1987ComAp..11..273L

Dark Matter: Dead Stars?

Most of the mass associated with large stellar systems has not been directly observed, and is detectable only through its gravitational effects. Significant amounts of dark matter are found, for example, in some globular clusters, the solar neighborhood, galactic halos, and in groups and clusters of galaxies. While many possibilities exist for the unseen matter in galactic halos and clusters of galaxies, more constraints can be placed, as will be noted below, on the nature of the dark matter in globular clusters and the solar neighborhood. The unseen matter in globular clusters, in particular, almost certainly consists of stellar remnants—white dwarfs, neutron stars, and small black holes. In the solar neighborhood the dark matter must consist of either stellar remnants or low-mass stars, and while low-mass stars cannot yet be excluded, a model with many attractive features can be constructed if the unseen mass is in the remnants of intermediate- and high-mass stars that formed at a higher rate in the past.

If the nearby dark matter consists of dead stars, simplicity suggests that the same may be true for the dark matter in galactic halos and clusters of galaxies. Such a picture is not implausible in the light of current knowledge, and it may offer new possibilities for understanding the structure of dark halos, since the halo matter must in this case once have been gaseous and therefore dissipative.

Comments Astrophys.
1987, Vol. 11, No. 6, pp. 273–282
0146-2970/87/1106-0273/$15.00/0

Printed in Great Britain

GLOBULAR CLUSTERS

Models of globular clusters based on detailed star counts show that the cluster cores must be dominated by unseen stellar remnants more massive than the visible stars.[1] The core light profiles can be reproduced with density profiles of the theoretically expected nearly singular form if a few percent of the mass is in heavy remnants with typical masses of $\sim$2.5 solar masses.[2] Velocity-dispersion profiles also indicate substantial total populations of remnants in the massive clusters 47 Tuc[3] and ω Cen[4]; for the former, the data are best fitted by a model in which 35% of the mass is in white dwarfs of mass comparable to the giant mass.[3] The mass-to-light ratio M/L_V of this model is 4.0. The inferred large number of remnants in 47 Tuc requires that relatively more intermediate- and high-mass stars must have formed in this cluster than would be predicted by a conventional Salpeter-like initial mass function.[3]

THE SOLAR NEIGHBORHOOD

The solar vicinity in our Galaxy contains a larger proportion of dark matter than the globular clusters discussed above: between one-half and three-quarters of the mass in a column through the Galactic disk at the Sun's radius is unobserved.[5,6] This unseen matter must be in a layer with a scale height no larger than 700 pc; otherwise the total mass present would exceed that allowed by the rotation curve.[6] Therefore the dark mass must consist of dissipative material that settled to a disk and formed condensed objects that are presently unobserved. The only reasonable possibilities are that these unseen objects are either very-low-mass stars ("Jupiters") or stellar remnants. Their typical masses cannot exceed about 2 $M_\odot$, or the observed nearby wide binary systems would have been disrupted.[7] For black hole remnants, typical masses larger than 10 $M_\odot$ are also excluded by the absence of accretion radiation.[8]

It has often been assumed that the local dark mass can be accounted for by low-mass stars, but extrapolation of the observed mass function to lower masses actually predicts very little mass in unseen faint stars,[9,10] especially if the mass function declines at the lowest masses.[11] Extensive searches[12,13] have so far, in fact, found very few objects less massive than about 0.1 $M_\odot$. While this result does not rule out a large population of undetectably faint "Jupiters," it at least suggests that the alternative possibility, that the unseen mass is in stellar remnants, be taken equally seriously. Because of the upper limit of 2 $M_\odot$ or less on the typical masses of the unseen objects, most of the mass is then likely to be in white dwarfs.[14]

A model consistent with all of the constraints on the content and evolution of the solar neighborhood can be constructed in which the dark mass is all in remnants, mostly white dwarfs.[15] The initial mass function (IMF) in this model is not of the usual power-law form but is double-peaked or bimodal, with a second peak at a mass near 2 $M_\odot$; this mass may have been larger at earlier times. A bimodal IMF is suggested by the apparent dip at about 0.7 $M_\odot$ in the mass function of nearby stars[16,11]; this dip indicates that the IMF is nonmonotonic, and probably has a second peak[11,15] at a mass above 1 $M_\odot$. If the IMF is not monotonic, the "continuity constraint" that has been used[17] to argue for a nearly constant star formation rate (SFR) is greatly weakened, and models in which the SFR declines strongly with time become possible.[18] Remnants then become a major contributor to the total mass, as may be seen from the fact that a model[10] with a constant SFR has a remnant column density of 10 $M_\odot$ pc^{-2}; thus a past average SFR equal to three times the present SFR, for example, would produce a remnant column density of about 30 $M_\odot$ pc^{-2}, comparable to the amount of unseen mass in the solar neighborhood.[5,6]

In the model that is most consistent with the data,[15] only the high-mass mode of star formation has a rate that declines strongly with time, while the low-mass mode has a constant rate. The model is then consistent with indications that the SFR for stars of nearly solar mass has not varied much with time,[19,11] and the model also predicts a relatively gradual increase of metallicity with time, as is observed.[19] The classical problem of the relative paucity of metal-poor stars is thus solved by having a variable IMF,[20] without requiring additional effects such as gas infall. A similar variation of the IMF with radius in our Galaxy can explain the observed radial gradient in oxygen abundance, and this result has been used to argue independently for a bimodal IMF.[21]

THE IMF AND REMNANTS IN OTHER REGIONS

A considerable amount of evidence has accumulated that the IMF in many regions of active star formation has a much higher proportion of massive stars than a conventional Salpeter IMF, and peaks at a mass of the order of a few solar masses or more. This has been inferred, for example, from observations of the inner disks of both our Galaxy[21] and M83[22] and the spiral arms of M81.[23] Similar or even more extreme deviations from a conventional IMF have been inferred from observations of a number of starburst and blue compact galaxies.[24–27] All of the data are consistent with a picture in which the formation of massive stars is favored at times and in regions where the local SFR is high. Because of the rapid formation and evolution of massive stars, the total mass in such regions soon becomes dominated by remnants.[28] It is thus not implausible that many regions, and perhaps entire galaxies, could contain large amounts of mass in the remnants of massive stars that formed at a higher rate at earlier times.

If the IMF is bimodal and galactic masses are indeed generally dominated by remnants, this will affect predictions of both the colors and the mass-to-light ratios of galaxies, and earlier results[29,30] based on a conventional monotonic IMF must be revised. A bimodal IMF represents better than a monotonic IMF the observed color range of galaxies, since it allows the colors of the bluest normal galaxies to be explained without requiring very young ages or extreme bursts of star formation.[15] The moderate variation of mass-to-light ratio with color in spiral galaxies[31,32] and the positive correlation of M/L with metallicity in elliptical galaxies[33] can also be understood if the IMF is bimodal and galactic masses are dominated by remnants.[15] In such a model, however, the mass-to-light ratio depends not only on the IMF but also on the SFR as a function of time, and since these functions are not independently constrained, no *a priori* prediction can be made of the mass-to-light ratio of a stellar system. The concept of "luminous mass" is then no longer very useful in discussing the dark matter problem, and it is more relevant to consider whether the dynamically measured masses of galactic systems can be entirely accounted for by stars and stellar remnants.

DARK MATTER SURROUNDING GALAXIES

A recent study[34] of the possible consequences of Population III stars concluded that the cosmological "missing mass" could be in the remnants of early "very massive objects" ($>100\ M_\odot$), but not in remnants of ordinary massive stars of 10–100 $M_\odot$ because this would lead to excessive production of heavy elements. However, the final evolution of massive stars is not yet well enough understood for element abundances to be used as a firm constraint on the number of massive stars formed at early times. It is possible, for example, that only a small range of stellar masses contributes to supernova and heavy element production, and that most massive stars simply collapse to black holes.[35–37] In this case not even the remnants of ordinary massive stars can be excluded as making up the dark mass associated with galaxies. For example, massive dark halos[38] could be produced if, during the early stages of protogalactic collapse, most of the initial gas is processed into massive stars and ultimately into black hole remnants.[39]

Such a picture is appealing in the context of dissipative models of galaxy formation,[40,41] in which it is difficult to obtain a major part of the mass in a disk without making large *ad hoc* modifications to the assumed star formation rate. If most of the mass of a galaxy is actually in a dark halo of remnants, such *ad hoc* modifications are not required and the only change needed is that the IMF must vary with time such that initially only massive stars form, while low-mass stars do not begin to form in large numbers until the residual gas has settled to a disk. It is plausible that the typical stellar mass would decrease with time in this way because the critical mass for fragmentation depends strongly on the gas temperature,[42] which must have been higher at earlier times. In this picture, the disk of a spiral galaxy would be a secondary system formed partly of gas recycled from halo stars.[43]

DISSIPATIVE DARK MATTER

If dark halos consist of the remnants of Population III stars, the halo matter must once have been gaseous and therefore dissipative, and this property may help in explaining the radial structure of dark halos. The observed nearly flat rotation curves of galaxies suggest that their halos are approximately isothermal and have density profiles of the form $\rho \propto r^{-2}$. However, many rotation curves actually continue to rise slowly with radius,[44,45] and imply $\rho \propto r^{-1.8}$. Such a shallow density profile cannot be produced by any purely dissipationless collapse, merger, or accretion process. The dissipationless collapse of a sphere[46,47] gives $\rho \propto r^{-4}$, while the collapse of an anisotropic[47] or clumpy[48] configuration yields approximately $\rho \propto r^{-3}$, in agreement with the observed light distributions in elliptical galaxies but still too steep for the dominant dark halos. Mergers[49,50] again yield approximately $\rho \propto r^{-3}$, so that halo formation by a hierarchy of mergers[51] will also produce too steep a profile if only dissipationless processes act. Delayed infall can flatten the density profile, perhaps nearly to r^{-2}, but no theories[52,53] or simulations[46] of this effect have yet yielded profiles as shallow as $r^{-1.8}$.

Collapse models that include dissipation[54–56] yield shallower density profiles than purely dissipationless models. Dissipation tends to keep the velocity dispersion of the gas approximately constant during the collapse, so that the gas acquires a density profile that is approximately r^{-2}. More generally, the effect of dissipation on the density distribution can be seen from the similarity solution[57] giving the asymptotic form of the density profile of a collapsing gas sphere with a polytropic equation of state $P \propto \rho^{\gamma}$; for $\gamma < 4/3$, the result is $\rho \propto r^{-2/(2-\gamma)}$. This form applies also to singular polytropic spheres in hydrostatic equlibrium. In a system that collapses with little or no dissipation, the velocity dispersion increases with increasing density, corresponding to $\gamma > 1$; the density profile is then predicted to be steeper than r^{-2}, as is found in all of the dissipationless collapse calculations. However, a strongly dissipative system can have a velocity dispersion that decreases with increasing density, which corresponds to $\gamma < 1$ and gives a profile shallower than r^{-2}. The form $r^{-1.8}$ inferred for dark halos from rotation curves results if $\gamma = 8/9$, i.e., if the velocity dispersion decreases slightly with increasing density.

The value of γ most appropriate for a collapsing protogalaxy cannot be predicted *a priori*, especially as such a system is almost certainly highly inhomogeneous and turbulent. However, it may be relevant that smaller clumpy and turbulent self-gravitating gas aggregates are presently observed in the form of giant molecular clouds, and that these clouds show some fairly general scaling properties.[58] The internal velocity dispersions, sizes, and densities of molecular clumps are correlated in a way that corresponds to $\gamma \sim 1/3$, indicating strong dissipation; the corresponding density–size relation is approximately $\rho \propto r^{-1.2}$. A possible "scale model" for a protogalaxy may be provided by the condensed star-forming region OMCl in the Orion molecular cloud, which is exceptional in that its velocity dispersion is more nearly independent of length scale[58]; in fact it varies with about the 0.1 power of region size, which happens to correspond exactly to $\gamma = 8/9$ and $\rho \propto r^{-1.8}$.

RADIATION FROM PROTOGALAXIES

If during the formation of a galactic halo most of the mass is processed into massive stars and ultimately into their remnants, a very large luminosity must be produced. Assuming that all of the mass ending up in remnants undergoes hydrogen burning during the stellar phase, the predicted bolometric light-to-mass ratio is about 10^2 if the period of active star formation lasts for 10^9 years, and 10^3 if it lasts for 10^8 years. Such L/M ratios are high but not completely unprecedented among observed systems, since infrared L/M ratios up to 10^2 are observed in the nuclear regions of some starburst galaxies.[24,25] Extremely large total luminosities of up to $5 \times 10^{12}\,L_\odot$, probably also caused by bursts of formation of massive stars, are observed for some galaxies that emit primarily at infrared wavelengths.[59,60] Given these results, it is not implausible that even higher rates of formation of massive stars could have occurred at earlier times in protogalaxies, and that the associated high luminosities could have been emitted mostly at infrared wavelengths.

To avoid conflict with observed limits on cosmic background radiation, any population of massive stars whose remnants make up the present dark matter in the universe must have formed at a sufficiently large redshift; if the total mass density in remnants corresponds to $\Omega = 0.2$, then the progenitor stars must have formed at a redshift of the order of 10 or more.[34] This is not a stringent constraint in a hierarchical picture of galaxy formation. If the redshift of formation is not much larger than this minimum value, thermalized radiation from Population III stars could contribute to,[34] and conceivably account for all of,[61] the observed 2.7 K background radiation. It may be relevant that the apparent dust temperatures in the luminous infrared-emitting galaxies[59] are mostly in the range 25–50 K, so that if similar temperatures were characteristic of protogalaxies, redshifts of the order of 10–20 would reduce the observed temperatures to a few K.

FOSSILS

Present observations, accordingly, do not rule out a pre-galactic era of rapid formation of massive stars whose remnants now make up most of the unseen mass in the universe. However, direct evidence for such stars or their remnants has not yet been found, and may remain difficult to find. Some indirect evidence may be provided by the oldest known fossil systems, the globular clusters that inhabit the same halo regions as the dominant dark matter. The heavy elements in these systems must have been produced by previous generations of massive stars, and the chemical homogeneity of most globular clusters indicates that the pre-cluster gas must also have been well mixed, presumably by turbulence generated by energy input from massive stars. The large masses of the globular clusters compared with those of younger clusters in our Galaxy suggest, furthermore, that early star formation occurred in much larger gas aggregates than the presently observed molecular clouds. Observed trends[62] and theoretical considerations[42] then suggest that these massive pre-galactic gas clouds could have produced almost exclusively massive stars. The present globular clusters may be exceptional objects that formed only in the densest clumps where fragmentation to smaller stellar masses could occur. Galactic evolution may thus have begun spectacularly with an "age of dinosaurs" during which the masses of the gas clouds, clusters, and stars formed were all typically much larger than at present; in this case all but a few of these early stars would have burned out by now, leaving the present universe a relatively dark and ghostly place dominated by unseen dead stars.

RICHARD B. LARSON
Astronomy Department,
Yale University,
Box 6666,
New Haven, Connecticut 06511

References

1. G. S. Da Costa, Ph.D. Thesis, Australian National Univ. (1977).
2. R. B. Larson, Mon. Not. Roy. Astron. Soc. **210**, 763 (1984).
3. G. S. Da Costa and K. C. Freeman, in *Dynamics of Star Clusters*, *IAU Symp. No. 113*, eds. J. Goodman and P. Hut (Reidel, Dordrecht, 1985), p. 69.
4. G. Meylan and M. Mayor, in *Dynamics of Star Clusters*, *IAU Symp. No. 113*, eds. J. Goodman and P. Hut (Reidel, Dordrecht, 1985), p. 93.
5. J. N. Bahcall, Astrophys. J. **276**, 169 (1984).
6. J. N. Bahcall, Astrophys. J. **287**, 926 (1984).
7. J. N. Bahcall, P. Hut and S. Tremaine, Astrophys. J. **290**, 15 (1985).
8. J. McDowell, Mon. Not. Roy. Astron. Soc. **217**, 77 (1985).
9. B. M. Tinsley, Astron. Astrophys. **89**, 246 (1980).
10. B. M. Tinsley, Astrophys. J. **250**, 758 (1981).
11. J. M. Scalo, Fundam. Cosmic Phys. ~~(in press).~~ 11, 1 (1986).
12. *The Nearby Stars and the Stellar Luminosity Function*, *IAU Colloq. No. 76*, eds. A. G. D. Philip and A. R. Upgren (L. Davis Press, Schenectady, 1983).
13. *The Astrophysics of Brown Dwarfs*, ed. M. Kafatos (Cambridge Univ. Press, in press).
14. P. Hut, in *Dark Matter in the Universe*, *IAU Symp. No. 117*, ed. G. R. Knapp (Reidel, Dordrecht, ~~in press).~~ 1986), p. 525.
15. R. B. Larson, Mon. Not. Roy. Astron. Soc. ~~(in press).~~ 218, 409 (1986).
16. A. R. Upgren and T. E. Armandroff, Astron. J. **86**, 1898 (1981).
17. G. E. Miller and J. M. Scalo, Astrophys. J. Suppl. **41**, 513 (1979).
18. T. E. Armandroff, in *The Nearby Stars and the Stellar Luminosity Function*, *IAU Colloq. No. 76*, eds. A. G. D. Philip and A. R. Upgren (L. Davis Press, Schenectady, 1983), p. 229.
19. B. A. Twarog, Astrophys. J. **242**, 242 (1980).
20. M. Schmidt, Astrophys. J. **137**, 758 (1963).
21. R. Güsten and P. G. Mezger, Vistas Astron. **26**, 159 (1983).
22. E. B. Jensen, R. J. Talbot and R. J. Dufour, Astrophys. J. **243**, 716 (1981).
23. F. N. Bash and H. C. D. Visser, Astrophys. J. **247**, 488 (1981).
24. G. H. Rieke, M. J. Lebofsky, R. I. Thompson, F. J. Low and A. T. Tokunaga, Astrophys. J. **238**, 24 (1980).
25. G. H. Rieke, R. M. Cutri, J. H. Black, W. F. Kailey, C. W. McAlary, M. J. Lebofsky and R. Elston, Astrophys. J. **290**, 116 (1985).
26. F. Viallefond and T. X. Thuan, Astrophys. J. **269**, 444 (1983).
27. R. Augarde and J. Lequeux, Astron. Astrophys. **147**, 273 (1985).
28. D. W. Weedman, Astrophys. J. **266**, 479 (1983).

29. L. Searle, W. L. W. Sargent and W. G. Bagnuolo, Astrophys. J. **179**, 427 (1973).
30. R. B. Larson and B. M. Tinsley, Astrophys. J. **219**, 46 (1978).
31. B. M. Tinsley, Mon. Not. Roy. Astron. Soc. **194**, 63 (1981).
32. J. P. Vader, in *Formation and Evolution of Galaxies and Large Structures in the Universe*, eds. J. Audouze and J. Tran Thanh Van (Reidel, Dordrecht 1984), p. 227.
33. J. P. Vader, Astrophys. J. ~~(in press)~~. 306, 390 (1986).
34. B. J. Carr, J. R. Bond and W. D. Arnett, Astrophys. J. **277**, 445 (1984).
35. B. A. Twarog and J. C. Wheeler, Astrophys. J. **261**, 636 (1982).
36. W. Hillebrandt, K. Nomoto and R. G. Wolff, Astron. Astrophys. **133**, 175 (1984).
37. A. Burrows and J. M. Lattimer, Astrophys. J. **299**, L19 (1985).
38. S. M. Faber and J. S. Gallagher, Ann. Rev. Astron. Astrophys. **17**, 135 (1979).
39. J. W. Truran and A. G. W. Cameron, Astrophys. Space Sci. **14**, 179 (1971).
40. R. B. Larson, Mon. Not. Roy. Astron. Soc. **173**, 671 (1975).
41. R. B. Larson, Mon. Not. Roy. Astron. Soc. **176**, 31 (1976).
42. R. B. Larson, Mon. Not. Roy. Astron. Soc. **214**, 379 (1985).
43. J. P. Ostriker and T. X. Thuan, Astrophys. J. **202**, 353 (1975).
44. D. Burstein, V. C. Rubin, N. Thonnard and W. K. Ford, Astrophys. J. **253**, 70 (1982).
45. V. C. Rubin, W. K. Ford, N. Thonnard and D. Burstein, Astrophys. J. **261**, 439 (1982).
46. J. R. Gott, Ann. Rev. Astron. Astrophys. **15**, 235 (1977).
47. J. V. Villumsen, Astrophys. J. **284**, 75 (1984).
48. T. S. van Albada, Mon. Not. Roy. Astron. Soc. **201**, 939 (1982).
49. S. D. M. White, Mon. Not. Roy. Astron. Soc. **184**, 185 (1978).
50. J. V. Villumsen, Mon. Not. Roy. Astron. Soc. **199**, 493 (1982).
51. S. D. M. White and M. J. Rees, Mon. Not. Roy. Astron. Soc. **183**, 341 (1978).
52. J. E. Gunn, Astrophys. J. **218**, 592 (1977).
53. J. A. Fillmore and P. Goldreich, Astrophys. J. **281**, 1 (1984).
54. R. B. Larson, Mon. Not. Roy. Astron. Soc. **145**, 405 (1969).
55. R. B. Larson, Mon. Not. Roy. Astron. Soc. **166**, 585 (1974).
56. R. G. Carlberg, Astrophys. J. **286**, 403 (1984).
57. R. B. Larson, Mon. Not. Roy. Astron. Soc. **145**, 271 (1969).
58. R. B. Larson, Mon. Not. Roy. Astron. Soc. **194**, 809 (1981).
59. J. R. Houck, D. P. Schneider, G. E. Danielson, C. A. Beichman, C. J. Lonsdale, G. Neugebauer and B. T. Soifer, Astrophys. J. **290**, L5 (1985).
60. G. Neugebauer, B. T. Soifer and G. K. Miley, Astrophys. J. **295**, L27 (1985).
61. M. J. Rees, Nature **275**, 35 (1978).
62. R. B. Larson, Mon. Not. Roy. Astron. Soc. **200**, 159 (1982).