Numerical Simulations of Galactic Outflows and Evolution of the IGM

Hugo Martel\textsuperscript{1,2}

\textsuperscript{1}Département de physique, de génie physique et d’optique, Université Laval, Pavillon Alexandre-Vachon, Quebec City, QC, G1V 0A6, Canada
\textsuperscript{2}Centre de Recherche en Astrophysique du Québec
E-mail: hmartel@phy.ulaval.ca

Abstract. Galactic outflows play a major role in the evolution of galaxies and the intergalactic medium (IGM). The energy deposited into the interstellar medium by supernovae and active galactic nuclei can accelerate the gas past the escape velocity, and eject it into the IGM. This will affect the subsequent evolution of the galaxy, by reducing or eliminating star formation, and quenching the accretion of matter onto the central AGN. Galactic outflows is the main process by which energy and processed interstellar matter is transported into the IGM. This affects the subsequent formation of other galaxies. The energy carried by outflows can strip protogalactic halos of their gas, preventing galaxies from forming. Conversely, the metals carried by outflows can modify the composition and cooling rates of the gas in protogalactic halos, favoring the formation of galaxies. In this paper, I review the various techniques used to simulate galactic outflows and their impact on galaxy and IGM evolution.

1. Galactic Outflows

Galactic outflows are the primary mechanism by which galaxies deposit energy and metal-enriched gas into the IGM. This can greatly affect the evolution of the IGM, and the subsequent formation of other generations of galaxies. Feedback by galactic outflows can provide an explanation for the observed high mass-to-light ratio of dwarf galaxies and the abundance of dwarf galaxies in the Local Group, and can solve various problems with galaxy formation models, such as the overcooling problem and the angular momentum problem (see [1] and references therein). Galactic outflows can explain the high metal content (0.1 - 1%\textsubscript{\odot}) of the IGM, observed via the Lyman-\alpha forest [2, 3, 4, 5, 6, 7], the high metal content (0.3\textsubscript{\odot}) of the intracluster medium in massive X-ray clusters, and the high entropy content and scaling relations in X-ray clusters [8, 9, 10, 11, 12, 13]. They also provide observational tests that can constrain theoretical models of galaxy evolution. Local examples of spectacular outflows in dwarf starburst galaxies include those of the extremely metal-poor I Zw 18 [14, 15] and NGC1569 [16]. More massive spirals, such as NGC7213 [17], also show evidence of global outflows. Figure 1 shows a composite image of the galaxy M82. The edge-on disc of the galaxy appears in the optical, while the gas expelled by the galaxy is seen in H\alpha. That gas forms a bipolar outflow aligned along the direction normal to the plane of the galaxy (image courtesy Smith, Gallagher, & Westmoquette).
2. Joint Evolution of Galaxies and the IGM

Figure 2 summarizes the various physical processes driving the evolution of galaxies and the IGM. Gas and dark matter in the IGM is converted into galaxies by the galaxy formation process. This normally results in a starburst: the rapid formation of a large number of stars in the newly-formed galaxy. Later-on, additional IGM matter can be accreted onto existing galaxies, possibly resulting in additional starbursts. Within galaxies, star formation converts ISM gas to stars, and some of that gas is eventually returned to the ISM by stellar winds, AGBs and SNe, resulting in a metallicity increase both in the ISM and in stars. When the energy deposited into the ISM by SNe, AGNs, and cosmic rays is sufficiently large, energy, momentum, and metal-enriched gas can be ejected from the galaxy and deposited into the surrounding IGM. This can have either a positive or a negative feedback effect of the subsequent formation of other galaxies. Note that galactic outflows are not the only process by with galaxies can return matter into the IGM. Interactions between galaxies might result in mergers, tidal disruption, or harassment, in which cases some of the content of galaxies (both gas and stars) can be dispersed into the IGM. Also, ram-pressure stripping and tidal destruction can have the same effect, though they normally do not involve field galaxies, and only take place in massive clusters.
3. Individual Outflows: Analytical Models

The propagation of galactic outflows into the IGM can be described with a simple analytical model\cite{18,19}. In this model, the injection of thermal energy into the ISM produces an outflow of radius $R$, which consists of a dense shell of thickness $R\delta$ containing a cavity. A fraction $1 - f_m$ of the IGM gas initially located inside radius $R$ is piled up in the shell, while a fraction $f_m$ of that gas is distributed inside the cavity. We normally assume $\delta \ll 1$, $f_m \ll 1$, that is, most of the gas is located inside a thin shell. This is called the thin-shell approximation.

The evolution of the shell radius $R$ expanding out of a galaxy of mass $M_{\text{gal}}$, is described by the following system of equations:

\begin{align}
\ddot{R} &= \frac{8\pi G (p - p_{\text{ext}})}{\Omega_b H^2 R} - \frac{3}{R} \left( \dot{R} - HR \right)^2 - \frac{\Omega H^2 R^2}{2} - \frac{GM_{\text{gal}}}{R^2}, \quad (1) \\
\ddot{p} &= \frac{L}{2\pi R^3} - \frac{5\dot{R}p}{R}, \quad (2)
\end{align}

where a dot represents a time derivative, $\Omega$, $\Omega_b$, and $H$ are the total density parameter, baryon density parameter, and Hubble parameter at time $t$, respectively, $L$ is the luminosity (rate of energy injection), $p$ is the pressure inside the cavity resulting from this luminosity, and $p_{\text{ext}}$ is the external pressure of the IGM. The four terms in equation (1) represent, from left to right, the driving pressure of the outflow, the drag due to sweeping up the IGM and accelerating it from velocity $HR$ to velocity $\dot{R}$, and the gravitational deceleration caused...
by the expanding shell and by the halo itself. The two terms in equation \(E\) represent the increase in pressure caused by injection of thermal energy, and the drop in pressure caused by the expansion of the shell, respectively. To use this model, we need to specify the sources of energy (SNe, AGNs, cosmic rays,...) driving the outflow, in order to determine the rate of energy injection \(L\). We also need to specify the external pressure \(p_{ext}\) of the IGM into which the outflow is propagating, which depends upon various approximations about the composition, temperature, and ionization state of the IGM\[^{20, 21}\].

4. Individual Outflows: Simulations

Numerical simulations of outflows from isolated dwarf galaxies have been performed by MacLow and Ferrara\[^{22}\]. In these simulations, they start with a disc galaxy in equilibrium. They then add a continuous source of energy in the center of the galaxy (hence this is not a starburst). The energy added drives the expansion of a bipolar outflow that propagates in the direction normal to the disk of the galaxy. For some combinations of the parameters, they found that the entire ISM is ejected and escapes the system.

One limitation of these simulations is that galaxies are treated as isolated. Martel & Shapiro\[^{23}\] simulated the formation of a galactic halo at the intersection of two filaments inside a cosmological pancake. The halo grows by gravitational instability, and when the gas density reaches a certain threshold, a large amount of thermal energy is deposited into the gas, simulating a starburst. That energy drives the expansion of an outflow. The galaxy is isolated (that is, not surrounded by other galaxies), but the cosmological environment is taken into account. The galaxy can accrete matter from the surrounding structures, and these structures influence the propagation of the outflow. These simulations show that galactic outflows tend to be anisotropic, and propagate along the direction of least resistance. In some cases, the entire ISM is blown away by the outflow, as in \[^{22}\], but accretion for the filaments can rebuild the gas content of the galaxies, possibly leading to additional starbursts.

5. Cosmological Simulations

Simulations of isolated galaxies have several limitations. They do not describe the effect of the outflow on the evolution of the IGM and the subsequent formation of other galaxies. They do not account (usually) for the effect of surrounding structures (filament, pancakes, other galaxies) on the propagation of the outflow. Finally, they do not describe the global effect of the galaxy population on the evolution of the IGM (filling fraction of metals, distribution of metals in the IGM, cross-pollution between galaxies, ...). To address these issues, we need to perform full cosmological simulations, with an entire galaxy population, inside a cosmological volume representative of the universe. This causes a major problem with dynamical range: cosmological simulations simply cannot resolve the galactic scales, where the physical processes generating the outflows are taking place.

The solution is to combine numerical simulations of large-scale structure with a subgrid treatment of galaxy formation and outflows. A numerical algorithm is used to simulate large-scale structure formation. During the simulation, the algorithm determines where and when stars and/or galaxies form, using some
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criterion. In gravity-only simulations, galaxies form when the matter density $\rho_{\text{DM}}$ exceeds a certain threshold $\rho_{\text{thres}}$. In hydrodynamical simulations, galaxies form in regions where the gas density is high and the temperature is low, $\rho_{\text{gas}} > \rho_{\text{thres}}$ and $T < T_{\text{thres}}$.

Once the galaxies have been located in the simulation, the algorithm can simulate the propagation of outflows and their effect on the nearby IGM matter. There are two possible approaches for doing this: analytical, or subgrid physics.

5.1. Numerical $+$ Analytical
The analytical approach consists of “painting” an analytical solution for outflows on a numerical solution of galaxy and large-scale structure formation. Once a galaxy forms, the algorithm calculates analytically the propagation of the outflow originating from that galaxy, taking into account the mass of the galaxy, its formation redshift, and the surrounding IGM. Early simulations\cite{20, 24, 25} used the basic Tegmark et al. analytical model\cite{18}, which assumes that the outflow propagates into a uniform IGM. This model was later modified to account for the radial\cite{26} or angular\cite{21, 27, 28} variations of the IGM density and pressure. Figure 3 shows a simulation of IGM enrichment, which combines an N-body simulation with an analytical outflow model\cite{28}. The black dots represent the particles, and show a network of clusters connected by filaments. These dense regions are the sites of galaxy formation. The gray areas represent the metal-enriched gas that has been deposited into the IGM by outflows.

These algorithms take into account, not only the enrichment of the IGM, but also the effect of outflows on other galaxies. If a protogalaxy is hit by an outflow, the algorithm estimates whether ram-pressure stripping is sufficient to prevent the galaxy from forming. If it is not, then the protogalaxy is enriched in metals, which reduces the cooling rate of the gas.

5.2. Numerical $+$ Subgrid Physics
In the subgrid approach, the algorithm identifies sites of star and/or galaxy formation. The algorithm then creates an object that represents structures at unresolved scales. In Lagrangian, particle-based simulations, these objects can be star particles, that represent a population of stars\cite{29, 30}, or, at larger scales, they can be Galaxy Objects (GALOBs), that represent groups of galaxies\cite{31}. In Eulerian, grid-based methods, the algorithm creates Galaxy Constructs (GALCONs), subgrids that represent individual galaxies\cite{32}.

Once these objects are created, they will affect the surrounding IGM, in the form of feedback and chemical enrichment. In Lagrangian algorithms, the algorithm identifies the gas particles located within a certain distance of each object. The metallicity of these particles is then increased, to reflect the enrichment caused by the outflow. There are two basic approaches used to handle feedback: thermal and kinematic. In the first case, the temperature of the nearby particles is increased\cite{33}. In the second case, the nearby particles are given an outward “kick”\cite{30, 34, 35}. This is illustrated in the first two panels of Figure 4. Notice that these two approaches often produce similar results. Increasing the temperature of the nearby particles results in a pressure gradient that will accelerate particles outward.
Figure 3. Cosmological simulation of structure formation and outflows in a ΛCDM universe, inside a computational volume (15 Mpc)$^3$. The simulation combines a numerical algorithm for the formation of large-scale structures with an analytical model for outflows. The figure shows the matter distribution (black particles) and the metal-enriched gas deposited in the IGM by outflows (gray areas), inside a slice of comoving thickness 0.1 Mpc, at redshift $z = 2$.

In Eulerian algorithms, we are dealing with cells and not particles. The algorithm identifies the cells located within a certain distance of each object. Chemical enrichment and feedback is then handled as in the Lagrangian algorithms. The metallicity in each nearby cell is increased, and either the temperature or the velocity in each cell is modified to account for feedback\cite{36,37}. This is illustrated in the last panel of Figure 4.

In all cases, the algorithm directly calculates the propagation of the outflow. Only the source of the outflow (stars or galaxies), their formation, energy production, and metal production, is treated using subgrid physics.
Figure 4. Prescriptions for implementation of feedback in numerical simulations. The large black dot shows the object producing the outflow, and the circle shows the neighboring region where feedback and metal-enrichment takes place. A) Thermal feedback in particle-based simulations. Thermal energy is deposited on neighboring particles (shown in black). B) Kinetic feedback in particle-based simulations. Neighboring particles are given an outward kick. C) Thermal and kinetic feedback in grid-based simulations. Energy is added to neighboring cells (shown by thick lines).

5.3. The Freeze-out Approximation
There is a third, radically different approach for including galactic outflows in cosmological simulations\cite{38}. Galaxies are identified in the output of an SPH simulation. Then, an algorithm calculates the propagation of outflows from these galaxies in $N$ different directions, by estimating the resistance encountered by the outflow in each of these directions. We refer to this method as the freeze-out approximation, because the dynamics of the IGM is not influenced by the outflow. Instead, the outflow propagates into a “frozen” IGM. The main limitation of this approach is that, since it uses the output of an SPH simulation and introduces the outflows \textit{a posteriori}, the feedback effect of these outflows cannot be simulated (i.e., outflows do not influence the formation of other galaxies). The main advantage is that several outflow models can be considered, and their parameters can be varied, without having to redo the full cosmological simulation.

6. Summary
Galactic outflows play a critical role in the formation of galaxies and the evolution of the IGM. Outflows expel interstellar gas into the surrounding IGM, reducing the mass of the ISM and potentially quenching star formation. The energy, momentum, and metal-enriched gas deposited into the IGM by outflow affects its evolution and the subsequent formation of galaxies, either by stripping protogalaxies of their gaseous content or by modifying the cooling rate of protogalactic gas.

Analytical models and numerical simulations of outflows produced by isolated galaxies are useful but have important limitations. They do not describe the evolution of the IGM and the subsequent formation of new galaxies, they do not account for the effect of surrounding structures on the propagation of outflows,
they often ignore the replenishment of ISM by accretion of gas from nearby structures, and finally they do not describe the global effect of an entire galaxy population on the evolution of the IGM.

Cosmological simulations are necessary to address these issues, but purely numerical simulations lack the necessary resolution to properly resolve cosmological and galactic scales simultaneously. The solution consists of combining cosmological simulations with a subgrid treatment of physical processes at galactic scales. This can be done using either an analytical outflow model or a subgrid numerical treatment of feedback and metal enrichment by outflows. Such simulations can describe the propagation of outflows and their impact on the evolution of the IGM inside an entire cosmological volume containing a representative part of the universe.

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