5th Workshop on Galactic Chemodynamics

CSIRO PUBLISHING

Publications of the Astronomical Society of Australia, 2004, **21**, 188–191

www.publish.csiro.au/journals/pasa

Physical Processes in Star–Gas Systems

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Received 2003 November 20, accepted 2004 March 11

Abstract: We first present a recently developed three-dimensional chemodynamic code for galaxy evolution from the Kiev–Kiel collaboration. It follows the evolution of all components of a galaxy, such as dark matter, stars, molecular clouds and diffuse interstellar matter. Dark matter and stars are treated as collisionless N-body systems. The interstellar matter is numerically described by a smoothed particle hydrodynamics approach for the diffuse (hot) gas and a sticky particle scheme for the (cool) molecular clouds. Physical processes, such as star formation, stellar death, or condensation and evaporation processes of clouds interacting with the ISM are described locally. An example application of the model to a star forming dwarf galaxy will be shown for comparison with other codes. Secondly, we will discuss new kinds of exotic chemodynamic processes, as they occur in dense gas–star systems in galactic nuclei, such as non-standard 'drag'-force interactions, destructive and gas-producing stellar collisions. Their implementation in one-dimensional dynamic models of galactic nuclei is presented. Future prospects to generalise these to three dimensions are in progress and will be discussed.

Keyword: Galaxy: formation

1 Introduction

This paper is a short progress report and outlook to show some examples of how physical and numerical modelling techniques of physical processes in star–gas systems are improved. The astrophysical aim is to understand the nature and formation of objects, where timescales of the dynamics of the interstellar medium and dynamic processes in non-dissipative matter (stars or dark matter) are comparable. The range of objects of interest to us spans dwarf galaxies to dense galactic nuclei. This paper is divided into two main sections, according to applications for dwarf galaxies and galactic nuclei. For each section a subset of authors is responsible, as indicated.

2 A New Chemodynamic Code and Application to Dwarf Galaxies

Authors: Berczik, Hensler, Theis, Spurzem

2.1 Introduction

We present a new three-dimensional chemodynamic code, based on our and other previous models using smoothed particle hydrodynamics (SPH). This includes a two-phase interstellar medium, consisting of cool clouds and a hot inter-cloud medium as an additional feature. SPH was invented as a consistent tool to model dynamic gas systems with gravity by using particles which are subject to non-gravitational forces (Lucy 1977; Gingold & Monaghan 1977; Monaghan 1992) in addition to gravity, tailored to model in a statistically correct way, for example pressure or radiation forces, viscous effects, heating and cooling. SPH calculations have been applied successfully to study the formation and evolution of galaxies. Its Lagrangian nature as well as its easy implementation, together with standard N-body codes allows for a simultaneous description of complex systems consisting of dark matter, gas, and stars (Navarro & White 1993; Mihos & Hernquist 1996; Carraro et al. 1998; Thacker et al. 2000; Springel et al. 2001). The main features of this SPH variant are: single-gas-phase star formation from SPH particles dependent on the mean mass density within each individual particle through their free-fall time; and stellar energy release and mass return to the same particle. This single-gas-phase SPH treatment was successfully applied to the overall evolution of a Milky Way Galaxy model (Steinmetz & Navarro 1999; Abadi et al. 2003; Berczik 1999, 2000; Nakasato & Nomoto 2003) in the sense that it could reproduce the main structural and chemical signatures of the global galaxy and of the disk like, for example, its density profile and metallicity gradient (see also Nakasato 2004, in this volume).

In our (multi-phase-gas) code we use a two-component gas description of the interstellar matter (ISM) (Theis et al. 1992; Samland et al. 1997). The basic idea is to add a cold (10^2–10^4 K) cloudy component to the smooth and hot gas (10^4–10^7 K) described by SPH. The cold clumps

10.1071/AS04028 1323-3580/04/02188

are modelled as N-body particles with some 'viscosity' (Theis & Hensler 1993). This viscosity models the processes of the cloud–cloud collisions. Also a drag force between the clouds and the hot gas component is implemented. The cloudy component interacts with the surrounding hot gas also through condensation and evaporation processes (Cowie et al. 1981; Köppen et al. 1998). For a similar approach see also Harfst, Theis, & Hensler (2003) and Harfst (2004, in this volume). For another three-dimensional chemodynamic model on galaxy formation, which is not based on SPH, but on a mesh-based approach, see Samland & Gerhard (2003) and Samland (2004, in this volume). Note also another recent multi-phase model by Semelin & Combes (2002), which globally resembles our approach, but, in detail, uses different approximations of physical processes. We provide a more detailed comparisons of their and our models elsewhere (P. Berczik et al., in preparation).

In the following list we summarise the ingredients of our present model:

- Hot gas: treated by SPH, metallicity-dependent cooling.
- Cloud system: sticky particles, using Larson's M–R relation.
- Evaporation of cloud material via thermal conduction in hot medium, condensation onto clouds via cooling of hot medium. Exchange of energy and momentum due to this between the components.
- Ram-pressure momentum exchange between clouds moving with a velocity relative to the hot medium.
- Simple star-formation prescription out of cold clouds (Schmidt's law), with delay of star formation due to the cloud's collapse time, to allow for self-regulation.
- Stellar particles each represent a single stellar population (SSP), metallicity-dependent Padova stellar lifetimes are used.
- Supernovae of type I and II, stellar winds and planetary nebulae feed mass and energy back into both the cloud system and the hot interstellar medium.

We use a second order, two step, Runge–Kutta–Fehlberg, predictor–corrector scheme, moving the particles according to the non-gravitational forces (SPH, interactions as listed above) and gravitational forces of all other particles. To calculate the self gravity we use the GRAPE5[1] computer system at the Astronomical Data Analysis Center of the National Astronomical Observatory, Japan.

2.2 *First Models of Dwarf Galaxies*

We choose the dwarf galaxy as an interesting astrophysical object to which to apply our new code, because in this case even with a relatively 'small' number of cold 'clouds' ($\sim 10^4$) we achieve the required physical resolution for a realistic description of individual molecular clouds ($\sim 10^5\,M_\odot$) as a separate 'cold' particle. In the simulation we use $N_{hot} = 10^4$ SPH and $N_{cold} = 10^4$ 'cold' particles. After 1 Gyr more than 10^4 additional 'stellar' particles are created.

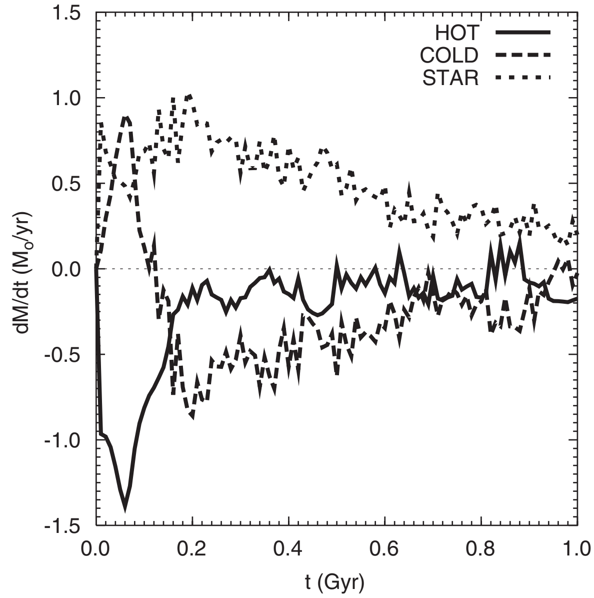

Figure 1 The temporal evolution of the mass-exchange rate for the different components of the model galaxy.

We follow the evolution of an isolated star-forming dwarf galaxy. The initial total gas content of our dwarf galaxy is $2 \times 10^9\,M_\odot$ (80% 'cold' + 20% 'hot'), which is placed inside a fixed dark matter halo with parameters $r_0 = 2$ kpc and $\rho_0 = 0.075\,M_\odot\,pc^3$ (Burkert 1995).

With these parameters the mass of dark matter inside the initial distribution of gas (20 kpc) is approximately $2 \times 10^{10}\,M_\odot$. The initial temperatures were set, for the cold gas, to 10^3 K and, for the hot gas, to 10^5 K. For the initial gas distribution ('cold' and 'hot') we use a Plummer–Kuzmin disk with parameters $a = 0.1$ kpc and $b = 2$ kpc (Miyamoto & Nagai 1975). The gas initially rotates in centrifugal equilibrium (in the total 'dark matter' + 'gas' gravitational field) around the z-axis.

Our model first exhibits a strong collapse initiated by cooling and cloud formation, and subsequently star formation sets in. In Figure 1 the growth or loss rates of the different components are shown. The star formation rate (SFR) peaks at a value of $1\,M_\odot\,yr^{-1}$ after 200 Myr. Afterwards it drops down to $0.2\,M_\odot\,yr^{-1}$ within several hundred Myr. After 1 Gyr the stellar mass has already reached $5 \times 10^8\,M_\odot$.

The metal content of the diffuse gas and the clouds differs significantly over the whole integration time (see Figure 2). Due to SNII and SNIa events the metallicity of the hot phase exceeds that of the clouds by almost one order of magnitude. The clouds mainly gain their metals by condensation of the hot phase. This shows that the two phases of the interstellar medium exhibit dynamically and chemically different behaviours and, thus, a correct physical treatment, like ours, is required for reliable modelling.

[1] A more detailed description of the board and further links and publications about GRAPE can be found at
`http://grape.astron.s.u-tokyo.ac.jp/grape`

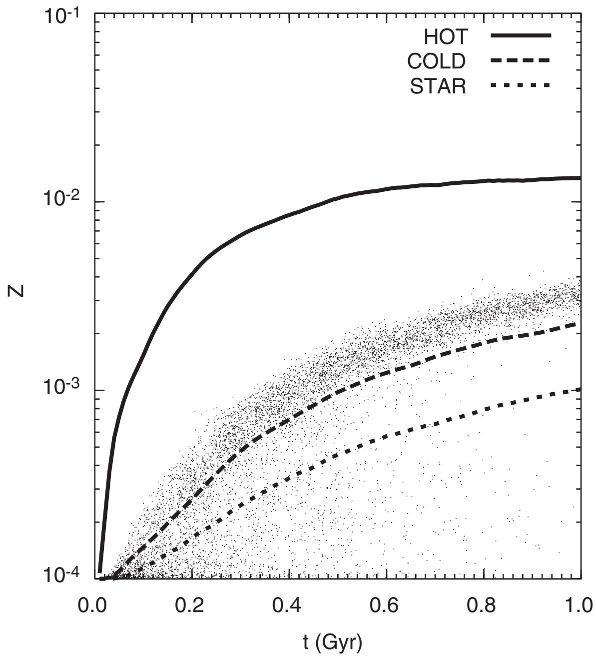

Figure 2 Temporal evolution of the total metallicity for the different components. Individual metallicities of newly born stars are marked by dots.

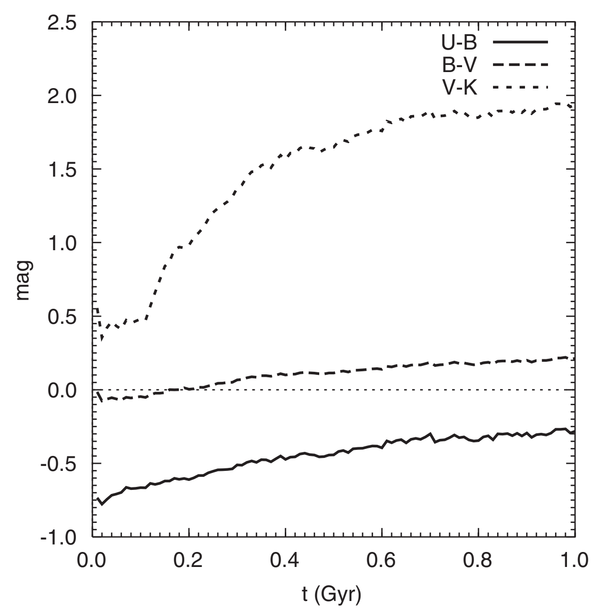

Figure 3 Temporal evolution of the model galaxy color indices.

In Figure 3 we present the evolution of the color indices in our model galaxy as an example what kind of data can be constructed for comparison with observational data. Our SSP model provides spectral information via six photometric channels from each star particle (representing its own SSP). The reader interested in more details about this or other features of our model is referred to (Berczik 1999; Berczik 2000; Berczik et al. 2003; P. Berczik, in preparation).

3 Dense Star–Gas Systems in Galactic Nuclei

Authors: Amaro-Seoane, Freitag, Just, Spurzem

At the time of the first collapse and star-formation epoch in galaxy formation, large amounts of gas will reach the galactic centre (Eisenstein & Loeb 1995; Zoltán & Loeb 2001). They may create a huge outburst of star formation, and in part be responsible for the ultraluminous IR galaxies in the young universe. In addition to that, once stars have been formed, very large amounts of additional gas will be liberated by disruptive stellar collisions (Freitag & Benz 2002). In some cases of massive galactic nuclei, gas-production rates as large as $50\,M_{\odot}\,yr^{-1}$ have been observed in the numerical models. Present stellar dynamical models, based on Monte Carlo or direct solutions of the Fokker–Planck equation, do not include star–gas interactions. Thus, they cannot follow the co-evolution of such a system, as is done in classical chemodynamical galaxy simulations. There is one exception, the so-called gaseous model of stellar dynamics (Louis & Spurzem 1990; Langbein et al. 1990; P. Amaro-Seoane, M. Freitag, & R. Spurzem, in preparation), which, at least in principle, could be coupled in an easy way to simulate joint gas and stellar dynamics. The reader interested in more detail and more references on the exotic star–gas interaction processes is referred to Langbein et al. (1990), where the terms are given in detail and the history of previous literature on the subject is presented.

Recently it has been pointed out that the formation of clusters of intermediate-mass black holes (Ebisuzaki et al. 2001) would be a possible way to create massive black holes in the centres of star clusters or galaxies. This is nicely suggested also by new Chandra images of M82, by Fabbiano et al. (2001).[2] Recent stellar dynamical Monte Carlo model including stellar evolution and mergers have strengthened this idea (Rasio, Freitag, & Gürkan 2003; Gürkan, Freitag, & Rasio 2003). In order to determine what initial and boundary conditions (e.g. from large scale galaxy formation) lead to the formation of supermassive black holes, what determines their further growth by star and gas accretion, and what will be the spectrophotometric appearance of such dense nuclei, we need to extend the classical chemodynamics into the regime of exotic processes in galactic nuclei. These are gas production by stellar collisions, star–gas drag under special conditions (covering very large ranges of Mach numbers), and energy transport in the presence of energetic radiation, which contributes to the hydrodynamic pressure significantly. The assumption of spherical symmetry on which the Monte Carlo and gas methods rely becomes highly questionable in the close vicinity of the black hole. One very recent, remarkable attempt of Bromm & Loeb (2003) uses an SPH ansatz, but is not able to follow the multi-phase dynamics of the interstellar matter, as we can do with our CD-SPH model presented in the first section (see also Harfst 2004, in this volume, for a similar ansatz). One example of the new and complex phenomena

[2] `http://chandra.harvard.edu/photo/cycle1/0094true/`

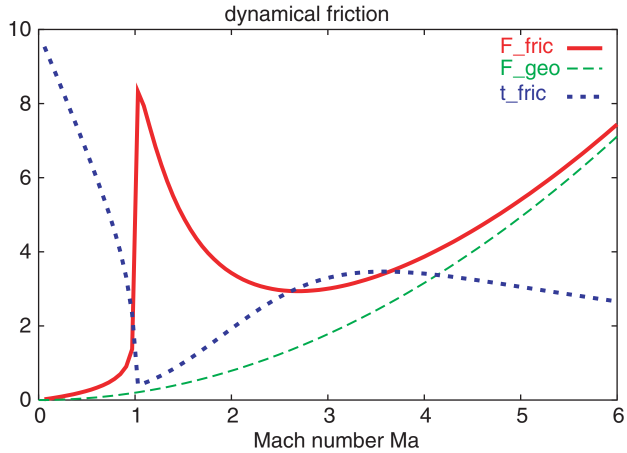

Figure 4 'Drag' force on a star moving through interstellar medium $F_{\rm geo}$ with Mach number *Ma* from a standard estimate using the geometrical stellar cross section and a ram pressure approach (see main text), compared with a more realistic dissipative interaction force $F_{\rm fric}$, obtained from a detailed analysis of fluctuations in the ISM, induced by a star moving through (see main text for citations and more explanations). The dotted curve is inversely proportional to $F_{\rm fric}$, since it plots the time scale connected to it.

is presented in Figure 4, which shows the star–gas interaction. Figure 4 shows a standard ram pressure force for a star moving supersonically in an ambient medium, as, for example, discussed in Bisnovatyi-Kogan & Syunyaev (1972), where the 'drag' force is proportional to the square of velocity (Mach number) and linearly dependent on the geometrical stellar cross section (strictly, since the velocity dependence is quadratic, this is not a drag force but it is often called so, therefore we put 'drag' in quotation marks to remind the reader about this ambiguity). The standard 'drag' force is compared with a non-standard one, which is valid also in the subsonic and transition regime ($Ma \approx 1$). The underlying formalism used is the analysis of fluctuations induced by a star moving through an ambient ISM and the feedback force they provide on the star's motion. For small Mach numbers ($Ma > 1$) the resulting force is large and related to a kind of dynamical friction process, while for highly supersonic motion we reach the asymptotic limit of the standard formula. In the subsonic case the interaction force drops sharply, but still differs from the standard formula. The basic method of the analysis of such kind of dynamical 'drag' between stars and the ISM is described in Just, Kegel, & Deiss (1986). The application to galactic nuclei will be presented in ongoing work (Just, in preparation). In galactic centres we expect that all ranges from subsonic to hypersonic (Mach numbers of a few thousand) will be realised.

Acknowledgments

This work has been supported by Sonderforschungsbereich (SFB) 439 'Galaxies in the Young Universe' at the University of Heidelberg in sub-projects A5 (R.S., A.J.) and B5 (R.S., P.B.). P.B. acknowledges kind hospitality at the University of Kiel and to G.H., Ch.T., and collaborators, where part of this work has been performed. Numerical models have been computed with the GRAPE5 system at the Astronomical Data Analysis Center of the National Astronomical Observatory, Japan.

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