DARK MATTER: KEY ISSUES

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ABSTRACT. Key outstanding questions regarding dark matter are formulated, as a backdrop to the upcoming discussions at this meeting. A major issue involves how many species of dark matter there are, and whether both baryons and non-baryons are implicated in cosmological dark matter. How is dark matter distributed relative to baryons on all scales? Are voids really empty? And finally, is there high-amplitude structure in the matter distribution of the universe on scales ~100 Mpc, and, if so, how can it be accounted for in terms of known, plausible physical processes?

INTRODUCTION. Two years ago marked the golden anniversary of Fritz Zwicky's landmark study of the Coma cluster (Zwicky 1933). The results provided dramatic evidence for dark matter that is still among the best we have. The way to final acceptance of dark matter was not smooth, however; the intervening fifty years were marked by incessant discussion and controversy that called into question every facet of the problem - from data, to theory, to the basic laws of physics. In astronomy, only the quasar redshift debate approached the "missing mass" controversy in sheer intensity, but QSOs were resolved to most astronomers' satisfaction in a much shorter period of time. And arguments over missing mass are not over yet.

Looking back, it is interesting to reflect on how utterly paralyzing dark matter was in those days for any rational attempt to model the dynamics of the universe. The turnaround since then has been remarkable. Now regarded as at least a decent working hypothesis, dark matter has turned from nemesis to powerful ally: initially invoked merely to bind galaxies and clusters of galaxies, it is now called upon to form them and, by some, even to close the universe itself. These achievements, though substantial, ought not to impress us unduly. If one is allowed to play freely with nine-tenths of the mass of the universe, miracles are not too much to expect!

After fifty years, it is fitting that we take stock to review how far we have come with dark matter (hereafter, often DM) and what we know and don't know about it. To that end, I have organized a few key ques-

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tions to introduce the following speakers. Let us start with what is still the most important and most basic question:

1. ARE WE SURE YET THAT DARK MATTER EXISTS?

Conservative sceptics can still attack inadequacies in the observational data and analyses. More radical sceptics can attack the law of gravity itself, as Dr. Milgrom will explain to us later. Actually, the basic astronomical data have not increased or altered much in recent years. Perhaps I am too pessimistic, but it is my feeling that, short of an actual detection in the laboratory, most of the direct evidence for DM is already in. What we will see in the future, I predict, is a slow testing over the years, as people work patiently to fit DM into the wider context of physics, astronomy, and cosmology. This indirect process has already started, with encouraging early results, and will doubtless continue for a long while to come.

Let us therefore pass by this basic issue and rather regard dark matter as a "decent working hypothesis," as suggested above. In this spirit, the next most vital question is:

2. HOW MANY SPECIES OF DARK MATTER ARE THERE?

2.1 Do we need baryonic dark matter?

In all, DM has been claimed to exist in five types of structures that differ greatly in size: the solar neighborhood, dwarf galaxies, large galaxies, groups and clusters, and superclusters. By well known arguments (White and Rees 1978), the last four seem to require that DM consist of material that entered into a dissipationless state before galaxies collapsed. The existence of DM in the solar neighborhood, by contrast, is usually assumed to require dissipation during or after the formation of the Milky Way, although this has not yet been rigorously shown.

The existence of DM in the solar neighborhood from the Oort-Bahcall analysis (Bahcall 1984) thus points strongly to a dissipative and hence probably baryonic component in dark matter. Fortunately, within the context of solar-neighborhood astrophysics, viable baryonic candidates are not hard to find. As Larson points out (this conference), plausible changes in the local IMF and history of star formation could increase the white-dwarf component in Bahcall's models considerably. Recall also that the local density, ρ_{tot}, derived in the models is directly proportional to the square of the assumed scale height of the stellar tracers, and thus to their assumed absolute magnitude: $\rho_{tot} \propto L$ (tracer). The assumed luminosities of the F dwarfs and K giants used as tracers must surely introduce uncertainties of at least a few tens of percent. Bahcall has also pointed out other difficulties, including how the dark component is assumed to be distributed with height. It is important to try to analyze critically the uncertainties in the Oort-Bahcall estimate to see if, after all, there is any troubling discrepancy with a plausible baryonic origin for the local DM.

Even if problems do remain, many people including myself would argue that, because dark matter in the solar neighborhood is probably dissipational, it can have little or no connection with cosmological dark matter, which is pretty clearly dissipationless. Others (e.g., Schramm and Freese 1985) are not convinced, arguing that, if we can establish the existence of dark baryons in the solar neighborhood, by continuity arguments this is powerful evidence for additional baryons in galaxy halos. Schramm and Freese point out that $\Omega_b h_{50}^2 \lesssim 0.01$ based on baryons that are detected in galaxies, whereas Big Bang nucleosynthesis requires $\Omega_b h_{50}^2 \gtrsim 0.03$. They thus argue for extra dark baryons outside galaxies and have shown that, within the errors, all DM in galaxy halos could be baryonic without violating nucleosynthesis constraints, provided $\Omega_{DM}^{TOT} \lesssim 0.2$ in total.

An alternative, equally interesting interpretation is that there are indeed extra baryons in the universe, but they are not DM around galaxies -- they are unseen baryons in voids associated with galaxies that failed to form, *i.e.*, biased galaxy formation. I confess outright that I am a strong believer in biased galaxy formation and regard it as a natural consequence in most hierarchical clustering scenarios. If biasing operates on large enough scales, it could obviously profoundly alter present notions about the large-scale distribution of matter in the universe.

Either way, "missing baryons" in the universe are important. It is therefore vital to review carefully the above limits on $\Omega_b h^2$ to assess how soft they are. The estimate of baryons detected in galaxies is now especially out of date. It is based simply on the mean luminosity density of Zwicky galaxies without regard to changing baryonic M/L with Hubble type or luminosity. The baryonic component of individual galaxies has also likely been overestimated, owing to inclusion of DM within the optical radii. Extra baryons in hot gas in X-ray clusters have not been allowed for either. The whole calculation is clearly ripe for more careful reconsideration.

2.2 Do we need non-baryonic dark matter?

There are two prime reasons for wanting non-baryonic DM: belief in inflation, which strongly implies $\Omega \approx 1$ (if $\Lambda = 0$), and the need to make galaxies by the present epoch without violating $\delta T/T$ in the microwave background (Bond and Efstathiou 1984, Vittorio and Silk 1984). Failing any known mechanism to generate galaxy-sized isothermal perturbations in a purely baryonic universe, the $\delta T/T$ argument seems fairly firm. There is admittedly an alternative picture of galaxy formation in which pregalactic perturbations are generated from hydrodynamic processes from winds and supernova explosions in an early generation of stars (Ostriker and Cowie 1981). These first stars must simply be posited, however, and the model also cannot explain structure on very large scales, the energy requirements being too great. The more usual unified approach, which attempts to explain all structures from galaxies to superclusters as arising from the same underlying DM fluctuation spectrum, is simpler and more elegant. I am therefore inclined to believe strongly in non-baryonic DM for this reason.

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With the door now open, the next critical question is whether there is so much DM that $\Omega = 1$. The main impetus for this comes from inflation -- a largely esthetic argument still not considered compelling by most astronomers. Until recently, I was myself deterred from $\Omega = 1$ by the great ages measured for globular clusters: several workers (see review by Sandage and Tammann 1983) had converged with great unanimity on the value 17 ± 2 b.y., whereas, even with H_0 as low as 50 km s^{-1} Mpc^{-1}, the age of the universe with $\Omega = 1$ must be under 14 b.y. An important change in this picture has now occurred, as Vandenberg (1985) has reconsidered cluster ages taking into account the fact that oxygen, the most abundant metal, is up by as much as +1.0 dex relative to Fe in metal-poor stars. Vandenberg's new ages are close to 14 b.y., in good agreement with $\Omega = 1$. This, coupled with some possible extra, uncounted mass in voids due to biased galaxy formation, makes $\Omega = 1$ an attractive astronomical option for the first time.

3. WHAT IS ρ_{DM}/ρ_{BARY} ON GALACTIC AND SUBGALACTIC SCALES?

Let us turn now to the distribution of dark matter relative to baryons in the universe. A precise understanding of this distribution is surely one of our most powerful clues to the identity of dark matter. It is clear that dark matter and baryons are radially separated on scales smaller than galaxies, where dissipation operates. The simplest picture is that all galaxies as a whole had initially the same ratio of baryons to DM, perhaps altered later by processes like tidal stripping of dark halos, ram-pressure stripping of baryons, ejection of baryons by supernovae, etc. It has been usual to assume a constant initial ratio (White and Rees 1978, Faber 1982a, Gunn 1982, Blumenthal et al. 1984, Dekel and Silk 1985), but, as this assumption is clearly fundamental, solid evidence is badly needed to confirm it.

It being virtually impossible to obtain an accurate measure of the total DM associated with any one galaxy, it is probably realistic to hope at this stage only to obtain indisputable evidence that every galaxy contains at least some dark matter. This has already been established for spirals over a wide range in luminosity. For ellipticals, the detection of dark matter is more tentative. We have a very recent report by Jean Brodie and John Huchra (Brodie and Huchra 1985) of a high halo velocity dispersion in the globular clusters around M87. More ellipticals might be studied in this way, but there will always be some ambiguity caused by the unknown anisotropy, β, of the globular cluster velocity ellipsoid (Binney 1982). This is why X-ray studies of ellipticals are so important, because β must be identically zero for gas in pressure equilibrium. Hot gas in the galaxy potential well thus gives an unambiguous mass distribution and also the true shape of the potential well, which can be compared to the shape of the visible isophotes. All this is possible provided both the gas density and temperature profiles are accurately known and the X-ray maps have sufficient angular resolution. The first images from Einstein (Forman, Jones, and Tucker 1985) hint strongly at dark matter around E's, but really adequate data will not be available until AXAF. This will be one of the most important applications of this satellite.

Until then, the only other evidence we have for dark matter around E's is indirect: flat rotation curves in disks associated with large spheroids (e.g., the Sombrero [Bajaja et al. 1984], the polar-ring SO A0136-080 [Whitmore et al. 1982], and the HI-rich SO NGC 4203 [Burstein and Krumm 1981]), plus the simple fact that groups and clusters dominated by E's and SO's always show the strongest dynamical evidence for dark matter. Analysis of the total baryon content of the latter (Blumenthal et al. 1984) in fact suggests a ratio of dark matter to baryons that is similar to spiral-dominated groups, within the quite considerable errors of measurement.

In addition to E's vs. spirals, there is also the major question of DM in little galaxies vs. big ones. This is a powerful test of elementary-particle models of dark matter that in principle could rule out neutrinos (Tremaine and Gunn 1979, Aaronson 1983, Lin and Faber 1983). Very small dwarf spheroidals are particularly attractive objects in which to search for dark matter, as their exceedingly low surface brightness (Bingelli et al. 1984) may reflect an abnormally low baryon content, perhaps due to some form of ram-pressure stripping (Lin and Faber 1983) or supernovae-driven gas loss (Dekel and Silk 1985). If the baryon deficit is large enough, one may even find a marked and unambiguous DM excess within the optical boundaries of the galaxy, a degree of excess that seems never to occur in larger spirals. According to this argument, dwarf spheroidals with exceptionally low surface brightness like Ursa Minor and Draco could show higher M_{DM}/M_{BARY} and M/L than brighter systems such as Fornax, and that is generally what the data are showing (Aaronson, this conference). However, doubts about stellar radial velocities due to stellar pulsation and binary motion are not yet fully resolved and will not be until a few more years of monitoring are available.

In gas-rich dwarf irregulars, comparable baryon loss has evidently not occurred, and M_{DM}/M_{BARY} in the inner regions might be closer to the one-to-one ratio typical of spirals. An average over the inner parts may therefore not show any clear DM excess, even though there may be much dark matter in the galaxy. In these dwarfs, as in ordinary spirals, one may be forced to infer dark matter from the shape of the rotation curve in the outermost regions. In many of these objects, the gas extends far beyond the optical boundaries, but rotation is often weak, random motions are significant, and the dynamics are difficult to analyze. Nevertheless, better 21 cm images will clearly be a very important tool in studying dark matter in dwarf galaxies in the near future (Kormendy, this conference).

Although the mass distributions of large spirals are better understood than E's or dwarf galaxies, major questions about dark matter still remain. The main goal at present is to study the total mass distribution with radius and decompose it into baryonic and DM components. This process can be criticized on several levels. On the lowest, there is concern that, in the bulge-dominated regions of early-type galaxies, the observed rotation curves may not represent true circular velocities. The prototype example is again the Sombrero, in which the rotation velocity of only 100 km s^{-1} at 1 Kpc indicates a local M/L_B of only 0.5

(Steiman-Cameron 1984), which is quite a lot lower than expected for an old bulge stellar population (Faber and Gallagher 1979). M/L_B also rises dramatically outward, finally reaching 5.0 at 10 Kpc, a reasonable value for bulge-type stars. Perhaps the ionized gas used to trace the inner rotation curve exhibits large random motions in addition to rotation, or perhaps the rotational motion is somehow impeded and slowed by a reservoir of slowly-rotating, million-degree plasma in the bulge, like that seen in E's (Bajaja et al. 1984). The Sombrero is admittedly an extreme example because its bulge is so large. However, if the effect exists generally in the bulge-dominated regions of spirals it could systematically distort attempts to decompose the DM and baryonic components versus radius.

A further, higher objection is that decomposition is never possible without at least one additional assumption. Up to now, this has usually been the "maximum disk" assumption applied to the baryons or an isothermal sphere assumption for the dark matter. Neither of these is well justified. The ratio M_{BARY}/L for disks is not known well enough to justify the maximum disk, whereas recent theoretical results (Blumenthal et al. 1985, Barnes 1985, Gunn and Ryden 1985) indicate that the DM density may be far from isothermal owing to baryonic compression during infall.

If these problems can be solved, for example, by following a new approach suggested by Athanassoula and Bosma based on Toomre's q-index (Freeman, this conference), the overall goal is clear and important: to determine ρ_{BARY} (r) and ρ_{DM} (r) versus Hubble type and other parameters. There is suggestive evidence (Tinsley 1981) that dissipative baryonic infall may be systematically larger in early Hubble types compared to late types. This might be discernible from accurate mass measurements and could play an important role in theories for the origin of Hubble types (Faber 1982a,b).

4. WHAT IS THE LARGE-SCALE STRUCTURE OF THE UNIVERSE, AND CAN DARK MATTER ALONE ACCOUNT FOR IT?

We now come to what I believe is currently the most critical problem in cosmology: the nature and origin of perturbations in the universe on large scales. The issues here are equally observational and theoretical. Observationally, there is still a severe lack of reliable data, although preliminary evidence for 100 Mpc-scale structure has come from galaxy redshift surveys (e.g., the Boötes void [Kirshner et al. 1984] and the Perseus-Pices supercluster [Giovanelli, Haynes, and Chincarini 1983]) and from significant large-scale amplitude in the cluster-cluster correlation function (Bahcall and Soneira 1983). Surveys to study large-scale structure are afflicted currently by two difficult problems: nearby 100-Mpc structures cover large angles on the sky, and it is hard to maintain strict uniformity of data in the face of variable Galactic extinction, seasonal variations in observing conditions, and different equipment in the northern and southern hemispheres. A more fundamental difficulty is that, with current sensitivity, we see out far enough to sample only a few 100-Mpc-sized volumes. We therefore do not know yet whether a large void such as Boötes is a rare event. To remedy this will unfortunately require extensive redshift surveys at faint levels.

We also need to question what the distribution of L_* galaxies, the subject of virtually all surveys so far, really tells us about the underlying total matter distribution. As noted above, biased galaxy formation may help to form large-scale voids and clumps and is a natural accompaniment to several scenarios, but it also introduces a major new degree of freedom in interpreting the data. It could imply that galaxies do exist in voids but that they are systematically smaller and/or of lower surface brightness than the familiar ones that populate the nearby Local Supercluster. Magnitude- or diameter-limited catalogs would systematically undersample such objects. Deeper, more careful searches using a variety of techniques are needed to answer the question: does a void really mean no baryons, no dark matter, both, or neither?

A related issue is how much weight should be placed on the standard galaxy-galaxy correlation function, ξ_{gal} (Peebles 1980), which has come to be accepted as a key test of all clustering models. As a number-density-weighted index, ξ_{gal} badly underestimates the correlation contribution on short scales from high-density cluster cores, where the stellar (M/L) is low and where additional baryons are present in the form of hot gas. On large scales, the missing contribution by baryons in voids due to biasing could likewise be important. In view of these uncertainties, it is perhaps unwise to view mismatches between models and observations too critically, as is sometimes done.

With regard to theory, there are also problems of practice and principle. There are two main methods so far for estimating the amplitude of ξ_{gal} derived from any of the common fluctuation spectra: N-body simulations and simple linear evolution of the initial density fluctuation spectrum. Both indicate strongly that ξ_{gal} derived from any of the common density fluctuation spectra plus random phases should go negative beyond about 30 Mpc (Dekel 1985). It has been proposed that the observed high amplitude of the cluster-cluster function, ξ_{clus}, on large scales is simply a "super-correlation" effect due to looking at 2-σ or 3-σ peaks in the Abell clusters (Kaiser 1984, Politzer and Wise 1984). This picture also predicts, however, that $\xi_{clus} \sim n^2\, \xi_{gal}$, where $n\sigma$ is the average overdensity of Abell clusters. Thus ξ_{clus} should also go negative at 30 Mpc, in contrast to the observations, which show it to be positive out to 100 Mpc (Bahcall and Soneira 1984).

A major question is whether it is possible to cure this problem without abandoning random phases simply by modifying the fluctuation spectrum slightly on scales near 100 Mpc. Recent work (Dekel 1984; Barnes, Dekel, Efstathiou, and Frenk 1985) has obtained good agreement with observation by adding a bump, or discontinuity, to the spectrum at this location, such as might result from a hybrid scenario with two types of DM particles. The critical question, not yet fully explored, is whether such a modification is compatible with the microwave background $\delta T/T$ limits. It may be that the real solution requires abandoning random phases, for example, by invoking large-scale strings (Vilenkin 1981). Several groups are now looking into this prospect.

We also need to question whether ξ_{gal} is really the optimum function for characterizing large-scale structure. It is not clear yet exactly

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how it is that ξ_{gal} tends to small values beyond 10 Mpc while the void-cluster pattern appears to have much higher amplitude on longer length scales. This suggests that ξ_{gal} is not especially well tuned to the particular structure of voids in our universe, as indeed mathematically it need not be. Perhaps it might be better to develop an alternative statistic keyed to voids, with particular regard to their sizes and shapes.

To summarize, it is not clear at this time what the true amplitude is of matter fluctuations in the universe on 100 Mpc scales and, if large, how these fluctuations may be generated from known, plausible physical processes. With strong observational constraints placed by the microwave background, galaxy counts, and radial velocity surveys, plus strong interest generated by the obvious connections to the early universe, large-scale structure is likely to remain one of the most lively and productive areas of observational cosmology in the near future.

5. HOW HAS DARK MATTER SHAPED THE STRUCTURE OF GALAXIES?

The influence of DM on the visible parts of galaxies began early and lasted through what may be idealized as three phases: initial formation; a period of isolated, self-contained evolution; and any later interactions. During the first phase, the central question is whether DM gravity controlled the gravitational collapse of galaxies, at least initially. If DM is the reason why galaxies formed early without violating the microwave background, the answer to this question must be "yes." If so, there are two further questions: what was the resultant angular momentum spectrum of galaxies, and what did a forming protogalaxy look like -- was it a centrally concentrated, rather symmetrical blob, or was it a collection of smaller lumps, each one collapsing simultaneously on its own and developing its own substructure? If the latter, we might have to add dynamical friction to the list of dissipational processes that shaped the structure of visible galaxy cores.

To understand the phase of isolated evolution, we need to know what is special about the dynamics of two-component galaxies in which at least one component, the dark halo, may be triaxial. A number of interesting phenomena have been suggested, including angular momentum exchange between the baryons and halo, stabilizing or destabilizing of disk orbits at certain radii, and disk warps induced by triaxial halos or stabilized by spherical ones. The timescale for halo-baryon interactions is especially important. Binney (this conference) speculates that transfer of angular momentum between disk and halo is efficient and that misalignment between the two can be only short-lived. He even suggests that gradual accumulation of a disk by infall can, by an adiabatic-invariant process, actually rotate the angular momentum vector of the original bulge to cause alignment between the two, as is observed. Conversely, instability timescales in the outer parts may be quite long, with the result that polar orbits in a flattened or slightly triaxial potential may be stable or at least quite long lived (Steiman-Cameron and Durisen 1982). The nature of stable orbits in tumbling potentials is also rather different from that in static potentials (Steiman-Cameron and Durison 1984; David, Steiman-Cameron, and Durison 1984). The net result is that it is proving quite a bit more difficult to infer the shape of the DM potential from the orientation and morphology of gas and dust lanes than was once hoped.

During the third, or interactive, phase, DM influences the frequency and nature of galaxy-galaxy interactions. Large DM halos considerably increase the cross-section for galaxy-galaxy collisions (White and Sharp 1977), and merger and coalescence are quite efficient whenever two halos strongly interpenetrate, provided the mutual orbital energy is low or negative (White 1978). Recent N-body simulations by Frenk et al. (this conference) suggest that, with a cold DM spectrum, merging of galaxy-sized halos continues to the present. This raises the question of whether galaxies have on average always continued to grow in size, even until now. On the other hand, perhaps the halos do continue to merge, but the luminous cores stay separated for long times. If binary galaxies and small groups have long lifetimes, this must indeed be what happens. It would be important to reassure ourselves that this is physically possible, perhaps using realistic two-component N-body simulations of binaries and small groups. On the other hand, if the luminous portions of galaxies continue to grow in size, too, this is an effect that could be searched for using lookback observations with Space Telescope and other instruments.

6. WHAT NEW AVENUES LOOK PROMISING FOR THE NEAR FUTURE?

In conclusion, we should mention a few new approaches to dark matter that have not been much discussed up to now but which may yield important insights in the near future. Most of these are well represented in the agenda of this conference. To me, the most interesting is gravitational lenses. As Ed Turner emphasizes (this conference), it is striking that an obvious lens candidate is apparent in only one of the known lenses. The situation is highly reminiscent of the original "missing mass" problem, in which a gravitational field was clearly present, but the matter causing it was invisible. Thus, lenses could be telling us that there are major mass concentrations in the universe that are not centered on visible galaxies. This would certainly cause a profound shift in our current picture of dark matter.

A second promising area is lookback studies to cosmological redshifts. The possibility of an increase in mean galaxy luminosity as a function of time owing to mergers was mentioned above. A related phenomenon is an evolution in the amplitude and slope of the galaxy-galaxy correlation function. A pioneering step in lookback studies of ξ_{gal} has been taken in a recent paper by Koo and Szalay (1984) based on galaxy counts, but the definitive treatment will have to await deep redshifts from the biggest telescopes.

Finally, there is the great arena of particle physics, to which astronomers look for theoretical inspiration and perhaps even experimental confirmation of dark matter. There are several possibilities for direct detection, including the measurement of a non-zero neutrino mass, watching axions interact with a magnetic field, or detecting phonons as DM particles collide with a crystal lattice at the weak interaction rate. These and other interesting possibilities will doubtless come to light in the next days of discussion.

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REFERENCES

Aaronson, M. 1983, Ap.J. Lett., 266, L11.

Bahcall, J. 1984, Ap.J., 287, 926.

Bahcall, N.A., and Soneira, R. 1983, Ap.J., 270, 20.

Bajaja, E., van der Burg, G., Faber, S.M., Gallagher, J.S., Knapp, G.R., and Shane, W.W. 1984, Astron. Ap., 141, 309.

Barnes, J. 1985, private communication.

Barnes, J., Dekel, A., Efstathiou, G., and Frenk, C. 1985, Ap.J., 295, 368.

Binggeli, B., Sandage, A.R., and Tarenghi, M. 1984, A.J., 89, 64.

Binney, J.R., 1982, Ann. Rev. Astron. Astrophys., 20, 399.

Blumenthal, G.R., Faber, S.M., Flores, R., and Primack, J.R. 1986, Ap.J. in press.

Blumenthal, G.R., Faber, S.M., Primack, J., and Rees, M. 1984, Nature, 311, 517.

Bond, J.R., and Efstathiou, G. 1984, Ap.J. Lett., 285, L45.

Brodie, J., and Huchra, J. 1985, private communication.

Burstein, D., and Krumm, N. 1981, Ap.J., 250, 517.

David, L.P., Steiman-Cameron, T.Y., and Durisen, R.H. 1984, Ap.J., 286, 53.

Dekel, A. 1984, Ap.J., 284, 445.

Dekel, A. 1985, private communication.

Dekel, A., and Silk, J. 1985, preprint.

Faber, S.M. 1982a, Astrophysical Cosmology: Proc. Study Week on Cosmology and Fundamental Physics, eds. Brück, H.A., Coyne, G.V., and Longair, M.S. (Vatican: Pontifical Scientific Academy), pp. 191-218.

Faber, S.M. 1982b, ibid., pp. 219-232.

Faber, S.M., and Gallagher, J.S. 1979, Ann. Rev. Astron. Astrophys., 17, 135.

Forman, W., Jones, C., and Tucker, W. 1985, Ap.J., 293, 102.

Giovanelli, R., Haynes, M., and Chincarini, G. 1983, as quoted by Oort, J.H., Astron. Astrophys. 21, 373, 1983.

Gunn, J.E. 1982, ibid., pp. 233-260.

Gunn, J.E., and Ryden, B. 1985, poster paper this conference and private communication.

Kaiser, N. 1984, Ap.J. Lett., 284, L9.

Kirshner, R.F., Oemler, A., Schechter, P.L., and Shectman, S.A. 1984, Ap.J.,

Koo, D.C., and Szalay, A.S. 1984, Ap.J., 282, 390.

Lin, D.N.C., and Faber, S.M. 1983, Ap.J. Lett., 266, L17.

Ostriker, J.P., and Cowie, L.L. 1981, Ap.J. Lett., 243, L127.

Peebles, P.J.E. 1980, The Large-Scale Structure of the Universe, (Princeton: Princeton University Press), Chap. 3.

Politzer, H.D., and Wise, M.B. 1984, Ap.J. Lett., 285, L1.

Sandage, A.R., and Tammann, G. 1983, in Large-Scale Structure of the Universe, Cosmology, and Fundamental Physics, eds. G. Setti, and L. Van Hove (Geneva: ESO-CERN), p. 127.

Schramm, D., and Freese, K. 1985, preprint.

Steiman-Cameron, T. 1984, Master's thesis, Indiana University.

Steiman-Cameron, T., and Durisen, R.H. 1982, Ap.J., 257, 94.

Steiman-Cameron, T., and Durisen, R.H. 1984, Ap.J., 276, 101.

Tinsley, B.M. 1981, Mon. Not. Roy. Astron. Soc., 194, 63.

Tremaine, S.D., and Gunn, J.E. 1979, Phys. Rev. Lett., 42, 407.

Vandenberg, D. 1985, colloquium delivered at U.C. Santa Cruz.

Vilenkin, A. 1981, Phys. Rev., D24, 2028.

Vittorio, N., and Silk, J. 1984, Ap.J. Lett., 285, L39.

White, S.D.M. 1978, Mon. Not. Roy. Astron. Soc., 184, 195.

White, S.D.M., and Rees, M. 1978, Mon. Not. Roy. Astron. Soc., 183, 341.

White, S.D.M., and Sharp, N.A. 1977, Nature, 269, 395.

Whitmore, B.C., Schweizer, F., and Rubin, V.C. 1982, Bull. A.A.S., 14, 643.

Zwicky, F. 1933, Helv. Phys. Acta., 6, 110.

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DISCUSSION

STEIGMAN: I'd like to make some comments relating to the issue of dark baryons. I think it is probably unfair to argue that there is a discrepancy between $\Omega = 0.01$ in visible matter and what is predicted by Big-Bang nucleosynthesis. I think the prediction goes down to about 0.01 and up to about 0.15, so there's a big range mostly connected with the uncertainty in the Hubble parameter. I'm also very pleased that you're emphasizing the importance of the hot gas. It's a point that Schramm and I have made over the years, that probably most of the baryons in the Universe are dark by the conventional astronomer's definition. They just happen to be shining in x-rays. And for that reason I would urge everyone here to distinguish between dark baryons and dark matter. When you ask, for example, for the ratio of baryons to dark matter, remember that some of the dark matter is clearly in the form of baryons.

RUBIN: Sandy, let me answer your question about the Sombrero galaxy, although the question is a general one. The evidence that we don't observe infall in the gas is that along the minor axis you see no velocity other than the systemic velocity. This seems to be true generally. In fact, in one specific case where we do see a normal rotation curve and rather peculiar things happening in the inner regions of the galaxy, things that I thought might be evidence for infall, the most plausible geometry says that the gas is moving the other way.

FABER: What do you think, then, about the resulting M/L ratios for the stars? Do you agree with the basic premise that in the Sombrero, at least, you would find a rather small value of M/L?

RUBIN: There are certainly things going on in the inner regions of galaxies that we don't understand. But in the work that we have done we are led to the conclusion that dark matter is important on very small scales, and that the dynamics in the inner parts of galaxies are not being controlled by the luminous stars.

FABER: I think it's fair to say that in no galaxy does one see the rapid rise to very large velocities and the decline farther out that one might have expected from the mass distribution derived from the light using conventional M/L ratios.

RUBIN: I agree.

DRESSLER: The surprisingly low rotation speed of gas in the central disk of the Sombrero galaxy is also found by Fillmore, Boroson and Dressler in several other early-type spirals. The gas rotation curves consistently fall below the velocity predicted from the stellar kinematics. We suggest that the gas is on non-circular orbits in these bulge-dominated regions, as would occur, for example, if it were being shed by stars in the spheroid.

FABER: You make the very interesting point that we have an independent estimate of the mass present from the stellar kinematics; this is in rough agreement with the usual estimates for an old stellar population but in strong disagreement with masses derived from the emission-line gas. That is exactly the point I wanted to make, but I didn't realize that there existed good data on galaxies other than the Sombrero.

FREEMAN: To qualify what Dressler just said: There are other ways of probing the potential in the inner parts of systems like the Sombrero - one can use the kinematics of the stars themselves. Kormendy and Illingworth have measured the rotation velocity and stellar dispersion in the inner parts of the Sombrero, and Jarvis has made simple dynamical models with circular rotation. These reproduce the stellar kinematics beautifully, both the rotation and the dispersion, and not just with radius but also up off the plane. Jarvis finds an M/L ratio of about 7.

P. QUINN: A comment about dark matter in ellipticals. Spirals have the advantage that we can make excellent assumptions about the orbits in their outer parts and so can say how much mass is out there. For ellipticals, anisotropy makes it not so simple, as you pointed out. However, the shells seen around some ellipticals can be used as test particles. Hernquist and I have just made an extensive study of the kinematics of shells. Shells are a complicated phenomenon, but we are confident that they are telling us a lot about the distribution of dark matter in at least some galaxies.

FABER: Yes, you're right.

E. TURNER: When you conclude from the microwave background limits that dark matter must play a dominant role in galaxy formation, do you discount the hydrodynamic, explosive galaxy formation theories or do these provide an escape from that conclusion?

FABER: Yes, in a sense I am discounting the hydrodynamic approach, since the origin of the explosive seeds has always seemed to me ad hoc. However, there is also a problem in matching the microwave background limits on cluster-sized masses and above. On these scales it is not clear that hydrodynamic effects are strong enough to create structure.

SCHECHTER: Your other firm conclusion was that there is clear evidence for non-baryonic dark matter. Scanning the meeting schedule, I am discouraged by the lack of any discussion of the constraints imposed on baryonic dark matter by the microwave background measurements. I hope the experts in this area will tell us more about it. Because I, for one, am loath to admit that the dark matter must be non-baryonic.

USON: The theoretical implications of the microwave background observations that Dave Wilkinson and I have made rest on a very strong assumption, which is that the initial perturbations had a Gaussian distribution. If this assumption is relaxed, the limits could go up by as much as a factor of 2.5 (for rather pathological initial conditions). Even then, isothermal fluctuations would still be allowed for $0.1 < \Omega < 0.3$. (Although these fluctuations are currently not popular, they could become fashionable again.) We have increased the size of our sample but the results are not yet available.

DEKEL: When considering constraints from fluctuations in the microwave background, we should consider the possibility of smearing by reionization. The energy may come from Population III stars or from galactic explosions, and can smear out fluctuations with scales smaller than 7°. Thus, this can not be used as a strong argument for non-baryonic dark matter.

FABER: I'm not familiar with the details, but I thought that the 7° limit requires high ionization until rather recent epochs, and consequently very high energy demands that are hard to satisfy.

LAKE: Just following up on Schechter's comment. There's a gap at the low end between the amount of material visible in the stars (including the stuff confined to the disk which is measured by the Oort limit) and the baryonic limit. However, there's an overlap between the value of Ω derived from large-scale surveys and the largest amount you measure dynamically. So the only real gap is the gap between stars and baryons, not between stars and dark matter.

OSTRIKER: The question has been raised in your talk and in prior questions as to whether diffuse (gaseous) baryons could contribute significantly to the mass density. The situation has not changed in any favorable way over the last decade. Cold gas is severely restricted by the Gunn-Peterson test. Very hot gas is limited by the x-ray background and by the Zel'dovich-Sunyaev effect on the microwave background. If the gas were smoothly distributed and kept at 0.1 to 0.3 keV a value of Ω_b of 0.1 would be possible. There are physical problems in keeping gas at this temperature and conflicts with pressure in the Lα clouds. Such gas will, in any case, soon be observable using the Helium Gunn-Peterson test.

STEIGMAN: In recent work, Henriksen, Mushotzky and Cowie studied the Coma and Perseus clusters out to about 3 Mpc radius; they argue that something like 30 to 40% of the binding mass on that scale is in hot gas. For some other Abell clusters, they quote even larger fractions. If that evidence were to stand up - and I don't know it well enough to judge it - then are we all in trouble trying to hide nine times as much non-baryonic mass as baryonic mass.

FABIAN: Field and I have just written a paper on the x-ray background. We get $\Omega_b = 0.2$ or 0.3 and in fact can fit the x-ray background better than a black body spectrum fits the microwave background.

BURKE: For what range of Hubble constants?

FABIAN: The scaling is $H^3\Omega^2$=constant. We're using H=50 km s^{-1} Mpc^{-1}.

OSTRIKER: The energy requirements of such a picture make explosive galaxy formation seem pitifully unimaginative (laughter).

FABIAN: The gas has to be in energy equipartition with the microwave background, like the gas in our Galaxy.

FELTEN: I would like to ask Andy Fabian to clarify what the x-ray background tells us about Ω_b. My understanding is that the intergalactic medium could emit the x-ray background if it were very hot ($T > 10^8$ K) and if its density were $\Omega_b \approx 0.2 - 0.3$. On the other hand, if we attribute the x-ray background to something else, then we could set T much lower, but still high enough to avoid the Gunn-Peterson constraint (say $T \sim 10^5$-10^6 K). We could then allow Ω_b to be as large as unity without violating any observation. Jerry Ostriker suggested that this isn't possible, but the arguments against it may not be conclusive.

FABIAN: You are quite right as regards the x-ray background. (Guilbert and I did allow about 15% of the background to originate in a power-law spectrum from point sources.)

FABER: The consensus seems to be that we can have at least $\Omega_b = 0.1$ and possibly as much as $\Omega_b = 0.2$ or 0.3 in diffuse hot gas. That is easily enough to be cosmologically significant, for if we apply the customary ratio of dark matter to baryons of ~ 10, we could easily have enough total matter to close the universe.

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