Maximum Galactic Disks vs. Hot Dark Halos

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Abstract. A series of arguments is presented for heavy galaxy disks not only in the optical regions, but also in the dark matter dominated regions of spirals. We are testing this possibility with extreme maximum disk $N$-body models without any conventional spheroidal dark halo.

1. The Dark Matter in Galaxies and the Shape of Dark Halos

The almost polar orbits of the Magellanic and Sagittarius streams, and the existence of polar ring galaxies, suggest that the potential quadrupolar term of the Milky Way and other spirals must be significant. But the determination of the corresponding density flattening remains delicate, e.g., from a hot component tracing the equipotentials such as X-ray gas, since potentials are usually much rounder than the mass distribution (the potential of a thin disk with flat rotation curve has still an axis ratio of about 0.7).

However other arguments suggest that the dark halo of spirals may depart substantially from the ellipsoidal shape family almost exclusively contemplated up to now. Namely, as we argue below, a strong rotational support in the dark matter component offers a solution for reconciling a series of problems raised recently in the literature.

1.1. Bright Spirals

In the optical regions of bright spirals, several observational and numerical works lead to an almost vanishing need of dark matter there.

The maximum disk hypothesis (e.g., van Albada et al. 1985) is insufficient to prove that the optical disks are self-gravitating, since the stellar $M/L$ ratio is insufficiently well constrained. But this hypothesis is consistent with observations. On the other hand, the wiggles in both the rotation curves and the luminous mass put some constraints on the temperature of the supposed dark halo since a massive hot component should damp the fluctuations seen in the kinematically cold component. However, in practice the projection effect and non-circular shapes and velocities complicate the test.

Independently of this argument, several authors (e.g., Fux 1997; Gyuk 1999) have noted that the numerous Milky Way bulge micro-lensing events can hardly be explained without an essentially maximum inner disk of star like objects. Other studies of Milky Way models compatible with a large body of observations also tend to favor a maximal disk (e.g., Sackett 1997). It is interesting to note that Dehnen & Binney (1998) find that parametric mass models tend
to produce hollow halos, which they reject since they assume implicitly hot, pressure supported halos.

The recent discovery of brown dwarfs in Orion (Zapatero Osorio et al. 1999; Lucas & Roche 2000) increases the likely mass estimate of detected baryons in stars by perhaps 10–30%, so is insufficient to explain the dark matter in spirals. However, since brown dwarfs form presumably in proportion to stars, the newly detected dark matter component occurs precisely in the optical regions where little space is left for another dark matter component. Thus, the discovery of a sizable fraction of “brown stellar matter” with a steeper profile ($\Sigma_\star \propto e^{-R/h}$) than dark matter ($\Sigma_{DM} \propto R^{-1}$) increases the difficulty to fit a dark halo with a density maximum in the region where it is in least demand.

Using constraints from dynamics, Debattista & Sellwood (1998) or Quillen & Frogel (1997) find that bars are better compatible with heavy optical disks and a small dark matter content. A too massive halo in the bar region brakes and destroys bars in a short time, while the detailed features associated with the bar resonances would be different with a fat dark halo that observed.

According to Dubinski et al. (1999), the length and shapes of tidal tails produced in N-body models of galaxy interactions suggest that the real tidal tails of interacting galaxies are mostly produced by galaxies with disk-dominated rotation curves and low concentration halos. This argument might perhaps be stronger with a wider exploration of the possible galaxy shapes, in particular with extreme dark matter disks as introduced here.

1.2. Faint Galaxies

In faint spiral galaxies the dark matter fraction is much higher than in bright galaxies, but in contrast the ratio of HI/dark matter varies little (Bosma 1981; Carignan & Purton 1998). Thus strangely enough dark matter behaves differently that the stellar baryons but knows very well about the gaseous ones. Since gas eventually becomes stars, and gas poor (or star rich) galaxies have little dark matter too, it is natural to suggest that at least a substantial fraction of it is a hard to detect phase of molecular hydrogen and helium (e.g., cold H$_2$ in gaseous, liquid, or solid forms), as we and others have discussed a few years ago.

Since dominated by dark matter, faint spirals are suited to probe the predictions resulting from CDM cosmological N-body simulations. But the predicted steep central cusp of CDM halos appears incompatible with the observed rotation curves (e.g., Moore et al. 1999).

Otherwise, the general presence of warps, spirals and asymmetries in the outer gaseous disks of spirals is a strong indication that the dark matter component there is not stabilizing much the disks. In particular the existence of a bar and large scale spiral arms in the dark matter dominated gaseous disk of NGC 2915 (Bureau et al. 1999) indicate to us a rather self-gravitating disk.

1.3. Gas Infall

The old hypothesis of secular gas infall in spirals has been recently revived in the context of the also old observational problem raised by the high-velocity clouds (HVCs) (Blitz et al. 1999). These clouds have also a high dark matter content in proportion to HI resembling the one found in faint galaxies. So if these clouds accrete onto the Milky Way at a rate sufficient to produce the observed HI, then
the Milky Way dark matter could come simultaneously from these clouds (a few \( M_\odot/\text{yr} \) of HI translates into a few tens \( M_\odot/\text{yr} \) of dark matter which becomes comparable to the galaxy total mass after 10 Gyr).

The important point to note about such a scenario is that the angular momentum content of HI and dark matter should be also the same. If dark matter has a high angular momentum content then there is no ground to suppose that the shape of the halos should be ellipsoidal. On the contrary, all the known highly rotating gravitating structures (e.g., protostellar disks, or rotating polytropes) adopt shapes like flaring disks or thick tori.

1.4. Dark Halo Shapes

If we remember the original motivations for introducing first spherical, and later spheroidal dark halos, we see that over the years most of them have disappeared. The original motivation was to prevent galaxies to make bars as easily as \( N \)-body simulations of disks did (e.g., Ostriker et al. 1974). The association of the dark halo with the then thought round and virialized stellar halo was natural. But today bars are understood to be the rule in spirals, including the Milky Way, while stellar halos appear rather non-virialized and made of the leftover streams from dissolved dwarf spheroidals and globular clusters.

The argument using Oort’s constraint on the local mass density in the Milky Way disk leads to require about twice as much density in a fatter halo in view of the disk rotation velocity. But this constraint depends largely on the assumption that the local density at the Sun is representative of the azimuthally averaged density at the Sun radius. In the past, most of the Milky Way models have been built on the assumption of strict axisymmetry, but today the Milky Way is known to be barred, and the arm–inter-arm density contrast in other spirals, as observed in the infrared, may be 2 or more! Thus Oort’s constraint appears weaker today than before as long as the Sun position with respect to the Milky Way major spiral arms and their effective amplitude are not better known.

In contrast to hot spheroidal halos, rotation supported dark halos offer better perspectives to satisfy these constraints: 1) the inner maximal optical disks, 2) the Bosma HI-DM relationship, 3) large angular momentum accretion from the HVC’s, and 4) flat rotation curves. Furthermore, unlike in ellipsoidal halos, in disk-like halos the gravitational force from the outside on the inside is strong, so disk-like halos are well “connected” by the mutual forces of each parts, the “halo-disk conspiracy” is non-existent. For a large class of non-ellipsoidal halo potentials producing flat rotation curves, see de Zeeuw & Pfenniger (1988).

2. \( N \)-body Models of Maximum Galactic Disks

With the above motivations in mind, we have undertaken to test the possibility of massive disks with \( N \)-body simulations. Since the rotation curves constrain little the 3D halo shapes except their average mass density profile, it appears obvious that, say, half rotation supported halos might easily satisfy the present constraints. Instead, it is more challenging to push the rotation support to the extreme limit, which is: 1) the scale-height of the dark component is comparable to the one observed in the baryons (HI or stars), 2) the \textit{time average} pressure support corresponds to a marginally stable Safronov-Toomre parameter \( Q \approx 1 \).
Figure 1. A massive disk collisionless model inclined by 60° from edge-on 2 Gyr after starting as a $Q \approx 1$ axisymmetric disk:
Left: The total density contours at 0.75 mag interval.
Right: The radial velocity contours at 10 km/s interval.

The other challenge is that realistic massive disks require a rather high numerical resolution. If one wants to resolve central features below 100 pc in disks extending to at least 30 kpc, which must be able to exchange angular momentum up to at least 100 kpc, one must have a time or a scale range of about $10^4$. Models with such a resolution (with $N = 2^{22} \approx 4.2 \times 10^6$) are run on the GRAVITOR Beowulf cluster at Geneva Observatory, with both particle-mesh code and a parallelized version of the Barnes-Hut treecode.

The initial conditions consist of a bulge, an optical exponential disk and a heavy flaring disk proportional to the HI as in the Milky Way, producing an almost flat rotation curve. Different initial velocity dispersions of the components are explored, since the component temperatures are crucial for the overall stability. Also different “equations of state” for treating the dissipation properties in the cold gas are considered, in particular the degree of collisionality is taken as a free parameter, from collisionless to viscous.

Fig. 1 shows the morphology of the total mass distribution and the corresponding velocity field of such a disk after 2 Gyr evolution. No energy dissipation is introduced in this example. A persistent double bar can be seen near the center and prominent spiral arms in the outer, dark matter dominated parts.

Overall, although rather flat, the models do not lead to clear contradictions with observations. Flaring maximum disks are not more unstable than disks embedded in spheroidal halos, on the contrary, dynamical friction between the visible and dark components vanishes. The bars (single or double) are long lived, as well as the transient but regenerated spiral arms, with characteristics times larger that a few Gyr. At 30 kpc radius the rotation period is of the order of 1 Gyr, therefore 10 Gyr time is short to obtain well virialized disks there. Actually, the outer disk radial asymmetries are morphologically similar to the ones frequently observed in the outer HI disks.
3. **Conclusions**

In the context of the current constraints about dark matter in spirals, rotation supported dark halos are attractive because they do allow simultaneously maximum baryonic inner disks and outer rotation supported dark matter associated with HI. The massive disk N-body models run up to now, although rather extreme, do not show obvious contradictions with observations.

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**Question:**

**John Hibbard:** Do you think that your massive disks can explain well-separated mergers (nuclei separated by > 5 kpc) with very long (> 100 kpc) tails (e.g., NGC 4038/9, Arp 299)? If the tails contain an order of magnitude more mass, they will carry away an order of magnitude more angular momentum.

**Daniel Pfenniger:** Yes, massive rotating disks offer favorable perspectives. In fact, in the conventional picture of a baryonic disk inside a hot dark halo, interacting galaxies should separate the low and high angular momentum matter, and tails should be mostly baryonic. But if dark and visible matter rotate the same, only the specific angular momentum matters, and the exact mass contained in the tails does not. The tail mass density may be critical for the formation or not of tidal dwarfs, and the dark matter content of the tidal dwarfs provides a test about their initial composition. Yet, if dark matter is cold gas, one can expect a generous star formation in the tidal dwarfs and a subsequent increase of the visible to dark matter ratio, complicating the test.