Abstract book

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ASTRONUM 2024

Maison de la Simulation

The abstract are sorted by alphabetical order of the first author

Nom	Prénom	Talk
Audit	Edouard	Programing models and supernova ejecta
Aunai	Nicolas	PHARE: Parallel Hybrid code with Adaptive mesh refinement
Bacchini	Fabio	Shearing-box simulations of plasma accretion in Particle-in-Cell codes
Balsara	Dinshaw	ABOUT MHD
Battarbee	Markus	Porting the grid-based 3D+3V hybrid-Vlasov kinetic plasma simulation Vlasiator to heterogeneous GPU architectures
Bauswein	Andreas	Moving-mesh simulations of neutron star mergers
Berta	Vittoria	Towards 3D magnetic reconnection in relativistic plasmas with a 4th-order accurate finite volume method for the PLUTO code
Boyd	Brendan	Low Mach Hydrodynamic Simulations of the Convective Urca Process in Type Ia Progenitors
Büchner	Jörg	Kinetic simulation of Current sheet formation and reconnection in collisionless turbulent plasmas
Burrows	Adam	The Emerging Predictive Theory of Core-Collapse Supernova Explosions
Che	Haihong	Ion Beam Instability and The Generation of Alfv\'en wave in Collisionless Plasma
Del Zanna	Luca	The ECHO code for GRMHD: acceleration on GPUs and recent applications
Delorme	Maxime	A simulation code for astrophysics fluids with adaptive mesh refinement in the exascale era
Drake	James	Modeling Particle Acceleration during Magnetic Reconnection in Macroscale systems
Dubey	Anshu	Performance Portability For the Next Generation

Nom	Prénom	Talk
Fedrigo	Giacomo	GRMHD simulations of accretion flows onto massive binary black hole mergers embedded in a thin slab of gas
Fraternale	Federico	MHD/Kinetic Simulations of the Solar Cycle with Kinetic Neutral Helium and Hydrogen Atoms: Constraining LISM Proton Density Using Voyager Observations in the Outer Heliosheath
Fujimoto	Keizo	Magnetic reconnection in turbulent current sheet
Furuseth	Sondre Vik	Benchmarking Astrophysical Simulations: An Analytical Solution for Non-Linear Diffusivity
Giacalone	Joe	Hybrid simulations of pickup ion evolution across the solar wind termination shock
Haahr	Michael	Towards Realistic Solar Flare Models
Hanawa	Tomoyuki	4th-order Accurate Scheme for Solving Hydrodynamic Equations with the Selfgravity
Hoeflich	Peter	Thermonuclear Supernovae during the Nebular Phase
Hotta	Hideyuki	Flows and magnetic fields in the solar convection zone
Just	Oliver	Modeling neutron-star mergers, their remnants, and their kilonova light curves
Kissmann	Ralf	High-Resolution Simulations of the Gamma-Ray Binary LS5039
Kleimann	Jens	Simulating turbulence in galactic haloes and in the outer heliosphere
Kolobov	Vladimir	Grid-based and PINN solvers for electron kinetics in collisional non-thermal plasmas
Kondratyev	Ilya	Magnetorotational neutron star kicks
Kornbleuth	Marc	Inferring Properties of the Heliosphere and the Surrounding Interstellar Medium Using Energetic Neutral Atoms From the Heliotail
Kritsuk	Alexei	Statistical Signatures of ISM Turbulence in Dust and Synchrotron Polarization Maps

Nom	Prénom	Talk
Lebreuilly	Ugo	Dynamics of dust grains during star formation
Lee	Dongwook	Transforming a shock-capturing strategy in astro-fluid simulations with a neural network
Li	Shengtai	Coupling Astro-Shemistry Modeling with Hydrodynamics in Proto-Planetary Disks
Liakh	Valeriia	MHD Numerical Simulations of Solar Prominence Dynamics using MPIAMRVAC Code
Linker	Jon	Solar Magnetic Surface Flux Transport Modeling for Time-Dependent MHD Simulations
Mac Low	Mordecai-Mark	Interactions of Small Scale and Large Scale Dynamos in the Interstellar Medium
Maci	Daniela	BxC Toolkit: Generating Tailored Turbulent 3D Magnetic Fields
Merkin	Viacheslav	Scientific advances from the Center for Geospace Storms
Messer	Bronson	Flash-X: A computational astrophysics code built for the exascale
Mignone	Andrea	A fourth-order finite-volume constrained transport method for classical and non-ideal relativistic MHD equations
Misugi	Yoshiaki	Evolution of the Angular Momentum of Molecular Cloud Cores in Magnetized Molecular Filaments
Müller	Wolf-Christian	Network model of magnetohydrodynamic turbulence
Nowak	Katarzyna	Optimising Multiple Stellar Flybys Setup in 3D Hydrodynamics Mesh Code
Pajkos	Michael	Applications of the SpECTRE Multiphysics Code
Pavaskar	Parth	Diagnostics of MHD modes in the ISM through synchrotron polarization statistics
Perri	Barbara	Numerical challenges of space weather solar wind forecasting
Pogorelov	Nikolai	HelioCubed: A high-order code for solving Reynolds-averaged MHD equations on adaptive cubed-sphere grids

Nom	Prénom	Talk
Popovas	Andrius	Realistic simulations of solar dynamics, from interior to the surface
Prasad	Avijeet	Towards Data-Constrained Radiative-Magnetohydrodynamics Simulations of the Solar Atmosphere using the Bifrost Code
Reiss	Martin	Innovations in CME Modeling at NASA's CCMC with CORHEL-CME
Sokolov	Igor	Flux and Logically Cartesian Grids Rendezvous in the Threaded Field Line Model for Low Solar Corona
Sorathia	Kareem	Building a Synthetic Aurora
Takita	Masato	Modeling of the sidereal cosmic-ray anisotropy at TeV energies with data from the Tibet ASgamma experiment
Teissier	Jean-Mathieu	High-order dimension-by-dimension finite-volume magnetohydrodynamics solvers
Toth	Gabor	Well-Behaved Extended MHD Solutions Across Discontinuities
Van der Holst	Bart	Multi-fluid Outer Heliosphere Model with Solar Wind Heating through isotropization of pickup ions
Yan	Huirong	Study of compressible turbulence from simulations and observations
Zank	Gary P	Characterization of Turbulent Fluctuations in the Sub-Alfvenic Solar Wind
Zanotti	Olindo	A new first--order formulation of the Einstein equations: comparison among different high order numerical schemes
Zingale	Michael	Strong Coupling of Hydrodynamics and Reactions in Astrophysical Flows

ASTRONUM 2024 - TALK SCHEDULE

Monday		Tuesday		Wednesday		Thursday		Friday	
CHAIR:		CHAIR:		CHAIR:		CHAIR:		CHAIR:	
Time	*Speaker*	*Time*	*Speaker*	*Time*	*Speaker*	*Time*	*Speaker*	*Time*	*Speaker*
8:45-9:00 AM	Welcome E. Audit								
9:00-9:25 AM	A. Mignone	9:00-9:25 AM	F. Fraternale	9:00-9:25 AM	M. Reiß	9:00-9:25 AM	M. Takita	9:00-9:25 AM	A. Prasad
9:25-9:50 AM	N Aunai	9:25-9:50 AM	O. Zanotti	9:25-9:50 AM	JM. Teissier	9:25-9:50 AM	V. Kolobov	9:25-9:50 AM	M. Haahr
9:50-10:15 AM	H. Che	9:50-10:15 AM	D. Balsara	9:50-10:15 AM	B. van der Holst	9:50-10:15 AM	H. Yan	9:50-10:15 AM	D. Maci
10:15-10:45: AM: BREAK		**10:15-10:45: AM: BREAK**		**10:15-10:45: AM: BREAK**		**10:15-10:45 AM: BREAK**		**10:15-10:45 AM: BREAK**	
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10:45-11:10 AM	A. Burrows	10:45-11:10 AM	G. Zank	10:45-11:10 AM	E. Audit	10:45-11:10 AM	L. Del Zanna	10:45-11:10 AM	P. Pavaskar
11:10-11:35 AM	P. Hoeflich	11:10-11:35 AM	T. Hanawa	11:10-11:35 AM	N. Pogorelov	11:10-11:35 AM	R. Kissmann	11:10-11:35 AM	B. Boyd
11:35-12:00 AM	O. Just	11:35-12:00 AM	M. Kornbleuth	11:35-12:00 AM	D. Lee	11:35-12:00 AM	J. Büchner	11:35-12:00 AM	B. Messer
12:00-1:30 PM: LUNCH		**12:00-1:30 PM: LUNCH**		**12:00-1:30 PM LUNCH**		**12:00-1:30 PM: LUNCH**		**12:00-1:30 PM: LUNCH**	
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1:30-1:55 PM	M. Mac Low	1:30-1:55 PM		1:30-1:55 PM	B. Perri	1:30-1:55 PM	A. Kritsuk	1:30-1:55 PM	
1:55-2:20 PM	V. Liakh	1:55-2:20 PM		1:55-2:20 PM	J. Drake	1:55-2:20 PM	Y. Misugi	1:55-2:20 PM	
2:20-2:45 PM	I. Sokolov	2:20-2:45 PM		2:20-2:45 PM	U. Lebreuilly	2:20-2:45 PM	Pajkos	2:20-2:45 PM	
2:45-3:10 PM	J. Kleimann	2:45-3:10 PM		2:45-3:10 PM	A. Dubey	2:45-3:10 PM	A. Popovas	2:45-3:10 PM	
3:10-3:40 PM: BREAK		**3:10-3:40 PM: BREAK**		**3:10-3:40 PM: BREAK**		**3:10-3:40 PM: BREAK**		**3:10-3:40 PM: BREAK**	
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3:40-4:05 PM	J. Linker	3:40-4:05 PM		3:40-4:05 PM	J. Giacalone	3:40-4:05 PM	G. Toth	3:40-4:05 PM	
4:05-4:30 PM	K. Fujimoto	4:05-4:30 PM		4:05-4:30 PM	H. Hotta	4:05-4:30 PM	M. Zingale	4:05-4:30 PM	
4:30-4:55 PM	M. Battarbee	4:30-4:55 PM		4:30-4:55 PM	S. Merkin	4:30-4:55 PM	WC Mueller	4:30-4:55 PM	
4:55-5:20 PM	K. Sorathia	4:55-5:20 PM		4:55-5:20 PM	M. Delorme	4:55-5:20 PM	A. Bauswein	4:55-5:20 PM	
5:20-5:45 PM		5:20-5:45 PM		5:20-5:45 PM	S. Li	5:20-5:45 PM	K. Schoeffler	5:20-5:45 PM	
		Conference diner							

Programing models and supernova ejecta

Edouard Audit, CEA / Maison de la Simulation

Exascale systems offer great opportunities for the numerical astrophysics community and also raise important technical challenges, especially for legacy codes and for code sustainability and portability. In order to tackle this challenge, we undertook the testing of various programming models. In this presentation, I will discuss the first results of this testing and a comparison of various programming models on several hardware architectures. Then I will present results of supernova ejecta modelling done with the Heracles++ code developed using the Kokkos library. I will concentrate on red super-giants explosion and on the evolution of the mixing length.

Title: PHARE: Parallel Hybrid code with Adaptive mesh refinement

Authors: Nicolas Aunai, LPP/CNRS - nicolas.aunai@lpp.polytechnique.fr

Co-authors: Roch SMETS, Philip Deegan, Andrea Ciardi, Alexis Jeandet, Alexandre de Larminat, Ulysse Caromel

Abstract:

Modeling multi-scale collisionless magnetized processes constitutes an important numerical challenge. By treating electrons as a fluid and ions kinetically, the so-called hybrid Particle-In-Cell (PIC) codes represent a promising intermediary between fully kinetic codes, limited to model small scales and short durations, and magnetohydrodynamic codes used large scale. However, simulating processes at scales significantly larger than typical ion particle dynamics while resolving sub-ion dissipative current sheets remain extremely difficult. This paper presents a new hybrid PIC code with patch-based adaptive mesh refinement. Here, hybrid PIC equations are solved on a hierarchy of an arbitrary number of Cartesian meshes of incrementally finer resolution dynamically mapping regions of interest, and with a refined time stepping. This paper presents how the hybrid PIC algorithm is adapted to evolve such mesh hierarchy and the validation of the code on a uniform mesh, fixed refined mesh and dynamically refined mesh.

Fabio Bacchini

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Title : Shearing-box simulations of plasma accretion in Particle-in-Cell codes

Abstract : The shearing-box (SB) paradigm has been employed for decades in magnetohydrodynamic (MHD) codes to simulate shearing plasmas, e.g. in Keplerian accretion disks around astrophysical compact objects. However, such plasmas are often collisionless and require fully kinetic simulations, e.g. with the Particle-in-Cell (PIC) method. The formulation of the shearing-box equations for a PIC code, especially when particles attain relativistic energies, is highly nontrivial and has represented a technical problem for three-dimensional PIC-SB runs. Here, we review recent PIC-SB developments allowing for multidimensional, fully kinetic simulations of plasma accretion and turbulence driven by continuous shearing around black holes.

Beyond MHD

Dinshaw Balsara[1], Deepak Bhoriya[2], Vladimir Florinski[3]

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Key Words: *MHD, CGL,, non-conservative PDE, finite difference, WENO*

The MHD equations have served plasma physicists, space physicists and astrophysicists very well for the past several decades. Even so, one comes to the realization that the MHD equations are only an approximation that applies to systems where the collision rate between charged particles is fast enough to rapidly restore isotropy in the pressure tensor. For many systems involving collisionless plasmas, this assumption of the isotropy of the pressure tensor is invalid. In such situations, the Chew Goldberger and Low [1] equations take over. They are based on a double adiabatic approximation and allow the pressure parallel to the field lines to differ from the pressure perpendicular to the field lines. While the CGL equations are well-formed, they have resisted numerical solution for a very long time. The reason is that if these equations are taken by themselves, they could potentially give rise to an unbounded increase in pressure anisotropy in certain circumstances. This unbounded increase in anisotropy can eventually result in a loss of hyperbolicity and a consequent code crash.

Real world systems, like the solar wind, show that there are limits to the pressure anisotropy. Therefore, to make sense of the CGL equations, and their physical import, one has to understand the plasma physics effects, such as the mirror instability and firehose instability, which restore pressure isotropy at a microphysical level. Folding in these physical effects also results in numerical challenges that have to be overcome. In this talk we show how the CGL equations can be made numerically tractable by a deft combination of physical reasoning and advanced numerical methods. Preliminary applications will also be presented.

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Markus Battarbee

University of Helsinki, Helsinki, Finland

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Title : Porting the grid-based 3D+3V hybrid-Vlasov kinetic plasma simulation Vlasiator to heterogeneous GPU architectures.

Abstract : Vlasiator is a space plasma simulation code which models near-Earth ion-kinetic dynamics in three spatial and three velocity dimensions. It is highly parallelized, modeling the Vlasov equation directly through the distribution function, discretized on a Cartesian grid, instead of the more common particle-in-cell approach. Modeling near-Earth space, plasma properties span several orders of magnitude in temperature, density, and magnetic field. In order to fit the required six-dimensional grids in memory, Vlasiator utilizes a sparse block-based velocity mesh, where chunks of velocity space are added or deleted based on the advection requirements of the Vlasov solver. In addition, the spatial mesh is adaptively refined through cell-based octree refinement. In this presentation, we describe the design choices of porting Vlasiator to heterogeneous CPU/GPU architectures. We introduce the memory management, algorithmic changes, and kernel construction as well as our unified codebase approach, resulting in portability to both NVIDIA and AMD hardware (CUDA and HIP languages, respectively). In particular, we showcase a highly parallel block adjustment approach allowing efficient re-ordering of a sparse velocity mesh. We detail pitfalls we have overcome and lay out a plan for optimization to facilitate future exascale simulations using multi-node GPU supercomputing.

Andreas Bauswein

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Title : Moving-mesh simulations of neutron star mergers

Abstract :

We present the first application of a moving-mesh scheme to neutron star mergers. The tool is based on the Newtonian Arepo code and was extended to to describe the equations of relativistic hydrodynamics. We coupled a solver for the Einstein field equations adopting the conformal flatness approximation. We discuss test problems and merger simulations. These first simulations indicate a relatively low degree of numerical damping for instance in the postmerger phase as compared to traditional grid-based or particle-based simulation tools for neutron star mergers.

Vittoria Berta

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Title: Towards 3D magnetic reconnection in relativistic plasmas with a 4th-order accurate finite volume method for the PLUTO code

Abstract:

We are presenting the preliminary results of a set of multidimensional magnetic reconnection simulations in relativistic plasmas triggered by the tearing mode instability employing the new 4th-order accurate finite volume method recently implemented in the PLUTO code (Berta et al. 2024, Mignone et al. 2024).

One of the most promising mechanisms of particle acceleration in highly energetic astrophysical sources (e.g., AGNs, magnetars and so on) is magnetic reconnection in thin current sheets (Del Zanna et al. 2016). This process consists in the topological rearrangement of magnetic field lines in regions of local dissipation. The formation of a current sheet and the ensuing reconnection are intimately linked also to the large-scale structure of the system.

In this scenario, 3D simulations of magnetic reconnection are of paramount importance since they introduce complexities that are absent in 2D simulations (Loureiro & Uzdensky 2015). However, current state-of-the-art fluid models struggle to describe such rich dynamics in 3D due to the enormous resolutions and the long simulation time required with well established computational paradigms (that is, 2nd-order methods and CPU architectures) which generally require integration times orders of magnitude greater than the corresponding 2D simulations.

Here we present a systematic numerical study obtained exploring the results of a set of simulations of tearing-unstable current sheets in the context of resistive relativistic magnetohydrodynamics (ResRMHD). Our results have been obtained applying our 4th-order accurate finite volume method ported on the GPU version of the PLUTO code. The novel algorithm has proven to intrinsically reduce the numerical dissipation introduced in a simulation, thus enhancing the accuracy of the outcoming results while reducing the computational costs. In particular, we have demonstrated (see Berta etal. 2024) that the 4th-order method assesses the convergence of simulations of smooth problems by using approximately only the square root of the grid points required by the same setup run with a traditional 2nd-order scheme. For non-smooth problems instead, like the one treated in this study, the computational gain is still remarkable. Compared to previous works employing similar, but lower order, schemes (e.g., Mignone et al. 2019, Puzzoni et al. 2021), our method reaches convergence at half the resolution required by traditional paradigms (Mignone et al. 2024). This feature combined with the power of GPU architectures, results in a significant computational gain that is allowing us to reach high resolutions also in 3D.

I will present the results obtained with high resolution 2D simulations that follow the onset of the ideal tearing instability, verifying the results obtained by Del Zanna et al. (2016). Moreover, I will show the first comparisons between our 2D and 3D simulations at increasingly higher plasma magnetizations (up to ultrarelativistic plasmas) in the linear phase of the instability.

These results are paving the way for our final set of high-resolution 3D simulations that will follow both the linear and nonlinear phases of the instability.

Brendan Boyd

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Title : Low Mach Hydrodynamic Simulations of the Convective Urca Process in Type Ia Progenitors

Abstract :

Type Ia supernovae are bright thermonuclear explosions that play important roles in many areas of astronomy such as cosmology and galaxy evolution. The single degenerate paradigm is a potential model for the origins of these supernovae. This model entails a white dwarf accreting material from a companion and gaining mass to the point of carbon fusion in the core. The onset of carbon fusion, called the simmering phase, drives convection and alters the evolution of the white dwarf as it approaches the thermonuclear explosion. A key factor during this phase is the convective Urca process which links convection with weak nuclear reactions that leak energy from the star. To study the effects of the convective Urca process, it is vital to accurately model the turbulent convection in the core. We run 3D hydrodynamic simulations of the convection zone of a simmering white dwarf using the low-Mach hydrodynamic code MAESTROeX. A low-Mach method is necessary to capture the slow convective flow. From these simulations, we find the structure of convective mixing has a profound impact on the convective Urca process and that this mixing is not well characterized by a locally diffusive approximation (as assumed in Mixing Length Theory). We analyze these simulations to find energy loss rates due to neutrino emission. And finally, we place limits on how much the convective Urca process restricts the size of the convection zone.

This research was supported in part by the US Department of Energy (DOE) under grant DE-FG02-87ER40317.

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Title:

"Kinetic simulation of Current sheet formation and reconnection in collisionless turbulent plasmas."

Abstract:

Hot, collisionless plasmas are ubiquitous in astrophysical environments as well as in laboratory (fusion) devices. In the course of the turbulence evolution coherent structures are formed like current sheets (CSs) and plasmoids. Their formation influences the spectral properties of the turbulence and contribute to the dissipation of the turbulent energy, as it has been demonstrated theoretically [1], observationally [2] and numerically [3]. The evolution of these structures is, however, not well understood, yet, in particular the energy dissipation at electron scales.

Since all these processes are strongly nonlinear numerical simulations are the method of choice. In the last decade, mainly 2D hybrid-kinetic simulations concentrated on the turbulence cascade at sub-ion scales [1,3]. 2D fully kinetic turbulence simulations have complemented those findings by determining the statistics of reconnection rates in current sheets and distinguishing between "standard" reconnection events and the newly proposed electron-only reconnection events (without ion coupling) [4,5,6]. In particular it was shown that electron-scale reconnection is likely occurs in low low-β turbulent plasmas. The reconnection rates were found to be in both regimes close to the standard normalized value 0.1 [5].

In 3D turbulence the characterization of current sheets and reconnection is much harder, so only currently some progress was made. A detection algorithm applied to hybrid-kinetic [7] and fully-kinetic 3D simulations revealed a number of physical signatures of the decaying CSs such as the presence of outflows and parallel electric field [8], in a similar way as detected by spacecrafts in space [9].

Currently we obtained new results by using the fully kinetic code ACRONYM and the hybrid-kinetic code CHIEF. The latter allows a description of the electrons as an inertial fluid, different from standard hybrid approaches where the electrons are massless [10,11].

Typically a decaying turbulence is initialized by randomly-phased Alfvén-waves at large, injection scales. In the course of the turbulence cascade CSs are formed which thin down until they dissipate, e.g. via magnetic reconnection, in plasmoids or structures at even smaller (electron-) scales. 2D hybrid kinetic simulations in the limit of massless electrons had shown that current sheet the thinning is limited only by the grid resolution [12]. For inertial electrons, however, the electron mass determines the limits of thinning and reconnection breakups. This was proven by means of hybrid fluid-kinetic plasma models [13]. In fact, 3D hybrid-kinetic turbulence simulations with consider inertial electrons have shown that the CS thinning is limited mainly by the electron inertia [14]. It was found that, unexpectedly, the electron inertia influences the spectra of the parallel-current fluctuations even well above the electron scales.

A comparison of the results obtained by fully kinetic and by finite-electron-mass hybrid simulations has revealed that the electron inertia limits the CS thinning and then almost completely balances the reconnection electric field either by the bulk electron inertia and, to a lesser degree, by the thermal-electron-inertia.

2D fully kinetic investigations showed that in finite-guide-field reconnection the CS properties depend lesser on the off-diagonal elements of the pressure tensor for larger β (e.g. =2.0) compared to small-β (e.g.=0.1) plasmas [15].

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Title : The Emerging Predictive Theory of Core-Collapse Supernova Explosions

Abstract :

Using more than 20 state-of-the-art 3D core-collapse simulations to unprecedented late times (fully in 3D), I provide correlations between core-collapse supernova observables and progenitor core structures that emerge. This is the largest such collection of 3D supernova models ever generated and allows one to witness and derive testable patterns that might otherwise be obscured when studying one or a few models in isolation. From this panoramic perspective, we have discovered correlations between explosion energy, neutron star gravitational birth masses, ^{56}Ni and α-rich freeze-out yields, and pulsar kicks and theoretically important correlations with the compactness parameter of progenitor structure. We find a correlation between explosion energy and progenitor mantle binding energy, suggesting that such explosions are self-regulating. We also find a testable correlation between explosion energy and measures of explosion asymmetry, such as the ejecta energyand mass dipoles. However, there is much that remains to do in supernova theory and I will close with suggested paths forward.

Presenter's first and last name : Haihong Che

Presenter's affiliation: University of Alabama in Huntsville

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Title : Ion Beam Instability and The Generation of Alfv\\'en wave in Collisionless Plasma

Abstract :
We investigate ion beam-driven instabilities in a low β collisionless space plasma using Particle-in-Cell (PIC) simulations. Specifically, we examine the effects of different ion drift velocities on the development of the Buneman and resonant electromagnetic (EM) right-hand (RH) ion beam instabilities. Our simulations reveal that both instabilities can be driven when the ion beam drift exceeds the thretical thresholds. However, we observe that the ion beam-driven Buneman instability is quenched effectively by the resonant EM RH ion beam instability, which dissipates the kinetic energy of ion beams weakly. Instead, the resonant EM RH ion beam instability dominates when $v_b > v_A$, leading to the generation of RH Alfv'en waves and RH whistler waves. We find that the intensity of Alfv'en waves decreases with decreasing ion beam drift velocity, while the intensity of whistler waves increases. Our results provide new insights into the complex interplay between ion beams and plasma instabilities in low β collisionless space plasmas.

Luca Del Zanna

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The ECHO code for GRMHD: acceleration on GPUs and recent applications

Abstract: The Eulerian Conservative High Order (ECHO) code for classic, special, and general relativistic MHD has been developed and continuously upgraded in Florence since 2000, and its main characteristic features (high order finite-difference reconstruction, two-wave HLL Riemann solver, upwind constrained transport method for preserving the solenoidality of B) are nowadays part of many other successful MHD and GRMHD codes. Here we describe the recent porting of ECHO on GPU accelerated devices, simply based on ISO modern Fortran constructs (DO CONCURRENT), avoiding CUDA and external libraries or APIs. The new version of the code is about 16 times faster than the previous one (4 GPUs versus 32 cores with 4 threads each, on a single node), and it shows a very good scaling up to 256 nodes (1024 GPUs) on the Leonardo pre-exascale supercomputer at Cineca. The new version of the code has been applied to 2D and 3D relativistic MHD turbulence of magnetized plasmas, preliminary results with application to the physics of Pulsar Wind Nebulae will be presented.

Dyablo : A simulation code for astrophysics fluids with adaptive mesh refinement in the exascale era

Arnaud Durocher, Maxime Delorme, CEA-Saclay, IRFU/DEDIP/LILAS

Dyablo is a new code for the simulation of astrophysical plasmas on exascale architectures using Adaptive Mesh Refinement. The code targets new and upcoming Exascale supercomputers with a new codebase in C++ using the Kokkos portability performance library. Kokkos allows us to write a unique code to target multiple hardware architectures including GPUs. Dyablo is based on modern software engineering principles to allow "separation of concerns" and collaboration between HPC engineers and physicists through abstract interfaces and modularity. Although Dyablo is still in development, the code is now deployable and usable on all major (French) supercomputers.

We will present Dyablo, how it's made and what challenges had to be resolved for AMR on GPUs. We will also present two physical problems we resolve with Dyablo in solar physics and cosmology.

Presenter's first and last name

James Drake

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Title : Modeling Particle Acceleration during Magnetic Reconnection in Macroscale systems

Abstract :
How the magnetic energy released during reconnection is transferred to hot electrons and ions and nonthermal components is a topic of broad importance both in the heliosphere and the broader universe. Observations of impulsive flares, the Earth's magnetotail and in the heliospheric current sheet close to the sun reveal that reconnection produces a hot thermal component as well as powerlaw tails that extend many decades in energy. Single x-line models fail to explain the generation of the nonthermal component. However, simulations reveal that reconnection in the weakly collisional or collisionless regime becomes turbulent with energy release taking place in a multi-x-line environment. A major surprise is that the energy gain of the most energetic particles is dominated by Fermi reflection in growing and merging magnetic flux ropes rather than the parallel electric fields in kinetic scale boundary layers. The implication is that the kinetic scale boundary layers that control the parallel electric field are not important in energy release in large-scale systems. Particle-in-cell simulations are beginning to reveal powerlaw distributions of both electrons and protons. However, the PIC models fail to produce the extended powerlaws seen in flare observations because of inadequate separation of kinetic from macroscales. A new computational model, kglobal, has been developed that blends MHD dynamics with electron and ion particles but all kinetic scales. Simulations of reconnection in a macro-scale system reveal powerlaw distributions of electrons and protons that extend nearly three decades in energy and that the dominant control parameter is the ambient guide magnetic field. The results suggest that modeling of particle acceleration in realistic macro-scale geometry will be possible.

Anshu Dubey

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Title: Performance Portability For the Next Generation

Abstract: The prevalent trend in the rapidly evolving high-performance computing (HPC) landscape is heterogeneity in platform architecture. The diversity in hardware platforms, comprising various accelerators such as GPUs, TPUs, FPGAs, and a possibility of specializable chiplets poses a significant challenge for scientific software developers aiming to harness optimal performance across different computing platforms while maintaining the quality of solutions. The emergence of heterogeneous architectures has introduced software development and maintenance complexities, requiring tailored optimizations for each hardware platform, which make code maintenance very challenging. Code generation provides a mechanism to mitigate this challenge. For Flash-X, a multiphysics software system for simulation of various astrophysical phenomena, we have developed a toolchain where variants of control flow can be expressed in the form of a recipe written in python. A set of code generation tools convert this recipe into compilable code, while simultaneously creating code for interfacing with a latency hiding runtime. Our experiments show that this mechanism is 3 to 5 times faster than CPU and upto 7 times faster than applying directive-based offloading without latency management. I will present the details of end-to-end performance portability, performance results on various platforms, and productivity gains using this approach.

GIACOMO FEDRIGO

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Title:
GRMHD simulations of accretion flows onto massive binary black hole mergers embedded in a thin slab of gas

Abstract:
Massive binary black hole (MBBH) mergers are powerful sources of low-frequency gravitational waves (GWs) and are targets for upcoming space-based missions like the Laser Interferometer Space Antenna.
These mergers are expected to occur in the aftermath of a gas-rich galaxy merger yielding bright electromagnetic (EM) signals, due to the interaction of the orbiting massive black holes (MBHs) with the gaseous environment in their vicinity. The simultaneous (multimessenger) detection of both GW and EM signals can provide unique information on the physics of accretion in violently changing spacetimes. In the last decade many studies have presented accurate simulations of accretion flows of MBBHs in Circumbinary Disks and in homogeneous gas clouds, in order to better understand the involved plasma dynamics and to predict EM emission signatures.
In my talk, I will present state-of-the-art general relativistic magnetohydrodynamic simulations of merging equal-mass spinning black holes embedded in an equatorial thin slab of magnetized gas, performed with the Einstein Toolkit infrastructure and the IllinoisGRMHD code. I explored different configurations: i) non-spinning black holes, ii) MBHs with spins aligned to the orbital angular momentum, iii) and with misaligned spins. The rest-mass density of the gas slab follows a Gaussian profile symmetric with respect to the equatorial plane and it is initially either stationary or with Keplerian rotational support. Throughout the inspiral phase, configurations with non-zero spins display modulations in the mass accretion rate that are proportional to the orbital frequency and its multiples. Frequency analysis suggests that these modulations are a generic feature of inflows on merging binaries. In contrast to binary models evolved in a gas cloud scenario, I did not observe a significant increase in the mass accretion rate after the merger in any of the simulations. A magnetic field amplification by one order of magnitude is witnessed, falling between values observed in similar runs of gas cloud accretion in ideal MHD and force-free regime electrodynamics simulations. My simulations provide invaluable insights into the correlations between gas dynamics, magnetic field dynamics and their potential role in generating electromagnetic emissions from massive binary black hole systems.
In conclusion, I will also introduce a recent effort aimed at extending the numerical scheme of the mesh-free GIZMO code, that has been shown to have many advantages compared to the standard fixed-grid and SPH techniques, to GRMHD. Such an extension will allow us to consistently simulate BH accretion and feedback from cosmological scales down to the event horizon for the first time.

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Title: MHD/Kinetic Simulations of the Solar Cycle with Kinetic Neutral Helium and Hydrogen Atoms: Constraining LISM Proton Density Using Voyager Observations in the Outer Heliosheath

Abstract:

We introduce the first solar-cycle simulations from our 3D, global MHD-plasma/kinetic-neutrals model, where both hydrogen and helium atoms are treated kinetically, and electrons and helium ions are described as individual fluids. We discuss the implementation of this new model and its application to simulations of the time-dependent interaction of the solar wind (SW) and the local interstellar medium (LISM). By comparing the results from different global models and using Voyager/PWS observations of electron density up to 160 AU from the Sun for validation, we conclude that the current estimates for the proton density in the LISM may need revision. Our findings indicate that the commonly accepted value of 0.054 cm^{-3} might be increased to around 0.07 cm^{-3} or even higher. We also investigate the impact of different assumptions regarding the proton velocity distribution function in the outer heliosheath on the global solution. These simulations reveal new features, particularly in the behavior of SW helium ions, which are crucial for inferring the properties of the LISM and of the global heliosphere, especially in the heliotail.

Keizo FUJIMOTO, Yi-Nan LIU, and Jin-Bin CAO

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Magnetic reconnection in turbulent current sheet

Abstract : Magnetic reconnection is an important process in space and astrophysical plasmas, facilitating fast energy release of the magnetic field energy into plasma kinetic energy. One of the major issues of reconnection is the impact of three-dimensionality on the reconnection processes such as the reconnection rate and plasma acceleration. The 3D current sheet is potentially unstable to a variety of shear flow and drift-type instabilities. However, the roles of such spontaneous instabilities and turbulence on reconnection have not been clearly understood because of the limitation of computer resources. Our large-scale PIC simulations in 3D system have revealed that the reconnection current layer is mainly unstable to the shear flow instabilities, leading to intense electromagnetic turbulence. It is found that the local reconnection rate in the turbulent current sheet is significantly enhanced due to forcing from the turbulence. The intermittent enhancement of the reconnection electric field is consistent with recent satellite observations in Earth's magnetosphere. We also found intense electron acceleration and heating in 3D than in 2D, which is caused by the induction electric field due to the turbulence and the associated electron scattering. These results suggest that the reconnection processes are essentially three-dimensional, so that 2D model limits the generation of the local electron jets and heating.

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Title : Benchmarking Astrophysical Simulations: An Analytical Solution for Non-Linear Diffusivity

Abstract :
To understand the physics in Solar, Stellar, and Interstellar media, we rely on complicated multi-physics simulations. This work presents an analytical solution for non-linear diffusivity in 1D, 2D, and 3D, against which one can test such simulations to ensure their validity. The solution is based on the self-similar solutions by Pattle, 1959, which required the diffusing quantity to be zero beyond a finite radius. Here, we surpass this constraint, allowing for a small non-zero background value. This problem is highly relevant in the Solar atmosphere, where energy released in the hot MK Corona diffuses down to the much colder kK Photosphere through Spitzer thermal conductivity. The analytical solution will benchmark the single and multi-fluid radiative MHD codes Ebysus and Bifrost, used to study the Sun. Additionally, since the derivation and argumentation is general, it can easily be followed to treat any non-linear diffusion problems.

Joe Giacalone

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Title : Hybrid simulations of pickup ion evolution across the solar wind termination shock

Abstract :
Hybrid simulations, those which treat ions kinetically using the usual particle-in-cell approach, and electrons as a massless charge-neutralizing fluid, are especially useful to study the ion microphysics of the solar wind termination shock. With modern computers, they can also be used to determine the physics of the initial acceleration process of ions at the shock leading to the formation of high-energy tails in the distribution. In addition to thermal solar wind ions, interstellar pickup ions are separate and vitally important additional ion species in the outer heliosphere, and these species are easily added to the hybrid simulation. In this talk, we will discuss recent insights into the evolution of the solar wind and pickup ion distribution across the termination shock. We will present comparisons with observations such as those of the high-energy tail made by the Voyager spacecraft, and also IBEX which observed energetic neutral atoms (ENA) that inform us of the charged-particle distribution in the outer heliosphere. We will present a key new result, which resolves a previously noted discrepancy between observed ENA spectra and predictions based on prior hybrid simulations.

Michael Haahr

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Title: Towards Realistic Solar Flare Models

Abstract:
We introduce a fully explicit Particle-In-Cell (PIC) solver within the DISPATCH framework. We aim to enhance solar flare simulations beyond the constraints of traditional Magnetohydrodynamics (MHD) models, which rely on simplified approximations like anomalous resistivity to model reconnection. This work marks the first step toward developing a hybrid MHD-PIC solver. This approach allows direct examination of the energy distribution in terms of heating, particle acceleration, and electric fields within solar flares. The validated PIC solver sets the foundation for a more accurate flare model, seeking to provide new insights into the mechanisms heating the solar atmosphere.

Advancing our work, we plan to integrate PIC with MHD, utilizing DISPATCH's capability for dynamic solver switching in response to local conditions within simulations. This hybrid MHD-PIC model seeks to unify microscale and macroscale dynamics, facilitating a more comprehensive, accurate, and efficient framework for solar flare simulations. This research contributes to the broader goal of solving the coronal heating problem by providing a clearer picture of the energy processes in the solar atmosphere.

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Title:

"**4th-order Accurate Scheme for Solving Hydrodynamic Equations with the Self-gravity**."

Abstract:

Gravity plays an essential role in the formation and evolution of many astronomical objects. Though gravity is dominant on a large scale, other forces compete, such as gas pressure, radiation, and magnetic fields. It is essential for numerical simulations to evaluate their interplay accurately. Here, we present a 4th-order accurate finite volume scheme to solve the hydrodynamic equations for a self-gravitating gas on a uniform Cartesian grid. It provides the gravitational acceleration (\rho g) and the gravitational energy release (\rho v g) as the source terms of the hydrodynamic equations. We apply this scheme to various test problems, including sound wave propagation and 3D equilibria, to prove the convergence. Our scheme guarantees the conservation of total linear momentum. The spurious heating or cooling due to the numerical evaluation of gravity decreases in proportion to the fourth power of the cell width. Another example shows the spherical collapse of a polytrope by a sudden decrease in the pressure near the center. This example includes a bounce and second collapse associated with a spherical accretion shock. We also show a method to smoothly downgrade the solution to second-order accuracy to avoid possible spurious oscillation near steep density and pressure gradients.

This work has been assigned a document release number LA-UR-24-24861.

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Title : Thermonuclear Supernovae during the Nebular Phase.

Abstract: Thermodynamical Supernovae, so called SNe Ia, are one of the keys to high precision cosmology and to decipher the nature of the dark energy and matter. Moreover, they provide a playground for numerical astrophysical processes for an, apparent, diverse group of explosions of White Dwarf stars.

What we observe as SNe Ia are low-energy photons, light curves and spectra, some days to months after the explosion is the light emitted from a rapidly expanding, envelope with 3D abundance imprints of the explosion from a low density and temperature plasma with population numbers far from thermodynamical equilibrium. The low-energy LCs and spectra are powered by radioactive decays producing hard X- and gamma-photons, and positrons with energies in the MeV-range. The transformation of high to low-energies involves particle cascading to low energy and, eventually, ionization of inner-shell electrons in a cold plasma, Auger effects etc.

Modern observations from the UV (HST) to the MIR (JWST) provide direct probes but demand complex radiation and particle transport, hydrodynamical simulations. Taking the complexity of the problems, the resulting synthetic spectra depend on details of physics and approximation.
We identify the link between high-energy and low-energy particles and photons as a main source for discrepancy. E.g. using the a) common assumption of energy distribution according to the electrons, b) cascading down of the high-energy leptons via the Spencer Fanu equation and c) full Monte Carlo treatment including ‘shielding’ of the non-thermal lepton cascade. We show that changes in the spectra by a), b) and c) produces larger variations than the underlying explosion physics. With observations as benchmark, we found c) to give good agreement and allows to identify and constrain the conditions where the explosive flame starts and its propagation.

Hideyuki Hotta

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Title : Flows and magnetic fields in the solar convection zone

Abstract :
We carried out a high-resolution simulation of the solar convection zone and, for the first time, reproduced the solar-like differential rotation without using any manipulation.
The sun rotates differentially with the fast equator and the slow poles, called solar-like differential rotation (DR). The DR is thought to be maintained by the turbulent thermal convection in the convection zone, but recent high-resolution simulations cannot reproduce the solar-like DR, i.e., the fast equator. The small-scale turbulence tends to transport the angular momentum radially inward, and the DR results in the anti-solar-like topology. This problem is one of the most essential mysteries in solar physics, called the convective conundrum. In order to resolve the problem, we carried out an unprecedentedly high-resolution simulation using Fugaku, and the solar-like DR is nicely reproduced. The result shows that the magnetic field is unexpectedly strong and has a dominant role in the angular momentum transport.

Oliver Just

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Title : Modeling neutron-star mergers, their remnants, and their kilonova light curves

Abstract : The first combined observation of gravitational waves and a kilonova from a binary neutron-star merger in 2017 finally confirmed that these types of events are indeed production factories of the heaviest elements in nature, such as gold and plutonium. Interpreting observations from neutron-star mergers is challenging, because it requires a careful theoretical modeling of complex physical phenomena connected to microphysics at extreme densities, neutrino radiative transfer, general relativistic gravity, and magnetohydrodynamic turbulence. In this talk I will outline the current state-of-the-art of merger modeling and report our recent studies taking steps towards building predictive end-to-end models, which describe the merger, its remnant, and the subsequent electromagnetic kilonova emission in a self-consistent fashion.

Ralf Kissmann

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Title: High-Resolution Simulations of the Gamma-Ray Binary LS5039

Abstract: I will present our model of the gamma-ray binary system LS5039. This system consists of an O-type star and a compact object in a mildly eccentric orbit. In our model we assume a wind-driven scenario for the gamma-ray emission from this system. This means, that in our model the compact object is assumed to be a pulsar. Correspondingly a wind-collision region between the massive stellar and the highly relativistic pulsar wind forms, the shape of which is heavily influenced by the orbital motion of the binary system.
The energetic particles, which eventually produce the gamma-ray emission, are assumed to be leptons from the pulsar wind. Thus, the most relevant emission channels are synchrotron emission and inverse Compton emission from interaction of the energetic leptons with the stellar radiation field.
In our model we investigate the dynamics of the system for three full orbital periods. Due to the highly relativistic pulsar wind, this required both high spatial resolution and small time steps leading to a numerically very expensive simulation. Alongside we simulated the dynamics of the energetic leptons propagating within the highly turbulent wind-collision region. I will show corresponding results both of the wind dynamics of the systems and of its gamma-ray emission, where we investigated the long-term dynamics and the orbit-to-orbit variability of this system.

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Title: Simulating turbulence in galactic haloes and in the outer heliosphere

Abstract:
First, simulations of the wind-filled halos of starburst galaxies are performed in the framework of single-fluid magnetohydrodynamics, suitably extended to also track the self-consistent evolution of additional turbulence-related quantities. These quantities comprise the turbulent energy density, the cross-helicity, and the turbulent length scale. After a brief discussion of these extended equations and the employed numerical approach, I will present selected simulation results, both for non-magnetized benchmark runs as well as for tests using the full system of equations. The dominant and unexpected feature of the former is a macroscopic flow instability near the rotational axis that prevents the outflow from reaching a steady state. Methods to determine the cause and nature of this instability are presented, followed by a preliminary analysis of the resulting turbulent properties.
Second, the above framework is extended further to account for a non-constant energy difference (or residual energy), which is not conserved in the absence of dissipation, in addition to the Elsasser energies and by allowing each of these quantities its own characteristic correlation length scale. This setting is then applied to the outer heliosphere beyond the termination shock, where the solar wind expands both sub-Alfvénically and nonradially. The resulting solutions of this six-equation model are illustrated and studied in some detail.

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Grid-based and PINN solvers for electron kinetics in collisional non-thermal plasmas

We explore physics-informed neural network (PINN) solvers for collisional kinetic equations in phase space. In our presentation, we will first describe and compare the key ingredients of the traditional finite volume (and finite element) solvers and PINN solvers for elliptic (Poisson), hyperbolic (advection), and parabolic (diffusion) equations in simple 2d settings. Then, we will describe the challenges of using traditional and PINN solvers for electron kinetic equations in plasmas. These challenges are due to the non-locality of the collision operators in velocity space and the multi-scale nature of the kinetic equations (the presence of a diffusion kinetic scale between the fully kinetic and fluid limits). An integral operator in velocity space describes the large-angle elastic scattering of electrons on atoms (instead of the Fokker Planck differential model for small-angle scattering). Inelastic collisions associated with energy loss quantum larger than the electron mean energy (temperature) are described by a non-local term with a shifted argument (in energy) rather than a continuum loss model for quasi-elastic collisions. The dominance of elastic scattering over collisions associated with energy loss results in an intermediate (diffusion) time scale in a phase space of deduced dimensions.

For plasma simulations, asymptotic-preserving properties ensuring specific conservation laws at different scales are desirable. Using spherical coordinates in velocity space and symmetry in the configuration space, we consider the phase space with minimal dimensions (2-3) and use traditional methods with adaptive Cartesian mesh. We compare the advantages and drawbacks of PINNs to state-of-the-art traditional solvers using adaptive mesh in phase space, implicit schemes, high-order methods, etc.

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Title : Magnetorotational neutron star kicks

Abstract : Neutron stars, which are born in highly aspherical supernova explosions, are believed to gain high linear velocities -- kicks -- due to anisotropic neutrino flash and/or matter ejection. We provide a study concerning a neutron star kick obtainment in a magnetorotational supernova explosion model. We simulate a series of core collapse supernova models of a massive (35 Solar masses) rapidly rotating star with initial equatorially asymmetric magnetic fields, using global 2D magnetohydrodynamic simulations with a neutrino leakage scheme, considering the dependence of the protoneutron star kick and explosion properties on various initial magnetic field configurations, such as compositions of magnetic multipoles, offset dipolar as well as dipolar + toroidal fields. Our simulations show, that protoneutron star kicks may be in order of 100-500 km/s at post-bounce times of order of 1 second. This may allow to explain the presence of bulk velocities of the neutron stars in the framework of magnetorotational supernova model.

Marc Kornbleuth

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Title: Inferring Properties of the Heliosphere and the Surrounding Interstellar Medium Using Energetic Neutral Atoms From the Heliotail

Abstract: Energetic neutral atoms (ENAs) offer the best method for investigating the global structure of the heliosphere. To date, the Interstellar Boundary Explorer (IBEX) and the Ion and Neutral Camera (INCA) that was on board Cassini provide the only global ENA observations of the heliosphere. While extensive modeling has been done at IBEX-Hi energies (0.52-6 keV), no global ENA modeling has been conducted for INCA energies (5.2-55 keV). Here, we use an ENA model of the heliosphere based on hybrid results that capture the heating and acceleration of pickup ions (PUIs) at the termination shock to compare modeled global ENA results with IBEX-Hi and INCA observations using both a long- and short-tail model of the heliosphere. We find that the modeled ENA results for the two heliotail configurations produce similar results from the IBEX-Hi through the INCA energies. We conclude from our modeled ENAs, which only include PUI acceleration at the termination shock, that ENA observations in currently available energy ranges are insufficient for probing the shape and length of the heliotail. However, as a prediction for the future IMAP-Ultra mission (3-300 keV) we present modeled ENA maps at 80 keV, where the cooling length (~600 au) is greater than the distance where the long- and short-heliotail models differ (~400 au), and find that IMAP-Ultra should be able to identify the shape of the heliotail via the high latitude heliotail lobe profile distinguished by high ENA flux. We also find that these heliotail lobes can be used to not only distinguish the heliotail structure, but can also provide information regarding the interstellar magnetic field (BISM) properties, which remains an open question. Analyses showed that these high latitude lobes are nearly aligned with the solar meridian, while also exhibiting a rotation with solar cycle. We show using steady state solar wind conditions that the inclination of the lobes reproduced with commonly used values for the angle between BISM and the interstellar flow in the hydrogen deflection plane is inconsistent with the IBEX ENA observations. Additionally, we find that the variation of the solar magnetic field magnitude with solar cycle causes the longitudinal rotation of the lobes observed by IBEX by affecting the inclination of the lobes.

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Title : Statistical Signatures of ISM Turbulence in Dust and Synchrotron Polarization Maps

Abstract :

We show that high-resolution simulations of magnetohydrodynamic turbulence in the multiphase interstellar medium (ISM) yield the EE/BB and TE/EE spectral ratios for polarized emission from Galactic dust in broad agreement with the *Planck* PR3 measurements at 353 GHz. In addition, the scale dependence of the BB, EE, and TE spectra is consistent with observations over approximately one decade of scales resolved in the simulations. Likewise, synthetic polarization maps for Galactic synchrotron emission at 30 GHz closely match *Planck* and WMAP measurements of the E-to-B ratio and EE, BB spectral slopes obtained at 30 GHz and 23 GHz, respectively. The simulations present an opportunity to understand the physical origin of the statistical signatures of ISM turbulence in dust and synchrotron polarization maps, and will help to develop more refined models of Galactic foreground emission of use for both current and future CMB experiments.

This research was supported in part by the NASA Grant 80NSSC22K0724 and by the LDRD program of LANL under projects 20220107DR and 20220700PRD1. Computational and storage resources were provided by the ACCESS program (MCA07S014), LRAC allocation at TACC (AST21004), and by the DOE award allocated at NERSC (FES-ERCAP-m4239). This research was also supported in part by the NSF Grant PHY-2309135 to the Kavli Institute for Theoretical Physics (KITP).

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Title: Dynamics of dust grains during star formation

Abstract: Dust is a key component of the interstellar medium. Although it represents only about 1% of its mass, this mixture of grains plays a major role in radiative transfer processes, the interplay between the neutral gas and the magnetic fields, the chemistry and, of course, planet formation. Dust is also very challenging to take into account in numerical simulations. Firstly, dust grains have a spectrum of sizes, ranging from a few nanometers to a few centimeters in protoplanetary disks. In addition, dust dynamics can significantly differ from the gas, with grains of different sizes behaving differently. Lastly, dust grains can stick or fragment through collisions which also alters their size distribution. These two processes lead to a dramatic evolution of the dust size distribution from the diffuse interstellar medium to protoplanetary disks. In this talk, I will review how we take dust into account in our numerical MHD simulations. I will first present our state-of-the-art methods to tackle gas and dust dynamics (Lebreuilly et al. 2019; Verrier et al., in prep) and our recent efforts to model dust-dust sticking and fragmentation (Lebreuilly et al. 2023a; Vallucci-Goy et al., submitted). Finally, I will present simulations of dust evolution from molecular clouds scales down to those of protoplanetary disks (Lebreuilly et al. 2020, 2023b; Commerçon et al. 2023).

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Talk Title: Transforming a shock-capturing strategy in astro-fluid simulations with a neural network

Talk Abstract: We present ongoing work on a machine-learning-based shock-capturing approach called the NN-GP-MOOD method. The method leverages the existing *a posteriori* GP-MOOD method as the primary building block, which controls the solution near shocks according to the improved MOOD (Multidimensional Optimal Order Detection) criteria. High-order accuracy is achieved using unlimited multidimensional GP reconstruction that adaptively cascades to a positive-preserving solution with MOOD. Expanding on this foundation, we delve into our pioneering integration of machine learning within the GP-MOOD framework. By employing a neural network (NN) to discern shock patterns, our *a priori* NN-GP-MOOD approach achieves an unparalleled equilibrium between high-order accuracy and stability, dynamically adjusting to local flow conditions. This sophisticated strategy optimizes numerical accuracy and stability while maintaining the overall predictive capabilities in simulating shock-dominant flows.

Shengtai Li

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Title : Coupling Astro-Shemistry Modeling with Hydrodynamics in Proto-Planetary Disks

Abstract : In this talk, we present an innovative algorithm to couple astro-chemistry modeling solved by astrochem package with our disk hydrodynamics code, LA-COMPASS. Almost all the previous research work on the astrochem assumes a steady state disk profile and transports the chemistry component with that profile. In our approach, we assume an evolutionary disk and couple the disk hydrodynamics with the astrochem package dynamically. We use LA-COMPASS to advance the both gaseous and dust component, and let dust grow from sub-micro to pebble size via dust coagulation process. The chemistry and ice species generated from the astrochem are coupled tightly with the hydrodynamics motion of the gas and dust. Specifically, the gaseous species will be transported with gas and the ice species will be transported with dust. During the dust coagulation, the ice will also be transferred accordingly from the small dust size to large dust size. The coupling will allow us to study the planet formation near the snow/ice line in proto-planetary disks.

Presenter's first and last name Valeriia Liakh

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Title : MHD Numerical Simulations of Solar Prominence Dynamics using MPI-AMRVAC Code

Abstract : Solar prominences are the birthplaces of coronal mass ejections, making studies of their pre-eruptive dynamics crucial for space weather. In this talk, I will review our most recent 2.5D numerical studies of prominence dynamics with MPI-AMRVAC code. The code employs various numerical schemes to solve partial differential equations. We control source terms and initial and boundary conditions. Regarding the nonadiabaticity, the code features an optically thin radiative cooling module and anisotropic thermal conduction.

We conducted a 2.5D MHD simulation focusing on the systematic rotation of a prominence within its coronal cavity. Starting with a nonadiabatic, gravitationally stratified corona, we form the flux rope (FR) through the convergence and shearing accompanied by randomized heating at the base. This heating induces left-right asymmetries in temperature and density distributions relative to the polarity inversion line, driving flows along the loops before FR formation. These motions are converted into swirling when an FR is formed. Synthesized images capture the simultaneous rotations of coronal plasma at 211 and 193 Å, alongside condensations observed at 304 Å.

Our investigation extends to the eruption evolution and the generation of coronal waves, which propagate over considerable distances through a magnetized medium and interact with FR prominence. This study also relies on a 2.5D numerical experiment performed with the MPI-AMRVAC code, using a gravitationally stratified corona and accounting for nonadiabatic effects. The initial magnetic field configuration comprises a dipole and a catastrophic 2.5D structure. The eruption gives rise to multiple energetic waves propagating throughout the magnetized corona. These waves ultimately reach distant prominences, evidently perturbing it. To validate our findings against SDO/AIA observations of similar events, we generated synthetic images for comparative analysis.

Jon Linker

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Title: Solar Magnetic Surface Flux Transport Modeling for Time-Dependent MHD Simulations

Abstract:
The solar magnetic field plays a key role in solar and heliospheric physics. The field is most easily measured in the photosphere, from ground or space-based telescopes, and these measurements are the essential input for models of the solar corona and solar wind, in the form of full-Sun magnetic maps. As nearly all of these observations are along the Sun-Earth line, a full solar rotation (27 days) is required to completely view the solar surface. Standard observatory maps are constructed over the course of a rotation, so they contain data that is as much as 27 days old. Coronal magnetohydrodynamic (MHD) models are typically time-relaxed using boundary conditions derived from such a map, providing an approximate time-stationary description of the corona for a given time period. In reality, the Sun's magnetic flux is always evolving, and these changes in the flux affect the structure and dynamics of the corona and heliosphere. Modeling the time evolution of the corona requires a description of the photospheric magnetic flux evolution. Assimilative Surface Flux transport (SFT) models can describe this evolution by incorporating known surface flows and processes, to produce a continuous approximation of the state of the surface field, as a sequence of maps. SFTs have a long history, but special considerations are required to create map sequences of sufficient fidelity to drive a time-dependent MHD model. In this presentation, we describe the use of the components of the Open-source Flux Transport (OFT) model to create suitable map sequences for near real time modeling of the solar corona. We illustrate this approach for the time period surrounding the April 8, 2024 total solar eclipse.

Research supported by NASA and NSF.

Mordecai-Mark Mac Low

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Title : Interactions of Small Scale and Large Scale Dynamos in the Interstellar Medium

Abstract : Observational evidence of near-equipartition magnetic fields at high redshift demonstrates that dynamo generation of fields must proceed quickly. We use numerical simulations of a shearing box with the Pencil Code, a high-order finite difference code, to study the supernova-driven interstellar medium (ISM). Turbulence drives a small scale dynamo (SSD) that proceeds at different rates in the different thermal phases of the ISM, and grows in direct proportion to the local vorticity. The SSD saturates at a few percent of equipartition with kinetic energy. Growth rates of a few megayears or less occur in well resolved models of the SSD, suggesting that galaxies are effectively born magnetized. Differential rotation drives a large scale dynamo (LSD) that also derives energy from the turbulent flow, and approaches saturation within 1 Gyr. Our local models of the LSD tend to produce a stronger mean field than observed, suggesting that global effects contribute to observed fluctuating fields.

Daniela Maci
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Title: BxC Toolkit: Generating Tailored Turbulent 3D Magnetic Fields

Abstract:

The BxC toolkit is a Python based generator of turbulent magnetic fields. It uses a combined approach of geometrical construcions and analytical formulas to efficiently generate data cubes of the order of up to (currently) ~1000^3 computational cells on desktops in under 15 minutes. Inspired by recent developments in the hydrodynamic community, the magnetic fields are generated through a concatenation of modified Biot-Savart laws, whose starting point is a gaussian white noise vector that is then subject to a non-linear transformation. Visual and statistical proper es of the generated fields, such as power-spectral behavior and intermittency, have been compared with the result of a direct numerical simulation (DNS), hence validating the BxC approach.

In addition to introducing the audience to the BxC algorithm, recent results concerning the further development of the code will be presented. BxC's potential lies in the relatively large set of input parameters available, which allows users to tailor the generated fields according to their needs. In order to fully exploit such capability, a study was conducted analyzing the effects of parameters variations on the power spectrum features. The results of this study confirm a direct rela on between input parameters and spectral exponent, large scale and small scale cutoff. Practically, the study led to explicit analytical relations between the input parameters and the spectrum features, which enable users to easily customize the field as needed.

In parallel to the parameter study, which is oriented toward a deeper understanding of the existing model, progress has been made in the improvement of the model itself, which aims at generating turbulent magnetic fields that resemble realistic scenarios. To this end, the model has been further developed id order to allow for anisotropy and structured magnetic field backgrounds. Results from this study will be presented to the audience, together with possible next step of the development and first applications of the model itself.

Viacheslav Merkin

Johns Hopkins Applied Physics Laboratory

Viacheslav Merkin

Title: Scientific advances from the Center for Geospace Storms

Abstract: The Center for Geospace Storms (CGS) is one of the three NASA DRIVE Science Centers which are large multi-institutional collaborations established to enable major advances in their respective sub-fields of Heliophysics. CGS is the only DRIVE Center devoted to the physics of geospace, especially focusing on the complexity of solar storms and their impacts in the near-Earth space. CGS science is rooted in the understanding of stormtime geospace as a system that is highly coupled across a wide range of spatiotemporal scales. This necessitates the need for physical models that are both holistic, i.e., treat all the relevant processes and domains, and possess sufficiently high resolution to capture all the relevant scales, within the limitations of the existing computer power. To this end, CGS is developing a Multiscale Atmosphere-Geospace Environment (MAGE) model that satisfies the above requirements. In this presentation, we review the recent work by the CGS team, using both the MAGE model and accompanying observations, concentrating on the multiscale nature of stormtime interactions in the geospace system. The highlights include the recent work by the CGS team on particle energization, localized flow jets and electric field channels, and massive plasma density plumes, including their global and local structure, forming throughout the system. We conclude by placing these representative cross-scale coupling processes in the context of the global mass and energy redistribution characteristic of stormtime geospace dynamics.

Bronson Messer

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Title : Flash-X: A computational astrophysics code built for the exascale

Abstract : Flash-X is a new incarnation of FLASH, which has served the astrophysics community along with several others for more than two decades. FLASH was used on a range of platforms, and on almost all high-end computing platforms. Flash-X continues that legacy. It was recently used on Frontier, the world's first exascale platform, as a part of the United States Depart of Energy's Exascale Computing Project. Specifically, Flash-X was used to run a core-collapse supernova simulation as a demonstration of the exascale capability for the ExaStar ECP project. The calculation exercised the integrated multi-physics of the code, including self-gravity, shock-capturing hydrodynamics, nuclear reactions, nuclear equation of state, and spectral neutrino transport. Each of these pieces of physics is necessary to produce simulations of these stellar transients that can be used to confront observations across photons, neutrinos, and gravitational waves.

Computing at scale on exascale platforms is extremely challenging due to heterogeneity in both hardware and software. While platform heterogeneity has been in the spotlight for a while, a similar challenge is presented by increasing diversity in solvers that applications such as core-collapse supernova simulation need to deploy has not been given needed attention. Popular heterogeneity solutions using C++ templates only address the former, we needed more innovation for the latter to meet our requirements. Moreover, the abstractions do not obviate the need for the developers to know the mapping between application and target hardware. Therefore, for Flash-X we have adopted the approach of co-designing the software architecture with an accompanying toolchain to provide a more enduring solution to performance portability across a wide variety of applications and platforms supported that can be supported. The code and the toolchain are both highly composable with building blocks that can be permuted and combined in different ways. In this presentation we distill our experience in preparing Flash-X for multiphysics astrophysical simulations on exascale platforms.

Name: Andrea Mignone

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Title:

"A fourth-order finite-volume constrained transport method for classical and non-ideal relativistic MHD equations."

Abstract:

We present a novel implementation of a genuinely 4th-order accurate finite volume scheme for multidimensional classical and special relativistic magnetohydrodynamics (MHD and RMHD) based on the constrained transport (CT) formalism in the PLUTO code (Mignone et al., ApJS, 2007 and Berta et al. JCP, 2024).
An extension to non-ideal resistive RMHD is also illustrated (Mignone et al., MNRAS, 2024 – accepted).

Our scheme is rooted over the method originally proposed by McCorquodale and Colella (Commun. Appl. Math. Comput. Sci., 2011) and introduces several novel aspects when compared to its predecessors, yielding a more efficient computational tool.
Among the most relevant ones: i) pointwise reconstructions (rather than one-dimensional finite volume ones); ii) upwind constrained-transport (UCT) method of Mignone and Del Zanna (JCP, 2021) to evaluate the electromotive force (EMF) at zone edges, including the addition of a new relativistic UCT-GFORCE average and iii) improved robustness through sophisticated limiting strategies that include both a discontinuity detector as well as an order reduction procedure.

We thoroughly tested such method, producing results that confirm its efficiency compared to traditional low order schemes.

Presenter's first and last name

Yoshiaki Misugi

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Title :

Evolution of the Angular Momentum of Molecular Cloud Cores in Magnetized Molecular Filaments

Abstract :

Star and planet are formed from the molecular cloud core which is a dense region of the molecular cloud. It is crucial to know the physical properties of molecular cloud cores because it determines the properties of the star and planet system. The angular momentum of molecular cloud cores plays a key role in the star formation process since it is an important parameter, for example, to determine whether a multiple system is formed or not resulting from the fragmentation of the molecular cloud core. Recent observations show that the molecular cloud cores along the filamentary structure which is a dense elongated structure in the molecular cloud. However, the evolution of the angular momentum of molecular cloud cores formed in magnetized molecular filaments is still unclear.

In this study, we perform 3D magnetohydrodynamics simulations to reveal the effect of the magnetic field on the evolution of the angular momentum of molecular cloud cores formed through filament fragmentation. We implement a Godunov smoothed particle magnetohydrodynamic (GSPM) method in the Framework for Developing Particle Simulator (FDPS) to parallelize the code. In this talk, we show that the angular momentum decreases by 30% and 50% at the mass scale of 1.0 $M_\odot$ in the case of the initial magnetic field strength of 2uG and 10uG, respectively. By analyzing the torques exerted on fluid elements, we identify the magnetic tension as the dominant process for angular momentum transfer for mass scales $< 3.0\ M_\odot$ for the 10uG case. This critical mass scale can be understood semi-analytically as the timescale of magnetic braking. We show that the anisotropy of the angular momentum transfer due to the presence of a magnetic field changes the resultant angular momentum of the core only by a factor of 2 in the case of 10uG. We also find that the distribution of the angle between the rotation axis and the magnetic field does not show strong alignment even just before the first core formation. Our results also indicate that the variety of the angular momentum of the cores is inherited from the difference in the phase of the initial turbulent velocity field. The variety could contribute to the diversity in size and other properties of protoplanetary disks recently reported by observations.

Presenter's first and last name

Wolf-Christian Müller
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Title : Network model of magnetohydrodynamic turbulence

Abstract : The numerical representation of fully developed high-Reynolds-number turbulence, particularly in the magnetohydrodynamic approximation, represents a formidable challenge. We report on an interesting modelling approach employing a network-based representation that shares fundamental characteristics with port-Hamiltonian structures known from model reduction. We show that this technique is able to reproduce the basic but non-trivial statistical properties of turbulence. This framework exhibits the logarithmic scaling of classical shell-models without their strong constraints regarding e.g. dimensionality or isotropy of the underlying physical system. The model furthermore allows to study the nonlinear dynamics of turbulence on a fundamental level.

Presenter's first and last name: Katarzyna Nowak

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Title : Optimising Multiple Stellar Flybys Setup in 3D Hydrodynamics Mesh Code

Co-author: Dr Martin G. H. Krause, Centre for Astrophysics Research, University of Hertfordshire, UK

Abstract :

We investigate the stability of accretion discs around hypothetical supermassive stars ($M > 1000\ M_{\odot}$) in dense young massive clusters, which are proposed candidates for polluters responsible for self-enrichment in globular clusters. These supermassive stars would form via runaways collisions, simultaneously with the cluster, hence their disc is perturbed by stellar flybys, inspiralling and colliding stars.

Stellar flybys on parabolic orbits are computed using Barker's equation. This is quite an expensive method when solved directly in 3D, which we combined with the hydrodynamics mesh code PLUTO. Instead we have implemented linear interpolation to calculate positions of typically 5000 perturbers in our simulations. This now works well with our 3D hydrodynamics disc models using an MPI set up with 480 processors.

We use this set up around a supermassive star with an accretion disc to examine how it reacts to those frequent encounters. We examine if the disc survives and remains dense enough to mase water lines. We then model kilomasers, which are generally associated with the forming super star cluster and compare it to an interesting candidate in the starburst galaxy NGC 253.

Name: Michael Pajkos

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Title: Applications of the SpECTRE Multiphysics Code

Abstract:
In this talk, I highlight the capabilities of the SpECTRE multiphysics code for binary neutron star and core collapse supernova (CCSN) simulations. With CCSNe as an emphasis, I will describe the physics capabilities of the code base---dynamical gravity and relativistic MHD---and ongoing developments---neutrino physics and microphysics. Likewise, I will show results from the so called ‘cartoon method’, which allows codes that use 3D Cartesian coordinates to be cast in axisymmetry and spherical symmetry.

Parth Pavaskar

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Title : Diagnostics of MHD modes in the ISM through synchrotron polarization statistics.

Abstract : Understanding Magnetohydrodynamic (MHD) turbulence, particularly identifying plasma mode components from observational data, remains a significant challenge. Previous research on synchrotron polarization from the interstellar medium (ISM) suggest that the dominant MHD modes can be identified via statistics of Stokes parameters, which would be crucial for studying various ISM processes such as the scattering and acceleration of cosmic rays, star formation, dynamo, etc. We have conducted a numerical study of the Synchrotron Polarization Analysis (SPA) method through systematic investigation of the statistical properties of the Stokes parameters from 3D ideal MHD simulations to identify the modes dominating the energy fraction from synchrotron observations. Our study proposes a classification criterion which allows us to distinguish between Alfv\'en mode and magnetosonic mode dominated turbulence. Additionally, we introduce a novel method for identifying fast modes by analyzing the asymmetry of the SPA signature. In this talk, I will discuss the modified SPA method, it’s numerical validation and its application to observational data.

Barbara PERRI

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Title :
Numerical challenges of space weather solar wind forecasting

Abstract :

Space weather has the difficult task to try to anticipate the propagation of eruptive events in order to assess their possible impact on the Earth's space environment. This requires an accurate description of the background in which these events propagate, mainly the continuum ejecta of particles that is the solar wind and the dynamo-generated heliospheric magnetic field. This proves challenging as the solar wind and dynamo magnetic field are interacting with each other depending on the activity cycle of our star, both at large and small scales. To be able to model accurately such a wide variety of scales and parameter regimes, the approach used by space weather forecasting facilities is to use a chain of models, taking advantage of existing codes to combine their strengths through numerical coupling across the heliosphere. The first step of this chain is the data-driven modelling of the inner corona, from photosphere measurements up until 0.1 AU, and it proves especially critical as it serves as boundary condition for the rest of the models. On top of these physical challenges also comes a computational one, as the models have to perform within an operational window of at most 24 hours with a reasonable number of allocated cores. Thus, the trade between speed and accuracy is a particularly difficult one for space weather forecasting.

To discuss these challenges, we will present here two coronal MHD models implemented as an alternative to semi-empirical models used so far in ESA forecastings. By using the COOLFluiD framework, we developed a new coronal model called COCONUT with implicit solving methods and unstructured meshes, which proves faster than traditional explicit methods on regular grids. We used the coronal code Wind-Predict to benchmark this new model for the simple polytropic approximation in the first place, and we present the similarities and differences obtained for data-driven configurations and compare them with observations. We then present the improvements foreseen for each code, especially for the heating terms: Wind-Predict will incorporate self-consistent Alfvén waves while COCONUT will use ad-hoc heating terms and a multi-species treatment. We will finally discuss the implications for the coupling with the rest of the model chain for the forecasting all the way to the Earth.

Nikolai Pogorelov

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HelioCubed: A high-order code for solving Reynolds-averaged MHD equations on adaptive cubed-sphere grids

A highly parallel, adaptive mesh refinement (AMR) solver for solving the Reynolds-averaged, ideal MHD equations describing the solar wind flow is proposed. These equations are accompanied by the equations describing the transport of turbulence. We are building on the Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS) collaboratively developed at UAH using the Chombo AMR framework. The new version of our software (HelioCubed) is being built on a newly developed Chombo 4 framework and allows us to perform simulations with the fourth order of accuracy in time and space, and use cubed spheres to generate meshes around the Sun. The numerical approach and its applications are discussed.

Andrius Popovas

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Title : Realistic simulations of solar dynamics, from interior to the surface

Abstract :
Due largely to computational resource limitations, solar research evolved as distinct "internal-" and "surface-" related research fields, preventing an integrated global view of the Sun's complex plasma dynamics. However, the Sun encompasses large-scale hierarchical structures, extending from its deep core to its outer atmosphere. Magnetic flux, pivotal for many phenomena, such as sunspots and solar flares, may be generated through both local and large-scale dynamo actions within the solar interior, interacting with motions in the convection zone that are ultimately driven by cooling at the very surface.
In this talk I will present our ongoing effort to develop and conduct a series of global high resolution magnetohydrodynamic simulations that spans from the core of the Sun all the way to the photosphere and beyond. These models bridge the internal dynamo simulations to the surface of the Sun on a truly global scale. The simulations are using a new, entropy-based Riemann solver and a new mesh decomposition on a DISPATCH framework that is capable of local time-stepping and supporting multi-physics and adaptive mesh refinement (AMR) approaches.

Presenter: Avijeet Prasad

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Title: Towards Data-Constrained Radiative-Magnetohydrodynamics Simulations of the Solar Atmosphere using the Bifrost Code

Abstract: Data-constrained magnetohydrodynamics (MHD) simulations initialized with magnetic field extrapolations based on photospheric magnetograms have been quite successful in capturing many aspects of energetic events in the solar corona, like flare reconnections and coronal mass ejections. On the other hand, radiative-MHD codes like Bifrost initialized with analytical inputs have provided very realistic simulations of the solar atmosphere by including the physics of non-equilibrium states and radiative transfer. The presented work aims to set up data-constrained simulations with the Bifrost code to study energetic events like flares in the solar corona. As a first step, we perform radiative-MHD simulations using the Bifrost code with an extrapolated magnetic field as input prescribed at the base of the convection zone to obtain a stratified atmosphere suitable for active regions. The magnetic field is derived from the photospheric magnetograms from the Solar Dynamics Observatory (SDO) of a flaring active region which was used as an input to a non-force-free field (NFFF) extrapolation code to model the magnetic field below and above the photosphere. The NFFF input was superposed with an existing quiet Sun simulation in stages and relaxed through MHD evolution. We present our initial results from the active region inspired simulations, highlighting magnetic reconnections and heating in the solar corona and discuss an outlook for further improving these data-constrained simulations with the extrapolated magnetic fields. In future we plan to study the subsequent evolution and compare them with observations of the event in extreme ultraviolet channels of the solar corona.

Presenter:
Martin Reiss 1,

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Damian Barrous-Dume 1, Ronald Caplan 2, Cooper Downs 2, Matthew Lesko 1, Jon Linker 2, Peter MacNeice 1, Leila Mays 1, Maksym Petrenko 1, Andres Reyes 2, Viacheslav Titov 2, Tibor Török 2, and Tina Tsui 1

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Title :
Innovations in CME Modeling at NASA’s CCMC with CORHEL-CME

Abstract :
We present recent innovations in the modeling of coronal mass ejections (CMEs) at NASA's Community Coordinated Modeling Center (CCMC) using the new CORHEL-CME framework, developed by Predictive Science Inc. This highly automated MHD modeling framework allows CCMC users to simulate multiple CMEs in a realistic coronal and heliospheric environment. With CORHEL-CME, the user can interactively design and and simulate multiple CMEs originating from complex active regions via a GUI-based web interface, enhancing both the accessibility and depth of CME simulations. In this talk, we discuss the main innovations that CORHEL-CME brings to the heliophysics community and showcase its application on two CMEs from March 7th, 2012. The new framework, including all simulation results shown in this presentation, is publicly accessible through the CCMC website.

Igor Sokolov

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Flux and Logically Cartesian Grids Rendezvous in the Threaded Field Line Model for Low Solar Corona

In formulating numerics for the Threaded Field Line model for the low solar corona (Sokolov et al, 2021) the mathematical problem occurs, which seems to have a general type, namely the rendezvous of two quite different kinds of grids. One of them fills in the gap between the upper chromosphere and low solar corona boundary, which may be referred to as the transition region, with the magnetic field lines of the potential field (“threads”) forming the typical system of flux coordinates. The turbulent waves and plasma flows transport as well as the electron heat conduction fluxes are aligned with the magnetic field lines, so that the transition region is described by numerical solution of multitude of the 1-D equations.

On the other hand, above the solar coronal model low boundary, the plasma motion and turbulence transport are described by a full set of essentially 3-D motional equations is solved numerically. The framework of finite volume method allows constructing conservative numerical schemes resulting in a global conservation of mass, momentum, and energy. In this way, the integral relationships can be studied between the Poynting flux at the solar surface and the solar wind characteristics (Huang et al, 2023).

In the present paper, we formulate the interface between the thread grid and 3-D Solar Corona model grid, to maintain the conservative property of coupled model. In this way, the integral relationships are maintained between the conditions at the solar surface, such as the observed and measured magnetic field and the energy fluxes, on one hand, and the coronal heating and powering and accelerating the solar wind, on the other hand. The problem to handle is complicated not only with the difference in the grid geometry, but also with unusual property of stream-aligned MHD (Sokolov et al, 2022) applied in the threaded gap to possess a low number of characteristics compared to the regular MHD working in the SC.

Kareem Sorathia

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Title : Building a Synthetic Aurora

Abstract :

Dazzling aurora displays viewed from the ground are the end result of a multiscale and multiphysics chain of geospace processes spanning the distant magnetotail, inner magnetosphere, ionosphere, and thermosphere. Energetic particles, primarily electrons, precipitate from the magnetosphere into the upper atmosphere and excite atoms and molecules which then emit light. The aurora exhibits a wide variety of forms such as arcs, spirals, and folds. There has been substantial recent interest on mesoscale auroral forms, referring to auroral forms with typical lengthscales O(100 km), as they can provide insight into the interconnected web of multiscale processes that bind the disparate geospace domains together.

Capturing the full chain of processes that connect the magnetosphere to its auroral manifestation requires highly detailed and diverse models that can capture a vast dynamic range. In this talk I will discuss recent work to combine first principles geospace modeling with empirical specifications of electron precipitation to identify the magnetospheric processes that drive these mesoscale auroral forms. With this kind of “grey box” modeling approach, we can capture the disparate scales that inform electron precipitation and build a synthetic aurora from the model.

Masato TAKITA

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Title :
Modeling of the sidereal cosmic-ray anisotropy at TeV energies with data from the Tibet ASgamma experiment

Abstract :
Various experiments have reported on the anisotropy in the arrival directions of galactic cosmic rays at the sidereal time frame, including underground muon telescopes and ground-based air-shower arrays.
The sidereal anisotropy of the order of 0.1 % at TeV energies observed at the Earth has two distinct large-scale structures: a deficit region ranging from ~150◦ to ~240◦ in right ascension (so-called Loss-Cone) and an excess region from ~40◦ to ~90◦ (so-called Tail-In). Recent experiments with high statistics have shown the unexpected change in the amplitude and phase above ~100 TeV from those below ~100 TeV. In this presentation, we make an attempt to model the anisotropy at the heliospheric outer boundary at TeV energies, by applying the idea of Liouville mapping with an MHD-model heliosphere to the experimental data from the Tibet ASgamma experiment.

Jean-Mathieu Teissier

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Title : High-order dimension-by-dimension finite-volume magnetohydrodynamics solvers

Abstract : The use of high-order numerical schemes can allow to spare computational resources, since they give results of comparable accuracy at a significantly coarser grid resolution, when compared to commonly used lower-order schemes. In this talk, a dimension-by-dimension finite-volume method for adiabatic magnetohydrodynamics is presented. The solenoidality of the magnetic field is preserved through the constrained-transport approach. A passage through point values at the cell interfaces leads to a modest increase of computing costs with numerical accuracy, as compared to the cost of increasing the grid resolution. Solvers up to order of accuracy 10 are compared with one another and the benefits of high-order numerics are illustrated on a turbulent flow.

Gabor Toth and Bart van der Holst

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Title : Well-Behaved Extended MHD Solutions Across Discontinuities

Abstract : It is commonplace to solve the extended magnetohydrodynamics (MHD) system of equations in non-conservative form, in particular using equations for pressures. This approach leads to unpredictable behavior at discontinuities such as shock fronts. Here we propose using a linear combination of entropy densities to distribute the non-adiabatic heating among the various pressure components in a deterministic manner. In particular, we describe algorithms that can distribute the non-adiabatic heating between electrons and ions when the electron and ion temperatures are solved separately, and between parallel and perpendicular pressures for anisotropic pressure MHD. The same approach can also be used for extended hydrodynamic equations. The algorithm is based conservation laws, which provides proper convergence to weak solutions as demonstrated by numerical tests.

Bart van der Holst

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Title :
Multi-fluid Outer Heliosphere Model with Solar Wind Heating through isotropization of pickup ions

Abstract :
The outer heliosphere model in the Space Weather Modeling Framework (SWMF) describes the dynamics of the thermal solar wind, pickup ions, electrons and neutrals. We have extended this multi-fluid model with turbulence transport to better capture the interaction of the solar wind with the interstellar medium. We analyze the effects of pickup ions and turbulence transport on the global heliosphere.

Huirong Yan

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Title : Study of compressible turbulence from simulations and observations

Abstract :

Plasma turbulence is largely shaped by the forcing on large scales and damping on small scales. Recent progress on studies of compressible turbulence will be presented along with its implication on particle transport. Both theoretical and observational studies will be presented. In the case of sub-Alfvenic driving, the weak to strong transition were identified in the decomposed Alfven modes from MHD simulations with the transition scales consistent with the theoretical prediction. Alongside, I will also report our recent discovery of the transition from analysing the magnetosheath data from Cluster. On small scales, compressible turbulence is much influenced by damping, which has a strong propagation angle dependence and influences the three-dimensional (3D) energy distributions. Based on an improved compressible MHD decomposition algorithm, our analysis of Cluster observations demonstrates nikolaithat collisionless damping enhances the anisotropy of compressible MHD modes, consistent with theoretical expectations and crucial for determining the particle scattering efficiency.

Gary P Zank

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Title : **Characterization of Turbulent Fluctuations in the Sub-Alfvenic Solar Wind**

Abstract : Parker Solar Probe (PSP) observed sub-Alfvenic solar wind intervals during encounters 8 - 14, and low-frequency magnetohydrodynamic turbulence in these regions may differ from that in super-Alfvenic wind. We apply a new mode-decomposition analysis [Zank_etal_2023] to the sub-Alfvenic flow observed by PSP on 2021 April 28, identifying and characterizing entropy, magnetic islands, forward and backward Alfven waves, including weakly/non-propagating Alfven vortices, forward and backward fast and slow magnetosonic modes. Density fluctuations are primarily and almost equally entropy and backward propagating slow magnetosonic modes. The mode-decomposition provides phase information (frequency and wavenumber k) for each mode. Entropy-density fluctuations have a wavenumber anisotropy k_|| >> k_perp whereas slow mode density fluctuations have k_perp > k_||. Magnetic field fluctuations are primarily magnetic island modes (delta B^i) with an O(1) smaller contribution from uni-directionally propagating Alfven waves (delta B^A+) giving a variance anisotropy of <delta {B^i}^2> / <delta {B^A}^2> = 4.1. Incompressible magnetic fluctuations dominate compressible contributions from fast and slow magnetosonic modes. The magnetic island spectrum is Kolmogorov-like k_perp^{-1.6} in perpendicular wavenumber and the uni-directional Alfven wave spectra are k_||^{-1.6} and k_perp^{-1.5}. Fast magnetosonic modes propagate at essentially the Alfven speed with anti-correlated transverse velocity and magnetic field fluctuations and are almost exclusively magnetic due to the plasma beta >> 1. Transverse velocity fluctuations are the dominant velocity component in fast magnetosonic modes and longitudinal fluctuations dominate in slow modes. Mode-decomposition is an effective tool in identifying the basic building blocks of MHD turbulence and provides detailed phase information about each of the modes.

OLINDO ZANOTTI

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Title : **A new first--order formulation of the Einstein equations: comparison among different high order numerical schemes**

Abstract : The solution of the Einstein--Euler equations by the vast majority of numerical codes is still based on traditional finite difference schemes for the Einstein sector, while it relies on conservative schemes for the matter part. This is because the celebrated BSSNOK formulation of the Einstein equations has second order in space derivatives. I will present a first-order (in space derivatives) formulation of the BSSNOK Einstein--Euler equations that is strongly hyperbolic and it allows for the implementation of a monolithic numerical scheme for its solution. A comparison will be shown among different numerical schemes such as Central WENO finite differences and Discontinuous Galerkin schemes, with important applications to the merger of binary astrophysical sources.

Michael Zingale

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Title : Strong Coupling of Hydrodynamics and Reactions in Astrophysical Flows

Abstract :
Stellar evolution is driven by the changing composition of a star from nuclear reactions. At the late stages of evolution and during explosive events, the timescale can be short and drive strong hydrodynamic flows. Numerical simulations of these environments requires strong coupling between the reactions and the hydrodynamics. Existing operator splitting methods can break down, and simply cutting the timestep is not efficient or accurate. Instead, methods that strongly couple these physical processes are needed—allowing the reactions to “see” the hydrodynamic flow and respond immediately as the burning proceeds. We demonstrate this new time integration method in the open-source simulation code Castro and show applications to Type Ia supernova and convection in massive stars and the transition to nuclear statistical equilibrium.