Physical Processes in Star-Gas Systems

R. Spurzem 1, P. Berczik 1,2, G. Hensler 3, Ch. Theis 3, P. Amaro-Seoane 1, M. Freitag 1, A. Just 1

1 Astronomisches Rechen-Institut, Mönchhofstr. 12-14, 69120 Heidelberg, Germany
{spurzem,pau,freitag,just}@ari.uni-heidelberg.de
2 Main Astronomical Observatory of Ukrainian National Academy of Sciences, Zabolotnoho Str. 27, 03680 Kiev, Ukraine
berczik@mao.kiev.ua
3 Institut für Theoretische Physik und Astrophysik, University of Kiel, Olshausenstr. 40, 24098 Kiel, Germany
{hensler,theis}@astrophysik.uni-kiel.de

Abstract

First we present a recently developed 3D chemodynamical code for galaxy evolution from the K**2 collaboration. It follows the evolution of all components of a galaxy such as dark matter, stars, molecular clouds and diffuse interstellar matter (ISM). Dark matter and stars are treated as collisionless N-body systems. The ISM is numerically described by a smoothed particle hydrodynamics (SPH) 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 chemodynamical 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 1D dynamical models of galactic nuclei is presented. Future prospects to generalize these to 3D are work in progress and will be discussed.

Keywords: Galaxy: formation

1 Introduction

This paper is a short progress report and outlook to show some examples, how physical and numerical modelling techniques of physical processes in star-gas systems are improved. The astrophysical aim is to understand nature and formation of objects, where time scales of the dynamics of the interstellar medium and dynamical processes in non-dissipative matter (stars or dark matter) are comparable. The range of objects interesting for us spans from 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 chemo-dynamical code and application to dwarf galaxies

Authors: Berczik, Hensler, Theis, Spurzem

2.1 Introduction

We present a new 3D chemodynamical code, based on our and other previous models using smoothed particle hydrodynamics (SPH), including a two phase interstellar medium consisting of cool clouds and a hot intercloud medium as an additional feature. SPH has been invented as a consistent tool to model gasdynamical 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 e.g. pressure or radiation forces, viscous effect, 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 they could reproduce main structural and chemical signatures of the global galaxy and of the disk like e.g. its density profile and metallicity gradient (see also Nakasato, this volume).

In our (multi-phase gas) code we use a two component gas description of the 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 are modeled as N-body particles with some “viscosity” (Theis & Hensler, 1993). This “viscosity” models the processes of the cloud-cloud collisions and also a drag force between clouds and hot gas component is implemented. The cloudy component interacts with the surrounding hot gas also via condensation and evaporation processes (Cowie et al., 1981; Köppen et al., 1998). See for a similar approach also Harfst, Theis, & Hensler (2003) and Harfst (this volume) and for another 3D chemodynamical model on galaxy formation which is not based on SPH, but on a mesh-based approach Samland & Gerhard (2003), Samland (this volume). Note also another recent multi-phase model by Semelin & Combes.
which globally resembles our approach, but in detail different approximations of physical processes are used. We would provide a more detailed comparisons of their and our models elsewhere (Berczik et al., 2004).

In the following list we summarize 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 relative velocity to hot medium.
- Simple star formation prescription out of cold clouds (Schmidt’s law), with delay of star formation due to cloud’s collapse time to allow for self-regulation.
- Stellar particles each represent a single stellar population (SSP), metallicity dependent Padova stellar lifetimes 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 2nd 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 GRAPE computer system at the Astronomical Data Analysis Center of the National Astronomical Observatory, Japan. A more detailed description of the board and further links and publications about GRAPE can be found in http://grape.astron.s.u-tokyo.ac.jp/grape/

2.2 First Models of Dwarf Galaxies

We choose the dwarf galaxy as an interesting astrophysical object to apply our new code, because in this case even with a relatively “small” number of cold “clouds” (∼ 10⁴) we achieve the required physical resolution for a realistic description of individual molecular clouds (∼ 10⁵ M⊙) as a separate “cold” particle. In the simulation we use N_{hot} = 10⁴ SPH and N_{cold} = 10⁴ “cold” particles. After 1 Gyr more then 10⁴ additional “stellar” particles are created.

We follow the evolution of an isolated star forming dwarf galaxy. The initial total gas content of our dwarf galaxy is 2 · 10⁹ M⊙ (80 % “cold” + 20 % “hot”) which is placed inside a fixed dark matter halo with parameters r_0 = 2 kpc and ρ_0 = 0.075 M⊙/pc⁶ (Burkert, 1995).

With these parameters the dark matter mass inside the initial distribution of gas (20 kpc) is ∼ 2 · 10¹⁰ M⊙. The initial temperatures for the cold gas were set to 10¹¹ K, for the hot gas to 10⁹ 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 “dm” + “gas” gravitational field) around the z-axis.

Our model first exhibits a strong collapse initiated by cooling, cloud formation, and subsequently star formation sets in. In Fig. 1 the growth or loss rates of the different components are shown. The star formation rate (SFR) peaks to a value of 1 M⊙yr⁻¹ after 200 Myrs. Afterwards it drops down to 0.2 M⊙yr⁻¹ within several hundred Myrs. After 1 Gyr the stellar mass has already reached 5 · 10⁵ M⊙.

The metal content of the diffuse gas and the clouds differs significantly over the whole integration time (see Fig. 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 get their metals by condensation of the hot phase. This shows that the two phases of the interstellar medium exhibit dynamically and chemically a different behaviour and thus a correct physical treatment like ours is required for reliable modelling.

In Fig. 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, 2000; Berczik et al., 2003, 2004).

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 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; Amaro-Seoane, Freitag, & Spurzem, 2004), 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 centres of star clusters or galaxies. This is nicely suggested also by new Chandra images of M82 by Fabbiano et al., see for a reference http://chandra.harvard.edu/photo/cycle1/0094true/ and recent stellar dynamical Monte Carlo models 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 and 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

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.

Figure 4: “Drag” force on a star moving through interstellar medium $F_{\text{geo}}$ with Mach number $M_a$ 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 $F_{\text{fric}}$ 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 just inversely proportional to $F_{\text{fric}}$, since it is plotting the time scale connected to it.
under special conditions (covering very large ranges of Mach numbers), 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 S. Harfst, this volume, for a similar ansatz). One example of the new and complex phenomena is presented in Fig. 4, which shows the star-gas interaction. Fig. 4 shows a standard ram pressure force for a star moving supersonically in an ambient medium, as e.g. 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, 2004, in prep.). 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 Univ. of Heidelberg in sub-projects A5 (RS, AJ) and B5 (RS, PB). PB acknowledges kind hospitality at the Univ. of Kiel and to G. Hensler, Ch. Theis 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.

References

Abadi M. G., Navarro J. F., Steinmetz M., Eke V. R., 2003, ApJ, 591, 499
Amaro-Seoane P., Freitag M., Spurzem R., 2004, MNRAS, to be subm.
Berczik P., 1999, A&A, 348, 371
Berczik P., 2000, Ap&SS, 271, 103
Berczik P., Hensler G., Theis Ch., Spurzem R., 2003, Ap&SS, 284, 865
Berczik P., Hensler G., Theis Ch., Spurzem R., 2004, A&A, to be subm.
Bisnovatyi-Kogan G.S., Syunyaev R.A. 1972, Sov. Astron., 16, 201
Bromm V., Loeb A., 2003, ApJ 596, 34.
Burkert A., 1995, ApJ, 447, L25
Carraro G., Lia C., Chiosi C., 1998, MNRAS, 297, 1021
Cowie L.L., McKee C.F., Ostriker J.P., 1981, ApJ, 247, 908
Ebisuzaki T., Makino J., Tsuru T.G., Funato Y., Portegies Zwart S., Hut P., McMillan S.L.W., Matsushita S., Matsumoto H., Kawabe R. 2001, ApJ, 562, 19L
Eisenstein D.J., Loeb A. 1995, ApJ, 448, 17L
Freitag, M., Benz, W., 2002, A&A, 394, 345
Güürkan M.A., Freitag M., & Rasio F.A. 2003, ApJ, in press (astro-ph/0308449)
Gingold R.A., Monaghan J.J., 1977, MNRAS, 181, 375
Harfst S., Theis C., Hensler G., 2003, Ap&SS, 284, 869
Just A., Kegel W.H., Deiss B.M. 1986, A&A 164, 337
Köppen J., Theis Ch., Hensler G., 1998, A&A, 331, 524
Langbein, T., Spurzem, R., Fricke, K.J., Yorke, H.W. 1990, A&A 227, 333
Louis P.D., Spurzem R., 1991, MNRAS, 251, 408
Lucy L., 1977, AJ, 82, 1013
Mihos J.C. & Hernquist L., 1996, ApJ, 464, 641
Miyamoto M. & Nagai R., 1975, PASJ, 27, 533
Monaghan J.J., 1992, ARA&A, 30, 543
Nakasato N., Nomoto K., 2003, ApJ, 588, 842.
Navarro J.F. & White S.D.M., 1993, MNRAS, 265, 271
Rasio F.A., Freitag M., Güürkan, M.A., 2003, in Carnegie Observatories Astrophysics Series, Vol. 1: Coevolution of Black Holes and Galaxies, ed. L.C. Ho (Cambridge: Cambridge Univ. Press), in press (astro-ph/0304038)
Samland M., Gerhard O. E., 2003, A&A, 399, 961
Samland M., Hensler G., Theis Ch., 1997, ApJ, 476, 544
Semelin B., Combes F. 2002, A&A, 388, 826
Springel V., Yoshida N. & White S.D.M., 2001, NewA, 6, 79
Steinmetz M., Navarro J. F., 1999, ApJ, 513, 555
Thacker R.J., Tittley E.R., Pearce F.R., Couchman H.M.P., Thomas P.A., 2000, MNRAS, 319, 619
Theis Ch., Burkert A., Hensler G., 1992, A&A, 265, 465
Theis Ch. & Hensler G., 1993, A&A, 280, 85
Zoltán, H., Loeb, A. 2001, ApJ 552, 459