds to the "MAssive Compact Halo Object" or "MACHO" scenario. This is motivated by the fact that the existence of galaxies implies that there must have been density fluctuations in the early Universe and, in many scenarios, these fluctuations would also give rise to a first generation of "Population III" stars [14]. If the background non-baryonic dark matter is "cold", it will necessarily fall into halo potentials, so halos would most naturally consist of a mixture of WIMPs and MACHOs. In this case, the epoch of Population III formation will be very important for their relative distribution. If the Population III stars form before galaxies, one would expect their remnants to be distributed throughout the Universe, with the ratio of the WIMP and MACHO densities being the same everywhere and of order 10. If they form in the first phase of protogalactic collapse, one would expect the remnants to be confined to halos and clusters. In this case, their contribution to the halo density could be larger since the baryons would dissipate and become more concentrated. This is discussed further by Rees [63].

4 Constraints on Baryonic Candidates

From a theoretical perspective, it is hard to predict the mass range of Population III stars (some people argue that they would have been smaller than at present, others that they would have been larger) but one can still use a wide variety of constraints to exclude certain candidates. Some of these constraints depend on where the compact objects are located.

Snowballs

This term is used to describe condensations of cold hydrogen which are smaller than $0.001 M_{\odot}$ and have atomic density; larger objects are degeneracy-supported and have more than atomic density. In fact, snowballs can almost certainly be excluded from solving any of the dark matter problems. In order to avoid being disrupted by collisions within the age of the Universe [38], they must have a mass of at least 1g. On the other hand, they are excluded by the upper limit on the frequency of encounters with interstellar meteors between 1g and $10^7 g$, by the number of impact craters on the Moon between $10^7 g$ and $10^{16} g$, and by the fact that no interstellar comet has crossed the Earth's orbit in the last 400 years between $10^{15} g$ to $10^{22} g$ [40]. These mass limits apply for disk objects; they are somewhat stronger for halo objects because of their larger velocities. De Rujula et al. [26] have claimed an even stronger limit on the grounds that snowballs smaller than $10^{26} g$ would be evaporated within the age of the Universe by their own heat. We will see that EROS microlensing limits also exclude halo objects in the range $10^{26} - 10^{30} g$, which leaves no mass range at all.

Brown Dwarfs

These are objects between $0.001 M_{\odot}$ and $0.08 M_{\odot}$, which are never hot enough to ignite hydrogen. Such objects are hard to find but it would be surprising if the stellar mass function happened to cut off just above $0.08 M_{\odot}$ and there is now incontrovertible evidence for at least one brown dwarf [56]. In determining the contribution of brown dwarfs to the dark matter density, the best strategy is to study the mass function of stars just above the hydrogen-burning limit and infer whether its extrapolation would permit a lot of lower mass objects. Studies of the mass function of Population I stars [47,55] suggest that brown dwarfs may dominate the number density - indeed Hawkins & Jones [37] may have already found such a population - but they can only contain about 1% of the mass. The situation is less clear when one considers Population II stars. Richer et al. [65] and Richer & Fahlman [64] claim these may have a steeper mass function but Mera et al.[55] disagree. In any case, there may be no connection between the mass function of halo stars and Population II stars since they form at a different time and place. As discussed below, the most important signature of brown dwarfs would be intensity fluctuations in background sources due to their microlensing effects.

M-Dwarfs

These are stars below $0.1 M_\odot$, which burn hydrogen but are very dim. Discrete source count constraints imply that such stars can comprise no more than 6% of the halo dark mass and 15% of the disk dark mass [7,30]. They would also seem to be excluded by infrared measurements of other galaxy halos. The K-band mass-to-light ratio exceeds 100 for M87 [12] and 140 for NGC 100 [18]. Since the mass-to-light ratio is less than 60 for stars bigger than $0.08 M_\odot$, the lower limit for hydrogen-burning [25], this suggests that any hydrogen-burning stars are excluded. Although Sackett et al. [69] and James & Casali [44] have claimed to detect a faint red halo around NGC 5907, suggesting that there are some M-dwarfs, there are not enough to provide all the halo mass.

White Dwarfs

These would be the natural end-state of stars with initial mass in the range $0.8 - 8 M_\odot$. They would be the most conservative candidate since white dwarfs certainly form prolifically today [73]. This scenario would have many interesting observational consequences, such as an abundance of cool white dwarfs [78]. However, one needs a very contrived mass spectrum if white dwarfs make up galactic halos: the IMF must be restricted to between 2 and 8 $M_\odot$ to avoid producing too much light or too many metals [68] and even then one must worry about excessive helium production. There are other problems with this scenario: the fraction of white dwarfs in binaries might produce too many type 1a supernovae [75] and deep galaxy surveys may already exclude the bright early evolutionary phase which would be expected if WDs provided even 10% of the halo mass [20]. Nevertheless, Chabrier [19] and Mathews et al. [53] argue that the WD scenario is not excluded. WDs could still provide the dark matter in the Galactic disk (if real) but the observed mass function does not indicate this.

Neutron Stars

Although these would be the natural end-state of stars in some mass range above $8M_\odot$, the fact that the poorest Population I stars have metallicity of order 10^{-3} places an upper limit on the fraction of the Universe's mass which can have been processed through the stellar precursors and this probably precludes their explaining any of the dark matter problems [15]. Another constraint on a population of neutron stars comes from their microlensing affects on the line-to-continuum ratio of quasars, only the continuum region being small enough to be microlensed. This would decrease the equivalent width of the emission lines, so in statistical studies of many quasars, one would expect the typical equivalent width to decrease as one goes to higher redshift because there would be an increasing probability of having an intervening lens. Recently Dalcanton et al.[23] have compared the equivalent widths for a high and low redshift sample of quasars and find no difference. This implies that that compact objects in the mass range $0.01 - 20M_\odot$ (which includes both neutron stars and other low mass objects) must have less than a tenth of the critical density.

Stellar Black Holes

Stars larger than $20 - 50M_\odot$ may leave black hole rather than neutron star remnants, with some of their nucleosynthetic products being swallowed. However, they will still return a lot of heavy elements through winds prior to collapsing [51], so normal stellar black holes are probably excluded from explaining any of the dark matter problems. On the other hand, "Very Massive Objects" larger than $200M_\odot$ undergo complete collapse and so may be better dark matter candidates [9]. However, since the precursors of VMOs would be highly luminous, an important constraint on the number of VMO black holes comes from background light limits. If the radiation from VMOs is affected only by cosmological redshift, then it would presently be in the near-infrared [10]. In this case, the COBE constraints imply that the VMOs could only have the density required to explain galactic halos if they burn sufficiently early ($z > 200$) for their light to be redshifted beyond 10μ (where it would be hidden by interplanetary dust emission). However, in many circumstances, one would expect the VMO light to be reprocessed into the submillimetre band by pregalactic dust [11], in which case the strong constraints on the spectral distortion of the microwave background imposed by COBE exclude almost all scenarios [88]. Another constraint on stellar black holes comes from the line-to-continuum lensing effect discussed above. This precludes [23] black holes having a critical density for masses in the range $60 - 300M_\odot$.

Supermassive Black Holes

Objects larger than $10^5 M_\odot$ would collapse directly to black holes without any nuclear burning due to relativistic instabilities, so they would not be excluded by either nucleosynthetic or background light constraints. However, halo black holes would heat up the disk stars more than is observed unless they were smaller than about $10^6 M_\odot$, so they would have to lie in the narrow mass range $10^5 - 10^6 M_\odot$ and the disruption of globular clusters and dynamical friction effects may exclude even this range. SMO black holes could still reside outside halos but dynamical effects imply that any cluster holes must be smaller than $10^9 M_\odot$. All these dynamical constraints are discussed by Carr & Sakellariadou [16]. Another constraint on supermassive black holes comes from macrolensing effects. If one has a population of compact objects, then they may form multiple images of distant sources: the mass of the compact objects M determines the separation between the images, while their density parameter Ω_{co} determines the probability of a given source being multiply-imaged [61]. One can therefore use upper limits on the frequency of macrolensing for different image separations to constrain Ω_{co} as a function of M. In particular, Kassiola et al. [46] have invoked lack of lensing in VLBI radio sources to infer $\Omega_{co}(10^7 - 10^9 M_\odot) < 0.4$, while a study of VLBA sources [39] leads to a limit $\Omega_{co}(10^5 - 10^7 M_\odot) < 0.1$.

5 Discussion

There is good evidence that a large fraction of the Universe is dark and - unless one believes the high deuterium measurements in quasar absorption systems - many of the baryons must also be dark. If these dark baryons are not contained in dwarf galaxies or an intergalactic medium, they are probably in the form of compact objects. Therefore at least some of the dark matter problems could have baryonic solutions. If the local dark matter is real, it is almost certainly baryonic and probably in the form of brown dwarfs or white dwarfs. However, observations of the Population I mass function give no reason for expecting this. In any case, this would only explain a small fraction of the missing baryons.

The halo dark matter could consist at least partly of Population III remnants and brown dwarfs are the favoured candidate from a theoretical point of view. Although observations of the Population II mass function may not support this suggestion, there need be no connection between halo stars and Population II stars anyway. Microlensing searches towards the LMC probably provide the best test of this scenario. The MACHO experiment, discussed by

Sutherland[77], currently has seven events and their timescale and frequency suggest[2] that the halo objects have a most likely mass of 0.5 $M_{\odot}$ and a halo fraction of about 0.5. Rather perplexingly, this indicates a lens mass in the white dwarf rather than brown dwarf range. However, the precise figures should not be taken too seriously since they depend on the halo model and the number of events is small. (For comparison, the first year data gave a mass of $0.1 M_{\odot}$ and a halo fraction of 0.2.) The EROS Schmidt plate search has yielded one LMC event with a duration of two months[3] but the CCD searches have given no detections, which excludes objects in the range $10^{-7} - 10^{-3} M_{\odot}$ from having the halo density[4].

Further evidence that halos are made of low mass objects may come from the detection of microlensing in macrolensed quasars. If a galaxy is suitably positioned to image-double a quasar, then there is also a high probability that an individual halo object will traverse the line of sight of one of the images and this will give intensity fluctuations in one but not both images[33]. There is already evidence of this effect[22,42] for the quasar 2237+0305, the observed timescale for the variation in the luminosity of one of the images indicating a mass below $0.1 M_{\odot}$[83]. However, Wambsganss et al.[82] argue that it might be as high as $0.5 M_{\odot}$, so one faces the same dilemma as with the local microlensing data.

The background dark matter must be mainly non-baryonic if one believes that inflation requires a critical density. In this case, the cluster dark matter must also be mainly non-baryonic, although there would need to be some baryonic fraction if halos are themselves baryonic. The most natural candidate is probably a WIMP (i.e. some "cold" elementary particle). It should be stressed that WIMPs would naturally collect into galactic halos, so one would expect halos to comprise a mixture of MACHOs and WIMPS. Therefore WIMP searchers should not be discouraged by the microlensing results.

One cannot yet exclude the background dark matter consisting of intergalactic compact objects rather than WIMPs. Microlensing by such objects could produce luminosity variations in distant quasars and evidence for this has already been claimed by Hawkins[35,36], who has been monitoring 300 quasars in the redshift range 1-3 over the last 17 years using a wide field Schmidt camera. He finds quasi-sinusoidal variations of amplitude 0.5m on a timescale 5 y and attributes this to lenses with mass $\sim 10^{-3} M_{\odot}$. The crucial point is that the timescale decreases with increasing z, which is the opposite to what one would expect for intrinsic variations. The timescale also increases with the luminosity of the quasar and he explains this by noting that the luminosity should increase with the size of the accretion disk. A rather worrying feature of Hawkins' claim is that it requires the density of the lenses to be close to critical so that the sources are being transited continuously. In this case, the lenses have to form before Big Bang nucleosynthesis, so he invokes primordial black holes which form at the quark-hadron phase transition at $10^{-5}s$. However, this requires fine-tuning since the fraction of the Universe going into black holes at that time needs to be 10^{-9}. Schild [72] claims to have found evidence for luminosity variations in quasar 0957+561 with a timescale of 90 days; he attributes this to microlensing by objects of planetary mass but it is unclear how this relates to Hawkins' claim.

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