NO NEED FOR DARK MATTER IN GALAXIES?

N.W. Evans
Theoretical Physics, Department of Physics, 1 Keble Road, Oxford OX1 3NP, England
E-mail: nwe@thphys.ox.ac.uk

Unhappily, there has been a maelstrom of problems for dark matter theories over the last few years and many serious difficulties still have no resolution in sight. This article reviews the evidence for dark matter in galaxies. Judged on the data from galactic scales alone, the case for dark matter is weak. Non-Newtonian theories of gravity have their own problems, but not on galactic scales.

1 Introduction

The best evidence for mass discrepancies in galaxies comes from rotation curves of neutral hydrogen. However, in the case of our own Galaxy, the rotation curve cannot be traced beyond $\sim 20$ kpc. It is the kinematics of stellar tracers of the distant halo – namely the bound dwarf galaxy satellites and distant globular clusters – that provide the mass estimates. The most recent analysis found the total dynamical mass of the Galaxy is $\sim 2 \times 10^{12} M_\odot$. By contrast, the mass of the stellar disk is $\sim 6 \times 10^{10} M_\odot$ and of the stellar bulge and spheroid is $\sim 3 \times 10^{10} M_\odot$. There are only two alternatives. The first is that the Galaxy is largely composed of dark matter. This is matter whose existence is inferred solely from its gravitational effects. The second is that Newtonian gravity is incorrect and needs modification. There is no hard evidence that conventional theories of gravity are correct on scales greater than at most a parsec. But, to many astronomers, the second option is unattractive, as the hard-won understanding of large-scale structure formation would then be jeopardised.

If dark matter exists, what is it? Microlensing surveys and Hubble Space Telescope pencil-beam searches strongly constrain the mass in dim stars and brown dwarfs. Suppose we rashly assume that all the lenses towards the Magellanic Clouds lie in the Galactic halo, then no more than $\sim 9 \times 10^{10} M_\odot$ of the mass within 50 kpc lies in such objects. Yet, the dynamically inferred mass is roughly five times greater than this. So, there is firm evidence that faint or failed stars do not make up most of the Galactic halo. In contrast, non-baryonic particle dark matter is an essential component of theories of structure formation. First, the total dynamical mass density in the Universe exceeds that permitted for baryonic dark matter by big bang nucleosynthesis, and second, the growth of structure requires pre-existing perturbations in the
non-baryonic component at the time of recombination. Cold dark matter theories (CDM) or their variants with a cosmological constant (ΛCDM) give a fine description of large-scale structure, but there remain stubborn problems on the scales of kiloparsecs. The recent years have seen increases in the quality, the quantity and the severity of these problems. Some astronomers have been led to question the very existence of dark matter, while others have been led to imbue the dark matter with additional, exotic properties. It is a measure of the seriousness of the situation that such drastic hypotheses are being put forward.

2 The Problems

A galaxy is described as having a “maximum disk” when the dark matter contribution to the central attraction in the inner regions is negligible compared to that of the luminous disk and bulge or bar. The haloes built up by hierarchical merging in dark matter cosmogonies (such as the Navarro-Frenk-White or NFW models) are cusped and dominated by dark matter at the very center. However, there is overwhelming evidence that the disks of large spiral galaxies are close to maximum and the haloes make only a small contribution to the rotation curve in the inner parts. For the dark-matter dominated low surface brightness and dwarf galaxies, matters are less clear-cut, but even here, the balance of the evidence is against cusped haloes.

2.1 The Microlensing Optical Depth to the Galactic Center

For example, there are extremely high microlensing optical depths towards Baade’s Window. The optical depth to the red clump stars is $3.9 \times 10^{-6}$. This is a crucial measurement as the red clump stars are bright (so the efficiency of the survey is high) and are known to reside in the Galactic bulge (so that contamination by background sources is unlikely). Even barred Galaxy models have real difficulty in generating the measurements without violating constraints on the Galactic force-field, while axisymmetric models are ruled out. The power of this argument is that it does not depend on the details of the modelling. It follows from computing the maximum contribution to the microlensing optical depth, consistent with the rotation curve, made by circular or elliptical rings of matter. Therefore, almost all the matter along the lines of sight to the Galactic bulge must be capable of causing microlensing and cannot be particle dark matter. This argument immediately rules out cusped profiles (like the NFW model) as realistic representations of the present-day structure of the Galaxy halo. They give values of the optical depth to the red clump stars that are seriously awry.
2.2 Hydrodynamical Modelling of the Galactic Bar

The other strong, albeit more model dependent, piece of evidence that the Galaxy has a maximum disk comes from hydrodynamical and stellar dynamical modelling of the Galactic bar\cite{weiner2001}. First, Weiner & Sellwood used a flux-splitting Eulerian grid code to model the gas flow in a reasonably realistic analytical force field. Second, Englmaier & Gerhard used smooth-particle-hydrodynamics to model the gas flow in the inner Galaxy using a mass distribution derived from the COBE surface photometry with a constant mass-to-light ratio. The studies conclude that to reproduce the terminal velocities of the HI gas, the bar and the disk must provide almost all the rotational support within the solar circle. Further evidence is provided by the stellar velocity dispersions and mean motions available at certain unobscured windows in the bulge. Häfner et al. built a stellar dynamical bar (using a similar mass model and normalisation as Englmaier & Gerhard) and showed it reproduced essentially all of the available stellar kinematical data in the inner Galaxy.

2.3 Stability of Unbarred Disk Galaxies

It is the problem of galactic stability that led to the introduction of dark haloes in the first place. Many simple models of self-gravitating disks disrupt to form bars on a dynamical time scale. Ostriker & Peebles\cite{osti99} argued that unbarred galaxies are stable because they contained a large fraction of mass in a dynamically hot component which was unable to participate in collective instabilities. Although they never said this, their paper has sometimes been misrepresented as stating that maximum disks are unstable. This misunderstanding persists in some papers on galaxy formation to this very day.

Toomre\cite{toomre77} showed that disks could be stabilized by making their centers impenetrable to density waves. One way to achieve this is for the circular speed to remain high towards the center, which forces an inner Lindblad resonance (ILR) that cuts the feedback loop to the swing amplifier. Even a fully self-gravitating disk can be stabilized against bisymmetric modes. Toomre’s prediction was almost immediately contested by numerical simulations\cite{katz1982}, which found no evidence for stabilization by hard centers. This contradiction was resolved by the realisation that large-amplitude disturbances in highly responsive disks could saturate the ILR, trapping particles in a large-scale bar similar to that which would have formed without the dense center\cite{massey1998}. The recent years have seen a number of examples of robustly bar-stable galaxy models having cool, maximal disks with dense centers\cite{sellwood2001}. For example, Sellwood & Evans have constructed a completely stable and reasonably realistic galaxy model in which the disk provides most of the central attraction in the inner parts. This model
has a quasi-exponential disk and an almost flat rotation curve that arises from a combination of the massive disk, a central bulge, together with a halo having very low central density. They showed, using both linear stability theory and numerical simulations, that it has no global instabilities whatsoever.

What stabilizes real unbarred disk galaxies: hard centers or dark haloes? High-resolution kinematic observations of spiral galaxies have uncovered high orbital speeds close to their centers. Galaxies with gently rising rotation curves at the center all have low luminosity. Such galaxies are required to have large dark matter fractions to suppress bar-forming instabilities. However, almost every galaxy with a circular speed in excess of 150 km s\(^{-1}\) has a steep inner rise in the rotation curve and must be bar-stable whatever its dark matter content. Bright unbarred disk galaxies are stabilized by their hard centers.

2.4 Pattern Speeds of Bars

Bars in galaxy models with cusped dark halos all experience strong drag from dynamical friction. The drag causes the bar to slow down and drives the corotation point out to distances well beyond the bar’s optical edge. This process acts swiftly, on the timescale of a few bar rotation periods. If dark matter dominates the central parts of barred galaxies, then bars are expected to be slow. Pattern speeds have now been measured for a handful of barred galaxies. The sample is small, but the results are consistent and confirm the theoretical expectation that bars in real galaxies are fast rotators. The corotation point typically lies just beyond the bar’s optical edge. Bars can maintain such high pattern speeds only if the disk provides most of the central attraction in the inner regions.

2.5 Rotation Curves

All the above evidence depends on dynamics and is much more reliable than the evidence based on rotation curves. Unsurprisingly, there is inevitable degeneracy in decomposing galaxy rotation curves into contributions from the disk, bulge and halo, as well as assessing the importance of experimental effects like beam-smearing. Consequently, this area has been beset by controversy.

For bright galaxies, maximum disks are favored by the fact that luminous matter alone accounts for the overall shape of the rotation curve in the inner parts. This is a point of view originally advocated by Kalnajs in 1983. For example, an extensive recent survey of 74 southern spirals found that ~ 75% are well-fitted by a mass-traces-light model for the inner parts. For dwarf and low surface brightness (LSB) galaxies, dark matter dominates everywhere. Early claims that the rotation curves are inconsistent with cusped haloes have
given way to an acceptance that the available data may not be good enough
to decide the issue. The HI rotation curves of the LSB disks, and probably the
dwarf spirals as well, are strongly affected by beam-smearing and are consistent
with both cusps and cores. Even so, for the dwarf spiral NGC 5585, the
highest quality HI and Hα data do appear to show that the halo density profile
rises to a finite and uncusped value. There is also a sample of five LSB
galaxies for which high resolution Hα rotation curves are available. This
study demonstrates that there is a tendency for the HI data to underestimate
the inner slopes of the rotation curves. Two galaxies in the sample have much
steeper inner slopes in Hα than HI, two are mildly steeper, while one (F568-3)
is unchanged.

A fair summary is that the data favor the absence of cusps, but the evidence
is far from conclusive. Only when the HI data is complemented by Hα
observations can robust conclusions be drawn. Then, there do appear to be
examples of galaxies – like the LSB galaxy F568-3 and the dwarf spiral NGC
5585 – which are only consistent with cores. On the other hand, there is no
clear-cut example of a galaxy whose halo requires a cusped profile.

3 Conspiracies and Catastrophes

Once it is accepted that bright spiral galaxies are dominated by baryons in
the inner parts, then dark matter theories become engulfed by two serious
problems – the disk-halo and the surface brightness conspiracies. No convincing
solution of these difficulties have ever been proposed. High resolution N-body
simulations have also uncovered a number of problems with galaxy formation
in cold dark matter (CDM) cosmogonies, the most serious of which are the
angular momentum and satellite catastrophes. (Other problems are listed in
Sellwood & Kosowsky).

3.1 The Disk-Halo Conspiracy

There is no feature in the galaxy rotation curve as the dominant source of
the gravity field changes from luminous to dark. In its original formulation,
CDM removed this difficulty, as the dark matter dominated everywhere, even
at the very centers of bright galaxies. Baryonic disks formed in the pre-existing
potential wells of dark haloes. However, this is no longer tenable as the evidence
that baryons dominate the central parts of bright galaxies is too strong. It is
very hard to understand why the circular velocity from luminous matter at the
center should be so similar to that from dark matter at large radii. If the dark
matter and the luminous matter are unrelated, the resolution of this difficulty
requires fine tuning.
3.2 The Surface Brightness Conspiracy

On dimensional grounds, we expect that \( v_{\text{circ}}^2 \sim GM/L \), where \( v_{\text{circ}} \) is the circular speed, \( M \) is the total mass and \( L \) is the characteristic size of a galaxy. So, we expect a low surface brightness galaxy to have a lower circular velocity than a high surface brightness of the same mass. This is not the case. We observe similar circular speeds in all galaxies of a given luminosity, no matter how widely dispersed the luminous material. In other words, extremely low surface brightness galaxies lie on the same Tully-Fisher relation as that derived for high surface brightness galaxies. This requires the dark matter fraction to rise as the luminous surface density declines. This is not easy to arrange without fine tuning, as the baryons dominate the mass of the inner parts of bright galaxies.

3.3 The Angular Momentum and Satellite Catastrophes

Any hierarchical merging cosmogony suffers from the angular momentum catastrophe. As they cool, the baryons lose angular momentum to the halo making disks that are much too small. The predicted scalelengths of disk are at least a factor of \(~5\) less than observed. CDM cosmogonies also suffer from the satellite catastrophe. High resolution N-body simulations have revealed large numbers of sub-clumps within large dark matter haloes, typically orders of magnitude more than are observed as satellite galaxies of (say) the Milky Way or M31. Both these catastrophes are a consequence of the persistence of sub-structure. Warm dark matter cosmogonies can partly evade the second problem, but not the first.

Processes such as feedback from star formation, explosions, ejection from gaseous bars and massive galactic winds have all been invoked to solve these problems and to remove the central cusp of the dark halo as well. For example, one suggestion is that galaxies first absorbed and then ejected a mass of baryons that is comparable to their current baryonic mass. The energy and angular momentum given up by the ejected baryons modify the structure of the dark halo, erasing the central cusp and removing substructure. Galactic disks are formed from material at the periphery of the volume from which the galaxy’s dark matter was drawn. On account of its large galactocentric radius, this material had more angular momentum than the disk it finally built.

Only simulations will tell us whether feedback processes can solve these catastrophes. At present, the simulations do suffer from resolution difficulties and lack some of the essential physics. At least as judged from the available simulations, it looks likely that feedback can solve the satellite catastrophe, but it looks unlikely that it can actually erase steep cusps.
4 Discussion

There is no observational evidence that requires dark haloes to have central cusps. And there is a lot of hard-to-circumvent dynamical evidence that they do not. It is worth stressing that the really damaging evidence against cusps comes from the dynamics and not from the rotation curves. The alternative to dark matter – namely non-standard theories of gravity – has been much less well explored. Nonetheless, it is striking that a theory like MOND resolves the disk-halo conspiracy and the surface brightness conspiracy at the cost of introducing a new fundamental scale. (In fact, it was a successful prediction of MOND that low surface brightness galaxies obey the same Tully-Fisher relation as high surface brightness galaxies). There is no theory of cosmology or galaxy formation available in MOND, so nothing can be said about the angular momentum or the satellite catastrophes. Judged on the evidence from galactic scales alone, the case for dark matter is weak and MOND is the better theory. Non-Newtonian theories of gravity have problems of their own (such as lack of covariance), but not on galactic scales.

A characteristic of most ultimately successful theories is that they work best in the régimes where the data are best understood, and work least well in the régimes where the data are poorest. CDM (and its variants) do not have this property. It is on galactic scales that distances are best known, samples are most complete and the data are best understood and here CDM has a number of stubborn problems. By contrast, the great triumph of CDM is in the reproduction of the large-scale distribution of galaxies.

References

1. M.I. Wilkinson, N.W. Evans, *MNRAS* **310**, 645 (1999).
2. For example, see M.J. Rees, *Perspectives in Astrophysical Cosmology*, Cambridge University Press (1995)
3. C. Alcock et al., *ApJ* **542**, 281 (2000); T. Lasserre et al., *A&A* **355**, L39 (2000)
4. J.N. Bahcall, C. Flynn, A. Gould, S. Kirhakos, *ApJ* **435**, L35 (1994)
5. Possible alternatives are discussed in E.J. Kerins, N.W. Evans, *ApJ* **517**, 743 (1999); H.S. Zhao, N.W. Evans, *ApJ* **545**, L35 (2000).
6. For example, see E.W. Kolb, M.S. Turner, *The Early Universe*, Addison-Wesley (1990)
7. C.S. Frenk, these proceedings
8. J.A. Sellwood, A. Kosowsky, In *Gas & Galaxy Evolution*, eds J.E. Hi bbard, M.P. Rupen, J. van Gorkom, in press (astro-ph/0009076); S.S. McGaugh, *ApJ* **541**, L33 (2000)
9. D.N. Spergel, P.J. Steinhardt, *Phys. Rev. Lett.* **84**, 3760 (2000); P.J.E. Peebles, *ApJ* **534**, L127 (2000); J. Goodman, *New Astron.* **5**, 103 (2000)
10. J. Navarro, C. Frenk, S.D.M. White, *ApJ* **462**, 563 (1996)
11. C. Alcock et al., *ApJ* **479**, 119 (1997); C. Alcock et al., *ApJ*, submitted [astro-ph/0002510]
12. J.J. Binney, N. Bissantz, O.E. Gerhard, *ApJ* **537**, L99 (2000); J.J. Binney, In *Microlensing 2000: A New Era of Microlensing Astrophysics*, eds J.W. Menzies, P.D. Sackett [astro-ph/0004362]
13. B. Weiner, J.A. Sellwood, *ApJ* **524**, 112 (1999); P. Englmaier, O.E. Gerhard, *MNRAS* **304**, 512 (1999); R.M. Häfner, N.W. Evans, W. Dehnen, J.J. Binney, *MNRAS* **314**, 433 (2000); O.E. Gerhard, In *Galaxy Disks and Disk Galaxies*, eds. J.G. Funes et al. [astro-ph/0010539]
14. J. Ostriker, P.J.E. Peebles, *ApJ* **186**, 467 (1973)
15. A. Toomre, In *The Structure and Evolution of Normal Galaxies*, eds S.M. Fall, D. Lynden-Bell, Cambridge University Press, (1981)
16. G. Efstathiou, G. Lake, J. Negroponte, *MNRAS* **199**, 1069 (1982)
17. J.A. Sellwood, *MNRAS* **238**, 115 (1989)
18. For example, see J.A. Sellwood, E.M. Moore, *ApJ* **510**, 125 (1999); N.W. Evans, J.C.A. Read, *MNRAS* **300**, 106 (1998); J.A. Sellwood, N.W. Evans, *ApJ*, in press [astro-ph/0006198]
19. V. Rubin, J.D.P. Kenney, J.S. Young, *AJ* **113**, 1250 (1997); Y. Sofue et al., *ApJ* **523**, 136 (1999)
20. M. Weinberg, *MNRAS* **213**, 451 (1985); V. Debattista, J.A. Sellwood, *ApJ* **493**, L5 (1998)
21. M. Merrifield, K. Kuijken, *MNRAS* **274**, 933 (1995); J. Gerrsen, K. Kuijken, M. Merrifield *MNRAS* **306**, 926 (1999)
22. P. Palunas, T.B. Williams, *AJ* **120**, 2884 (2000)
23. F. van den Bosch, *AJ* **119**, 1579 (2000)
24. S. Blais-Ouellette et al., *AJ* **118**, 2123 (1999)
25. R.A. Swaters, B.F. Madore, M. Trewella, *ApJ* **531**, L107 (2000)
26. J.N. Bahcall, S. Casertano, *ApJ* **293**, L7 (1985)
27. M.A. Zwaan, J.M. van der Hulst, W.J.G de Blok, S.S. McGaugh, *MNRAS* **273**, L35 (1995)
28. N. Katz, J.E. Gunn, *ApJ* **377**, 365 (1991)
29. A.A. Klypin, A.V. Kravtsov, O. Valenzuela, F. Prada, *ApJ* **522**, 82 (1999); B. Moore et al., *ApJ* **524**, L19 (1999)
30. J.J. Binney, O.E. Gerhard, J. Silk, *MNRAS*, in press [astro-ph/0003199]
31. M.-M MacLow, A. Ferrara, *ApJ* **513**, 142 (1999)
32. For example, see S.S. McGaugh, In *Galaxy Dynamics: a Rutgers Symposium*, eds. D. Merritt, J.A. Sellwood, M. Valluri, p. 528