DOI: 10.14529/jsfi180412

High Performance Computing of Magnetized Galactic Disks

Sergey A. Khoperskov [1], ***Yulia A. Venichenko*** [2], ***Sergey S. Khrapov*** [3], ***Evgenii O. Vasiliev*** [4,5]

A parallel implementation of the magneto-hydrodynamical code for global modeling of the galactic evolution is reported. The code is parallelized by using MPI interface, and it shows ideal scaling up to 200–300 cores on Lomonosov supercomputer with fast interconnect. In the benchmarking of this code, we study the dynamics of a magnetized gaseous disk of a galaxy with a bar. We run a high-resolution 3D magnetohydrodynamic simulation taking into account the Milky Way-like gravitational potential, gas self-gravity and a network of cooling and heating processes in the interstellar medium. By using this simulation the evolution of morphology and enhancement of the magnetic field are explored. In agreement to hydrodynamical models, when the bar is strong enough, the gas develops sharp shocks at the leading side of the bar. In such a picture we found that when typically the magnetic field strength traces the location of the large-scale shocks along the bar major axis, the magnetic field pressure weakens the shocks and reduces the inflow of gas towards the galactic center.

Keywords: magnetohydrodynamics, galactic dynamics, galactic magnetic field, parallelization.

Introduction

In recent observations it has been established that magnetic fields in galaxies have very complex structure [1]. Moreover, the energy enclosed in galactic magnetic fields is of the same order as the thermal energy of the interstellar gas. Then, magnetic fields are believed to play a significant role in global galactic evolution [2]. Magnetic fields are mainly locked in the plane of the galactic disk, where the magnetic induction is maximum. However, they embrace the entire disk of the galaxy and reach galactic halos due to galactic fountains and winds. In spiral galaxies like our Galaxy, the magnetic fields are mainly frozen into the gas and follow its flows. So that to understand the energy exchange between magnetic fields and gas in galaxies, a self-consistent modeling of galactic evolution is required. A significant advance in numerical techniques closely related to a rapid growth of computational resources allow to construct three-dimensional high-resolution numerical simulations of global galactic magnetic field evolution in more realistic conditions.

In this paper, we consider the global evolution of magnetized galactic disks using our MPI-parallelized magneto-hydrodynamical code and study the parallel efficiency of this code on Lomonosov supercomputer [11].

1. Methods and Model

To investigate the global gas dynamics in magnetized spiral galaxies, we have conducted a set of the numerical simulations using our three-dimensional code based on TVD MUSCL (Total Variation Diminishing Multi Upstream Scheme for Conservation Laws) scheme. For magnetic field divergence cleaning, we adopt the constrained transport technique for magnetic field transport through the computational domain [5]. In this approach the magnetic field strength is

[1] Institute of Astronomy, Russian Academy of Sciences, Moscow, Russia
[2] Heidelberg University, Heidelberg, Germany
[3] Volgograd State University, Volgograd, Russia
[4] Southern Federal University, Rostov-on-Don, Russia
[5] Special Astrophysical Observatory of Russian Academy of Sciences, Nizhnii Arkhyz, Russia

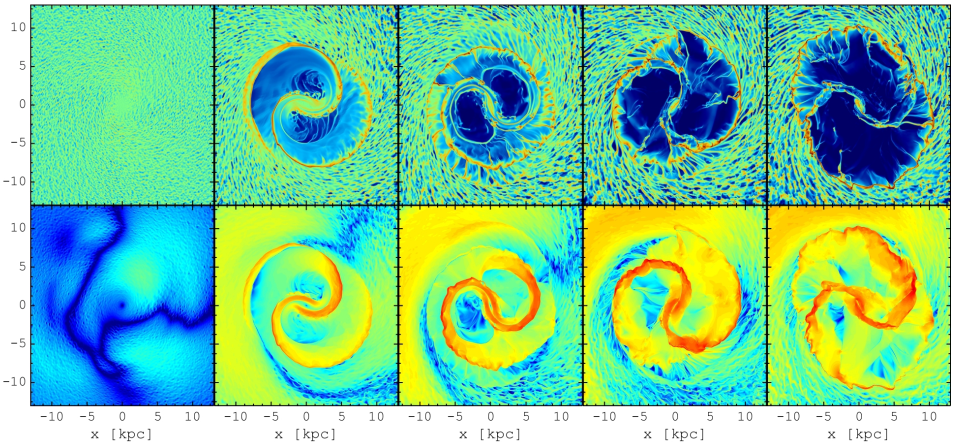

Figure 1. Evolution of gas surface density (top row) and magnetic field strength (bottom row) at 5, 50, 100, 150, 200 Myr

defined at faces of a cell, while the other gas dynamical variables are calculated at the center of a cell [9]. The code has successfully passed the standard tests for magnetic gas dynamics and has been already utilized for several galactic-scale simulations [6, 8].

We carry out 3D hydrodynamic simulations (Cartesian geometry) of a galactic disk in the computational box of size $20 \times 20 \times 4$ kpc with spatial resolution of $4,096 \times 4,096 \times 256$ grid zones in the x-, y-, and z-directions, respectively, that corresponds to a physical cell size of ≈ 4 pc. Such cell size is high enough to resolve molecular clouds at galactic scales.

To parallelize our code, the Message Passing Interface (MPI) software library is applied. The parallelization strategy is based on two-dimensional domain decomposition into cubic blocks, which are distributed across nodes. In our code, we use the third-order approximation of primitive gas dynamical variables, then two ghost cells are exchanged between nodes for boundary conditions. Despite the fact that our method of solving of the Poisson equation requires inefficient all-to-all communication, fast interconnect implemented on the Lomonosov cluster allows to reach good scaling on several tens of nodes or several hundred cores. To gain better scaling in the Riemann solver, we combine several scalar values into vector ones, that is favorable for using Advanced Vector Extensions (AVX2) instructions without complication of the code.

The gas density radial profile is distributed exponentially with a radial scale of 6 kpc and central density value equal to $10 M_{\odot}\ pc^{-2}$. The gaseous disk in the vertical direction is set in the hydrostatic equilibrium with a scale height of ≈ 100 pc. The equilibrium state of the gaseous disk is found according to the radial balance between the gas rotation versus radial gradient of gas pressure, gravitational forces (external potential and self-gravity) and magnetic field pressure. To mimic the turbulent structure of the magnetic field in the disk plane, its components are established as a superposition of two modes with (pseudo-) random location in the disk and various amplitudes [7].

2. Results

Global galactic disk evolution is driven by self-gravity, thermal instability, and rotation of the bar. These processes inevitably lead to the fragmentation of gaseous disk and formation of small-scale isolated clumps – giant molecular clouds, which may collide and merge with each other. A detailed description of this picture can be found in [3, 4, 10]. Figure 1 shows the distributions of

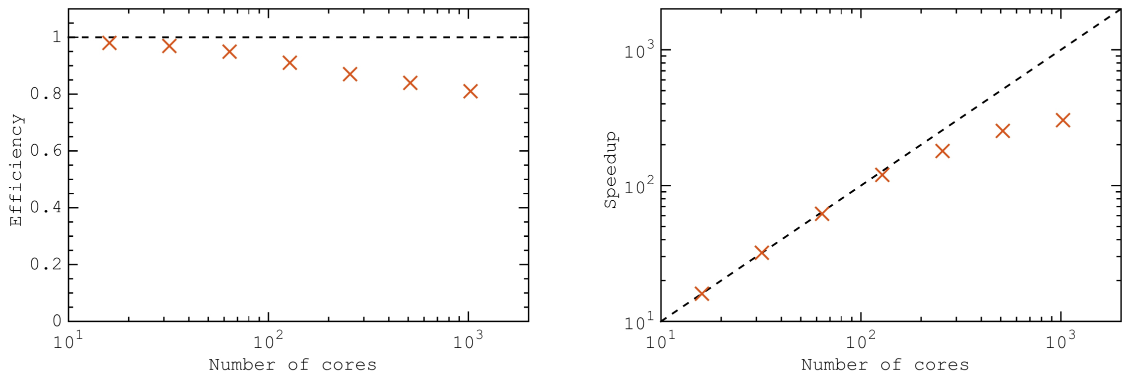

Figure 2. Parallel efficiency and speedup for the parallel code described in Section 1

gas density (top row) and magnetic field strength (bottom row). One can find that the magnetic field strength closely correlates with the gas density in the bar region, $r < 5$ kpc, where the field strength follows to gas adiabatically compressed when it moves through the spiral arms or bar. In our simulations the mean magnetic-field strength is consistent with that measured in the galactic disk, then we believe that the magnetic field inside clouds selected from the simulation should be similar to that in real giant molecular clouds. Mean magnetic energy is close to the equipartition with mean thermal and kinetic energies averaged over the whole galactic disk. Figure 1 demonstrates that the global magnetic field has a toroidal configuration.

The parallel code was benchmarked on Lomonosov supercomputer [11]. The number of cores in our runs has varied from 8 to 10^3 cores. We have rescaled our measurements in the way that the efficiency is equal to unity for a run on eight CPUs. Figure 2 shows how efficiency (left panel) and speedup (right panel) depend on the number of cores. One can find that both efficiency and speedup are ideal sat up to 200–300 cores. The efficiency remains higher than 0.8 till up to 10^3 cores. It is worth noting that the measured parallel efficiency depends on the load balance of processors, that in turn is determined by physical parameters of a simulated task.

Conclusions

In this paper we have studied the parallelization efficiency of the magneto-hydrodynamical code for global modeling of the galactic evolution. This code is parallelized by using MPI interface. A technique for more efficient use of AVX2 instructions has been applied. The code shows almost ideal scaling up to 200–300 cores. This code has been mainly developed to study the global evolution of disk galaxies. It can be used for modeling generation of spiral structure and evolution of interstellar medium taking into account self-gravity, thermal processes, magnetic fields, chemical kinetics, and so on. Here the evolution of the galactic magnetic field in barred galaxies is studied. In particular, we have found that the magnetic field strength closely correlates with the gas density in the bar region.

Acknowledgments

The research is carried out using the equipment of the shared research facilities of HPC computing resources at Lomonosov Moscow State University supported by project RFMEFI62117X0011. SAK is supported by RFBR according to research project 16-32-60043.

SSK has been supported by the Ministry of Education and Science of the Russian Federation (government task No. 2.852.2017/4.6). EOV is thankful for support from the Russian Scientific Foundation (grant 14-50-00043).

References

1. Beck, R.: Galactic and Extragalactic Magnetic Fields. Space Science Reviews 99, 243–260 (2001)

2. Beck, R., Brandenburg, A., Moss, D., Shukurov, A., Sokoloff, D.: Galactic Magnetism: Recent Developments and Perspectives. Annual Review of Astronomy and Astrophysics 34, 155–206 (1996), DOI: 10.1146/annurev.astro.34.1.155

3. Dobbs, C.L., Burkert, A., Pringle, J.E.: Why are most molecular clouds not gravitationally bound? Monthly Notices of the Royal Astronomical Society 413, 2935–2942 (2011), DOI: 10.1111/j.1365-2966.2011.18371.x

4. Dobbs, C.L., Pringle, J.E.: The exciting lives of giant molecular clouds. Monthly Notices of the Royal Astronomical Society 432, 653–667 (2013), DOI: 10.1093/mnras/stt508

5. Evans, C.R., Hawley, J.F.: Simulation of magnetohydrodynamic flows – A constrained transport method. Astrophysical Journal 332, 659–677 (1988), DOI: 10.1086/166684

6. Khoperskov, S.A., Bertin, G.: Spiral density waves in the outer galactic gaseous discs. Monthly Notices of the Royal Astronomical Society 451, 2889–2899 (2015), DOI: 10.1093/mnras/stv1145

7. Khoperskov, S.A., Khrapov, S.S.: Global enhancement and structure formation of the magnetic field in spiral galaxies. Astromony and Astrophysics 609, 104–118 (2018), DOI: 10.1051/0004-6361/201629988

8. Khoperskov, S.A., Vasiliev, E.O.: A Kennicutt–Schmidt relation at molecular cloud scales and beyond. Monthly Notices of the Royal Astronomical Society 468, 920–926 (2017), DOI: 10.1093/mnras/stx532

9. Khoperskov, S.A., Vasiliev, E.O., Khoperskov, A.V., Lubimov, V.N.: Numerical code for multi-component galaxies: from N-body to chemistry and magnetic fields. Journal of Physics Conference Series 510(1), 012011 (2014), DOI: 10.1088/1742-6596/510/1/012011

10. Khoperskov, S.A., Vasiliev, E.O., Ladeyschikov, D.A., Sobolev, A.M., Khoperskov, A.V.: Giant molecular cloud scaling relations: the role of the cloud definition. Monthly Notices of the Royal Astronomical Society 455, 1782–1795 (2016), DOI: 10.1093/mnras/stv2366

11. Sadovnichy, V., Tikhonravov, A., Voevodin, V., Opanasenko, V.: "Lomonosov": Supercomputing at Moscow State University. In: Contemporary High Performance Computing. pp. 283–307. Chapman & Hall/CRC (2013)