THE DISTRIBUTION OF DARK MATTER IN THE MILKY WAY GALAXY

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A wealth of recent observational studies shows the dark matter in the Milky Way to have the following fundamental properties:

1) there is no detectable dark matter associated with the Galactic disk – the dark matter is distributed in a purely halo distribution with local volume density near the Earth \( \approx 0.3\text{GeV/cm}^3 \equiv 0.01 M_{\odot}\text{pc}^{-3} \);

2) The stellar mass function is both universal and convergent at low masses – there is no significant very low luminosity baryonic dark matter associated with stellar light. Fundamentally, dark mass does NOT follow light.

3) The smallest scale length on which dark matter is clustered is in the Milky Way’s satellite dwarf Spheroidal galaxies, where dark matter has a characteristic length scale \( \sim 1\text{kpc} \equiv 10^{20}\text{m} \) and mass density \( \sim 0.05 M_{\odot}\text{pc}^{-3} \equiv 1.5\text{GeV/cm}^3 \).

1 Dark Matter In The Galactic Disk: An Update

1.1 The Kuijken-Gilmore Standard determination of the local dark matter density

The standard determination of the volume density of matter near the Sun is that due to Kuijken and Gilmore (Kuijken & Gilmore 1989a,1989b,1989c,1991). Kuijken and Gilmore developed a new maximum likelihood technique to analyse the joint kinematic and spatial distribution functions, under the constraint of physical realisability, which they applied to new photometric and kinematic data. Their analysis utilised their kinematic and photometric survey of K dwarf stars towards the South Galactic Pole, perpendicular to the Galactic Plane. The essential aspects of their method derive from the fact that determination of the mass distribution of the Galactic disk from stellar kinematic tracers essentially requires comparison of the velocity distribution function at some height from the disk mid-Plane with the spatial density of the same tracer population above that height.

For this reason, purely local determinations of the volume mass density are inherently inaccurate, as they must compare both local all-sky and distant pencil-beam data. The Kuijken and Gilmore analysis utilised velocities for stars up to \( \sim 1\text{kpc} \) from the Galactic Plane, thereby minimising dependence on poorly determined local quantities. This provided a robust determination of the total, integral, surface mass density of all gravitating matter within 1.1kpc.
of the Galactic Plane, which is \(71 \pm 6 \, M_\odot \, pc^{-2}\). By combining this result with large scale constraints on the mass distributions in the disk, bulge and halo, from the Galactic rotation curve, Kuijken and Gilmore determined the column integral mass density of the Galactic disk to be \(48 \pm 9 \, M_\odot \, pc^{-2}\).

The question immediately arises as to what fraction, if any, of this total disk mass might be (cold) dark matter distributed with a disk-like density distribution. Recall that the 1-D velocity dispersion associated with the Galactic disk density distribution is \(\sim 30 \, km/s\), so any disk-like dark matter must indeed be cold dark matter. There is no reason to expect any mass with such a cold distribution to be related to the mass which dominates the large scale galactic potential of course. Direct observational measurement of the identified baryonic disk mass is not easy. Kuijken and Gilmore (1989b) describe the contributions and methods, while Gilmore, Wyse and Kuijken (1989) summarise the situation in the wider, Galactic, astrophysical context. Basically, one must use the local observed stellar mass function and kinematic distribution function, integrated through the gravitational potential determined by Kuijken and Gilmore, to determine the stellar contribution to the column integral. The contribution from atomic and molecular gas is then added, to provide the total. Proceeding in this way, Kuijken and Gilmore calculated the identified baryonic mass surface density of the Galactic disk to be \(48 \pm 8 \, M_\odot \, pc^{-2}\).

Thus, there is no evidence for any significant unexplained mass associated with the Galactic disk. Rather, the mass required to support the Galactic rotation curve, in addition to the identified disk and bulge mass, must be distributed in an extended halo. It is this mass whose local volume density is \(\approx 0.3 \, GeV/cc = 0.01 \, M_\odot \, pc^{-3}\), and which has a velocity distribution appropriate to an extended halo distribution, which is the target of the particle dark matter searches described elsewhere in this volume.

1.2 Developments subsequent to the Kuijken/Gilmore experiment

There are four aspects of the determination of the Galactic Gravitational Force Law \(K_z(z)\) which can be tested using more recent data. The adopted distribution of chemical elements in the tracer stars; correctness of the kinematics; correctness of the photometry, and calculation of the identified baryonic disk mass.

1) Potentially the most important is the stellar chemical abundance distribution function far from the Galactic Plane. Distances for the tracer stars, and hence the distance scale of the experiment, are determined essentially from the Hertzsprung-Russell diagram, which relates stellar colours to intrinsic luminosity. Thus, determination of a stellar colour and the inverse square law
are the primary scale factors. Stellar colours are however also systematically dependent on the abundances of the chemical elements, a distribution which was very poorly known, for stars far from the Galactic plane, at the time of the Kuijken/Gilmore experiment. Should the abundance distribution function adopted be systematically in error, then a systematic error would ensue in the derived force law, and generating mass distributions.

Determination of stellar abundances far from the Plane is a technically challenging and time-consuming task in its own right. An extensive project to improve its determination has recently been completed by Wyse and Gilmore (1995), utilising techniques and results from Jones, Gilmore and Wyse (1996), Jones, Wyse and Gilmore (1995), and Gilmore, Wyse and Jones (1995). More recently, further support for this result has been provided from analyses by B. Nordstrom and J. Andersen (pri. commn) based on detailed studies of very large samples of bright stars, and by Reid, Gizis, et al (in preparation), based on smaller samples of very faint low-luminosity stars. The abundance distribution function derived in these projects, from careful analysis of spectra and kinematics of large samples of stars, are in surprisingly (to this author) good agreement with that adopted by Kuijken and Gilmore (1989b).

2) Measurement of radial velocities using the multi-plex optical fibre technique utilised by Kuijken and Gilmore was at the time a new technology. Since that time, both the methodology (eg Ibata and Gilmore 1995) and the detailed results in this line of sight, have been confirmed by several authors (eg Gould, Bahcall and Flynn 1996 and refs therein). The kinematics seem reliable.

3) The Kuijken and Gilmore sample of tracer stars, and the corresponding spatial density profile of these stars, were derived from photographic photometry, inevitably requiring several large systematic corrections for conversion to a calibrated scale. The relevant photometric techniques are complex, and require considerable corrections during their application. A description is provided by Gilmore (1983). Recent technological developments now allow appropriate surveys with sensitive, linear, photometric detectors, obviating the need for complex photographic photometry. The first independent test of the results of the photographic technique has been provided by a massive survey, using contemporary linear CCD digital detectors, by Caldwell and Schecter (1996). These authors show the Kuijken/Gilmore photometry to be accurate to within 2 percent in zero point, and 3 percent in colour calibration, in the range of interest. Thus the basic photometric data are of sufficient precision for the conclusions to be unaffected.

4) Potentially the least reliable part of the determination of the density of dark matter near the Sun is the calculation of the actual baryonic mass density associated with the Galactic disk. This calculation involves a conversion
from the observed luminosity distribution of stars to their mass distribution: a conversion which is poorly known, and difficult to check. Pending an eventual future agreement among the very many groups modelling the luminosity-mass conversion, we note here that the most recent available determinations all agree, within better than two sigma, that the identified mass density is indistinguishable from the dynamical mass density. Among the very many relevant papers supporting this basic result are those by Kroupa, Tout and Gilmore (1990, 1991, 1993), Gould, Bahcall and Flynn (1996), Mera, Chabrier and Baraffe (1996) and Chabrier (this volume).

Thus, all the very many aspects of the evidence are consistent with the statement that there is no statistically significant evidence for the existence of any dark matter associated with the Galactic disk. Inside the Milky Way Galaxy, there is no evidence that dark matter can concentrate on scales shorter than $10^{20}$ m, and a considerable body of evidence that it is collected only on much longer scales. The full implications of this result for the velocity dispersion and equation of state of the dark matter remain to be explored.

1.3 Future improvements

Is a future improvement plausible? Yes indeed. The ESA HIPPARCOS astrometric satellite, the results of which will become available in early 1997, will provide both direct trigonometric calibration of distance scales and very accurate kinematics. A very substantial improvement in the precision of the relevant measurements is certain. Preliminary results (Pham 1997) strongly indicate that there is indeed no significant dark matter distributed like the luminous mass in the Galactic disk. The galactic dark matter is a property of the Galactic halo.

2 Does Halo Dark Matter Follow Light?

An enduring interest in studies of dark matter is the extent of a baryonic contribution, associated with a high mass-light ratio part of the stellar mass function (Lynden-Bell & Gilmore 1990). This might include, among more exotic possibilities, very low mass M-dwarf or brown dwarf stars, or very old, cool, extremely low-luminosity, white dwarfs. From the work of Reid and Gilmore (1982), utilising the new automated photographic measuring machines and Schmidt telescope surveys, to the ultra-deep Hubble Space Telescope survey of the Hubble Deep Field (Elson, Gilmore, & Santiago 1996), the limits in apparent luminosity of surveys for such low luminosity sources have been increased by a factor approaching one million. With every increase in experimental sen-
sitivity, the possibility of a substantial population of low-mass, low-luminosity stars - always marginally significant, at the limits of sensitivity, at best - has receded. Recent work, including the recent gravitational microlensing results (Rich, this volume, Sutherland, this volume), together with the first detection of a real brown dwarf (Kulkarni, this volume) now provide convincing evidence that very low mass stars can indeed be found, that their volume density is very low, and that they are irrelevant for galactic gravitational potentials.

The contribution of low mass stars to the total mass budget is determined through the stellar mass function, the relative number of stars per unit mass which are ever formed. Recent experimental and theoretical results tightly constrain both the functional form of, and possible variations in, this function.

2.1 Stellar mass functions in many environments

Recent results from the Hubble Space telescope have substantially revised and improved understanding of the stellar mass function. Accurate determination of cluster stellar luminosity functions are now available from several authors, for in total 2 open clusters and 11 globular clusters. In addition, many authors have determined the field star luminosity function, with excellent agreement between independent analyses (cf, eg Elson, Gilmore & Santiago 1996; Flynn, Gould & Bahcall 1996; Gould, Bahcall & Flynn 1996; Mendez, Minnitti, de-Marchi, Baker & Couch 1996; Reid, Yan, Majewski, Thompson & Smail 1996; Santiago, Elson & Gilmore 1996).

Analysis of these very many observational result shows excellent agreement, even though a very wide range in chemical element abundances and physical environment is considered. To excellent precision, all luminosity functions have a broad maximum at a luminosity which corresponds to a mass of $0.25M_\odot$ (Kroupa, Tout & Gilmore 1993; Santiago, Elson & Gilmore 1996; von Hippel, Gilmore, Tanvir, Robinson & Jones 1996).

Conversion of these luminosity functions to mass functions at the lowest masses remains uncertain. Recent results however suggest a stellar mass function which is perhaps slowly rising at very low masses, but with a sufficiently shallow slope that no significant mass remains to be accounted for (Kroupa, Tout & Gilmore 1993; von Hippel, Gilmore, Tanvir, Robinson & Jones 1996; Gould, Bahcall & Flynn 1996; see also Chabrier, this volume). Thus, the stellar mass function is probably universal, and has no dynamically significant mass at very low masses. Low mass stars are irrelevant for the dark matter which dominates galactic halos, and the Universe on large scales.

We emphasise here that this is no more than the well-known and usually ignored result derived from elementary kinematic analyses: the distribution of
dark matter derived from rotation curve analyses is fundamentally different, in every case studied, from the distribution of the (stellar, baryonic) light. Mass does NOT follow light in galaxies: total mass is invariably much more extended than is the baryonic mass which generates the stellar light. Thus, adjusting the mass to light ratio of any identified contribution to the observed luminosity profile cannot, in principle, ever explain dark matter. Matter which is distributed in space inherently differently from all detected sources of luminosity is required to explain the kinematic observations.

We thus are left with two questions concerning the distribution of dark matter in the galaxy: is there a form of baryonic dark matter distributed differently than the luminous stellar mass, and so forming the Galactic halo? Does dark matter cluster on any detectable scale smaller than the whole galaxy, so that we may constrain its nature?

3 Does Baryonic Matter Contribute to the Galactic Dark Halo?

If the answer to this question were known there would be no need for this meeting. Substantial constraints are however rapidly emerging. The EROS microlensing experiment effectively excludes compact objects with masses below the stellar hydrogen burning limit from contributing to the Galactic halo (Rich, this meeting). At significantly higher masses, normal stars would be readily visible, and have long been excluded. Two possibilities have remained: low mass, but nonetheless hydrogen-burning, stars, too faint to have been detected in available surveys; and very old white dwarfs.

3.1 Low Mass Stars as Halo Dark Matter?

Both these possibilities can be tested with the new, ultra-deep Hubble Space Telescope surveys, especially that in the Hubble Deep Field (eg Elson, Gilmore, & Santiago 1996), and from the wider-area Medium Deep Survey Key Project (Santiago, Elson & Gilmore 1996). The several relevant analyses of these, and similar HST data, are in excellent agreement, and limit the possible contribution of low mass normal stars to the Galactic halo mass to being at an insignificant level, with at most a few percent (Santiago, Gilmore & Elson 1996) of the mass which generates the rotation curve being allowed in this form. Low mass stars are no longer viable as a substantial part of the Galactic dark halo mass. Something more exotic is implicated.
3.2 *Old White Dwarfs as Halo Dark Matter?*

White dwarf stars are the cooling remnants of the cores of intermediate-mass stars after they have exhausted their internal energy sources. Their cooling rate is a weak function of mass, with faster cooling, and hence lower predicted luminosities, at higher masses. While white dwarfs from the normal disk and halo stellar populations all have masses very near $0.6 M_\odot$, the mass function for a new, hypothetical, population may be different. After suitably long times, white dwarf remnants can attain luminosities even lower than those of the lowest-mass hydrogen-burning stars, and so can be very hard to detect observationally. Could a population of very old white dwarf stars descended from a parent population of normal stars make up the Galactic halo? This is extremely unlikely.

There are several relevant astrophysical constraints. Some constraints derive from the fact that a huge number of parent stars would have been necessary. There is no evidence from surveys for luminous objects at high redshift – quite the reverse – that any such massive star formation phenomenon was universal in the Universe at very high redshifts. And recall that no explanation for the dark matter halo of the Milky Way Galaxy which requires special circumstances is viable: dark matter is universal, so that its explanation must be fundamental to the nature of the Universe at large.

Some constraints derive from the very large production of chemical elements heavier than hydrogen which must have accompanied the lives of the parent stars of the putative white dwarfs: all available evidence is that the earliest generations of stars known - those which must have formed after the putative early population - have extremely low chemical abundances. The oldest stars known in the Milky Way, those which form the stellar halo, cannot have had precursors. Some constraints derive directly from the deep star counts outlined above: one simply does not see any plausible candidate very old white dwarfs (Elson, Gilmore & Santiago 1996).

An interesting new limit, which seems to exclude the white dwarf hypothesis effectively, has been derived by Fuchs & Jahreiss (1997). They calculate the local, Solar neighbourhood, number of high-velocity, low-luminosity, white dwarfs which must exist if the old white-dwarf halo model is viable. Since such stars are in the immediate Solar neighbourhood, they are sufficiently apparently luminous to be visible, irrespective of age. Additionally, since they form an extended halo distribution, they have extreme halo kinematics, hence are readily recognisable from their space motions. Comparing this required number with that observed, Fuchs and Jahreiss can exclude old halo white dwarfs as a viable model for the Galactic halo.
We now consider what positive information concerning the distribution of dark matter can be derived from stellar kinematics in the Galactic satellites.

4 Does Dark Matter Cluster on Short Length Scales?

Dark matter can be detected in principle on any length scale for which a suitable kinematic tracer is available. The shortest relevant length scale is the few parsec size of globular clusters. Globular clusters show no evidence for the existence of dark matter. The next measurable length scale is the thickness of the Galactic disk, of order 300 parsecs. As noted above, the Kuijken/Gilmore analysis provides the unexpected result that dark matter does not cluster on scale lengths of a few hundred parsecs. Rotation curve analyses show however that dark matter is gravitationally dominant on length scales of a few kpc or so in all spiral, and perhaps elliptical, galaxies. What happens in between?

The only intermediate scale length available for study is the 1 kpc scale size of the dwarf spheroidal galaxies, nine of which are companion satellite galaxies of the Milky Way.

4.1 Dark Matter in the Galactic Satellites

The Galaxy’s dwarf spheroidal satellites are very low surface brightness, purely stellar, companion galaxies, each containing some $10^6$ to $10^8$ stellar masses of stars, and with characteristic size of order 1 kpc, $10^{20} \text{m}$. The expected internal kinematic velocity dispersion, assuming a purely stellar system, is therefore $\sim 4-5 \text{km/s}$. It was discovered in the early 1980’s that measured velocity dispersions are significantly higher, of order 10 km/s, indicating dominance by very cold dark matter. A long debate followed concerning the true precision of the kinematic data, and the possible contribution to the apparent velocity dispersion from orbital motions in unresolved stellar binaries. Recently, several independent groups have confirmed the requisite quality of the kinematic data (eg Hargreaves, Gilmore, Irwin & Carter 1994), while extensive Monte Carlo modeling has proven that unresolved binarism is not an important factor (Hargreaves, Gilmore & Annan 1996). The dwarf spheroidals are in fact gravitationally dominated by dark matter throughout their volume, with the dark matter density being several times the stellar mass density even in the galactic core.

In 1994 the closest and the largest dwarf spheroidal, the Sagittarius dwarf, was discovered only 15 kpc from the centre of the Milky Way, by Ibata, Gilmore & Irwin (1994, 1995). This object is deep inside the Galactic halo potential, (it is only twice as far from the Galactic centre as is the Sun) and thereby un-
dergoing strong tidal stresses, and is also, by a substantial factor, the closest
dark-matter dominated system to the Sun. It provides an unrivalled opportu-
nity to test the true spatial distribution of dark matter, by allowing calculation
of its mass distribution independently from stellar kinematics and from tidal
survival arguments.

This analysis has recently been completed by Ibata, Wyse, Gilmore, Irwin
& Suntzeff (1997). These authors conclude that the Sagittarius dwarf galaxy
is indeed dark matter dominated, and that its central dark matter density
is $\sim 0.05 \ M_\odot \text{pc}^{-3} = 1.5 \text{GeV/cc}$. Interesting, and uniquely in this case, a
length scale can also be determined reliably, from the tidal radius of the system
imposed by the Galactic potential. This length scale is $\sim 1 \text{pc} = 10^{20} \text{m}$. The
mass density profile of the dark matter can also be calculated, from tidal
survival analysis. This profile is flat, resembling a Heaviside function. Thus,
one may self-consistently, for the first time, associate a density and a (tidally
truncated) length scale to the dark matter which dominates galaxies. A similar
length scale has been suggested from (very model-dependent) analyses of the
rotation curves of dwarf spiral galaxies. Interestingly, this $10^{20} \text{m}$ length scale
is entirely consistent with the absence of a substantial dark matter component
associated with the much smaller length scale of the Galactic disk, in excellent
agreement with the results summarised above.

5 Conclusion

In summary, the news is good for particle experimenters: all plausible candi-
dates for baryonic contributions to the Galactic dark matter can be excluded,
or at least very severely constrained. The only alternatives to particle dark
matter which have not yet been excluded require astrophysically implausible
scenarios.

The dynamics of the Galaxy and its Satellites provide both a value for
the local dark matter density $\approx 0.3 \text{GeV/cc} = 0.01 M_\odot \text{pc}^{-3}$, and strong
evidence that it has an extended halo-like distribution, with smallest character-
istic length scale $\sim 1 \text{kpc} = 10^{20} \text{m}$ and maximum observed mass density
$\sim 0.05 M_\odot \text{pc}^{-3} = 1.5 \text{GeV/cc}$.

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