Multi-phase galaxy formation and quasar absorption systems

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Abstract. The central problem of galaxy formation is understanding the cooling and condensation of gas in dark matter halos. It is now clear that to match observations this requires further physics than the simple assumptions of single phase gas cooling. A model of multi-phase cooling (Maller & Bullock 2004) can successfully account for the upper cutoff in the masses of galaxies and provides a natural explanation of many types of absorption systems (Mo & Miralda-Escude 1996). Absorption systems are our best probes of the gaseous content of galaxy halos and therefore provide important constraints on models for gas cooling into galaxies. All physical processes that effect gas cooling redistribute gas and therefore are detectable in absorption systems. Detailed studies of the nature of gas in galaxy halos using absorption systems are crucial for building a correct theory of galaxy formation.

1. Multi-phase cooling

Modern theories of galaxy formation rest on the concept of gas cooling in dark matter halos (White & Rees 1978). However, simple models of single phase cooling predict a mass function of galaxies significantly higher than observed. Fig. 1, taken from Maller *et al.* (2005), shows the cumulative mass function of galaxies in an hydrodynamical simulation compared to the observations of Bell *et al.* (2003). The number density of galaxies at a fixed mass is too high at all masses, but becomes increasingly discrepant at high and low masses. Thus the mass of cooled gas must be significantly reduced from the simple single phase cooling implemented in the hydrodynamical simulation, especially in high and low mass halos.

One solution to the problem for high mass halos is to consider multi-phase cooling. A cooling astrophysical plasma is thermally unstable and will naturally fragment and form a two-phase medium (Field 1965). This means that a significant fraction of the halo gas can remain in a hot low-density galactic corona, while the remaining gas cools into warm clouds and settles into a galactic disk only after losing kinetic energy from collisions or ram pressure (Maller & Bullock 2004). The result of such a model is to significantly reduce cooling in massive dark matter halos, bringing the high mass end of the galaxy mass function into agreement with observations (see Fig. 2). Specifically, for a galaxy in a Milky Way size halo, if we take the warm clouds to have a mass of $10^6 M_\odot$, then the mass of the galaxy's disk is half of what it would be in single-phase cooling and in good agreement with estimates of the Milky Way's mass. For the gas that does not end up in the disk, two thirds are in a hot galactic corona while one third are in the form of warm clouds.

Besides the agreement with the high mass end of the observed stellar mass function we would like to see observational evidence for the multi-phase nature of halo gas. Maller & Bullock (2004) argue that the population of high velocity clouds seen in HI around the Milky Way represent this fragmented cloud population, the neutral component of mostly
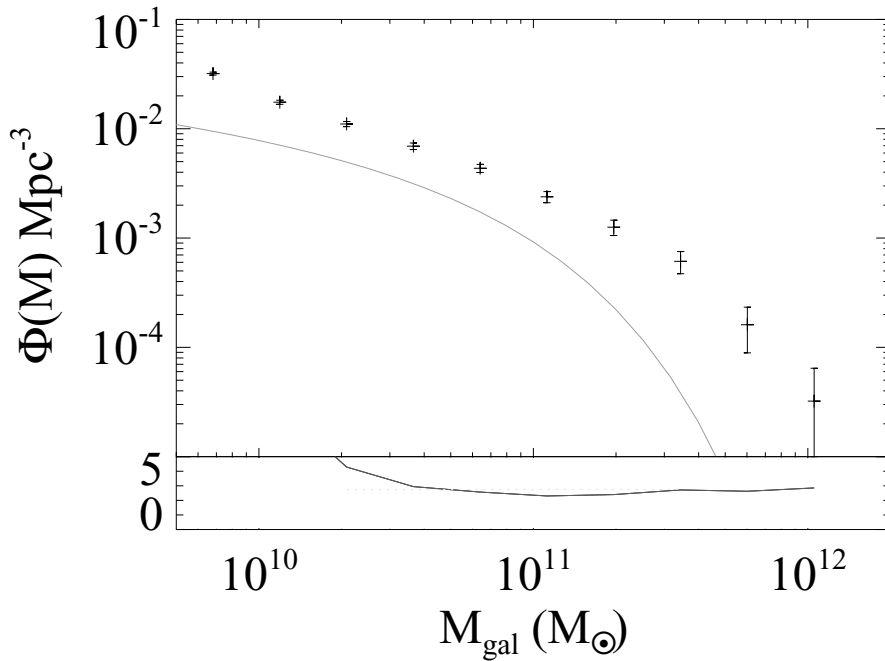
Figure 1. The upper panel shows the cumulative galaxy mass function at $z = 0$ for an hydrodynamical simulation, and for comparison the Schechter function fit of Bell *et al.* (2003). The y-axis is in co-moving units with $h = 0.7$. The simulation produces far too many low and high mass galaxies, but galaxies around the bend in the Schechter function are only a factor of 2-3 too massive. The bottom panel shows the factor by which the simulated galaxies masses should be divided in order to agree with the observations. For the galaxy masses of $2 \times 10^{10} M_\odot < M_{gal} < 6 \times 10^{11} M_\odot$, the correction is roughly a factor of 2.75 as shown by the dotted line and does not depend strongly on galaxy mass.

ionised 10^4 K clouds. For other galaxies, quasar absorption systems are the best way to verify this picture. Also, while we know that the cooling is thermally unstable, we do not know what the resulting distribution of warm cloud masses should be and how it might depend on halo mass and redshift. Thus studying these clouds in differing environments is crucial to understanding the effect of multi-phase cooling on galaxy formation.

It has long been assumed that quasar absorption systems can be identified with the gaseous content of galaxy halos (Bahcall & Spitzer 1969). In fact the very multi-phase model discussed here has been proposed as the source of Lyman limit and metal-line systems by Mo & Miralda-Escude (1996). In the next section I describe the gaseous content of a galaxy's halo and how observations of absorption systems may help us constrain their properties.

2. The gaseous content of a galaxy's halo

Fig. 3 shows a sketch of possible components of the gaseous content of a galaxy's halo. While we know a neutral gas disk is present in all spiral galaxies locally, the hot gas disk is only detected in the Milky Way (Wang *et al.* 2005). The existence of a Galactic corona was postulated for the Milky Way long ago (Spitzer 1962); however, it remains difficult to detect directly. This same component is clearly seen in clusters and groups where the
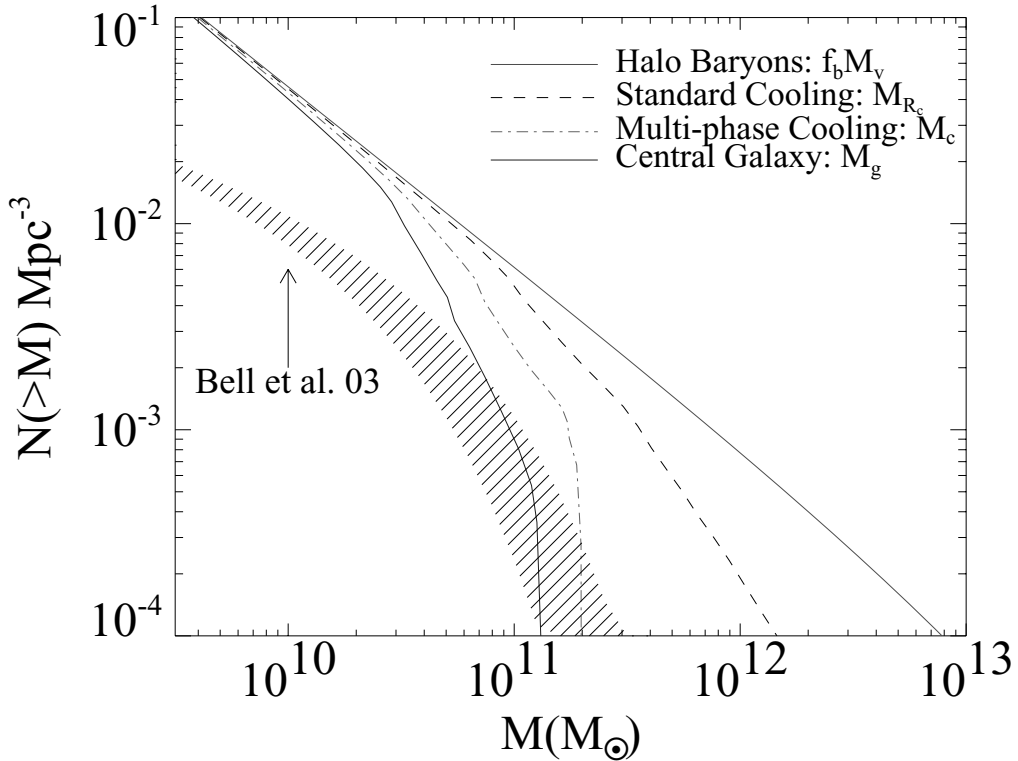
Figure 2. The cumulative baryonic mass function of galaxies reported by Bell *et al.* (2003) (shaded band) compared to the cumulative mass function of halo baryons (top solid line). The short-dashed line shows the (central) galaxy mass function that arises from assuming all of the mass within each halo's cooling radius cools onto the central galaxy. This is the same result seen in the hydrodynamical simulations (previous figure). The dot-dashed line is the cooled mass function that arises in the Maller & Bullock (2004) picture, which allows for the presence of a hot corona in each halo. Finally, the lowest solid line shows the central galaxy mass function that results from modelling the survival probability of cooled clouds in the halo, assuming a typical cloud mass of $5 \times 10^6 M_\odot$. Only clouds that fall to the centre of each halo are assumed to contribute to the central galaxy. No merging has been accounted for in this estimate. Merging will tend to populate the massive tail of the galaxy mass function, likely bringing it even more closely in line with what is observed.

higher temperature makes it visible in X-rays. Recently, there has been indirect evidence for the existence of a Galactic corona around the Milky Way from its interaction with high velocity clouds (e.g. Tripp *et al.* 2003).

As described below, the contributions of gas stripped from satellite galaxies, cooled from the Galactic corona, or ejected by energetic feedback to the gaseous halo is still unclear. While all these processes happen at some level, their relative importance is model dependant and probably a function of halo mass and redshift. Further observations and more detailed modelling are needed to build a more complete picture. Below I give a brief description of each component and what absorption systems they maybe associated with.

• *The neutral gas disk.* Neutral gas in a galaxy's disk is the fuel for star formation and is observed in HI and as damped Lyman alpha and Lyman limit systems. However,

based on the kinematics of damped Lyman alpha systems (Prochaska & Wolfe 1997; 1998) it is not clear that at high redshift neutral gas is primarily associated with gas disks (Haehnelt *et al.* 1998; Maller *et al.* 2001). It is also unclear where the transition from predominantly neutral to predominantly ionised gas occurs, except that it is below the defining column density of damped Lyman alpha systems.

• *The hot gas disk.* The Milky Way's disk is enveloped in a second hot ($\sim 10^6 K$) disk with a scale length ~ 1 kpc. The cooling times for this component are short, so it must be constantly refuelled (or re-energised) most likely from supernova explosions. This component is the dominant source of X-ray absorption around the Milky Way making direct detection of the Galactic corona and the local warm hot intergalactic medium extremely difficult (Wang *et al.* 2005).

• *The Galactic corona.* This is the relic gas from the formation of a galaxy's dark matter halo. In clusters and massive groups it is observed in X-ray emission. In smaller mass halos cooling times are shorter and the Galactic corona must have a lower density (in the Milky Way of order 10^{-4}cm^{-3}). Therefore, it is difficult to detect in X-rays, which is further complicated by the existence of the hot gas disk. In dwarf galaxies the cooling times are so short that there is effectively no hot gas corona.

• *Gas stripped from satellite galaxies.* Gas stripped from satellite galaxies during mergers will also inhabit a galaxy's halo (Mayer *et al.* 2005). The most impressive example of this locally is the Magellanic Stream. This gas can be thought of as a subset of warm clouds infalling into the galaxy with multi-phase cooling and can be a source of Lyman limit and metal-line systems.

• *Gas clouds from multi-phase cooling.* With multi-phase cooling we expect warm clouds to condense out of the cooling galactic corona (Maller & Bullock 2004; Mo & Miralda-Escude 1996). These clouds (seen perhaps as high velocity clouds in the Milky Way) may give rise to Lyman limit and metal-line systems. This gas can help explain the kinematics of high-ionisation-state gas in damped Lyman alpha systems (Maller *et al.* 2003).

• *Gas ejected by supernova or other feedback.* Supernova and other energetic sources (e.g. AGN) can eject gas from a galaxy's disk into the halo and possibly entirely out of the halo. This is directly detected around star-bursting galaxies. This gas can give rise to metal-line and Lyman limit systems and even possibly damped Lyman alpha systems at high redshift.

It is important to note that low mass dark matter halos are expected to have a negligible mass in the Galactic corona. Therefore, there is little mass in warm clouds in these halos, *and* it is easier to eject gas by supernova driven winds. Thus, it is likely that the content of a galaxy's halo may be a strong function of the galaxy's halo mass. Most absorption systems could be the result of more than one component, complicating the interpretation of observations. Therefore, it is important to look for ways to distinguish which component of the gaseous halo is the source of an absorption system. Metallicities, ionisation states, and kinematics can all be useful diagnostics in this endeavour. Constraints on the properties of each component can be used to distinguish between models of gas cooling in galaxies and thus are central to understanding galaxy formation.

3. Conclusions

I have shown how multi-phase cooling can match the high mass end of the galaxy mass function above and that observations of absorption systems are an important probe of this model. Only from absorption systems can we probe how the warm cloud masses vary with halo mass and redshift. Furthermore, I have outlined the gaseous content of
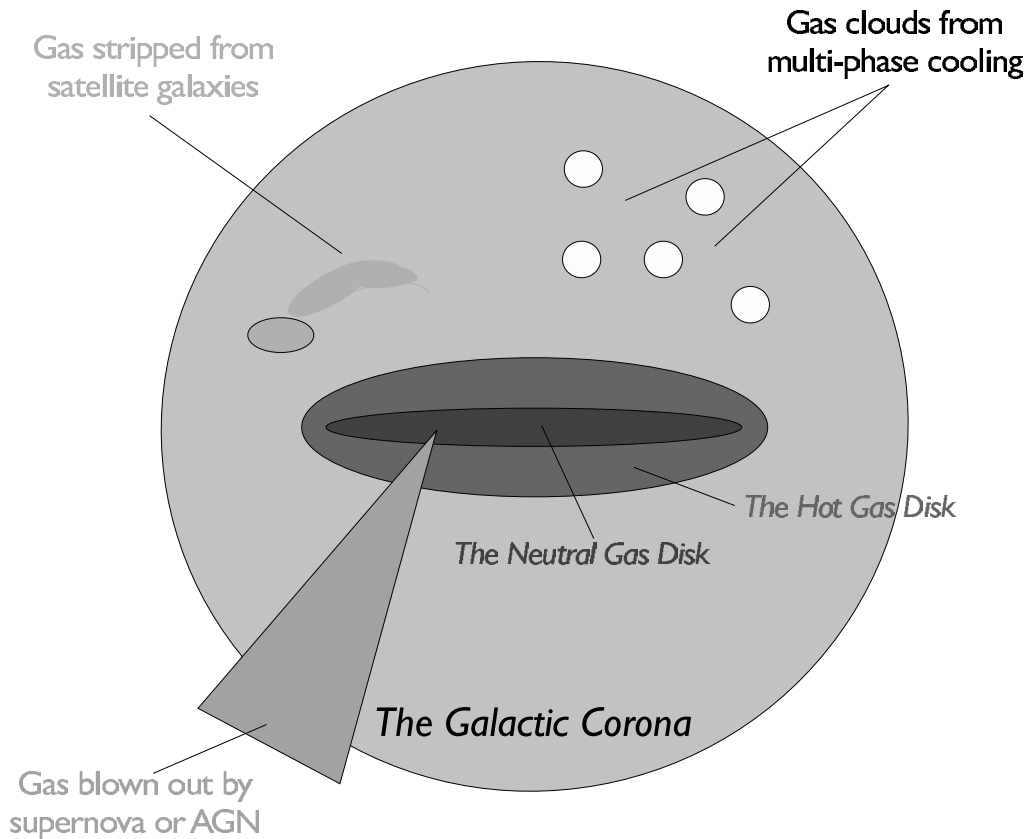
Gas stripped from
satellite galaxies

Gas clouds from
multi-phase cooling

The Hot Gas Disk

The Neutral Gas Disk

The Galactic Corona

Gas blown out by
supernova or AGN

Figure 3. This figure shows the possible gaseous contents of a Milky-way-type galaxy halo. The neutral gas disk and surrounding hot gas disk are both embedded in the galactic corona which fills the galaxy's dark matter halo. Both the hot gas disk and the galactic corona have temperatures of $\sim 10^6$ K. The galaxy's halo may also contain gas stripped from infalling satellites, gas clouds that have cooled out of the galactic corona (multi-phase cooling), and gas that has been ejected from the disk because of energetic feedback. All of these sources of gas may give rise to absorption systems in quasar spectra.

a galaxy's halo and how absorption systems probe various components of it. Because different components can give rise to the same type of absorption system it is necessary to use other diagnostics to determine what component the absorption system is probing. In summary, the study of absorption systems is crucial to understanding how gas cools in dark matter halos and therefore how galaxies form.

Acknowledgements

References

Bahcall, J. N., Spitzer, L. J., 1969, ApJ, 156, L63

Bell, E. F., McIntosh, D. H., Katz, N., Weinberg, M. D., 2003, ApJS, 149, 289

Field, G. B., 1965, ApJ, 142, 531

Haehnelt, M. G., Steinmetz, M., Rauch, M., 1998, ApJ, 495, 647

Maller, A. H., Bullock, J. S., 2004, MNRAS, 355, 694

Maller, A. H., Katz, N., Keres, D., Dave, R., Weinberg, D. H., 2005, MNRAS, submitted

Maller, A. H., Prochaska, J. X., Somerville, R. S., Primack, J. R., 2001, MNRAS, 326, 1475

Maller, A. H., Prochaska, J. X., Somerville, R. S., Primack, J. R., 2003, MNRAS, 343, 268

Mayer, L., Mastropietro, C., Wadsley, J., Stadel, J., Moore, B., MNRAS, submitted, astro-ph/0504277

Mo, H. J., Miralda-Escude, J., 1996, ApJ, 469, 589

Prochaska, J. X., Wolfe, A. M., 1997, ApJ, 487, 73

Prochaska, J. X., Wolfe, A. M., 1998, ApJ, 507, 113

Spitzer, L., 1962, Physics of Fully Ionized Gases, (New York: Interscience)

Tripp, T. M., *et al.*, 2003, AJ, 125, 3122

Wang, Q. D., Yao, Y., Tripp, T. M., Fang, T. T., Cui, F., 2005 ApJ, submitted

White, S. D. M., Rees, M. J., 1978, MNRAS, 183, 341