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Forming disk galaxies in magneto-hydro-dynamical simulations of the Universe

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LRZ Project ID: pr85je (Gauss Large Scale project)

Introduction

Our Universe is permeated with magnetic fields – they are found on the Earth, in and around the Sun, as well as in our home galaxy, the Milky Way. Often the magnetic fields are quite weak: for example, the magnetic field on Earth is not strong enough to decisively influence the weather on our planet. In galaxies like the Milky Way, the field is however so strong that its pressure on the interstellar gas in the galactic disc is of about the same size as the gas thermal pressure. Astrophysicists hence conclude that magnetic fields could play an important role here although their origin still remains mysterious. Current hypotheses argue that they either already existed directly after the Big Bang and were then greatly amplified with time, or that the field was produced by the first stars and has then been dispersed in the Galaxy.

In principle, computer simulations that follow the formation and evolution of galaxies starting at the Big Bang ought to be able to answer these questions. However, they have thus far mostly failed because the predicted galaxies did not agree with astronomical observations. In fact, the formation of disk galaxies has long been a puzzling conundrum for cosmologists: computer simulations produced typically far too massive and too small disks, a problem that persisted for decades. Also, the simulations have not been able to follow the dynamics of magnetic fields within the full cosmological context. Treating the latter is mathematically and numerically considerably more challenging than the plain gas dynamics, which has typically been employed for computing galaxies so far.

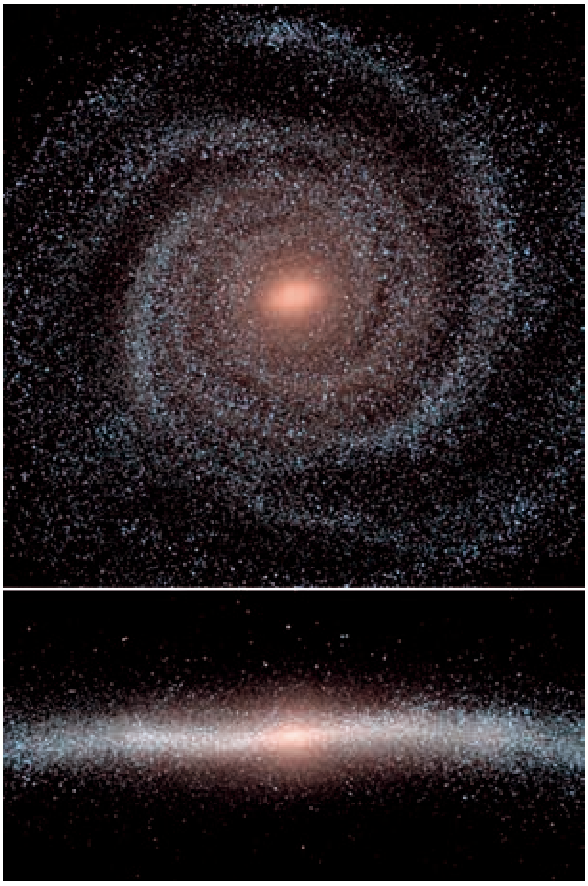

Figure 1: Stellar structure of a Milky Way-like galaxy formed in one of our magneto-hydrodynamical cosmological simulations after 13 billion years of evolution. The face-on projection on top nicely reveals spiral structure in the disk.

Results

Within our project pr85je on SuperMUC, we use the massively parallel simulation code AREPO, developed at the Heidelberg Institute for Theoretical Studies, to study galaxy formation within a fully cosmological setting, using a comprehensive treatment of the physics and much higher numerical resolution than ever used before. AREPO is a so-called „moving mesh code“. What distinguishes it form other astrophysical codes is that AREPO does not partition the simulated universe with a fixed mesh but rather uses a movable and deformable mesh, which allows a particularly accurate processing of the vastly different size and mass scales occurring in individual galaxies. Thanks to the very low advection errors of the method, it is particularly well suited to the highly supersonic flows occurring in cosmology, and to treating subsonic turbulence within the gas of virialized halos. These properties make it superior to smoothed particle hydrodynamics and adaptive mesh refinement codes that use a stationary Cartesian mesh. AREPO also follows the dynamics of dark matter with high accuracy, as required to compute cosmic structure growth far into the non-linear regime.

In our recent work, we have succeeded in including additional physical processes such as magnetic fields in the simulations, thereby improving them in a decisive way. In fact, with the help of our novel numerical methods and the progress on parallelization achieved, we could leverage the power of SuperMUC to form a virtual galaxy that closely resembles our own Milky Way. It has the right stellar mass for its dark matter halo mass of about 1012 solar masses, forms a disk of the right scale length, and the relation between mean age of stars and the total stellar mass of the disk is consistent with observations, too. Also, the predicted content of metals in the gas synthesized in stars and stellar explosions is consistent with observational data. This represents a major success over previous attempts to form disk galaxies, and demonstrates that the futile attempts in the past to do so were not due to an inherent flaw of the underlying cosmological ΛCDM paradigm.

In addition, we were for the first time able to predict the expected structure of the magnetic field in a spiral galaxy directly from the initial conditions left behind after the hot Big Bang. It turns out that already an extremely tiny magnetic field left behind by the Big Bang is sufficient to explain the orders of magnitude larger field strengths observed today. We were able to show that the magnetic field first grows exponentially for about 1 billion years due to gas motions in the early Universe, before the field reaches a stationary average value that is independent of its initial strength at the beginning. Once the first disk galaxies have formed (ca. 2.5 billion years after the Big Bang), the rotational motion of the disk further amplifies the field linearly with time, yielding field strengths at the micro-Gauss level. The revolving flow of the gas in the disk also pulls the magnetic field lines and directs them tangentially along this motion. Interestingly, the magnetic field strength found in the simulation does not only agree very well with the values measured for the Milky Way and neighboring galaxies, it also reproduces the observed vertical and horizontal profiles. This is remarkable given that there are no free parameters that could be tuned to influence the final field strength.

The successful formation of disk galaxies with a small bulge-to-disk ratio constitutes a long sought breakthrough in the intricate problem of the formation of galaxies in hydrodynamical cosmological simulations. It is fascinating that this can at the same time explain the formation of typical magnetic field found in galaxies like the Milky Way. These findings also promise to help in understanding the deflection of cosmic ray particles in the magnetic field of the Milky Way, and in providing clues for tracking down the sources of these particles, which is still an unsolved problem in observational astronomy.

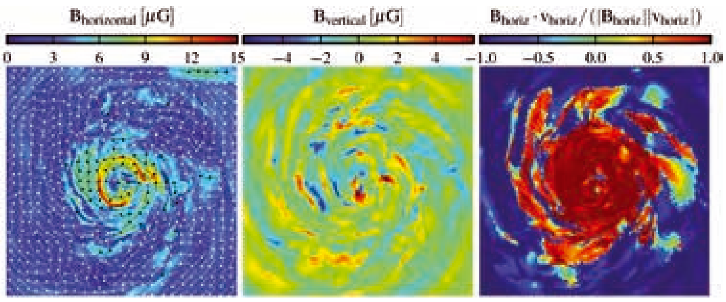

Figure 2: Structure of the magnetic field in one of our simulated Milky Way-sized galaxies. The left and center panels show the strength of different components of the magnetic field. The right panel shows the pitch angle, illustrating that the field develops a large-scale orientation in the disk where it is aligned with the rotational motion.

On-going research

SuperMUC has played a decisive role in making the present simulations possible. Within our project, we are currently working on substantially scaling up the numerical resolution and dynamic range achieved in our simulations of the formation of Milky Way-sized galaxies, thereby allowing a treatment of the small-scale physics that is more faithful to the processes of the interstellar medium than possible in past work. In particular, we aim to carry out the first cosmological hydrodynamic simulation of galaxy formation with more than one billion resolution elements within the virialized region of a single Milky Way-sized halo, thereby advancing the state-of-the-art by about two orders of magnitude. The resulting Milky Way models will contain more than 100 million star particles alone. This should facilitate predictions of transformative quality for the stellar and metallicity structure of the disk, and the bulge and halo components.

For example, previous isolated galaxy models had problems to reproduce the long-lived spiral arms that rotate about the Galaxy with a constant pattern speed. Instead, spiral arms in previous simulation models appear to be very short-lived transient features that co-rotate with the stars. Evidence against density wave theory has also been presented in several extragalactic observational works that report that the spiral arms rotate with radially decreasing pattern speed. Therefore, the time has come to reassess how spiral arms form. Our currently prepared high-resolution cosmological simulations of the Milky Way's formation will have for the first time a large enough number of star particles in their disks to allow these questions to be meaningfully studied within a proper cosmological setting.

References and Links

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