MASS DETERMINATIONS AND DARK MATTER AT INTERMEDIATE SCALES

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1. HISTORICAL BACKGROUND

The issue of "dark matter" in astronomy is extremely confusing. Difficulties exist on two levels. First there are the, in principle, straightforward scientific questions of measurement. A certain region of space is studied, and by some technique, the mass within it is determined. Separately the energy output in some wavelength band from the region is measured and then, with due allowance for distance uncertainties, a "mass-to-light" ratio is determined. These measurements are difficult, with the results affected both by small number statistical uncertainties (as when using globular clusters to determine the mass of the galactic halo), measurement errors (as with binary galaxies), and systematic questions of interpretation (as with X-ray emitting gas around galaxies). Ultimately, with patience and skill these problems have been reduced and, as we shall see in subsequent sections of this report, there exists moderate agreement among observers concerning the large mass ($\sim 10^{12}$ $M_\odot$) and high mass-to-light ratio ($M/L_B > 100$ $M_\odot/L_\odot$) for material integrated over distances in the range (30 kpc < r < 300 kpc) from the centers of giant galaxies.

But there is another level of confusion which is purely semantic, is less defensible, and where little improvement is apparent. This occurs when observed values of M or M/L are translated into statements about "missing matter" or "dark matter". In fact most of the detected optical light is from giant stars contributing very little to the mass of stellar systems. And most of the "observed stellar mass" reported is from low mass $0.1 < M/M_\odot < 0.6$ normal stars which contribute almost nothing to the observed flux and whose presence is simply assumed on the basis of a presumed analog to the solar neighborhood. This mass is estimated from the observed light times an assumed value of (M/L). Thus, the "observed mass" is really the implicit product of an observed light and an assumption. Then, from the dynamically determined mass, one subtracts off this inferred (or assumed) stellar mass, calling the residual material "dark matter". Given this procedure, identical

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observations of M and L can give rise to wildly and meaninglessly different estimates for the amount of "dark matter" in the system. While it is sometimes useful to have such estimates, they can only be interpreted if presented with a detailed description of the assumptions under which they were derived.

The use of the term "missing mass" is even more peculiar since even the sign of this quantity is often unknown. It is used both to describe matter known to be present from dynamical studies (i.e., "dark matter") but not seen or inferred from the visual light, and also used for the opposite case of mass not observed dynamically but whose presence is expected on the basis of some other argument such as a preference for a certain form of inflationary cosmology. Thus one does not know if the "missing matter" in a given case is a positive or negative entry on the dynamical ledger. Fortunately, the phrase is being abandoned with increasing use instead of the slightly preferable term "dark matter".

Historically, the intermediate mass range has been very important in clarifying our understanding of the dark matter problem. As early as 1937 Zwicky pointed out that the mass-to-light ratio for clusters of galaxies was much larger (× 100) than estimates for the solar neighborhood with only a relatively small part of the difference attributable to difference in types of stars found in the two environments. The amount of local dark matter required to balance the books in the solar neighborhood using the Oort analysis was much smaller; it seemed either to be an entirely different phenomenon or merely a reasonable accounting error given the inaccuracy of the measurements on which it was based. On the other hand, Zwicky's anomalous result was so odd as to indicate the necessity of a "cosmological" explanation, or to deny the validity of the virial method when applied to clusters. It required the relatively recent measurements at intermediate scales, detailed in the next section, to show that a mass-to-light ratio gradually increasing with radius is a common characteristic of stellar systems. It can be understood (though not uniquely so) by an ever greater admixture of dark matter with increasing radius as we proceed from the Oort to the Zwicky scale.

But before reviewing the modern results, it is worth pointing out that several careful early studies had indicated an increasing (M/L) at intermediate scales. In our own galaxy estimates of the mass based on the rotation curve were for, well known reasons, limited to radii less than the sun's galactocentric orbit. Most other galaxies were simply too far away for spectroscopic observations of extended parts. But the Andromeda Nebula had been studied to fairly large galactocentric radius by Babcock in thesis work (1939), Wyse and Mayall (1942) and in an extremely prescient paper by Schwarzschild (1954) who noted that the rotation curve of that galaxy was apparently flat, implying a mass-to-light ratio increasing rapidly with radius. He also observed that there was a trend with size from globular clusters having mass-to-light ratios of order unity through spiral and elliptical galaxies to the giant clusters of galaxies like Coma which Zwicky (1937) had discovered had mass-to-light ratios in the range $10^{2.5}$–10^3 $M_\odot/L_\odot$.

The early work certainly indicated that the mass-to-light ratio of large systems was much greater than that in the solar neighborhood or in globular clusters but a good deal of skepticism remained. The observations were admittedly fragmentary. Could they be in error? Or, if correct, could the interpretation, based normally on the virial theorem, be seriously fallacious? In the two decades after Schwarzschild's paper, evidence accumulated in favor of "dark matter". It was summarized in a paper by Ostriker, Peebles and Yahil (1974), which contained no new work, but rather sought to display the substantial body of data indicating that conventional estimates of the mass and radius of galaxies might be severe underestimates.

Those authors reviewed the evidence primarily from local group spirals for mass at intermediate distance scales. Tidal limits of local dwarf spheroidals, which give $(M(r)/r^3)$ at perigalacticon (Hodge 1966), indicated a surprisingly large interior mass but the result depended on the statistics of small numbers, the poorly known masses of the test objects and orbital undertainties. The radio rotation curve of M31 (Roberts and Rots 1973) confirmed the earlier optical evidence for flatness but did not extend very far. Binary galaxies studied by several investigators gave conflicting results. The strongest individual piece of evidence reviewed had been brought forward by Kahn and Woltjer (1959) who noted the fact that M31 was approaching our Galaxy. This innocent observation, pertaining to two objects which are presumably unaffected by forces other than gravity and initially taking part in the expanding Hubble flow, indicated an attracting mass in the system far in excess of the assumed stellar mass. The important result has sometimes been called the "timing argument", since it depends on achieving the velocity reversal in a given time period. With then current observational numbers, assigning the mass of unknown origin to the two galaxies in rough proportion to their luminosities, a total mass of 5×10^{12} $M_\odot$ was obtained or about 2×10^{12} $M_\odot$ for our galaxy out to a distance of 300 kpc. In a recent re-examination of the problem, prompted by Sandage's (1986) analysis of local group velocities, I found that the timing argument is quite sensitive to assumptions about the distribution of the attracting mass. For example, if it is all placed at the center of mass of the system, the total mass is reduced by a factor of nine, to values even less than obtained from the individual rotation curves.

Einasto and co-workers (1974) at the same time obtained similar results on the basis of similarly fragmentary evidence. One could summarize the situation at that time, a decade ago by saying that all the evidence pointed to assigning a mass per giant spiral galaxy of order 10^{12} $M_\odot$ within $10^{5.5}$ pc of the galactic center, but that none of the evidence was very good.

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2. RESULTS OF THE DECADE 1975-1985

2.1. Binary Galaxies and Satellites of Galaxies

There were two new and important surveys in this period by Turner (1976) and Peterson (1979) using, respectively, optical and radio data samples large enough, $\sim 10^{1.5}$ -10^2 galaxies, to reduce some of the statistical uncertainties. Despite careful efforts, misidentifications (due to projection effects creating "optical binaries"), isolation from clusters, velocity errors and a host of other difficulties make the analysis of this data prone to serious uncertainty. The best analysis of this data to date with the most current observations and analytical techniques by White et al. (1983) determined for this data base the result

$$M(r) = 1.3 \times 10^{12} \; (r/100 \text{ kpc})$$

independent of H_0 with an uncertainty of approximately 30% -50% . It is interesting to compare this result with the original findings of Turner and Ostriker (1977) and Peterson (1979), the former obtained 2.2×10^{12} at 270 kpc separation and the latter quotes 1.0×10^{12} $M_\odot$ per galaxy at a separation of 130 kpc. Thus, surprisingly all results are in quite good agreement. Phrased in terms of mass-to-light ratio, the binary results give

$$(M/L_B) \approx (70 \pm 20)h^1 \times (M/L_B)_\odot$$

within a radius of about 100 h^{-1} kpc. This is smaller than the (M/L) ratios for clusters, but significantly larger than the (M/L) ratios obtained from rotation curves of similar galaxies. Davis and Peebles (1983) taking an alternative statistical approach using the two-and three-particle distribution functions, which does not depend on isolation, determined a typical mass for an L_* spiral galaxy of 2×10^{12} $M_\odot$ in conformity with the binary and local timing results.

My re-analysis of the observations, summarized above, does not differ significantly from the earlier review by Faber and Gallagher (1979).

2.2 Satellites of Galaxies

Hartwick and Sargent (1978) analyzed the orbits of a group of distant globular clusters to infer the mass of the Galaxy interior to the group. Since only radial velocities are available (and tidal limits only eliminate the possibility of an extremely radial distribution of orbits), the assumed degree of orbital eccentricity affects their results as does statistical noise from the small sample of 11 objects. They found $M(r) = (8 \pm 2) \times 10^{11}$ $M_\odot$ within r = 50 kpc for an isotropic orbital distribution.

Recently Peterson (1985) obtained improved spectroscopic velocity measurements for these clusters with several additional distant objects measured. Using the analytical methods of Lynden-Bell et al. (1983) she obtains a mass of $(5.1 \pm 3.1) \times 10^{11}$ $M_{\odot}$ for isotropic velocities within a galactocentric distance of about 80 kpc. Since, the satellites are very diffuse and could not survive a close galactocentric passage, an alternate solution with high eccentricity orbits excluded was made; this gave a mass four times larger. In order to improve further these measurements, larger samples will be required such as distant R-R Lyrae stars. But either proper motion data, or an extremely detailed density distribution for the test particles will be required before the uncertainties due to unknown orbital eccentricity can be lessened.

2.3 X-Ray Halos about Massive Galaxies

Luminous elliptical cluster galaxies emit thermal X-ray bremsstrahlung at high enough rates to allow determination of both temperature and density radial profiles. The best studied case is M87 where Fabricant et al. (1980) compute a mass, based on hydrostatic equilibrium of 2×10^{13} $M_{\odot}$ within 230 kpc of the galaxy center. Binney and Cowie (1981) found only 5×10^{11} $M_{\odot}$ within r = 100 kpc for that galaxy, but the inconsistency is apparent not real, since these authors also compute a total mass of 2×10^{13} $M_{\odot}$ within r = 230 kpc but attribute most of it to the cluster. The mass-to-light ratio of the material between 100 and 200 kpc in any case exceeds 100 $(M/L)_{\odot}$ whether it is regarded as galaxy or cluster material. It will be interesting to see if, when equivalently high quality data is available for "field" galaxies, the results are similar. Preliminary results by Forman, Jones and Tucker (1986) and analysis by Muzhotsky (1985) for more isolated ellipticals indicate total masses of order 5×10^{12} $M_{\odot}$ within 100 kpc of the center of these early type systems, with (M/L) ratios far in excess of 10^2 in the region 30-100 kpc containing most of the mass.

2.4 Gravitational Lensing

There are several ways that beams of light to background objects passing through galactic halos can be used to probe for the existence of dark matter. If there are point-like masses in the beam, there can be a significant amplification of the brightness of some background stellar objects--an effect studied by Canizares (1982) and Vietri and Ostriker (1983) for quasars. Alternatively, extended background objects like galaxies will appear slightly crescent shaped, a phenomenon noted by Russell (1937) and investigated recently by Tyson et al. (1984). Suffice to say that these methods, while potentially powerful and completely independent of those using mass points as the test particles, give, at present, conflicting and highly insecure results.

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2.5 Theory of Merging Systems

Similarly, extended massive halos will promote rapid merging of stellar systems,especially in groups with low velocity dispersion (relative to the internal velocity dispersion within galaxies). Simulations by Barnes (1985) and Mamon (1985) indicate higher rates of merging for galaxies with substantial halos than are permitted by the observation that thin spiral discs imply merging has been at most a few percent effect for most galaxies. Once again the evidence is too fragmentary for firm conclusions to be drawn.

3. SUMMARY AND CAVEATS

The bulk of the evidence seems to indicate that within a volume between spheres of radio $10^{4.5}$ pc and 10^5 pc surrounding a normal giant spiral of luminosity $L_* = 1.5 \times 10^{10}\ L_\odot$ there is typically found $2 \times 10^{12}\ M_\odot$ with a mass-to-light ratio exceeding $10^{2.5}\ (M/L_B)_\odot$. For ellipticals of the same luminosity the mass found is typically twice as much.

However Yahil (1977) found that, although a statistically secure (M/L) ratio might be definable, there was no correlation detectable between M and L, even when allowance was made for the variation due to galactic types. Peterson (1979) puzzlingly found no correlation between (M/L) and galaxy pair separation and White et al. (1983) found no correlation between Δv and Δr or L in the best analyzed binary data.

Thus, although the presence of substantial amounts of dark matter in the outskirts of galaxies seems to be established, it is not at all clear, at this time, how well bound or even how well correlated the "light" and "dark" components are. It seems attractive to this observer to consider galaxy formation and the development of halos as two relatively separate phenomena with the halos accumulating around galaxies at late times. Then environmental influences will produce the apparent irregularities which we see.

REFERENCES

Babcock, H. W. 1939, Lick Obs. Bull., 19, 41.
Barnes, J. 1985, M.N.R.A.S., 215, 517.
Binney, J. and Cowie, L. L. 1981, Ap. J., 247, 464.
Canizares, C. 1982. Ap. J., 263, 508.
Einasto, J., Kaasik, A. and Saar, E. 1974, Preprint #1 of Tartu Observatory.
Faber, S. and Gallagher, J. 1979, Ann. Rev. Astron. & Astroph., 17, 135.
Fabricant,, D., Lecar, M. and Gorenstein, P. 1980, Ap. J., 241, 552.
Forman, W., Jones, C. and Tucker, 1986, Ap. J. (in press).
Hartwick, F. D. A. and Sargent, W. L. W. 1978, Ap. J., 221, 512.
Hodge, P. W. 1966, Ap. J., 144, 869.
Huchra, J., Lathan, D. and Davis, M. 1983, M.N.R.A.S., 203, 701.

https://doi.org/10.1017/S0074180900149927 Published online by Cambridge University Press

Kahn, F. D. and Woltjer, L. 1959, Ap. J., 130, 105.
Lynden-Bell, D., Cannon, R. D. and Godwin, P. J. 1983, M.N.R.A.S., 204, 87P.
Mamon, G. 1985, Ph.D. Thesis, Princeton University.
Muzhotsky, R. 1985, private communication.
Ostriker, J. P., Peebles, P. J. E., and Yahil, A. 1974, Ap. J. (Lett.), 193, L1.
Davis, M. and Peebles, P. J. E. 1983, Ap. J., 267, 465.
Peterson, S. D. 1979, Ap. J., 232, 20.
Peterson, R. 1985, Ap. J., 297, 309.
Roberts, M. S. and Rots, A. H. 1973, Astron. & Astroph., 26, 483.
Russell, H. N. 1937, Scientific American, 84, 76.
Sandage, A. 1986 (preprint).
Schwarzschild, M. 1954, A. J., 59, 273.
Turner, E. L. 1976, Ap. J., 208, 304.
Turner, E. L. and Ostriker, J. P. 1977, Ap. J., 217, 24.
Tyson, T., Valdes, F., Jarvis, J. F. and Mills, A. P. 1984, Ap. J., (Lett.), 281, L59.
Vietri, M. and Ostriker, J. P. 1983, Ap. J., 267, 488.
Wyse, A. B. and Mayall, N. J. 1942, Ap. J., 95, 24.
Yahil, A. 1977, Ap. J., 217, 27.
Zwicky, F. 1937, Ap. J., 86, 217.

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DISCUSSION

PEEBLES: Jerry, you don't want too much irregularity in the process of accumulating halos or you won't get the remarkable uniformity of rotation-curve shapes that Vera Rubin showed us. It would be difficult to get this if you added the components stochastically.

OSTRIKER: You're right.

YAHIL: The second problem with making the halo after the disk is that you need it to stabilize the disk.

OSTRIKER: I wouldn't necessarily make the halo after the disk, because both components accrete fairly late. The models by Gunn and others in which the disk is produced late are interesting because there do not seem to be many stars in the solar neighborhood which are much older than the Sun. This suggests that these ideas may be right.

LAKE: What is disk formation late with respect to?

OSTRIKER: The formation of the spheroid. I have in mind a more-or-less straightforward one-parameter sequence of spheroids or ellipticals which are made by the Divine Hand at a redshift of 10-20. Then, later on, depending on the environment and other circumstances, the spheroids accrete gas, sometimes, and halos.

PACZYNSKI: I am confused about this 10^{12} $M_{\odot}$ business. In all of the diagrams for pairs of galaxies which you showed us there was a linear relationship between the mass within R and R; i.e., $M(R) \propto R$, with rather little scatter. The diagrams suggested that the circular velocity is roughly the same for all these galaxies. Yet you know that for spirals V_c varies from 70 to 500 km s^{-1}. How do you reconcile these two statements?

OSTRIKER: My own guess - and we can't tell from the observations as they presently exist - is that at large distances from the Sombrero you would find V_c decreasing, while at large distances from a dwarf elliptical you'd find V_c increasing.

PEEBLES: Didn't you show averages over the range of V_c from 70 to 500 km s^{-1}, rather than individual cases?

OSTRIKER: Yes, I did show averages. But I'm also suggesting that there is less variation in V_c at large radii than at small radii.

SANDERS: Earlier you mentioned that only satellites and binaries would be seriously affected by dynamical friction. But now you're suggesting that the two members of a binary pair might be swimming in a common halo. Is it an embarrassment that we see binaries at all?

OSTRIKER: Ed Turner and I looked at that in a paper about five years ago. We calculated the merging rate and found that there's no problem.

TURNER: It's just a case of steady-state flow.

OSTRIKER: Let me stress that point, because the same thing arises with the growth of cD galaxies. You have to worry about the continuity equation. Given the shape of the two-particle correlation function, you keep on forming new binaries and so can withstand some merging without changing the observed distributions.

SANDERS: And you preserve the two-point correlation function?

OSTRIKER: Yes. But that's not the constraint. The constraint is that you don't mess up the disk too much.

GUNN: Since there is a very nice correlation between mass and luminosity or rotation velocity and luminosity on the scales that the 21-cm and optical rotation curves sample, would you comment on the continued believability of the statement that on your scales, which are really not all that much larger, L and M seem to be uncorrelated? Isn't this really a problem?

OSTRIKER: It doesn't strike me as a problem because of the timescales. I can easily believe that during the formation process, all of the inner parts were magically formed with a constant ratio of dark matter to baryons. But when other material accreted later, there were additional effects, like competition from other galaxies. So I don't see why L and M have to be correlated.

GUNN: But don't you have to do something drastic to the rotation curves between ~20 kpc, where they are well observed, and 50 kpc, where they go to hell?

OSTRIKER: No. Because the amount of dark matter you need inside the visible galaxy is less than or comparable to the baryonic mass, whereas the amount you need at larger radii can be ten times that amount. So the amount in the center doesn't have much influence on the amount outside.