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EVALUATING THE DISK FORMATION PARADIGM IN THE LCDM FRAMEWORK: CONSTRAINTS FROM THE MILKY WAY

Rachel S. Somerville

Department of Astronomy, University of Michigan

RESUMEN

Investigamos las propiedades de una galaxia similar a la Vía Láctea en el contexto de la teoría estándar para la formación del disco, en un Universo ΛCDM. Empleando la hipótesis usual de que los bariones conservan el momento angular específico cuando colapsan, concluimos que las propiedades *medias* del modelo de galaxias concuerdan bien con las de la Vía Láctea y otras galaxias espirales similares, pero que la dispersión predicha para la longitud de escala de los discos puede ser demasiado grande. Un modelo en el que la mitad del momento angular específico inicial se transfiere a la materia oscura puede dar dispersiones menores, siempre y cuando los discos muy compactos sean inestables y evolucionen hacia esferoides o galaxias tempranas.

ABSTRACT

We investigate the properties of a galaxy similar to the Milky Way within the context of standard disk formation theory in a ΛCDM universe. Using the standard assumption that baryons conserve specific angular momentum when they collapse, we conclude that the *mean* properties of the model galaxies are in good agreement with the Milky Way and other similar spiral galaxies, but the predicted scatter in disk scale lengths may be too large. A model in which half of the initial specific angular momentum is transferred to the dark matter may produce a smaller scatter, if very compact disks are unstable and evolve into spheroids or early type galaxies.

Key Words: **GALAXIES: FORMATION — GALAXY: FUNDAMENTAL PARAMETERS**

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1. INTRODUCTION

Cold Dark Matter (CDM) seems to provide a very successful paradigm for explaining many different kinds of observations on large scales, but suffers from several problems on small scales. Perhaps the most worrisome of these is the "cusp" problem: it seems that the radial profiles of dark matter halos produced in cosmological simulations based on CDM are inconsistent with the observed rotation curves of at least some dwarf and low surface brightness galaxies (e.g. van den Bosch & Swaters 2001 and references therein). It is important to establish whether or not this problem is peculiar to this particular class of galaxies. It is more difficult to assess whether the rotation curves of luminous, high surface brightness galaxies are consistent with CDM dark matter halos, because in these galaxies, baryons contribute significantly to the gravitational force in the central part of the galaxy, where rotation curves are observed. It is therefore expected that the inner dark matter profile is significantly modified by the collapse of the baryons. It is possible to calculate the effect of this baryon-induced "contraction" on the dark matter halo using a well-established analytic formalism. However, the large degeneracies due to the many unknown parameters make it difficult to obtain strong constraints from the observed rotation curves of most luminous galaxies.

The Milky Way galaxy offers a special opportunity to investigate this question. We know about the dynamical properties of our Galaxy in much greater detail and over a larger range of scales than any other galaxy. For example, the mass profile of our Galaxy as a function of radius is constrained by velocity measurements from scales of a few pc (from stellar velocities) to 100 kpc (from satellite galaxies). Also, observations of microlensing events towards the Galactic bulge place strong lower limits on the mass of *baryonic* material within about 3 kpc. In Klypin, Zhao & Somerville (2002; KZS02; see also the contribution by A. Klypin in this volume), we showed that these combined data place very strong constraints on the parameters of the Milky Way Galaxy and its dark matter halo. KZS02 concluded that, within the framework of the popular ΛCDM cosmological model: (1) the Milky Way must occupy a halo with a total mass in the range 1–2 $\times 10^{12}$ $M_\odot$; (2) half of the baryons within the virial radius of this halo must have been ejected; (3) standard disk formation models, in which the gas conserves its specific angular momentum during collapse, have difficulty obeying the combined microlensing and dynamical constraints. However, if angular momentum is *transferred* from the baryons to the dark matter, the dark matter gains angular momentum and so moves outward. The inner dark matter "cusp" is flattened out,

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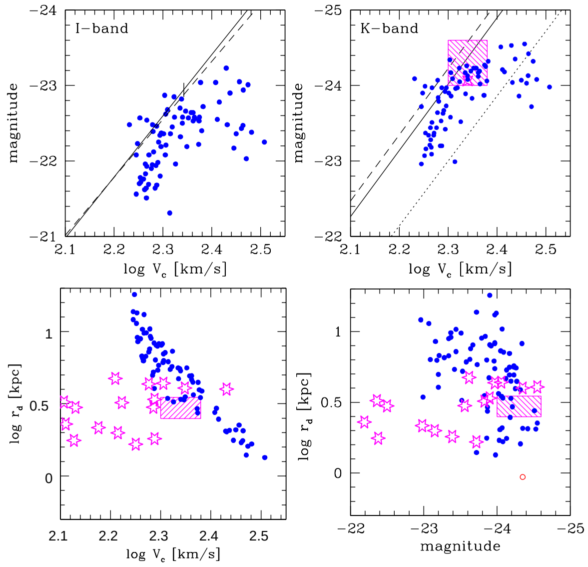

Fig. 1. Fundamental plane relations predicted by semi-analytic models, for an ensemble of "Milky Way" mass galaxies (total mass of baryons plus dark matter $10^{12}\mathrm{M}_\odot$), assuming that the specific angular momentum of the baryons is conserved. Large star symbols show the observed relations for the Ursa Major sample of normal spirals from Verheijen (2001). Shaded areas indicate the acceptable range of values for the Milky Way. Dots show the model galaxies, with filled symbols indicating galaxies that should be globally stable, and open symbols showing galaxies that may be unstable to bar/bulge formation.

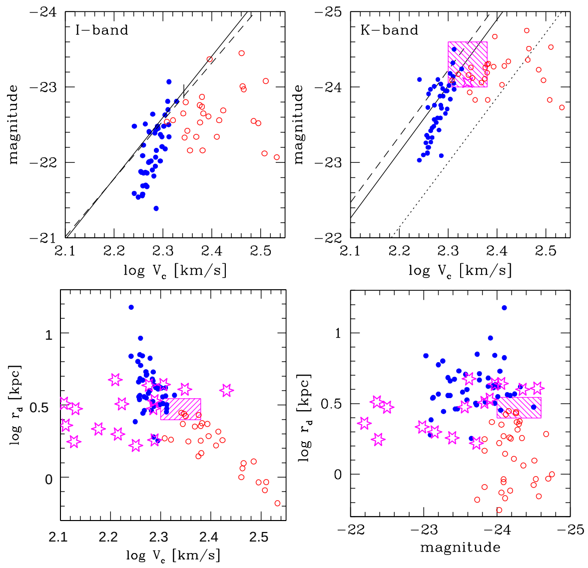

Fig. 2. The same as Fig. 1, except that angular momentum transfer is included using the formalism developed by KZS02. Note that while the agreement with the observational locus is better, a large number of unstable disks are predicted (shown by open symbols).

leaving more room for baryons in the inner part of the Galaxy. KZS02 concluded that a model in which about half of the initial specific angular momentum was lost by the baryons could accommodate all of the data.

This brings up several further questions. How typical is our Galaxy? Does it lie near the mean of the distribution of objects predicted by the theory, or is it an outlier? Is it reasonable that such a large fraction of the baryons could be ejected from a relatively massive halo? Are the photometric properties of a "Milky Way" produced in this framework consistent with observations? Is the distribution of stellar ages and metallicities in such a model consistent with observations in the Galaxy? These questions will be addressed in a companion paper to KZS02 (Somerville, Klypin & Zhao, in prep). Here, we will briefly address a few of these questions.

2. PROPERTIES OF MODEL "MILKY WAYS"

Our chosen tool for this investigation is a semi-analytic model of galaxy formation. These models treat the hierarchical history of galaxy formation using a "merger tree", and include recipes for gas cooling, star formation, and supernova feedback. We use an updated version of the models presented in Somerville & Primack (1999) and Somerville, Primack & Faber (2001); see those references for details. New aspects of the model used here include (1) realistic dark matter halo profiles, (2) more detailed modelling of disk formation, including the contraction of the halo, based on the "adiabatic invariant" formalism (Blumenthal et al. 1986; Flores et al. 1993; Mo, Mao & White 1998). Dark matter halos are assumed to follow the universal Navarro-Frenk-White (NFW) profile (Navarro, Frenk & White 1997) and are characterized by the NFW "concentration" parameter c_{NFW}. The angular momentum of a dark matter halo is characterized by the dimensionless spin parameter λ, and spin parameters are chosen randomly from a log-normal distribution (Bullock et al. 2001a). The adiabatic invariant formalism then allows us to calculate, at a given redshift, the exponential disk scale length r_d and the maximum rotation velocity $V_{\max}$ as a function of the halo parameters c_{NFW} and λ, and the fraction of baryons that ends up in the disk+bulge of the galaxy, $f_{\rm gal} = (m_{\rm disk} + m_{\rm bulge})/(f_b M_{\rm vir})$, where $m_{\rm disk}$ and $m_{\rm bulge}$ are the mass of the disk and bulge, f_b is the universal baryon fraction, and $M_{\rm vir}$ is the virial mass of the halo. In the semi-analytic models, $f_{\rm gal}$ is determined by the efficiency of cooling, star formation, and gas ejection by feedback, and varies from halo to halo depending on its formation history.

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We simulate a large ensemble of halos with a mass of 10^{12} $M_{\odot}$, as in the fiducial Milky Way model of KZS02. The assumed cosmology is a "standard" ΛCDM model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 1$, and $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The three main free parameters in our model are the efficiency of star formation and supernova feedback, and the effective yield of heavy elements. These parameters are adjusted by requiring the average mass of the disk+bulge of the "Milky Way" to be close to 5×10^{10} $M_{\odot}$, as favored by the dynamical arguments, the gas fraction to be close to ten percent, and the mean stellar metallicity to be close to solar, as observed. These conditions are achieved easily, with physically reasonable values of the parameters.

The "Fundamental Plane" scaling relations obtained for this ensemble of Milky Way mass galaxies are shown in Fig. 1, for the standard assumption of conservation of specific angular momentum. Here, we have assumed a one-to-one relationship between halo mass and c_{NFW} (using the model of Bullock et al. 2001b), so the scatter comes from the range of values of $f_{\rm gal}$, the distribution of spin parameter λ, and the spread in mass-to-light ratio caused by the variation in star formation and enrichment history. Note that although much of the scatter at fixed halo mass moves galaxies *parallel* to the Tully-Fisher relation, there are outliers at high circular velocity. The mean properties of the "Milky Way" galaxies in the ensemble are in good agreement with the observational constraints. However, in comparison with a larger sample of spiral galaxies, it seems the predicted scatter in size at fixed $V_{\rm max}$ or magnitude may be too large.

Predictions including angular momentum transfer of a factor of ~ 2, as proposed by KZS02, and worked out using the formalism presented there, are shown in Fig. 2. We see that including this effect produces galaxies with smaller scale radii but with nearly the same maximum rotation velocity. Many extremely compact galaxies are now produced. However, these objects are very unlikely to be stable. We have indicated with open symbols the objects that are expected to be unstable to formation of a bar and/or bulge, according to the condition $\varepsilon_m \equiv [V_{\rm max}/(GM_d/r_d)]^{1/2} < 0.75$ (see Mo et al. 1998). If these objects are removed, the mean of the distribution is still in good agreement with the observations, while the width of the distribution is narrower, in better agreement with the global observed distributions. It remains highly uncertain, however, how accurate this simple stability condition really is, what the appropriate threshold value should be, and what happens to unstable objects.

3. WHAT ABOUT THE SCATTER IN CONCENTRATION AT FIXED MASS?

It is well-known that there is actually a significant scatter in the halo concentration at fixed mass in cosmological simulations (e.g. Bullock et al. 2001b). Most investigations of disk properties have ignored this, as we have done above. Recently, it has been demonstrated that this scatter comes from variation in the *formation history* of the halos, with early-forming halos having high values of c_{NFW} and late-forming halos having smaller values (Wechsler et al. 2002). When we include this correlation in our semi-analytic merger trees using the scaling found by Wechsler et al. (2002), we find noticeable correlations between the halo concentration and many observable properties of the galaxies, such as color, gas fraction, and stellar age and metallicity (see the contribution by Wechsler in this volume). Similarly, the expected connection between halo mass accretion history and rotation curve shape was already pointed out some time ago by Firmani & Avila-Reese (2000). These results suggest that the properties of galactic disks are not determined only by their spin parameters, as has often been emphasized, but that halo concentration is also an important factor.

REFERENCES

Blumenthal, G., Faber, S., Flores, R., & Primack, J. 1986, ApJ, 301, 27
Bullock, J. S., et al. 2001a, ApJ, 555, 240
Bullock, J. S., et al. 2001b, MNRAS, 321, 559
Firmani, C. & Avila-Reese, V., 2000, MNRAS, 315, 457
Flores, R., Primack, J., Blumenthal, G., & Faber, S. 1993, ApJ, 412, 443
Klypin, A., Zhao, H., & Somerville, R. S. 2002, ApJ, 573, 597
Mo, H., Mao, S., & White, S. 1998, MNRAS, 295, 319
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Somerville, R. & Primack, J. 1999, MNRAS, 310, 1087
Somerville, R. S., Primack, J. R., & Faber, S. M. 2001, MNRAS, 320, 504
van den Bosch, F. C. & Swaters, R. A. 2001, MNRAS, 325, 1017
Verheijen, M. A. W. 2001, ApJ, 563, 694
Wechsler, R. H., Bullock, J. S., Primack, J. R., Kravtsov, A. V., & Dekel, A. 2002, ApJ, 568, 52

Astronomy Department, University of Michigan, Ann Arbor, MI 48109 (rachel@astro.lsa.umich.edu)