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Albarran, Robert	***Kinetic Modeling of Ionospheric Outflows Observed by the VISIONS-1 Sounding Rocket*** Robert Albarran, University of California- Los Angeles, USA Matthew Zettergren, Embry-Riddle Aeronautical University, USA Doug Rowland, NASA Goddard Space Flight Center, USA Jeff Klenzing, NASA Goddard Space Flight Center, USA Rob Pfaff, NASA Goddard Space Flight Center, USA Plasma escape from the high-latitude ionosphere (ion outflow) serves as a significant source of heavy plasma to magnetospheric plasma sheet and ring current regions. Outflows alter mass density and reconnection rates, hence global responses of the magnetosphere. The VISIONS-1 (VISualizing Ion Outflow via Neutral atom imaging during a Substorm) sounding rocket was launched on Feb. 7, 2013 at 8:21 UTC from Poker Flat, Alaska, into an auroral substorm with the objective of identifying the drivers and dynamics of nightside ion outflow at altitudes where it is initiated, below 1000 km. Energetic ion data from the VISIONS-1 polar cap boundary crossing show evidence of an ion ``pressure cooker'' effect whereby ions energized via transverse heating in the topside ionosphere travel upward and are impeded by a parallel potential structure at higher altitudes. A new fully kinetic model is constructed from first principles which traces large numbers of individual O+ ion macro-particles along curved magnetic field lines, using a guiding-center approximation, in order to facilitate calculation of ion distribution functions and moments. Particle forces in a three-dimensional global Cartesian coordinate system include mirror and parallel electric field forces, a self-consistent ambipolar electric field, and a parameterized source of ion cyclotron resonance (ICR) wave heating, thought to be central to the transverse energization of ions. The model is initiated with a steady-state ion density altitude profile and Maxwellian velocity distribution and multiple particle trajectories are advanced via a direct simulation Monte Carlo (DSMC) scheme. This document outlines the design and implementation of the kinetic outflow model and shows applications of simulated outflows representative of conditions observed during the VISIONS-1 campaign. This project provides quantitative means to interpret VISIONS-1 data and related remote sensing approaches to studying ion outflows and serves to advance our understanding of the drivers and particle dynamics in the auroral ionosphere and to improve data analysis for future sounding rocket and satellite missions.
Brchnelova, Michaela	***Numerical Challenges of Global Coronal Modelling*** Błażej Kuźma, ISSAT, HIT, China Barbara Perri, AIM - CEA Saclay, France Fan Zhang, KU Leuven, Belgium Andrea Lani, KU Leuven, Belgium Stefaan Poedts, KU Leuven, Belgium With the growth of our reliance on space and digital infrastructure, our society is becoming more and more vulnerable to space weather effects. To model these effects accurately, a variety of models are required to propagate the energy budget from the low solar corona all the way to the Earth. In space weather forecasting toolchains such as the Virtual Space Weather Modelling Centre, the first model employed is typically the “coronal model”, resolving plasma properties at 0.1AU. These then serve as an input to the heliospheric model. For now, semi-empirical techniques such as the WSA model are usually employed. Recently, we have developed the COCONUT global coronal solver based on 3D computational fluid dynamics with an implicit scheme (see e.g. Perri & Leitner et al. 2022), to replace the semi-empirical approximations and provide better physical accuracy. A global coronal model can also help us better understand the physical processes in the corona and the energy transfer between the separate layers once we include chromosphere and the transition region in the simulation in the future. Here, we present some of the numerical challenges and trade-offs that had to be resolved for the COCONUT solver to still provide sufficiently accurate solutions while preserving its speed and robustness such that it is suitable for operational running. We discuss the effects that aspects such as the mesh design, the boundary conditions and the prescribed magnetic fields have on the behavior of the solver and accuracy of the results. We show that through understanding of these effects and through an implementation of the respective modifications in the numerical setup, operational performance and accuracy can be greatly enhanced.
Burrows, Adam	***State-of-the-Art 3D Models of Core-Collapse Supernova Explosions*** Adam Burrows, Princeton University, USA Using our code Fornax we have simulated the collapse and explosion of the cores of many massive-star models in three spatial dimensions. This is the most comprehensive set of realistic 3D core-collapse supernova (CCSN) simulations yet performed and has provided very important insights intothe mechanism and character of this 60-year-old astrophysical puzzle. Most 3D models explode naturally and without artifice by the neutrino mechanism, aided by turbulent convection. I will present detailed results from this suite of runs and the novel conclusions derived from our new capacity to simulate many 3D full physics models every year.

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Claes, Niels	***Legolas 2.0: Extensions to a Linear MHD Spectroscopic Framework*** Niels Claes, Centre for Mathematical Plasma-Astrophysics, KU Leuven, Belgium Rony Keppens, Centre for Mathematical Plasma-Astrophysics, KU Leuven, Belgium The Legolas code [1, 2, 3] is an open-source, finite element-based, numerical framework to solve the linearised (magneto)hydrodynamic equations for a three-dimensional force- and thermally balanced state with a nontrivial one-dimensional variation. The standard Fourier modes imposed in the other coordinates give rise to a complex, generalised non-Hermitian eigenvalue problem which is then solved to quantify all linear wave modes of the given system in either Cartesian or cylindrical geometries. Physical effects included in the framework are background flows, optically thin radiative losses, anisotropic thermal conduction, external gravity, resistivity, viscosity, and Hall MHD, allowing for a full spectroscopic treatment of highly generalised setups in various environments ranging from laboratory conditions to astrophysical systems. The framework was recently extended to treat subsystems of the eight linearised MHD equations, allowing for pure hydrodynamic setups in 3D, only 1D density/temperature/velocity variations, or even omitting the energy equation altogether to treat specific closure relations. Additionally, the code now has the possibility to fully visualise eigenfunctions associated with a given wave mode in multiple dimensions, such that links between linear stability analysis and fully nonlinear simulations are becoming a reality, along with in-depth studies of system stability and wave mode behaviour. In this talk an overview will be given of all the new updates to the Legolas framework that are currently available and the new possibilities these open up. References [1] Claes, N., De Jonghe, J., & Keppens, R. (2020). Legolas: a modern tool for magnetohydrodynamic spectroscopy. The Astrophysical Journal Supplement Series, 251(2), 25. [2] De Jonghe, J., Claes, N., & Keppens, R. (2022). Legolas: magnetohydrodynamic spectroscopy with viscosity and Hall current. Journal of Plasma Physics, 88(3), 905880321. [3] https://legolas.science
Federrath, Christoph	***Modelling MHD Turbulence and Star Formation*** Christoph Federrath, Australian National University, Australia In this talk, I will present recent work from our research group on modelling turbulent magnetohydrodynamical (MHD) flows and star formation. I will explain the key roles that MHD turbulence and feedback (both mechanical and radiative) play for the structure and dynamics of the interstellar medium, and for the formation of stars.
Kang, Hyesung	***A Simulation Study of Particle Acceleration in High-beta Shocks via Weibel Amplification: Implications for Galaxy Cluster Outskirts*** Hyesung Kang, Pusan National University, South Korea Dongsu Ryu, Ulsan National Institute of Science and Technology, South Korea Cosmological structure formation simulations predict that external accretion shocks form in the outer region of galaxy clusters owing to supersonic gas infall from filaments and voids in the cosmic web. These shocks are characterized by high Mach numbers and propagate into an almost unmagnetized medium. Using 2D particle-in-cell simulations, we show that collisionless shocks could form via the Weibel-amplified magnetic fields, and that electrons can be pre-accelerated via the stochastic Fermi process to be injected into diffusive shock acceleration. Based on these findings, we propose analytic models for the energy spectra of shock-accelerated cosmic-ray (CR) protons and electrons that utilize conventional thermal leakage injection concept. Applying these model CR spectra to numerical shock zones in structure formation simulations, we estimated nonthermal emissions, including synchrotron and inverse Compton radiation due to CR electrons and pi^0-decay gamma-rays due to CR protons, around simulated clusters. The synthetic synchrotron maps produced by our model calculations are consistent with recent radio observations of the Coma Cluster. However, detecting nonthermal X-rays and gamma-rays from accretion shocks in the outer region of galaxy clusters with current observational facilities would be challenging.
Mathews, Nat	***Solving 3D Magnetohydrostatics with RBF-FD: Applications to the Solar Corona*** Nat Mathews, NASA GSFC, USA We present a novel magnetohydrostatic numerical model that solves directly for the force-balanced magnetic field in the solar corona. This model is constructed with Radial Basis Function Finite Differences (RBF-FD), specifically 3D polyharmonic splines plus polynomials, as the core discretization. This set of PDEs is particularly difficult to solve since in the limit of the forcing going to zero it becomes ill-posed with a multitude of solutions. For the forcing equal to zero there are no numerically tractable solutions. For finite forcing, the ability to converge onto a physically viable solution is delicate as will be demonstrated. The static force-balance equations are of a hyperbolic nature, in that information of the magnetic field travels along characteristic surfaces, yet they require an elliptic type solver approach for a sparse overdetermined ill-conditioned system. As an example, we reconstruct a highly nonlinear analytic model designed to represent long-lived magnetic structures observed in the solar corona.

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Moesta, Philipp	***Magnetic Fields, Jets, and Turbulence in the Multimessenger Era*** Philipp Mösta, GRAPPA, University of Amsterdam, NL Magnetic fields, turbulence, and jet-driven outflows play a critical role in core-collapse supernovae and compact-object mergers. These transients belong to the most luminous and energetic events observed in the universe and are key targets for time-domain astronomy surveys. I will discuss the unique challenges in both input physics and computational modelling for these systems and highlight recent breakthroughs in full 3D simulations. I will pay particular attention to challenges in performing these simulations on modern high-performance computational systems and how to extract as much scientific insight as possible from the produced datasets.
Pajkos, Michael	***Accounting for Relativistic Effects in Core-collapse Supernova Simulations*** Michael A. Pajkos, California Institute of Technology, USA Describing the dynamic environment inside core-collapse supernovae requires a multitude of physics. As fluid velocities approach the speed of light and strong gravitational fields create compact objects such as black holes, a proper relativistic description of the internal physics is paramount to reliably predict observables. Furthermore, efficiently dividing the computational cost of a simulation across multiple computing units must be considered, in order to make use of upcoming 'exascale machines'. In this talk, I will review two multiphysics codes that aim to meet these needs. First, I will present relativistic additions to the Flash framework, alongside simulation results incorporating these changes. Second, I will outline recent additions to the SpECTRE code, as it moves towards properly capturing the explosive endings of massive stars.
Phillips, David	***An Operator Splitting Approach to Highly Magnetised Relativistic Magnetohydrodynamics*** David Phillips, University of Leeds, UK Serguei Komissarov, University of Leeds, UK Conservative schemes are an extremely powerful tool in Relativistic Magnetohydrodynamics for modelling astrophysical phenomena. But while these able to handle low magnetisation with ease (where the ratio of magnetic components to inertial components is small), these schemes show significant failures at higher magnetisation - in some cases, failing even at ratios as small as 1. On the other extreme, Force-free models that neglect the inertial components entirely are unable to resolve crucial details such as current sheets. Here we present a novel operator splitting approach to the high-magnetisation regime of special relativistic magnetohydrodynamics, and describe 1D and 2D test simulations demonstrating its accuracy in both the low-and high-magnetisation regimes.
Ryu, Dongsu	***A New Code for Relativistic Hydrodynamics and Studies of Radio Jets*** Dongsu Ryu, UNIST (Ulsan National Institute of Science and Technology), Korea Hyesung Kang, Pusan National University, Korea Jeongbhin Seo, UNIST (Ulsan National Institute of Science and Technology), Korea We developed a new special relativistic hydrodynamic (RHD) code that can simulate ultra-relativistic flows with Lorentz factors of up to ~ 100 with high-order accuracy. It employs the finite-difference weighted essentially non-oscillatory (WENO) scheme, a high-order scheme for numerical flux calculation, and the strong stability preserving Runge-Kutta (SSPRK), a high-order time integration method. In addition, the code includes an equation of state (EOS) that closely approximates the EOS of the single-component perfect gas in the relativistic regime, and is optimized for reproducing complex structures in ultra-relativistic flows. Using this code, we simulated the dynamical evolution of relativistic jets with a wide range of model parameters covering both FR I and FR II radio galaxies. As in previous studies, we confirm that the jet power mainly governs flow dynamics, while the jet-to-background density and pressure ratios play secondary roles. We also find that jet-induced flows contain numerous structures involving shocks, shear, and turbulence. Furthermore, through Monte Carlo simulations, we followed the transport and acceleration of energetic particles in the jet-induced flows. We find that the particles can be boosted into ultra-high energy cosmic rays (UHECRs) with energies of up to E ~ 10^{20} - 10 10^{21} eV via diffusive shock acceleration (DSA), turbulence shear acceleration (TSA), relativistic shear acceleration (RSA). In this talk, we present the new RHD code and studies of radio jets using the code.

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Sako, Takashi	***Modeling of TeV Galactic Cosmic-ray Anisotropy based on Intensity Mapping in an MHD Model Heliosphere*** T. K. Sako on behalf of the Tibet ASgamma Collaboration A lot of past and present cosmic-ray experiments have reported small anisotropic features with amplitudes of ~0.1% in the arrival directions of TeV galactic cosmic rays observed at the Earth. We are attempting to derive anisotropic features at the boundary of the heliosphere by applying the idea of Liouville mapping to the experimental data of the Tibet ASgamma experiment. Our preliminary results have so far indicated small, possibly spurious, anisotropic structures, with angular scales of ~10 degrees in the cosmic-ray intensity distribution at the heliospheric boundary, and we are suspecting that the higher-order residues of the model anisotropy at the heliospheric boundary could be removed if the stochastic scattering of cosmic-ray particles by magnetic irregularities inside the heliosphere are taken into account. In this presentation we will present the latest results of our improved intensity-mapping method.
Strauss, Du Toit	***The Use of the Locally One-Dimensional (LOD) Method in Cosmic Ray Transport Models*** Du Toit Strauss, Centre for Space Research, North-West University, South Africa The Locally One-Dimensional Method (LOD) can be used to transform a N-dimensional partial differential equation into a set of N one-dimensional differential equations. The latter is, of course, much easier to handle numerically. We begin by discussing some early applications of the LOD method from the 1990s where it was extensively applied to cosmic ray studies in the isotropic limit. More recently, the LOD method has been successfully applied to solve the focused transport equation in order to simulate the transport of solar energetic particles. This equation changes from an advective-type to a diffusive-type equation between the Sun and the Earth, posing a problem for more traditional numerical algorithms (e.g. of the Crank-Nicholson type). We discuss details of this application, its numerical implementation, and give details regarding the applied boundary conditions. Example solutions of the resulting solar energetic particle intensities are also presented and discussed.
Xu, Siyao	***Turbulence in the Partially Ionized very Local Interstellar Medium and Implications on IBEX Ribbon*** Siyao Xu, Institute for Advanced Study, USA Hui Li, Los Alamos National Laboratory, USA The cascade of magnetohydrodynamic (MHD) turbulence is subject to ion-neutral collisional damping and neutral viscous damping in the partially ionized interstellar medium. By examining the damping effects in the warm and partially ionized local interstellar medium, we find that the interstellar turbulence is damped by neutral viscosity at ~261 au and cannot account for the turbulent magnetic fluctuations detected by Voyager 1 and 2. The MHD turbulence measured by Voyager in the very local interstellar medium (VLISM) should be locally injected in the regime where ions are decoupled from neutrals for its cascade to survive the damping effects. With the imposed ion-neutral decoupling condition and the strong turbulence condition for the observed Kolmogorov magnetic energy spectrum, we find that the turbulence in the VLISM is sub-Alfvenic, and its largest possible injection scale is ~194 au. I will also discuss the implications of the turbulence on explaining the features of IBEX ribbon.
Zingale, Michael	***Modeling Explosive Reactive Flows*** Michael Zingale, Department of Physics and Astronomy, Stony Brook University, USA Tight coupling of hydrodynamics and reactions is essential to accurately modeling explosive reactive flows. When reactions are vigorous, operator splitting methods traditionally resort to cutting the timestep of the simulation to improve the coupling, but this comes at large computational expense. We have been developing several different time integration strategies built on the idea of spectral deferred corrections to tightly coupling hydrodynamics and reactions, and also achieve fully fourth-order in space and time reactive flow capabilities. In this talk, I will describe the different methods implemented in our open source Castro hydrodynamics code (https://github.com/amrex-astro/Castro), show some test problems, and describe the astrophysical applications we are applying these methods to.