Volker Gaibler, Max Camenzind, and Martin Krause, 'Evolution of the ISM and Galactic Activity', paper presented at the1st Arizona/Heidelberg Symposium "The High Redshift Frontier", 30 November 2004 - 3 December 2004, Tucson, AZ, USA.

Evolution of the ISM and Galactic Activity

Volker Gaibler*, Max Camenzind, Martin Krause
Landessternwarte Heidelberg–Königstuhl

1 Introduction

We examine the impact of time-dependent mass injection and heating on the evolution of the interstellar medium (ISM) in elliptical galaxies. As the large and luminous ellipticals have supermassive black holes at their cores, which were probably much less massive in the young universe, feeding these black holes is essential. The evolution of the ISM, controlled by supernova and/or AGN heating as well as cooling by bremsstrahlung (Mathews & Brighenti 2003), could provide an abundant matter supply for this if a sufficient fraction of the ISM flows towards the center.

The hot phase of the ISM has typical temperatures around $10^7\,\mathrm{K}$ at the galactic cores. While stellar winds and planetary nebulae are widely seen as the sources of the interstellar gas, there is no generally established model to explain the heating of the ISM (supernovae, AGN heating, collisions). We concentrate on supernovae as a source of the heating.

2 Model and Basic Equations

We use simple Plummer models as well as combined Hernquist/NFW models for the mass distribution of our galaxies, with $\rho_\star(r)$ being the stellar mass density. In addition, we have a black hole with mass M_H at the center. Most calculations are performed in one spatial dimension, some in 2D including random disturbances, with the magnetohydrodynamic code NIRVANA by Udo Ziegler (Ziegler & Yorke 1997).

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = \alpha\rho_\star \tag{1}$$

$$\frac{\partial(\rho\mathbf{v})}{\partial t} + \nabla\cdot(\rho\mathbf{v}\otimes\mathbf{v}) = -\nabla p - \rho\nabla\Phi \tag{2}$$

$$\frac{\partial e}{\partial t} + \nabla\cdot(e\mathbf{v}) = -p\nabla\cdot\mathbf{v} + \alpha\rho_* c_\mathrm{v} T_0 - \rho^2\Lambda \tag{3}$$

*Contact: V.Gaibler@lsw.uni-heidelberg.de

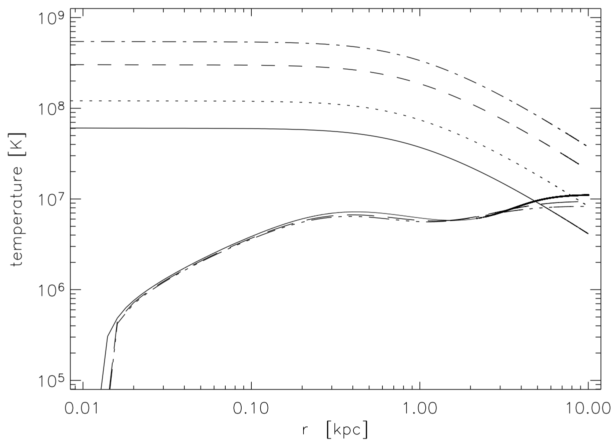

Figure 1. Typical temperature profiles of steady state outflow and inflow solutions. The two types of solutions can be easily distinguished in this figure: While inflows generally have low temperatures and positive gradients, galactic winds show high temperatures and negative gradients, which might be very difficult to observe directly as the densities are much lower. $\alpha = 10^{-19}\,\mathrm{s}^{-1}$, inflows: $T_0 = 5 \cdot 10^5\,\mathrm{K} \ldots 10^7\,\mathrm{K}$, outflows: $T_0 = 1 \cdot 10^8\,\mathrm{K} \ldots 9 \cdot 10^8\,\mathrm{K}$.

Here ρ, $\mathbf{u}$, T, p and e (energy density) are the state variables of the gas, $\rho^2\Lambda$ is the cooling rate, and $c_\mathrm{v}T_0$ is the supplied energy relative to the injected matter $\alpha\rho_\star$, so the heating is controlled by the value of T_0. The mass injection by stellar mass loss as well as the supernova heating are assumed to be proportional to the stellar density because of their physical origins.

3 ISM Simulations

For constant mass injection and heating we find steady state solutions, which can be characterized as inflow and outflow types (Figure 1). Inflow solutions show temperatures near the virial temperature and subsonic gas flows towards the center (cooling flows) independent of the heating rate. Outflows on the other hand generally are supersonic, of high temperature and low gas density. Their velocity and temperature profile is independent of the mass injection rate.

Although there is a transition region between inflow and outflow in the (α, T_0) parameter space where we have spatially bimodal flows, this region seems to be narrow. If there exists at least a partial inflow, then a significant fraction of the globally injected mass flows towards the center.

Figure 2 shows the distribution of the two solution types in the parameter space. There obviously exists a critical heating parameter $T_{0,\mathrm{crit}}$ which separates these types. This can be explained easily by checking the energy balance. The ISM evolution in our simulations with time-dependent mass injection and heating can be understood by examining the evolution of the model in the (α, T_0) parameter space.

The time-dependence of mass injection follows from the initial mass function of the

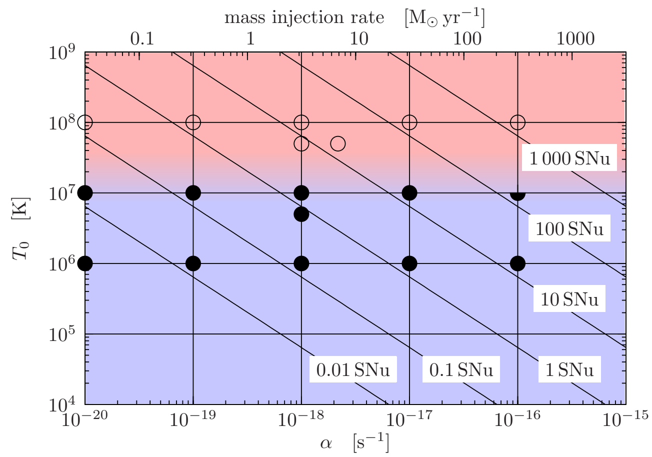

Figure 2. Distribution of inflow (filled symbols) and outflow (open symbols) solutions in the (α, T_0) parameter space for our model galaxy (dark matter contribution is not included). The mass injection parameter α directly corresponds to the overall mass injection rate in the galaxy, while the heating parameter T_0 depends on the supernova rate (in SNu) and the mass injection. 1 SNu corresponds to 1 supernova per 100 yr and $10^{10}\,\mathrm{L}_\odot$. The diagonal lines represent constant supernova rates.

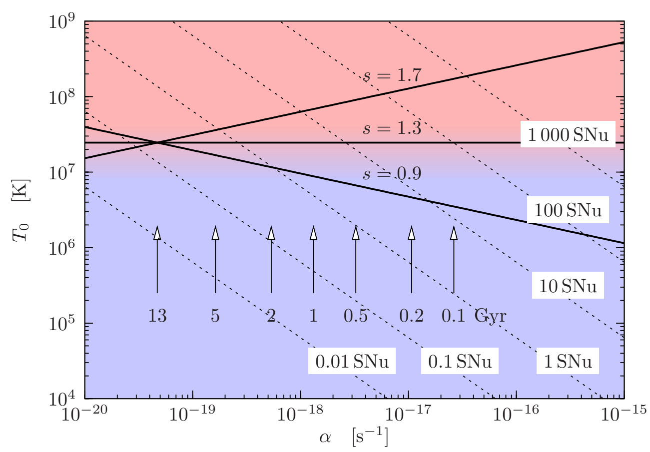

Figure 3. Evolution of SN Ia heating in the (α, T_0) parameter space for a powerlaw behavior at late times in the galaxy: supernova rate $\propto t^{-s}$ and mass injection $\alpha \propto t^{-1.3}$. The arrows indicate the α-position of the galaxy at a given time.

stellar population generated by a monolithic starburst. The amount of mass injection seems to be in good agreement with observations (Bregman & Athey 2004).

The time-dependence of the supernova rate is rather unknown. During the initial starburst there is much contribution from SNe II, but soon after SNe Ia are the only ones occurring. At late times, in passively evolving galaxies, the evolution of the SN Ia heating rate is often assumed to be a powerlaw ($\propto t^{-s}$), but observational confirmation for this is still missing so that the powerlaw exponent could vary over a large range. Figure 3 shows the evolutionary tracks of the model for three different powerlaw exponents.

The critical heating parameter is governed by the virial mass of the galaxy, and supernova rates in local ellipticals (Cappellaro et al. 1999) suggest that our model galaxy of $10^{11}\mathrm{M}_\odot$ virial mass should be near the turnover region between inflow and outflow. For early times, we find a galactic wind for $s = 1.7$ and inflow for $s = 0.9$. This shows that higher supernova rates in the past ($s > 0$) are not sufficient to drive galactic winds — they have to increase stronger ($s > 1.3$) than the mass injection (Ciotti et al. 1991).

For a galaxy with much higher or much lower mass, the position of the turnover region is much more important than the evolution of the supernova rate so that high-mass galaxies would generate inflows with high X-ray luminosities while low-mass dwarf galaxies would have strong galactic winds and unobservable X-ray luminosities.

4 Impact of the Initial Starburst

At very early times in the galaxy, during its formation, the abovementioned powerlaw behavior of course breaks down. Figure 4 shows the evolution of the parameters α and T_0 during galaxy formation based on two very simple scenarios with data from Starburst99 (Leitherer et al. 1999): The galaxy is *instantaneously* formed from a gas cloud or the galaxy is formed during 500 Myr by a *constant star formation rate*. The mass injection α decreases with increasing formation timescale, but the heating parameter T_0 remains the same because T_0 is proportional to the heating rate per injected mass.

The extremely high supernova rates during the starburst lead to high heating rates, but this does not necessarily lead to galactic winds. Figure 4 shows that $T_0 \sim 10^8\,\mathrm{K}$ during the starburst. This would drive a galactic wind for the model galaxy, but couldn't do so for a galaxy with a virial mass of $\gtrsim 10^{12}\,\mathrm{M}_\odot$ as the threshold-T_0 for winds increases proportional to the galaxy mass. The reason is that a huge amount of injected matter would have to be lifted out of the galaxy's gravitational potential.

5 Effects on Black Hole Growth

The evolution of the ISM might be a crucial factor for fuelling central black holes. If a galactic wind arises and stays for a long time, this could effectively avoid black hole growth because of low gas densities and high temperatures. A big galaxy in inflow state, on the other hand, could easily accrete some $10^{10}\,\mathrm{M}_\odot$ because the total injected gas mass is of the order of the stellar mass of the galaxy.

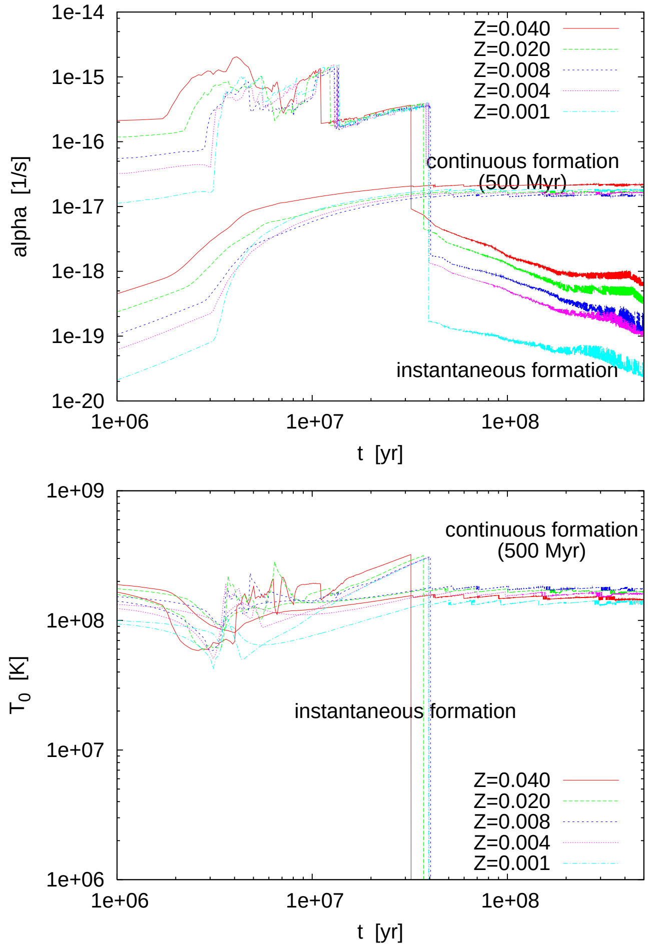

Figure 4. Evolution of the mass injection and heating parameters α and T_0 during galaxy formation for different metallicities Z, derived from Starburst99. The time-dependence of mass injection (*top*) and heating parameter (*bottom*) are shown for instantaneous formation of the galaxy and continuous formation during 500 Myr. Heating by SNe Ia is not included.

Depending on the galaxy mass and the evolution of the heating rate, there is a rich variety of possible scenarios for the interstellar gas. Inflow at early times can produce supermassive black holes very quickly and possibly resulting activity could provide a feedback through additional heating which could turn the inflow into an outflow. The impact of further star formation in cooling flows could be a similar feedback mechanism and induce a cyclic behavior.

References

[Bregman & Athey 2004] J. N. Bregman & A. E. Athey. Elliptical Galaxy Cooling Flows. In *Proceedings of The Riddle of Cooling Flows in Galaxies and Clusters of Galaxies*, 2004.

[Cappellaro et al. 1999] E. Cappellaro, R. Evans, & M. Turatto. A new determination of supernova rates and a comparison with indicators for galactic star formation. *A&A*, 351:459–466, 1999.

[Ciotti et al. 1991] L. Ciotti, S. Pellegrini, A. Renzini, and A. D'Ercole. Winds, outflows, and inflows in X-ray elliptical galaxies. *ApJ*, 376:380–403, 1991.

[Leitherer et al. 1999] C. Leitherer, D. Schaerer, J. D. Goldader, R. M. G. Delgado, C. Robert, D. F. Kune, D. F. de Mello, D. Devost, & T. M. Heckman. Starburst99: Synthesis Models for Galaxies with Active Star Formation. *ApJS*, 123:3–40, 1999.

[Mathews & Brighenti 2003] W. G. Mathews & F. Brighenti. Hot Gas in and around Elliptical Galaxies. *ARA&A*, 41:191–239, 2003.

[Ziegler & Yorke 1997] U. Ziegler & H. W. Yorke. A nested grid refinement technique for magnetohydrodynamical flows. *Computer Physics Communications*, 101:54–74, 1997.