1st North American Phantom Users Workshop

July 8 – 12, 2024

Memorial University of Newfoundland
St. John's, NL, Canada

Prepared by the SOC:
Terrence Tricco, Rebecca Nealon, Daniel Price

Conference Schedule

Time (NDT)	Monday, July 8	Tiuesday, July 9	Wednesday, July 10	Thursday, July 11	Friday, July 12
9:30 am	Terrence Tricco	**Griselda Arroyo-Chávez**	Collaborative Hack Session		Daniel Price
9:40 am				**Alessia Franchini**	
9:50 am					
10:00 am	Narges Vadood	Rebecca Nealon			David Felipe Bambague Sichaca
10:10 am					
10:20 am	Coffee	Coffee	Coffee	Coffee	Coffee
10:30 am					
10:40 am					
10:50 am					
11:00 am	**Rebecca Martin**	**Cassandra Hall**	Collaborative Hack Session	**Chengcheng Xin**	Michael Power
11:10 am					
11:20 am					Debojyoti Garain
11:30 am	Madeline Overton	Shunquan Huang		Ariel Chitan	
11:40 am					Youssef Zaazou
11:50 am	Sahl Rowther	Nicholas Owens		Fathima Manooja	
12:00 pm			Lunch		Lunch
12:10 pm	Lunch	Lunch		Lunch	
12:20 pm					
12:30 pm					
12:40 pm					
12:50 pm					
1:00 pm			**Whale Watching Excursion**		Hack Presentations
1:10 pm					
1:20 pm					
1:30 pm					
1:40 pm	Hack Planning	**Anna Childs (Keynote Speaker)**		Collaborative Hack Session	
1:50 pm					
2:00 pm					Closing
2:10 pm					
2:20 pm					
2:30 pm	Coffee	Coffee		Coffee	
2:40 pm					
2:50 pm					
3:00 pm	Collaborative Hack Session	Collaborative Hack Session		Collaborative Hack Session	
3:10 pm					
3:20 pm					
3:30 pm					
3:40 pm					
3:50 pm					
4:00 pm					
4:10 pm					
4:20 pm					
4:30 pm	Hack Huddle	Hack Huddle		Hack Huddle	
4:40 pm					
4:50 pm	End of Day	End of Day		End of Day	
5:00 pm	**Welcome Event**				
5:30 pm					
6:00 pm					
6:30 pm				**Astronomy on Tap**	
7:00 pm			**Conference Dinner**		
9:00 PM					

Abstracts

Relativistic Apsidal Precession in Binary Systems

Anna Childs

Binary systems will undergo prograde apsidal precession due to general relativity (GR). We implement relativistic apsidal precession of the binary into PHANTOM to study how this affects the evolution of the circumbinary disk and the binary. Depending on how the relativistic binary apsidal precession timescale compares to the disk nodal precession timescale, GR can suppress the stable polar alignment of a circumbinary disk. Systems with a very short relativistic precession timescale cannot polar align and instead move toward coplanar alignment. However, in systems with longer relativistic precession timescales, polar alignment is possible close to the binary but not beyond a critical radius. This can lead to disk breaking with an inner polar ring and an outer disk moving coplanar. If the binary disk is just a few percent of the binary, it can significantly increase the binary eccentricity through von-Zeipel–Kozai–Lidov (ZKL) like oscillations. The inner polar ring drives fast retrograde apsidal precession of the binary that weakens the ZKL effect. This allows the binary eccentricity to remain at a high level and may significantly shorten the black hole merger time.

Angular momentum from molecular cloud to core scales with Phantom

Griselda Arroyo-Chávez

The transfer and distribution of angular momentum from giant molecular clouds to protoplanetary disks scales is key in the star formation process. In this talk I will discuss the use of the Phantom code to solve the famous angular momentum problem on these scales, and how we can quantify the relative importance between gravity, turbulence and magnetic field as part of the solution to this problem. In addition, I will show some of the properties of the filamentary structures generated in our simulations, and how the comparison between them could help us distinguish between different star formation models. Finally, I will talk about future work exploring new initial conditions with Phantom.

Exploring variants of smoothed particle hydrodynamics for computational astrophysics

David Felipe Bambague Sichaca

Smoothed Particle Hydrodynamics (SPH) is a versatile method for solving hydrodynamics equations, particularly suited for complex geometries and highly compressible fluids in astrophysics. However, the standard SPH formulation suffers from significant numerical errors, especially in low-velocity regimes. This project aims to explore alternative SPH formulations to improve accuracy, focusing on both hydrodynamics and magnetohydrodynamics (MHD). We are modifying and utilizing the Phantom SPH code to conduct simulations of magnetized star formation, small-scale dynamo amplification of magnetic fields due to turbulence, and the Kelvin-Helmholtz instability. Our goal is to enhance the accuracy of modeling astrophysical phenomena, especially in subsonic and strongly magnetized fluid regimes.

Massive Black Hole Triplets

Ariel Chitan

We analysed mergers of massive black holes (MBHs) from Obelisk, a cosmological radiative hydrodynamical simulation of a proto-cluster of galaxies (Trebitsch et al., 2021). From this dataset, we constructed merger trees and found potential hierarchical MBH triplets. A grid of initial conditions for N-body simulations of MBH triplets was then formed. In total, 48,000 MBH triplets were simulated in vacuum using ARC code (Mikkola and Tanikawa, 2013). In these simulations we defined the lifetime of a MBH triplet as ending in either of two ways: 1. a merger of two of the MBHS or 2. an escape from the center of mass of the system of one of the MBHs. We found that in 30% of cases simulations ended via merger while in 70% of cases, simulations ended via escape. In >99% of the simulations ending in escape, this runaway MBH is able to escape the host galaxy entirely. This has implications for the Obelisk simulation as black holes that may have been counted as merging due to spatial resolution limits might have actually resulted in runaway MBHs. In the astrophysical realm, this may correspond to MBHs that have been found offset from the centers of their galaxies.

Modelling X-ray binaries outbursts

Alessia Franchini

Be star X-ray binaries are transient systems that show two different types of outbursts. Type I outbursts occur each orbital period while type II outbursts, much brighter, have a period and duration that are not related to any periodicity of the binary system. Observations of these outbursts from different sources show that their characteristics and occurrence depend on the binary orbital properties. In particular, some sources can display type II outburst pairs as well as non-periodic type I outbursts. In this talk I will present our recent effort to explain these very interesting and peculiar phenomena through the dynamics of eccentric and precessing Be star discs using Phantom.

Partial tidal disruptions of spinning eccentric white dwarfs by spinning intermediate mass black holes

Debojyoti Garain

Intermediate mass black holes (IMBHs, $\sim 10^2-10^5M_{\odot}$) are often dubbed as the missing link between stellar mass ($\lesssim 10^2M_{\odot}$) and super-massive ($\gtrsim 10^{5-6} M_{\odot}$) black holes. Observational signatures of these can result from tidal disruption of white dwarfs (WDs), which would otherwise be captured as a whole by super-massive black holes. Recent observations indicate that IMBHs might be rapidly spinning, while it is also known that isolated white dwarfs might have large spins, with spin periods of the order of minutes. Here, we aim to understand the effects of ``coupling'' between black hole and stellar spin, focussing on the tidal disruption of spinning WDs in the background of spinning IMBHs. Using smoothed particle hydrodynamics, we perform a suite of numerical simulations of partial tidal disruptions, where spinning WDs are in eccentric orbits about spinning IMBHs. We take a hybrid approach, where we integrate the Kerr geodesic equations while being in a regime where we can treat the internal stellar fluid dynamics in the Newtonian limit. We observe dependencies of core mass and mass differences between tidal tails on ``coupled'' spin effects. However, observable quantities such as mass fallback rates and gravitational wave amplitudes show minimal variations with ``coupled'' spin effects.

A talk of two halves: applications of PHANTOM in gravitational instability and machine learning
Cassandra Hall

Observations at mm wavelengths have detected large-scale spiral structure in protoplanetary accretion disks. One possibility is that these spirals are due to gravitational instability, which occurs when the disc is sufficiently massive relative to its host star mass. I discuss applications of PHANTOM in interpreting these observations. In the second half of the talk, I discuss PHANTOM's role in the development of a machine learning model that identifies velocity perturbations from planets in protoplanetary accretion discs.

Excitation of Binary Eccentricity by Massive Polar-Aligned Circumbinary Disks
Shunquan Huang

Many post-AGB star binaries are observed to have relatively high orbital eccentricities (up to 0.6). Recently, AC Her was observed to have a polar aligned circumbinary disk. We perform Smoothed-Particle Hydrodynamics (SPH) simulations to explore the impact of a polar-aligned disk on the eccentricity of a binary. For a binary system with a 2.1 M_s central mass, we find that the eccentricity can be enhanced from 0.2 up to 0.7 in 5000 yrs by a disk with mass 0.1 M_s and eventually the eccentricity settles around 0.3-0.5. Even if the disk mass is as low as 0.01 M_s, the eccentricity grows within our simulation time while the system remains stable. These eccentricity variations are associated with the variations of the inclination between the disk and the binary orbit due to von Zeipel-Kozai-Lidov oscillations. We show that our results are in good agreement with the analytical estimates.

Task-based parallelism in SPH

Fathima Manooja

Parallelism is used to speed up scientific computations by dividing a program into parts that can run concurrently. Phantom implements data parallelism using OpenMP. In data parallelism, the data is divided equally among all the threads. Since a big portion of data is given to each thread, it can be difficult to avoid resource conflicts where different threads need to access the same data. Task-based parallelism is an alternative approach that divides the program into many small tasks. This avoids locking of resources for long periods of time. Here, we look at our implementation of task-based parallelism to an SPH simulation code in C++.

Primordial giant planet obliquity driven by a circumplanetary disk

Rebecca Martin

Detached circumplanetary disks are unstable to tilting as a result of the stellar tidal potential. A tilted circumplanetary disk affects the evolution of the spin axis of an oblate planet. For a disk with a sufficiently large mass, the planet spin quickly aligns to the misaligned disk. The tilt of the planetary spin axis then increases on the same timescale as the disk. This can be an efficient mechanism for generating primordial obliquity in giant planets. Directly imaged exoplanets at large orbital radii, where the disk mass criterion is more likely to be satisfied, could have significant obliquities due to the tilt instability of their circumplanetary disks.

Adaptive Particle Refinement in Phantom

Rebecca Nealon

In SPH simulations the resolution is generally concentrated where most of the mass is - although this is often desired, there are a number of examples where this is actually problematic. Adaptive particle refinement (APR) offers a solution to this problem by allowing the user to choose multiple resolutions in the same simulation. I will present our implementation of APR in Phantom, showing examples of APR working in different applications, its extension to problems involving self gravity and (because it's a Phantom workshop) doing a brief tutorial to show how it can be used. My intention is for APR to be pushed to the main repository by the time of this conference, making it available for everyone to use.

Retrograde discs around one component of a binary

Madeline Overton

Be/X-ray binaries consist of a massive Be main sequence star and a compact object companion which is commonly a neutron star. The Be star hosts a decretion disc of material that may be captured by the compact object. Through the formation process of the neutron star, the binary orbit may become misaligned, and even retrograde, relative to the decretion disc. With hydrodynamic simulations, we show that a coplanar disc around one component of a binary can be unstable to global tilting when the disc orbits in a retrograde direction relative to the binary. The disc experiences the largest inclination growth in the outermost radii of the disc, closest to the companion. This tilt instability also occurs for test particles. A retrograde disc is much larger than a prograde disc since it is not tidally truncated and instead spreads outwards to the orbit of the companion. The coplanar retrograde disc remains circular while a coplanar prograde disc can become eccentric. We suggest that the inclination instability is due to a disc resonance caused by the interaction of the tilt with the tidal field of the binary. This model is applicable to Be/X-ray binaries in which the Be star disc may be retrograde relative to the binary orbit if there was a sufficiently strong kick from the supernova that formed the neutron star companion. The accretion on to the neutron star and the resulting X-ray outbursts are weaker in the retrograde case compared to the prograde case.

Hyperbolic conduction and plasma physics in SPH

Nicholas Owens

Hot plasma, as observed in the superbubbles surrounding clustered supernovae, is integral to our understanding of the galactic medium. Hot winds driven by superbubbles regulate star formation and cycle hot gas through the circumgalactic medium. This behaviour relies on temperatures that are regulated by thermal conduction. Hyperbolic conduction is an improvement on traditional, parabolic, conduction, where heat is only allowed to propagate at the speed of the carrying particles (e. g. electrons in plasma). It is more physical and computationally cheaper. We present the first implementation of hyperbolic conduction in smoothed particle hydrodynamics (SPH, Gasoline parallel code), using a novel artificial diffusion term based on Kurganov and Tadmor (2000).
This method reproduces traditional conduction in the limit of moderate conductivity and qualitatively new behaviour for high conductivity. Simulations of superbubbles with hyperbolic conduction produce bubbles that are qualitatively similar to those produced with traditional conduction but at lower computational expense.

The Curious Case of V CVn - Computational Details and Results

Michael Power

Observationally, the star V Canum Venaticorum (V CVn) has strange behaviour regarding the maxima and minima of its light curve and polarization, which have a roughly inverse relationship (sometimes with a lead/lag time between them) and an almost constant polarization position angle over many decades. One theory proposed to explain this strange behaviour is the existence of a bow shock driven by a dusty wind from the star, which varies with time due to radial pulsations. This work uses a new framework developed in Zeus3D, a multi-physics magnetohydrodynamics code, to test this theory. Simulation results show that when a time-varying stellar wind is at its maximum brightness, a dense, symmetric shell forms around the star, causing the polarization signal to be dominated by symmetry, forcing it to a minimum. Conversely, when the brightness is at a minimum, the symmetric shell around the star is much less dense, and the polarization is instead dominated by the asymmetric bow shock structure, causing the polarization signal to attain a maximum value. Numerically reproducing the observed inverse relationship between the polarization and light curve provides a strong theoretical argument that a variable stellar wind bow shock is the solution to the curious case of V CVn.

Short-lived gravitational instability in irradiated discs

Sahl Rowther

Irradiation from the central star controls the temperature profile in protoplanetary discs. Yet simulations of gravitational instability typically ignore the stellar irradiation, assuming heat generated by spiral shocks is balanced by cooling, leading to a self-regulated state. In this paper, we perform the first simulations of irradiated, gravitationally unstable protoplanetary discs using 3D hydrodynamics coupled with live Monte-Carlo radiative transfer.

We find that the resulting temperature profile is approximately constant in time, but that the disc self-regulates by angular momentum transport induced by the spiral arms, leading to a steady decrease in surface density, and hence quenching of the instability. Thus, strong spiral arms caused by self-regulation would not persist for longer than ten thousand years, although weak spiral structures remain present over longer timescales. Using synthetic images at 1.3mm, we find that the spirals formed in radiative transfer simulations are challenging to detect.

The Phantom of the Future

Terrence Tricco

What does the next 10 years look like for Phantom? I will provide thoughts on challenges and changes needed for the future. First is that hardware continues to become increasingly more parallel, but also there is a trend towards inclusion of GPUs. Scaling Phantom to larger simulations will require adaptation of the internal code base to these hardwares. Second is the maintainability of the external code base in terms of input / output to the code, documentation, CI/CD pipelines, and governance structures. Third is how traditional numerical simulations may be affected by their intersection with machine learning.

Comparing 2-Fluid and 1-Fluid SPH Methods in a Supersonic Turbulent Diffuse Dusty Molecular Cloud

Narges Vadood

In this study, Phantom is used to simulate a supersonic turbulent dusty molecular cloud using two different numerical methods: the two-fluid and one-fluid dust methods. The choice of method depends on the degree of dust-to-gas coupling. The two-fluid method is more effective for larger grains with lower coupling (longer stopping time), while the one-fluid method is preferable for smaller grains that are more strongly coupled to the gas (shorter stopping time). We focus on medium-sized grains to compare these two methods. In this regime, the gas density determines which method is more effective. In high-density regions, where dust is more coupled to the gas, the one-fluid method is more suitable. Conversely, in low-density areas, the two-fluid method performs better.

“Tidal Peeling Events”: Low-eccentricity Tidal Disruption of a Star by a Stellar-mass Black Hole

Chengcheng Xin

Close encounters between stellar-mass BHs and stars occur frequently in dense star clusters and in the disks of active galactic nuclei. Recent studies have shown that in highly eccentric close encounters, the star can be tidally disrupted by the BH in a microtidal disruption event (microTDE), resulting in rapid mass accretion and possibly bright electromagnetic signatures. Here we consider a scenario in which the star might approach the stellar-mass BH in a gradual, nearly circular inspiral, under the influence of dynamical friction in a circum-binary gas disk or three-body interactions in a star cluster. We perform hydrodynamics simulations of this scenario using PHANTOM, and we find that under certain circumstances (for initial eccentricity $e0 \gtrsim 0.4$ and penetration factor $\beta = 1$, or $e0 < 0.4$ and $\beta \lesssim 0.67$), the mass of the star is slowly stripped away by the BH. We call this gradual tidal disruption a “tidal-peeling event.” Additionally, we discover that some low-eccentricity microTDEs ($e0 < 0.4$ and $\beta = 1$) are a new form of fast luminous transients similar to parabolic microTDEs. Depending on the initial distance and eccentricity of the encounter, these low-eccentricity microTDEs might exhibit significant accretion rates and orbital evolution distinct from those of a typical (eccentric) microTDE.

Mapping Galaxy Images Across Ultraviolet, Visible and Infrared Bands Using Generative Deep Learning

Youssef Zaazou

We demonstrate that generative deep learning can be used to map astronomical observations of galaxies across various photometric bands including ultraviolet, visible and infrared bands. We do so by using mock observations from the Illustris cosmological simulations to train our models. To date, this is a novel use of Illustris' mock observations. We demonstrate that models trained on mock observations can generalize and extend the learned mapping to real observations. This could allow astronomers to significantly augment existing observations, specifically in areas where multi-wavelength observations do not exist, with minimal inference cost.