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USING OF THE SUPERCOMPUTER CALCULATIONS FOR STUDY OF SOLAR FLARE MECHANISM VIA CORONAL MHD SIMULATION

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Abstract. Numerical magnetohydrodynamic (MHD) simulation above the active region in the real scale of time, necessary to study the solar flare mechanism at the present stage, requires a significant increase in the calculation speed, which is achieved by parallelizing the calculations using a supercomputer. For this purpose, hardware and software for a supercomputer based on CUDA NVIDIA technology with a TESLA M2050 graphics card have been adjust. An example of parallelization using CUDA technology for the test problem of solving the Poisson equation showed an acceleration of the calculation by 20-100 times. The parallelization of the program for solving MHD equations using CUDA technology was carried out. However, attempts to execute a parallelized complex program for solving MHD equations on an assembled supercomputer showed the need to work on dividing parallelized subroutines into smaller ones. This work has now been completed, but errors often occur when transferring values to the memory of the graphics card. For the correct execution of a parallelized program, it is necessary to introduce additional control of data transfer into it. Currently, such work is being carried out. A parallelization of the program for solving MHD equations in the Open MP system was carried out, which on a computer with an 8-core Intel Xeon 3.1Ghz processor with 16 threads accelerated the calculation by 50-70 times. The first results MHD simulation in the real scale of time above the active region of AO 10365 using parallelized in the system OpenMP program showed the formation of current sheets in the solar corona, in whose magnetic field the flare energy is accumulated.

Introduction

The appearance of a solar flare in the solar corona, proved by numerous observations [1-4], is explained by the accumulation of energy in the magnetic field of the current sheet [5]. The sheet appears as a result of the accumulation of disturbances in the vicinity of the X-type singular line of magnetic field. Magnetic energy is released during the transition of the current sheet to an unstable state with all observational manifestations explained by the electrodynamical model of the flare [6]. Since it is impossible to determine the configuration of the magnetic field in the corona from observations, to study the flare mechanism it is necessary to perform MHD simulation, in which the magnetic field observed in the photosphere is used to set the boundary conditions. MHD simulation in the reduced scale of time showed the formation of a current sheet, the position of which coincides with the position of the observed flare source of thermal X-ray emission [7-9]. For an accurate study of the flare situation, it is necessary to perform MHD simulation in real time [13], which is impossible without the use of parallel calculations on a supercomputer.

In the future, MHD simulation in the real scale of time will be used for a more detailed understanding of the solar flare mechanism and, possibly, to improve the flare forecast based on an understanding of their physical mechanism. The forecast of flares is an important task because of their impact on human life. First of all, this is the need for timely protection of astronauts from exposure to solar cosmic rays. Also, radio emission from flares can interfere with navigation. X-ray emission of flares in the absence of a protective ozone layer near the North and South poles can cause irradiation of polar explorers. Induction of an electric field in the atmosphere due to magnetic substorms caused by solar flares can lead to spoilage and even failure of power lines. However, it must be recognized that the latter is extremely rare. However, there is no need to exaggerate the effect of flares, especially on human health, in order to artificially draw attention to this problem. The study of the mechanism of solar flares is an important task, both because of their existing influence on human life, and in connection with the need to understand the physics of an interesting phenomenon that can occur both in space plasma and in laboratory plasma.

Setting of the problem for MHD simulation in the real scale of time

Simulation was carried out above the active region of AR 10365, which produced a series of flares on May 27, 2003. The MHD equations were solved numerically in the computational domain ($0\leq x \leq 1$, $0\leq y\leq 0.3$, $0\leq z \leq 1$, in dimensionless units). The unit of length was chosen equal to $L_0=4\times10^{10}$ cm. The Y axis is directed from the Sun normally to the photosphere. The XZ plane ($y = 0$) is the photosphere plane with the X axis in the direction from East to West and the Z axis in the direction from North to South. The characteristic value of the field in the active region B0 = 300 G was chosen as the unit of the magnetic field. The dimensionless units of plasma concentration and its temperature are taken to be their typical values in the corona above the active region $\rho_0/m_i = 10^8$ cm^{-3}, $T_0 = 10^6$ K (m_i

is the ion mass). The dimensionless units of velocity, time, and current density have the form: $V_0 = V_A = B_0 / \sqrt{4\pi\rho_0}$ ~0.5×10^{10} cm/sec, $t_0 = L_0/V_0$~10 sec. The 3D dimensionless system of MHD equations has the form:

$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{rot}(\mathbf{V}\times\mathbf{B}) - \frac{1}{\mathrm{Re}_m}\mathrm{rot}\left(\frac{\sigma_0}{\sigma}\mathrm{rot}\mathbf{B}\right) \quad (1)$$

$$\frac{\partial \rho}{\partial t} = -\mathrm{div}(\mathbf{V}\rho) \quad (2)$$

$$\frac{\partial \mathbf{V}}{\partial t} = -(\mathbf{V},\nabla)\mathbf{V} - \frac{\beta_0}{2\rho}\nabla(\rho T) - \frac{1}{\rho}\left(\mathbf{B}\times\mathrm{rot}\mathbf{B}\right) + \frac{1}{\mathrm{Re}\rho}\Delta\mathbf{V} + G_g\mathbf{G} \quad (3)$$

$$\frac{\partial T}{\partial t} = -(\mathbf{V},\nabla)T - (\gamma-1)T\mathrm{div}\mathbf{V} + (\gamma-1)\frac{2\sigma_0}{\mathrm{Re}_m\sigma\beta_0\rho}\left(\mathrm{rot}\mathbf{B}\right)^2 - (\gamma-1)G_q\rho L'(T) +$$

$$+\frac{\gamma-1}{\rho}\mathrm{div}\left(\mathbf{e}_{\|}\kappa_{dl}(\mathbf{e}_{\|},\nabla T) + \mathbf{e}_{\perp1}\kappa_{\perp dl}(\mathbf{e}_{\perp1},\nabla T) + \mathbf{e}_{\perp2}\kappa_{\perp dl}(\mathbf{e}_{\perp2},\nabla T)\right) \quad (4)$$

The limitations associated with the finite step of the difference scheme do not allow the use of real values of dimensionless parameters; therefore, the principle of limited modeling was used to select the parameter values [10]. According to this principle, dimensionless parameters much larger and much smaller than one, are specified in the calculations much larger and much smaller than one, without the exact preservation of their values.

The numerical solving of MHD equations is initiated three days before the flare, when there are no strong disturbances and the magnetic field in the active region of the solar corona can be considered as potential one. The potential magnetic field is found by solving of the Laplace equation for the magnetic potential φ_B ($B = -\nabla\varphi_B$) with the tilted derivative along the line-of-sight as the boundary condition on the photospheric boundary:

$$\Delta\varphi=0;\ \ \partial\varphi/\partial l_{sight}|_{PhBoun}=-B_{lsight};\ \ B=-\nabla\varphi. \quad (5)$$

The distribution of the line-of-sight magnetic field component B_{lsight} on the photosphere is taken from magnetic maps obtained by SOHO MDI (*http://soi.stanford.edu/magnetic/index5.html*).

When MHD equations are solved, it is necessary to specify two field components at the photospheric boundary, which should be parallel to this boundary. The component perpendicular to the boundary is determined from the divB=0 condition. Since the field near the photosphere is fairly well approximated by the potential field, the two field components at the boundary were taken from calculated potential magnetic field by solving of the equation (7) by the same way as for the initial moment of time. Distributions of two parallel to the photosphere magnetic field components are found in time moments May 24, 2003 at 20:47:59 UT; May 25, 2003 at 20:47:59 UT; May 26, 2003 at 20:47:59 UT; May 27, 2003 at 20:47:59 UT. The boundary conditions at each moment of time were found by interpolation between these time moments.

Numerical methods for solving MHD equations, parallelization of calculation, results

To solve the system of MHD equations (1-4) in the region ($0\le x \le 1$, $0\le y\le 0.3$, $0\le z \le 1$), an absolutely implicit, finite-difference scheme [11, 12], conservative with respect to magnetic flux, was developed. The creation of special numerical methods for solving MHD equations was needed to speed up the calculation, for which it is necessary to maximally increase the time step at which the difference scheme remains stable. Under conditions of the complex problem of numerically solving MHD equations in the solar corona, special methods are actually needed so that such a task can be performed, i.e. to be able to carry out calculations for the foreseeable time. In the scheme, instead of the components of the magnetic field vector, averaged magnetic fluxes through the boundaries of the grid cells are used. The transfer terms of both magnetic fluxes and other quantities were approximated by first-order upwind finite differences. Implicit finite-difference equations were solved by the iteration method. To improve convergence of iterations, the values at the central stencil point of the difference scheme were taken in the next iteration. The nonuniform spatial grid of 135×39×135 was used in the computational domain of the corona; in the main subregion with a large magnetic field, the smallest step was chosen, which amounted to 0.01 of the region's size. The algorithm of MHD equations solving using developed finite-difference scheme is realized in PERSVET program.

In the previous calculation, in a greatly reduced (10^4 times) time scale [7–9], the time step was 0.5×10^{-3} of the time interval taken as a unit $t_0=L_0/V_A$ ~ 10 sec ($V_A = B_0/\sqrt{4\pi\rho_0}$).This interval corresponded to the evolution above the active region during the day. On a personal computer with a 2.79 GHz processor, it took ~ 2 days to calculate the evolution above the active region during the day. At present, there is a need (for details, see [13]) to perform more accurate MHD simulation in the real scale of time. Calculations showed that for simulation in the real scale of time, the scheme is stable for a step of 10^{-6} days. With this step, it will take ~ 3 years to calculate the evolution above the active region during the day on a computer with a 2.79 GHz processor. To perform such MHD simulation in the foreseeable time, it is necessary, by parallelizing the program, to increase the calculation speed by at least 20-100 times. The work on parallelization of computations was carried out both in the OpenMP system using many computing streams of a multi-core processor, and on CUDA technology using a large number of processors of the TESLA graphics card. The calculation of the iterative transition has been parallelized.

Parallelization in the OpenMP system was performed in various ways. It turned out to be the most effective when the parallelized subroutine divides the computational domain into subdomains, so that each thread calculates the values at the next iteration in its subdomain. Calculation on a computer with an 8-core Intel Xeon 3.1Ghz processor with 16 threads gave a calculation acceleration of 50-70 times, which has made it possible to obtain the first results of MHD simulation in the real scale of time during the first day of evolution above the AR 10356. The calculation was performed within 11 days.

For parallelization using CUDA technology, a supercomputer with a TESLA M2050 graphics card was assembled (Fig. 1a), and software based on CUDA NVIDIA technology was tuned. The algorithm for parallelizing calculations using Nvidia CUDA is shown in Fig.1b. The PGI (Portland Group) FORTRAN was used. When parallelizing using CUDA technology, the calculation of the values at the next iteration at each point of the spatial grid was carried out in its own computational thread. A parallelized test program for solving the Poisson equation, performed using a difference scheme similar to the scheme for solving MHD equations, but significantly simplified, showed an acceleration of the calculation by 20-100 times depending on the grid used. A parallelization of the program for the numerical solution of MHD equations was carried out. During the execution of parallelized routines, failures occurred without any diagnosis of their causes. Apparently, there were difficulties in exchanging data with the memory of the graphics card. Experience also showed that similar failures can occur when a parallel program is run for numerically solving MHD equations on supercomputers with the most modern graphics cards. This problem was solved by replacing the parallelized routines with smaller ones; the two main parallelizable routines are divided into almost 20 small routines. As a result, the program runs without failures, but often gives incorrect results, apparently due to errors in transferring data from the memory of the graphics card. Currently, work is underway to establish in the program additional control of data transfer from the memory of the graphic card.

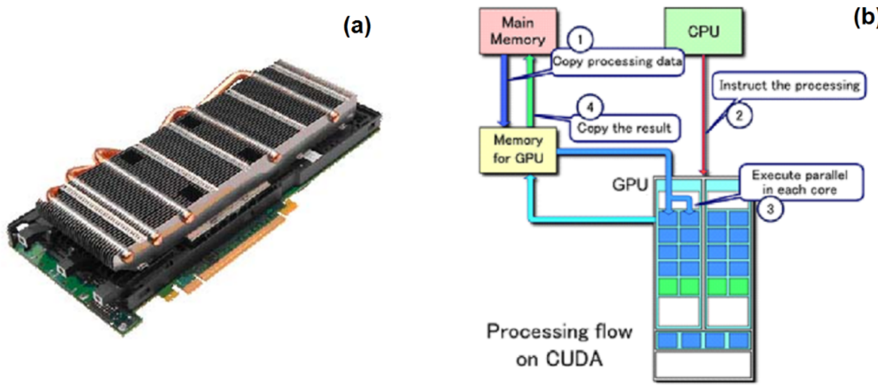

Figure 1. (***a***) - Graphics card used for parallel calculations GPU Nvidia Tesla M2050, Double Precision Support; (***b***) - Parallelization algorithm: (1) CPU copies data from RAM to the memory of GPU device. (2) CPU transfers control to GPU device. (3) The GPU device runs the CUDA kernels in parallel for calculations, after performing of which the GPU device transfers control to CPU device. (4) CPU copies the data-results of the calculations into RAM.

The existing experience in performing the test task of solving the Poisson equation and individual parallelized routines of the program for numerically solving MHD equations showed that due to difficulties associated with transferring data to the memory of the graphics card, the acceleration in calculations parallelized using CUDA technology may have limitations. Perhaps it will not exceed the acceleration by more than several times for calculations parallelized in the OpenMP system performed on modern multicore clusters. To verify such a statement, which may affect the choice of the strategy for using parallelization methods for more accurate MHD modeling above the active region, it is necessary to complete the parallelization using CUDA technology, introducing additional control of data transfer from the graphics card memory into the program, and perform calculations on supercomputers using various video cards, including the most modern.

Fig. 2 presents the results of MHD simulation in the real scale of time (see [13] in detail) using the PERESVET program parallelized in the OpenMP system. Magnetic lines and current density levels are shown in the plane of the current sheet configuration in the vicinity of the 304th local maximum of the current density at the point (0.455, 0.04502, 0.445), near which more than a day later an M1.4 flare should occur, according to the data of MHD simulation in reduced time scale [7-9].

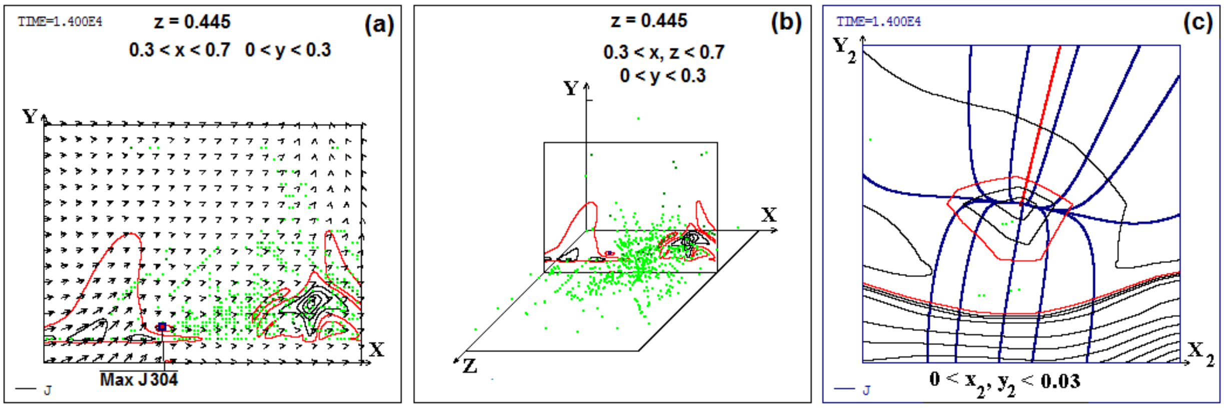

Figure 2. The 304th local maximum of the current density in the z = 0.445 plane. (***c***) – magnetic lines and lines of equal current density in the plane of current sheet configuration.

Conclusion

The parallelization of the program for solving the system of MHD equations was performed both in the OpenMP system using computational threads of a multi-core processor and using CUDA technology with calculations on a large number of processors of the TESLA graphics card. The calculation speed of a program parallelized in the OpenMP system on a computer with an 8-core Intel Xeon 3.1GHz processor with 16 threads increased by 50-70 times, which made it possible to obtain the first results of MHD simulation above the active region AR 10365 in the real scale of time. The formation of current sheets in the solar corona is shown, in the magnetic field of which the energy is accumulated for solar flares. The results obtained and the experience gained allow further improvement of the parallelized program to increase the calculation speed. Such a program is necessary for a more accurate study of the solar flare mechanism by MHD simulation above the active region and, in the future, it is supposed to consider the possibility of using it to improve the forecast of solar flares.

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