Part 7

Baryonic Dark Matter

Dark Matter in Galaxies
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Galaxy Formation and Baryonic Dark Matter

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Abstract. The ΛCDM scenario to form galaxies encounters many problems when confronted with observations, namely the prediction of dark matter cusps in all galaxies, and in particular in dwarf irregulars, dominated by dark matter, or the low angular momentum and consequent small size of galaxy disks, or the high predicted number of small systems. We will consider the hypothesis that the baryonic dark matter could be in the form of gas and could be continuously involved in the galaxy formation scenario. By accreting cold gas throughout a galaxy's life, angular momentum could be increased, galaxy disks could be more dominated by baryons than previously thought, and small systems could merge more frequently.

1. Introduction: main problems of the ΛCDM paradigm

One of the main problems encountered by the CDM model has already been debated actively in this conference: the observed dark halo profiles of DM-dominated galaxies (dwarfs and LSB) are much better fitted with constant-density cores than with the steep power-law slopes predicted by CDM simulations (e.g. Navarro, Frenk & White 1997). Rotation curves have now sufficiently high spatial resolution (their dynamic range is even larger than in simulations), and it appears that it is no longer possible to explain the discrepancy by observational artefacts (de Blok et al. 2003). While the observed slope is on average ~ -0.2, recent simulations show that the predicted slopes are not flatter than -1.5 (Fukushige & Makino 2003). The amount of discrepancy is however disputed (e.g. Swaters et al. 2003).

A second problem is the low angular momentum of condensed baryons in CDM models, and consequent small predicted radii of galaxy disks, much too small compared to observed ones (Navarro & Steinmetz 2000). CDM simulations reproduce the Tully-Fisher slope and scatter, but not the zero point. They end up with dark halos too concentrated, and therefore a dark-to-visible mass ratio much too large within the observable disk.

A third problem is the high predicted number of small haloes, a power spectrum for structures favouring the small-scales, leading to a large number of substructures that are not observed (Moore et al. 1999).

Can the hypothesis that a large fraction of dark baryons are in the form of cold condensed gas help to solve the problems? If we believe the primordial nucleosynthesis constraints, 90% of baryons are dark, and several hypotheses have been explored for the nature of these dark baryons; baryons in compact objects (brown dwarfs, white dwarfs, black holes) are either not favoured by micro-lensing experiments or suffer major problems (Lasserre et al. 2000, Alcock et al. 2001, Afonso et al. 2003). The best hypothesis today is gas, either hot gas in the intergalactic and inter-cluster medium, or cold gas in the vicinity of galaxies (Pfenniger et al. 1994, Pfenniger & Combes 1994). The presence of large amounts of warm and diffuse gas in space cannot solve the problems, as shown by most ΛCDM cosmological simulations based on this hypothesis, so we will concentrate on the second option.

2. Cusps in Galaxy centers

This central problem has been the subject of many efforts to solve it, either redistributing the dark matter or changing its nature, but up to now no one study is perfectly satisfying: black hole binaries can heat and flatten cusps (Milosavljevic & Merritt 2001), but they do not exist in dwarf galaxies; stellar feedback (Gnedin & Zhao 2002), but even generous amounts of feedback are insufficient to destroy the central halo cusp, while the inner density is lowered only by a modest factor of 2 to 6; bars (Weinberg & Katz 2002) have only weak effects and are not likely in dwarf irregulars. Among the various alternatives to the ΛCDM model, warm dark matter (WDM) appears not to be promising (Knebe et al. 2002), nor does self-interacting dark matter (SIDM; Spergel & Steinhardt 2000). Changing the cosmological parameters, matter density or power spectrum, allowing little power on galaxy scales (McGaugh et al. 2003), brings only partial solutions.

Dwarf Irr galaxies are dominated by dark matter, but also their gas mass is dominating their stellar mass. It is remarkable that they obey the relation σ_{DM}/σ_{HI} = const., revealing that the dark-matter and HI gas surface densities have the same radial distribution (e.g. Hoekstra et al. 2001). All rotation curves can be explained, when the observed surface density of gas is multiplied by a constant factor, around 7-10. This σ_{DM}/σ_{HI} ratio is almost constant from galaxy to galaxy, being slightly larger for early-types (Combes 2002). A solution to the problem of non-observed CDM cusps is that CDM would not be dominating in LSB galaxy centers, as is already the case in more evolved early-type galaxies, dominated by the stars. On the contrary, the mass in the center of LSB HI-dominated galaxies could be predominantly baryonic, in the form of cold condensed molecular gas. The column density of this H_2 gas would be about one order of magnitude larger than the HI column density, which is already the case in early-type galaxies (where the larger metallicity of the gas allows us to observe the H_2 tracer, i.e. the CO molecule). That the gas mass has an essential dynamical role is supported by the success of the baryonic Tully-Fisher relation (McGaugh et al. 2000). It is interesting to note that dark haloes at cluster scales are also observed with a core (and not a cusp, Sand et al. 2002), and this could be due to the mass domination of baryons in the center (El-Zant et al. 2003).

The influence of the baryon fraction Ω_b on galaxy formation has been investigated through numerical simulations by Gardner et al. (2003): they show that increasing Ω_b does not change the amount of diffuse gas in the intergalactic medium, but on the contrary the condensed phase associated to galaxies increases faster then Ω_b, due to the increased cooling rate. This leads to a considerably larger baryon representation in virialized systems with respect to their universal fraction. Another factor is the limited spatial resolution of the simulations, which could reduce the concentration of the dissipative material.

3. Angular momentum and disk formation

Most CDM cosmological simulations encounter a fundamental problem to form galaxy disks: due to low specific angular momentum for baryons, disks end up with too small radii (e.g. Abadi et al. 2003). Similarly elliptical systems end up too concentrated (Meza et al. 2003). In the commonly adopted paradigm, baryons at the start have the same specific angular momentum as dark matter. But then, in the course of evolution, baryons lose their angular momentum to the CDM, through dynamical friction. This is due to the main formation mechanism of galaxies, through hierarchical merging. The problem is the too early concentration of baryons, and the subsequent formation of galaxy disks as the final outcome of a sequence of merger events. Instead disks could be formed essentially through gas accretion from large-scale filaments, and this accretion could be prolonged until late times.

3.1. Feedback and cold gas accretion

The main solution to the angular momentum problem has been to increase the efficiency of feedback processes due to star formation. Supernovae should provide enough energy in the interstellar medium to prevent further collapse and star formation, and maintain disks with angular momentum close to the value required to fit observations (Thacker & Couchman 2001). In the same vein, Binney et al. (2001) propose that, after the formation of protogalactic disks, massive winds expel considerable amounts of baryons. This contributes to the expansion of the inner dark matter (and the formation of cores), while the presently observed disks form late, when the dark halo contribution in the inner parts has been reduced.

Weil et al. (1998) varied the gas cooling epoch, and found that disks can form by the present day with correct angular momenta if radiative cooling is suppressed until z=1. This means that feedback processes must be efficient enough to prevent gas from collapsing until late epochs. Eke et al. (2000) delay the gas cooling until z=1, and succeed in forming disks with angular momentum approximately conserved during collapse. They show however that keeping enough specific angular momentum depends on the cosmology adopted, on the inhomogeneity of the haloes after the gas begins to collapse, and of course on the value of Ω_m, larger values of Λ for flat universes being much more favourable.

How does the gas collapse? In semi-analytical models (e.g. Mo et al. 1998), the gas is assumed to be hot and shock heated to the virial temperature of the halo. But another way to accrete mass is cold gas mass accretion (Katz et al. 2003, Binney 2003). Gas is channeled through filaments, and only moderately heated by weak shocks, and radiates quickly. It never heats to the virial temperature of its halo. Accretion is not spherical, gas keeps angular momentum and

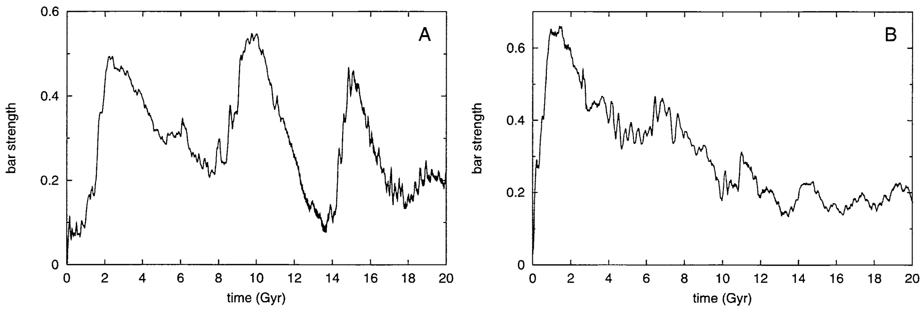

Figure 1. Evolution of the bar strength over a Hubble time, showing that external gas accretion can revive bars in galaxy disks (numerical simulations from Bournaud & Combes 2002).

rotates near the galaxies, making it more easy to form disks. This cold mode of gas accretion is the most efficient at z larger than 1.

3.2. Gas accretion and bar strength

The bar frequency in present day galaxy disks can provide a way of quantifying gas accretion. It is well known that bars provoke their own destruction, by driving gas towards the center (e.g. Hasan & Norman 1990). After 5 Gyr of galaxy disk evolution, there should not be any bar left. Why do we observe so many bars today? More than 2/3 of galaxies are barred. There are even more bars detected in NIR images, when dust extinction does not blur them.

The only way to renew a bar in a galaxy is to accrete external cold gas. The gas will increase the disk mass, and reduce the bulge-to-disk mass ratio, destabilizing the disk again. Several bar episodes can process in a Hubble time (Fig 1; Bournaud & Combes 2002).

We have recently quantified the frequency of bars, in a sample of 163 galaxies imaged in the NIR by Eskridge et al. (2002). The gravity torques have been estimated by computing first the potential of the galaxy, through a Fourier transform of its NIR image. The intensity Q_2 of the $m = 2$ torques is defined by the maximum over the disk of the ratio $F_t(m = 2)/F_r$, with F_t the tangential force, and F_r the radial force. Similarly, the total torques are estimated by the maximum of F_t/F_r, with all m included (Block et al. 2002). The surprising result is the dearth of axisymmetric galaxies (Fig. 2). Simulations of external gas accretion have been made in a sample of objects very similar in types to the observed sample. The frequency of bars was estimated in the simulated sample in the same way as for the observed sample. Comparison of the two histograms of torque intensity allows a quantification of the accretion rate (Fig. 2). It reveals that a galaxy doubles its mass in about 10 Gyr, through cold gas accretion.

3.3. Avoidance of dynamical friction

If the gas is condensed very early in galaxies, and is tightly bound to massive entities, it will experience strong dynamical friction at each merging stage, against

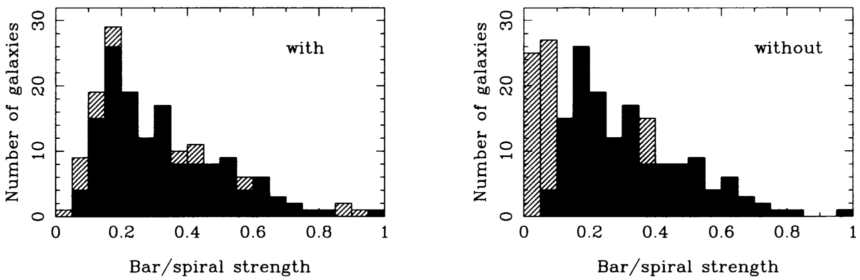

Figure 2. Histograms of the bar strength Q_b, defined as the ratio of maximum $m = 2$ tangential force to radial force. **Left** The black histogram is the observed one, and the grey is from a model with gas accretion, the galaxy doubling its mass in 10 Gyr. **Right** The black histogram is the observations, and the grey is now the model without gas accretion. (from Block et al. 2002).

the dark matter particles. A way to avoid this is to eject hot gas in supernovae feedback processes, but this might be insufficient (e.g. Gnedin & Zhao 2002, Maller & Dekel 2002).

Another scenario is that the gas accretes slowly in a cold phase onto galaxies, the hierarchical merging will lose less angular momentum through dynamical friction (Fig 3). Gas in this scenario is only slightly bound to galaxies, and does not form stars too early. Effective accretion occurs later. In a merger, the gas is rapidly stripped, and does not experience friction.

4. Disruption of small structures

CDM models predict for a large-scale halo thousands of substructure clumps, which at cluster scale correspond to galaxies and are compatible with observations. However, this substructure feature is also expected at galactic scale, and raises many problems, when applied for example to our Galaxy. These small objects are not observed, and could be only dark halos (Chiu et al. 2001), but then would yield to an excessive heating if present (Moore et al. 1999). The assumption of some warm dark matter (WDM) helps to reduce the problem (Colin et al. 2000). Sub-structures do form in WDM models, but with an average concentration parameter which is approximately twice as small as that of the corresponding CDM sub-halos. This difference in concentration leads to a higher satellite destruction rate in WDM models, and a better agreement with observations. Models of self-interacting dark matter (SIDM), with primordial velocity dispersion also reduce substructure and eliminate central cusps (Hogan & Dalcanton 2000), but at the expense of new problems and fine tuning.

In the scenario where baryons dominate the mass in the center of galaxies, there is more cold gas in dwarf haloes, and much less mass concentration. Baryonic clumps heat dark matter through dynamical friction and smooth any cusp in dwarf galaxies (El-Zant et al. 2003, in prep).

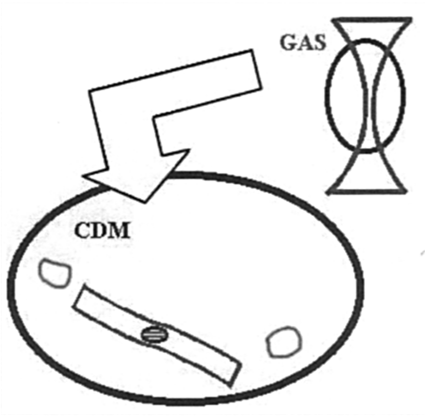

Figure 3. Schema indicating how the angular momentum loss can be avoided in mergers of galaxies. A large part of the gas mass in the infalling disk at right is cold and loosely bound in the outer parts of the galaxy. It is stripped away in the beginning of the interaction, and as very small clouds, does not experience the dynamical friction like the baryons bound to the galaxy.

The material inside galaxies is more dissipative, more resonant, and more prone to disruption and merging. The high merging rate may change the mass function for low-mass galaxies (e.g. Mayer et al. 2001). The disruption of dwarf satellites explains the formation of the stellar halo of the Milky Way (Bullock et al. 2001). The solution of the cusp problem, leading to more fragile galaxies, easier to disrupt, can lead also to the solution of the substructure problem.

5. Dark Matter in galaxy clusters

The fact that the baryonic gas could be highly condensed in galaxies is supported by the high baryon fraction in clusters. In rich clusters, the mass of the hot gas in the intra-cluster medium (ICM) can be much larger than the stellar mass in galaxies. Most of the baryons are in the hot ICM, which represents nearly the baryon fraction of the matter in the universe $f_b = \Omega_b/\Omega_m \sim 0.16$. The relative radial distribution of dark and visible matter is reversed, the mass becomes more and more visible with radius, contrary to what occurs in galaxies (David et al. 1995, Ettori & Fabian 1999, Sadat & Blanchard 2001).

Moreover, the hot gas has a relatively high metallicity (1/3 solar), and most of the metals in a cluster come from the ICM: there is about twice as much Fe in the ICM than in galaxies (Renzini 1997, 2003).

Since the metals are synthesised in galaxies, this means that either part of the hot gas comes directly from galaxies (by stripping, or disruption), or that stellar winds and supernovae have enriched the ICM. In fact, both sources of metals must be there, since metals expelled by SNe would not be sufficient. There is the same M_{Fe}/L_B in clusters and galaxies, implying the same processing in clusters as in the field. Clusters have not lost iron, nor accreted pristine material since the ratio between α elements (made in SNII) and iron is about solar in the ISM of all clusters (with little or no variation from cluster to cluster). This means that the metals come from normal stellar nucleosynthesis, and observations are compatible with the origin of the gas from the outskirts of galaxies.

6. Conclusion

The physics of the baryonic gas plays a crucial role in the formation of galaxies. The usual assumption that gas is shock heated to the virial temperature of the dark haloes might not be true. Instead, there could be cold gas accretion onto galaxies, with the consequence of more baryons accreted at a later time, and generally, more baryons condensed in galaxies, including dark baryons (Valageas et al. 2002). The main consequences are:

- baryons dominate in the centers of galaxies, masking the dark matter cusps;
- existence of large gas extent around galaxies, and less angular momentum lost by dynamical friction;
- small galaxies are more prone to disruption and merging, which reduces substructures within massive galaxies.

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