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Cold Blobs in Hot Winds

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Many galaxies that have undergone periods of rapid star formation show strong winds that can transport material to great distances from the plane of the galaxy. These outflows are complex and contain hot, ionised gas as well as cold, atomic gas. The fate of the cold gas in these hot, often supersonic winds is the subject of much debate. The topic is important for our understanding of the cycle of matter in the universe. For this purpose we simulate the evolution of cold blobs in hot winds. In particular, we investigate the impact of thermal conduction and magnetic fields and cosmic rays onto the survival of the clouds and the observational consequences.

1 Introduction

Powerful events inside galaxies drive strong winds that can expel substantial amounts of matter from the gravitational pull of the galaxy. Observations of such often spectacular events show fast winds with complex thermal structures. Outflows occur in star-forming galaxies and they play a central role in the history of galaxy formation[9]. They are thought to cause the strong correlation between mass and metallicity observed in low-mass galaxies[10]; they are needed to reconcile the number density of observed galaxies with our cosmological model[1]; and they are essential to the transport of heavy elements into the intergalactic medium. However, despite the central importance of galaxy outflows, the processes that control their evolution are extremely difficult to constrain, both, theoretically and observationally.

From the observational point of view, the most important issue is measuring and interpreting the evolution of the wide range of multiphase material found in galaxy outflows. The colder phases have complex velocity profiles[22] that are strongly correlated with various properties of the galaxy. The final fate of this material is not known, for example, whether it eventually mixes with the hot gas or condenses into very dense clumps. In fact, even the presence of this medium is surprising, as simple theoretical estimates predict that it should be disrupted by interactions with the hot wind fluid well before it is accelerated to significant velocities[16].

Furthermore, this uncertainty is somewhat surprising given that simulations of cold clouds interacting with a hot, high-velocity medium have been carried out by many authors, with simulations going back almost 5 decades. Several groups have carried out, both, two and three-dimensional simulations: neglecting radiative cooling[13], including radiative cooling[12], including both radiative cooling and thermal conduction[14,15], including the impact of magnetic fields[19], and including non-equilibrium chemistry effects[11]. Yet, despite the usefulness of these studies in elucidating the physics of cold clouds in a hot medium, none of them has spanned the range of parameters and timescales necessary to study galaxy outflows.

The key issue in this case is the ability for the hot wind to accelerate cold material, before it disrupts it. In the definitive study of the non-radiating, hydrodynamic case, Klein *et al.* (1994) showed that if hot material pasts a cloud at a velocity that is much greater than the cloud's internal sound speed, it will shred the cloud on a so-called "cloud crushing" timescale. Subsequent studies showed that magnetic fields and radiative cooling can delay this disruption by a few cloud crushing times but not prevent it[15]. Thus it would appear that cold clouds never survive to reach velocities comparable to that of the hot wind. However, if cloud cooling is efficient and the velocity exceeds the sound speed in the hot medium, a bow shock develops in front of the cloud, which protects it from ablation, both by reducing heating and squeezing it to even higher densities. When combined with radiative cooling, these mitigating effects allow the cloud to remain intact for many cloud crushing times. This has been simulated by Kwak *et al.*[11], but in both studies the cloud was accelerated out of the simulation volume before a final answer was obtained.

We have overcome this limitation by carrying out adaptive mesh refinement (AMR) simulations in which we automatically shift the frame of the calculation to the centre of mass frame of the cloud once per cloud crushing time, allowing us to run until the cloud is fully disrupted, regardless of the exterior Mach number. In this way, we are able to carry out a suite of simulations that spans the parameter space relevant for hot material interacting with the cold clouds that provide us with the bulk of the observational constraints on galaxy outflows.

The presence of magnetic fields changes the dynamics in several ways: Magnetic pressure, especially in the front of the blob changes the stand-off distance of the shock and changes the velocity and pressure in the downstream region. Magnetic tension can suppress the KH-instability and finally, magnetic fields affect the thermal conduction. The same is true for cosmic rays. Non-thermal particles, usually referred to as cosmic rays (CRs) are produced by supernova explosions and deposit energy and momentum in the interstellar medium. Because of the long cooling times of CR protons, they can be important drivers of galactic winds[2,23,21].

CR-driven winds can reproduce a number of key observations: simulations show that such winds produce the correct number of galaxies at the faint luminosity end, and reproduce the observed correlation between wind velocity and galaxy circular velocity. Unlike supernova-driven outflows, CRs are able to drive a multi-phase wind on scales comparable to galactic scale heights and whose velocities rise with distance from the disk, as observations suggest. The difficulty in dealing with CRs is the incomplete understanding of CR transport processes. The diffusion coefficients parallel and perpendicular to magnetic field lines as well as the streaming speed along magnetic field lines depend on microphysical processes that are poorly understood.

The key questions that we are trying to address in our simulation work are:

1. **How long do cold clouds survive in a hot supersonic flow subject to radiative cooling and thermal conduction in winds?**

2. **How efficient are cosmic rays at accelerating cold clouds and how long do the clouds survive in magnetised winds?**

2 Methods and Numerical Implementation

2.1 Magnetohydrodynamics

For the simulations, we used the FLASH code (version 4.3), a multi-dimensional AMR hydrodynamics code[7] that solves the Riemann problem on a Cartesian grid. A directionally unsplit staggered mesh algorithm (USM) that solves ideal and non-ideal MHD governing equations in multiple dimensions is based on a finite-volume, high-order Godunov method combined with a constrained transport type of scheme. It ensures that the solenoidal constraint of the magnetic fields on a staggered mesh geometry. In this approach, the cell-centred variables such as the plasma mass density ρ, plasma momentum density ρv and total plasma energy ρE are updated via a second-order MUSCL-Hancock unsplit space-time integrator using the high-order Godunov fluxes. The rest of the cell face-centred (staggered) magnetic fields are updated using Stokes' Theorem as applied to a set of induction equations, enforcing the divergence-free constraint of the magnetic fields.

We track the cloud using a massless scalar and computed its centre of mass (COM) position $\mathbf{x}_{\rm cloud}$ and velocity $\mathbf{v}_{\rm cloud}$, and as well as its radial extent in the x, y, and z directions, calculated as the mass weighted average values of $\mathrm{abs}(x - x_{\rm cloud})$, $\mathrm{abs}(y - y_{\rm cloud})$, and $\mathrm{abs}(z - z_{\rm cloud})$. At run-time, we then move the simulation from a frame in which the cloud was drifting out towards the $+z$ boundary, to a new frame in which the cloud was drifting (much more slowly) towards the $-z$ boundary. Thus, we are able to keep the cloud COM close to $z = 0$ at all times.

Optically thin cooling is implemented[20] assuming solar metallicity and we have used sub-cycling within the cooling routine itself. Saturated thermal conduction is implemented using the implicit diffusion module in FLASH. It uses the HYPRE library to solve the discretised diffusion equation. The saturation limit is enforced using the Larsen flux limiter.

2.2 Cosmic Rays

For the second part of the work presented here, we need to compute the evolution of CRs in the framework of the magnetohydrodynamical solver. It is assumed that he wave-particle interactions result in a short mean free path, such that the CRs can be described by a fluid that can be characterised by an isotropic pressure. For the conditions that we are interested in, we can furthermore assume that diffusion is negligible and that CRs stream at the Alfven speed relative to the gas.

The transport equation for CRs[3] is given by

$$\frac{\partial p_{\rm CR}}{\partial t} = (\gamma_{\rm CR} - 1)(\mathbf{u} + \mathbf{v_A}) \cdot \nabla p_{\rm CR} - \gamma_{\rm CR} \nabla \cdot (p_{\rm CR}(\mathbf{u} + \mathbf{v_A})), \qquad (1)$$

where $p_{\rm CR}$ is the CR pressure, $\mathbf{v_A}$ the Alfven velocity, $\mathbf{u}$ the gas velocity and $\gamma_{\rm CR}$ the adiabatic index of the CRs. In this work, we use a mass scalar in FLASH4.3 for the cosmic ray energy per mass. For the CR energy per volume, $\epsilon_{\rm CR}$ (mass scalar times density), we solve

$$\frac{\partial \epsilon_{\rm CR}}{\partial t} + \nabla \cdot (\epsilon_{\rm CR} \mathbf{u}) = -\mathbf{v_A} \cdot \nabla \epsilon_{\rm CR} - \gamma_c \epsilon_{\rm CR} \nabla (\mathbf{u} + \mathbf{v_A}) + \epsilon_{\rm CR} \nabla \cdot \mathbf{u}. \qquad (2)$$

The advection is handled by the magnetohydrodynamical routine and the source terms on the right hand side are handled by a heating routine. The CRs have $\gamma_c = 4/3$ and the gas has $\gamma = 5/3$. Finally, the cosmic rays affect the gas via $F = -\nabla p_{\rm CR} = -(\gamma_c - 1)\nabla\epsilon_{\rm CR}$ (which for practical reasons implement in a modified gravity routine).

As in Wiener *et al.*[23] we compute the Alfven velocity with which the CRs are streaming along field lines to

$$\mathbf{v_A} = -\frac{B}{\sqrt{4\pi\rho}} \tanh(l_R \nabla p_{\rm CR}/p_{\rm CR}), \tag{3}$$

where B is the magnetic field strength, ρ the gas density and l_R is a regularisation parameter that we set to a fraction of the length of the simulation box ($l_R = L/10$). The timestep limitation imposed by the CR streaming is given by

$$dt_{\rm stream} \sim dx^2/l_R p_{\rm CR}|v_A| = 10^{11} \left(\frac{dx}{100\,{\rm pc}}\right)^2 \left(\frac{|v_A|}{200\,{\rm km/s}}\right)^2 \left(\frac{l_R}{10\,{\rm kpc}}\right)^{-1} {\rm s}, \tag{4}$$

where dx is the width of the computational cell. As for diffusive processes, the time step constraint scales as dx^2 which can drive up the computational costs.

3 Results

Below, we present the results from two separate studies: the first one is concerned with the effect of thermal conduction. The second study investigates the role of CRs in a magnetised wind and this work is in progress.

3.1 Thermal Conduction

In our first study, we only looked at the effect of thermal conduction on the survival of the cold cloud in a hot wind. In Scannapieco & Brüggen[4], we focus on the impact of one such key physical process: thermal conduction, which occurs as rapid electrons from the hot surrounding medium move into the colder medium. Previous investigations on the effect of this process on multiphase gas dates back several decades. In ground-breaking work on thermal instabilities, Field[6] identified a characteristic spatial scale below which thermal instabilities are suppressed by conduction. This length scale arises from a basic difference between radiative cooling, which increases proportional to volume, and conductive heat flux, which increases proportional to area. In other early work, Graham & Langer[8] investigated the balance between cosmic-ray heating and cooling and found that thermal conduction plays a role in determining cloud sizes, and Cowie & McKee[5] computed the analytic mass loss rate of a (non-radiating) spherical cloud embedded in a hot plasma, both for classical conduction, as well as saturated conduction, in which the electrons stream into the clouds at their thermal speed. Fig. 1 shows an example of a part of the parameter study. Displayed are cuts of the logarithm of the gas density through the three-dimensional simulation box.

Performing a parameter study of three-dimensional adaptive mesh refinement hydrodynamical simulations, we showed[4] that thermal conduction causes cold clouds to evaporate, but it can also extend their lifetimes by compressing them into dense, cold filaments. This

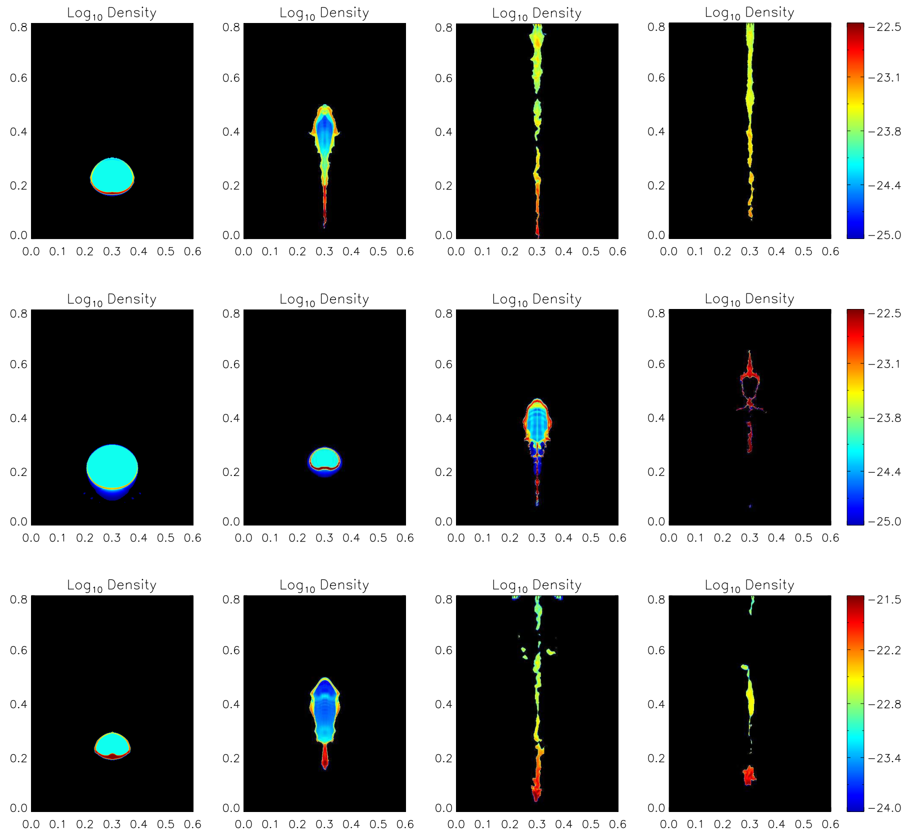

Figure 1. Density (log) slices from simulations with Mach numbers ≈ 6 and ≈ 11, at times at which the fraction of the mass at or above 1/3 the original density of the cloud is 90% (t_{90}, first column), 75% (t_{75}, second column), 50% (t_{50}, third column), and 25% (t_{25}, fourth column). *First row:* $v = 1700$ km/s *Second row:* $v = 3000$ km/s *Third row:* $v = 3000$ km/s at ten times cloud density. The density contrast between cloud and wind was 300 in all cases. At the lower z boundary of the simulation domain, we continuously added material to the grid with the same values of $v_{\rm h}$, and $c_{\rm h}$ and density as in our initial conditions, and in the x and y directions, as well as at the $+z$ boundary we adopted the FLASH "diode" boundary condition, which assumes a zero normal gradient for all flow variables except pressure and does not allow material to flow back onto the grid. The large x and y size of the simulation was chosen such that this zero gradient condition did not effect the shape of the shock, which can become unnaturally planar in an overly small simulation domain. The simulation box was divided into $8 \times 8 \times 6$ blocks of 8^3 cells each and we allowed for 5 levels of refinement yielding a minimum cell size of $\Delta x = R_{\rm c}/64 = 4.8 \times 10^{18}$cm.

is a surprising result as one might have expected that thermal conduction leads to the rapid evaporation of the cold clouds that are embedded in a hot medium. We distinguish between low column-density clouds, which are disrupted on very short times, and high-column density clouds with much-longer disruption times that are set by a balance between impinging thermal energy and evaporation. We provide a fit to this evolution that can be used in galaxy-scale simulations of outflows, in which the evolution of individual clouds cannot be modelled with the required resolution. Since evaporation leads to very high cloud densities, we could show that cold gas is only accelerated to a small fraction of the ambient velocity. This implies that either magnetic fields strongly suppress thermal conduction, or that the cold clouds observed in galactic outflows are not formed of cold material driven out of the galaxy. Some of the runs were run on JURECA at the Forschungszentrum Jülich. The 3D runs on adaptive grids with up to 5 levels of refinement and, typically, such runs can take $10^5 - 10^6$ CPU hours.

3.2 Cosmic Rays

In this part, we describe a windtunnel-type of experiment where we accelerate a cold blob in a magnetised medium that is accelerated by a cosmic-ray front.

We set up a simple system in 2D with a source term that maintains a constant CR pressure (twice the thermal pressure) on the $x = 0$ boundary. The physical size of the domain is 100 kpc $\times$ 100 kpc, resolved by an adaptive grid that produces an effective resolution of 256^2 cells. More highly resolved runs have been performed to check for numerical convergence. In the domain we set up a circular blob with a radius $R = 10^{22}$ cm. The density inside the blob is 10 times the ambient density. The edges of the cloud are softened with a Gaussian taper that helps against numerical artefacts. Pressure is constant throughout. We only include CR streaming at $v_{\rm A}$ and no CR heating. In the first set of simulations, we initialise the magnetic field to a uniform value in the x-direction. As found elsewhere, the cloud gets disrupted on a streaming timescale R/v_A.

Next we investigated whether magnetic tension can help to keep the cloud intact. Here the setup is the same as before except for the magnetic field inside the dense blob. For this purpose, we inserted a field loop inside the cloud by defining a magnetic vector potential, $A_z(r) = A_0(r - R), r < R$, where r is the distance from the centre of the cloud and R the radius of the cloud. A_0 is chosen such that the total magnetic field is continuous at $r = R$. Outside the cloud, the magnetic field remains uniform in the x-direction. The thermal pressure in the cloud is lowered, such that the sum of thermal and magnetic pressures is uniform across the simulation box. In Fig. 2, we show the evolution of the gas density, the magnetic field and the cosmic-ray pressure. The CRs are seen to push the cold blob ahead of it. The lower Alfven speed inside the cloud (because of the higher density) prevents the CRs from quickly streaming through the clouds. Hence, the CRs build up in front of a cloud in an effect that is called the bottleneck effect. This can be seen in the bottom panels of Fig. 2. As the cloud gets accelerated, it gets compressed and as a result the magnetic field strength rises inside and ahead of the cloud. The cloud stays intact as the tension of the magnetic field in the cloud acts against the instabilities that seek to disrupt the cloud. In contrast to the non-magnetic case, the cloud flattens in the direction perpendicular to its velocity. The resulting increase in its cross-section leads to a higher acceleration and should have observational consequences.

The results shown for the CR simulation have been done in two dimensions. It remains to be seen whether the results hold in three dimensions. This is the subject of current work. Other avenues consist of including isotropic or anisotropic diffusion of CRs and of CR heating. The dynamical effect competes with the effect of CR heating in the interstellar medium, as $t_{\rm dyn}/t_{\rm heat} \sim M\beta^{-1/2}$, where M is the Mach number and β the ratio between magnetic and thermal pressure[23].

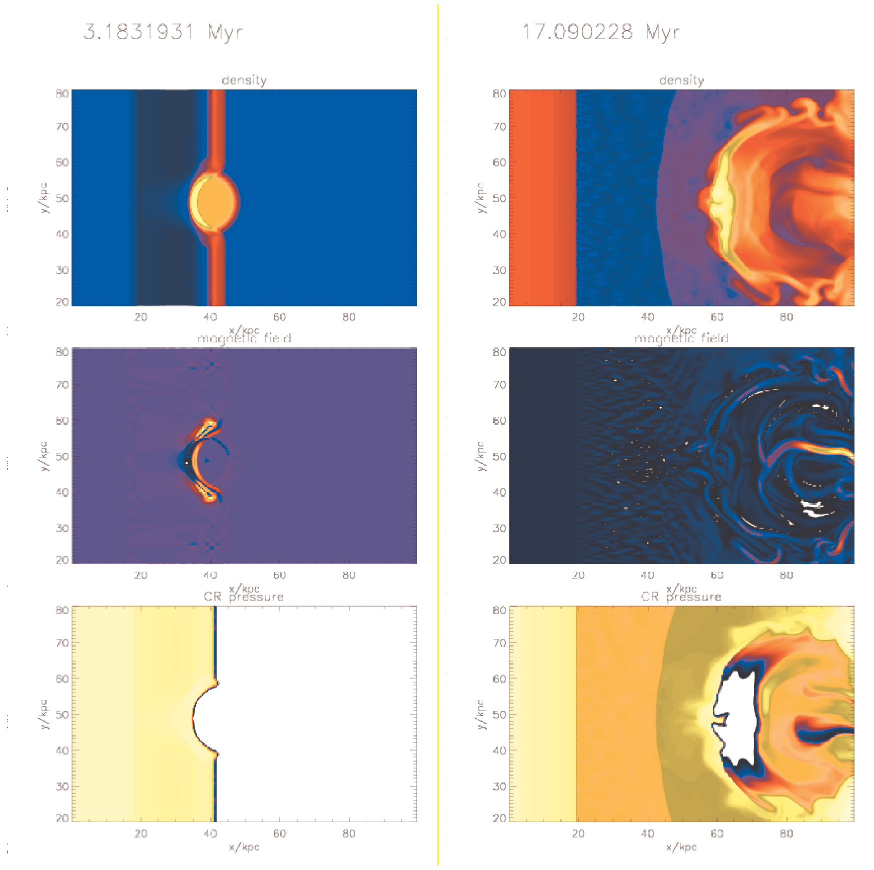

Figure 2. Snapshots of gas density, B-field and CR-pressure for the case, where a field loop was inserted into the cold blob. $\rho_{\rm amb} = 10^{-27}$ g cm^{-3}, $\rho_{\rm cl} = 10^{-26}$ g cm^{-3}, $p = 1.38 \times 10^{-13}$ erg cm^{-3}, $B_x = 3\mu$G, $B_y = 0$.

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