Abstracts of the talks at the worskhop *Modelling of Multiphase Astrophysical Media*

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1 Scientific Rationale

A wide range of astrophysical systems are multiphase. Gas phases at vastly different temperatures are co-spatial, interact with each other, and often lie at the core of understanding the matter and energy flows determining the dynamics of those systems.

Multiphase systems are ubiquitous - some examples include coronal rain, the interstellar medium, galactic winds, intracluster and intergalactic medium.

This workshop is intended to bring theorists from different sub-fields of astrophysics together to discuss challenges and solutions in modeling multiphase systems and the relevant physical processes shaping them.

The key questions to be addressed include (but are not limited to):

- Under which conditions do multiphase systems form?
- What sets the mass / momentum / energy transfer rates between the phases?
- Which morphology and what kinematics do multiphase systems have?
- How can we model multiphase gas computationally?

In the program of the workshop[1], we opted for shorter talks to have more time for (formal and informal) discussions. To make long individual introductions with similar contents obsolete, we also have short "intro" slots for each session where one or two speakers will introduce the main problems / challenges of the subfield.

Below we list abstracts of the talks (in authors alphabetical order), please check the Table of Contents in the end of this document for quick navigation.

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[1] `https://wwwmpa.mpa-garching.mpg.de/conf/multiphase2023/program.html`

2 Abstracts

2.1 Matthew Abruzzo (*Columbia University*)

The Inner TuRMoiL of Cloud-Wind Interactions

Turbulent radiative mixing layers (TRMLs) play an important role in many astrophysical contexts where cool ($T_{cl} <\sim 10^4$ K) clouds interact with hot flows (e.g., galactic winds, high velocity clouds, infalling satellites in halos and clusters). The fate of these clouds (as well as many of their observable properties) is dictated by the competition between turbulence and radiative cooling; however, turbulence in these multiphase flows remains poorly understood. We have investigated the emergent turbulence arising in the interaction between clouds and supersonic winds in hydrodynamic simulations. In order to obtain robust results, we employed multiple metrics to characterize the turbulent velocity, v_{turb}. We find four primary results, when cooling is sufficient for cloud survival. First, v_{turb} manifests clear temperature dependence. Initially, v_{turb} roughly matches the scaling of sound speed on temperature. In gas hotter than the temperature where cooling peaks, this dependence weakens with time until v_{turb} is eventually constant. Second, the relative velocity between the cloud and wind initially drives rapid growth of v_{turb}. As it drops (from entrainment), v_{turb} starts to decay before it stabilizes at roughly half its maximum. At late times cooling flows appear to support turbulence. Third, the magnitude of v_{turb} scales with the ratio between the hot phase sound crossing time and the minimum cooling time. Finally, we find clear evidence for a length-scale associated with resolving turbulence, that affects large-scale morphological features in the cloud. Under-resolving this scale may cause violent shattering and affect the cloud's large-scale morphological properties.

2.2 Patrick Antolin (*Northumbria University*)

Fine structure and multi-wavelength variability associated with coronal rain

Coronal rain is the most dramatic cooling phenomenon of the solar corona and is pervasive in active regions. The Thermal Non-Equilibrium (TNE) - Thermal Instability (TI) scenario in which coronal rain forms, has been hypothesised to be partly responsible for the observed puzzling filamentary structure and variability of the solar corona, particularly in the EUV. In this talk we will show results from 2.5-D radiative MHD simulations and Solar Orbiter EUI-HRI observations of coronal rain. We report structure and variability associated with the TNE-TI scenario at a wide range of scales. At the smallest resolvable spatial scales (few hundred km on the Sun) and seconds timescale, we have coronal rain clumps and fireballs. At the large coronal loop scales and up to hours timescales, coronal strands are produced by the condensation-corona interface or whole loop bundles reheat due to the rebound shock and flow from rain impact. We aim to discuss the morphology and variability of the solar corona associated with coronal rain and compare it with analogue phenomena at much larger scales in the universe.

2.3 Mohammadreza Ayromlou (*Heidelberg University*)

The fate of the CGM gas

I will present our recent discovery of a new characteristic scale which determines the fate of CGM gas after being ejected from the halo due to feedback. In collaboration with Dylan Nelson and Annalisa Pillepich, I use three cosmological hydrodynamical simulations – IllustrisTNG, EAGLE, and SIMBA – and show that feedback processes significantly redistribute the baryons in and around haloes. I show how gas flows between the Circumgalactic Medium (CGM) and Intergalactic Medium (IGM). The ejection of the CGM gas lowers the baryon fraction inside haloes while simultaneously accumulating material outside the virial radius. We introduce the ”closure radius”, the distance within which all baryons associated with the dark matter halo are found. This closure radius depends strongly on halo mass, as well as halo baryon fraction within the virial radius. Observationally, we predict that the currently missing baryons associated with high-mass haloes will be found within 1-2.5 Rvir. Our results constrain theoretical models, particularly the physics of feedback, as well as its correlations with environmental processes, through comparison with current and future X-ray and SZ observations.

2.4 Yuval Birnboim (*Hebrew University*)

Gas dynamics in the CGM

My group is working on various processes that occur in CGM. i will discuss the steady state multiphased turbulence driven by shocks in 3D shock tube simulations, and the internal dynamics of the cold phase driven by these shocks. Then, I’ll discuss the CGM radial profiles of MW typed galaxies, including interactions with stellar winds and convection driven by these winds. Finally, I will address the origin of the multiphased gas in absorption line measurements (the COS survey), and discuss how well they constrain the galactic halo content.

2.5 Marcus Brüggen (*Universität Hamburg*)

Cold clouds in hot supersonic winds

Outflows are observed in star-bursting galaxies of all masses and at all cosmological epochs. They play a key role throughout the history of the Universe. Yet, a complete model of galaxy outflows has proven to be elusive, as it requires both a better understanding of the evolution of the turbulent, multiphase gas in and around star-bursting galaxies. We explore the impact of electron thermal conduction on the evolution of radiatively-cooled cold clouds embedded in magnetized flows of hot and fast material, as they occur in outflowing galaxies. Using adaptive-mesh simulations we could track the acceleration, disruption, and optical properties of such cold cloud/hot phase interactions, spanning the full range of conditions relevant for galaxy outflows. Moreover, we investigate the effects of non-equilibrium ionization on the observational properties of cold clouds. Finally, I will report on efforts to transfer our results to an easily usable subgrid model to use the results on the evolution of cold gas in cosmological simulations.

2.6 Chris Byrohl (*ITA, Heidelberg University*)

Lyman-alpha emission signatures as a tracer of multiphase gas

The Lyman-alpha emission line is a powerful tracer of high-redshift galaxies and their surrounding gas. Its resonant spatial and spectral signatures are shaped by the line radiative transfer sensitive to the complex density and velocity structure in the intervening multiphase gas. At the same time, multiple spatial scales from ISM, CGM, to IGM, leave their imprints. Reconciling the effective treatment of the multiphase medium, on the smallest scales, while incorporating the impact of the cosmological environment remains challenging. Here, I present our recent efforts modeling Lyman-alpha emission in galaxy formation simulations within cosmological volumes: key scientific results, outstanding challenges, and future prospects.

2.7 Christopher Carr (*Columbia University*)

Comparing Multiphase Galactic Winds close to the Galactic Disk in TIGRESS and FIRE

2.8 Miha Cernetic (*MPA*)

Multiphase astrophysical systems on a new multiGPU Discontinuous Galerkin code

High-order Discontinuous Galerkin methods are characterized by superior convergence rates and high computational efficiency, making them particularly promising for understanding the multiphase flows present in a variety of astrophysical systems ranging from interstellar to intracluster. I will present a novel multi-GPU/multi-node realization of Discontinuous Galerkin hydrodynamics written in CUDA and explain how we achieve exponential convergence with increasing order for smooth problems and linear for shocks up to 10th order, a first for an astrophysical implementation of DG. Our new code runs efficiently on different hardware configurations, ranging from a single core on a single node, to all available GPUs and CPUs on large compute clusters using MPI-parallelisation between nodes. The GPU version achieves a speedup of about 50x compared to the CPU version, allowing for a whole new range of problems to be investigated and parameter studies to be performed. Lastly, I will introduce our latest multiphase driven turbulence simulations as a showcase of our new code.

2.9 Eugene Churazov (*MPA, IKI*)

X-ray diagnostic of cold/warm/hot gas.

2.10 Hitesh Kishore Das (*MPA Garching*)

Multiphase Gas with Turbulence, with a pinch of magnetic fields

It is well-known that astrophysical mediums are multiphase and turbulent in nature. At first glance, these two properties don't seem to fit well together, as a turbulent medium would tend to mix a multiphase medium into a homogeneous one. This dilemma was alleviated by recent studies which showed that radiative cooling could hold the key. But, a big piece in the puzzle is still missing, magnetic fields. Magnetic fields drastically change the nature of dynamical processes in a turbulent multiphase medium, and it has been showed that magnetic fields decrease the mixing of multiphase gases in mixing layers by orders of magnitude. This can go on to affect properties like the cold gas growth rate and morphology. In this talk, I will present our recent results from our study of small-scale MHD simulations to understand the effects of magnetic fields. I will show evidence confirming the effects of magnetic fields in turbulent radiative mixing layers (TRMLs). This presents a conundrum due to the surprising lack of change in outcomes from larger hydrodynamic and MHD turbulent box simulations. In my talk, I will present the solution to this puzzling duality.

2.11 Klaus Dolag (*USM/LMU*)

The WHIM in our local neighbourhood

First results of simulations of non thermal signatures within the IGM/ICM in the outskirts within our local universe.

2.12 Alankar Dutta (*Indian Institute of Science*)

Cold clouds in outflows and more on CGM environments

I will talk about my recent work on cloud crushing simulations in radially expanding outflows observed in the Circumgalactic medium (CGM, hereafter). I'll highlight the importance of geometrical expansion in answering the question of survival and growth of cold clouds in outflows. I'll also demonstrate how to use an open-source package on CGM models that our group is developing. This package builds a unified library of many recent theoretical and empirical models of the CGM. These models can then be simply called and used to predict observables like column densities, dispersion measures, X-ray and UV spectra and emission maps in different projections. We believe that this interface will enable the community to quickly check feasibility of different models and easily add more models and observables for both Milky Way as well as external galaxies.

2.13 Ryan Farber (*MPA*)

The Origin and Fate of Cold Gas in the CGM

Cosmic star formation is clearly observed to reach a peak at redshift ~ 2, decreasing an order of magnitude to the present day. However, the future fate of star formation and the exact cause of its decline remains unclear. Particularly puzzling are observations of a short gas depletion time by star formation $\sim$ few Gyr, compared to the $\sim$10 Gyr duration of star formation in local galaxies. Likely, gaseous disks are constantly replenished not only by cosmological accretion but by large reservoirs of cold gas in their circumgalactic medium. The origin of this gas remains one of the hottest debated topics in galaxy evolution: does cold gas survive in galactic winds to populate the circumgalactic medium? Or is it shredded by the hot turbulent phase? If cold gas forms in situ from thermal instability, how is the dust phase populated? With new surveys of H-I by GMRT, Meerkat, ASKAP, and JVLA complemented by molecular probes by ALMA, now is the perfect time for decisive theoretical predictions of the alternative theories for cold gas formation in the circumgalacitc medium to be made. I will present cutting-edge uniform volume resolution of galactic winds from disk to the virial radius, designed specifically to determine the origin and fate of cold gas in the CGM with Lagrangian tracer particles tagging cold gas.

2.14 Claude-Andre Faucher-Giguere (*Northwestern University*)

Interplay between Cosmological Processes and Small-Scale Physics in Producing Multiphase Structure in the CGM

I plan to make some basic points about the role of cosmological processes (such as inflows, galactic winds, and satellite galaxies) in producing multiphase structure in the circumgalactic medium. These points will be based on lessons drawn from a combination of cosmological simulations and more idealized simulations and analytics. This will go beyond the fact that cosmological structures contain cold gas and include more subtle points about how the realistic background affects small-scale physics such as the thermal instability.

2.15 Drummond Fielding (*CCA*)

Multiphase Turbulence Meets Magnetic Reconnection

2.16 Silvio Fortuné (*USM/LMU*)

The "Bathtub" Model in the Magneticum Pathfinder Simulations

Star formation is a key process in the interplay of gas flows and exchange between phases. The "Bathtub" gas regulator model provides a fundamental description of the evolution of gas and star formation. It depends on gas accretion, the processes determining the efficiency of transformation of gas into stars and the effect of stellar and AGN feedback on the interstellar medium. Cosmological hydrodynamical simulations combine our understanding of the processes involved. They provide us with the means to identify and trace types of galactic formation scenarios through time and to test against observations on a statistical level. This talk aims to provide insight into the interplay of gas and star formation in the Magneticum Pathfinder simulations as well as comparisons to expectations and observations.

2.17 Ritali Ghosh (*Indian Institute of Science*)

A Tale of 3 Phases: Ram pressure strpping

Galaxy environments influence the properties of various galaxy components - the circumgalactic and interstellar media (CGM and ISM hereafter, respectively). During its motion through the intracluster medium (ICM hereafter), the ram pressure exerted on the gaseous component of a galaxy can significantly perturb it. In this talk, I will present our recent work exploring the possibilities of survival of the circumgalactic gas around Miky Way-like galaxies undergoing ram-pressure stripping. Previous models of ram-pressure stripping have intensively focused on the ISM - ICM interaction. Including the CGM in this scenario has been challenging because of the wide range of scales involved. The virial temperature of the CGM is such that it is unstable to radiative cooling, which introduces further challenges in sustaining a volume-filling warm CGM phase without a subgrid feedback prescription. We propose a robust yet simple model for initializing the galactic environment with a stable CGM. In my talk, I will emphasize the parameter space that can be explored to identify signatures of CGM gas survival in the ram-pressure stripped tails of Milky Way-like galaxies. Our model can further be extended to study ram-pressure stripping of dwarf galaxies like those involved in forming the Large Magellanic stream, as recently observed.

2.18 Philipp Grete (*Hamburg Observatory*)

Feedback and energetics from magnetized AGN jets in galaxy groups and clusters

I will present latest results from a new suite of simulations of magnetized AGN jets in isolated galaxy groups and clusters that aim to resolve both the internal structure of the central galaxy, the accretion process as well as the surrounding intragroup/intracluster medium.

2.19 Frederick Groth (*USM LMU*)

Turbulence with MFM

There exist a variety of different methods to solve the hydrodynamical equations in cosmological contexts. We implement Meshless Finite Mass (MFM) in OpenGadget3, as an alternative to smooth particle hydrodynamics. We analyze the impact the scheme has on simulations, both for idealized test cases and galaxy clusters. MFM improves the modelling of mixing instabilities. For decaying subsonic turbulence, MFM performs best in capturing the turbulent power spectrum. Compared to other methods, the slope is closest to the expected Kolmogorov value. It works down to very small Mach numbers. Thus, MFM will improve our modelling of galaxy clusters and galaxies in the environment of clusters.

2.20 Roark Habegger (*University of Wisconsin-Madison*)

Cosmic Ray Injections in a Multiphase Interstellar Medium

In terms of energy density, cosmic rays are a significant component of the interstellar medium (ISM). How do cosmic rays, as a sink and source of energy in a galaxy, affect the evolution of a galaxy structure? Through cosmic ray magnetohydrodynamic simulations, we examine the impact of cosmic rays on the local ($\sim$1kpc^3) structure of a galactic disk. We inject cosmic rays into a vertically stratified, multiphase ISM. These injections have a small radius ($\sim$10pc) and a large intensity (10^{50}erg), representing the creation of cosmic rays by a supernova explosion. We place these injections at different points in the disk, and have them occur at different times. We vary injection frequency and dominant cosmic ray transport. Using these simulations, we examine how cosmic ray injections adjust galactic structure and change the distribution of thermal gas in different phases and ionization states. I will present preliminary simulation results along with our implementation of stochastic cosmic ray injection and multiphase ISM physics.

2.21 Andrew Hillier (*University of Exeter*)

Strong magnetic fields, radiative mixing layers and the cooling of the solar corona

The solar corona (a hot, tenuous phase) is filled with localised pockets of cool dense material as well as strong magnetic fields. The interaction through mixing of the two phases in the corona can create intermediate material with strong radiative losses. In this talk I will present our work developing an analytic model for a radiative mixing layer with strong cooling and strong magnetic fields. The key difference we find from hydrodynamic models by including strong magnetic fields is that they breaks the connection between the dynamics and the thermodynamics making the dynamic evolution of the mixing layer independent of cooling. This allows simple predictions of the cooling time to be developed. Applying this model to the solar corona we find that observations that have been proposed as signatures of heating are likely to actually be showing cooling induced by mixing.

2.22 Cameron Hummels (*Caltech*)

Observational Signatures of Different CGM Configurations

2.23 Suoqing Ji (*Shanghai Astronomical Observatory*)

Subsonic and Supersonic Turbulent Mixing Layers

2.24 Manohar Teja Kalluri (*University of Exeter*)

Magnetic Rayleigh-Taylor mixing and reconnection

A magnetic Rayleigh-Taylor instability (MRTI) is characterized by the growth of plumes on the boundary between high density and low density fluids in the presence of a magnetic field. This instability is observed to occur in many astrophysical systems including supernovae, the solar atmosphere and in solar flares. At the large magnetic Reynolds numbers commonly found in astrophysical systems, magnetic fields are to good approximation tied to the fluid. However, the interaction between rising and falling plumes results in the contact of magnetic field lines with opposite polarity, possibly leading to magnetic reconnection. This reconnection process allows fluids of different densities to interact, and consequently mixing to happen. We hypothesise that the reconnection could be a fundamental process in mixing in MHD systems. However, a comprehensive understanding of the influence of reconnection on fluid mixing is still missing. The current research work aims to probe into this, through numerical simulation of MRTI using an incompressible spectral solver, Dedalus. A particular focus is on comparing the mixing, mixing efficiency between hydrodynamic and MRTI cases over a wide range of magnetic field strengths.

2.25 Rony Keppens (*CmPA, KU Leuven*)

Multiphase dynamics in the solar corona : rain and prominences!

The thermal structuring of the (magnetized) solar atmosphere, where a million-degree hot solar corona sits on top of a cooler and denser chromosphere, is mysterious in its own right, and drives modern research in solar coronal heating. Equally intriguing, and much less researched to date, is the omnipresent cooler (order 10000 K) material in the corona, in the form of coronal rain and solar prominences/filaments. In the context of an ongoing ERC project PROMINENT (https://erc-prominent.github.io), we made significant steps forward to unravel the physics behind these (radiatively driven) condensations. I will discuss the challenges associated with multi-dimensional, magnetohydrodynamic models of the solar corona, and show simulations that resolve the spontaneous formation and dynamics of these multiphase ingredients in full detail. They all exploit our open-source MPI-AMRVAC (http://amrvac.org) framework, and I emphasize the many advantages of using a dimension-independent, fully automated block-grid adaptive simulation tool.

2.26 Ildar Khabibullin (*USM LMU / MPA*)

Warm intergalactic medium in Magneticum: spatial distribution, velocities and metallicity

We will present a view on properties of warm intergalactic medium in cosmological hydro simulations Magneticum, focusing on spatial distribution of various phases, their velocities and metal contents. These ingredients are key for determining observational prospects of detecting bulk of the baryons in the modern Universe with future X-ray facilities.

2.27 Lachlan Lancaster (*Columbia University*)

The Evolution of Feedback Bubbles around Massive Stars

Star formation in GMCs is a fundamental part of understanding how stars form in galaxies. This process is thought to be principally regulated by the most massive stars that form within these clouds, which inject energy in multiple different ways into the surrounding gas acting to disperse the cloud and halt star formation. I will discuss the different ways in which energy from these massive stars is injected into the surrounding gas and how this gives rise to several gas phases that interact with one another in complex ways. Particular attention will be paid to how the bubble's driven by stellar winds in these clouds are cooled through mixing layers at their surfaces and how the dynamics of these mixing layers change when considering the presence of background magnetic fields and photo-ionized gas.

2.28 Katrin Lehle (*Heidelberg University, ITA*)

A Weather Forecast for Galaxy Clusters in IllustrisTNG

I will discuss our results studying the thermodynamic properties and multiphase nature of gas in the intracluster medium (ICM) of galaxy clusters. The highly multi-scale gas structure and large dynamic range of spatial and temporal scales of the key physical processes makes numerical simulation of the ICM a computational challenge. In this work we use magnetohydrodynamical simulations from the IllustrisTNG suite (TNG50) together with the new TNG-Cluster project to study ICM gas physics in the full cosmological context, within the framework of a well-validated and comprehensive physical model for galaxy formation and AGN feedback physics. These simulations come with a large sample of well-resolved galaxy clusters including the "full" physics TNG model which allows us to study the heterogeneity and diversity of clusters. We study the fraction of galaxy clusters with a short central cooling time (cool-core clusters) based on different diagnostics as central electron density, central entropy, concentration and cuspiness. We investigate the astrophysical processes which are most effective in turning cool-core clusters in non-cool-core clusters. We study if mergers can be made responsible for the whole population of non-cool-core clusters. We also explore how the TNG model for SMBH feedback can produce episodic periods of self-regulation, leading to intermittent phases of cool gas abundance in the centers of clusters, which are then subsequently dispersed.

2.29 Yuan Li (*University of North Texas*)

Multiphase Gas in Galaxy Clusters

Galaxy clusters can host multiphase gas both in the central region and in the outskirts. The centers of cool-core clusters often harbor extended multiphase filaments that shine brightly in Halpha and CO. These filaments are thought to be created via thermal instability of the hot intra-cluster medium (ICM) under the influence of supermassive black hole (SMBH) "feedback". We have analyzed the kinematics of the central filaments in more than a dozen nearby clusters by measuring their velocity structure functions. We find that the motions of the filaments are directly linked to the activities of the SMBHs. In all systems, the VSF is steeper than the classical Kolmogorov expectation and the slopes vary from system to system. In a small subset of clusters, the VSF of the outer filaments flattens on small scales to a slope consistent with classical Kolmogorov. This suggests that in the central tens of kpc, the ICM is dominated by bulk motions induced by SMBH feedback, and turbulence cascade can only be detected further away from the SMBH. We have also analyzed multiphase gas in the tails of jellyfish galaxies which are formed as a result of ram pressure stripping. We find that the motion of the tail is dominated by turbulence driven by Kelvin-Helmholtz instability, which quickly overwhelms the original ISM turbulence. We compare the kinematics of different phases of the ICM, including the hot X-ray plasma, the warm ionized gas, and the molecular component. Within the observed dynamical range, all different phases appear well-coupled kinematically. Using cooler gas as a tracer of the hot plasma, we can put a constraint on the isotropic viscosity to be below 0.01

2.30 Tirso Marin Gilabert (*USM LMU*)

The Role of Viscosity in Galaxy Clusters

The impact of viscosity on the Intracluster Medium (ICM) is still under debate and it can be essential in mixing and turbulence processes and, therefore, the interaction of galaxies within galaxy clusters and the evolution of galaxies. For this reason, a deep study on the effect that viscosity has in the evolution of Galaxy Clusters from a numerical simulation point of view can give us a hint of gas properties and the dynamics going on in the ICM. The results show a lack of mixing in the more viscous clusters compared to the runs without viscosity, leading to, for instance, morphological differences, different shock propagation or different magnetic field strength.

2.31 Dustin Nguyen (*The Ohio State University*)

Insights on mass-loaded galactic winds and feedback from rings

As galactic winds are driven out from the host galaxy, they may sweep up and entrain cold clouds. The addition of mass can decelerate the flow. I present analytic results and 3D simulations of hot flows, both spherical and planar, undergoing sub-grid mass-loading. I will show that mass-loading can seed a larger scale thermal instability. In addition, I present new simulations of parameterized feedback in a ring. Ring-like arrangements of superstar clusters are expected to arise from gas flow settling into a galaxy's Lindblad resonance. I discuss results and provide insight on how this geometric arrangement of feedback naturally leads to multi-phase galactic outflows.

2.32 Charalampos Nikolis (*LMU*)

A multifluid wind model

We propose an analytical model for the evolution of multi-phase galactic winds, based on the interaction of a hot fluid with multiple colder populations of different initial mass and same temperature. The model consists of source terms from hydro-dynamical simulations to account for the hot wind - cold clouds interactions and a varying cooling area for the colder components. The equations governing the system are solved for different distributions of initial cold gas masses as well as for limiting cases of the cloud-wind interactions to compare with hydro-dynamical simulations. Finally, the Lyman-alpha halo surface brightness is computed in order to connect our model with observations.

2.33 Peng Oh (*UCSB*)

Thermal Instability with Non-Thermal Forcing

We describe how non-thermal ingredients like magnetic fields and cosmic rays alter the nature of thermal instability (TI), and interaction between phases. TI with magnetic fields can lead to long lived gas motions and streaming along magnetic flux tubes. We show how this appears in some parameter regimes but not others, depending on isobaric/isochoric thermal stability. TI with cosmic ray heating in a stratified medium can trigger a CR-driven wind even for a medium initially in hydrostatic and thermal equilibrium – local thermal instability triggers a dynamical instability, at fixed CR luminosity.

2.34 Ramon Oliver (*University of the Balearic Islands*)

T.N.E. it's dynamite

2.35 Viraj Pandya (*Columbia University*)

Multiphase flows within the context of a novel unified model for galaxy–CGM co-evolution

I will present a new time-dependent, two-zone model for how galaxies and their circumgalactic medium (CGM) co-evolve. The model comprises a system of eight coupled ordinary differential equations that track the flows of mass, metals and energy between multiple components of the galactic ecosystem. We account for the physics of cosmic accretion, radiative cooling, turbulence dissipation, star formation, supernova-driven winds that heat and stir turbulence in the CGM, and large-scale outflows from the halo into the intergalactic medium when the CGM becomes overpressurized. The turbulence modeling is novel and accomplishes two things: (1) it provides pressure support for the CGM even when it has short cooling times, and (2) its dissipation introduces a heating term that limits CGM cooling, ISM accretion and star formation. Our physically-grounded model is able to effectively emulate the mass assembly histories and baryon cycles of individual galaxies in highly complex and expensive cosmological hydrodynamical simulations. Furthermore, our model strikingly predicts that the CGM should undergo a global "phase transition" from a cool, turbulence-supported phase at early times to a roughly virial-temperature, thermal-supported phase at later times ("CGM thermalization"). I will briefly discuss possible implications for multiphase gas in real observed systems and in simulated numerical experiments with the goal of identifying further extensions and applications of the model in collaboration with workshop attendees.

2.36 Rahul Ramesh (*ITA Heidelberg*)

The CGM of TNG50 Milky Way-likes

We will discuss recent results from the TNG50 simulation of IllustrisTNG on the CGM of Milky-Way (MW) like galaxies. Our sample consists of 132 galaxies with a stellar mass range of $10^{10.5} - 10^{10.9}$ Msun. The physical properties and structure of the CGM - its distribution, phase, kinematics, and halo-scale magnetic field - all show significant variation, as well as compelling correlations with the properties of the galaxy and central SMBH. We will also present results from a second study where we explore the occurrence and origin of small, cold clouds of gas that form in the CGM, similar to the high velocity clouds (HVCs) observed in the gaseous halo of our Milky Way. These cold gas clouds are often observed to be clustered (i.e. not randomly distributed throughout the CGM), preferentially around massive satellite galaxies. With our Lagrangian tracer particle analysis, we estimate the lifetime of individual clouds, as well as their physical origin. On the other end of the temperature spectrum, we will also discuss the occurrence and properties of hot bubbles of outflowing gas, originating from the centers of Milky Way-like galaxies in TNG50, much like the Fermi/eROSITA bubbles observed in the Milky Way halo. Finally, we plan to present early results from a new set of super-Lagrangian CGM refinement simulations which resolve cold clouds in cosmological simulations to new scales, demonstrating how we can bridge the gap to idealized cloud-scale simulations.

2.37 Leonard Romano (*LMU Munich*)

SISSI: Supernovae In a Shearing, Stratified Interstellar Medium

Supernovae (SNe) are an important driver of the multiphase structure in the Interstellar Medium (ISM) and play an important role for regulating star formation. SNe inflate large bubbles of hot gas dubbed "Superbubbles"(SBs), contributing to the volume filling hot phase, and may further drive galactic outflows. In this work, I am using zoom-in simulations of SBs embedded in a Milky-Way analogue, in order to investigate how environmental effects like shear and vertical stratification can affect the structure of SBs.

2.38 Evan Schneider (*University of Pittsburgh*)

Interpreting the Multiphase CGM

Recent high resolution observations of quasar absorption spectra through the CGM of galaxies have shown many complex features indicative of a turbulent, cloudy medium. Interpreting these spectra remains a challenging task. In this talk, I will highlight some lessons-learned from applying mock-observational techniques to simulated CGM clouds and outflows.

2.39 Prateek Sharma (*Indian Institute of Science*)

Linear and nonlinear aspects of thermal instability and multiphase condensation

2.40 Matthew Smith (*ITA, Heidelberg University and MPIA*)

Modelling multiphase galactic winds in cosmological simulations with Arkenstone

In light of the growing consensus that the evolution of stellar feedback driven galactic winds and their impact on the baryon cycle is highly dependent on their multiphase nature, we have developed a new subgrid model that accounts for it. Implemented in the Arepo code, "Arkenstone" is designed for simulations where the multiphase ISM and CGM cannot be properly resolved and is intended for use in large volume cosmological simulations. The model has three novel features. Firstly, winds are launched with hot and cool components with separate mass and energy loadings. Within these components, wind temperature and velocity are drawn from distributions measured in resolved simulations. This permits simultaneous ejective and preventative feedback. Secondly, because this splitting of the wind into two phases results in a high specific energy component, special attention has to be paid to the way in which these hot, fast, low density flows are resolved. Finally, we utilise a new "cloud particle" scheme to treat unresolvable cold clouds embedded in the hot flow. These exchange mass, energy, momentum and metals bidirectionally with the hot flow. Clouds lose mass as they are shredded by the interaction with the ambient medium, but can also gain mass as hot wind material cools onto them, providing a significant source of acceleration in some cases (see e.g. Gronke & Oh 2018, 2020; Gronke et al. 2022; Fielding & Bryan 2022). The Arkenstone model permits results from small scale theory of multiphase gas evolution and interactions to be applied in a wider galactic and cosmological context, where we lack the resolution to resolve the relevant physics a priori.

2.41 Ben Snow (*University of Exeter*)

Mixing in multi-level partially ionised systems

Mixing can occur between media of extremely different compositions, for example a solar prominence (which is weakly ionised) and the solar corona (which is strongly ionised). In such a scenario, the bulk media either side of the interface have different underlying rules, with the corona being mostly ionised and magnetohydrodnamic (i.e., directly influenced by the magnetic field), whereas the prominence material can be mostly neutral and hydrodynamic. The mixing in such a system is non-trivial. Here I present two-fluid numerical simulations of the Kelvin-Helmholtz instability using a multi-level hydrogen model, with ionisation, recombination and radiative losses. Across the interface, the composition of the medium changes. When the system mixes, radiative losses peak within the mixing layer, effectively removing thermal energy from the system. We analyse how this system behaves and compare the results to an equivalent MHD model.

2.42 Ulrich Steinwandel (*CCA*)

The origin of multiphase galactic winds

Galactic winds are observed to be of multiphase nature and consist out of cold, warm and hot gas that can well be traced by HI and CO in the cold, H-alpha in the warm and at the highest gas temperatures via photo-ionized metal species such as MgII or OIII or X-rays. While this presents a strong challenge for outflow observations due to the fact that we need to invest in different techniques and instruments, the challenge with respect to the numerical modeling is equally hard due to the small-scale physics involved and the high resolution needed to resolve the launching and subsequent mixing of the gas further out in the CGM. I will present a set of high-resolution simulations (solar mass and sub-parsec) of isolated dwarf galaxies, that are targeted to understand the launching, evolution and interaction of galactic winds with their host systems and their surrounding ambient medium. Our simulations include single star formation, non-equilibrium cooling and chemistry as well as the resolved feedback from photo-ionizing radiation as well as supernovae. Consistent with a number of different outflow simulations we find that the warm wind (T $\sim$1e4 K) is transporting most of the mass while the hot wind is responsible for the bulk of the energy budget in the wind (T$\sim$5e5 K). At high altitude ($\sim$10 kpc) the hot starts to cool adiabatically and subsequently merges with the hot CGM. Our simulations are able to successfully reproduce the observed low mass loading factors observed in local dwarf galaxies and can recover their multiphase nature. However, the energy loading appears lower than predicted by some theoretical models, posing a joint challenge for analytic wind theory and direct numerical simulation.

2.43 Rosie Talbot (*MPA Garching*)

How AGN jets affect and are affected by multiphase gas

Supermassive black holes, residing in the nuclei of most galaxies, are capable of imparting extreme amounts of energy to their surroundings. Whilst the jet mode of AGN feedback is often associated with highly collimated, light, relativistic outflows, it is becoming apparent that these jets may, additionally, be capable of driving wide-angle, large-scale, multiphase outflows. In this talk, I will present simulations of AGN jets launched from isolated galaxies and also from galaxies undergoing a major merger and discuss the conditions under which jets are able to drive large-scale, multiphase outflows. I will explore the properties and evolution of these outflows and, additionally, examine how the presence of cool, inflowing gas in the CGM that has arisen due to previous jet outbursts, then affects the evolution of the BHs and galaxies themselves.

2.44 Brent Tan (*UCSB*)

Cloud in Realistic Galactic Winds

Wind tunnel simulations have been used to derive models for cloud survival and growth, which in turn have been used to construct subgrid prescriptions for clouds in galactic winds. We present work on how well these models hold up in realistic turbulent winds driven by clustered SN from simulations.

2.45 Megan Tillman (*Rutgers University*)

AGN Feedback and the Low Redshift Lyman-alpha Forest

Feedback from activate galactic nuclei (AGN) is generally calibrated to reproduce galactic observables such as the gas fraction, stellar mass function, and quenching. Recently the role of AGN feedback in the circum galactic medium (CGM) and the intracluster medium (ICM) has acquired further attention as SMBH jets can play a significant role in the movement and heating of baryonic material located in these regions. State-of-the-art cosmological hydrodynamic simulations are vital tools in constraining different AGN feedback sub-grid models utilizing ISM, CGM, and ICM statistics. Recently many independent groups have discussed how different AGN feedback models might affect gas as far out as the IGM, particularly the Lyman-alpha forest at low redshifts (z¡∼0.4). In particular AGN jet feedback, with highly collimated, fast moving, heated jets can reach and affect the Lyman-alpha forest statistics all the way down to column densities of 10^{12} cubic cm. We explore the jet feedback model in the Simba simulations and show that these jets are necessary in order to reproduce the observed Lyman-alpha forest column density distribution across a column density range of 5 orders of magnitude. We also utilize the CAMELS simulations to explore the effects of the AGN feedback as the strength of the feedback is varied, and we analyze the interplay between the stellar and AGN feedback. We find that the jet speed plays a significant role in the effect that AGN feedback has on the

IGM. We additionally find that strong stellar feedback can efficiently suppress the AGN feedback and thus indirectly affect Lyman-alpha forest statistics.

2.46 Stephanie Tonnesen (*CCA, Flatiron Institute*)

Fireballs: What do star-forming clouds in the ICM tell us about mixing?

Ram pressure stripping is the direct removal of gas from satellites via an interaction with the host's halo gas. In some cluster galaxies, stars have been observed to form in this stripped gas. I will discuss how our simulations, including radiative cooling and star formation, of clouds in an intracluster wind compare to observations, and share the physical insights we have gained into this process.

2.47 Aditi Vijayan (*RSAA, ANU*)

Metallicity Gradients of Galactic Outflows

Multiphase galactic outflows, generated by supernova feedback, are likely also metal-enriched due to incomplete mixing between supernova ejecta and the ambient ISM. This enrichment is likely important to shaping galactic metallicities and metallicity gradients, but a quantitative estimate of it requires high-resolution simulations aimed towards resolving mass, momentum and energy exchanges between the different phases of the outflows. In this context, we will share results from simulations conducted using Quokka, a new AMR radiation hydrodynamics code optimised for GPUs. We will discuss the generation and subsequent evolution of multiphase outflows from a wide range of galactic environments and star formation rates, with particular emphasis on the transport of metals within and between phases, a phenomenon we can study owing to the sub-parsec resolution that our simulations achieve.

2.48 Rainer Weinberger (*CITA*)

Modeling unresolved multi-phase gas in cosmological simulations

Gas in and around galaxies can frequently be found in a multi-phase state: cold clouds embedded in a hotter, more dilute medium. Modeling this state in hydrodynamic simulations is challenging due to the small size of the clouds and complex interactions at their interfaces. For large-scale simulations of galaxy formation, the inability to model these states accurately, most prominently in the interstellar and circumgalactic medium, limits the predictive power severely. I will present a new 2-fluid approach to model multi-phase states in cosmological simulations, show its behavior in a number of test simulations and discuss its application in future simulations of galaxy formation.

2.49 Benjamin Wibking (*Michigan State University*)

Accelerating Cold Clouds with Both Hot Winds and Radiation

I will discuss new simulations of cold cloud acceleration in the presence of a hot wind for conditions near the Galactic Center, including the additional possibility of radiative levitation of clouds by FUV dust absorption. I also discuss the effects of including low-temperature cooling and heating physics to a minimum temperature of 100 K in comparison to previous work that has focused on cooling to 10^4 K. I also highlight advances in simulation technology that allow us to simulate clouds under these conditions with hundreds of cells per cloud radius.

2.50 Zhiyuan Yao (*HUJI*)

A new survival criterion in cloud crushing problem

2.51 Congyao Zhang (*The University of Chicago*)

X-ray Bubbles in Galaxy Clusters and their Role in Generating Internal Gravity Waves and Shaping Ha Filaments

Radio-mode of AGN feedback has been widely accepted as a promising heating mechanism of the intracluster medium (ICM). High-resolution X-ray observations show that the mechanical energy released inside the bubbles of relativistic plasma is sufficient to balance the radiative cooling losses in cluster cores. However, through what specific way(s) the bubble energy is transferred to the ICM is still under debate. This is one of the biggest remaining questions in cluster studies. In this talk, I will introduce internal gravity waves as an attractive way to solve the problem. These waves are generated through long-term interaction between intact X-ray bubbles and stratified ICM. They propagate horizontally and downwards from the rising bubbles, spreading energy over large volumes of the cluster core. Such a process was always missed in the previous studies due to the difficulty of modeling long-live bubbles in numerical simulations. We overcame this issue by developing a novel rigid-bubble model and found that terminal velocities of the flattened bubbles are small enough to drive efficiently internal waves. If our findings are scaled to the conditions of the Perseus cluster, the expected bubble's terminal velocity is ∼100-200 km/s near the cluster inner region, broadly consistent with the direct measurement by the Hitomi satellite. Meanwhile, our simulations showed that buoyantly rising bubbles play an important role in shaping the ∼10-100 kpc long ionized/molecular filaments (e.g., Ha and CO) in cluster cores. The gas is dragged up by the eddies in the bubble wake and radially stretched during the propagation, which is expected to have high radial velocities, i.e., by a factor of ∼2-3 higher than the bubble's rise velocity. Our model explains both the shape and amplitude of the filaments' velocity structure function measured in nearby clusters.

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