Non-Equilibrium Processes in the Solar Corona and their Connection to the Solar Wind

A Proposal for an ISSI International Team

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Abstract

Coronal emission reflects the time-dependent and non-equilibrium processes connected with plasma dynamics, e.g. coronal heating or flaring activity. Impulsive coronal heating by nano-flares, whether by small-scale reconnection or waves is non-stationary and should produce non-equilibrium ionization and accelerated particles similar to reconnection processes in solar flares. Additionally, the presence of the high-energy non-Maxwellian tails of the particle distributions observed in-situ in the solar wind should indicate their presence in the solar corona.

The focus of this project is to study these complex non-equilibrium processes, with emphasis on their observational signatures in remote sensing measurements of the EUV and X-ray radiation. In particular, the team will investigate whether these signatures can be linked to the in-situ measurements of the solar wind, and whether these signatures can be distinguished from the effects of plasma inhomogeneities. To tackle these questions, the proposed ISSI International Team will bring together experts on diverse fields, ranging from atomic physics and spectroscopic observations to solar wind modeling. The Team will contribute to the international development of future space missions for an advanced study of the coronal dynamics and associated non-equilibrium processes, and pave the way e.g. for the interpretation of the future Solar Orbiter observations.

Introduction

The highly structured and dynamic solar corona radiates strongly in the UV, EUV and X-ray regions and is also the source of the solar wind. Its high temperature results in the presence of multiply-ionized ions of various elements. Since the heating of the corona is probably of an impulsive nature (e.g., Tripathi et al. 2010, Viall & Klimchuk 2011), the continuous existence of the solar corona means that such heating should recur on timescales shorter than those of radiative and conductive cooling. In the absence of direct probing of the solar corona, the emitted radiation is the only carrier of information about the physical conditions in the emitting plasma. An accurate interpretation of the observations is thus of paramount importance.

The strongest impulsive energy release in the solar atmosphere occurs during solar flares. During this rapid energy release by reconnection, the magnetic energy is converted to plasma kinetic energy, resulting in electron temperatures of up to several tens of millions K. Particle acceleration is also a common process observed in flares (e.g., Fletcher et al. 2011) It manifests itself as hard X-ray radiation, from which the properties of electron high-energy tails can be inferred (e.g., Oka et al. 2013).

The solar wind has for a long time been observed to be out of thermal equilibrium. In particular, the distribution of particle velocities is not Maxwellian, but is characterized by a kappa-distribution (e.g., Maksimovic et al. 1997; Le Chat et al. 2011). The electron mean-free path in the solar wind is about 1 AU, meaning that the solar wind should retain at least some properties of the coronal regions where it is accelerated. This provides additional indication that the corona is possibly non-Maxwellian.

Despite all this, the solar EUV and X-ray line spectrum is, in vast majority of cases, interpreted in terms of ionization equilibrium and the equilibrium Maxwellian distribution. This is usually the case even under flare conditions, where rapid heating and the high-energy tail of the electron distribution are observed. Non-equilibrium ionization can occur during heating or cooling events, significantly affecting line intensities and subsequently the plasma diagnostics (e.g., Bradshaw & Mason 2003a,b, Bradshaw et al. 2004). In addition, departures from the equilibrium Maxwellian distribution have been inferred from transition region line emission (Dzifčáková & Kulinová 2011). Such effects have important consequences for the energetics of the solar corona and flares (e.g., Dudík et al. 2011). Not recognizing the significance of non-equilibrium processes can lead coronal and flare physics into difficulties with the mis-interpretation of observations.

The reason why these effects are largely neglected in the analysis of solar spectra and modelling are twofold. First, these effects can easily be masked by the temperature and density dependence of the line intensities. Second, the widely used CHIANTI database (e.g., Landi et al. 2012) allows for fast calculation of synthetic spectra, but only in equilibrium conditions.

Key Questions

In this ISSI team, we will consider these key questions concerning non-equilibrium processes in the solar corona from the perspective of recent advances in both the theory and observational capabilities from space (including remote-sensing and in-situ observations):

- What indications are there for the presence of the non-equilibrium ionization and non-Maxwellian distributions from the theories of coronal heating and solar wind acceleration?

- Can the presence of non-Maxwellian distributions in the solar wind, as inferred from the in-situ observations, be linked to the properties of the likely coronal source regions, whether coronal holes or open structures in the active regions? What are the spectroscopic signatures of the non-Maxwellian distributions in these source regions? At which wavelengths are these best observed?
- How can the presence of non-equilibrium ionization be inferred from observations? What are the most common observational signatures? Can these signatures of non-equilibrium ionization lead to constraints on the plasma energetics, e.g., duration of the heating and the amount of energy released, both during impulsive coronal heating and in flares?
- Could and to what degree can the spectroscopic signatures of non-equilibrium ionization and non-Maxwellian distributions be distinguished from the effects of plasma inhomogeneities, e.g., plasma multithermality?
- Is the current remote-sensing instrumentation suitable for discerning these effects from the temperature and density dependence of line and continuum intensities?
- What new observations using the existing space instrumentation are required?
- What new instruments could be developed to probe the non-equilibrium processes?

Scientific Value

The coronal heating and solar wind acceleration problem still remains one of the major unsolved problems in astrophysics. Careful interpretation of the observed data focused on discerning the non-equilibrium effects and/or the presence of non-Maxwellian distributions in the plasmas of the solar corona could provide the strongest constraints on contemporary coronal heating theories. This is because unlike other observables, the effects of the non-equilibrium ionization and/or non-Maxwellian distributions would provide a direct probe into the microphysics of the coronal heating. Detecting such non-equilibrium effects can then help us to solve e.g. the steady versus impulsive heating controversy. The presence of distributions characterized by a high-energy tail would point to similarities between coronal heating and flare physics, i.e., to magnetic reconnection. Similarly, a study of the non-equilibrium effects in solar flares can provide further, independent insights into particle acceleration during magnetic reconnection. Moreover, diagnosing similar type of non-Maxwellian distributions in the solar wind and in the solar corona would provide very strong indications that the solar wind indeed originates in the lower corona, where the majority of the EUV and X-ray emission is being produced. Vice versa, non-detecting such distributions in the believed source regions would mean that the solar wind is accelerated at higher altitudes. Below we discuss in more detail some of the most important recent developments and the set of questions to be addressed by the proposed ISSI Team.

Constraints on the coronal heating theories

Impulsive heating is currently considered to best explain the observed lifetimes, emission measures, intensity and temperature profiles of not only the coronal loops, but active region corona in general (e.g., Tripathi et al. 2010, Klimchuk et al. 2010, Viall & Klimchuk 2011). The heating is thought to occur in “nanoflare storms”, repeated bursts of energy lasting several hundreds of seconds on individual magnetic field lines. Such processes should lead to the appearance of non-equilibrium ionization, as discussed e.g., by Bradshaw & Mason (2003a,b). To date, detection of this is still lacking. Furthermore, if the impulsive heating is occurring due to reconnection, power-law high-energy tails are expected to be present in a similar way to flare conditions. However, power-law tails can also occur due to wave heating (e.g., Vocks et al. 2008). Power-law tails have been inferred from the ratios of line intensities, but so far only in the transition region (Dzifčáková & Kulinová 2011). The profiles of coronal lines also indicate that the particle distribution in the corona is not Maxwellian (Lee et al. 2013). The detection of non-Maxwellian distributions would provide a strong indication for impulsive coronal heating.

Coronal heating and solar wind acceleration in source regions

The distribution of particle velocities in the solar wind has been for a long time observed to be non-Maxwellian (e.g., Maksimovic et al. 1997) and stable over long distances (e.g., Le Chat et al. 2011). The solar wind is believed to originate in the open structures in the solar corona, whether at outer boundaries of the active regions or in coronal holes. Therefore, these source regions should exhibit presence of non-Maxwellian distributions as well. The current picture of acceleration of slow solar wind in open active region structures involves magnetic reconnection occurring high in the solar corona (e.g., Del Zanna et al. 2011), which provides additional indication that high-energy suprathermal electrons should indeed be present in the source regions. This scenario also predicts that the ion and electron temperatures should not be equal (Bradshaw et al. 2011), providing further indications for the presence of other non-equilibrium effects.

The presence of non-Maxwellian distributions or non-equilibrium effects would influence intensities of EUV and X-ray lines produced in these regions, yielding possible detectability using remote-sensing spectroscopic measurements (e.g., Dzifčáková & Kulinová 2011, Mackovjak et al. 2013). These observations can at present be difficult, since they can require weak lines. We note however that the spectral range investigated so far is quite limited.

Multi-thermality and non-equilibrium effects

Flares and active regions have for long time been interpreted as multi-thermal (e.g., Schmelz et al. 2007, 2013). Multi-thermality implies sub-structuring, i.e., that the observed signal originates in many unresolved, but equilibrium structures. If there are many emitting structures seen along the line of sight, this is certainly the case. However, if there is only one discernable coherent emitting structure (e.g., a single, evolving loop structure) then assuming an equilibrium situation could lead falsely to a multi-thermal interpretation. This is because the non-equilibrium effects and/or non-Maxwellian distributions can cause the line intensities to depart from the equilibrium values. Thus, it is important to separate the plasma multi-thermality from non-equilibrium effects. Conversely, it is unknown to what degree these effects can mask one another. To our knowledge, no such investigation has yet been attempted. The increasing sub-arc second spatial resolution only underlines the importance of such an analysis. Many astrophysical environments could be out of equilibrium, but are difficult to resolve spatially due to their distance. Since the non-equilibrium radiative effects have a general application to astrophysical plasmas, separating them from the multi-thermality issue can prove an invaluable tool for discerning the plasma properties e.g. in active stars, supernova remnants, or active galaxies.

Effect of non-Maxwellian high-energy tails on ionization and line intensities

Dzifčáková et al. (2011) considered the effect of flare-like high-energy tail on ionization equilibrium and flare line intensities. These authors dealt with only a small number of X-ray lines of Si. Nevertheless, the temperature-sensitive ratio of allowed Si XIV / Si XIII lines was found to be sensitive to the presence of a high-energy tail. In addition, it was also strongly sensitive to changes in the bulk of the distribution function at energies of several keV, i.e., below the RHESSI range. Although the changes in the bulk of the distribution seems to be connected with the appearance of electron beams (Kulinová et al. 2011), its diagnostic potential has not yet been explored extensively.

Timeliness and Relationship to Ongoing International Activities

The current multitude of space instruments for observations of solar plasma offers unprecedented spectral coverage, with imaging capabilities providing the necessary context and spatial information. These instruments include the SDO/EVE, Hinode/EIS, as well as RHESSI instruments. They provide diagnostic potential for detection of non-Maxwellian distributions and non-equilibrium ionization. However, this diagnostic potential has not been explored extensively. The coming or proposed instruments, such as IRIS, the EUV spectrometer for Solar-C and the SPICE spectrometer for the Solar Orbiter include much greater spatial resolution (e.g., 0.3" for the IRIS instrument) and temporal cadence than the previous instruments. It will be the task of this Team to exploit these data and data from existing instruments for signatures of the non-equilibrium ionization and non-Maxwellian distribution effects. This will include proposing new observations with the existing space instruments. In addition, the Team should provide insight into what instrumentation should be proposed for the future. We have team members who deal directly with instrument design (J. and B. Sylwester). Linking the properties of in-situ measurements of the solar wind with the source regions is among the main goals of the Solar Orbiter.

The current availability of codes allowing for self-consistent treatment of non-ionization equilibrium (e.g., the HYDRAD code of Bradshaw & Cargill 2010, see also Del Zanna et al. 2011) and the modification of CHIANTI for the non-Maxwellian distributions (Dzifčáková 2006) enables us to tackle the wealth of observational data. We note that some of the controversies in coronal physics, e.g., the steady/impulsive heating, have been around for more than a decade. Similarly, both the flare observations and theory have shown that the flares are highly dynamic even on small time-scales. Thus, the time is ripe for in-depth exploration of the important questions that have been put forward by this Team, and to try and find new ways to tackle and answer the old questions – hence to challenge the fundamental paradigms.

Goals of the Proposal

The major objectives will be to attain a better understanding of the influence of non-Maxwellian distributions and non-equilibrium process on EUV and X-ray spectra. To achieve this, the Team will

1. Survey the state of the field in detail, both current observational capabilities and the theoretical background. Theories for the acceleration of solar wind, with emphasis on the non-Maxwellian distributions, will be assessed with respect to possible effects in the assumed source regions. This knowledge will be shared amongst the team, and the directions for future improvement will be set out.
2. Search for appropriate observations of the solar corona sensitive to the non-equilibrium effects and non-Maxwellian distributions. The observations should include both active regions, quiet Sun and coronal holes, in particular the source regions of the solar wind, so that the effects may be studied in connection with the magnitude of the heating and the acceleration of the solar wind. If necessary, new observations with existing and coming instruments will be proposed.
3. Parallel to the previous goal, the Team will use the numerical codes to model impulsive energy release and study it in terms of the non-equilibrium ionization in connection to the emission of coronal EUV and X-ray lines. Observables will be identified.
4. Differential emission measure analysis will be performed on the observations and the effect of non-equilibrium ionization and non-Maxwellian distributions on such analysis techniques will be assessed. The relevance of the DEM to forward modelling will be discussed.
5. Multi-wavelength analysis of the possible source regions will be performed to infer the plasma conditions in

those regions. This will include not only the diagnostics of temperature, density and non-equilibrium effects, but analysis of the morphology in connection to the magnetic field and its topology. High-cadence observations will be used to study the evolution of these regions in detail, in an attempt to discern whether there are typical time-scales connected with the non-equilibrium effects and particle acceleration.

6. The methods for calculation of non-equilibrium synthetic spectra will be proposed for implementation in the CHIANTI database.

Expected Output and Advances

Aside from the already discussed identification of observable signatures of non-equilibrium ionization and/or non-Maxwellian distributions, leading to a possible change in the fundamental pictures, the expected advances are:

- Review of the state of the theory and space observations, leading to a single, comprehensive study of as many aspects of the spectroscopic signatures of non-thermal and non-equilibrium processes as possible. This will complement the previous, narrower studies and provide a reference for future work in this field. This review will be submitted for refereed publication.
- Since the uncertainties in the atomic data are in turn reflected in the uncertainties in any analysis of the emitted radiation, identification of the best diagnostic procedures will lead to review of the necessary atomic data and identification of any problems therein. As the progress in atomic data calculations is stimulated by the necessity of their application, we expect this to be a by-product of the need for aforementioned advances.
- The atomic data necessary for non-equilibrium calculations within CHIANTI (cf. Dzifčáková & Mason 2008) will be computed and made available to the community, together with the associated software.
- Identification of the non-equilibrium processes in the solar wind source regions will drive the observational proposals and instrument observational programmes.
- Identification of the currently unavailable spectral ranges that may provide further information on the processes and dynamics of the solar corona, transition region and flares. This will lead to recommendations for future space instrumentation and provide a stimulus for improved instrument design.

Added value provided by ISSI

The framework of the ISSI International Teams offers an excellent opportunity to bring together a diverse group of specialists, so that we may work towards tackling the long-neglected and challenging aspects of the spectroscopic diagnostics of the non-equilibrium phenomena. The Team will combine atomic physics and predictions of coronal heating and solar wind driving theories with multi-wavelength observations made by different instruments in search for the signatures of the dynamics of coronal heating, and the acceleration of particles in both solar flares and wind. A considerable part of our agenda is to push for new observations and suggest design of space-borne instruments. The object of this study is the Sun, with a reach to solar-terrestrial connection, and applications to other astrophysical plasma environments. Therefore, the goals of this proposal are clearly compatible with the aims and purposes of the ISSI.

Team

To achieve the goals of this Team, we need experts in data reduction from both remote-sensing and in-situ observations, as well as experts in spectroscopic modelling, instrument design, and also theory. We have firm commitments to participate from experts in EUV and X-ray spectroscopy, including data reduction and interpretation of observations from various instruments (G. Del Zanna, P. Young, H. Mason), hard X-ray modelling and analysis (S. Krucker), and in-situ observations of the solar wind (N. Meyer-Vernet) as well as the modelling of solar wind (C. Vocks, L. Matteini). The team also includes experts with experience in the non-equilibrium ionization and non-Maxwellian distributions (E. Dzifčáková, H. Mason, G. Del Zanna, J. Dudík), as well as instrument operation (D. Williams) and design (J. and B. Sylwester). We also have CHIANTI team members onboard (P. Young, G. Del Zanna, H. Mason). The full team is:

Elena Dzifčáková (*Czech* Leader, Astron. Inst., Ondřejov), **Helen E. Mason** (*UK* co-leader, DAMTP, University of Cambridge)

Giulio Del Zanna (DAMTP, Cambridge, UK), **Jaroslav Dudík** (Comenius Univ., Bratislava, *Slovakia*, University of Cambridge, *UK*), **Säm Krucker** (Univ. of California, *USA*; University of Applied Sciences North Western *Switzerland*), **Lorenzo Matteini** (Università degli Studi di Firenze, Largo E. *Italy*; Imperial College London, *UK*), **Nicole Meyer-Vernet** (LESIA, Observatoire de Paris, *France*), **Janusz Sylwester** (Polish Academy of Sciences, Wroclaw), **Barbara Sylwester**, (Polish Academy of Sciences, Wroclaw), **Christian Vocks** (Astrophysikalisches Institut Potsdam, *Germany*) **David Williams** (MSSL, University College London, UK), **Peter Young** (NRL/GMU, USA).

Schedule

We plan three three- to four-day meetings at ISSI within 18 months of its start. The first meeting is planned to take a place between October and December 2013. The subsequent meetings should be held in middle 2014 and at the beginning of 2015.

Facilities and Support Requested

The standard ISSI workshop facilities are required, i.e., a meeting room for up to 12 people, equipped with data projection facilities, wireless internet access and some limited printing facilities. Team members will have their own laptops. We request support for the living expenses for 12 team members and travel support for the Team Leaders.

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TEAM (in alphabetic order)**:**

Giulio Del Zanna (DAMTP, Cambridge, UK) CHIANTI, atomic data benchmarking, EIS calibration, plasma diagnostics, loops, moss, flare - MHD model of flaring loops

Jaroslav Dudik (CU, Bratislava, Slovak Republic, DAMTP, Cambridge, UK) non-thermal distributions, plasma diagnostics, non-thermal continuum, modeling of the EUV and X-ray emission of AR, calculation of coronal magnetic field,

Elena Dzifcakova (Astron. Inst., Ondrejov, Czech Republic) ionization and excitation equilibrium for non-thermal electron distributions, calculation of the non-thermal line spectra and continua in corona, transition region and for the flares, non-thermal diagnostics, modeling of the EUV and X-ray emission of AR

Säm Krücker (Switzerland / USA) - HXR, RHESSI, Foxsi, Solar Orbiter

Lorenzo Matteini (Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze, Largo E. Fermi 2, I-50125 Florence, Italy ; Imperial College London, London SW7 2AZ, UK)

Helen Mason (DAMTP, Cambridge, UK) CHIANTI, atomic data, plasma diagnostics, data analysis; loops, moss, DEM, flares-multi-wavelength, loop MHD heating and cooling

Nicole Meyer-Vernet (Laboratoire d'Etudes Spatiales, Observatoire de Paris-Meudon) – solar wind, in-situ measurements

Janusz Sylwester (Polish Academy of Sciences, Wroclaw, Poland) observations, X-ray instruments, design, performance, X-ray line and continuum spectra, flare plasma diagnostics,

Barbara Sylwester, (Polish Academy of Sciences, Wroclaw, Poland) observations, X-ray line and continuum spectra, flare plasma diagnostics,

Christian Vocks (Astrophysikalisches Institut Postdam, Germany) – solar wind modeling

David Williams (MSSL, UCL, Surrey, UK) (observations, EIS performance, data analysis, non-thermal flows in flares, static coronal heating, coronal waves),

Peter Young (NRL/GMU, USA) CHIANTI, Hinode/EIS, non-Maxwellians, loops, flares, spectroscopic exhibition of magnetic reconnection

+ 2 young scientists