SUMMARY. The dark matter in galactic halos and in clusters could in principle be in stars of exceedingly low mass, or in black hole remnants of very massive stars (VMOs). Various lines of evidence could further constrain (or reveal) such objects - e.g. dynamical effects, infrared observations, gravitational lensing, etc.

1. INTRODUCTION

Dr Primack has discussed non-baryonic candidates for cosmic dark matter. It's my task to present the "dull man's" viewpoint - to be a baryon chauvinist and discuss whether this matter could be contributed by baryons aggregated in forms (such as low mass stars or stellar remnants) that yield high mass-to-light ratios. The late Professor Redman of Cambridge, a no-nonsense observer with little taste for speculation, once claimed that "Any competent astrophysicist can reconcile any theory with any set of facts". An even more cynical colleague extended this claim, asserting that the astrophysicist often needn't even be competent! Dr Primack and I are perhaps exemplifying Redman's theorem and its extension. All things considered, the existence of dark matter is quite unsurprising - there are all too many forms it could take, and the aim of observers and theorists must be to narrow down the range of options. These topics have been discussed and reviewed at greater length elsewhere (e.g. Dekel, Einasto and Rees 1986, and references cited therein); the present written text is therefore just a brief summary of the issues.

2. NUCLEOSYNTHETIC CONSTRAINTS ON $\Omega_b$

Primordial nucleosynthesis depends on the expansion timescale when $kT \approx 0.1 - 1$ MeV (which depends essentially on the number of particle species present at that epoch) and on the baryon density at that same epoch (proportional to $\Omega_b h^2$, $h$ being the Hubble constant in units of $100 \text{ km s}^{-1}\text{Mpc}^{-1}$). The predicted $^4$He abundance, though it depends on the number of neutrino species, is rather insensitive to the matter density: measurements can however be made with sufficient precision to suggest that the upper limit to the primordial $^4$He abundance implies $\Omega_b h^2 \lesssim 0.1$. For full discussions of this topic, see the proceedings of the ESO conference on helium (1984).
Stronger constraints on $\Omega_b$ come from deuterium - this is an intermediate product in helium synthesis, the amount that survives being a steeply decreasing function of $\Omega_b$. According to Yang et al. (1984), only if $\Omega_b h^2 \leq 0.04$ can enough be produced in a standard hot big-bang to provide the observed abundance; and $\Omega_b h^2 > 0.01$ is required in order not to overproduce deuterium or $^3$He. Also, weak constraints consistent with the other requirements are provided by $^7$Li.

How strongly we believe these constraints depends on how we assess the plausibility of explaining deuterium in non-standard ways. There are "astrophysical" schemes for making deuterium which, while somewhat contrived, cannot be ruled out (Audouze 1986, Ramadurai and Rees 1985 and references cited therein). "Cosmological" D-production could be reconciled with $\Omega = 1$ if inhomogeneities induced by a quark-hadron phase transition in the early universe made the neutron/photon ratio vary from place to place ((Applegate and Hogan 1985). An unconventional production of D and $^3$He by early photosynthesis as a result of the decay of hypothetical massive neutrinos or gravitinos can also be consistent with higher $\Omega_b$ (Audouze, Lindley & Silk 1985). Finally, there might be large-amplitude inhomogeneities in the initial baryon distribution, such that all the baryonic material we can now sample comes from underdense regions, the overdense regions having turned into dark "population III" objects (Rees 1984). Although some of the above may evade the limits on $\Omega_b$, any such unconventional explanation erodes the appeal of the standard model, which can concurrently account for $^4$He, $^3$He, D and $^7$Li.

Because the relevant parameter in primordial nucleosynthesis is $n_b/n_\gamma = \Omega_b h^2$, more precise comparisons of models with observation must await a firmer value of the Hubble constant. If $h = 1$ (corresponding to a Hubble time of $\approx 10^{10}$ years) then the simplest inference would be that most of the dynamically detected dark matter - both in the halos of individual galaxies and in clusters and groups - was non-baryonic; but if $h = 1/2$ (corresponding to a Hubble time of $\approx 2 \times 10^{10}$ years) the lower limit to $\Omega_b$ set by the requirement not to overproduce D + $^3$He implies that some dark matter - maybe that in halos, if not in intergalactic space - must be baryonic, though only enough to contribute $\Omega_b \approx 0.1$.

If the dark matter in halos and in virialised clusters is baryonic, then there are two main "conventional" possibilities - very low mass stars ($\lesssim 0.1 \mathrm{M}_\odot$) or the remnants of very massive stars. Masses above $0.1 \mathrm{M}_\odot$ would contribute too much background light unless they had all evolved and died, leaving dark remnants. But the remnants of ordinary massive stars of $10 - 100 \mathrm{M}_\odot$ would produce too much material in the form of heavy elements. Limits on the range $100 - 1000 \mathrm{M}_\odot$ are uncertain because only helium may be ejected, the 'heavies' in the core collapsing into a black hole remnant. An uncertainty in the evolution of massive or supermassive stars is the amount of mass loss during H-burning;
however the hypotheses that most primordial material goes into very massive objects (VMOs) of greater than about $10^3 M_\odot$ is compatible with the nucleosynthesis constraints. A further consideration favouring these high masses is that VMOs are likely to terminate their evolution by a collapse which swallows most of the mass: if most of the material were ejected, 'recycling' through several generations would be necessary in order to end up with most of the material in black holes rather than gas. Detailed discussions of pregalactic stars are given by Carr, Bond and Arnett (1984).

3. "VMO" REMNANTS

Massive stars could have formed and died early in galactic history. If this happened at a substantial redshift, background light limits offer no constraints. A more conspicuous vestige of such objects would, however, be their contribution to chemical enrichment. Heavy elements are expelled from massive stars in their terminal phases unless they are so massive that they end their lives by collapsing to black holes after the pair-production instability (Truran & Cameron 1971; Woosley & Weaver 1982; Ober, El Eid & Fricke 1982; Carr, Bond & Arnett 1984 and references cited therein). Collapse rather than explosion is thought to occur for (non-rotating) core masses above $200 M_\odot$. If the hidden mass was in VMOs, then the requirement that heavy elements should not be overproduced requires an initial mass function (IMF) such that only $\sim 10^{-3}$ of the mass goes into stars lighter than $\sim 200 M_\odot$. Moreover, there must be a cutoff above $\sim 10^6 M_\odot$, at least for objects within individual halos, because dynamical friction would have increased the velocity dispersion of disc stars to an excessive degree (Lacey 1984; Ipser & Semenzato 1985; Lacey & Ostriker 1986; Carr 1985 and references cited therein). Within the context of VMO theories, we have little evidence on whether the preferred mass is closer to $10^3$ or to $10^6 M_\odot$.

The upper mass limit could be pushed downward if we had a firmer understanding of what luminosity would result from accretion onto black holes passing through the galactic disc (Ipser & Price 1982; McDowell 1985; Lacey & Ostriker 1986). The accretion rate for supersonic motion at speed $v$ through gas of density $n$ is proportional to $nv^{-3} M^2$. The luminosity depends on the accretion rate, and also on the uncertain efficiency $\epsilon$. For spherical accretion, where the efficiency is low because the radiative cooling time is long compared to the free-fall time, $\epsilon$ should scale with $M$, making the luminosity proportional to $M^2$. For disc-like accretion, $\epsilon$ may be as much as 0.1, independent of $M$. The spectrum of the emergent radiation is also uncertain. The case of spherical inflow has been considered by Ipser and Price (1982), who argue that the radiation emerges mainly in cyclotron harmonics from thermal electrons whose temperatures are marginally relativistic. This emission would peak in the infrared. Disc-type
accretion could yield a high luminosity, predominantly thermal radiation in the ultraviolet.

The most conspicuous holes would be those which were passing through dense gas clouds and which had \( v \) much less than the mean velocity. For a Maxwellian distribution, the fraction with speed \( < v \) is proportional to \( v^3 \) but, the resultant higher accretion rate (\( \dot{M} = v^{-3} \)) makes these specially slow-moving holes more readily detectable.

If the typical mass were \( 10^3 M_\odot \) or more, the nearest object passing through a dense interstellar cloud would be at 1 kpc distance, and would contribute a 10 micron flux well above the IRAS detection limit (McDowell 1986); the same object would have an optical magnitude \( V = 10 \) (plus some correction for absorption). Lacey and Ostriker (1986), assuming disc-mode accretion, predict even higher luminosities, but suggest that this would be UV radiation giving rise to an HII region. The Ipser & Price estimates of luminosity are indeed rather conservative even on the basis of their assumed spherical infall, since a possible non-thermal tail of electrons is neglected. Unfortunately, the distinctive signature of an accreting black hole is hard to estimate, and so one cannot at the moment place firm limits on the number (or mass) of putative halo objects of this kind. Nevertheless, it already seems unlikely that the bulk of the mass could be in objects that are individually as heavy as \( 10^6 M_\odot \).

Dynamical constraints, as discussed by Carr, Bond and Arnett (1984), rule out a dominant contribution by masses \( >> 10^6 M_\odot \) in galactic halos. (The limits on genuinely intergalactic holes are much less stringent.) There is, however, an independent reason for conjecturing (despite the accretion constraints) that our Galactic Halo may primarily consist of objects with masses near the upper limit permitted by dynamical arguments. Interaction with halo objects could then, in principle, account for the way the scale height and velocity dispersion of the disc stars depends on age. Other possible explanations for this trend - for instance, interactions with molecular clouds or spiral arms - do not, it is claimed, account so naturally for the observed ratio of the velocity components in and perpendicular to the disc plane. Carr and Lacey (1986) propose a hybrid model for the halo objects which retains this feature but evades (or at least eases) the accretion constraints: they suggest that halos consist of clusters, each of mass \( 2 \times 10^6 M_\odot \), composed of stellar or sub-stellar dark objects.

4. JUPITERS OR "BROWN DWARFS"

Some direct constraints on low-mass stars in galactic halos come from optical and infrared observations of the halos of external galaxies such as M87 (a giant elliptical) or NGC 4565 (an edge-on spiral) - e.g. Arp and Bertola 1969, Hegyi and Gerber 1977, Bougn, Saulson and Seldner 1981. There are also limits to
the number of faint red objects, and objects with high proper motion, in our own Galaxy - see Bahcall (1986), Probst (1986) and other papers in Kafatos (1986).

The mass function of faint stars even in our own Galactic Disc is still uncertain and controversial. This issue, which is specially relevant to the total amount of matter in the Disc (the well-known "Oort discrepancy") was recently discussed at the conference on brown dwarfs at George Mason University, Virginia, . The forthcoming published proceedings of this meeting (Kafatos 1986) contain several up-to-date assessments.

The theoretical relation between mass and bolometric luminosity is not specially uncertain (Nelson, Rappaport and Joss 1986). The threshold mass for H-burning is around $0.08 \, M_\odot$, and for masses of this order the bolometric luminosity (at age ~$10^{10}$ yrs) is very sensitive to mass: a star of $0.1 \, M_\odot$ will have $L_{bol} \approx 10^{-3}L_\odot$, but a star of $0.04 \, M_\odot$ will have $L_{bol} \approx 10^{-7}L_\odot$. However, the bolometric corrections are highly uncertain for these very cool stars with high surface gravity. Below 2500 K, molecules and dust grains contribute a surface opacity that depends strongly on observing wavelength. In particular, the flux in the R-band can be 2.9 magnitudes fainter than a black body of the same size and effective temperature. Allowance for these complications greatly increases the number of dwarfs needed to account for the faint objects revealed by star counts - indeed it may well be that the mass function in our Disc obeys a power law, continuing to rise towards small masses, right down to $0.1 \, M_\odot$ or below (D'Antona and Mazzitelli 1985). Even though only one bona fide "brown dwarf" probably below the H-burning mass threshold is known (the recently discovered binary companion of vB8, with $M \approx 0.07 \, M_\odot$ and $T_{eff} \approx 1300$ K), there is as yet no way of ruling out ~$10^{12}$ similar (or even lower-mass) objects in a typical galaxy.

Improved infrared limits to the brightness of halos can in principle constrain the properties of these hypothetical "brown dwarfs", as of course can IRAS-type searches for high-proper-motion objects in our own Galaxy. However, because the luminosity is such a steep function of mass below $0.1 \, M_\odot$, even a substantial improvement of such tests would only tighten the IMF constraints slightly.

The IMF derived by Miller & Scalo (1979) and Scalo (1986) for the solar neighbourhood (which is in any case controversial at the low mass end) does not look like the single power-law first discussed by Salpeter (1955), but rather resembles two superposed log-gaussian distributions. Larson (1986) suggests that these represent the products of two distinct modes of star formation, and that the relative importance of these two modes may have varied over galactic history: if the higher mass mode was favoured in the past, then there could perhaps be enough white dwarfs to account for the entire Disc mass. Conceivably the star...
formation process relevant to the halo involved a third mode with a different characteristic mass. If the halo objects formed at an early pregalactic epoch when there were neither heavy elements nor large-scale magnetic fields (and subsequently cluster non-dissipatively into galaxies and clusters) then there would be even less reason to suspect their IMF to resemble that of stars forming here and now. The cooling flows deduced from X-ray data in clusters of galaxies (Fabian, Nulsen & Canizares 1984, Sarazin 1986 and references cited therein) where the gas pressure is \( \sim 100 \) times higher than in the interstellar medium of our Galactic Disc, might imply star formation with a very steep IMF. Stars in the halo may have formed when the baryonic content of the galaxy was in a form of hot gas. The conditions would then have resembled those in cooling flows more than they resembled those in our Galaxy now.

Theories of star formation do not reliably tell us the shape of the IMF, nor the minimum mass. As regards the latter, considerations based on the "minimum Jeans mass" yield values as low as \( \sim 10^{-2}M_\odot \) (Rees 1976; Larson 1985 and references cited therein). Moreover, even these are not strict lower limits—they obviously do not apply to fragmentation in the kind of spinning disc that is thought to have evolved into our Solar System.

5. GRAVITATIONAL LENSING

Halos could be made from compact objects whose masses range from \( 10^6M_\odot \) down to Jupiters, about \( 10^8 \) times smaller, or even from smaller objects. One way of discriminating between these options is by searching for manifestations of gravitational lensing. The probability of seeing lensing due to an object in the halo of our own galaxy is only of order \( 10^{-6} \) (Refsdal 1964). But it is, ironically, much easier to detect objects in the halos of galaxies half way out to the Hubble radius. The probability that a compact source at redshift \( z \geq 1 \) is significantly lensed by objects along the line of sight is of order \( \Omega_L \), (the fractional contribution of the lenses to the critical density) independent of the individual lens mass involved (Refsdal 1970, Press and Gunn 1974); for a source at redshift \( z < 1 \) the probability is \( \sim z^2\Omega_L \). The angular separation, \( \theta_L \), of the lens images is, however a diagnostic of the lens mass \( m_L \): \( \theta_L \sim 2 \times 10^{-6}(m_L/M_\odot)^{0.5}\max(z^{-1}) \) arc sec. For \( m_L \geq 10^5M_\odot \), very long baseline radio interferometers provide adequate resolution. Characteristic image shapes (which are more complicated than a simple double if \( \Omega_L \neq 1 \), because more than one object can contribute to the deflection of light rays) were discussed by Press and Gunn (1973) and Blandford and Jaroszynski (1981). From the fact that few high-z compact radio sources show the double structure characteristic of lensing, we can probably exclude \( \Omega = 1 \) in \( 10^6M_\odot \) objects, but not \( \Omega = 0.1 \).
For $m_\odot \leq 0.1 \ M_\odot$ ("Jupiters") the angular scale is $< 10^{-6}$ arc sec. This cannot yet be directly resolved. There is nevertheless an indirect method of detecting lensing of this kind via the variability that would ensue if the lens were to move transversely (Chang and Refsdal 1979, Gott 1981, Young 1981). It takes only a few years for an object at the Hubble radius moving at $\sim 10^2$ km s$^{-1}$ to traverse an angle $10^{-6}$ arc sec. The image structure and time variation are more complicated, and can be more rapid, if the line of sight passes through (e.g.) a galactic halo, thereby encountering an above-average column density of dark matter. Several objects may then contribute to the imaging, yielding a flickering "frosted glass" effect (Young 1981, Paczynski 1986, Schneider 1986, Kayser, Refsdal and Stabell 1986). "Minilensing" could also affect the optical continuum of quasars, but would not affect the spectral lines so much if the latter come from a more extended region of angular scale $> \theta_x$ (Canizares 1982). If there were a firm observational limit to the scatter in the equivalent widths of the lines from quasar to quasar (i.e. in the line/continuum ratio) this would constrain the value of $\sum$ contributed by small compact objects.

No conventional astrophysical process could predominantly produce macroscopic discrete masses $\ll 10^{-2} \ M_\odot$. Such objects could, however be the outcome of, for instance, phase transitions at early epochs; primordial black holes are another possibility (Carr 1986). Is there any class of source, detectable out to large $z$, that could be even more compact than quasars, and thereby able to lens such masses? One such candidate would be supernovae, whose effective radius at peak light is a few times $10^{14}$ cm. Type I supernovae can be detected out to cosmological distances, and have been suggested as "standard candles" from which Hubble's constant and the deceleration parameter might be determined. A significant contribution to $\sum$ in any compact objects of $\gtrsim 10^{-4} \ M_\odot$ would prevent supernovae from behaving as standard candles (Efstathiou and Wagoner 1986). Highly-lensed objects would be disproportionately represented in a magnitude-limited sample. If the compact masses were no larger than $\sim 10^{-4} \ M_\odot$ (and $\theta_x$ were comparable with the intrinsic angular size) the light curve would be distorted because, as the envelope expanded, the magnification along a typical line of sight would change. Each segment of the photospheric limb of a supernova envelope would be linearly polarized because of the dominance of electron scattering opacity. No net polarization would normally be seen unless the envelope were non-spherical (Shapiro and Sutherland 1982); compact lensing objects of $\sim 10^{-4} \ M_\odot$ would, however, magnify different parts of the envelope by different amounts, thereby causing an observable net polarization even for spherical supernovae.
Lensing of cosmologically distant objects could offer the only real chance of detecting the entities constituting the dark matter if the characteristic masses were well below 0.1 $M_\odot$.

6. CONCLUDING COMMENTS

In an influential review paper published a decade ago, Gott et al. (1974) summarised the evidence bearing on $\Omega$. They concluded that the dynamical evidence favoured a value in the range $0.1 - 0.2$, and noted that if the matter were all baryonic, this range was compatible with the value favoured by standard big bang nucleosynthesis [provided that $H_0 \leq 50 \text{ km s}^{-1}\text{Mpc}$, a value consistent with the ages of globular clusters]. Much new evidence has accumulated over the last 10 years, and some relevant theoretical issues have been refined and elaborated. But, if one were to update Gott et al.'s discussion, their net conclusion would not change much.

Theorists' attitudes have, however, changed markedly in recent years because non-baryonic matter is now taken much more seriously - its existence seems in some ways almost a natural expectation; moreover, as discussed in Primack's paper, the formation of galaxies can then be interpreted via an attractive scheme with few free parameters. But the main new element in the discussion is the concept of "inflation", which has widespread theoretical appeal (see, however, Penrose 1986 for a dissenting viewpoint). It seems to resolve some stubborn cosmological paradoxes in such a natural way, that it instills a strong prejudice in favour of $\Omega = 1$.

I shall conclude by summarising two candidate cosmologies, both of which now seem appealing in their different ways:

A The first model has $\Omega_b = \Omega_{\text{total}} \approx 0.15$ ($H_0 \leq 50 \text{ km s}^{-1}\text{Mpc}$). The baryons would be partly in "luminous" form (stars and gas) and partly in dark matter" (low mass stars and/or black holes).

B Alternatively, theoretical predilection may dispose us to favour $\Omega_{\text{total}} = 1 \pm 10^{-4}$. (The small uncertainty would arise only from the initial curvature fluctuations, which need to be $10^{-4} - 10^{-5}$ on the scale of galaxies and clusters, and would, in the simplest models, extend with similar amplitude up to the Hubble radius and even beyond.) Conventional big bang nucleosynthesis then suggests $\Omega_{\text{baryon}} \approx 0.1$, $\Omega_{\text{non-baryon}} \approx 0.9$, and introduces a new dimensionless ratio into cosmology. The large-scale structure of the Universe involves some kind of biasing in the formation of bright galaxies (Rees 1985, Dekel 1986 and references cited therein), and can then be interpreted in two alternative ways:
Either (i) $\rho_b/\rho_{\text{total}} \approx 0.1$ on all scales $\gtrsim 1$ Mpc. As much as $\approx 90\%$ of baryons could be in intergalactic gas in voids, the dynamically-inferred dark matter in halos and clusters being non-baryonic.

Or (ii) There is large-scale segregation of baryonic from non-baryonic matter on scales up to $\approx 20$ Mpc; clusters, including their "dark" components, could then be mainly baryonic, as in (i) above.

Apart from attempts to detect the dark matter, it may become easier to decide among the options when we have a better knowledge of the interlinked processes of galactic evolution and star formation. It is still unclear whether the luminous parts of galaxies result from infall into a preformed halo composed of quite different stuff; or whether, contrariwise, galaxies and their halos resulted from a single dissipative collapse process whereby the IMF gradually changed as contraction proceeded.

REFERENCES