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Fifth Workshop on Numerical Modeling in MHD and Plasma Physics: Methods, Tools, and Outcomes

Virtual hosted in Novosibirsk, Russia
October 12-14, 2022

BOOK OF ABSTRACTS

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Topics

- Numerical methods for MHD equations
- Particle-in-cell method
- High performance computing
- Computational Fluid Dynamics
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Computing the gravitational potential on nested Cartesian meshes using the convolution method

Eduard Vorobyov[1], James McKevitt[1], Igor Kulikov[2], Vardan Elbakyan[3]
[1]University of Vienna, Vienna, Austria
[2]ICM&MG SB RAS, Novosibirsk, Russia
[3]Southern Federal Univeristy, Rostov-on-Don, Russia
eduard.vorobiev@univie.ac.at

Gravity play a key role in the dynamics of many astrophysical objects. Finding the gravity force of an arbitrary mass distribution requires the numerical solution of the Poisson equation. Often such a solution must be obtained on non-homogeneous numerical meshes, which allow a finer numerical resolution in the regions with higher mass concentration. An example of such meshes are so-called nested grids. A contemporary solution of the Poisson equation on the nested grids involves marching from the coarsest grid toward the finest one using for the boundary conditions the potential at the coarser grid. However, such an outside-in solution is difficult to parallelize. It also requires the knowledge of the boundary potential at the outer coarsest grid, which is obtained through a time-consuming multipole expansion of the potential in spherical harmonics.

An alternative approach is to employ the convolution theorem for computing the gravity using its integral representation (e.g., Hockney & Eastwood). This method involves fast fourier transform and is usually not computationally efficient on non-homogeneous meshes. Here, we present a modification to the convolution method, which can be efficiently applied to nested meshes (or adaptive meshes, in general).

This method is easily parallalizable (including GPUs) and does not require the costly multipole expansion to find the boundary conditions at the outermost grid. The method can equally well be applied to finding the electrostatic forces on nested grids.

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Fast ion-ion collisions simulation in particle-in-cell method

I.S.Chernoshtanov[1], A.A.Efimova[1], A.A.Soloviev[1],V.A.Vshivkov[1]
[1]Institute of Computational Mathematics and Mathematical Geophysics SB RAS
cherivn@ngs.ru, efimova@ssd.sscc.ru, solowey@rambler.ru, vsh@ssd.sscc.ru

Complete treatment of collisions in problems related to the development of plasma confinement systems is a problematic task [1]. The article presents a specialized algorithm for the particle-in-cell method aimed to fast simulation of pairwise collisions without the use of trigonometric functions. This approach is a development of the ideas presented in [2]. The brief essence of the method is that any two particles in a cell can interact (regardless of the distance and direction of velocities). The effectiveness of the developed algorithm was studied in comparison with other algorithms, including classical ones [3].

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Numerical simulation of beam injection into an open magnetic trap

G.I. Dudnikova, V.A. Vshivkov, M.A. Boronina,
A.A. Efimova, I.S. Chernoshtanov, K.V. Vshivkov
Institute of Computational Mathematics and Mathematical Geophysics SB RAS
gdudnikova@gmail.com

Nowadays one of the widely used methods for maintaining the density, temperature, and current in CTS facilities is associated with additional neutral beam injection. A detailed theoretical study of the essentially nonlinear processes of interaction between the injected beam and the background plasma in a self-consistent electromagnetic field is possible only on the basis of numerical simulation. A numerical model of ion beam injection into an open magnetic trap and the results of implemented on its basis computational experiments are presented in this work. The two-dimensional axially symmetric numerical model is based on the solution of the Vlasov kinetic equation for the ion components of the injected beam and the background plasma by the particle-in-cell (PIC) method. To solve the MHD equations for electrons, finite-difference schemes of the second order of accuracy are used. The system of Maxwell's equations for a self-consistent electric-magnetic field does not take into account the displacement current and uses the plasma quasi-neutrality condition. The model includes the main transfer coefficients due to plasma conductivity and electronic thermal conductivity. Cases of continuous off-axis injection of one and two ion beams are considered. On the basis of the computational experiments, the dependence of the spatial and temporal characteristics of the formed magnetic field cavern and the background plasma on the current and injection angle is studied. The created model describes the concept of the diamagnetic regime of plasma confinement in open magnetic traps as applied to laboratory experiments at the CAT facility in BINP SB RAS.

The work is supported by Russian Science Foundation (project N 19-71-20026).

Semi-implicit numerical method for differentially rotating compressible astrophysical flows

Ilya A. Kondratyev, Sergey G. Moiseenko
Space Research Institute RAS
Mrkondratyev95@gmail.com

Simulation of astrophysical fluid flows is one of most fruitful approaches for theoretical studies of a wide range of astronomical phenomena. Some types of flows, like e.g., magnetorotational supernova explosions, deal with a highly variable Mach number (from M << 1 near the protoneutron star to M >> 1 near the shock wave expelling in the stellar envelope) and strong differential rotation of the envelope. The Courant-Friedrichs-Lewy (CFL) stability condition of explicit finite-volume schemes (density-based solvers) in such cases could be rather restrictive due to a very large sound speed in the protoneutron star. In such case, semi-implicit schemes (pressure-based solvers) may give a superior performance.

In this work, we construct a semi-implicit finite-volume method for solution of the gas dynamical equations, in which the acoustic waves are treated implicitly, relaxing the CFL condition. The scheme is built in the spherical geometry on an axially moving grid. The latter feature of the proposed approach permits to use the semi-Lagrangean treatment of differential rotation, which allows to distinguish the large-scale differential rotation from the scheme, like in codes suited for accretion discs, decreasing the numerical viscosity, and increasing the stability of the method. Test calculations with and without rotation and self-gravity demonstrate, that the method is well-suited for effective simulations of astrophysical fluid flows with differential rotation and in the presence of sufficiently subsonic and supersonic flow regions.

Numerical study of the influence of plasma inhomogeneity with bremsstrahlung and photorecombination radiation on the absorption of an Alfven wave

A. A. Taiurskii[1,2]
[1]Keldysh Institute of Applied Mathematics
[2]Bauman Moscow State Technical University
tayurskiy2001@mail.ru

A mathematical model of the nonlinear absorption of a plane Alfven by a dissipative inhomogeneous plasma, due to dissipative effects, also bremsstrahlung and photorecombination radiation, are numerically investigated in the report. Density inhomogeneities specified using a Gaussian distribution are considered. This study is due to the mechanism proposed by a number of authors in 2011 for heating the solar corona as a result of absorption in the plasma of Alfven waves generated in the lower, much colder solar layers. The study is based on the equations of two-fluid electromagnetic hydrodynamics with full allowance for the inertia of electrons. The proposed implicit difference scheme for calculating plane-parallel flows of a two-fluid plasma made it possible to reveal a number of important absorption patterns. In particular, it is shown that the dependence of absorption with allowance for bremsstrahlung and photorecombination radiation for an inhomogeneous plasma leads to the effect of blocking the Alfven wave in a dissipative plasma and the appearance of a quasi-stationary mode of absorption of the Alfven wave. The dependences of the depth of penetration of the Alfvén wave and the maximum temperatures of electrons and ions on the values of the density inhomogeneity are obtained.

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Towards ML-based diagnostics of focused laser pulse

Yury Rodimkov[1], Valentin Volokitin[1,2], Evgeny Efimenko[3], Iosif Meyerov[1,2]
1. Department of Mathematical Software and Supercomputing Technologies, Lobachevsky University, 603950 Nizhni Novgorod, Russia
2. Mathematical Center, Lobachevsky University, 603950 Nizhni Novgorod, Russia
3. Institute of Applied Physics of the Russian Academy of Sciences, 603950 Nizhni Novgorod, Russia
rodimkov@itmm.unn.ru, meerov@vmk.unn.ru

Currently, machine learning (ML) methods are widely used to process the results of physical experiments. In some cases, due to the limited possibility of collecting experimental data, ML models can be pretrained on synthetic data simulated based on the developed analytical theory and then fine-tuned using experimental data. A limitation of this approach is the presence of hidden parameters of the analytical model, which values are difficult or impossible to estimate from the experiment. Setting these parameters incorrectly may induce a dataset shift when applied to real data. To solve this problem, we propose to train ML models on a dataset with randomly varied hidden parameters of the physical model. Thus, one can try to force the ML model to concentrate on more general patterns that depend weakly on the hidden parameters of the physical model.

The proposed approach is used for the problem of focusing of an extremely short laser pulse, taking into account the complex structure of the wavefront. In experiments, diagnostics is often carried out by recording the energy flow in the focal plane using a camera that justifies applying computer vision methods, in particular, convolutional neural networks. The structure of the wavefront can be modeled analytically by dividing the entire spectral range into several subranges and specifying the respective parameters (e.g. tilt and phase) of the various spectral components individually. In order to form datasets for training and testing, a family of physical models is used. These models are parameterized by latent parameters of intensity and boundary wavelengths corresponding to different spectral subranges. We observe good accuracy of reconstructing the physical parameters of the problem (spectral subranges phases and tilts) when training and testing the ML model on datasets generated for different values of the hidden parameters. This confirms that in the problem under consideration, the convolutional neural network selects relevant information without overfitting for specific features inherent in certain hidden parameters of the analytical model. We believe that this approach will enrich possible applications of ML methods to experimental diagnostics of laser-plasma interactions.

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Genetic Algorithm for Searching unipolar and bipolar single-flux-quantum pulse sequences for qubit control

M.V. Bastrakova[1,2], D.S. Kulandin[1,3], T. Lapteva[1,4], A.V. Liniov[1,5]
[1]Lobachevsky State University of Nizhny Novgorod

[2]mar.denisenko@gmail.com
[3]kulandin08@gmail.com
[4]tetyana.laptyeva@gmail.com
[5]alin@unn.ru

Nowadays most of superconducting quantum processors use charge qubits of a transmon type. They require implementation of energy efficient qubit state control mechanism. A promising approach is the use of superconducting digital circuits operating with single-flux-quantum (SFQ) pulses. The duration of SFQ pulse control sequence is typically larger than that of conventional microwave drive pulses but its length can be optimized for system with known parameters. Here we introduce a genetic algorithm for finding unipolar or bipolar SFQ control sequences that minimize qubit state leakage from the computational subspace. The algorithm is also able to search for a solution in the form of a repeating subsequence, which makes it possible to save memory. Its parallel implementation can find the appropriate sequence for arbitrary system parameters from a practical range in a reasonable time. The algorithm is illustrated by the example of the Hadamard gate for which it provides a fidelity over 99.99%. In this paper, we present the results for a single-qubit system, but in the future we will apply the developed approach to study a system of two qubits.

Imprints of spin on the solution and emission spectrum of accretion flows around black holes

Shilpa Sarkar, Indranil Chattopadhyay, Sanjit Debnath
Aryabhatta Research Institute of Observational Sciences, Nainital, India
shilpa.sarkar30@gmail.com

We investigate accretion flows around rotating black holes (BHs) and obtain self-consistent transonic solutions in full general relativistic prescription. The flow is assumed to be viscous and radiative. Viscosity helps in the removal of angular momentum outwards, allowing matter to get accreted inwards. In addition, viscous heat dissipated makes the matter hotter. On the other hand, radiation mechanisms like bremsstrahlung, synchrotron, and their inverse-Comptonisations cools down the matter. Thus, the solution depends highly on the interplay between heating and cooling processes. In our work we investigate the entire energy–angular momentum parameter space and obtain both shocked and shock-free accretion solutions. Because of the spin in Kerr black holes, the event horizon is dragged to a region <2GM/c^2, increasing the efficiency of accretion process. Ample of works showed a rotating BH to yield high temperature solutions compared to a Schwarzschild BH. This suggests higher emission. We investigate the effect of this spin on the spectrum obtained from accretion flows around BHs. We find efficiencies reaching >30% for maximally rotating BHs.

Verification and Validation of KI-1 plasma simulation code

A.V.Snytnikov, G.G.Lazareva
Institute of Automation and Electrometry SB RAS,
Peoples' Friendship University of Russia
snytav@gmail.com

KI-1 is a 3D electromagnetic parallel Particle-In-Cell [1] code. The is being validated with basic particle motion test, Poisson equation solution and two-stream instability. The correctness of two-stream instability simulation is verified by means of a neural network.

The name of the code is given by the KI-1 plasma experimental facility in the Institute of Theoretical and Applied Mechanics, Novosibirsk, USSR.

This code was created on the basic of the code created by Professor Vitaly A. Vshivkov that is sometimes referred as UMKA[2]. The difference between KI-1 and UMKA is the following:

- KI-1 uses dimensional variables
- KI-1 employs pure Boris push, while UMKA employs relativistic push.
- KI-1 uses Poisson equation solver together with the FDTD method to compute electric field.
- KI-1 employs MPI and CUDA parallelization within the common GCPIC parallelization strategy. The basic “UMKA code was parallelized with PVM.

These points may need some explanation. Using dimensional variables may result in precision loss, though it is not confirmed by the present tests. On the other hand, it makes the code more clear and simplifies understanding of physical results.
The same is about the push function. Scope of the KI-1 code is deliberately restricted to non-relavistic plasmas for the sake of clarity.

The purpose of the present paper is physical validation of the code. While its mathematical and algorithmic properties were studied a lot, physical correctness of the code needs detailed confirmation.

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New algorithm for solving relativistic equations of charged particles motion

A. Efimova, G. Dudnikova, E. Voropaeva, K. Vshivkov

The Institute of Computational Mathematics and Mathematical Geophysics SB RAS
anna.an.efimova@gmail.com

A new algorithm for solving relativistic equations of charged particles motion in electromagnetic fields is presented. It is taken into account that the electromagnetic field remains constant at each time step, and the value of the Lorentz factor is determined during the solution. We compared the accuracy, convergence, and efficiency of particle trajectory calculations for the created new scheme, the Boris method [1], and some of its modifications [2,3] using two-dimensional and three-dimensional test problems. It is shown that the accuracy of all considered schemes decreases with the growth of the relativistic factor. At the same time, the accuracy of the new scheme is higher compared to other schemes considered and retains the second order of approximation. The presented new scheme can be used in the numerical solution of a wide range of problems in astrophysics and thermonuclear fusion when high accuracy in determining the trajectories of particles in non-uniform electromagnetic fields is required.

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MHD Simulation of Laboratory Jets in a Toroidal Magnetic Field

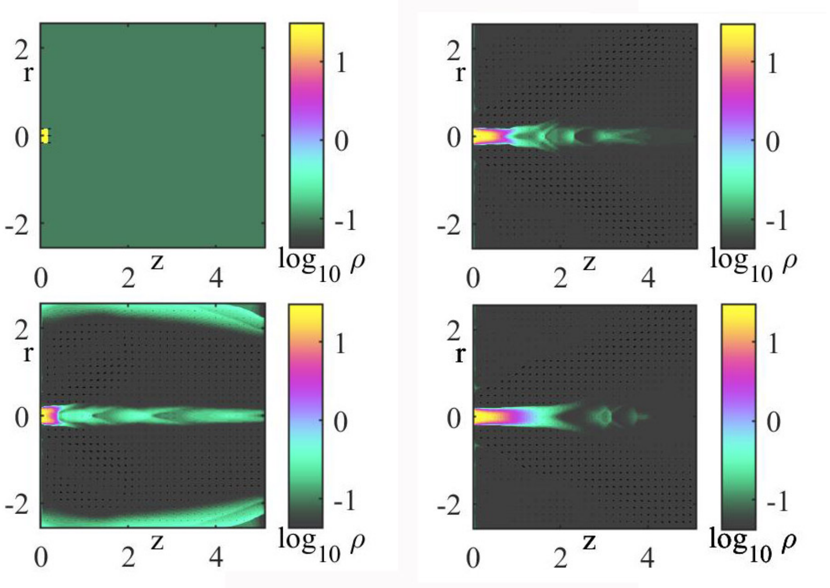
O.D. Toropina, G.S. Bisnovatyi-Kogan, S.G. Moiseenko

Space Research Institute
toropina@iki.rssi.ru

We present the results of MHD simulations and analysis of the results of laboratory experiments designed to imitate the formation and the propagation of astrophysical magnetized jets. We set an initial toroidal magnetic field in the entire simulation region and consider two cases. In the first, inflowing matter does not carry a magnetic field. In the second, inflowing matter carries a toroidal magnetic field.

In each case we obtained a picture of the plasma flow, the distribution of the plasma density and energy, and the structure of the jet at different distances. In the first case jet collimation does not occur. Non-magnetized matter quickly displaced the initial magnetic field from the simulation region. In the second case the magnetized matter is collimated into a directional jet and can be observed as a ring structure on the opposite side of the chamber. The size of the ring depends on the strength of the magnetic field.

We compared the numerical simulation results with the jet parameters obtained in a laboratory experiment at the NEODIM laser installation at TsNIIMASH using the derived similarity criteria.



Mathematical modeling of plasma transport in a spiral magnetic field

I.P Oksogoeva, G.G. Lazareva
Peoples' Friendship University of Russia
oksogi@mail.ru

Open magnetic systems for plasma confinement have been considered as possible configurations for a fusion reactor since the early days of fusion research. The paper presents a mathematical model of the plasma transport in a spiral magnetic field for a new installation SMOLA [1] for plasma confinement, created at the Budker Institute of Nuclear Physics of SB RAS. Numerical simulation of the transport equation in a helical magnetic field is carried out [2]. The stationary equation of plasma transport in the axially symmetric formulation contains the second derivatives, including mixed ones. The equation also contains the following variables Λ is the ratio of the system length L to the mean free path λ, n is the normalized concentration, φ the plasma potential, T the sum of ionic and electron temperatures. Magnetic plasma confinement for fusion power [3] involves the formation of a self-consistent configuration of plasma and magnetic field. Such a configuration should be able to prevent the loss of particles and energy and exist for some time, long enough on the scales of plasma processes. The distribution of the substance concentration obtained by numerical simulation has a qualitative correspondence with the data of field experiments.

In the future, a more accurate comparison with experimental data is planned, the use of the method of successive over-relaxation, as well as the variation of parameters: the depth of corrugation, diffusion and plasma potential.

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Mathematical Simulation of the Distribution of the Electron Beam Current in Tungsten Vapor during Pulsed Heating of a Metal Target

G.G. Lazareva
Peoples' Friendship University of Russia
lazareva-gg@rudn.ru

A model of the current distribution in a tungsten sample and an evaporating substance during surface heating by an electron beam is considered. The report considers the case when the equations for fields and currents are written for a tungsten sample in a cylindrical coordinate system, taking into account the electromotive forces arising in the gas above the sample [1]. It is assumed that the characteristic change time is large in comparison with the time of establishing the equilibrium of the equations of electrodynamics on the scale of the problem. The model is based on solving the equations of electrodynamics and the two-phase Stefan problem for calculating the temperature in the sample area in a cylindrical coordinate system. The current is considered as a possible source of substance rotation, which is observed in the experiment. The simulation results [2] showed that the thermal currents in tungsten vapor above the plate is necessary to obtain an acceleration capable of initiating the rotation of the melt. The model parameters are taken from the experiments at the Beam of Electrons for materials Test Applications (BETA) [3], created at the BINP SB RAS.

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Development of numerical methodology for transient conjugate heat transfer in multicomponent flows

O.B. Feodoritova [1], N.D. Novikova[1], V.T. Zhukov[1]
[1]Keldysh Institute of Applied Mathematics RAS
feodor@kiam.ru, nn@kiam.ru, vic.zhukov@gmail.com

Recently we proposed a new numerical approach [1] for conjugate heat transfer (CHT) problem of fluid–solid interaction. A fluid flow is a multicomponent mixture of ideal gases, taking into account the viscosity, thermal conductivity and diffusion of the components. As a heat-conducting solid body, elements of aircraft, combustion chamber of an engine etc., can be considered. The fluid dynamic model is based on the Navier-Stokes system with the introduction of the multicomponent diffusion equations. The developed algorithm exploits the fluid dynamic simulation framework in which the heat transfer in the fluid flow and in the solid are fully coupled. The fluid-solid interface condition for the energy equation: temperature and normal heat flux continuities. We use 3D multiblock unstructured grids and node-based finite-volume discretization. Each grid block corresponds to a single fluid/solid region. The time step computation is split into the hyperbolic and parabolic substeps [2]. The energy equation for solid and fluid regions is solved as a unique equation with automatic approximation of the continuity conditions of temperature and heat flux. To solve this energy equation we use the explicit iteration scheme LINS [2] which provides the basis for uniform calculation in the fluid and solid. The procedure is multi-regional: at each LINS iteration the calculation is made separately for each region, then the grid values of internal energy on the fluid–solid interface are adjusted. In this work, special attention is paid to features of the multi-block implementation of the algorithm and the experimental study of the accuracy of the approximation of continuity conditions on the fluid –solid interface.

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Calculation of radiation characteristics in the ionizing gas flow for the KSPU-T installation

A.N. Kozlov [1,3], N.S. Klimov [2], K.M. Gutorov [2], V.S. Konovalov [1], D.V. Kovalenko [2], V.L. Podkovyrov [2], A.D. Yaroshevskaya [2]

[1] Keldysh Institute of Applied Mathematics, RAS, Moscow
[2] Institute for Innovation and Fusion Research, Troitsk, Moscow
[3] Lomonosov Moscow State University, Faculty of Mechanics and Mathematics
andrey-n-kozlov@mail.ru

Numerical study of radiation characteristics in the ionizing gas flow was carried out in the channel of the quasi-stationary plasma accelerator QSPA-T [1] in the presence of additional longitudinal magnetic field. The MHD model of ionizing gas flows is based on the transport equations for multicomponent medium consisting of atoms, ions, and electrons. The modified MHD equations for two-dimensional axisymmetric flows in the presence of longitudinal magnetic field [2] are presented in terms of the azimuthal components of the magnetic field and the vector potential of the magnetic field, taking into account radiation transport, electrical conductivity and thermal conductivity. Radiation transport is calculated in the 3D formulation of the problem using the method of long characteristics in the multigroup approximation, taking into account the main mechanisms of emission and absorption of photons [3]. The modeling of the processes was carried out in the local thermodynamic equilibrium approximation. The integral radiation characteristics of the medium are determined. In the direction of various rays emerging from the plasma volume, the emission spectra for the Lyman and Balmer series in hydrogen plasma, as well as for separate spectral lines of helium impurity [4], are calculated. The experimental data and calculation results for radiation spectra of the hydrogen plasma are compared.

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Comparison of time integration methods for solving nonlinear heat conduction problems

M.A. Botchev[1,2], V.T. Zhukov[1]
[1]Keldysh Institute of Applied Mathematics, RAS, Moscow,
[2]Marchuk Institute of Computational Mathematics, RAS, Moscow
botchev@ya.ru, vic.zhukov@gmail.com

We consider nonlinear heat conduction problems of the form

$$u_t(x,t) = (k(u)u_x)_x\,,$$

supplied with initial and boundary conditions, where $k(u)=\kappa u^\sigma$. Nonlinear heat conduction problems constitute a highly challenging class of problems. This is caused by strong nonlinearity as well as by high stiffness of the operator. In this work we carry out extensive numerical tests to thoroughly examine several modern time integration schemes and to compare their computational performance for solving this problem class. The tested schemes include different approximate implicit schemes, stabilized explicit schemes and exponential time integration methods where various Krylov subspace methods are employed to approximate actions of the matrix exponential. Different Krylov subspace techniques are tested based on regular polynomial, rational shift-and-invert and block Krylov subspaces. It is shown that certain numerical methods demonstrate a computational performance which is nearly independent of the spatial mesh, i.e., the total number of iterations needed for time integration stays approximately constant as the spatial mesh gets finer.

Calculation of the parameters of tungsten vapor under pulsed heat load

Maksimova A.G.
The Institute of Computational Mathematics and Mathematical Geophysics SB RAS
maksimova@oapmg.sscc.ru

Nowadays, it is of interest to study the behavior of refractory metals under the influence of strong heating. During the operation of a nuclear reactor tokamak, contaminants enter the plasma, due to which the internal walls overheat. To the removal of waste material from the plasma a diverter is provided in the design. The surface of the divertor must withstand enormous thermal loads, so refractory metals such as tungsten are used to create them.

To study the behavior of tungsten, a facility BETA was created at the BINP SB RAS. In the course of an experiment, a tungsten plate was subjected to a pulsed heat load. As a result, metal evaporation was detected, which can affect the operation of the diverter.

The paper considers a numerical model that describes the process of tungsten evaporation from a heated surface. The system of gas-dynamic equations is implemented by the Belotserkovsky-Davydov large particle method. The rapid increase in temperature leads to the need to work with small steps in time and space. Of particular interest are the boundary conditions on the plate. Calculations have shown that with a normal surface temperature distribution, a spherical shape tungsten vapor exit front is formed.

Classical stationary solutions to the Vlasov-Poisson system

Yu.O. Belyaeva
RUDN University, Moscow, 117198 Russia
yilia-b@yandex.ru

It is considered the first mixed problem for the Vlasov-Poisson system in an infinite cylinder $Q = G \times \mathbb{R}$, where $G \subset \mathbb{R}^2$ is a bounded domain with a smooth boundary. Mixed problems for the Vlasov-Poisson system in an infinite cylinder describe the model of kinetics of charged plasma particles in the mirror trap.

For the Vlasov-Poisson system in an infinite cylinder with trivial electric field potential and sufficiently large induction of the external magnetic field there are constructed new compactly supported stationary solutions.

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Cloud-resolving numerical modeling of hurricane-like quasi-tropical cyclones over the Black Sea

Galina Levina
Space Research Institute RAS, Moscow, Russia
levina@cosmos.ru

The ongoing climate change leads to an increase in the number of intense atmospheric vortices (tropical and quasi-tropical cyclones, polar hurricanes, tornadoes) and the expansion of the geographical and seasonal limits of their occurrence.

Quasi-tropical cyclones (quasi-TCs) are often called subtropical cyclones, mesocyclones, or storms in the Russian scientific publications and media. The first satellite images of the Black Sea mesoscale cyclonic vortices, which presented a hurricane “eye”– type feature, date back to 2002 and can be found in the archives of the Met Office in the UK. However, these vortices had a very short lifetime and have not been studied. The first Black Sea quasi-TC studied in detail was a mesocyclone observed in the southwestern part of the sea on September 25–29, 2005 [1,2]. Many in the Russian meteorological community believed that such an exotic event was unlikely to happen again.

However, in August–October 2021, several quasi-TCs appeared over the Black and Azov Seas, were identified by foreign meteorologists from the Europe, USA and Australia, and discussed at the international professional internet-forum on tropical cyclones – tstorms.org (with the participation of the author).

We are going to present a new approach for the timely identification and investigation of quasi-TCs near the territory of Russia. The approach utilizes a combination of atmospheric cloud-resolving modeling and satellite data, and was substantiated thoroughly for the diagnostics of tropical cyclone genesis [3]. Some results of the investigations started for the vortex observed over the Black Sea in 2005 are discussed.

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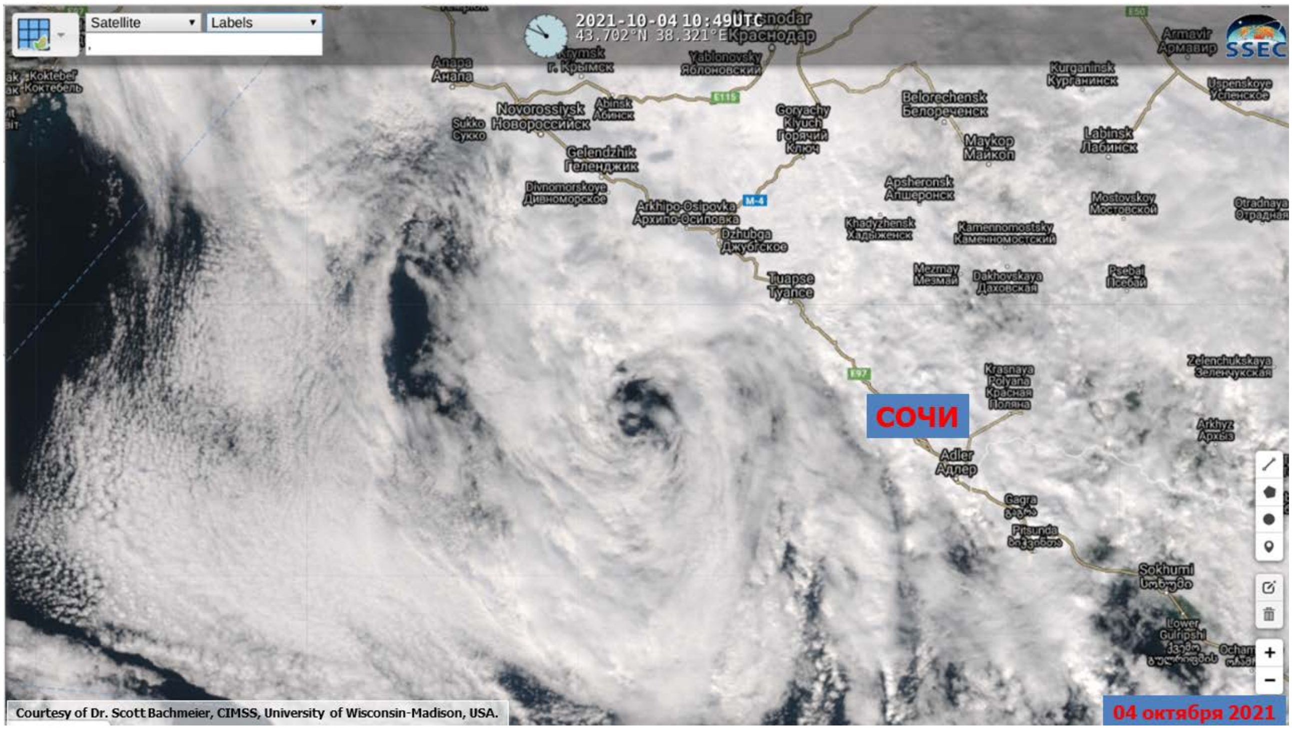

Courtesy of Dr. Scott Bachmeier, CIMSS, University of Wisconsin-Madison, USA.

04 октября 2021

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