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Simulating the ionisation and metal enrichment history of the intergalactic medium

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Abstract. Simulations of galaxy formation require strong feedback to produce realistic galaxies. Observations of starburst galaxies both at low and high redshift often show signatures of strong galaxy-wide winds. Are such winds common, and are they the mechanism which pollutes the intergalactic medium with metals? Which are the sources of ionising photons at higher redshift? Detailed observations of galaxies and their surroundings and comparison with cosmological simulations to eliminate biases and test models are required to address these questions.

Keywords. galaxies: formation, intergalactic medium; quasars: absorption lines

1. Introduction

Feedback is thought to play an important role in the formation of galaxies. Theoretical models invariably include strong feedback from star formation for several reasons, for example to avoid overproducing the number of low mass galaxies (White & Rees 1978) or the fraction of baryons that cools (e.g., Balogh *et al.* 2001). Semi-analytical models (e.g., Cole *et al.* 2000) that combine a strong feedback prescription with the hierarchical built-up of dark matter dominated haloes do well in reproducing the observed statistical properties of galaxies as determined from large surveys (e.g., Eke *et al.* 2004).

Simulations could follow the feedback dynamics in detail in principle, yet the huge range of scales involved means that they too need to model some of the processes in a more heuristic fashion. Springel & Hernquist (2003) use a multi-phase model (see also Yepes *et al.* 1997) for the interstellar medium (ISM) to describe the interaction between cold, star forming gas, and the warmer interstellar medium that gets heated by supernovae explosions. They illustrate how the cosmological star formation history depends on numerical parameters, such as box size and resolution, by comparing results from a large number of runs. The numerical resolution can be improved by performing a ‘zoomed simulation’, in which the region of interest is simulated at high resolution whereas its cosmological surroundings are followed at a much lower resolution. Okamoto *et al.* (2005) show that such higher resolution simulations are able to produce galaxies that resemble present day spirals, but only when strong feedback is included. The formation history of the stars and their abundance pattern can be compared with detailed observations of nearby galaxies (e.g., Harris & Zaritsky 2004). This is a promising route to constrain some of the uncertain parameters in the models. The feedback in most of these simulations results from supernovae, but active galactic nuclei might also play a role, both in galaxies (e.g., Di Matteo *et al.* 2003) and in galaxy clusters (e.g., Dalla Vecchia 2004).

Observations of galactic winds, both in local starbursts (e.g., Heckman 2000) and in high-redshift Lyman Break galaxies (e.g., Pettini *et al.* 2001), show that strong feedback may indeed result in a galaxy-wide wind, but how common is this phenomenon?

The complex interplay between the different ISM phases can be modelled in a variety of ways. For example the sticky particle model of Booth, Okamoto & Theuns (in preparation) yields quiescent star formation such as occurs in most disk galaxies today without requiring strong feedback. Clearly simulations need more constraints from observations. One promising avenue is to investigate whether the intergalactic medium (IGM) shows evidence for the presence of wide-spread galactic winds.

2. Metals in the IGM and galactic winds

The IGM can be observed in great detail in the spectra of background quasars. These contain hundreds of absorption lines due to (neutral) hydrogen left over from the Big Bang (see Rauch 1998 for a review), but curiously also contain lines due to (highly ionised) transitions of carbon, silicon and other 'metals' (e.g., Cowie *et al.* 1995). Although this would not be surprising for sight lines passing through the ISM of a galaxy, metals also seem to be present at densities far lower than in the ISM. Therefore these metals, synthesised in stars, managed to escape from where they were formed, possible swept out of the galaxy by a galactic wind. The Pixel Optical Depth (POD) method derives the metal distribution from a quasar spectrum, by correlating the optical depth in a given hydrogen pixel with those in the metal pixels at the same redshift (Aguirre *et al.* 2002). The density corresponding to a given hydrogen optical depth is inferred from simulations, and care needs to be taken because of differences in thermal broadening between different species, but the major uncertainty in inferring a *metallicity* is the ionisation correction. Simulations are used to estimate the uncertainties and biases in the interpretation. This method detects carbon at densities below the cosmic mean, at redshifts $z \sim 3$, and finds little evidence for redshift evolution over the range $2 \leqslant z \leqslant 4.5$ (Schaye *et al.* 2003). Songaila (2005) finds that this apparent lack of evolution extends to even higher $z \leqslant 5$ with a decrease in metallicity by a factor ~ 2 to $z = 6.4$.

The apparent lack of metallicity evolution is surprising, given the vigorous star formation and presumably associated metal production occurring at redshifts $z \sim 3$. Theuns *et al.* (2002a) performed cosmological hydrodynamical simulations of galaxy formation, in which the metals were swept out of a galaxy by a hot metal enriched galactic wind produced by supernovae explosions. The wind progresses furthest in the lower density surroundings of the galaxy leaving the nearby filaments mostly intact. This is why even strong winds have no obvious effect on observed hydrogen lines, since those result mostly from sight lines crossing filaments (see also Theuns, Mo & Schaye 2001)

These simulations are able to reproduce the observed statistics of the stronger CIV systems, including the large scatter between CIV and HI column densities, as illustrated in Fig. 1. The metallicity of the hot wind bubble that surrounds the galaxy is quite high, with most of the carbon in gas too hot to produce significant CIV absorption. This may be why there is little evidence for metallicity evolution yet vigorous star formation: the metals are collisionally ionised and do not absorb in the observed lower ionisation transitions.

Is the observed CIV the low temperature tail of this hot gas? The more detailed POD analysis by Aguirre *et al.* (2005) of this simulation, and another similar simulation by V. Springel, also looked at other transitions to get a handle on the temperature and density of the metal enriched gas. Neither simulation matches the data well, implying that the observed temperature-density structure is different from the simulated one. Curiously, a simulation without any feedback, where the metals were introduced by hand, *did* reproduce the data: were the observed metals put in place at much higher redshifts as a result of population III star formation?

Adelberger *et al.* (2005) used the Lyman-break technique to identify galaxies close to the sight line of high $z \sim 3$ QSOs. They find a strong correlation between the presence of

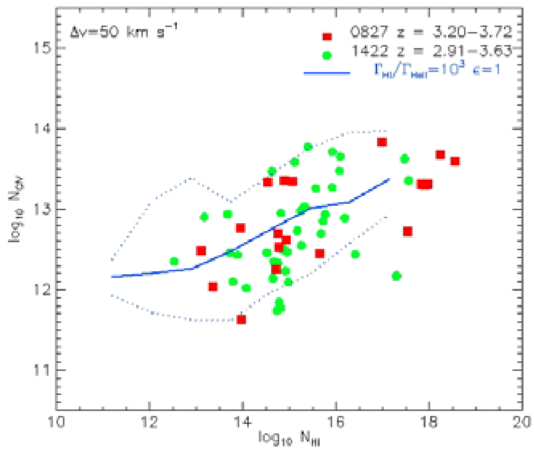

Figure 1. Comparison of the observed correlation between HI and CIV column density in QSOs APM 08279+5255 (squares) and Q 1422+231 (circles), and that obtained from a hydrodynamical cosmological simulation (full line: median, dotted lines 5 and 95 per centiles) in which carbon is swept out of galaxies by a hot galactic wind. The simulation reproduces both the mean and the observed large scatter in CIV/HI See Theuns *et al.* (2002a) for more details.

metals in the spectrum, and a galaxy at the same redshift. Consequently they argue that it is the observed galaxies that produce the observed metals. Clearly the jury is still out, since biasing could potentially convince an early generation of pop III stars to pollute what will become the surroundings of later Lyman-break galaxies.

The interpretation of metal lines data in terms of *metallicity* will always depend on details of the ionisation correction, which suffers from uncertainties in the shape of the UV-background, and on the detailed temperature-density relation of the gas. An alternative way to study the surroundings of galaxies is to investigate the distribution of neutral hydrogen around them, using the *proximity effect.*

3. The surroundings of galaxies as probed through the proximity effect

Quasar light needs to pass through the presumably high-density region of its parent galaxy on its way to us. Rollinde *et al.* (2005) describe a novel way, based on optical depth statistics, to probe the surroundings of the very bright QSOs observed with UVES as part of an ESO Large Programme. They note that the optical depth probability distribution function (PDF) evolves with redshift (due to the expansion of the Universe) in a simple manner. Calibrating this scaling then allows one to compare the mean (neutral) hydrogen density in a redshift independent way. Applying this technique in regions near and far from a QSO allows one to infer the density distribution around these bright sources. They infer over densities of a few on scales of several Mpc for a typical value of the amplitude of the ionising background, typical for the over density around massive proto-clusters as inferred from large simulations. This interpretation depends on the amplitude of the ionising background, which is not very well constrained.

4. The amplitude of the ionising background

The hydrogen photo-ionisation rate Γ due to the ambient UV-background evolves with redshift as the sources evolve. This important parameter is presently still rather poorly

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constrained. Observations of the proximity effect (Scott *et al.* 2000) reveal a large scatter in Γ between different QSOs at the same redshift, presumably partly due to the fact that the amount of absorption also depends on the density structure around the QSO. Determinations of Γ based on the mean level of absorption in the Lyman-α forest depend on the assumed level of the continuum which may be difficult to determine (Bernardi *et al.* 2003; Bolton *et al.* 2005). Comparison to models of the emissivity evolution (Haardt & Madau 1996) suggest that at higher $z \geqslant 4$, Γ is increasingly dominated by galaxies. Because galaxy spectra are softer than quasar spectra, this has important effects on the interpretation of metal line data (Aguirre *et al.* 2004) and the ionisation state of Helium (Theuns *et al.* 2002b).

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Discussion

Gallagher: Can you make an estimate of how much mass loss you need to achieve the feedback to make disks? Also, mass might be more easily lost for cases where galaxies are in motion with respect to the local IGM, i.e. later rather than very early-on when velocities were low.

Theuns: Strong mass loss may not be required to make realistic disks, but the low baryon fraction of galaxies suggests a significant amount of gas has in fact been lost. It may be easier to loose mass early since the potential wells of small galaxies are less deep than of older, more massive ones.