Observe Local Think Global: What Solar Observations Can Teach us about Multiphase Plasmas across Astrophysical Scales

ISSI Proposal for an International Team in Space and Earth Sciences - March 2022
ISSI Location: Bern

Team leaders: Patrick Antolin & Clara Froment

Abstract

Cool plasmas (mostly at $\approx 10^4$ K) embedded in a larger, much hotter (generally $\gtrsim 10^6$ K) medium are ubiquitous in different astrophysical systems such as solar & stellar coronae, the circumgalactic (CGM), interstellar (ISM) and intra-cluster (ICM) media. The role of these multiphase plasmas has been highlighted in mass and energy cycles at all such scales, from thermal non-equilibrium (TNE) cycles in the solar atmosphere to precipitation-regulated feedback cycles that drive star and galaxy formation. The properties of the cool plasmas across these multiple scales is strikingly similar, intimately linked to the yet unclear but fundamental mechanisms of coronal and ICM heating and instabilities of thermal or other nature. Being so close and governed by small timescales, the solar corona constitutes a formidable astrophysics laboratory where we can spatially and temporally resolve the physics of producing and removing such multiphase plasma. Recent ISSI team efforts have shown the multi-faceted response of the solar atmosphere to the heating, best exemplified by TNE cycles that manifest through puzzlingly week-long EUV intensity pulsations despite the stochastic nature of the solar atmosphere, and are now recognised as a major solar conundrum which we aim at solving. At small ($\sim$ 100 km) scales, the solar atmospheric response comes through the generation of cool coronal rain, the seed of prominences, whose mysterious properties are similar to that of multiphase filamentary structure in the ISM and ICM or to molecular loops in the Galactic centre. Coronal rain also occurs across a wide energetic scale extending to flares. However, flare-driven rain, whose features seem recurrent in active stars, is often ignored and is not understood despite its significant energy budget. In all cases, a finely-tuned response to the heating is observed in the form of cooling, which we aim at quantifying. The formation and destruction of coronal rain and prominences has recently received further attention in stellar evolution, due to their potentially significant contribution and diagnostic capabilities to the otherwise unknown wind mass-loss rate. While the quantity and morphology of the cool plasma in the solar atmosphere is now known to be closely linked to the properties of coronal heating, the theoretical investigation of multiphase gas is far ahead in the ISM/ICM. These results therefore provide a new perspective and strong new constraints on the mass and energy transfer in the solar corona that we will exploit. Furthermore, they provide unique cross-disciplinary opportunities for knowledge transfer offered by the multi-scale and multi-energetic manifestation of cool plasma across the universe. In this team we combine the appropriate expertise to tackle these multi-disciplinary problems. With the help of the advanced theoretical knowledge achieved in the ISM and ICM fields, we will use the models from the extragalactic community and test them on the high resolution solar observations to investigate the role of multiphase plasma in the establishment of the solar atmospheric mass and energy cycle. In turn, the understanding achieved will be applied to the larger unresolved scales.

Scientific Rationale

Systems with heating, mixing, and cooling processes leading to self-regulating mass and energy cycles exist at multiple scales in the Universe. Recent advances from solar to extra-galactic physics, captured in the recent review by the proposed team leaders [1], have shown several similarities between these cycles, driven by scale-free fundamental physical processes whose understanding constitute some of the greatest challenges in astrophysics.

At the solar scales, closed magnetic fields anchored at the solar surface permeate the external atmosphere. The constant stressing by magneto-convection combined with the chromospheric mass reservoir and with yet undetermined dissipation processes lead to the generation of $10^6 - 10^7$ K coronal loop structures filled with plasma. This chromosphere-corona mass and energy cycle is at the heart of coronal heating. Recent observations by the proposed team have shown that the interplay between coronal heating and cooling, and the amount of mass in the closed corona is highly fine-tuned [2]. Large amounts of stratified (footpoint) heating of coronal loops leads to higher densities, which puts them in a state of thermal non-equilibrium (TNE) and are subject to thermal instability (TI) [3, 4]. This leads to an increase of coronal rain − cool and dense filamentary and clumpy material raining down, thereby evacuating the loops and setting a natural limit to the amount of material that can be sustained in the closed corona [5, 6]. This feeding process via heating and measured cooling response is exemplified in our recently discovered ubiquitous and large-scale EUV intensity pulsations [7, 8, 9, 10] with periodic cool coronal rain in the UV/optical spectrum [11]. These TNE-TI cycles can be mind-blowingly periodic and last over a week. Such emergent behaviour at global scales despite the stochastic small-scale perturbations is now recognised as a major solar conundrum that we will tackle.

On the other hand, at the large scales of galaxy formation, observations indicate a strong correlation between the hot $10^7 - 10^8$ K ICM medium, the presence of multiphase gas in the form of filamentary molecular clouds, and star formation in the cool cluster cores [12, 13, 14, 15]. A promising hypothesis behind this multi-scale relation in the ICM evolution relies on a feedback mechanism, also known as the 'the precipitation limit' [16, 17], in which TI plays a central role. While the heating mechanisms of the ICM are still under debate, it is generally accepted that the cooling via TI and the subsequent dense multiphase 'galactic rain' onto the central supermassive black hole energises the outflows. These outflows, in turn, control the density and temperature of the ICM [18, 19], as well as the formation and destruction of multiphase gas through dynamic instabilities and mixing [20, 21], thereby regulating the precipitation. This theoretical model offers a solution to the observed TNE-TI cycle on the Sun, with TI serving as a locking and regulating mechanism leading to the large-scale emergent behaviour. To test this hypothesis, multi-dimensional simulations that self-consistently generate a solar atmosphere are needed. However, only now with newly-available numerical techniques developed by team members and adapted to numerical codes we can efficiently model the transition region (properly regulating the energy flux across), the radiative losses [22, 23], and the chromospheric response to the heating. Therefore, using these codes and inspired by the precipitation limit model in the ICM, we will investigate TNE-TI in a realistic setup to decipher the emergent EUV pulsation phenomenon in the stochastic solar atmosphere.

Previous ISSI team efforts have shown that the properties of TNE-TI cycles, such as the periods, the spatial and temporal characteristics of the heating are linked to the cooling rate of coronal plasma, suggesting a strong relation to the amount of coronal rain [24, 25]. Despite its huge importance, no quantification of this cool material and the associated TNE volume in the solar atmosphere exists to date, but first results suggest the existence of active regions in which TNE is prevalent [26]. Flares provide a prime example of this measured heating-cooling response. Coronal rain is a common flare feature whose quantities seem proportional to the energy release and represent a significant part of the flare energy budget. However, flare-driven rain is often ignored and remains largely not understood, pointing to a fundamental gap in the standard flare scenario [27]. We will aim at bridging this gap by combining an observational and numerical approach. We will exploit the characteristic features of coronal rain (morphology and dynamics) to apply automated detection algorithms based on machine learning (ML) and other rapid feature recognition codes (e.g. RHT) [28], building statistics with long-standing, currently available telescopes such as SDO and IRIS. On the numerical side, we will build on recent achievement by team members on the first realistic flare-driven coronal rain modelling in 2.5D MHD and investigate rain production due to multi-dimensional effects and secondary energy sources in addition to electron beams [29]. We will extrapolate our results to the stellar flare range, for which coronal rain is a prime candidate to explain the observations of large red-shifts in UV lines [30, 31, 32].

The morphology of multiphase plasma carries far-reaching implications in terms of its survival and dynamics, and thermal and dynamic instabilities have long been invoked to explain the observed filamentary, multiphase structure in the ISM and ICM [33, 34, 35, 36]. 3D MHD simulations have shown that dynamic instabilities (such as KHI) and the generated turbulence play an essential role in the formation and destruction of multiphase plasma in the ICM [37, 20]. The details of the TI-driven cooling rate and the structure of the eigenmodes, whose theory is greatly extended in the ISM/ICM fields [35, 36], directly influence the quantity and morphology of the multiphase plasma, which are still under debate in the ISM/ICM due to the lack of direct observational constraints [38]. On the other hand, coronal rain is similarly clumpy and filamentary [5], and the solar corona, as the ISM and ICM, can be magnetically dominated and turbulent [39, 40], but is the only environment in which such multiphase plasma can be properly spatially and temporally resolved. The recent theoretical result by [35] for the ISM/ICM on the dynamical behaviour and morphology of condensations under non-adiabatic conditions (such as 'shattering' and 'splattering') have initiated a search for similar processes in the solar atmosphere [41, 42, 43], now possible with MHD spectral codes such as 'Legolas', developed by team members [44]. Similary, the numerical result by [33] revealing the fine-scale, filamentary magnetic and X-ray imprint of condensations in the ISM/ICM has inspired a search for this possibility in the solar corona. Using 2.5D radiative MHD simulations, [45] show that TI can explain the long-standing puzzle of the filamentary structured EUV solar corona.

The creation of multiphase plasma in the ISM/ICM is governed by the ratio of the cooling time to the free fall time $t_{\rm cool}/t_{\rm ff}$, a key parameter that dictates the amount of material that is subject to condensation [46, 47]. Interestingly, the same value for this ratio is theoretically predicted in the inner solar corona [34]. However, the physics behind this ratio are still unclear, and solar observations have not yet put this ratio to the test. The free-fall time is linked to the universal phenomenon of accretion and similar dynamics to coronal rain are observed at larger scales of molecular loops in the Galactic centre [48, 49] and multiphase ICM plasma [50]. Being so close, coronal rain can serve as a template for stellar and ICM accretion [51]. In the solar context, the final speeds, determined by the mass transfer rate, are observed to be much lower than free-fall [5], and appear linked to gas pressure restructuring [52, 53] and can be used to probe models of turbulent radiative mixing in the ICM [37, 20]. A signature of this deceleration mechanism is the existence of a peculiar mass-velocity relation, predicted by numerical simulations, which we will observationally test [52, 54, 55].

A star's rotational evolution crucially depends on its mass loss rate via its wind. However, the hot and tenuous stellar wind of cool stars is extremely difficult to detect. Such stars can support 'slingshot prominences' [56, 57], which are far easier to observe and have been shown to be potentially significant contributors to the stellar wind, thereby acting as 'wind gauges' [58]. Yet, this proxy crucially depends on the formation and removal of the multiphase plasma from the star's co-rotation radius, thereby strongly benefiting from the knowledge from the solar and ICM sides.

Goals, methodology and team members

We propose to integrate the study of similar mass and energy cycles across multiple scales in the Universe, from the solar to stellar, ISM and ICM scales, for which multiphase plasma plays a similar and essential role. We will focus on the high-resolution solar observations and exploit the deep link between the cool multiphase plasma properties and the properties of the heating as a novel and powerful way to study the heating mechanisms, drawing inspiration from results in the ISM/ICM and, in-turn, seeking to provide feedback at those larger unresolved scales. Our key target open questions are:

- What is the fraction of the coronal volume that is subject to TNE-TI? How pervasive is coronal rain and how does it vary across the solar cycle? We expect the amount of coronal heating (including flares) to be reflected in the amount of coronal rain. This, in turn, will shed light into other systems with similar self-regulating cycles, such as the ICM, and may constitute a test for the precipitation limit theory. Recent observations indicate that the TNE volume within an active region could be on the same order as the coronal volume [26]. Characterising coronal rain features pave the way for automated detection using ML techniques developed by our team members. We will use transfer learning from a deep pre-trained convolutional neural network and adapt it to provide classifications and object detection [59]. Differential Emission Measure (DEM)-based [60] and morphology-based (Blind Source Separation, [61]) routines are being developed by team members that disentangle the hot and cool emission in AIA 304 images, thereby unlocking coronal rain detection with a decade long AIA data. For IRIS spectra we will use classification methods such as k-means [62].

- Is the creation of multiphase plasma in the solar corona and in the ISM/ICM governed by the same physics? Is the predicted $t_{\mathrm{cool}}/t_{\mathrm{ff}}$ ratio, common to both scenarios, supported by solar observations? Using the analysis from the previous point we will be able to measure this ratio accurately and compare with the values found in the ISM/ICM. Furthermore, we will be able to test the predicted mass-velocity relation, which will reveal the underlying physics behind the characteristic accretion of coronal rain. The mass transfer rate in the solar atmosphere is expected to affect the terminal velocity of coronal rain, thus, its dynamics can be used to probe models of turbulent radiative mixing layers in ICM and shed light on the dynamics of molecular loops in the Galactic centre.

- What are the properties of TNE-TI in realistic 3D MHD simulations? How can we reconcile the week-long TNE-TI pulsations with the stochastic solar atmosphere? We will conduct the first realistic 3D MHD simulation at high-resolution of an active solar network, long enough to capture the EUV pulsations, now possible with highly efficient algorithms for transition region modelling [63]. The TNE-TI onset in various magnetic topologies will help understand the formation of molecular loops in the CGM [48], and that of multiphase plasma at a star's co-rotation radius. This in turn will help assess the role of slingshot prominences in the contribution to stellar mass-loss rates.

- How is flare-driven rain produced and how common is it? Is the rain quantity highly correlated to the energy release? The understanding of flare-driven rain will bridge a major gap in the standard flare model. With the HYDRAD code (in 1D, [27]) and MPI-AMRVAC (in 2.5D, [29]), particularly suited for flare investigation, we will numerically explore multi-dimensional effects (such as loop-top pressure increase due to above-the-loop flare sources) and identify secondary heating mechanisms that added to electron beams can lead to coronal rain. We will conduct a parameter space investigation quantifying the amount of rain in each case with the aim at building power laws of energy input versus rain ouput. We will extrapolate these power laws to the stellar energy flare range to infer properties of the heating and cooling processes at large stellar scales.

- What determines the clumpy and filamentary morphology of multiphase plasma? What is the true morphology of condensations from solar to ISM/ICM conditions? Increasingly higher spatial resolution reveals a tip-of-the-iceberg distribution, with increasingly higher clump numbers. MHD simulations and spectral codes (such as Legolas) indicate distinct morphologies, such as splattering, shattering and so forth [35, 38], which are strongly linked to the character of TI and interaction between modes. Accordingly, can we distinguish various kinds of condensations in solar observations? Combined high-resolution observations with Solar Orbiter, IRIS and DKIST[1] will reveal the internal workings of TI, with far reaching consequences for the ISM/ICM.

To achieve these goals, we propose a team that will focus on solar observations (experts PA, CF, FA, LK) combining quiescent and flare-driven coronal rain modelling (CD, CJ, RK, JR), TNE & wave theory (JK, RO, RK) and ML expertise (ES, LK) while bringing in the theoretical knowledge from the CGM/ISM/ICM fields in instability theory (MG, PS) and stellar evolution (MJ, RK, LK) (see Table 1). To strengthen the skill set from our core group we will consider inviting experts in the ICM/CGM feedback effect (M. Voit, MSU, US), non-linear TI theory (D. Proga, U Las Vegas, US; P. Choudhury, Cambridge, UK), observations of multiphase gas in the CGM (J. Werk, U Washington, US), multi-dimensional simulations of molecular loops in the Galactic centre (R. Matsumoto, Chiba U, Japan) and quiescent/flare-driven coronal rain and prominence modelling (C. Xia, U Yunnan, China; W. Ruan, KU Leuven, Belgium; G. Pelouze, IAS, France).

[1]two PI-led projects approved in DKIST Cycle 1 (one specifically tailored for coronal rain) will run in spring 2022.

Table 1: TL: Team leader; F: Fully funded; A: Only accommodation funding; SS: Self-supported

Team member	Institute	Country	Comment
Patrick Antolin	Northumbria U.	UK	TL, F, Solar
Clara Froment	LPC2E, CNRS, U. Orléans	France	TL, F, Solar
Cooper Downs	Predictive Science	USA	F, Solar
Moira Jardine	U St Andrews	UK	F, Stellar, ISM
Craig Johnston	GMU/NASA GSFC	USA	F, Solar
Rony Keppens	KU Leuven	Belgium	F, Solar, Stellar, ISM
Lucia Kleint	UNIGE	Switzerland	F, Solar, Stellar
Jim Klimchuk	GSFC/NASA	USA	A, Solar
Max Gronke	MPA	Germany	F, CGM/ISM/ICM
Ramon Oliver	UIB, Mallorca	Spain	F, Solar
Prateek Sharma	IISc, Bangalore	India	F, ISM/ICM
Elie Soubrié	IAS / UIB	France / Spain	F, Computer scientist
Frédéric Auchère	IAS, Paris	France	SS, Solar
Jeffrey Reep	NRL, Washington	USA	SS, Solar

Timeliness, value of ISSI and expected output

With this proposal we want to profit from the momentum gathered in our previous ISSI team in 2018[2], and the workshops (2019) and conference sessions (2018, 2021) that spawned from it[3]. Furthermore, a NAM session on this topic is scheduled in 2022 (SOC a subset of this group). These events reflect the recent international recognition of the importance of this topic, and we will continue proposing sessions in international conferences (e.g. COSPAR, AGU) based on the topic of our team. At ISSI we aim at solving major open solar questions with astrophysical analogues by drawing inspiration from ISM/ICM results. We further aim at exploring new powerful ideas through a-first-of-its-kind cross-disciplinary approach based on multiphase plasma across multiple cosmic scales. This proposal focuses on solar observations for which very high resolution instrumentation are now available that span the whole temperature range of coronal heating and TI-driven cooling (in particular SDO and IRIS). Solar Orbiter data is now available, of which EUI's unprecedented $2-4\times$ AIA resolution allows to probe the link between fine coronal loop structure and the heating/cooling processes (co-PI and several co-Is in the team). DKIST will be added to this list, for which Cycle I projects (from several team members) are set to run in spring 2022. With a 30 km spatial resolution, multi-wavelength coverage and coronal magnetic field measuring capabilities, DKIST will provide a unique insight on the internal workings of TI. On the numerical side, realistic multi-dimensional quiescent and flare-driven coronal rain is only recently made possible by the team members [45, 64, 65] thanks to new techniques for efficient transition region modelling [63, 23]. Furthermore, the new MHD spectroscopy tool Legolas has been developed by the team members [44] providing insight into the complex routes to instability. With its modus-operandi, ISSI offers the ideal scenario to carry out the collaboration we are seeking within this essentially new team. To consolidate our team output we will suggest a Special Issue publication around our topic, collecting our team's cross-disciplinary works.

Schedule, Facilities and Financial Support

The schedule would consist of 2 meetings, each 1-week long. Given the country distribution of our team members we consider that the ISSI-Bern headquarters are the most appropriate. We will complement the 2 ISSI meetings with various online meetings at regular intervals to enhance discussion and motivation, and to keep our schedule on track. To kick-off our discussions, a meeting will take place in June 2022 for a subset of our team. We request the standard financial support for 12 team members (accommodation and per diem, see Table 1).

[2]'Observed multi-scale variability of coronal loops as a probe of coronal heating' (2018, PIs: Froment & Antolin)

[3]COSPAR 2018 event D2.2/E3.2; 1-day ISSI Team Workshop in St Andrews in 2019; COSPAR 2021 event D2.3/E3.3

Appendices

Acronyms

CGM: Circumgalactic Medium; EUI: Extreme Ultraviolet Imager; ICM: Intracluster Medium; IRIS: Interface Region Imaging Spectrograph; ISM: Interstellar Medium; MHD: Magnetohydrodynamics; ML: Machine Learning; SDO: Solar Dynamics Observatory; SolO: Solar Orbiter; TI: Thermal Instability; TNE: Thermal Non-Equilibrium

References

[1] Patrick Antolin and Clara Froment. **Multi-scale variability of coronal loops set by thermal non-equilibrium & instability as a probe for coronal heating**. In: *Frontiers in Astronomy and Space Sciences* Accepted (2022).

[2] C. Froment, P. Antolin, V. M. J. Henriques, P. Kohutova, and L. H. M. Rouppe van der Voort. **Multi-scale observations of thermal non-equilibrium cycles in coronal loops**. In: *A&A* 633, A11 (Jan. 2020), A11. DOI: 10.1051/0004-6361/201936717. arXiv: 1911.09710 [astro-ph.SR].

[3] James A. Klimchuk. **The Distinction Between Thermal Nonequilibrium and Thermal Instability**. In: *Sol. Phys.* 294.12, 173 (Dec. 2019), p. 173. DOI: 10.1007/s11207-019-1562-z. arXiv: 1911.11849 [astro-ph.SR].

[4] Patrick Antolin. **Thermal instability and non-equilibrium in solar coronal loops: from coronal rain to long-period intensity pulsations**. In: *Plasma Physics and Controlled Fusion* 62.1, 014016 (2020), p. 014016. DOI: 10.1088/1361-6587/ab5406.

[5] P. Antolin and L. Rouppe van der Voort. **Observing the Fine Structure of Loops through High-resolution Spectroscopic Observations of Coronal Rain with the CRISP Instrument at the Swedish Solar Telescope**. In: *ApJ* 745, 152 (Feb. 2012), p. 152. DOI: 10.1088/0004-637X/745/2/152. arXiv: 1112.0656 [astro-ph.SR].

[6] P. Antolin, G. Vissers, T. M. D. Pereira, L. Rouppe van der Voort, and E. Scullion. **The Multi-thermal and Multi-stranded Nature of Coronal Rain**. In: *ApJ* 806, 81 (June 2015), p. 81. DOI: 10.1088/0004-637X/806/1/81. arXiv: 1504.04418 [astro-ph.SR].

[7] F. Auchère, K. Bocchialini, J. Solomon, and E. Tison. **Long-period intensity pulsations in the solar corona during activity cycle 23**. In: *A&A* 563, A8 (Mar. 2014), A8. DOI: 10.1051/0004-6361/201322572. arXiv: 1312.3792 [astro-ph.SR].

[8] C. Froment, F. Auchère, K. Bocchialini, E. Buchlin, C. Guennou, and J. Solomon. **Evidence for Evaporation-incomplete Condensation Cycles in Warm Solar Coronal Loops**. In: *ApJ* 807, 158 (July 2015), p. 158. DOI: 10.1088/0004-637X/807/2/158. arXiv: 1504.08129 [astro-ph.SR].

[9] C. Froment et al. **On the Occurrence of Thermal Nonequilibrium in Coronal Loops**. In: *ApJ* 855, 52 (Mar. 2018), p. 52. DOI: 10.3847/1538-4357/aaaf1d. arXiv: 1802.04010 [astro-ph.SR].

[10] Gabriel Pelouze, Frédéric Auchère, Karine Bocchialini, Clara Froment, Susanna Parenti, and Elie Soubrié. **Spectroscopic detection of coronal plasma flows in loops undergoing thermal non-equilibrium cycles**. In: *A&A* 634, A54 (Feb. 2020), A54. DOI: 10.1051/0004-6361/201935872. arXiv: 1912.02538 [astro-ph.SR].

[11] F. Auchère, C. Froment, E. Soubrié, P. Antolin, R. Oliver, and G. Pelouze. **The Coronal Monsoon: Thermal Nonequilibrium Revealed by Periodic Coronal Rain**. In: *ApJ* 853, 176 (Feb. 2018), p. 176. DOI: 10.3847/1538-4357/aaa5a3. arXiv: 1802.01852 [astro-ph.SR].

[12] S. D. M. White and M. J. Rees. **Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering.** In: *MNRAS* 183 (May 1978), pp. 341–358. DOI: 10.1093/mnras/183.3.341.

[13] R. J. H. Dunn and A. C. Fabian. **Investigating heating and cooling in the BCS and B55 cluster samples**. In: *MNRAS* 385.2 (Apr. 2008), pp. 757–768. DOI: 10.1111/j.1365-2966.2008.12898.x. arXiv: 0801.1215 [astro-ph].

[14] Kenneth W. Cavagnolo, Megan Donahue, G. Mark Voit, and Ming Sun. **An Entropy Threshold for Strong Hα and Radio Emission in the Cores of Galaxy Clusters**. In: *ApJ* 683.2 (Aug. 2008), p. L107. DOI: 10.1086/591665. arXiv: 0806.0382 [astro-ph].

[15] Deovrat Prasad, Prateek Sharma, and Arif Babul. **Cool Core Cycles: Cold Gas and AGN Jet Feedback in Cluster Cores**. In: *ApJ* 811.2, 108 (Oct. 2015), p. 108. DOI: 10.1088/0004-637X/811/2/108. arXiv: 1504.02215 [astro-ph.GA].

[16] G. M. Voit, M. Donahue, G. L. Bryan, and M. McDonald. **Regulation of star formation in giant galaxies by precipitation, feedback and conduction**. In: *Nature* 519 (Mar. 2015), pp. 203–206. DOI: 10.1038/nature14167. arXiv: 1409.1598.

[17] Mark Voit et al. **Circumgalactic Gas and the Precipitation Limit**. In: *BAAS* 51.3, 405 (May 2019), p. 405.

[18] D. A. Rafferty, B. R. McNamara, and P. E. J. Nulsen. **The Regulation of Cooling and Star Formation in Luminous Galaxies by Active Galactic Nucleus Feedback and the Cooling-Time/Entropy Threshold for the Onset of Star Formation**. In: *ApJ* 687.2 (Nov. 2008), pp. 899–918. DOI: 10.1086/591240. arXiv: 0802.1864 [astro-ph].

[19] B. R. McNamara and P. E. J. Nulsen. **Heating Hot Atmospheres with Active Galactic Nuclei**. In: *ARA&A* 45.1 (Sept. 2007), pp. 117–175. DOI: 10.1146/annurev.astro.45.051806.110625. arXiv: 0709.2152 [astro-ph].

[20] Max Gronke and S. Peng Oh. **The growth and entrainment of cold gas in a hot wind**. In: *MNRAS* 480.1 (Oct. 2018), pp. L111–L115. DOI: 10.1093/mnrasl/sly131. arXiv: 1806.02728 [astro-ph.GA].

[21] Brent Tan, S. Peng Oh, and Max Gronke. **Radiative mixing layers: insights from turbulent combustion**. In: *MNRAS* 502.3 (Apr. 2021), pp. 3179–3199. DOI: 10.1093/mnras/stab053. arXiv: 2008.12302 [astro-ph.GA].

[22] C. D. Johnston and S. J. Bradshaw. **A Fast and Accurate Method to Capture the Solar Corona/Transition Region Enthalpy Exchange**. In: *ApJ* 873, L22 (Mar. 2019), p. L22. DOI: 10.3847/2041-8213/ab0c1f. arXiv: 1903.01132 [astro-ph.SR].

[23] Yu-Hao Zhou, Wen-Zhi Ruan, Chun Xia, and Rony Keppens. **Transition region adaptive conduction (TRAC) in multidimensional magnetohydrodynamic simulations**. In: *A&A* 648, A29 (Apr. 2021), A29. DOI: 10.1051/0004-6361/202040254. arXiv: 2102.07549 [astro-ph.SR].

[24] C. D. Johnston, P. J. Cargill, P. Antolin, A. W. Hood, I. De Moortel, and S. J. Bradshaw. **The effects of numerical resolution, heating timescales and background heating on thermal non-equilibrium in coronal loops**. In: *A&A* 625, A149 (2019), A149. DOI: 10.1051/0004-6361/201834742. arXiv: 1904.07287 [astro-ph.SR].

[25] James A. Klimchuk and Manuel Luna. **The Role of Asymmetries in Thermal Nonequilibrium**. In: *ApJ* 884.1, 68 (Oct. 2019), p. 68. DOI: 10.3847/1538-4357/ab41f4. arXiv: 1905.09767 [astro-ph.SR].

[26] Seray Sahin and Patrick Antolin. **Prevalence of Thermal-Non-Equilibrium over an Active Region**. In: *ApJ* In preparation (2022).

[27] Jeffrey W. Reep, Patrick Antolin, and Stephen J. Bradshaw. **Electron Beams Cannot Directly Produce Coronal Rain**. In: *ApJ* 890.2, 100 (Feb. 2020), p. 100. DOI: 10.3847/1538-4357/ab6bdc. arXiv: 2002.07669 [astro-ph.SR].

[28] T. Schad. **Automated Spatiotemporal Analysis of Fibrils and Coronal Rain Using the Rolling Hough Transform**. In: *Sol. Phys.* 292, 132 (Sept. 2017), p. 132. DOI: 10.1007/s11207-017-1153-9. arXiv: 1809.03635 [astro-ph.SR].

[29] Wenzhi Ruan, Yuhao Zhou, and Rony Keppens. **When Hot Meets Cold: Post-flare Coronal Rain**. In: *ApJ* 920.1, L15 (Oct. 2021), p. L15. DOI: 10.3847/2041-8213/ac27b0. arXiv: 2109.11873 [astro-ph.SR].

[30] T. Ayres and K. France. **Warm Coronal Rain on Young Solar Analog EK Draconis?** In: *ApJ* 723 (Nov. 2010), pp. L38–L43. DOI: 10.1088/2041-8205/723/1/L38.

[31] T. R. Ayres. **The Flare-ona of EK Draconis**. In: *AJ* 150, 7 (July 2015), p. 7. DOI: 10.1088/0004-6256/150/1/7. arXiv: 1505.02320 [astro-ph.SR].

[32] Fuhrmeister, B. et al. **The CARMENES search for exoplanets around M dwarfs - Wing asymmetries of H I D, and He I lines**. In: *A&A* 615 (2018), A14. DOI: 10.1051/0004-6361/201732204. URL: https://doi.org/10.1051/0004-6361/201732204.

[33] P. Sharma, I. J. Parrish, and E. Quataert. **Thermal Instability with Anisotropic Thermal Conduction and Adiabatic Cosmic Rays: Implications for Cold Filaments in Galaxy Clusters**. In: *ApJ* 720 (Sept. 2010), pp. 652–665. DOI: 10.1088/0004-637X/720/1/652. arXiv: 1003.5546 [astro-ph.GA].

[34] Prateek Sharma. "Astrophysical coronae: Lessons from modeling of the intracluster medium". In: *Astronomical Society of India Conference Series*. Vol. 9. Astronomical Society of India Conference Series. Jan. 2013, pp. 27–31. arXiv: 1304.2408 [astro-ph.CO].

[35] Tim Waters and Daniel Proga. **Non-isobaric Thermal Instability**. In: *The Astrophysical Journal* 875.2 (2019), p. 158. DOI: 10.3847/1538-4357/ab10e1. URL: https://doi.org/10.3847/1538-4357/ab10e1.

[36] Vijit Kanjilal, Alankar Dutta, and Prateek Sharma. **Growth and structure of multiphase gas in the cloud-crushing problem with cooling**. In: *MNRAS* 501.1 (Feb. 2021), pp. 1143–1159. DOI: 10.1093/mnras/staa3610. arXiv: 2009.00525 [astro-ph.GA].

[37] Drummond B. Fielding, Eve C. Ostriker, Greg L. Bryan, and Adam S. Jermyn. **Multiphase Gas and the Fractal Nature of Radiative Turbulent Mixing Layers**. In: *ApJ* 894.2, L24 (May 2020), p. L24. DOI: 10.3847/2041-8213/ab8d2c. arXiv: 2003.08390 [astro-ph.GA].

[38] Max Gronke and S. Peng Oh. **Is multiphase gas cloudy or misty?** In: *MNRAS* 494.1 (May 2020), pp. L27–L31. DOI: 10.1093/mnrasl/slaa033. arXiv: 1912.07808 [astro-ph.GA].

[39] A. C. Fabian et al. **Magnetic support of the optical emission line filaments in NGC 1275**. In: *Nature* 454.7207 (Aug. 2008), pp. 968–970. DOI: 10.1038/nature07169. arXiv: 0808.2712 [astro-ph].

[40] I. Zhuravleva et al. **Turbulent heating in galaxy clusters brightest in X-rays**. In: *Nature* 515.7525 (Nov. 2014), pp. 85–87. DOI: 10.1038/nature13830. arXiv: 1410.6485 [astro-ph.HE].

[41] Claes, N. and Keppens, R. **Thermal stability of magnetohydrodynamic modes in homogeneous plasmas**. In: *A&A* 624 (2019), A96. DOI: 10.1051/0004-6361/201834699. URL: https://doi.org/10.1051/0004-6361/201834699.

[42] Niels Claes and Rony Keppens. **Magnetohydrodynamic Spectroscopy of a Non-adiabatic Solar Atmosphere**. In: *Solar Physics* 296.9 (2021), p. 143. DOI: 10.1007/s11207-021-01894-2. URL: https://doi.org/10.1007/s11207-021-01894-2.

[43] D. Y. Kolotkov, D. I. Zavershinskii, and V. M. Nakariakov. **The solar corona as an active medium for magnetoacoustic waves**. In: *Plasma Physics and Controlled Fusion* 63.12, 124008 (Dec. 2021), p. 124008. DOI: 10.1088/1361-6587/ac36a5. arXiv: 2111.02370 [astro-ph.SR].

[44] Niels Claes, Jordi De Jonghe, and Rony Keppens. **Legolas: A Modern Tool for Magnetohydrodynamic Spectroscopy**. In: *The Astrophysical Journal Supplement Series* 251.2 (2020), p. 25. DOI: 10.3847/1538-4365/abc5c4. URL: https://doi.org/10.3847/1538-4365/abc5c4.

[45] Patrick Antolin, Juan Martínez-Sykora, and Seray Şahin. **Thermal Instability-Induced Fundamental Magnetic Field Strands in the Solar Corona**. In: *ApJ* 926.2, L29 (Feb. 2022), p. L29. DOI: 10.3847/2041-8213/ac51dd.

[46] Prakriti Pal Choudhury and Prateek Sharma. **Cold gas in cluster cores: global stability analysis and non-linear simulations of thermal instability**. In: *MNRAS* 457.3 (Apr. 2016), pp. 2554–2568. DOI: 10.1093/mnras/stw152. arXiv: 1512.01217 [astro-ph.GA].

[47] Prakriti Pal Choudhury, Prateek Sharma, and Eliot Quataert. **Multiphase gas in the circumgalactic medium: relative role of t_{cool}/t_{ff} and density fluctuations**. In: *MNRAS* 488.3 (Sept. 2019), pp. 3195–3210. DOI: 10.1093/mnras/stz1857. arXiv: 1901.02903 [astro-ph.GA].

[48] Y. Fukui et al. **Molecular Loops in the Galactic Center: Evidence for Magnetic Flotation**. In: *Science* 314 (Oct. 2006), pp. 106–109. DOI: 10.1126/science.1130425.

[49] Kazufumi Torii et al. **A Detailed Observational Study of Molecular Loops 1 and 2 in the Galactic Center**. In: *PASJ* 62 (2010), pp. 1307–1332. DOI: 10.1093/pasj/62.5.1307. arXiv: 0906.2076 [astro-ph.GA].

[50] L. L. Cowie and J. Binney. **Radiative regulation of gas flow within clusters of galaxies: a model for cluster X-ray sources.** In: *ApJ* 215 (Aug. 1977), pp. 723–732. DOI: 10.1086/155406.

[51] F. Reale, S. Orlando, P. Testa, G. Peres, E. Landi, and C. J. Schrijver. **Bright Hot Impacts by Erupted Fragments Falling Back on the Sun: A Template for Stellar Accretion**. In: *Science* 341 (July 2013), pp. 251–253. DOI: 10.1126/science.1235692.

[52] R. Oliver, R. Soler, J. Terradas, T. V. Zaqarashvili, and M. L. Khodachenko. **Dynamics of Coronal Rain and Descending Plasma Blobs in Solar Prominences. I. Fully Ionized Case**. In: *ApJ* 784, 21 (Mar. 2014), p. 21. DOI: 10.1088/0004-637X/784/1/21.

[53] S. P. Moschou, R. Keppens, C. Xia, and X. Fang. **Simulating coronal condensation dynamics in 3D**. In: *Advances in Space Research* 56 (Dec. 2015), pp. 2738–2759. DOI: 10.1016/j.asr.2015.05.008. arXiv: 1505.05333 [astro-ph.SR].

[54] R. Oliver, R. Soler, J. Terradas, and T. V. Zaqarashvili. **Dynamics of Coronal Rain and Descending Plasma Blobs in Solar Prominences. II. Partially Ionized Case**. In: *ApJ* 818, 128 (Feb. 2016), p. 128. DOI: 10.3847/0004-637X/818/2/128. arXiv: 1510.08277 [astro-ph.SR].

[55] D. Martínez-Gómez, R. Oliver, E. Khomenko, and M. Collados. **Two-dimensional simulations of coronal rain dynamics. I. Model consisting of a vertical magnetic field and an unbounded atmosphere**. In: *A&A* 634, A36 (Feb. 2020), A36. DOI: 10.1051/0004-6361/201937078. arXiv: 1911.06638 [astro-ph.SR].

[56] R. D. Robinson and A. Collier Cameron. **Fast Hα variations on a rapidly rotating spotted star.** In: *Proceedings of the Astronomical Society of Australia* 6 (Jan. 1986), pp. 308–311. DOI: 10.1017/S1323358000026928.

[57] D. Steeghs, K. Horne, T. R. Marsh, and J. F. Donati. **Slingshot prominences during dwarf nova outbursts?** In: *MNRAS* 281.2 (July 1996), pp. 626–636. DOI: 10.1093/mnras/281.2.626.

[58] Moira Jardine and Andrew Collier Cameron. **Slingshot prominences: nature's wind gauges**. In: *MNRAS* 482.3 (Jan. 2019), pp. 2853–2860. DOI: 10.1093/mnras/sty2872. arXiv: 1810.09319 [astro-ph.SR].

[59] Shaoqing Ren, Kaiming He, Ross Girshick, and Jian Sun. **Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks**. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 39.6 (2017), pp. 1137–1149. DOI: 10.1109/TPAMI.2016.2577031.

[60] Paul J. Wright et al. *DeepEM: Demonstrating a Deep Learning Approach to DEM Inversion*. Version v1.0. Mar. 2019. DOI: 10.5281/zenodo.2587015. URL: https://doi.org/10.5281/zenodo.2587015.

[61] T. Dudok de Wit et al. **Coronal Temperature Maps from Solar EUV Images: A Blind Source Separation Approach**. In: *Solar Physics* 283.1 (2013), pp. 31–47. DOI: 10.1007/s11207-012-0142-2. URL: https://doi.org/10.1007/s11207-012-0142-2.

[62] Brandon Panos et al. **Identifying Typical Mg II Flare Spectra Using Machine Learning**. In: *ApJ* 861.1, 62 (2018), p. 62. DOI: 10.3847/1538-4357/aac779. arXiv: 1805.10494 [astro-ph.SR].

[63] C. D. Johnston, A. W. Hood, I. De Moortel, P. Pagano, and T. A. Howson. **A fast multi-dimensional magnetohydrodynamic formulation of the transition region adaptive conduction (TRAC) method**. In: *A&A* 654, A2 (Oct. 2021), A2. DOI: 10.1051/0004-6361/202140987. arXiv: 2106.03989 [astro-ph.SR].

[64] C. Xia, R. Keppens, and X. Fang. **Coronal rain in magnetic bipolar weak fields**. In: *A&A* 603, A42 (July 2017), A42. DOI: 10.1051/0004-6361/201730660. arXiv: 1706.01804 [astro-ph.SR].

[65] Y. Mok, Z. Mikić, R. Lionello, C. Downs, and J. A. Linker. **A Three-dimensional Model of Active Region 7986: Comparison of Simulations with Observations**. In: *ApJ* 817, 15 (Jan. 2016), p. 15. DOI: 10.3847/0004-637X/817/1/15.