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Cool Multiphase Plasma in Hot Environments

A White Paper submitted to the Heliophysics Decadal Survey

Submitted by: P. Antolin¹

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Science area: Solar Physics

Emerging Opportunities: interstellar medium, astrospheres (and their stars)

Other topic relevant to solar and space physics/heliophysics: Intracluster medium, circumgalactic medium

Summary:

Cool plasmas (mostly at $\approx 10^4$ K) embedded in a larger, much hotter (generally $>10^6$ 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 such multiphase plasma. Recent 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, and through the generation of cool coronal rain and prominences whose mysterious properties are like 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, remains poorly investigated partly due to lack of multi-temperature coverage at appropriate resolution. In all cases, a finely tuned response to the heating is observed in the form of cooling that needs to be quantified. The formation and stability-loss of prominences is of major importance to space weather and human space exploration. Furthermore, the theory of cool plasma formation can greatly benefit the theory of stellar evolution due to the unique diagnostic capabilities to the wind mass-loss rate from slingshot prominences. Unique knowledge transfer across disciplines is thus offered by the multi-scale and multi-energetic manifestation of cool plasma across the universe, for which the solar field is uniquely positioned. **These exciting new cross-disciplinary possibilities call for a high-resolution multi-wavelength imaging and spectroscopic solar instrument able to capture the multithermal, dynamic and pervasive nature of the multiphase plasma in the hot solar corona.**

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Background Information

In the solar context, focus has traditionally been set either on the investigation of hot emission ($10^6 - 10^7$ K) behind coronal heating and space weather or the cool lower solar atmospheric layers ($<10^4$ K) where the magnetic field is energised. An unintended consequence of this dichotomy is the lack of ideal instrumentation able to capture the full extent of cool material occurring in the hot solar corona. In the following we make the case for support of the cool material in hot environments, for which the corona is uniquely positioned, highlighting the benefit of such studies as well to other astrophysical communities.

Systems with heating, mixing, and cooling processes leading to self-regulating mass and energy cycles exist at multiple scales in the Universe. The plasma in these cycles co-exists at widely different temperatures ($\sim 10^4$ K – 10^7 K), and is generally known as multiphase. Recent advances from solar to extra-galactic physics have shown several similarities between these cycles and the multiphase plasma, driven by scale-free fundamental physical processes whose understanding are essential to resolve major astrophysical problems [1].

On the Sun, closed and open magnetic fields anchored at the solar surface permeate the external atmosphere. The constant stressing by magneto-convection combined with the chromospheric mass reservoir tapped by yet undetermined dissipation processes lead to the generation of $10^6 - 10^7$ K coronal loop structures filled with plasma. A major question driving the field is *what are the properties of the chromosphere-corona mass and energy cycle, regulated by heating and cooling processes?* Recent observations 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 ($10^4 - 10^5$ K) and dense (10 – 1000 higher than hot environment) filamentary and clumpy material raining down [5, 6], thereby evacuating the loops and setting a natural limit to the amount of material that can be sustained in the closed corona (Figure 1). This feeding process via heating and measured cooling response is observed across wide energetic scales, from the yet unresolved pico/nanoflare range responsible for coronal heating to the flare range. It is further exemplified in the recently discovered ubiquitous and large-scale EUV intensity pulsations [7, 8, 9, 10] with periodic cool coronal rain in the UV/optical spectrum [2, 11]. These TNE-TI cycles can be stunningly periodic and last over a week. A major solar conundrum is *how such emergent behaviour exists at global scales despite the stochastic small-scale perturbations?*

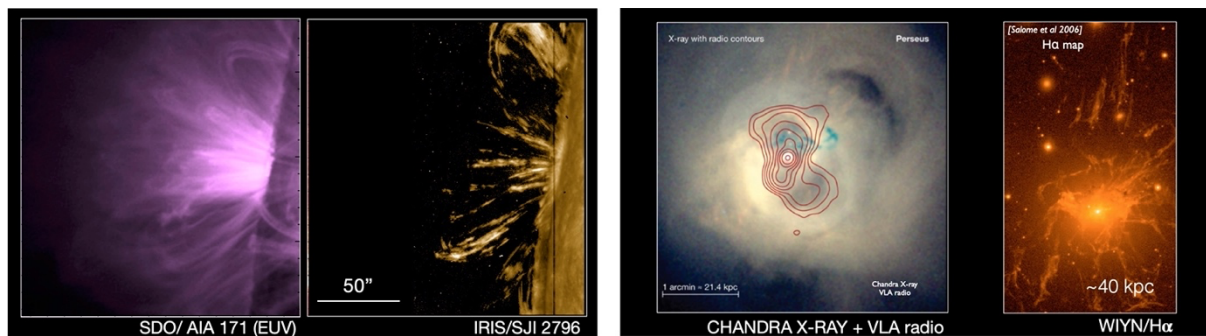


Figure 1: Observations of cool multiphase plasma in hot environments. (Left) A solar active region co-observed by AIA in the 171 ($\sim 10^6$ K, left) and IRIS 2796 ($\sim 10^4$ K, left middle). Coronal rain corresponds to the clumpy material seen in the cool bands, following coronal loop structures (taken from [4]). (Right) The hot ICM plasma of the Perseus observed in X-RAY with CHANDRA ($10^7 - 10^8$ K, right middle) harbours cool filaments ($<10^4$ K, right) observed in $H\alpha$ with WIYN [75].

At the large scales of galaxy formation, observations indicate a strong correlation between the hot $10^7 - 10^8$ K intracluster (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] (Figure 1). Clearly, once the cold 10^4 K gas reaches the central galaxy, it fuels further star-formation. However, the pressing question is *what causes this cold gas to form in the hot ICM halo?* 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 energetic 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.

The precipitation limit model of the ICM may offer 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-wavelength observations spanning chromospheric to coronal temperatures combined with multi-dimensional simulations that self-consistently generate a solar atmosphere are needed. Only now numerical techniques adapted to numerical codes have been developed that allow to efficiently model in 3D the transition region (properly regulating the energy flux across), the radiative losses [22, 23], and the chromospheric response to the heating. Therefore, in preparation for next generation solar instrumentation, we can now make a numerical investigation of the TNE-TI scenario to decipher the EUV pulsation phenomenon in the stochastic solar atmosphere, inspired by advanced theoretical models in other fields such as the precipitation limit model in the ICM.

Studies of coronal rain in the solar atmosphere indicate that the cooling rate of the plasma, and therefore the amount of coronal rain, is not only a measure for the coronal volume under TNE but also for the spatio-temporal properties of the heating, such as the repetition time of heating events and their spatial distribution in coronal loops [9, 24, 25]. The quantification of the cool plasma such as coronal rain and associated TNE volume is therefore a major coronal heating constraint. Major questions are therefore *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? What is the spatial distribution of cool material across latitudes and longitudes in the solar corona?* A first attempt at quantifying the TNE-TI volume indicates the existence of active regions in which TNE is prevalent, with at least 50% of coronal loops hosting coronal rain [26, Fig. 1]. This indicates strongly stratified heating that is high-frequency in nature. However, such studies have been limited to coronal rain close to the limb due to AO constraints [5] or insufficient signal-to-noise, and it is unclear how much cool material exists at larger heights. Unveiling the cool material at loop apexes and above is also important because of the distinct magnetic topologies and plasma conditions encountered. At large heights plasma becomes more turbulent and magnetic dips and null points are usually found where cool material can accumulate to form prominence/coronal rain hybrids [1]. Such structures remain poorly understood despite their importance as large mass reservoirs and role in the mass and energy circulation of the solar atmosphere [27], as well as because of interchange reconnection processes that are expected to take place, thereby providing a source to the solar wind [28] and observed in-situ phenomena such as switchbacks [29] (Figure 2). The study of these cool structures high up in the corona are therefore linked to the *chromosphere-corona mass and energy cycle, the elusive sources of the solar wind, the nature of switchbacks and associated particle acceleration.*

The solar atmospheric response to the heating in the form of coronal rain also occurs across a wide energetic scale extending to flares. 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 unquantified and poorly understood. Indeed, flare-driven rain cannot be directly produced by the electron beam issued from the reconnection region, the generally accepted prime flare energy transport mechanism, pointing to a fundamental gap in the standard flare model [30, 31]. Furthermore, flares are recurrent in active stars and signatures of flare-driven rain are often reported [32, 33, 34]. While the short impulsive phase is elusive to observations, the gradual phase where coronal rain occurs is more readily accessible and can therefore provide essential information about stellar flares if properly understood. The pressing questions here are therefore *How is flare-driven rain produced and how common is it? Is the rain quantity highly correlated to the energy release? Can flare-driven rain be a proxy for the properties of the flare energy release?*

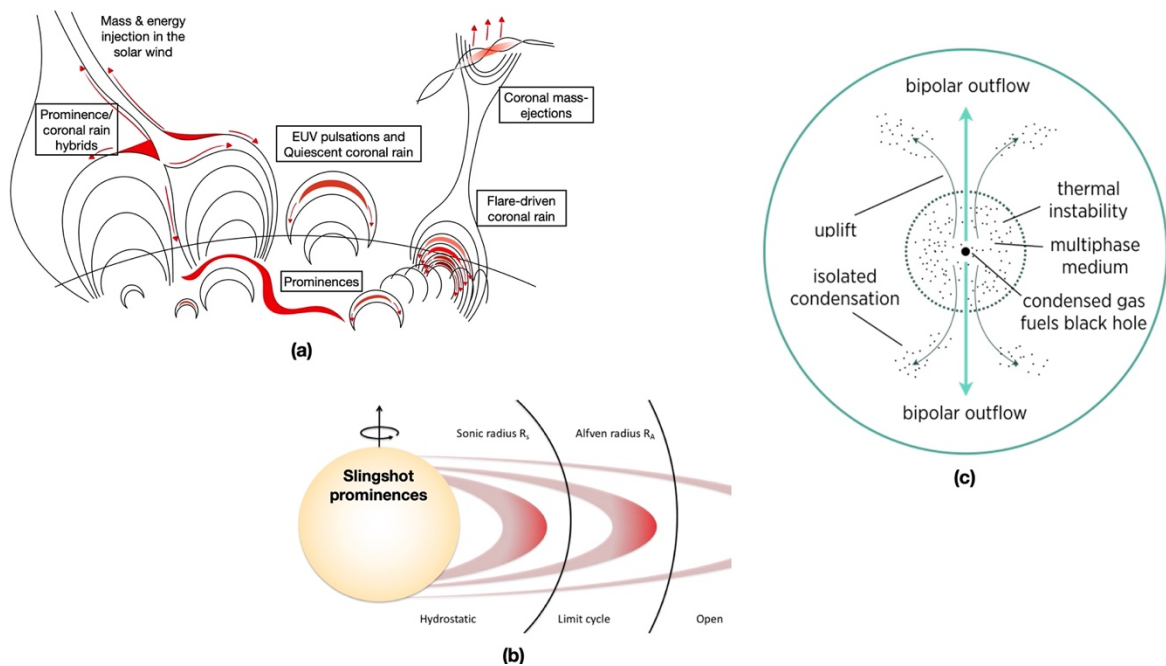


Figure 2: Sketch of three environments where multiphase plasma is found in the Universe and play a major role. (a) Coronal rain (quiescent, flare-driven) and prominences are cool material in the solar corona that are often associated with TNE-TI cycles, long-period (EUV) intensity pulsations and CMEs. (b) ‘Slingshot prominences’ form in young stars’ co-rotation radii, contributing and serving as proxy to the stellar wind mass loss rate (from [71]). (c) ‘Precipitation limit’ cycle in the ICM whereby multiphase plasma forms in the ICM and fuels the centre black hole, which regulates the ICM temperature and density (from [17]).

The presence of cool material in hot environments can indeed serve as a proxy to directly or indirectly determine important physical quantities that are otherwise very difficult to measure. Prime examples in the solar context are *the mapping and measurement of the coronal magnetic field* (through e.g. spectro-polarimetry or seismology techniques) [35, 36, 37], *the enigmatic coronal heating function* [38], *the level of turbulence or the presence of braiding at sub-arcsecond scales*. These quantities are essential in *assessing the energy budget and dissipation mechanisms of coronal heating mechanisms such as braiding-induced magnetic reconnection and transverse MHD waves* [39].

Moreover, *direct signatures of coronal heating mechanisms in action can also be captured more readily through observations of cool coronal plasma rather than hot plasma, such as the*

recently discovered reconnection-driven nanojet [40, 41]. This phenomenon corresponds to fast (~ 100 km/s), short-lived (< 20 s) and tiny (500 km in widths, 1500 km in lengths) jet-like phenomena, with energies in the nanoflare (10^{24} ergs) range. Since the rain is partially ionised (with high ionisation fraction), cool and dense [1], it was hypothesised that it plays the role of a high-resolution tracer of the coronal magnetic field dynamics, and in this case, the reconnection dynamics within coronal loops. However, it is possible that thermal instability facilitates the triggering of tearing modes [42]. In turn, the plasmoids generated through this process can cool more effectively due to their thermally insulated topology and become coronal rain clumps. Therefore, either through the generation of magnetic dips (leading to heavy prominence/coronal rain hybrids) or through the facilitation of tearing modes, *magnetic reconnection clearly has a role in the generation of cool plasma* that needs to be further elucidated. It is thus important to conduct high-resolution ($0.33''$), high cadence (< 20 s) multi-thermal (chromospheric and coronal) spectroscopic observations to fully validate the hypothesis and define the role of thermal instability in reconnection. On the other hand, direct detection in hot spectral lines of magnetic energy dissipation mechanisms is still largely lacking to date, which suffer particularly from line-of-sight superposition effects due to optically thin emission. This effect leads to broad coronal spectral lines that hide the contribution of wave turbulence [43] and significantly reduce the magnetic field strength. Being optically thicker in chromospheric lines, coronal rain showers allow to identify coronal loops in the so-called ‘coronal veil’ [44], and proof of concept studies of magnetic field measurement from coronal rain emission have now been carried out [35, 45, 46], elucidating its potential.

Thermal and dynamic instabilities have long been invoked in the ISM/ICM to explain the observed mysterious filamentary, multiphase structure of the plasma [47, 48, 49, 50]. While TI is recognised to be the main formation mechanism of the cool plasma, 3D MHD simulations have shown that dynamic instabilities (such as the Kelvin-Helmholtz Instability) and the generated turbulence play an essential role in the subsequent evolution of the multiphase plasma in the ICM [51, 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, directly influence the quantity and morphology of the multiphase plasma [49, 50]. However, quantifying these properties requires a spatial resolution that cannot be achieved in those fields [52]. On the other hand, the solar corona is the only environment in which multiphase plasma can be properly spatially and temporally resolved. Recent theoretical results for the ISM/ICM on the dynamical behaviour and morphology of condensations under non-adiabatic conditions (such as ‘shattering’ and ‘splattering’, [49]) have initiated a search for similar processes in the solar atmosphere [55, 56, 57], now possible with MHD spectral codes such as ‘Legolas’ [58]. Similarly, the numerical result by [47] 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. Coronal rain at the highest resolution achieved so far show similar widths of a few hundred km as the smallest EUV coronal strands observed with Hi-C [6, 59], and, guided by the ISM/ICM result, a TI-driven mechanism has been proposed to explain this effect [60]. These numerical results show that TI generates a thin condensation corona transition region (CCTR) that strongly emits in the UV and EUV, thereby providing an explanation to the long-standing puzzle of the filamentary structured EUV solar corona (a phenomenon also observed in the ISM/ICM). This result leads to the question of *What is the role of cool material in the observed multi-wavelength variability of the solar atmosphere?* – a question that can only be answered through high-resolution multi-wavelength observations spanning chromospheric to coronal temperatures.

Dynamic instabilities such as KHI have been observed in prominences and may likely also play a role in coronal rain [53, 54]. The mixing and heating obtained through these instabilities, as in the ISM/ICM, is also likely to play a role in the evolution of these cool structures in the solar atmosphere. *Solar observations can therefore be used to probe models of turbulent radiative mixing in the ICM* [51, 20]. These studies point to the *existence of transverse and longitudinal inhomogeneities at small scales linked to either thermal or dynamic instabilities, which are important for magnetic energy dissipation*. The general question is therefore *What is the role of MHD waves and associated thermal and dynamic instabilities in the formation processes of cool material in the solar atmosphere? High-resolution observations of the cold corona can therefore reveal the sub-structure and the fundamental spatial scales of energy transport involved in coronal heating*.

The creation of multiphase plasma in the ICM is governed by the ratio of the cooling time to the free fall time $t_{\text{cool}}/t_{\text{ff}}$, a key parameter that dictates the amount of material that is subject to condensation and therefore star formation [61, 62]. Interestingly, the same value for this ratio is theoretically predicted in the inner solar corona [48]. However, the physics behind this ratio are still unclear, and solar observations have yet to 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 [63, 64] and multiphase ICM plasma [65]. Being so close, *coronal rain can serve as a template for stellar and ICM accretion* [66]. In the solar context, the final speeds are observed to be much lower than free-fall [5], and appear linked to gas pressure restructuring [67, 68]. A signature of this deceleration mechanism is the existence of a peculiar mass-velocity relation, predicted by numerical simulations, which needs to be observationally tested [66, 69, 70]. Accurate measurements of coronal rain dynamics can be done with a spectroscopic instrument capturing the plane-of-the-sky and line-of-sight velocity components.

Prominences, coronal rain's famous relative, can be unstable and erupt, becoming key factors of space weather. However, their formation process and loss of stability leading to their eruption are still strongly debated. *The theory of prominence formation can greatly benefit the theory of stellar evolution*. Indeed, prominences are now thought to be significant contributors to the wind mass loss rate in young stars [71], which in turn influences the rotational evolution of stars. Known as 'slingshot prominences' [72, 73, 74], they represent unique stellar wind gauges because they are far easier to detect than the hot and tenuous stellar wind of cool stars. Yet, this proxy crucially depends on the formation and removal of the multiphase plasma from the star's co-rotation radius, and therefore on the knowledge of prominence formation and destruction mechanisms (Figure 2).

The deep link between the cool multiphase plasma properties and the properties of the heating provides a novel and powerful way to study the heating mechanisms that needs to be further exploited. It is now clear that new cross-disciplinary possibilities are offered by the multi-scale and multi-energetic manifestation of cool plasma across the universe, through which knowledge transfer can be achieved and for which the solar field is uniquely positioned.

Description of required facilities

To address the scientific questions in this paper, we call for a high-resolution multi-wavelength imaging and spectroscopic solar instrument able to capture the multithermal, dynamic and pervasive nature of the multiphase plasma in the hot solar corona.

As described above, multiphase plasma in the solar corona can be as small as a few hundred km, is highly dynamic (requiring cadence of <20 s particularly when subject to heating mechanisms) and spans chromospheric to coronal temperatures. Moreover, it is pervasive in the solar atmosphere, thus requiring large FOV for its detection.

Ground-based facilities such as the SST, GST or NVST have greatly advanced the field of cool plasmas in the solar corona by providing high resolution (spatial, temporal and spectral) spectro-polarimetric observations in the optical range. These observations are usually restricted to a small (60×60 Mm²) field-of-view (FOV), strongly constrained by the fact that the cool coronal material can only be effectively detected in off-limb observations, for which adaptive optics technology is ineffective, thereby further limiting the detection. Moreover, the temperature range probed by this instrumentation is limited to the cool chromospheric range, while multiphase plasmas (and particularly their formation mechanism) involve important transition region and coronal temperature components.

IRIS has provided a new high-resolution window into the interface temperature region, bridging the chromosphere and the corona, which has proved to be essential in showing the expanse and importance of the cool material in the solar atmosphere. However, IRIS is strongly limited by a single slit and relatively small FOV, which does not allow to capture the phenomena of interest at the necessary high temporal resolution.

DKIST observations will provide unprecedented resolution on the order of 10s of km for coronal rain observations in optical and infrared lines with ViSP, VTF and DL-NIRSP, expanding the temperature range to the transition region and corona, while also expanding the off-limb FOV particularly with Cryo-NIRSP in the infrared. Such observations will allow to measure for the first time the large- and small-scale magnetic field in the corona (in both hot and cool spectral lines). While essential for detecting heating and cooling processes, probing the physical processes behind the formation of cool material and examining the effect on the morphology and variability of the solar atmosphere, these observations will be limited for assessing the destruction, loss of stability and escape of the cool material, as well as its effect on the solar wind and space weather. DKIST will be limited by either single-slit measurements or small FOV.

The EUI instrument on board of Solar Orbiter is now providing a new window on cool coronal plasma thanks to the EUV absorption signatures and the high-resolution capabilities of HRI 174, allowing a unique view of coronal rain on-disk. This would have been greatly complemented by the HRI Ly-alpha channel, which unfortunately has suffered from unexpected degradation. The imaging capabilities in only 1 channel mean that investigations on the thermal evolution of the cool plasma are not possible.

While all the above-mentioned instruments are strongly limited in terms of their temporal coverage (allowing only relatively short continuous observations), the full disk and continuous EUV observations from EIT/SoHO and then AIA/SDO made possible the detections of long-period EUV pulsations and their statistical study across more than one solar cycle. Moreover,

the combination of multi-thermal channels of AIA/SDO have been critical to identify these pulsations as a multi-thermal coronal response of TNE cycles. The AIA 304 passband has proved essential for detecting the cool plasma in the off-limb solar corona. However, AIA passbands are now strongly affected by CCD degradation, which will eventually affect our capability of making statistics and thermal analysis of the TNE cycles, especially because the detection of long-period EUV pulsations is currently exclusively done with AIA. The availability of continuous and global observations of the EUV corona will be critical for detecting and studying this phenomenon.

Future instrumentation such as EUVST (due 2026) will fully bridge the temperature gap in the transition region, thus allowing to fully probe the catastrophic cooling process leading to the formation of cool plasma, while providing high resolution spectral and spatial information. These observations will be strongly limited however by the single slit and lack of context imaging, enforcing large rasters with large enough FOV to have limited temporal cadence. Other initiatives currently in development phase, such as MUSE, are well-tuned to capture large FOV at high temporal, spatial and spectral resolution the heating and eruptive processes in the corona with the multi-slit approach. However, MUSE will be mostly limited to hot plasma detection [19, 20]. **To address the scientific questions in this paper, an instrument like MUSE but modified to detect the cool material (i.e. a multi-slit IRIS-MUSE) would be the ideal instrument.**

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