MASS NEAR THE SUN

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Abstract.

I review the dynamical measurements of mass in the solar neighborhood and show that, within 1 kpc, $\sim 40\%$ is unaccounted for by known stars and gas. I discuss several interpretations of the data including the 'standard model' where the extra mass is due to a spherical dark halo. I argue that the evidence for a radically different picture of an ultra-flat distribution is at least as compelling as the standard model.

1. Introduction

There are two basic approaches to determining the amount of mass near the Sun. The first is to take an inventory of various types of objects that may be found in the solar neighborhood such as stars, interstellar material (ISM), and dark objects. The stars (with the exception of the very late M dwarfs) are easily counted and these account for the majority of the known material. The ISM is by mass primarily gas and this is also reasonably well known. If the dark objects (which might be brown dwarfs, other baryonic compact objects, WIMPs, or other things) exist at all, they have so far escaped detection.

The second approach is to infer the local mass from its gravitational effects on the distribution of stars. If the two approaches give similar results, then the mass in the solar neighborhood is basically accounted for by the inventoried objects. If not, there is evidence for a so-far unobserved dark population. This is the problem of disk dark matter which has existed in some form for several decades.

If this comparison is carried out in the immediate solar neighborhood, say within 5 pc, then the stars are very well measured and the gas is rea-

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sonably well measured, meaning that the inventory is quite complete, at least for known classes of objects. However, the gravitational effects of this material are so small that they cannot be measured even in principle. To carry out the comparison, it is necessary to move to scales of 100s of pc. In this case, the gas is measured reasonably well, but we must *assume* that the solar-neighborhood stars are representative of the stars from a much larger region. One may show, however, that this assumption is quite reasonable.

2. Deriving the Potential from Tracer Stars

The standard approach pioneered by Oort (1932) is to measure the density and velocity of tracer stars of some specific type in a cone whose axis is perpendicular to the Galactic plane. If the stellar population is old (and hence presumably well-mixed) then the Jeans equation relates the vertical gradient of the pressure to the gravitational field, $d(\nu < v^2 >)/dz = -K\nu$. Here the tracer number density, ν, the tracer velocity dispersion $< v^2 >$, and the disk gravity K are all functions of height above the plane z. By Gauss's Law, $K(z)$ is proportional to $\Sigma(z)$ the total disk column between $-z$ and z: $K(z) = 2\pi G\Sigma(z)$. For the special case where the tracers are isothermal and where measurements are made above most of the matter in the disk, K and $< v^2 >$ are independent of height. The Jean's equation then becomes

$$\frac{d\ln\nu}{dz} = -\frac{1}{h}, \quad h \equiv \frac{< v^2 >}{2\pi\Sigma_0},$$

where Σ_0 is the total disk column.

This equation, taken together with two well known facts yields an immediate estimate of Σ_0. First, the Bahcall-Soneira model (Bahcall 1986), which predicts star counts very well to $V \sim 19$ has a disk exponential scale height of $h \sim 325\,\mathrm{pc}$ for late-type dwarfs. Star counts are basically sensitive to stars that are ~ 3 scale heights above the plane since for $z < 2h$ the star-count cone has very little volume and for $z > 4h$, the stellar density is exponentially suppressed. Hence, the model scale height should reflect the true scale height at $z \sim 3h$, i.e., well above most of the known material in the disk. Second, the velocity dispersion of late-type dwarfs near the plane is measured to be $< v^2 > \sim 20\,\mathrm{km\,s^{-1}}$. One infers,

$$\Sigma_0 = \frac{1}{2\pi G}\frac{< v^2 >}{h} \sim 46\,M_\odot\,\mathrm{pc}^{-2} \quad \text{(naive)},$$

apparently in excellent agreement with the observed material in the disk (Bahcall 1984b),

$$\Sigma_{\rm obs} \sim 48\,M_\odot\,\mathrm{pc}^{-2}.$$

That is, there would appear to be no missing matter.

There are only three problems with the above analysis: the scale height is wrong, the velocity dispersion is wrong, and the observed disk column against which it is to be compared is wrong.

The scale height seems to be on exceptionally secure footing since it is embedded in a well-tested model. However, as Bahcall (1986) has taken pains to emphasize, the only claim made for star-count models is that they correctly predict star counts, not that they express the true structure of the Galaxy. In particular, the Bahcall-Soneira model uses a locally-determined color-magnitude (c-m) relation and applies this to stars at all heights. One expects that the zero point of the c-m relation changes as a function height, because more distant stars are likely to be more metal poor, and low metallicity stars are fainter at the same color. However, since changing the scale height has almost exactly the same effect as changing the zero-point, the model does not have to incorporate zero-point changes to correctly predict star counts. If stars at $\sim 1\,\mathrm{kpc}$ are $\sim 15\%$ fainter than those at the plane, then $h \sim 280\,\mathrm{pc}$.

The local velocity dispersion of late type stars is well measured. However, the relevant quantity is the dispersion at $z \sim 3h$. The local stars are not perfectly isothermal, but rather are a mixture of populations at several different dispersions. The hotter stars tend to rise well above the plane and dominate at 3 scale heights. Without offering any justification, I will simply assert that $< v^2 > \sim 25\,\mathrm{km\,s^{-1}}$ is a better estimate for the dispersion at $z \sim 3h$. Using these values for the scale height and dispersion, I find

$$\Sigma_0 = \frac{1}{2\pi G}\frac{< v^2 >}{h} \sim 82\,M_\odot\,\mathrm{pc}^{-2} \quad \text{(less naive)}.$$

Now there appears to be a great deal of dark matter. And in fact even within the standard model one expects a lot of dark matter: since the measurement is being made at $z \sim 800\,\mathrm{pc}$ above the plane there should be $2z\rho_0 \sim 14\,M_\odot\,\mathrm{pc}^{-2}$ of dark matter if the standard spherical dark halo with a local density $\rho_0 = 0.009\,M_\odot\,\mathrm{pc}^{-3}$ is correct.

The point is that the problem of measuring the local column density is much trickier than it might first appear. In addition to the problems of fixing the distance scale and velocity dispersion already mentioned, there are other systematic effects such as Malmquist bias, rotation of the velocity ellipsoid, unresolved binaries which vary as a function of height, and poor determination of the large-scale structure of the Galaxy, each of which can affect the final result at the level of tens of per cent. The bottom line is that this is a very tough measurement which requires great care.

Nevertheless, the naive estimate of $\Sigma_0 \sim 82\,M_\odot\,\mathrm{pc}^{-2}$ below 800 pc poses a few important questions. First, is the estimate roughly correct? Second, if it is roughly correct, where are the other $\sim 35\,M_\odot\,\mathrm{pc}^{-2}$ beyond what is measured for $\Sigma_{\rm obs}$? As noted above, the standard model can account for only $\sim 15\,M_\odot\,{\rm pc}^{-2}$ of dark material.

3. Historical and Modern Determinations

Historically, the problem was first attacked by Oort (1932). It was Oort (1960) who first pointed to a factor ~ 2 discrepancy between the observed material and the gravitationally inferred mass. Bahcall (1984a) revived the investigation by developing a new method of self-consistent models and applying this method to archival data (Bahcall 1984b,c). One of Bahcall's two conclusions, that the factor ~ 2 problem remained, has been widely disseminated. However, his other principal conclusion that systematic errors were dominant over statistical errors has unfortunately received less attention. Bahcall's work stimulated several groups to acquire new samples and undertake new analyses.

Bienaymé, Robin, & Crézé (BRC 1987) inferred a local column density of $\Sigma_0 = 64 \pm 12\,M_\odot\,{\rm pc}^{-2}$ (excluding a dark halo) using a method of generalized star counts. They regarded this result as consistent with no missing matter, but if missing matter were allowed, their best fit to its scale height was $h \sim 600\,{\rm pc}$.

Kuijken & Gilmore (KG 1989, 1991) obtained a new sample of K dwarfs sensitive to mass in the range $300\,{\rm pc} < z < 2000\,{\rm pc}$ and concluded $\Sigma_0 = 46 \pm 9\,M_\odot\,{\rm pc}^{-2}$ plus $\sim 25\,M_\odot\,{\rm pc}^{-2}$ in dark halo below $z < 1.1\,{\rm kpc}$.

Kuijken (1991) added a local sample of K dwarfs to the KG cone sample making the combined sample sensitive to the range $0 < z < 300\,{\rm pc}$. He finds that the local density $\rho(0)$ is related to the no-missing-matter value by $\rho(0) = (1.02 \pm 0.15)\rho_{\rm NMM}(0)$.

Bahcall, Flynn, & Gould (BFG 1992) analyzed a cone of K giants (the first tracer sample specifically chosen to test the local mass density) and found $\Sigma_0 = 85 \pm 25\,M_\odot\,{\rm pc}^{-2}$ not including the contribution from the halo. Their study is sensitive in the range $200\,{\rm pc} < z < 500\,{\rm pc}$.

Finally, Flynn & Fuchs (1994) expanded the BFG sample in a parallel way to that used by Kuijken to expand the KG sample: they added a local sample of K giants. Like Kuijken's, their study was sensitive to $0 < z < 300\,{\rm pc}$ and they found $\Sigma_0 = 52 \pm 8\,M_\odot\,{\rm pc}^{-2}$ or $\Sigma_0 = 56 \pm 12\,M_\odot\,{\rm pc}^{-2}$ depending on assumptions and not including the dark halo.

All of these studies are subject to some criticism. The general star count method of BRC is subject to the same systematic errors that were illustrated in the simple example given above. As I will argue below, KG's results actually indicate a large amount of disk dark matter, $\Sigma_0 \sim 65\,M_\odot\,{\rm pc}^{-2}$ despite their claim to have found no disk dark matter. Kuijken's (1991) study depends on comparison of inhomogeneous data sets. This is also a problem for the Flynn & Fuchs (1994) study although probably less so because DDO photometry allows them to select a more uniform sample. However, both Flynn & Fuchs (1994) and BFG are insensitive to mildly hot dark matter. Finally, while the BFG study is probably the most free from systematic errors, it suffers from poor statistics.

Let me now turn to a reanalysis of the KG study. The main message which has reached the community about KG is that they measured one number, the total column density of the disk, and found it to be consistent with the no-missing-mass value. In fact, KG measured two numbers, K and F, the linear and quadratic terms in the potential high above the plane,

$$\psi(z) = \text{const.} + Kz + Fz^2.$$

The measurement they made from their data alone showed,

$$F \sim 0, \qquad \frac{K}{K_{\rm obs}} = \frac{\Sigma}{\Sigma_{\rm obs}} = 1.4.$$

Roughly speaking, the linear term corresponds to the total column of the disk and the quadratic term corresponds to the local halo density. Hence, what KG actually found was that there is no halo dark matter and a large amount of disk dark matter (or alternatively an extremely flattened halo). Why then did they report the opposite: a standard dark halo, but no disk dark matter? KG assumed a standard *spherical* dark halo and then asked, given this assumption, what was the best-fit value for the disk. However, this best fit value is in conflict with their data at the 2.5 σ level. See Figures in Gould (1990).

My tentative impressions of all the results to date are

1) This is a tough problem: it is still possible that we do not understand the systematics.

2) KG tell us there is $\sim 25\,M_\odot\,\text{pc}^{-2}$ of dark matter within 1 kpc which is consistent with our expectation of a round halo.

3) But KG also tell us that the dark matter is flatter than 1 kpc which is inconsistent with a round halo.

4) Kuijken (1991) and Flynn & Fuchs (1994) tell us the dark matter is not extremely close to the plane.

5) BFG provide systematically clean but statistically weak evidence for a substantial amount of dark matter.

A working hypothesis that is consistent with all the known data is that there is $\sim 25\,M_\odot\,\text{pc}^{-2}$ of dark matter in a relatively flat distribution, $h \sim$ 400–700 pc. This could be either a massive thickish disk or a very flat (E10!) halo.

4. Other Evidence

I turn now to other evidence which might help constrain this picture: from star counts, from measurements of the shape of other galaxy halos, and from Macho (Massive Compact Object) detections.

Bahcall, Flynn, Gould, & Kirhakos (1994) examined a pair of deep ($\geq$ 2 hr) *Hubble Space Telescope* images of a high latitude field to a limiting magnitude of $I = 25.2$. They found no red stars $V - I > 3$. From this lack of detections, they concluded that faint red stars above the hydrogen burning limit do not contribute significantly to the mass of disk, thick disk, spheroid, or halo. If there is a substantial amount of dark matter in a flattened distribution, it must be in something other than stars.

Polar ring galaxies potentially provide information about the flatness of the mass distribution of other galaxies because the polar ring probes the potential perpendicular to the disk of the galaxy. Penny Sackett and her collaborators have spent several years acquiring new precision data on polar ring galaxies and subjecting these data to a more refined analysis than had been done previously. There are now very good constraints on two such galaxies. For NGC 4650A, Sackett et al. (1994) find an axis ratio 10:4 to 10:3, corresponding to E6–E7. For A0136-0801, Rick Pogge has obtained a spectacular Fabry-Perot velocity cube with 2700 independent data points. Preliminary analysis of these data by Sackett & Pogge (1994, in preparation) indicates the galaxy halo is E4–E5. The remarkable thing about both these flatness ratios is that, to within the errors, they are identical to the flatness ratios of the luminous disks of the respective galaxies. It is often remarked that polar ring galaxies are very special in that they have polar rings, so they might also be special in terms of the flatness of their halos. In fact, galaxies with high flatness ratios will have difficulty sustaining a polar ring unless the ring's axis occupies a very small region of parameter space. Hence, this argument would lead one to the opposite conclusion from the intended one: polar ring galaxies should actually be rounder than average. Another point which I think has more force is that the shapes of only two halos have been measured and we might therefore be the victims of unlucky statistics. However, it remains the case that the only two halos that have been measured have been found to be flat. If the Milky Way also had a dark halo distributed like its light, this halo would have an axis ratio ~E10.

Finally, the detection rates of microlensing events toward the Galactic center and the Large Magellanic Cloud (LMC) also are consistent with a highly flattened mass distribution. The detection rate toward the LMC (Alcock et al. 1993; Aubourg et al. 1993) is too high to be due to known stars in the Galactic disk, thick disk, or spheroid (Bahcall et al. 1994) or stars in the LMC itself (Gould 1995), and too low to be due to Machos in a standard spherical halo. It could, however, be due to Machos in a disk (Gould, Miralda-Escudé, & Bahcall 1994) or a thick disk (Gould 1994). The event rate measured toward the Galactic bulge by Alcock et al. (1994) and Udalski et al. (1994) is much higher than was anticipated due to a standard disk (Paczyński 1991; Griest et al. 1991) or to the Galactic bulge, even if the latter is barred (Kiraga & Paczyński 1994; Han & Gould 1994a; Zhao, Spergel, & Rich 1994). While it is still possible that the high event rate is due to statistical fluctuations (which are larger than one might naively expect – Han & Gould 1994b), recent unpublished reports (D. Bennett 1994, private communication) indicate an optical depth near the plane that is so high ($\tau \sim 7 \times 10^{-6}$) that it can scarcely be explained other than by a massive disk-like structure.

5. Conclusions

In conclusion then, there is certainly some dark matter within 1 kpc of the plane of the Milky Way. The absolute amount could be consistent with that expected from a standard spherical halo, but the internal evidence would seem to indicate that it is more flattened. In addition, we must keep in mind that the systematic errors could be large. Whatever this dark matter is, it is not hydrogen-burning stars.

The halos of the only two other galaxies that have ever been measured are both significantly flattened. There is no reason to assume that ours is any different.

The high rate and distribution of Macho detections seems to indicate an enormous amount of dark matter near the plane.

My best guess: $30 M_\odot\,\mathrm{pc}^{-2}$ of dark material near the Sun with scale height $h \sim 500\,\mathrm{pc}$.

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DISCUSSION

J. Anderson: What would your favorite tracer population be, in terms of observable parameters like age and metal abundance? In other words, what should we (the observers) work on?

Gould: For mass, photometric surveys, I would favor K dwarfs. However, the precision photometry of F stars that you are doing will also allow isolation of an old population and will provide a very useful sample of tracer stars.

J. Binney: As Kuijken has told us, the dominant uncertainty in his study comes from the rotation of the velocity ellipsoid. I think this is an indication of a general trend: we have reached the limit of what we can learn by local analysis - another example is the problem with the observed value of $x=\sigma_\phi^2/\sigma_R^2$. It is now possible to model the Galaxy as a whole, three-dimensional object and doing so should largely eliminate many unnecessary uncertainties that plague local analyses. Of course, there will still be plenty of uncertainties left when unnecessary theoretical ones have been eliminated!

Gould: While I don't disagree with the goal of global analysis, I do think that more can be accomplished with local analyses. In particular, metallicity measurements of K dwarf would allow isolation of the disk and thick disk populations which would produce much better constraints on the potential.

K. Kuijken: I would like to emphasize that the uncertainty in the K+G analysis is largely affected by uncertainty in the velocity ellipsoid tilt at larger z. While measurement of K is affected at the 10-20 % level, F is <u>much</u> more uncertain, and it is very risky to take the modeled value of F too seriously.

Question: Can you be more quantitative about which bulge axis ratio is required to explain the microlensing of opt. depth?

Gould: A 3:1 axis ratio (such as measured by Dwek et al. from the COBE data) is still not adequate to explain the high observed optical depth toward the bulge.

M. Ruiz: I would like to mention one other source of dark matter, that is "cool white dwarfs", they have M/L $\sim 10^{-4}$ to 10^{-5}. In a deep proper motion survey of only three 5^0 by 5^0 areas of the sky I found 8 cool white dwarfs, contributing with $\sim 0.02\ \mathrm{M}_\odot/\mathrm{pc}^3$ to the density of matter in the Solar neighborhood. An extension of this survey is needed to confirm this preliminary result.

Gould: This is a very exciting result.

K. Stanek: I just want to mention that your and OGLE interpretations of OGLE results differ in that we think there is a hole in the stellar disk and also majority of lensing objects is in the bar. What we find is that if the lenses are in the disk, their average mass is $M \approx 0.6 M\odot$ - it would be difficult to hide many such stars, if lenses were in the disk.

H. van Woerden: My impression is that our galaxy offers a better chance to determine the vertical distribution of disk matter than other galaxies - but I would trade my impression for a better-educated opinion.

Gould: In principal I agree. So far, however, I don't think that the potential has been achieved.

R. Wyse: A comment on white dwarfs as candidates for dark matter in the Galaxy in significant amounts. Although white dwarfs are preferred over neutron stars by chemical evolution arguments, there are still severe problems with the elements such as Helium produced during quiescent stellar evolution of the progenitor stars. Further, should the white dwarfs be in binary systems, as may be expected on both observational and theoretical grounds, then Type Ia supernovae will most probably result, continuing on very long timescales. These of course produce further problems with chemical enrichment and should be observable in the outer halves of galaxies (ref Smecker & Wyse ApJ 1990). Thus the reason that White dwarfs are not discussed much is there are real problems, requiring continued models.