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SEARCHES FOR DARK MATTER IN THE FORM OF BROWN DWARFS*

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** Talk given at Royal Astronomical Society Meeting on 11 March 1994 in which it is argued that there may be lots of baryonic dark matter in the form of brown dwarfs. The possible detection of such brown dwarfs through microlensing and infrared searches is discussed*

Evidence for dark matter has been claimed in four different contexts: (i) there may be local dark matter in the Galactic disk with a mass comparable to that in visible form (M_{dark}~M_{vis}); (ii) there may be dark matter in the halo of our own and other galaxies with a mass which depends upon the (uncertain) halo radius R_h and is of order M_{dark}~$10M_{vis}(R_h/100kpc)$; (iii) there may be dark mass associated with clusters of galaxies (M_{dark}~$10M_{vis}$), which may or may not derive from the original galactic halos; (iv) if one believes the inflationary scenario, there may also be smoothly distributed background dark matter, required in order that the total cosmological density have the critical value (M_{dark}~$100M_{vis}$).

Candidates for the dark matter may be classified as *non-baryonic* or *baryonic*. It is naive to assume that all these dark matter problems will have a single explanation, so there may be both. Most of the non-baryonic candidates are elementary particle relics from the early Universe and the term "Weakly Interacting Massive Particle" or "WIMP" is often used to describe these. The baryonic candidates are usually assumed to be the remnants of a first generation of pregalactic or protogalactic stars and - in the context of the halo dark matter problem - these are sometimes described by the term "Massive Compact Halo Object" or "MACHO".

The main argument for both baryonic and non-baryonic dark matter comes from Big Bang nucleosynthesis: the standard picture can explain the primordial light element abundances only if the baryonic density parameter is $\Omega_b \approx 0.01h^{-2}$, where h is the Hubble parameter in units of 100 km $s^{-1}Mpc^{-1}$. This is well below 1, which suggests that no baryonic candidate could provide the critical density required in the inflationary scenario. In recent years attention has focussed on the question of whether one can circumvent this conclusion by invoking inhomogeneities induced at the quark-hadron phase transition. However, even in this case one requires $\Omega_b<0.1h^{-2}$, so a critical density of baryons is still excluded for reasonable values of h. On the other hand, the value of Ω_b required by cosmological nucleosynthesis almost certainly exceeds the density of visible baryons, the density in stars and hot gas being only $\Omega_V\approx0.003$. It therefore seems that one needs some dark baryons.

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The baryonic density would certainly suffice to explain the dark matter in galactic disks (if this exists) since the associated density parameter is only $\Omega_{disc}\approx0.001$. On the other hand, the cluster dark matter has a density $\Omega_c\approx0.1$ and could not be purely baryonic unless one invoked inhomogeneous nucleosynthesis. This leaves the interesting question of whether baryons could provide the dark matter in galactic halos. If our galaxy is typical, the density associated with halos would be $\Omega_h\approx0.01h^{-1}(R_h/35kpc)$, so *all* the halo dark matter could be baryonic only for $R_h < 35h^{-1}$kpc. The minimum size of our halo is 70 kpc, which would just be compatible with this, but it could be much larger, in which case the baryonic fraction could only be $(R_h/35h^{-1}kpc)^{-1}$. Halos may therefore be a mixture of MACHOs and WIMPs, especially if the WIMPs are "cold" so that they can cluster inside galactic halos.

The relative contribution of WIMPs and MACHOs depends on the epoch at which the MACHOs form. If they form *before* galaxies, one might expect them to be distributed throughout the Universe with the WIMP-to-MACHO density ratio being the same everywhere and of order 10. On the other hand, if they form at the same time as galaxies, perhaps in the first phase of protogalactic collapse, one would expect them to be confined to halos and clusters. The local WIMP-to-MACHO density ratio would then be reduced to around unity since the baryons could dissipate and become more concentrated before turning dark.

In assessing the most likely form for the MACHOs, it must be appreciated that - while stars leave dark remnants in most mass ranges - they have other consequences which may preclude them having an appreciable density. For example, the precursors of white dwarfs, neutron stars and stellar black holes - if numerous enough to provide galactic halos - are likely to have nucleosynthetic consequences inconsistent with observation; they might also produce too much background radiation. Supermasssive black holes (those larger than

$10^5 M_\odot$ which never undergo nuclear burning) would avoid these problems but would still have impossible dynamical consequences. The most plausible candidates would therefore seem to be Low Mass Objects (LMOs), i.e. stars much smaller than $0.1 M_\odot$ which would have a large enough mass-to-light ratio to explain halos. This possibility is accentuated by the claims that gas is turned into LMOs with high efficiency in cluster cooling flows.

In determining how small LMOs would need to be to provide the disk or halo dark matter, important information comes from red and infrared source counts. These already suggest that the local number density of stars in the hydrogen-burning mass range $0.08\text{-}0.1 M_\odot$ can be at most 0.01 pc^{-3}, which is a hundred times too small to explain the local dark matter and ten times too small to explain the halo dark matter. A similar conclusion is indicated by infrared observations of other spiral galaxies, the K-band mass-to-light ratio usually exceeding 60, the maximum mass-to-light ratio for hydrogen-burning stars. One is therefore left with the possibility of Brown Bwarfs (BDs), i.e. stars smaller than $0.08 M_\odot$ which never burn hydrogen. There is no reason, in principle, why the first stars should not have been as small as this and theoretical arguments suggest that the first clouds could have fragmented into objects as small as $0.001 M_\odot$. We therefore assume that the MACHOs have a mass in the range $0.001\text{-}0.08 M_\odot$.

Although it is difficult to observe BDs directly (indeed there is no definite evidence for them at all), one can 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 smaller objects. If one assumes that the IMF scales as m^{-x}, at least over some mass range, 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 LMO range is difficult but the most recent studies suggest that stars in the disk (Population I) have $x=2.7$ for $m>1 M_\odot$, $x=2.2$ for $0.5<m<1 M_\odot$ and $0.7<x<1.8$ for $0.08 M_\odot<m<0.5 M_\odot$. This suggests that stars of $0.5\ M_\odot$ should dominate the disk density and, unless the value of x changes below $0.2 M_\odot$, BDs could only contain 1% of the total disk mass.

The situation is less clear for Population II stars. Some groups claim that the IMF for metal poor Globular Clusters and the Galactic Spheroid has $x=3\text{-}5$ in the mass range 0.14 to $0.5 M_\odot$. This would allow most of the mass to be in LMOs; indeed BDs could explain all the halo dark matter if the IMF extended down to $M_{min}=10^{2-x} M_\odot \sim 0.01 M_\odot$. In fact, other arguments suggest that such a steep IMF could not extend below $0.05 M_\odot$, so it is unlikely that Population II stars themselves can explain the halo dark matter (which is not surprising since they probably form at a different time and place). The main point of these results is that they lend support to the suggestion that low metallicity may enhance the fraction of mass in low mass objects.

Even though BDs do not burn hydrogen, they still generate some luminosity in the infrared. They radiate first by gravitational contraction 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. There are various strategies: one could search for the background radiation from all the BDs in the Universe, for the collective emission of all the BDs in our own or other galactic halos, or for the emission of individual disk or halo BDs in the Solar vicinity. Eamonn Kerins and I have shown that current constraints on BDs are rather weak but that the prospects of detection will be much improved with impending space satellites.

Let us consider the prospects of detecting the nearest BD in our halo. If the BDs all have the same mass m, then the local halo density implies that the expected distance to the nearest one is $0.6(m/0.01 M_\odot)^{1/3}$pc. A comparison of the expected spectra with the sensitivity of the IRAS satellite shows that IRAS gives no useful constraints (it is too weak by a factor of 2 even for the optimal mass of $0.07 M_\odot$). However, the ISOCAM instrument on the ISO satellite (due for launch in 1996) could detect $0.08 M_\odot$ BDs in a few hours, $0.04 M_\odot$ BDs in a few days and $0.01 M_\odot$ BDs in a few months. Note that disk BDs would be younger and locally more numerous than halo BDs; IRAS already implies that BDs with a discrete IMF could provide the disk dark matter only for $m< 0.01 M_\odot$. We have also considered the possibility that the BDs are assembled into clusters. One might expect them to be easier to detect in this case. However, dynamical constraints imply that the clusters would probably be extended rather than point sources, in which case they could well cover the sky and detecting them would be equivalent to detecting the halo background. ISO would take several months to detect the Galactic background, even in the optimal case with $m=0.08\ M_\odot$.

The other way to look for BDs is through microlensing, the apparent increase in luminosity of an astronomical source due to a compact object traversing its line of sight. 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 may 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 10^{-6}, so one has to look at many stars for a long time. If one monitors 10^6 stars, the likely event rate is $(M/M_\odot)^{-1/2}yr^{-1}$, so small masses give frequent short-duration events and are best sought with CCDs, while large masses give rare long-duration events 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.

Three groups are involved in this search 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 Galacic Bulge. After analysing 4 fields near the centre of the LMC, they have obtained one event: the duration is 34 days (corresponding to a mass of 0.1 $M_\odot$) and the amplification is A=6.8. The French group (EROS) has been studying stars in the LMC; they are seeking both 1-100 day events with digitized red and blue Schmidt plates obtained with the ESO telescope in Chile and 1 hour to 3 day events with CCDs taken at the Observatoire de Haute Provence. The CCD searches have given no results but analysis of $3x10^6$ stars on the Schmidt plates yields two events: one has A=2.5 and P=54d (corresponding to a mass of $0.2M_\odot$), the other has A=3.3 and P=60d (corresponding to a mass of $0.3M_\odot$). They have also confirmed the MACHO event in red light. The Polish group (OGLE) is using the Las Campanas telescope in Chile to look at $7x10^5$ stars in the Galactic bulge. They have claimed one event with A=2.4 and P=42d (corresponding to a mass of $0.3M_\odot$) but they only have data in one colour.

These results are very exciting but one must be cautious about their interpretation. The timescales are marginally too long for the lensing objects to be BDs, so there may be an inconsistency with the infrared constraints. Also the amplitude of the events is rather high; one would expect many more low amplitude events. Even if the microlensing events are confirmed, they do not necessarily exclude WIMPs because microlensing of stars in the LMC only probes Galactocentric radii from 10-20 kpc and the halo itself could extend much further. In any case, the combination of infrared and microlensing searches should confirm or exclude the presence of halo BDs very soon.

Professor R.J. Tayler. How do the masses you get for the brown dwarfs depend on (1) their direction relative to the line of sight, and (2) how far away they are? That, of course, means how big is our halo?

Dr. Carr. The masses depend on all of these factors. That's why one can only derive a statistical distribution for the mass, because one has to allow for the possible range of distances and velocities for the halo objects. The most likely mass is around 0.1 to 0.3 $M_\odot$ but the distribution is very broad and and there is quite a high probability that it is somewhat lower (i.e. in the brown dwarf mass range). The important point to bear in mind is that, because the LMC is about 50 kpc away, the biggest effect comes from lenses about 20 kpc away (that is, around halfway). I should also stress that confirmation of the lensing events would not exclude the possibility that there may also be a substantial admixture of non-baryonic material in the haloes. In this case, the MACHOs would probably be concentrated in the middle, with the WIMPs being more extended.

Dr. D. Hughes. If brown dwarfs are not represented in the tail of the stellar or planetary mass function, where do they come from?

Dr. Carr. Brown dwarfs are not represented in the tail of the stellar mass function for disc stars, but there is perhaps an indication that they are present in the mass function of Population II stars. This suggests that stars which form with small metallicity may have lower masses. Of course, Population III stars - the halo objects themselves - may not have formed at the same time as Population II. The most natural picture is that they formed in a protogalactic collapse stage before Population II, in which case they would have no metals and there is no reason why they should have the same IMF as either Population I or Population II. The purpose of the diagram I showed was to indicate

that low metallicity may be associated with having more mass in low mass objects. The connection with the planetary mass function is interesting. You might have asked: could these low mass objects be even smaller than brown dwarfs, could they be comets or snowballs? That is hard to rule out definitively. There are constraints on whether, for example, snowballs could make up the dark mass. It seems fairly clear that any snowball smaller than $10^{-6} M_\odot$ would have evaporated by now but there is a window from 10^{-6} to 10^{-3} $M_\odot$ where you could in principle have cometary-type objects making up the dark mass. The trouble is that it seems rather hard to envisage a scenario where a lot of the mass would go into such snowballs.

Dr. M.E. Bailey. Have you considered whether the dark objects in the Spheroid would significantly perturb the comets in the Oort cloud?

Dr. Carr. Not specifically. We have considered all sorts of dynamical effects, such as the disruption of star clusters. I myself don't know of any work on perturbations of the Oort cloud by brown dwarfs. The chances are that the nearest brown dwarf is about half a parsec away, so that encounters with brown dwarfs may not be sufficiently frequent for this to give an important limit. Maybe I'm wrong - you would be able to answer that better than me.

Dr. Bailey. I was just picking up on your figure of half a parsec. That is the size of the Oort cloud, so it sounds as if you've always got one of these brown dwarfs inside the Oort cloud.

Dr. Carr. In that case, let me revise my answer and say that maybe you could get an interesting constraint! The question is whether the brown dwarfs have enough mass to significantly perturb the Oort cloud.

A Fellow. Is there any chance of detecting brown dwarfs in the 2-micron surveys that are going on at present?

Dr. Carr. Yes, the people involved in the 2-Micron All Sky Survey (2MASS) have done a pilot study. They already have some constraints but these are not much better than the IRAS ones. When 2MASS is complete, it should give constraints comparable to ISO, although ISO will go to somewhat longer wavelengths. I ought to stress that there is still no incontrovertible evidence that brown dwarfs exist at all. There have, of course, been many searches for brown dwarfs in binary systems but perhaps the most exciting evidence comes from clusters like the Pleiades, where people claim to have found about 20 candidates - again it's controversial. One should not be too perturbed by this because brown dwarfs are inevitably hard to detect and it would really be a miracle if the mass function of stars happened to stop at the mass of 0.08 $M_\odot$ where hydrogen-burning turns on. So the fact that we have not found brown dwarfs should not be held against them. They are just very hard to see, and that is why the chance to seek their microlensing and infrared effects is very important.

President. Could I follow that by saying that you expect there to be lots of baryons in the form of intergalactic gas. That being so, how many brown dwarfs would they have to find to embarrass you with regard to the number of baryons in the Universe?

Dr. Carr. Do you mean embarrassed because there aren't enough?

President. No, because there are too many, given that lots of baryons produced in the Big Bang are in the form of intergalactic gas, in clusters, in Lyman-α clouds and so forth.

Dr. Carr. The missing baryons, the discrepancy between the 0.01 expected from nucleosynthesis and the 0.003 seen in visible gas, could indeed be contained in a hot intergalactic medium, in the form of Lyman-α clouds. There are certainly some baryons in such clouds but we don't know what their contribution to the cosmological density is. If we believe that all the dark baryons are in an intergalactic medium, we must conclude that the dark mass in the halo is in the form of WIMPs. Looking for WIMPs may therefore be a good way of seeing whether we need an intergalactic medium.