BARYONIC DARK MATTER: AN OVERVIEW

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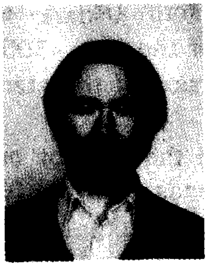

ABSTRACT

We first review the evidence for dark matter in various astronomical contexts and then discuss the likelihood that some of it could be baryonic. The dark matter in galactic disks (if real) is almost certainly baryonic and, in this case, the form of mass function for Population I stars suggests that it is probably contained in white dwarfs. The dark matter in galactic halos could also be partly baryonic and, in this case, it is likely to be contained in the remnants of a first generation of Population III stars. The various constraints on the nature of such remnants, summarized in my first lecture, suggest that brown dwarfs are the most plausible halo candidates. In this case, the combination of microlensing and infrared searches should confirm their existence within a few years.

1. Evidence for Dark Matter

A gravitationally bound system of mass M and radius R has a characteristic velocity $V \approx (GM/R)^{1/2}$. A dark matter problem arises whenever the mass inferred from the measured values of V and R exceeds the mass in visible form. Evidence for dark matter has been claimed in four different contexts (Carr 1994):

* There may be local dark matter in the Galactic *disk* with a mass comparable to that in visible form ($M_{dark} \sim M_{vis}$); in this case, R is associated with the thickness of the disk ~300 pc and V is associated with the vertical velocity dispersion of the stars ~20 km s^{-1}.

* There may be dark matter in the *halo* of our own and other spiral galaxies with a mass which depends upon the (uncertain) halo radius R_h and is of order $M_{dark} \sim 10 M_{vis}(R_h/100kpc)$; in this case, V is associated with the rotation velocity of the stars or the gas (around ~200 km s^{-1} for our galaxy and roughly independent of radius).

* There may be dark matter associated with *clusters* of galaxies ($M_{dark} \sim 10 M_{vis}$); in this case, R characterizes the size of the cluster ~10Mpc and V is associated with the velocity dispersion of the galaxies or the gas (the latter specifying the gas temperature), both of these being around ~10^3 km s^{-1} .

* In the inflationary scenario, there may also be smoothly distributed *background* dark matter, required in order that the total cosmological density have the critical value which separates ever-expanding models from recollapsing ones ($M_{dark} \sim 100 M_{vis}$); in this case, one can interpret V as the speed of light and R as the Hubble radius ~6000 Mpc.

The form of the dark matter need not be the same in all these contexts: some of it may be baryonic (i.e. deriving from protons and neutrons), some of it non-baryonic (most probably elementary particle relics from the early Universe). In order to assess when baryonic dark matter may be implicated, we must discuss the evidence in more detail.

1.1 Local Dark Matter

Measurements of the stellar velocity and density distribution perpendicular to the Galactic disk provide an estimate of the total disk density. This turns out to be about 0.1 $M_{\odot}pc^{-3}$ and it has long been suspected that this exceeds the density in visible stars. *The possibility of disk dark matter is very important in the present context because - of all the dark matter problems - this is the one most likely to have a baryonic solution.* Unfortunately, the evidence is very controversial. Bahcall (1984) used counts of F dwarfs and K giants to conclude that the density of unseen material must be at least 50% that of the visible material. He also concluded that the disk dark matter must have an exponential scale height of less than 700 pc, so that it must itself be confined to a disk. However, Bahcall assumed a particular model and doubt was cast in a series of papers by Kuijken & Gilmore (1989,1991), who used the full distribution function for the velocities and distances of K dwarfs rather than assuming a particular model. More recently Bahcall et al. (1992) have concluded from another analysis of K giants that the best-fit model has a dark density of 0.15 $M_{\odot}pc^{-3}$, which corresponds to a dark fraction of 60%. For present purposes the existence of disk dark matter should be regarded as an open question.

1.2 Galactic Halos

The best evidence for dark matter in galactic halos comes from the rotation curves of spirals, the dependence of the rotation speed V upon galactocentric distance R being a measure of the density profile $\rho(R)$. An important feature of our own and many other spiral galaxies is that the rotation speed, after an initial rise, remains approximately constant with increasing R (Rubin et al. 1980). This implies that the mass within radius 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 (Sancisi & van Albada 1987). *In considering the baryonic contribution to galactic halos, the crucial issue is how far the halos extend.* For our own galaxy the minimum halo radius consistent with rotation curve measurements, the local escape speed and the kinematics of globular clusters and satellite galaxies is 35 kpc but the dynamics of the Local Group of galaxies may require a halo radius of 70 kpc (Fich & Tremaine 1991). We will see that these values are marginally consistent with a baryonic halo. However, Zaritsky et al. (1993) argue from observations of the satellite systems of other galaxies that spirals typically have 200 kpc halos and this would not be.

Other sorts of galaxies also have dark halos. The mass distribution in ellipticals can be probed by measuring the velocity dispersion of the stars and globular clusters. Unfortunately the velocities do not determine the density profile uniquely but better information comes from X-ray observations of the hot gas in ellipticals and these do provide evidence for dark matter, in many cases indicating the same M~R law which characterizes spirals (Forman et al. 1985, Sarazin 1986). There is also evidence for dark matter in dwarf galaxies. The rotation curves in many dwarf irregulars indicate that they have even higher dark mass fractions than bright spirals and measurements of velocity dispersions for six dwarf spheroidals within the Local Group suggest that these also have dark halos (Lin & Faber 1983, Aaronson 1983).*The presence of dark matter in dwarf galaxies is crucial in the present context because it requires that halos consist either of baryonic or "cold" non-baryonic dark matter.*

1.3 Groups and Clusters of Galaxies

Galaxies are clumped on various scales (from small groups to rich clusters) and their velocity dispersion indicates that the dynamical mass exceeds the visible mass on all these scales by at least a factor of 10. This is confirmed by X-ray data on the gas temperature (which provides an independent measure of the gravitational potential). We saw from Bohringer's talk that a typical rich cluster has 2-7% of its mass in galaxies, 10-30% in gas and 60-85% in dark matter. Further evidence for dark matter in clusters comes from the lensing of background galaxies: the galaxies are distorted into arclets by the cluster potential and the properties of these arclets can be used to infer the dark matter distribution (Tyson et al. 1990). In assessing whether the dark matter in groups and clusters can be baryonic, it is important to determine whether it is the same as the halo dark matter. 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 (White 1976) - 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 their individual halos to form a collective halo (White & Rees 1978). However, this would only explain all the cluster dark matter if the original galactic halos were larger than 200 kpc and in this case it could not be baryonic.

1.4 Background Dark Matter.

None of the forms of matter discussed above can have the critical density required for the Universe to recollapse: $\rho_{crit} = 3H_0^2/8\pi G = 2\times10^{-29}h^{-2}$ g cm^{-3} where $h=H_0/(100$ km s^{-1}Mpc$^{-1})$. However, according to the currently popular inflation theory (Guth 1981), in which the Universe undergoes an exponential expansion phase at some early time, the total density should have almost exactly the critical value (Ω=1). 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 (Kaiser 1984, Dekel & Rees 1987) in the sense that galaxies form preferentially in just 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. One can probe the density on scales above 10 Mpc, for example, by analysing large-scale streaming motions (Dressler et al. 1987, Bertschinger & Dekel 1989) or by determining the dipole moment of the IRAS sources (Rowan-Robinson et al. 1990). In all these analyses, the inferred density depends on the bias parameter b and more sophisticated analyses are required to determine Ω and b separately (Peacock & Dodds 1994, Nusser & Dekel 1993). The evidence for Ω=1 is suggestive but not yet compelling (Coles & Ellis 1994).

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 [viz. $X(^4He)\approx0.24$, $X(^2D)\sim X(^3He)\sim10^{-5}$, $X(^7Li)\sim10^{-10}$] only applies if the baryon density parameter Ω_b lies in the range (Walker et al. 1991)

$$0.010h^{-2} < \Omega_b < 0.015h^{-2} \qquad (1)$$

the upper and lower limits coming from the upper bounds on ^{4}He and ^{2}D+^{3}He, respectively. 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 (Mathews et al. 1993). The standard scenario therefore assumes that the total density parameter is 1, with only the fraction given by eqn (1) being baryonic. On the other hand, the value of Ω_b allowed by eqn (1) almost certainly exceeds the density of visible baryons Ω_v. A careful inventory by Persic & Salucci (1992) 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 $(2.2+0.6h^{-1.5})\times10^{-3}$, so eqn (1) implies the fraction of baryons in dark form must be in the range 80% to 95% for $0.5 < h < 1$. *Thus it seems that one needs both non-baryonic and baryonic dark matter.*

Various provisos should be stressed at this point and these are expanded upon in my other talk. Firstly, the Persic-Salucci estimate does not include any contribution from dwarf galaxies, low surface brightness galaxies or Lyman-α clouds. Secondly, the discrepancy between Ω_b and Ω_v could be resolved if the missing baryons were in a hot intergalactic medium, although the temperature would need to be finely tuned in this case in order to satisfy the Gunn-Peterson test and the COBE limit on the Compton distortion of the microwave background. We will therefore assume that there is a need for at least some non-diffuse baryonic dark matter.

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. (1992), this only corresponds to $\Omega_d \approx 0.001$ - well below the value required by eqn (1). On the other hand, the cluster dark matter has a density $\Omega_c \approx 0.1$-0.2 and eqn (1) implies that this cannot be baryonic unless one invokes inhomogeneous nucleosynthesis. The more interesting question is whether dark baryons could suffice to explain galactic halos. If the Milky Way is typical, the density associated with halos would be $\Omega_h \approx 0.01h^{-1}(R_h/35\text{kpc})$, so eqn (1) implies that *all* the dark matter in halos could be baryonic only for

$R_h < 50h^{-1}$kpc. We saw in §1.2 that the minimum size for our halo is 70 kpc, which would just be compatible with this. Otherwise the baryonic fraction could be at most $(R_h/50h^{-1}\text{kpc})^{-1}$. The various values of Ω required by the above arguments are summarized in Figure (1).

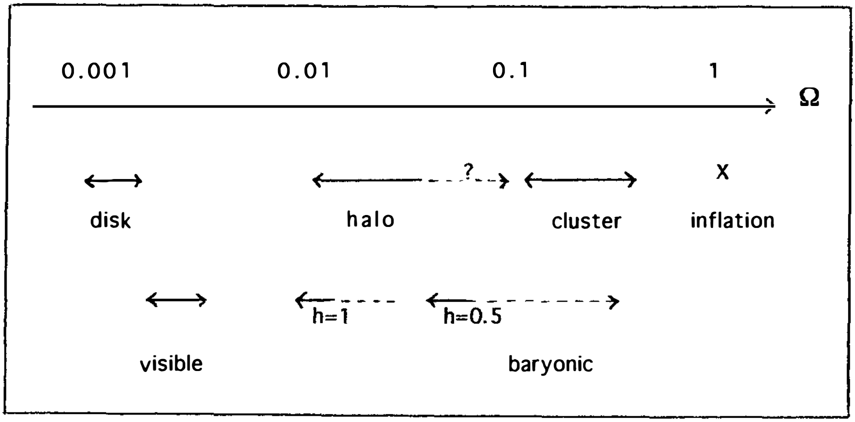

Figure (1). This compares the values of Ω associated with the various dark matter problems to the density in visible form and the baryonic density required by cosmological nucleosynthesis (with the inhomogeneous case shown dotted). The halo density depends on the typical halo radius and this must exceed 200 kpc to reach the cluster density.

Although the standard scenario assumes $\Omega_v \approx 0.003$, $\Omega_b \approx 0.01h^{-2}$ and $\Omega_{tot}=1$, so that one needs both baryonic and non-baryonic dark matter, two problems have recently arisen with this point of view. Firstly, as reviewed in Evrard's lecture, 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 implied by eqn (1). In particular, ROSAT observations of Coma suggest that the baryon fraction within the central 3 Mpc is about 25%, which is 5 times as large as the cosmological ratio (White et al. 1993). 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 the cosmological density is well below the critical value or that the baryon density is higher than allowed by the homogeneous nucleosynthesis scenario. Secondly, as stressed in Dar's talk, recent measurements of the deuterium abundance in quasar absorption systems give a value around 10^{-4} and this is an order of magnitude larger than is usually assumed (Songaila et al. 1994, Carswell et al. 1994). In this case, the upper limit in eqn (1) is reduced to $0.005h^{-2}$, which is only marginally larger than the Persic-Salucci estimate of Ω_V. As far as this talk is concerned, this would consistute an even more serious "baryon catastrophe" since there would then be no need for dark baryons at all! However, the evidence for such a high deuterium abundance is not yet conclusive.

3. Population III Stars

The fact that at least some of the halo dark matter could be baryonic gives rise to the possibility that halos contain the dark remnants of a first generation of stars and the term "Massive Compact Halo Object" or "MACHO" has been coined in this context. This contrasts with the possibility that the halo dark matter is non-baryonic and in the form of "Weakly Interacting Massive Particles" or "WIMPs". The precursors of the halo objects are sometimes termed "Population III" stars to distinguish them from the "Population I" and "Population II" stars which reside in the disk and spheroid of the Galaxy respectively. However, there is some confusion in the literature because the term "Population III" has also been used to describe the stars which generate the first metals. Such stars must exist, since heavy elements can only be generated through stellar nucleosynthesis, but the most natural assumption is that they are merely the ones at the high mass end of the Population II mass spectrum (which evolve fastest), in which case they do not warrant a special name. Henceforth I will use the term "Population III" specifically in dark matter sense.

Although there are no observations which require that most of the baryons in the Universe were processed through Population III stars, there are theoretical reasons for anticipating their formation. This is because the existence of galaxies and clusters of galaxies implies that there must have been density fluctuations in the early Universe and, in many scenarios, depending on the nature of the fluctuations and the nature of the dominant dark matter, these fluctuations would also give rise to a population of pregalactic clouds. The question then arises of what happens to these pregalactic clouds. They could face various possible fates. They might just turn into ordinary stars and form objects like globular clusters. On the other hand, the conditions of star formation could have been very different at early times and several alternatives have been suggested:

* Some people propose that the first stars could have been much *smaller* than at present. Fairly general arguments suggest that the minimum fragment mass could be as low as 0.007 $M_\odot$ (Low & Lynden-Bell 1976, Rees 1976) and it is possible that conditions at early epochs - such as the enhanced formation of molecular hydrogen (Palla et al. 1983, Yoshii & Saio 1986) - could allow the formation of even smaller objects. One might also invoke the prevalence of high pressure pregalactic cooling flows (Ashman & Carr 1988, Thomas & Fabian 1990, Ashman & Carr 1991), analagous to the cluster flows observed at the present epoch (Fabian 1994) but on a smaller scale.

* Other people argue that the first stars could have been much larger than at present. For example, the fragment mass could be increased before metals formed because cooling would be less efficient (Silk 1977). There is also observational evidence that the IMF may become shallower as metallicity decreases (Terlevich 1985), thereby increasing the fraction of high mass stars. Another possibility is that the characteristic fragment mass could be increased by the effects of the microwave background (Kashlinsky & Rees 1983) or by the absence of substructure in the first bound clouds (Tohline 1980).

* It is possible that the first clouds collapse directly to supermassive black holes (Gnedin & Ostriker 1992). Usually clouds will be tidally spun up by their neighbours as they become gravitationally bound and the associated centrifugal effects then prevent direct collapse. However, just after recombination, Compton drag could prevent this tidal spin-up, especially if the gas becomes ionized (Loeb 1993, Umemura et al. 1993). Even if rotation is important, one could still get a supermassive disk which slowly shrinks to form a black hole due to angular momentum transport by viscous effects.

* In the baryon-dominated "isocurvature" scenario (Peebles 1987), with highly non-linear fluctuations on small scales, the collapse of the first overdense clouds depends on the effects of radiation diffusion and trapping. Hogan (1993) finds that sufficiently dense clouds collapse to black holes, while clouds below this critical density delay their collapse until after recombination and produce neutron star or brown dwarf remnants. This scenario might allow a baryon density parameter higher than indicated by eqn (1) because the nucleosynthetic products in the high density regions are locked up in the remnants, leaving the products from the low density regions outside (Gnedin et al., 1995).

This discussion indicates that, while there is clearly considerable uncertainty as to the fate of the first bound clouds, they could well fragment into stars which are larger or smaller than the ones forming today. One certainly needs this if they are to produce a lot of dark matter. We note that there is no necessity for the Population III stars to form *before* galaxies, just as long as some change in the conditions of star formation makes the mass function different from what it is today. However, the epoch of Population III formation will be very important for the relative distribution of baryonic and non-baryonic dark matter, especially if the non-baryonic dark matter is "cold" so that it can cluster in galactic halos. In this case, if the Population III stars form *before* galaxies, one might expect their remnants to be distributed throughout the Universe, with the ratio of the non-baryonic and baryonic densities being the same everywhere and of order 10 from eqn (1). If they form at the same time as galaxies, perhaps 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 probably dissipate and become more concentrated. Angular momentum considerations suggest that the local baryon fraction should increase by at least 10 (Fall & Efstathiou 1981).

The various constraints on baryonic dark matter, summarized in Figure (2), show that there are only two plausible halo candidates: the black hole remnants of very massive stars ($M>10^2M_\odot$) or very dim brown dwarfs which are too small ($M<0.08M_\odot$) to burn hydrogen. The first option now seems less plausible in view of the COBE results, so for the rest of this talk we focus on the brown dwarf scenario .

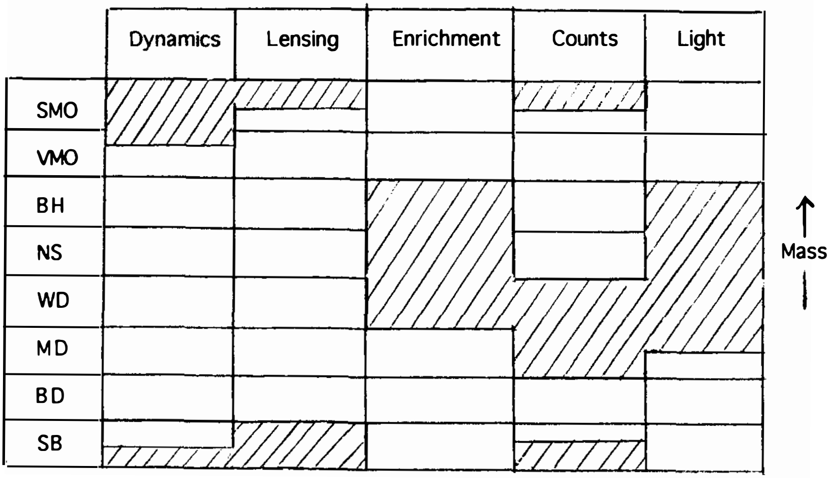

Figure (2): Constraints on compact halo objects (see accompanying paper). SMO, VMO and BH refer to the black hole remnants of Supermassive Objects, Very Massive Objects, and ordinary stars; WD=white dwarf; MD=M-dwarf; BD=brown dwarf; SB = snowball.

4. Brown Dwarfs

There are several reasons why brown dwarfs (BDs) are attractive dark matter candidates: (i) there may be direct evidence from cluster cooling flows that baryons can turn into low mass stars with high efficiency even at the present epoch; (ii) recent data on the initial mass function (IMF) for stars in our own galaxy suggests there may be a higher fraction of low mass objects when the metallicity is low; (iii) microlensing data may already indicate that there is dark matter in the form of BDs. The first point has been recently reviewed by Fabian (1994), so here we only focus on the second two points.

4.1 Evidence from Population I and Population II

The evidence for any stars in the brown dwarf mass range (Simons & Becklin 1992, Steele et al. 1993) is controversial but this merely reflects the fact that they are hard to find and it would be very surprising if the IMF happened to cut off just above $0.08M_\odot$. The best hope is to study the IMF of stars in the mass range just above the hydrogen-burning limit and infer whether its extrapolation would permit a lot of BDs. If one assumes for simplicity that the IMF has the power-law form

$$dN/dm \sim m^{-x} \quad \text{for} \quad m_{min} < m < m_{max} \qquad (2)$$

then most of the mass is in the smallest stars for x>2 and the largest ones for x<2. Determining the value of x in the low mass range is difficult: partly because obtaining the luminosity function is hard and partly because there are large uncertainties in the mass-luminosity relation as one approaches the hydrogen-burning limit. Nevertheless, opinion does now seem to be converging.

Let us first consider the possibility that the disk dark matter (if it exists) is in the form of BDs. Early studies of the luminosity function for nearby stars (Gilmore et al. 1985) suggested that the IMF is too shallow for BDs to have an interesting density and more recent data of Tinney et al. (1993) indicates that the mass function flattens off below 0.2 $M_\odot$. This is also consistent with the results of Kroupa et al. (1993) who find $x=2.7$ for $m>1M_\odot$, $x=2.2$ for $0.5<m<1M_\odot$ and $0.7<x<1.8$ for $0.08M_\odot<m<0.5M_\odot$. This suggests that stars of 0.5 $M_\odot$ should dominate the disk density. BDs may dominate the *number* density but, unless the value of x changes below $0.08M_\odot$, they can only contain 1% of the mass.

The situation is less clear-cut when one considers Population II stars. Richer et al. (1991) claim that metal poor Globular clusters have $x=3.6$ below $0.5M_\odot$ down to at least $0.14M_\odot$, while Richer & Falman (1992) claim that stars in the Galactic Spheroid have $x=4.5\pm1.2$ in the same mass range. Although this conclusion needs to be confirmed (indeed Space Telescope data may already contradict it), this *would* allow the possibility that most of the mass is in the smallest objects; indeed BDs could explain all the halo dark matter if the IMF extended down to $M_{min}\sim0.01M_\odot$. However, Richer & Falman also point out that the form of the Galactic rotation curve requires that the total spheroid mass cannot exceed $7\times10^{10}M_\odot$ and this implies that such a steep IMF cannot extend below $0.05M_\odot$. It is therefore unlikely that Population II stars themselves could explain the halo dark matter. The point of these results is that they lend support to the suggestion that low metallicity enhances the fraction of low mass objects. In any case, there may be no connection between the IMF of halo stars and Population II stars since they probably form at a different time and place. One should thus be wary of attempts to exclude halo BDs on the grounds that Population II stars have a particular IMF, as do Hegyi & Olive (1986, 1989).

4.2 Infrared Searches for Brown Dwarfs

Even though BDs do not burn hydrogen, they still generate some luminosity in the infrared. They radiate first by gravitational contraction (for about 10^7 yr) and then by degenerate cooling. If the disk or halo dark matter is in the form of BDs, it is therefore important to consider whether they can be detected via this infrared emission. Current constraints on BDs are rather weak (Beichmann et al. 1990, Nelson et al. 1993) but the prospects of detection will be much better with impending space satellites (like ISO and SIRTF) and ground-based surveys (like 2MASS and DENIS). The problem has been addressed in various contexts by several authors. Karimabadi & Blitz (1984) have calculated the expected intensity from BDs with a discrete IMF comprising an $\Omega=1$ cosmological background. Adams & Walker (1990) have discussed the possibility of detecting the collective emission of the brown dwarfs in our own Galactic halo for both a discrete and power law IMF. Daly & McLaughlin (1992) have considered the prospects of detecting the emission of individual halo brown dwarfs of a given mass in the Solar vicinity, as well as the collective emission of brown dwarfs in other galaxy halos. Kerins & Carr (1994) have discussed how infrared observations at different wavelengths could be used to probe the mass spectrum of the brown dwarfs and also considered the possibility that the BDs are assembled into dark clusters.

As an illustration of the feasibility of detecting radiation from BDs, let us consider the prospects of detecting the nearest one in our halo. If the BDs all have the same mass m, then the local halo density ($\rho_0=0.01M_\odot pc^{-3}$) implies that the expected distance to the nearest one is $0.55(m/0.01M_\odot)^{1/3}$pc. The expected spectra are shown and compared to the sensitivities of IRAS and ISO in Figure (3), which is taken from Kerins & Carr (1994). This assumes the temperature and luminosity of Stevenson (1986) where the BD age and opacity are taken to be 10^{10}yr and $0.01cm^2g^{-1}$ (corrresponding to electron-scattering). This shows that IRAS gives no useful constraints (it is too weak by a factor of 2 even for the optimal mass of $0.07M_\odot$) but the ISOCAM instrument on ISO could detect $0.08M_\odot$ BDs in a few hours, $0.04M_\odot$ BDs in a few days and $0.01M_\odot$ BDs in a few months. Note that disk BDs would be younger, locally more numerous and more opaque than halo BDs, so the constraints are stronger. Indeed IRAS already implies that BDs with a discrete IMF could provide the disk dark matter only for $m< 0.01M_\odot$.

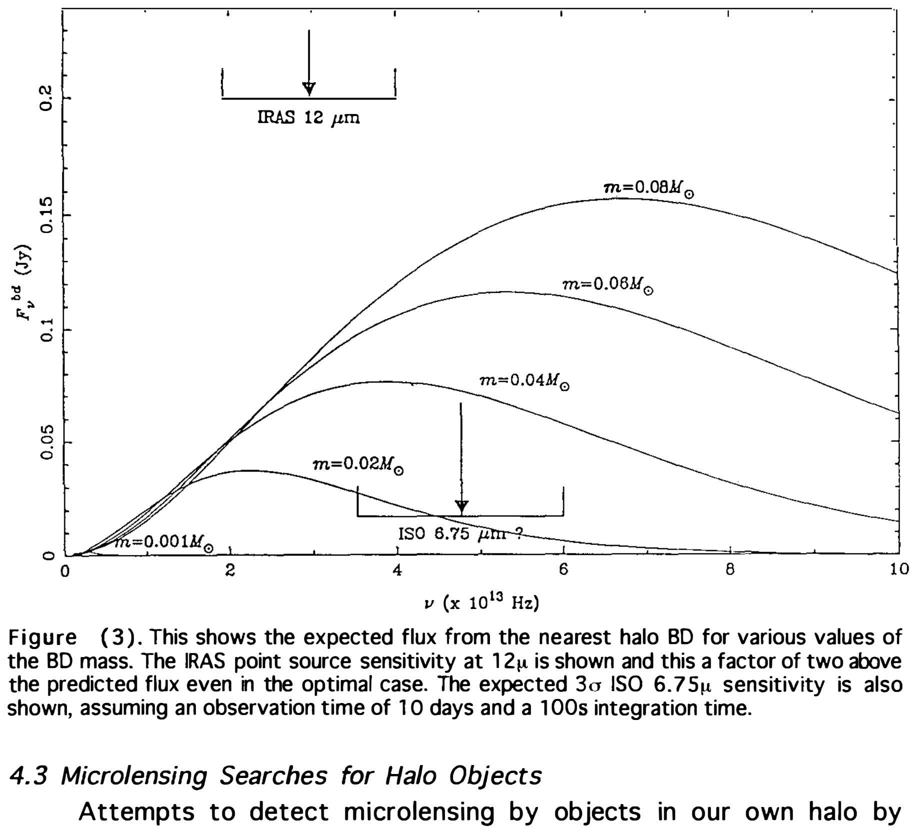

Figure (3). This shows the expected flux from the nearest halo BD for various values of the BD mass. The IRAS point source sensitivity at 12μ is shown and this a factor of two above the predicted flux even in the optimal case. The expected 3σ ISO 6.75μ sensitivity is also shown, assuming an observation time of 10 days and a 100s integration time.

4.3 Microlensing Searches for Halo Objects

Attempts to detect microlensing by objects in our own halo by looking for intensity variations in stars in the Magellanic Clouds and the Galactic Bulge have now been underway for several years and have already met with success. In this case, the timescale for the variation is $P=0.2(M/M_\odot)^{1/2}$y, so one can seek lenses over the mass range 10^{-8} - 10^{2} $M_\odot$, but the probability of an individual star being lensed is only $\tau \sim 10^{-6}$, so one has to look at many stars for a long time (Paczynski 1986). The likely event rate is $\Gamma \sim N \tau P^{-1} \sim (M/M_\odot)^{-1/2} yr^{-1}$ where $N \sim 10^{6}$ is the number of stars. Thus small masses give frequent short-duration events (eg. 0.01 $M_\odot$ events would last a week and occur a few times a year) and are best sought with CCDs, while large masses give rare long-duration events (eg. 10 $M_\odot$ events would last a year and occur every few years) and are best sought with photographic plates. The key feature of these microlensing events is that the light-curve is time-symmetric and achromatic and this may allow them to be distinguished from intrinsic stellar variations (Griest 1991).

Three groups are involved and each now claims to have detected lensing events. The American group (MACHO) has used a dedicated telescope at Mount Stromlo to study 10^7 stars in red and blue light in the LMC, the SMC and the Galactic bulge. They currently have 3 LMC events (with durations of order a month) and around 45 bulge events (Alcock et al. 1993). The French group (EROS) has been studying stars in the LMC and their approach is two-pronged: they are seeking 1-100 day events (corresponding to 10^{-4}-$1M_{\odot}$ lenses) with digitized red and blue Schmidt plates obtained with the ESO telescope in Chile and 1 hour to 3 day events (corresponding to 10^{-7}-$10^{-3}M_{\odot}$) with CCDs taken at the Observatoire de Haute Provence (Auborg et al. 1993). The CCD searches have given no results, which implies a limit $\Omega_C(10^{-7}$-$10^{-3}M_{\odot}) < 0.1$, but analysis of $3x10^6$ stars on the Schmidt plates yields two events, each with duration of about two months. The Polish collaboration (OGLE) are using the Las Campanas telescope in Chile to look at $7x10^5$ stars in the Galactic bulge and have claimed 11 events (Udalski et al. 1993).

As indicated in Pratt's lecture, the timescale for the LMC events suggests that the halo objects have a mass just below 0.1 $M_{\odot}$ (as required in the BD scenario) but the freqency (although larger than that expected from ordinary stars) is only about a fifth that anticipated if the halo consists entirely of BDs. However, we have already seen that one would expect halos to comprise a mixture of MACHOs and WIMPS, so this result should occasion no surprise. It is therefore important that WIMP seachers should not be too discouraged by the microlensing results. In any case, the microlensing searches only probe the halo at Galactocentric radii from 10-20 kpc and, if the dark baryons are preferentially concentrated as a result of dissipation, there could be many more WIMPs further out. Note that the number of bulge events is anomalously high and, as stressed in Gould's lecture, this may imply that one needs a "maximal" disk, in which case even the LMC events may not be due to halo objects. The results of the AGAPE project, reported by Melchior, which is searching for microlensing events in M31, may help to resolve this dilemma.

5. Conclusions

There is good evidence that a large fraction of the baryons in the Universe are dark. If the missing baryons are not contained in dwarf galaxies or an intergalactic medium, they are probably in the remnants of a first generation of pregalactic or protogalactic stars. The *local dark matter* (if it exists) could be brown dwarfs but observations of the Population I IMF gives no reason for expecting this and it is more likely to be in white dwarfs. The *halo dark matter* could consist at least partly of brown dwarfs, especially if observations of the Population II IMF continue to indicate a preponderance of low mass stars at small metallicity. Microlensing searches may already provide evidence for halo brown dwarfs and the combination of infrared and microlensing searches will confirm or disprove their existence soon.

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