N-body simulations of galaxy mergers: the role of stellar evolution feedback

Applicant: Mgr. Kateřina Bartošková
Supervisor: RNDr. Bruno Jungwiert, Ph.D.

Key words: galaxy formation and evolution; galaxy collisions and mergers; elliptical galaxies; N-body simulations; dark matter; stellar evolution; stellar mass-loss; stellar feedback; active galactic nuclei (AGN); quasars; massive black-holes (BH); fueling BH growth; AGN feedback;

I Objectives and original contribution of the project

Background Large-scale cosmological simulations of galaxy formation and evolution are a key topic of the current research in astrophysics. Essential ingredients involve gravitational dynamics of dark matter and the complex physics of baryonic matter (gas and stars).

The former has been a subject of huge advances within the last decade, leading, when combined with observational constraints, to a picture of hierarchical structure formation in the Universe. According to the hierarchical scenario – today referred to as Λ Cold dark matter (Λ-CDM) theory – more massive objects are formed from smaller building blocks. Today's elliptical galaxies are considered as remnants of a major galaxy merger (collision of two roughly equal mass disk galaxies) or even series of accrections of smaller galaxies and minor mergers (accrection of two differently massive galaxies), which are much more common. Some of them became massive central galaxies and are continuing to grow by "galactic cannibalism" (by swallowing up much smaller satellite objects bound in gravitational potential of the giant galaxy). More detailed observations in recent years are revealing more and more evidences of past and present galactic interactions in agreement with the hierarchical theory.

The physics of baryonic matter, involving star formation and stellar evolution in connection with the surrounding environment (galactic evolution), is however much less understood in details due to issues related to finite spatial and mass resolutions in N-body gas-dynamical simulations as well as to a considerable degree of ignorance about the nature of the underlying physical processes.

The massive black holes (SMBH), common in galaxy centers and giving rise to active galactic nuclei (AGN) are another piece of the galaxy evolution puzzle, involving the AGN fueling by the matter of the host galaxy and the AGN, energetic feedback on the interstellar and intergalactic media (ISM and IGM).

The current state-of-the art N-body models of galaxy evolution incorporate a rather complex treatment of the baryonic physics: multi-phase ISM, turbulence, supernova feedback, AGN feedback, gravitational instabilities, ISM cooling/heating, star formation.

The goal of this project, described in detail in the next section, is to explore the role of the long-term stellar mass-loss on galaxy evolution in the context of the hierarchical galaxy formation.

mapgraf_shells4.png

In my master thesis I already dealt with the N-body simulations of minor merger system, a head-on collision of giant elliptical (gE) and dwarf elliptical (dE) galaxy, using the code GADGET-2 in Newtonian space. Initial conditions contain a combination of stellar and dark matter models for representation of massive galaxiy, approaching the observed objects. The simulation (see the picture above – evolution of surface density distribution of star particles of the smaller galaxy during the simulation) led to successful reproduction of a shell galaxy – the observed phenomenon of many elliptical galaxies. The original results were presented as a poster at the conference JENAM 2010.

The project The long-term stellar mass-loss from low-mass and intermediate mass-stars is a known but largely unexplored aspect of stellar evolution feedback on galaxy evolution. Its first implementations into N-body codes of galactic evolution are due to Jungwiert et al. (2001) and Lia et al. (2002), the former being formulated in a deterministic way while the latter relying on a probabilistic description. However, surprisingly little work on the topic has been done since, and most current simulations of galaxy evolution largely ignore and probably underestimate the effect of the mass-loss on galaxy structure/dynamics, star formation rate and gas consumption timescale.

Recently, Martig & Bournaud (2010) have revived the subject by showing the overwhelming importance of the long-term stellar mass-loss in large scale simulations of disk galaxies, in particular on the formation of bulges and resulting bulge-to-disk ratios. They have speculated that the long-term stellar mass-loss might be a key ingredient in current cosmological simulations that fail to produce realistic late-type disk galaxies.

Motivated by these recent advances in the field, we have decided to explore the effects of stellar mass-loss in another cosmologically crucial context, namely that of galaxy mergers. We intend to focus predominantly, though not uniquely, on elliptical galaxies, both giant and dwarf. Elliptical galaxies have mostly old stellar populations, formed largely by redshift 2 (lookback time $\sim 1 \cdot 10^{10}$ yr[1]) and evolving passively since. This passive evolution is accompanied by stellar mass-loss, potentially accumulating a huge gas reservoir in these galaxies. The fate of such gas in galaxy collisions and mergers was never studied so far, to our knowledge. We suspect, that a lot of so called "dry mergers" (mergers of gas-poor galaxies) are not so dry in reality.

the applicant will work on detailed study of evolution of merger systems in high resolution and in redshift range from $z \sim 2$ to $z = 0$ (cosmological treatment will include simulations from from $z \sim 5$). That takes in time approximately about $1 \cdot 10^{10}$ yr evolution (lookback time).

In the course of the project, I will be using a freely available and renowned code GADGET-2 (Springel 2005; GAlaxies with Dark matter and Gas intEracT) for self-consistent cosmological N-body simulations, a very versatile modeling tool (involving effective TreePM method for stars and dark matter and the TreeSPH algorithm for gaseous particles in various resolutions and metrics). The published version does not consider the transfer of mass between stars and gas, however, due to its vast possibilities, we decided to use this code and to modify it for the purpose of the project.

hs-2007-39-c-full_jpg.jpg

Figure 1: Image taken with Hubble Space Telescope shows the quasar, known as MC2 1635+119 (Canalizo G., Bennert N., Jungwiert B., et al., 2007, ApJ 669, 801), and its host galaxy together with the star shells structure. Is there any connection of these phenomenas? Are they pointing to the same merging event in the past of the galaxy?

Overall contribution and goals of the project:

- Connect nowadays information from observations and theoretical studies with galaxy evolution predicted by N-body simulations in the CMD universe – galaxy mergers evolved in cosmological environment.
- Our main astrophysical goal is to explore whether the gas return from stars, accumulated over long periods, can provoke, during mergers, starbursts and increased AGN fueling.
- Source code of the patch implementing mass-loss into the code of GADGET-2, created during solving of the project, will be released for free usage by the astronomical community using GADGET or other galaxy evolution codes.

[1]Assuming Hubble constant $H_0 \sim 70.5$ km/s/Mpc, and the cosmological parameters $\Omega_{\rm matter} \sim 0.27$ and $\Omega_\Lambda \sim 0.73$.

II Theoretical framework, applied methods and techniques, basic references

Initial conditions and simulations A distribution of matter (gravitational potential) of a giant galaxy takes important role in the evolution of the minor merger system. To keep consequent simulations realistic as much as possible, when constructing initial galactic models, we need to take into account current constraints on dark and baryonic matter – from observations of real galaxies and cosmological N-body simulations. (i.e. density models – NFW halo, Sersic law etc.).

We intend to use a snapshot from cosmological simulations from a higher redshift ($z \sim 5$) to initialize the dark matter; subsequently we will add the baryonic matter and follow the evolution of all the three components, using zoom techniques (see below) to increase the resolution in the central parts.

Numerical realization of N-body simulations As already mentioned, numerical treatment of the system evolution will be computed by N-body tool GADGET-2. We are going to use a "zoom-in" techniques to aquire a higher resolution within the computational bounds: Simulations for searching in parameter space and cosmological simulations will be treated in less precision. For the purpose study of merging mechanisms and hereafter central AGN feedback, we could use a snapshot from the former simulations and partially resimulate the chosen region in a more detail.

Because of high resolution requirements (large number of particles and accuracy needs in high density areas) the simulations are to be cpu-time consuming. Parallel codes naturally favor computation on clusters or multi-processor blade servers, etc. For the purpose of higher resolution I have gained access to OCAS (Ondřejov Cluster for Astrophysical Simulations). Other possibility, in the near future, may be to use a MetaCentrum (an activity of CESNET association) resources (e.g. usage of multiprocessor machines or clusters at the Faculty of informatics MU), which are available for persons from academic environment.

References

Springel V., 2005, MNRAS 364, 1105; Ho, Luis C., 2009, ApJ 699, Issue 1, 626-637; Lia C., Portinari L., Carraro G., 2002, MNRAS 330, 821; Jungwiert B., Combes F., Palous J., 2001, A&A 376, 85; Martig M., Bournaud F., 2010, ApJ 714, 275; Hopkins P. & Quataert E., 2010, MNRAS 407, 1529

III Time schedule and key milestones of the project

Academic Year	**Milestones**
2010/2011	Study present state of gas treatment in N-body simulations and prepare some preliminary simulations of galaxy mergers without stellar feedback, Become more closely familiar with stellar mass loss treatment across stellar populations and start implementing the modification of GADGET-2.
2011/2012	Simulations with stellar feedback; Cosmological simulations – environment; Publication of the code GADGET-2 modifications; study AGN-feedback.
2012/2013	Detailed analysis of various classes of merger simulations with stellar mass-loss feedback.
2013/2014	Publish papers to international conferences and high impact factor international journals. Write a PhD dissertation using the project results and related topics.

During the all project stages: The applicant will participate in summer schools, conferences and workshops related to galaxy evolution and computing. Results obtained during the project solving will be published throughout all stages.

IV Institutions where the project will be implemented

The project will be carried out jointly at two collaborating institutions, the **Institute of Theoretical Physics and Astrophysics**, Masaryk University in Brno (hereafter UTFA; home institution of the PhD study), and the **Astronomical Institute of the Academy of Sciences of the Czech Republic.**[2] (hereafter AsU).

The immediate working environment will consist of an informal Prague (AsU) – Brno (UTFA) working group on AGN host galaxies, lead by B. Jungwiert. The group meets regularly, on a weekly basis, since 2007 (the applicant actively participates since 2009). The group involves PhD (presently 5, including the applicant) and undergraduate students as well as one postdoctoral researcher (I. Stoklasová), and has strong collaborative ties with foreign astronomical institutions (e.g. Dr. Giovanni Carraro, European Southern Observatory (ESO[3]), Santiago, Chile; Dr. G. Canalizo, University of California-Riverside; Dr. N. Bennert, University of California-Santa Barbara; Dr. S. Sanchez, Calar Alto Observatory, Spain).

V Expert consultants and their contribution to the project

The supervisor, **Dr. Bruno Jungwiert**, is a staff researcher at AsU and external lecturer at UTFA. He is currently supervising/advising 2 other PhD students at UTFA and 2 PhD students at the Charles University, as well as several diploma/bachelor students.

Dr. Giovanni Carraro, staff researcher at the European Southern Observatory (ESO[3]) in Chile, and a co-author of one of the N-body schemes for stellar mass-loss (Lia, Portinari, & Carraro 2002) will be a consultant of the project. He is already involved in co-advising, together with B. Jungwiert, another PhD project involving a PhD student at UTFA, Ms. Lucie Jílková, currently on a 2-year leave in ESO.

VI Relation between the applicant's project and doctoral thesis

The project is tightly connected with and significantly extends the topic of PhD thesis: *N-body simulations of galaxy mergers*, which is targeting minor mergers. In addition, the project will be interested in major mergers.

VII Motivation for solving the project

Tracking the galactic evolution is one of the most evolving tasks today's astrophysics. I am interested in the issue of elliptical galaxies since my bachelor thesis project and in the field of N-body computing since my master thesis. This project is a great way to combine a scientific work on astrophysical phenomenas, which I am interested in, with computational informatics, which is my second main interest.

elaborated by: approved by:

[2]The applicant has succeeded, in June 2010, in a competition for a part-time (25%) PhD position at the Astronomical Institute ASCR (from 1.10 2010 to 30.9. 2011). In this framework, AsU has agreed to provide to the access to its computer facilities, including its linux cluster for large astrophysical simulations, located at the Ondřejov observatory.

[3]ESO (www.eso.org) is an intergovernmental organization for astronomical research, involving 14 European countries, and operating the largest astronomical telescopes in the world; the Czech Republic is member since 2007