Dark Matter Substructure, Filaments and Assembling Disks

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Abstract. We review some general properties of assembling galactic dark matter (DM) halos which have a direct effect on the baryon dynamics. Specifically, we focus on the mutual dynamical feedback between baryons and DM which influence disk formation and evolution, by comparing models with and without baryons evolved from identical initial conditions. Baryons are found to be capable of modifying the DM density profiles of inner halos, leading to isothermal profiles rather than the NFW cusps. Those can be leveled off by the subsequent dynamical friction of the subhalos at lower $z$. Furthermore, subhalos appear efficient in triggering galactic bars and ablating cold gas from the disks, and therefore quenching of star formation there.

1. Adding Baryons to Forming Galaxies

Formation of luminous parts of galaxies is inherently connected with baryon dynamics in the background of the dark matter (DM). While only one sixth of the matter is baryonic in the WMAP3 Universe (e.g., Spergel et al. 2007), it apparently dominates the inner regions of galaxies because of the ability to dissipate energy. The associated efficiency in getting rid of the angular momentum leads to de facto separation between baryons and DM. The relevant galactic dynamics probably transcends the simple adiabatic contraction (e.g., Blumenthal et al. 1986) and the actual evolution appears to be more complex. To more fully understand the role of baryons in galaxy evolution, we focus on two issues: (1) how do baryons affect the background DM in galaxies, and (2) how does the distribution of DM on scales larger and smaller than galactic halos influences the accumulation and dynamics of baryons in the central regions, where disks form and grow. In the following, we make a broad use of representative models of pure DM (PDM models) and baryon+DM (BDM models), which have been evolved from identical initial conditions (Romano-Diaz et al. 2009a). The general properties of DM halos which have been established so far lead to important consequences for baryon evolution in the galactic centers. Those in turn exert feedback on the DM, which affects shapes, density profiles, angular momentum and substructure. We limit out discussion to those properties which have a direct impact on disk evolution.

Filaments and accretion through filaments emerge as the dominant mode of galaxy growth (e.g., Dekel et al. 2008). It is important that the cosmological filaments which dominate the large-scale DM structure initially extend to the very small scales of a few kpc where the seed galactic disks form at intermediate $z$ (Shlosman 2009). The characteristic “cat’s cradle” displays how the inflowing baryons smoothly join the disk, experiencing little ‘shocking’ (Fig. 3 in Heller...
Figure 1. DM influx rates along the filaments in the pure DM (left) and baryons+DM (right) models, with identical initial conditions. The color-coded curves correspond to the fixed radii of 10 kpc – 300 kpc and the DM virial radii, as a function of $z$ and the cosmological expansion parameter $a$ (Romano-Diaz et al. 2009b).

Figure 2. Left: As in Fig. 1 but for the gas inflow along the filaments (Romano-Diaz et al. 2009b). Right: Evolution of DM density profiles $\rho(R)$ within the inner 20 kpc in the PDM and BDM models. The insert shows $\rho$ within 200 kpc. The curves are displaced vertically for clarity (Romano-Diaz et al. 2008a).

et al. 2007). At small radii, the clumpy gas influx appears tangent to the protodisk, in apparent repelling action of the angular momentum. The inflow along the DM filaments prevents the gas from being virialized before it joints the disk. Furthermore, it assures that the gas will lose some fraction of its angular momentum to a filament. The typical DM accretion rates along the filaments decay with time and show a mild difference between the PDM and BDM models (Fig. 1a,b). This difference amounts to a somewhat supressed influx rate in the inner 10 kpc—20 kpc after $z \sim 1$ and is related to the action of baryons as we discuss below. The typical gas accretion rate along the filaments fits comfortably to the overall picture of galaxy growth. Fig. 2a exhibits inflow
which is sufficient for a massive disk formation in the long run and can support the currently observed star formation rates in a Milky Way-type galaxies.

2. DM and Baryon Settling in Pure DM and DM+Baryons Models

The DM halo buildup, in the absence of baryons, is known to lead to a universal density profile with a characteristic scale $R_s$, corresponding to the logarithmic slope of –2 (e.g., Navarro et al. 1997, NFW). Within this radius, the density is cuspy, its slope tends to –1 when $R \rightarrow 0$. The reason for this universality is currently debated but it is important that baryons can substantially modify this density profile (El-Zant et al. 2001; 2004; Tonini et al. 2006), bridging the gap with observations. Those hint at a central flat density core rather than a cusp (e.g., de Blok 2007; Kuiz de Naray et al. 2008). Romano-Diaz et al. (2008b) find that the NFW cusp formation is by-passed in favor of an isothermal DM cusp, in BDM models (Fig 2b). The isothermal cusp in turn can be leveled off by the action of penetrating minor mergers after $z \sim 1$. To avoid the ambiguity in the definition of $R_s$ in the BDM models, we invoke the radius of a maximal circular velocity, $R_{\text{vmax}}$, in the halo instead. The fraction $\gamma \equiv R_s/R_{\text{vmax}} \sim 0.46$ is universal for the NFW fit. For all models we define $\tilde{R_s} \equiv R_{\text{vmax}}$.

While formation of isothermal cusps is related to the adiabatic contraction and involves a certain degree of dissipation by baryons, their demise can be associated with clumpy accretion of DM subhalos glued by baryons. It happens well beyond the epoch of major mergers, after $z \sim 1$. Romano-Diaz et al. (2008a,b) have shown that the late stages of inflow along the filaments involve subhalos which cluster there, and enter the prime halo before they merge among themselves. Due to higher binding energy, the subhalos in the BDM models can penetrate the inner halo. Within the virial radius of the prime halo, the mass function of subhalos evolves strongly, especially when baryons are present (Romano-Diaz et al., in preparation). The mass ratio of the most massive subhalo to the prime halo decreases with time, but is $\sim 8 \times 10^{-4}$ even at $z = 0$, higher than the minimum required by El-Zant et al. (2001) for the dynamical friction to be efficient over orbital times. The influx of subhalos is well correlated with the ‘smooth’ DM streaming out of the center and ‘cooling’ down.

Cold, rotationally supported baryons are expected to accumulate within $\tilde{R_s}$, subject to expulsion by stellar or AGN feedback. Some baryons will be trapped in the filaments and in shells outside the virial radius, $R_{\text{vir}}$. These shells form when incoming subhalos are tidally disrupted but avoid capture by the gravitational well. Hence, it is not clear at present to what extent the baryonic content of a galaxy corresponds to the universal fraction of baryons. For a MW-type galaxy, Romano-Diaz et al. (2009a) find that major mergers tend to increase the baryon fraction, while minor mergers decrease it — the net effect appears to be negligible. This result is based on a fine-tuning of the stellar feedback parameter, based on a large number of disk models (Heller et al. 2007).

What is the source of the inner halos’ DM, say within $\tilde{R_s}$, and when do the inner halos form? Does the DM accumulation within $\tilde{R_s}$ end with the major mergers epoch (e.g., Wechsler et al. 2002). Comparison between the PDM and BDM models reveals that only about 15% and 33% of the DM mass found within this radius at $z = 0$ is contributed by the subhalos, for PDM and BDM
respectively. The rest comes from the ‘smooth’ accretion. Here we, rather arbitrary, limit the ‘clumpy’ (i.e., subhalo) accretion to the clump-to-prime halo mass ratios in excess of $10^{-4}$ of the prime halo virial mass at $z = 0$. This includes about 4% and 20% (PDM and BDM) coming from the major mergers, i.e., the mass ratios of $\gtrsim 1:3$, and 11% and 13% (PDM and BDM) from the minor mergers. Overall merger contribution to the central mass falls slowly with the decreasing merger mass ratio. Second, while the DM density profile is established early (except in the central few kpc), most of the DM is not confined to within the characteristic radii, $\tilde{R}_s$ and $R_{\text{vmax}}$ — only 13% and 20% of DM found within these radii, respectively, are bound there. The majority makes much larger radial excursions. Hence the buildup of the inner halos continues to $z = 0$. The flow of the unbound DM contributes about 80% of the DM within $\tilde{R}_s$ after the merger epoch, but the net influx of this material is zero, and this region appears to be rather in a steady state. Most of the DM particles within $\tilde{R}_s$ reside there for a short crossing time only. One hopes that these numbers are representative and reflect the basics of the DM halo assembly.

Equally important for the disk evolution appears to be the highly anisotropic flux of DM and baryons toward the center. The background potential of the DM is strongly triaxial at the peak of the inflow. The shapes of DM halos respond to the presence of baryons by reducing their triaxiality (e.g., Kazantzidis et al. 2004; Berentzen & Shlosman 2006) and a number of factors are involved (Fig. 3). Both, the clumpiness of baryons, their central concentration and out-of-phase response to the DM driving lead to a decrease in the halo flatness and to a loss of its equatorial ellipticity, when the disks form (e.g., Shlosman 2007). Moreover, the halo figure tumbling appears insignificant both with and without baryons, irrespective of whether it is located in the field (i.e., isolated) or in a denser environment of a filament, based on $\sim 900$ snapshots (Heller et al. 2007; Romano-Diaz et al. 2009a), which agrees well with Bailin & Steinmetz (2004) estimates. The angular momentum acquired by halos is channeled into the internal streaming rather than figure rotation. Such an exceedingly slow tumbling of DM halos has important dynamical consequences for growing disks by moving the halo’s outer inner Lindblad resonance to very large radii, beyond $R_{\text{vir}}$.
Figure 4. Evolution of the DM halo in the PDM (left) and BDM (right) models shown in the $R - v_R$ plane at $z = 3$, i.e., during the major merger epoch and the appearance of fingers. The colors correspond to the DM particle density on the $R - v_R$ surface. The vertical arrows show $R_{\text{vir}}$, the dashed white line $v_R = 0$, and the blue line — the average $v_R$ at each $R$. Accretion along the large-scale filament is seen as a stream at $v_R < 0$ (Romano-Díaz et al. 2009a).

3. DM Halo Relaxation Beyond Virialization

While the DM halos are being virialized, this process is clearly incomplete because a cosmological halo is an open system. In addition, when the density profile is established early, oscillations of the central potential decay fast, except during major mergers. This limits the efficiency of the violent relaxation process (Lynden-Bell 1967). However, the ongoing accretion of a clumpy material can steer the halo, especially its outer region where they are favored because of the material influx along the large-scale filaments. It is informative, therefore, to look at the fate of the incoming subhalos and compare the PDM and BDM models. For this purpose we use the $R - v_R$ phase diagrams which allow to quantify the substructure contributions, where $R$ is the spherical radius (Fig. 4).

We define three types of subhalo relics, which partially represent various stages of their dissolution. The (bound) subhalos can be easily seen because of their vertical spikes (subhalo internal velocities) in Fig. 4. Those that are in the process of tidal disruption are accompanied by inclined spikes (‘fingers,’ partially bound). Lastly, the tidally disrupted subhalos persist as streamers for a long time, those represent $R - v_R$ correlations (unbound). The cold filament-driven influx appears de-focused after passing the pericenter of its motion. As its constituents move out, their slowdown in tandem with the tidal disruption lead to the formation of shells that persist for a long time. Shells that form later in time have larger outflow velocities and can cross shells that formed earlier. For the survival of these shells it is important that they form after subhalos pass the pericenters of their orbits.

Both the spikes and fingers appear longer by $\sim 2$ in the presence of baryons. The streamers survive for a long time, and those that form after $z \sim 1$ survive till present. Hence, the prime halo goes through inefficient relaxation beyond its virialization. The ability of subhalos in the presence of baryons to penetrate deeper into the prime halo and survive for a long time has also implications for the disk evolution in the BDM models. The residual currents in the halo continue to mix the halo environment even in the absence of large-amplitude variability in the central potential.
4. Disk-Substructure Interactions

Evidence points to a variety of processes that affect the disk assembly in a DM halo. Major mergers act to destroy the forming disk, but if the system has a substantial reservoir of cold gas and/or large-scale filaments continue to supply such gas, the disk can be rebuilt at lower $z$. From general arguments, the gravitational potential of the inner halo is not axisymmetric, and can include the penetrating filaments, at least at high $z$. Under these conditions, the initially gas-dominated disk will be strongly non-axisymmetric and turbulent. Bar formation is favored and the properties of such gas/stellar bars differ from those studied in the galactic dynamics. Because of the low central density concentration, the first generation of bars will tumble with very low speeds (e.g., Heller et al. 2007; Romano-Diaz et al. 2008b). This property is crucial to avoid the developing chaos (Shlosman 2009) which is expected to dissolve the bars formed in non-axisymmetric potentials because of the destructive interactions between stellar and DM quadrupoles (El-Zant & Shlosman 2002). A rapid growth of the disk brings along the bar growth as well, together with the pattern speed-up. Moreover, the disk material, especially the gas but also the stars, is aware of the large-scale orientation of the DM potential. One should expect a nonlinear response of the disk shape to this perturbations. Numerical simulations show that this leads to large distortions in the outer disk, including prominent spiral arms, which are followed by a nearly axisymmetric stage (Heller et al. 2007). Various waves are excited in the disk and the beat phenomenon is frequently observed. Due to the presence of the gas, nested bar cascade is plausible and will lead to a rapid angular momentum loss from the central regions, leading to the formation of a single massive object (Begelman et al. 2006).

The DM substructure can have a profound effect on the prevailing morphology in the disk (Gauthier et al. 2006; Romano-Diaz et al. 2008b). Here, we mention two effects only: triggering of galactic bars and cold gas ablation from the disk. The former constitutes a finite perturbation and allows to circumvent various problems associated with the linear stage of the bar instability. Trigger-
ing bars with galaxy perturbations has been known for some time (e.g., Byrd et al. 1986; Noguchi 1987), but subhalos can make it even more efficient and, paradoxically, less dependent on the environment.

A potentially new effect is the ablation of the cold disk gas by subhalos, as shown in Fig. 5a. It is clearly related to the penetrating encounters with the subhalos. In addition to heating up the cold gas, the hot gas component is driven out, in conjunction with the inner DM, as discussed in §1. The immediate corollary of this process is a sharp, factor of 10 decrease in the star formation rate associated with the disk (Fig. 5b). This can be a general stage in the evolution galaxies, when the star formation is quenched by interactions with the DM substructure.

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