The Astrophysical Journal, 675: L65–L68, 2008 March 10

BEYOND INSIDE-OUT GROWTH: FORMATION AND EVOLUTION OF DISK OUTSKIRTS

Rok Roškar,[1] Victor P. Debattista,[1,2,3] Gregory S. Stinson,[1,4] Thomas R. Quinn,[1]
Tobias Kaufmann,[5] and James Wadsley[4]
Received 2007 October 29; accepted 2008 January 30; published 2008 February 8

ABSTRACT

We have performed a high mass and force resolution simulation of an idealized galaxy forming from dissipational collapse of gas embedded in a spherical dark matter halo. The simulation includes star formation and effects of stellar feedback. In our simulation a stellar disk forms with a surface density profile consisting of an inner exponential breaking to a steeper outer exponential. The break forms early on and persists throughout the evolution, moving outward as more gas is able to cool and add mass to the disk. The parameters of the break are in excellent agreement with observations. The break corresponds to a rapid drop in the star formation rate associated with a drop in the cooled gas surface density, but the outer exponential is populated by stars that were scattered outward on nearly circular orbits from the inner disk by spiral arms. The resulting profile and its associated break are therefore a consequence of the interplay between a radial star formation cutoff and redistribution of stellar mass by secular processes. A consequence of such evolution is a sharp change in the radial mean stellar age profile at the break radius.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: photometry — galaxies: spiral — galaxies: structure — stellar dynamics

1. INTRODUCTION

Since the early work of de Vaucouleurs (1958) it has been recognized that the disks of spiral galaxies generally follow an exponential radial surface brightness profile, and various theories have explored the physical causes and consequences of this property (e.g., Fall & Efstathiou 1980; Lin & Pringle 1987; Dalcanton et al. 1997; Mo et al. 1998; van den Bosch 2001). However, since van der Kruit (1979, 1987) it has been known that the outer regions of disks exhibit more varied behavior. This has been confirmed by an abundance of recent data (e.g., Pohlen et al. 2000, 2002; Bland-Hawthorn et al. 2005; Erwin et al. 2005; Pohlen & Trujillo 2006, hereafter PT06). In a sample of nearby late-type galaxies from the Sloan Digital Sky Survey, PT06 found that about 60% have an inner exponential followed by a steeper outer exponential (downward-bending), ~30% have the inner exponential followed by a shallower outer exponential (upward-bending), while only ~10% have no detectable breaks. Therefore breaks are a common feature of disk galaxies that any complete theory of galaxy formation must be able to explain. Furthermore, the discovery of UV emission at radii well beyond the Hα emission cutoff (Gil de Paz et al. 2005; Thilker et al. 2005, 2007), the observational evidence for inside-out disk growth (Muñoz-Mateos et al. 2007), and detections of disk breaks in the distant universe (Pérez 2004; Trujillo & Pohlen 2005), suggest that the outer disks provide a direct view of disk assembly.

Several theories of the formation of breaks have been investigated. Van der Kruit (1987) proposed that angular momentum conservation in a collapsing, uniformly rotating cloud naturally gives rise to disk breaks at roughly 4.5 scale radii. Van den Bosch (2001) suggested that breaks are due to angular momentum cutoffs of the cooled gas. More commonly breaks have been attributed to a threshold for star formation (SF), whether due to low gas density which stabilizes the disk (Kennicutt 1989), or to a lack of a cool equilibrium ISM phase (Elmegreen & Parravano 1994; Schaye 2004). Using a semianalytic model, Elmegreen & Hunter (2006) demonstrate that a double-exponential profile may result from a multicomponent star formation prescription. The existence of extended UV disks (e.g., Thilker et al. 2007) and the lack of a clear correlation of Hα cutoffs and optical disk breaks (Pohlen et al. 2004; Hunter & Elmegreen 2006) further complicate the picture. Regardless, while a sharp SF cutoff may explain the disk truncation, it does not provide a compelling explanation for extended outer exponential components. Alternatively, Debattista et al. (2006) demonstrated that the redistribution of angular momentum by spirals during bar formation also produces realistic breaks in collisionless *N*-body simulations.

In this Letter we present the first results from a series of high-resolution smooth particle hydrodynamics (SPH) simulations of isolated galaxy formation aimed at exploring the formation and evolution of disk breaks and outskirts in a massive, high surface brightness galaxy without a strong central bar. Resulting breaks are analogous to downward-bending breaks seen in observations. The clear advantage of our approach over past attempts is that we use a fully self-consistent physical model of the system, making no a priori assumptions about the distribution of material in the disk. Rather, we allow the disk to grow spontaneously under the effects of gravity and gas hydrodynamics, itself influenced by star formation and feedback. The *N*-body approach (at sufficiently high mass and force resolution) ensures that we capture the dynamical processes contributing to disk evolution. Furthermore, the inclusion of prescriptions for SF and feedback allows us to make observational predictions across the break region. We show that (1) the break forms rapidly ($\lesssim$1 Gyr) and persists throughout the evolution of the system, moving outward as the disk mass grows; (2) the break is seeded by a sharp decrease in star

[1] Astronomy Department, University of Washington, Box 351580, Seattle, WA 98195; roskar@astro.washington.edu, debattis@astro.washington.edu, stinson@astro.washington.edu, trq@astro.washington.edu.
[2] Brooks Prize Fellow.
[3] RCUK Fellow at Centre for Astrophysics, University of Central Lancashire, Preston PR1 2HE, UK.
[4] Department of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada; wadsley@mcmaster.ca.
[5] Department of Physics and Astronomy, Center for Cosmology, University of California, Irvine, CA 92697; tobias.kaufmann@uci.edu.

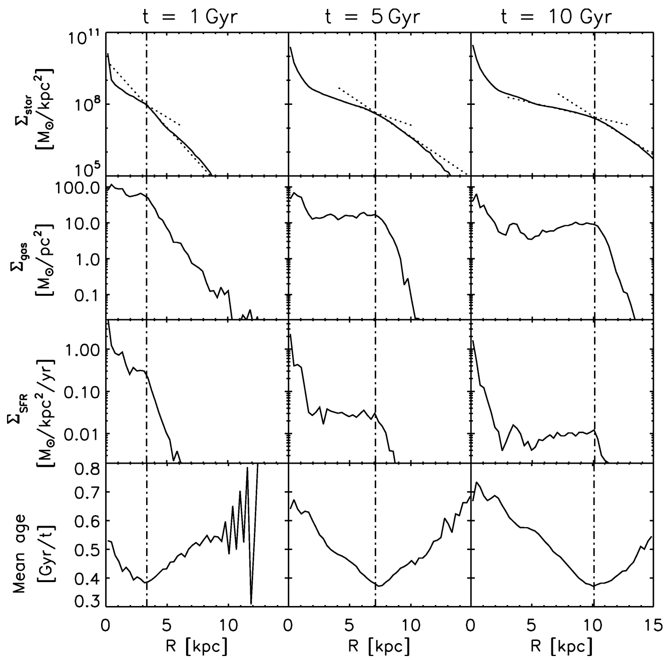

FIG. 1.—Azimuthally averaged properties of the disk at 1, 5, and 10 Gyr. The top panels show the stellar surface density profiles, with the dotted lines representing double exponential fits. The two exponential components were fit simultaneously to the profile, excluding the innermost and outermost regions. The point of intersection of the two exponentials is taken as the break radius. In all panels, the vertical lines indicate the location of the break. The second row shows the surface density of cool gas. In the third row, we show the SFR density calculated from the stellar mass formed in the previous 10 Myr. The mean stellar age (normalized by time of output) as a function of radius is shown in the bottom row.

formation which is caused in our simulation by a rapid decrease in the surface density of cool gas; (3) the outer disk is populated by stars that have migrated, on nearly circular orbits, from the inner disk, and consequently the break is associated with a sharp change in the radial mean stellar age profile; and (4) break parameters agree with current observations.

2. SIMULATION METHODOLOGY

Resolved stellar population data in disk outskirts, which are now becoming available (e.g., Ferguson et al. 2007; Barker et al. 2007; de Jong et al. 2007), provide strong constraints on theories of break formation. Therefore, the inclusion of SF and feedback is required to assess break formation models. For this reason we have run simulations of gas cooling, collapsing, and forming stars inside a live dark matter halo within which the gas is initially in hydrostatic equilibrium. This has the further advantage of making no assumptions about the angular momentum distribution within the disk, which can strongly affect its subsequent evolution (Debattista et al. 2006).

We construct initial conditions as in Kaufmann et al. (2007). The initial system consists of a virialized spherical NFW dark matter halo (Navarro et al. 1997) and an embedded spherical hot baryonic component containing 10% of the total mass and following the same density distribution, which at the end of the simulation yields a disk mass fraction of ∼5%. The mass within the virial radius is $10^{12}\ M_{\odot}$. A temperature gradient in the gas component ensures an initial gas pressure equilibrium for an adiabatic equation of state. Velocities of gas particles are initialized according to a cosmologically motivated specific angular momentum distribution with $j \propto r$ and an overall spin parameter $\lambda = (j/G)(|E|/M^3)^{1/2} = 0.039$ (Bullock et al. 2001). Each component is modeled by 10^6 particles; the dark matter halo is composed of two shells, with the inner halo of 9×10^5 particles (each of mass $\sim 1 \times 10^6\ M_{\odot}$) extending to 200 kpc and an outer halo of 1×10^5 particles (each of mass $\sim 3.5 \times 10^6\ M_{\odot}$) beyond. All gas particles initially have a mass of $1.4 \times 10^5\ M_{\odot}$. We use a softening length of 100 pc for all dark matter particles and 50 pc for baryonic particles. We adopt the best-fit values from Stinson et al. (2006) for the parameters governing the physics of star formation and feedback. Our cooling prescriptions do not account for effects of UV background or metal line cooling. The global criteria for SF are that a gas particle has to have $n > 0.1\ \mathrm{cm}^{-3}$, $T < 15{,}000$ K and be a part of a converging flow; efficiency of star formation is 0.05, i.e., 5% of gas eligible to form stars is converted into stars per dynamical time. Star particles form with an initial mass of 1/3 gas particle mass, which at our resolution corresponds to $4.6 \times 10^4\ M_{\odot}$. A gas particle may spawn multiple star particles but to avoid gas particles of unreasonably small mass, the minimum gas particle mass is restricted to 1/5 of the initial mass. The simulation is evolved with the parallel SPH code GASOLINE (Wadsley et al. 2004) for 10 Gyr.

We have also performed simulations with 10^5 and 10^7 particles per component, thus bracketing our fiducial run. While the details of the gas cooling are somewhat resolution-dependent (Kaufmann et al. 2006), resulting in morphological differences, we find convergence in the modeling of overall halo cooling, star formation and its dependence on gas surface density, and disk dynamics. We therefore consider the conclusions and predictions of this Letter numerically robust. The 10^6 particle resolution used here represents a compromise between adequate statistics for detailed analysis in the outer disk and computational cost for 10 Gyr of evolution.

Our simulation should be thought of as modeling disk formation and evolution from the cooling of hot gas after the last gas-rich major merger, as suggested by cosmological simulations (Brook et al. 2004, 2007). Although we make use of simplifications such as an initially spherical distribution of matter, a lack of halo substructure, the ignoring of subsequent accretion of dark matter and baryons, and an initial gas density profile that mimics that of the dark matter, studying the idealized isolated case allows us to analyze in detail the important dynamical processes affecting the evolution of a massive isolated disk. The lessons we learn from this idealized case will later be applied to galaxies evolved in a full cosmological context (R. Roškar et al., in preparation).

3. BREAK FORMATION AND THE OUTER DISK

In Figure 1, the break is already evident as soon as a stable disk forms at 1 Gyr, moving outward as the disk grows and persisting throughout the simulation. A sharp drop in the local SFR is always present at the break radius. The drop in SFR is not due to a volume density threshold for star formation, but is instead associated with a rapid decrease in the gas surface density (the star formation follows a Kennicutt-Schmidt law at all times) and a corresponding sharp increase in the Toomre Q parameter. We verified that the break is not seeded by our star formation recipe by running several simulations with different values of the threshold density and found that the location of the break did not depend on the particular value used. Since density is inversely proportional to radius, the cooling time increases outward. By construction, the angular momentum is directly proportional to cylindrical radius, which means that higher angular momentum material will take longer to cool.

This leads to the radial extent of the gas disk (and subsequently the star-forming disk) being limited by the maximum angular momentum of material that has been able to cool.

Figure 1 shows clearly that a sharp change in the mean stellar age profile coincides with the location of the break. We now investigate the cause of this ubiquitous feature. Figure 2 shows a 2D mass-weighted histogram of final ($t = 10$ Gyr) versus formation radii of stellar particles on nearly circular orbits, defined as having $J_z/J_c(E) > 0.9$, where $J_c(E)$ is the angular momentum of a circular orbit with the energy of a given particle. This criterion is satisfied by ~80% of the outer disk particles. Therefore the outer disk is a rotationally supported structure. It is clear from Figure 2 that significant redistribution has occurred throughout the disk; including all of the particles in this figure, the root-mean-square change in radius during the lifetime of each particle $[\overline{(\Delta R)^2}]^{1/2} = 2.4$ kpc (mean $\Delta R \sim 0$). Most strikingly, nearly all (~85%) particles beyond the break (Fig. 2, *right*) have migrated there from the inner disk. The mean epicycle radius of these *outer disk* particles is only ~2 kpc, while the mean $\Delta R = 3.7$ kpc. Hence, the presence in the outer disk of particles which formed in the inner disk cannot be attributed to radial heating alone but is a signature of secular radial redistribution.

Sellwood & Binney (2002) describe how transient spiral arms move corotating stars radially without heating the disk. Fourier analysis shows that spirals of a wide range of pattern speeds are present in different parts of the disk at all times, enabling shuffling of stars at all radii. As the disk size increases, spirals of ever larger corotation radii and lower pattern speeds become common, enabling transport of material over large distances. The largest migrations coincide with the growth of strong spirals, confirming that the migrating stars are in resonance with the spirals. Thus radial migration is common and stars of all ages are continuously transported to well outside the break. Details of these mechanisms will be presented in a future paper.

Since the surface density break also corresponds to a break in SFR, the outer disk is relatively deficient in young stars. The outermost regions of the disk are populated by old stars which migrated from the inner disk, since they have had the most time to reach there. This redistribution naturally leads to the minimum in stellar age at the break and a positive age gradient in the outer disk. Although the importance of spiral arms for the evolution of the outer disk has already been demonstrated by Debattista et al. (2006), in their models the break was formed by resonant coupling between the central bar and spiral arms. The cause of the break in our model is fundamentally different since it is ultimately caused by a drop in the SFR, while the outer exponential is populated by secularly redistributed stars. While a recurring oval does appear in the disk, a strong bar like the ones described in Debattista et al. (2006) does not form here.

The radial migrations are not directed only outward; indeed spirals cause much more radial mixing than transport. Figure 2 shows that the radial changes are symmetric for particles with small deviations ΔR and at smaller radii. However, for particles with larger ΔR or larger initial radii, more particles move outward than inward. Part of the excess angular momentum required for this transport is provided by the gas, which is funneled toward the center.

4. COMPARISON WITH OBSERVATIONS

Our simulation is not intended to reproduce all properties of real galaxies since we lack the full cosmological context. Nevertheless, the evolution of disks in isolated galaxies since the epoch of last major mergers at $z \sim 2$ (i.e., about 10 Gyr) should not be very different from that in our model. We may therefore anticipate that our model matches nature well if it captures the essential physics.

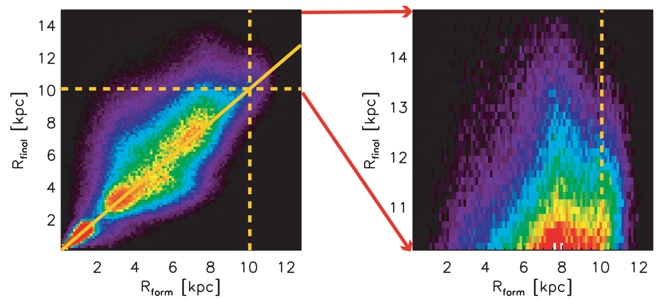

FIG. 2.—Two-dimensional histogram of final particle radii vs. particle formation radii for particles on nearly circular orbits at 10 Gyr. The right panel shows only particles beyond the break.

We have investigated how the break structural parameters of our simulated disk at different points in the simulation compare to those observed by PT06 and Pohlen et al. (2002). Ratios of break radius to inner scale length agree well with the data from PT06 throughout the simulation. The mean ratio of break radius to inner scale length, R_{br}/h_{in}, in our simulation is 2.6, while PT06 find a mean value of 2.5, an indication that our simulation captures the correct scale of the phenomenon.

De Jong et al. (2007) presented radial star count profiles of the edge-on galaxy NGC 4244 for different stellar populations. Their main result was that the break occurs at the same radius regardless of age and distance from the midplane. In Figure 3 we show edge-on density profiles for stars from our model with age bins roughly corresponding to those used by de Jong et al. (2007). Solid lines correspond to stars in the midplane ($|z| < 0.5$ kpc), dashed lines to stars at 0.5 kpc $< |z| < 1.0$ kpc, and dotted lines to stars at 1.0 kpc $< |z| < 1.5$ kpc. The vertical line marks the break as determined from the face-on profile. The break occurs at the same radius for all age bins, but becomes less pronounced with age due to radial redistribution. In the two oldest age bins (where we have enough particles to make a meaningful comparison), the break is also constant with height away from the midplane. Transient spirals are responsible for the largest amounts of redistribution, which is very efficient and can operate on relatively short timescales. Therefore the agreement of the location of the break between stars of different ages is a natural consequence of migration caused by transient spirals in a growing disk.

The decrease in mean stellar age with radius is unsurprising if disks form inside-out, and such trends have indeed been observed (de Jong 1996; Bell & de Jong 2000; MacArthur et al. 2004; Muñoz-Mateos et al. 2007). Thus, the negative age gradient out to the break is expected, but the abrupt change in the gradient and its close correlation with the break radius has not previously been noted. However, a positive age gradient beyond the break has been observed in M33 (Barker et al. 2007), but to our knowledge no complementary age profile exists for the inner part of that galaxy.

5. CONCLUSIONS

We have shown that in a self-consistent model, where the stellar disk forms through gas cooling and subsequent star formation within a dark matter halo, breaks in the stellar surface

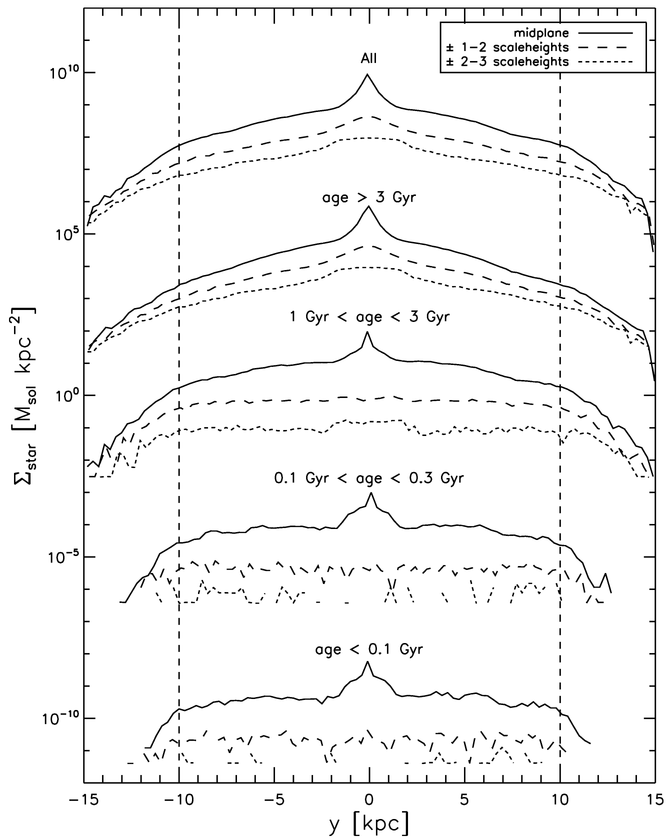

FIG. 3.—Stellar density profiles for stars in different age bins. An arbitrary offset has been applied for clarity. See text for details.

density form through the combination of different effects. A rapid drop in the SFR seeds the break and secular evolution populates the outer exponential. In our model the SFR drop is due wholly to a drop in the surface density of gas. However, a break in SFR induced by other means (e.g., a volume density threshold or perhaps warps) would lead to similar behavior of the outer disk and stellar density break parameters. Our model properties satisfy current observational constraints, both in the statistical sense of break properties from galaxies in SDSS, as well as the much more detailed observations of breaks in stellar populations of NGC 4244. Although our model does not account for the effects of evolution in a full cosmological context, its simplicity assures that this is the minimal degree of evolution (with no interactions or formation of a significant bar) and should therefore be rather generic provided that a disk is massive enough for strong transient spirals to form. The model predicts that there should be an abrupt change in the radial mean stellar age profile coincident with the break, which can be tested with future observations.

This research was supported in part by the NSF through TeraGrid resources provided by TACC and PSC. Access to additional computing resources was made possible by a grant from the U. W. Student Technology Fee and support from the U. W. PACS team. R. R., V. P. D., G. S. S., and T. R. Q. were supported by the NSF ITR grant PHY-0205413 at the University of Washington. R. R. acknowledges support for a visit to the University of Central Lancashire from a Livesey Award Grant held by V. P. D. Over the course of this Letter V. P. D. was also supported by a Brooks Prize Fellowship and an RCUK Fellowship at the University of Central Lancashire.

REFERENCES

Barker, M. K., Sarajedini, A., Geisler, D., Harding, P., & Schommer, R. 2007, AJ, 133, 1138
Bell, E. F., & de Jong, R. S. 2000, MNRAS, 312, 497
Bland-Hawthorn, J., Vlajić, M., Freeman, K. C., & Draine, B. T. 2005, ApJ, 629, 239
Brook, C. B., Kawata, D., Gibson, B. K., & Freeman, K. C. 2004, ApJ, 612, 894
Brook, C., Richard, S., Kawata, D., Martel, H., & Gibson, B. K. 2007, ApJ, 658, 60
Bullock, J. S., Dekel, A., Kolatt, T. S., Kravtsov, A. V., Klypin, A. A., Porciani, C., & Primack, J. R. 2001, ApJ, 555, 240
Dalcanton, J. J., Spergel, D. N., & Summers, F. J. 1997, ApJ, 482, 659
Debattista, V. P., Mayer, L., Carollo, C. M., Moore, B., Wadsley, J., & Quinn, T. 2006, ApJ, 645, 209
de Jong, R. S. 1996, A&A, 313, 377
de Jong, R. S., et al. 2007, ApJ, 667, L49
de Vaucouleurs, G. 1958, ApJ, 128, 465
Elmegreen, B. G., & Hunter, D. A. 2006, ApJ, 636, 712
Elmegreen, B. G., & Parravano, A. 1994, ApJ, 435, L121
Erwin, P., Beckman, J. E., & Pohlen, M. 2005, ApJ, 626, L81
Fall, S. M., & Efstathiou, G. 1980, MNRAS, 193, 189
Ferguson, A., Irwin, M., Chapman, S., Ibata, R., Lewis, G., & Tanvir, N. 2007, in Island Universes: Structure and Evolution of Disk Galaxies, ed. R. S. de Jong (Dordrecht: Springer), 239
Gil de Paz, A., et al. 2005, ApJ, 627, L29
Hunter, D. A., & Elmegreen, B. G. 2006, ApJS, 162, 49
Kaufmann, T., Mayer, L., Wadsley, J., Stadel, J., & Moore, B. 2006, MNRAS, 370, 1612
Kaufmann, T., Mayer, L., Wadsley, J., Stadel, J., & Moore, B. 2007, MNRAS, 375, 53
Kennicutt, R. C., Jr. 1989, ApJ, 344, 685
Lin, D. N. C., & Pringle, J. E. 1987, ApJ, 320, L87
MacArthur, L. A., Courteau, S., Bell, E., & Holtzman, J. A. 2004, ApJS, 152, 175
Mo, H. J., Mao, S., & White, S. D. M. 1998, MNRAS, 295, 319
Muñoz-Mateos, J. C., Gil de Paz, A., Boissier, S., Zamorano, J., Jarrett, T., Gallego, J., & Madore, B. F. 2007, ApJ, 658, 1006
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Pérez, I. 2004, A&A, 427, L17
Pohlen, M., Beckman, J. E., Hüttemeister, S., Knapen, J. H., Erwin, P., & Dettmar, R.-J. 2004, in Penetrating Bars through Masks of Cosmic Dust, ed. D. L. Block et al. (Cambridge: Cambridge Univ. Press), 713
Pohlen, M., Dettmar, R.-J., & Lütticke, R. 2000, A&A, 357, L1
Pohlen, M., Dettmar, R.-J., Lütticke, R., & Aronica, G. 2002, A&A, 392, 807
Pohlen, M., & Trujillo, I. 2006, A&A, 454, 759 (PT06)
Schaye, J. 2004, ApJ, 609, 667
Sellwood, J. A., & Binney, J. J. 2002, MNRAS, 336, 785
Stinson, G., Seth, A., Katz, N., Wadsley, J., Governato, F., & Quinn, T. 2006, MNRAS, 373, 1074
Thilker, D. A., et al. 2005, ApJ, 619, L79
———. 2007, ApJS, 173, 538
Trujillo, I., & Pohlen, M. 2005, ApJ, 630, L17
van den Bosch, F. C. 2001, MNRAS, 327, 1334
van der Kruit, P. C. 1979, A&AS, 38, 15
———. 1987, A&A, 173, 59
Wadsley, J. W., Stadel, J., & Quinn, T. 2004, NewA, 9, 137