Sixth Coronal Loops Workshop

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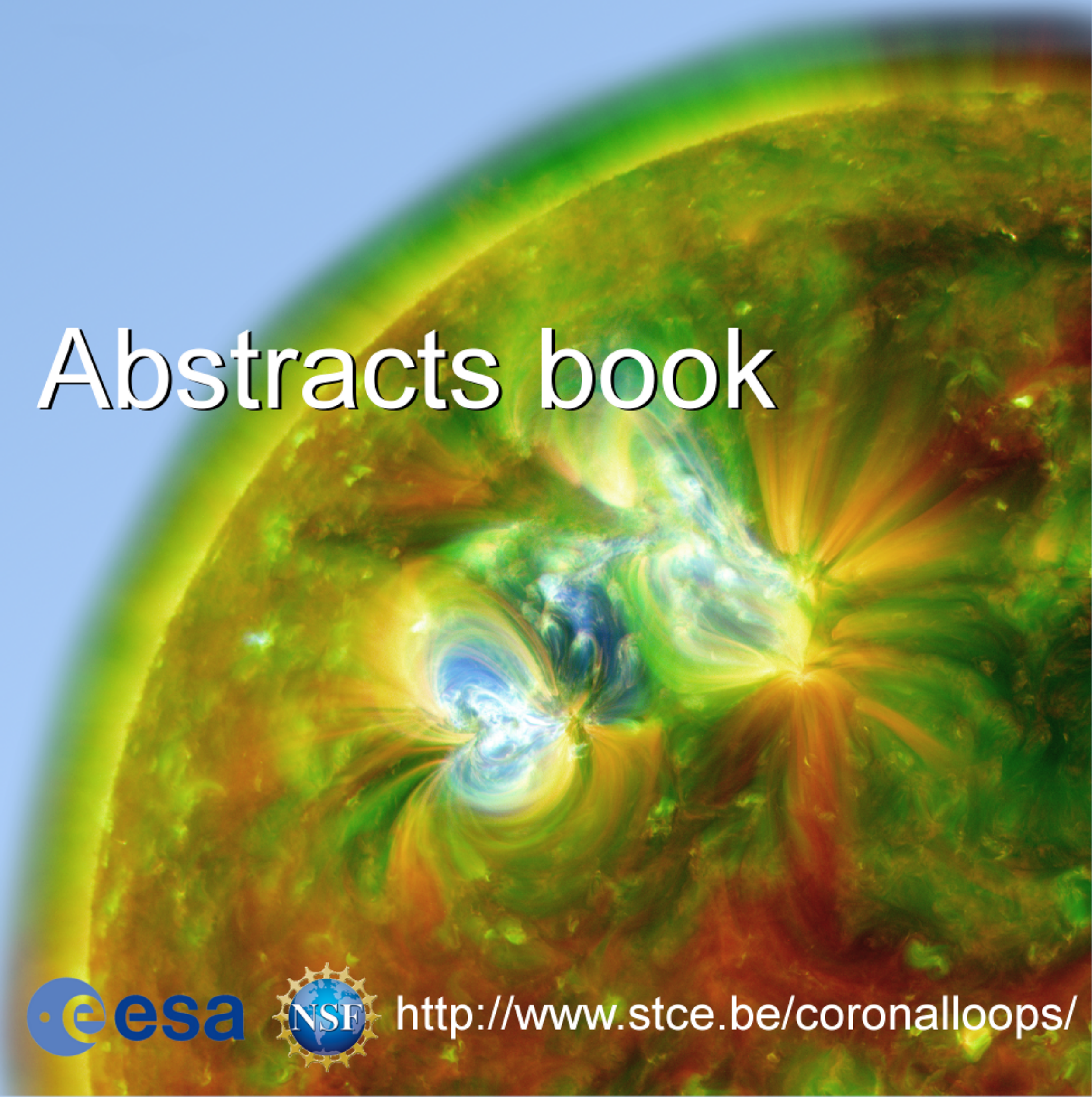

Abstracts book

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List of abstracts

Session 1

Heating and high spatial resolution: what we have and what we really need

Oral presentations

Modeling fine structure of coronal loops (invited)

Philippa Browning
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Modelling based on the MHD equations shows that fine structure naturally arises in coronal loops. One approach is that braiding of the footpoints leads to current sheets in the corona, and I will briefly review this idea. I will also show how even very simple footpoint motions, in the form of rotations, can lead to kink instabilities which generate fine structure. The results of 3D MHD simulations of unstable twisted loops will be presented, including recent results which consider realistic curved loops in a stratified atmosphere, showing how a fragmented current sheet arises. Approaches to modelling fine structure in currents sheets, including limatations of the MHD approach, will also be briefly discussed. The relationship with observations will be considered.

New insights on coronal structuring and heating from Hi-C (invited)

Paola Testa
Harvard-Smithsonian Center for Astrophysics

the Hi-C team
MSFC, SAO, LMSAL, UCLAN, Lebedev Physical Institute, SWRI, Univ. of Oslo

The Hi-C (High resolution coronal imager) sounding rocket has provided the highest resolution EUV solar observations ever obtained, resolving structures down to ~ 0.3 arcsec. The unprecedented spatial and temporal resolution of Hi-C data has revealed several new features, including highly braided coronal loops undergoing reconnection, and very rapid variability (down to ~ 15 s) in the moss of bright hot loops. I will review some of the first results obtained from Hi-C data, focusing on the new insights they provide in coronal heating.

Structure of solar coronal loops: from miniature to large-scale

Hardi Peter
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We will use new data from the High-resolution Coronal Imager (Hi-C) with unprecedented spatial resolution of the solar corona to investigate the structure of coronal loops down to $0.2''$. During a rocket flight Hi-C provided images of the solar corona in a wavelength band around 193 Å that is dominated by emission from Fe X showing plasma at temperatures around 1.5 MK. We analyze part of the Hi-C field-of-view to study the smallest coronal loops observed so far and search for the a possible sub-structuring of larger loops. We find tiny 1.5 MK loop-like structures that we interpret as miniature coronal loops. These have length of the coronal segment above the chromosphere of only about 1 Mm and a thickness of less than 200 km. They could be interpreted as the coronal signature of small flux tubes breaking through the photosphere with a footpoint distance corresponding to the diameter of a cell of granulation. We find loops that are longer than 50 Mm to have a diameter of about $2''$ or 1.5 Mm, consistent with previous observations. However, Hi-C really resolves these loops with some 20 pixels across the loop. Even at this greatly improved spatial resolution the large loops seem to have no visible sub-structure. Instead they show a smooth variation in cross-section. The fact that the large coronal loops do not show a sub-structure at the spatial scale of $0.1''$/pixel implies that either the densities and temperatures are smoothly varying across these loops or poses an upper limit on the diameter of strands the loops might be composed of. We estimate that strands that compose the $2''$ thick loop would have to be thinner than 15 km. The miniature loops we find for the first time pose a challenge to be properly understood in terms of modeling.

Small-scale heating events observed with Hi-C

Stephane Regnier
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Robert Walsh, Caroline Alexander
University of Central Lancashire

Hi-C was sounding rocket dedicated to the observation of the hot EUV corona at high spatial resolution (0.2 arcsec) and high time cadence (5 s). The Hi-C instrument flew on July 11, 2012 and provided observations in the 193 Å channel of a large complex of active regions (NOAA 11519-21). We have discovered small-scale (0.68 Mm) and short duration (25 s) brightenings, called EUV bright dots (EBDs) at the edge of the active regions. The comparison with SDO/AIA observations in the 193 Å channel shows that EBDs can also be observed at the very limit of the noise level. EBDs also exist in the 171 Å, 211 Å and 335 Å channels, and have a small contribution in the 304 Å channel. This strongly suggests that EBDs are transition region and/or coronal transient features. This is confirmed by the EM loci method. By comparing with SDO/HMI magnetograms and with the support a potential field extrapolation, the observed EBDs are located in unipolar regions at the foot-points of large-scale trans-equatorial loops. We discuss the viable mechanisms that can produce such a short burst/release of energy by comparing the different time scales of the plasma evolution.

Statistical analysis of coronal heating in active region loops – is the heating steady or variable?

Andrzej Fludra
STFC Rutherford Appleton Laboratory

We present a statistical study of heating of coronal loops in active regions, based on EUV observations in the transition region and coronal emission. Comparing EUV spectral line intensities, summed over the active region area, with the total magnetic flux in 50 active regions we obtain tight power laws and examine whether they are capable of distinguishing between different heating mechanisms (Fludra and Ireland, 2008). In contrast, comparing spatially resolved transition region emission with the underlying magnetic flux density on small spatial scales gives distributions with a large amount of scatter. This demonstrates that the predominant heating mechanism in the transition region is variable and/or significantly dependent on other factors in addition to the local magnetic flux density and loop length (Fludra and Warren, 2010). We have found, however, a lower boundary of these distributions, the same in all analysed regions, suggesting the presence of a steady basal heating. We derive the dependence of the heating rate on the magnetic flux density and loop length for the basal component. We discuss the differences between the global and spatially resolved analyses, and the implications for placing observational constraints on the coronal heating mechanism.

LEMUR/EUVST: the high spatial and temporal resolution spectrograph for the Solar C mission

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Coronal loops are the building blocks of the solar atmosphere. Thus, the understanding of their thermodynamical structure and of the dominant heating mechanism(s) at work would provide a major advance in our knowledge of the solar corona. Although observations from instruments, in particular spectrographs, with increasingly higher sensitivity and spatial resolution have greatly improved our knowledge of these structures, crucial aspects such as the plasma temperature distribution across and along loops and their internal structure remain controversial. This controversy prevents a conclusive comparison with the different models of coronal heating proposed and refined in the past ten years. On the other hand, available spectroscopic observations (filling factor measurements) and the very recent images of the corona from the Hi-C experiment show that resolving most of these structures can be achieved with instruments with about 200 km resolution. The LEMUR/EUVST spectrometer proposed for the Solar C mission, will obtain spectra at this resolution over lines formed at practically all temperatures between 10000 K and 20 MK with high spectral and temporal resolution. Thus, it has the capability of increasing enormously or understanding of coronal loops and of the physical mechanism(s) that maintain them.

Hi-C and AIA observations of transverse waves in active region structures

Richard Morton
Northumbria University

James McLaughlin
Northumbria Univeristy

The recent launch of Hi-C provided a unique opportunity to study wave phenomena in the solar corona. The high spatial resolution of Hi-C should allow for the observation of the corona's fine-scale structure and have the potential to resolve transverse (kink) wave motion partially resolved in AIA and CoMP. First, we present the details of a robust technique for measuring low amplitude transverse waves. Second, the analysis of active region coronal loop structures (observed in both Hi-C and AIA), spicular and fibrillar structures in a moss region (Hi-C only) and the measurements of transverse wave properties will be discussed. The results demonstrate that the coronal loop structures show small amplitude (<3 km/s) periodic motion for low frequency (50-500 s) waves. We will demonstrate this behavior is not just particular to the coronal loops under observation by Hi-C, but appears to be the case for other coronal loops observed with AIA. Hi-C also allows for the observation and measurement of kink waves in spicular and fibrillar features connected to the moss regions. The measured wave parameters agree with previous results from typical chromospheric lines, i.e., Ca II H and H alpha. The results demonstrate that the features in the moss regions are much more energetic on short time-scales than the coronal loops structures.

Session 1

Heating and high spatial resolution: what we have and what we really need

Posters

S1-1: Coronal active region modeling based on SDO data

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The heating of the solar corona, which has a temperature of order of 10^6 K compared to 5000 K in the photosphere, is yet a puzzling problem. Several models to describe the physical parameters, e.g. temperature or density, along coronal loops with different assumptions for the relevant physical processes (like wave damping) were suggested in the past, for example the RTV78 model by Rosner, Tucker and Vaiana. With these models and the knowledge of the 3D configuration of the magnetic field above an active region it is possible to calculate the radiation emitted by the coronal loops above this region. This 3D field configuration is provided for an active region with the help of a nonlinear force free field optimization code from photospheric SDO/HMI vector magnetograms as boundary conditions. We use this field to model the plasma along these loops with the RTV78 model and create artificial coronal images in different wavelength, which we compare with images obtained with the multispectral imager SDO/AIA. Such comparisons allow us to evaluate the quality of our model approach.

S1-2: New directions in coronal imaging

Leon Golub
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We present several instrument concepts for EUV coronal imaging to address two major scientific questions. An "inwardly directed" ultra-high resolution imager based on the Hi-C sounding rocket will explore the physics of coronal dynamics and reconnection, while an "outwardly directed" wide-field EUV imager will address the way in which the corona transitions from closed to open. The practical limitation of a high-resolution EUV imager, given reasonable mass and cost constraints, is $\approx 0.1''$ pixel scale, or $0.2''$ resolution, with a low-noise detector providing ≈ 1 s exposure times. For a wide-field EUV imager, we have demonstrated via AIA, TESIS and SWAP, that coronal structures can be observed at least out to 2.5 $R_\odot$, and we calculate that CMEs can be seen out to at least 5 $R_\odot$. Simultaneous on- and off-disk imaging of CMEs is readily implemented in such a high-sensitivity imager.

S1-3: Lower hybrid drift instability in coronal loops

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Almost 70 years after the discovery, the solar coronal heating puzzle is still one of the major challenges in astrophysics. It is commonly accepted that many mechanisms contribute to the temperature of the solar corona. However, determining which process dominates in what region, has proven to be very difficult. Many heating models have already been proposed for the coronal heating problem, and the two theories that currently stick out are the theory of wave heating and the theory of magnetic reconnection. Although a lot of research is still needed on these two theories, it is very unlikely that they will be able to fully explain the problem since they rely on the continuum or fluid approximation (Magnetohydrodynamics, MHD). Hence, these models cannot really explain coronal heating completely because i) it is clear that the actual heating takes place at length scales much smaller than those on which the (macroscopic) MHD model is justified; and ii) it is obvious that the observed discrepancy between ion and electron temperatures in the corona, as well as iii) the observed large temperature anisotropy in the inner corona ($T_\perp > T_\parallel$) and iv) the observed preferential heating of the heavier ions are beyond the (single!) fluid model.

The alternative that is explored here is based on the kinetic theory of drift waves. Assuming drift waves as the cause of the coronal heating implicitly states that the energy source of the heating is located in the corona itself, viz. in the ubiquitous density gradients present there. Though drift waves are studied intensively in the context of nuclear fusion research, not many studies are available on drift waves in solar context. Hence, it is important to look for methods to confirm the presence of drift waves in e.g. the solar corona. Here, the Vlasov theory will be used to study the presence of the lower hybrid drift instability in plasmas with a density gradient perpendicular to the magnetic field. A new approach for this study of Vlasov theory will be used. The main idea consists of expanding the distribution function in a series of Hermite polynomials in velocity space. This approach will facilitate the interpretation of the results obtained, as every expansion term has a specific physical meaning. The study has both numerical and analytical components in an attempt to quantify the presence of drift waves in the solar corona and their contribution to the heating problem.

S1-4: Applications of XBPS to understand the solar corona

Rangaiah Kariyappa
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The X-ray Bright Points (XBPs) observed with Hinode/XRT have been used to investigate the following issues: (i) Intensity oscillations; (ii) Temperature flucutations & (iii) coronal rotation. The important results derived from these analysis will help us understand the physics of the solar corona. It is found that the XBPs exhibit in their intensity periodicity ranges from minutes to hours, the temperature ranges from 1 MK to 3.4 MK and the corona rotates differentially like the photosphere. The XBPs show a significant contribution in the heating of the solar corona.

Session 2

Diagnostic tools: DEMs/EM, Doppler-shifts, plasma, flows and lines profile, importance of energetic particles, filling factor

Oral Presentations

Coronal loop observations and diagnostics (invited)

David Brooks
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We will consider recent coronal loop spectroscopic measurements and developments in diagnostics, with a view to establishing how close we are to providing meaningful constraints for loop heating models. We will do this by discussing whether we can now reach a consensus on some of the original questions of the loop workshop series. In particular, what is the cross-field temperature distribution of coronal loops? What do the diagnostics (filling factors, new techniques) tell us about their magnetic (sub-)structure? Recent results suggest that traditional filling factors are too small, and that loops formed near 1.6 MK are composed of only a few magnetic threads. This is consistent with their temperature distributions, which are nearly isothermal, and suggests that we may be close to resolving them. We will also discuss recent plasma composition measurements in active regions that are providing new information on the evolution of loops and the connection of closed-open field regions to the solar wind.

The multi-thermal emission in solar active regions

Giulio Del Zanna
University of Cambridge

Simultaneous SDO AIA and Hinode EIS observations of active regions are used to study their multi-thermal emission. New atomic data and a new EIS calibration provide very good agreement between the EIS observations and those in the AIA EUV bands. The main contributions to each of the AIA EUV bands are discussed, with particular attention to the measurements of the hot emission at 3 MK and above. A newly identified Fe XIV emission turns out to be an important contribution, together with the continuum, to the 94 Å band. Fe XVIII in this band is often formed at low temperatures. The EIS observations allow a description of the temperatures, abundances and filling factors with unprecedented accuracy. New results are presented. A new DEM modelling technique for the AIA EUV bands is used to describe the multi-thermal emission at the AIA resolution, in particular to describe the coronal loops observed during the Hi-C rocket flight, which achieved the highest spatial resolution to date. Requirements for future missions are briefly addressed.

Coronal cooling and multithermal analysis of AIA loops

Joan Schmelz
University of Memphis

Recent analysis finds some evidence that warmer loops require broader Differential Emission Measure (DEM) distributions. Loops selected in images of warm coronal lines like Si XII and Fe XV or XRT images tend to have broader DEMs, but those selected in images of somewhat cooler lines, usually Fe XII, have DEMs that are less broad but still not isothermal. Many loops selected in images of cool coronal lines like Mg IX and Fe IX show narrow DEMs and even isothermal plasma. If the observed loops are cooling, it would make intuitive sense that loops that have had time to cool to temperatures below a million degrees might not have significant associated hotter plasma. The Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory is ideal for investigating this problem. AIA is a state-of-the-art imager with the potential to do unprecedented time-dependent multithermal analysis at every pixel. The EUV filters peak at different coronal temperatures, making AIA ideal for determining the cross-field temperature distribution. Recent upgrades to the CHIANTI atomic physics data base have resulted in more complete calculations of the synthetic spectra in the AIA wavelength bands, especially near 94 and 131 Å. These advances have led to improved results for the DEM analysis of coronal loop cross-field temperatures calculated from AIA data. The evolution of loops can be observed as they cool through the AIA passbands, and the DEMs can be constructed reliably with the new AIA response functions.

Age dependence of EM distribution in AR cores

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The EM distributions in the cores of two ARs (NOAA 11057 and NOAA 11193) have been studied, once when they appeared for the first time near the central meridian and again when they appeared near the central meridian after a solar rotation. Hinode/EIS and SDO/AIA observations have been studied, in particular the slope of the EM between $\log T = 6.0$ and $\log T = 6.6$ has been derived for the hot core loops. For both active regions, the slope appears to decrease with age indicating that high frequency heating events dominate initially, leading to low frequency events for older active regions.

Can the Differential Emission Measure diagnostic be used to constrain the timescale of energy deposition in the corona?

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Differential emission measure (DEM) analysis is a widespread tool used to diagnose the thermal properties of coronal plasmas. The slope of the DEM distribution coolward of the coronal peak (near 3–4 MK in active regions) can be used to diagnose the timescale for the energy deposition repeating on a given magnetic strand. Recent AR studies suggest that some active region cores are consistent with low frequency heating mechanisms, where the plasma cools completely before being reheated, while other show consistency with high frequency energy deposition, where rapid reheating causes the temperature to fluctuate about a particular value. Distinguishing between these possibilities is important for identifying the physical mechanism of the heating. It is therefore crucial to understand the uncertainties in measurements of observed DEM slopes.

In this work, based on a probabilistic approach and Monte Carlo simulations, we carefully assess the errors in the slopes determined from EIS data. We consider both the random errors due to photon counting statistics, and the systematic errors associated with uncertainties in atomic physics and instrument calibration. The technique developed provides all the solutions consistent with the data and their associated probabilities. We demonstrate how the quality and the accuracy of the inversion are affected by the presence of noises and systematic errors, and we characterize the quality of the DEM inversion and its statistical properties. From these results, estimation of the uncertainties in the reconstructed slopes can be derived, thereby allowing a proper interpretation of the degree of agreement between observations and heating model predictions.

Thermal structure of coronal loops as seen with Norikura coronagraph

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The thermal structure of a coronal loop, both along and across the loop, is vital in determining the exact plasma heating mechanism. High resolution spectroscopic observations of the off-limb corona were made simultaneously in four forbidden Iron emission lines using 25 cm Norikura coronagraph, located at Norikura, Japan. Using the temperature sensitive emission line ratios, we compute electron temperatures along 18 different loop structures observed on different days. We find a significant negative temperature gradient in most of the structures observed in (Fe XIV, Fe XIII) line pair and a positive temperature gradient in the structures observed in (Fe XI, Fe X) line pair. From the results, we infer that the loop tops, in general, appear hotter when observed in colder lines and colder when observed in relatively hotter lines when compared to their coronal foot points. We suggest that this contrasting trend observed in the temperature variation along the loop structures can be explained by a gradual interaction of different temperature plasma. The exact mechanism responsible for this interaction needs further quest and has potential to constrain loop heating models.

Cross-sectional properties of coronal loops and their implications

Henry Winter III
Smithsonian Astrophysical Observatory

Anna Malanushenko
Montana State University

The solar corona is filled with loop-like structures that appear bright against the background when observed in the extreme ultraviolet wavelengths. These loops have several remarkable properties. Warm loops (1 MK) appear to be 2-9 times as dense at their apex than the predictions of hydrostatic atmospheric models. These loops also appear to be of constant, circular cross-section despite the fact that the strength of a potential magnetic field should decrease in the corona, causing the loops to expand. Why many active region loops appear to be of constant cross-section is not well understood. Theories range from an internal twist of the magnetic field to observational effects. In this work we simulate active region loops with different expansion factors heated by nanoflare storms. We show that even modest tapering ratios can lead to drastic changes in the density profiles of active region loops, and can also explain the overpressure at the apex of these loops. We find that all loops whose sizes are near the resolution limit, even those with large expansion factors, appear to be of near constant cross-section when images are simulated in AIA passbands. We also use potential field models to show that flux tubes, in circumstances relevant to the solar corona, in general do not maintain the same cross-sectional shape along their length and therefore the assumption of a constant, circular cross-section is rarely true. Loops with oblate cross-sections would show enhanced emission due to an increased column depth when viewed along the semi-major axis of their cross-section compared to emission viewed along their semi-minor axis. This line of sight effect would impose a bias towards selecting loops that appear not to be expanding as seen projected on the plane of sky. An implication of this selection bias is that the preferentially selected non-circular loops would appear to have increased pressure scale heights even if they are resolved by current instruments. These results put the common assumption of loops with constant, circular cross-sections, which is used to simplify many hydrodynamic models, in doubt and may help explain the extraordinary properties of coronal loops.

Observations of flows in active-region loops: as a response to coronal heating (invited)

Hirohisa Hara
National Astronomical Observatory of Japan

Coronal loops are the closed magnetic structures that are the building block of the tenuous 10^6 K outer atmosphere of the Sun. The source of energy in heating is the convective motion on the solar surface, and the partial energy is given to the corona via magnetic coupling above the photosphere. At the site of energy deposition, characteristic motions of ions are expected as dynamical responses of heated plasma. The detection of such motions from observations is possible by imaging spectroscopy. In this talk, I will review spectroscopic observations of flows in coronal loops that are driven by the ensemble of impulsive heating events.

Non-Gaussian coronal spectral lines profiles in active region cores

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Multi-component spectral line profiles have been recently observed in coronal dimmings (McIntosh et al., 2010; Dolla & Zhukov, 2011), in a flare arcade (Imada et al., 2008), in active regions (Peter, 2010) or at their edge (Bryans et al., 2010). Here we investigate the non-Gaussian behaviour of line profiles in active regions cores as a function of the line formation temperature, with the EUV Imaging spectrometer on-board Hinode. We find that non-Gaussian line profiles are present even for non-blended lines. We analyse possible interpretations in terms of inhomogeneities of flows and temperatures, and how these observations constrain models of coronal heating in active regions.

Core and wing densities of asymmetric coronal spectral profiles: implications for the mass supply of the solar corona

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Recent solar spectroscopic observations have shown that coronal spectral lines can exhibit asymmetric profiles, with enhanced emissions at their blue wings. These asymmetries correspond to rapidly upflowing plasmas at speeds exceeding $\approx 50\ \mathrm{km\,s^{-1}}$. Here, we perform a study of the density of the rapidly upflowing material and compare it to that of the line core which corresponds to the bulk of the plasma. For this task we use spectroscopic observations of several active regions taken by the Extreme Ultraviolet Imaging Spectrometer of the Hinode mission. The density sensitive ratio of the Fe XIV lines at 264.78 and 274.2 Å is used to determine wing and core densities. We compare our findings with predictions of theoretical models of the coronal mass supply.

Density of active region outflows derived from Fe XIV 264/274

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Takaaki Yokoyama
Univ. of Tokyo

One of the discoveries from *Hinode* is active region "outflows" revealed by EUV Imaging Spectrometer (EIS). Previous studies on these outflows (hereafter referred to as "upflows") have shown that (1) they are emanated from the edge of active region core, (2) they are observed in emission lines from Fe XI–XV ($\log T = 6.2 - 6.4$), (3) the duration of them is up to $\sim$ days, and (4) emission line profiles consist of main component almost at the rest and minor component in the blue wing ($\geq 50\,\mathrm{km\,s^{-1}}$). Several mechanisms which produce these upflows were proposed so far: impulsive heating, active region expansion, interchange reconnection, etc. However, we have not determined which mechanism does work. Physical quantities like electron density of upflows are possible clue to understand the nature of these upflows.

In this study, we derived the electron density of upflows for the first time at the edge of AR10978 using density-sensitive line pair of Fe XIV 264.78/274.20. Upflow component was extracted by double Gaussian function consistently fitted to two emission lines (*i.e.*, corresponding component in two emission lines has the same Doppler shift). Density diagnostics for each component show that the electron density of the upflows is $10^{8.7\pm0.3}$ while that of rest component is $10^{9.2\pm0.1}$. In addition, emission lines of various temperature from Si VII to Fe XV ($\log T = 5.8 - 6.4$) are all blueshifted (*i.e.*, upflow) at the analyzed region. These results indicate that the observed upflows may not be caused by the impulsive heating which produces the hot and dense upflow from the transition region into the corona, followed by the downflow observed for cooler lines. Other mechanism is needed to satisfy the observed properties.

HXR observations of non-flaring active regions and coronal loops (invited)

Iain Hannah
University of Glasgow

The hard X-ray signatures from active region flares of all magnitudes (from X-class down to A) indicate that electron acceleration is core element of flare physics. Active regions contain hot loops even when no flares are detected (down to current observational limits) so are flare-like processes, involving accelerated particles, heating these loops? I will review the current state of HXR observations of non-flaring coronal loops and active regions as well as possible future advances.

Session 2

Diagnostic tools: DEMs/EM, Doppler-shifts, plasma, flows and lines profile, importance of energetic particles, filling factor

Posters

S2-1: Collisional ionization equilibrium for the Kappa-distributions in the solar corona

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We calculate collisional ionization equilibrium for all elements from H to Zn under the assumption of kappa-distributions. These distributions are characterized by an enhanced supra-thermal tail and a nearly Maxwellian core, and have been detected in the solar transition region and the solar wind. The kappa-distributions widen and flatten the ionization peaks, leading to larger temperature intervals for formation of individual ions. The ionization peaks are shifted to lower or higher temperatures as well. Most notably, the Fe VIII - XIV ions are affected, with possible consequences for reinterpretation of the coronal observations.

S2-2: The kappa-distributions and DEM analysis

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We investigate the influence of the non-Maxwellian kappa-distributions on the differential emission measure (DEM) of the active region core in AR 11089 observed by Hinode/EIS on 23 July 2010. The DEM was calculated using the regularized inversion method of Hannah & Kontar (2012). In general, the kappa-distributions widen contribution functions for individual spectral lines. This behavior is reflected in the reconstructed DEMs, which can be more multithermal for the kappa-distributions. We discuss the implications of these changes in DEM with the kappa-distributions for the physics of active region corona.

S2-3: Magnetic and thermal acceleration in the Extreme-Ultraviolet jet

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We have studied the relationship between the velocity and temperature of a solar EUV jet. The highly accelerated jet occurred in the active region NOAA 10960 on 2007 June 5. Multi-wavelength spectral observations with EIS/*Hinode* allow us to investigate Doppler velocities at the wide temperature range. We analyzed the three-dimensional angle of the jet from the stereoscopic analysis with *STEREO*. Using this angle and Doppler velocity, we derived the true velocity of the jet. As a result, we found that the cool jet observed with He II 256 Å $\log_{10} T_e[\mathrm{K}] = 4.9$ is accelerated to around 20 $\mathrm{km\,s^{-1}}$ which is over the upper limit of the chromospheric evaporation. On the other hand, the velocities observed with hot lines have temperature dependence and are under the upper limit of the chromospheric evaporation. We consider the two types of the acceleration, i.e., the magnetic acceleration by the magnetic reconnection and the thermal acceleration by the chromospheric evaporation. Our interpretation of observational results is that cool plasma is accelerated by the magnetic force and hot plasma is accelerated by the chromospheric evaporation. In other words, the magnetic acceleration and thermal acceleration occur simultaneously.

S2-4: Off-limb thermal structure of AR 11459

Susanna Parenti
Royal Observatory of Belgium, STCE

Fabio Reale [1], Paola Testa [2], Helen Mason [3]
[1] University of Palermo,
[2] Harvard-Smithsonian Center for Astrophysics,
[3] University of Cambridge

The thermal structure of active regions and loops are one important element needed to characterize the way these structures are heated. In particular, in recent years much attention has been devoted to identify the properties of the high temperature component (> 3 MK) of the plasma seen during non-flaring conditions. This, in fact, is the observational aspect predicted by impulsive heating models which is not expected to be seen when the steady heating is at work. We present preliminary results of an investigation aiming at characterizing the thermal structure of AR 11459 under non-flaring conditions. The AR was observed at the west limb using the Hinode/EIS instrument and the data covers the temperature range up to about 8 MK.

S2-5: Comparative analysis of emission measure in an active region: hot vs cool components

Antonino Petralia
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Recent analysis has revealed the presence of minor but very hot plasma (6–8 MK) components in active regions, which may be signature of nanoflaring activity in coronal loops. The evidence consists mainly of highly ionized line emission (e.g. Fe XVIII, Ca XVII) observed with Hinode/EIS and of emission in channels of imaging instruments including such hot lines. The question is to assess tighter constraints to the temperature of such hot components. Important information comes from the global analysis of EUV spectra, from which we are able to reconstruct the temperature distribution of the emission measure along the line of sight. Here we report on the reconstruction of the emission measure in an active region where previous work had revealed the presence of the hot component. Our approach is to use a limited but carefully selected set of lines, in particular only one strong and well-identified line with peak formation temperature in each temperature bin, and to minimize the emission uncertainty. This allows us a very strong control on the emission measure reconstruction. We use the MCMC reconstruction method, and apply it to two selected zones of the active region, one including the hot component and one not including it. We find very different emission measure distributions and, through the comparison between them and with the aid of images, we are able to provide constraints on the emission measure reconstruction and on the different emission measure components. We also assess the importance of including spectral information from narrowband EUV channels (SDO/AIA) and from X-ray filterbands (Hinode/XRT). The analysis seems to confirm the possible presence of a very hot tail of the emission measure distribution, but the result may still not be conclusive.

S2-6: Thermal X-ray emission in kink-unstable coronal loops

Rui Pinto
LESIA, Observatoire de Paris

Nicole Vilmer
LESIA, Observatoire de Paris

We study the temporal evolution of the thermal X-ray emission on kink-unstable coronal loops based on a series of MHD numerical simulations. The numerical setup used consists of a highly twisted loop embedded in a region of uniform and untwisted background coronal magnetic field. Magnetic reconnexion occurs continuously near the flux-rope's boundaries, heating up the plasma there. The density, temperature and X-ray emissivity evolve in time as the kink instability proceeds and the loops relax to a lower energy state.

S2-7: Red and blueshifts in multistranded coronal loops

Stephane Regnier
University of Central Lancashire

Robert Walsh
University of Central Lancashire

Coronal loops have been termed the building blocks of the solar atmosphere. However, it must be recognised that if the range of loop structures we can observe do consist of many "sub-resolution" elements, then current one-dimensional hydrodynamic models are really only applicable to an individual plasma element or strand. Thus a loop should be viewed is an amalgamation of these strands. They could operate in thermal isolation from one another with a wide range of temperatures occurring across the structural elements. This scenario could occur when the energy release mechanism consists of localised, discrete bursts of energy that are due to small-scale reconnection sites within the coronal magnetic field – the nanoflare coronal heating mechanism. These energy bursts occur in a time-dependent manner, distributed along the loop/strand length, giving a heating function that depends on space and time. An important observational discovery with the Hinode/EIS spectrometer is the existence of red and blue-shifts in coronal loops depending on the location of the footpoints (inner or outer parts of the active region), and the temperature of the emission line in which the Doppler shifts are measured. Based on the multi-stranded model developed by Sarkar and Walsh (2008, ApJ, 683, 516), we show that red and blue-shifts exist in different simulated Hinode/EIS passbands: cooler lines (O V-Si VII) being dominated by red-shifts, whilst hotter lines (Fe XV-Ca XVII) are a combination of both. The distribution of blue-shifts depends on the energy input and not so much on the heating location. Characteristic Doppler shifts generated fit well with observed values. We also simulate the Hinode/EIS rasters to closely compare our simulation with the observations. We extend this study to IRIS and Solar Orbiter/SPICE spectrometers.

S2-8: Absolute measurement of spectral fluxes using simultaneous EIT/SOHO and SPIRIT/CORONAS-F data

Sergey Shestov
Lebedev Physical Institute

Anton Reva, Sergey Kuzin
Lebedev Physical Institute

We present results of absolute measurements of spectral fluxes in the EUV spectral range using simultaneous data from EUV telescope EIT/SOHO and EUV spectroheliograph SPIRIT/CORONAS-F. The 1^{st} level EIT images are given in units DN and can be expressed as a convolution of EIT spectral response function and actual spectral flux. The SPIRIT spectroheliograph, whereas have no absolute calibration, provides information on spectral composition of the flux. Using simultaneous data of EIT and SPIRIT allows us to calculate absolute fluxes in particular spectral lines and ultimately, convert both EIT and SPIRIT data into physical units $\mathrm{erg\,s^{-1}\,cm^{-2}}$. We performed an analysis of simultaneous EIT and SPIRIT data. The obtained calibration of SPIRIT allows to measure absolute spectral fluxes of several large solar flares, observed by SPIRIT. The analysis can be extended to measuring fluxes produced by active regions (and other bright structures) with spectral resolution provided by SPIRIT.

S2-9: Forward modelling of coronal loop emission

Tom Van Doorsselaere
KU Leuven

Patrick Antolin, Veronika Reznikova
KU Leuven

At the KU Leuven, we have implemented a code for the efficient forward modelling of coronal emission. Currently, the code can calculate line emission, emission in temperature-based filters, and gyrosynchrotron (radio) emission. This opens up possibilities of quantitative comparison between 3D coronal loop models and observations. The capabilities and restrictions of this code will be highlighted in this talk. As a proof of concept, we have computed the line and gyrosynchrotron emission from a cylinder oscillating with a sausage mode. The results of this study will be briefly presented as an example.

S2-10: Cross-sectional properties of coronal loops

Matthew West
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Andrei Zhukov [1], James Klimchuk [2]
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In this work we assess if coronal loop cross sections observed in EUV images are symmetrical or asymmetrical in nature. To do this, we identified individual loop structures observed in EUV images taken with the EUVI instruments on the STEREO satellites. To image loops from two unique angles, we chose loops clearly discernible in both EUVI imagers during the period when the satellites were separated by approximately 90 degrees, allowing us to make observations of individual loops from two unique vantage points. Preference was given to loops which could be clearly identified in both satellites, especially those which were not crossed by other bright structures or loops, so reasonable background subtractions could be made. Once identified, the images were co-aligned and straightened, using a spline routine, for comparison. In total we identified 11 clearly discernible loops and derived the standard deviation and widths for both perspectives of the loop. It was found that within instrumental errors the loops can be considered circular in nature.

S2-11: The importance of nonthermal particles in coronal phenomena

Henry Winter III
Smithsonian Astrophysical Observatory

Nicholas A. Murphy, Katharine K. Reeves
Smithsonian Astrophysical Observatory

The energetics of the solar corona is a subject of intense study within the solar physics community. Coronal loops constitute the primary structural component of the corona. In order to evaluate theoretical models of loop formation and evolution, much software has been developed to numerically simulate coronal loops. The HyLoop code is a suite of software that combines a magnetohydrodynamic (MHD) equation solver with nonthermal particle tracking codes, allowing for the simulation of both the thermal and nonthermal components of the plasma (as opposed to treating nonthermal particles analytically, or assuming a static atmosphere). In this study a series of loops undergoing nanoflare heating were simulated. Each nanoflare had a thermal and nonthermal component. Physical parameters, such as tapering of the magnetic field, loop length, etc. were varied and statistical analyses were applied to examine how these parameters correlated with observable properties of the loop, such as maximum temperature and density at the loop apex. Synthetic XRT images of the loops were also created, highlighting HyLoop's capacity to connect theory and observation. We also discuss the role of nonthermal particles in other coronal phenomena, such as CME fronts, and discuss preliminary modeling efforts of these phenomena.

Session 3

Connection of the different layers of the atmosphere

Oral presentations

Modeling the energetics and dynamics of the outer solar atmosphere (invited)

Viggo Hansteen
Institute of Theoretical Astrophysics

A number of increasingly sophisticated numerical simulations spanning the convection zone to corona have shed considerable light on the workings of the solar chromosphere, transition region and corona. This includes the importance of the magnetic field for heating and the interplay between waves and the structure of the chromospheric plasma. Complementing the numerical models, high cadence temporal and high resolution spatial observations, both space based and on the ground, are changing and challenging previously held views. In this talk we will discuss the interplay between simulations and observations with special attention on the IRIS satellite, due to be launched during the meeting.

Asymmetries in coronal emission lines and their emission measure

Durgesh Tripathi
IUCAA, Pune

James A. Klimchuk
NASA, GSFC, Washington DC

We have studied Red-Blue Asymmetries (RBAs) in two different moss regions located in an active region using different spectral lines forming across a range of temperatures. Since there are different methods proposed in the literature for determining the RBAs, we have first used Fe XIII 202 (one of the cleanest line) for benchmark purpose. It was realised that these methods have some drawbacks. A new method was developed by Klimchuk et al. (2013) to overcome these drawbacks and determine the asymmetries. Using this method RBAs are very small and most of the time negative, suggesting red-wing enhancement over blue-wing. There are no systematic patterns to our measurements. In order to study long term variations and any effect of line-of-sight geometry, we have tracked a moss region from centre-to-limb. The results did not show any systematic trend. These results led us to conclude that the amount of fast upflowing material is either negligible or very small at all of the observed temperatures.

A coupled model for the formation of active region corona

Feng Chen
Max Planck Institute for Solar System Research

Hardi Peter [1], Sven Bingert [1], Robert Cameron [1], Manfred Schüssler [1], Mark C. M. Cheung [2]
[1] Max Planck Institute for Solar System Research,
[2] Lockheed Martin Solar and Astrophysics Laboratory

We will present the first model that couples the formation of an active region corona to a model of the emergence. This allows us to study when, where, and why active region loops form, and how they evolve. For this we use an existing 3D radiation MHD model of the emergence of an active region through the upper convection zone and the photosphere as a lower boundary for a coronal model. Our 3D MHD coronal model accounts for the braiding of the magnetic field lines that induces currents in the corona that is getting filled with the emerging magnetic field. Starting with a basically field-free atmosphere we follow the flux emergence until numerous individually identifiable hot coronal loops have been formed. The temperatures in the coronal loops of well above 1 MK are reached at densities corresponding to actually observed active region loops. The loops develop over a very short time period of the order of several minutes through the evaporation of material from the chromosphere. Because we have full access to the heating rate as a function of time and space in our computational domain, we will try to determine the conditions under which these loops form.

Multidimensional modeling of coronal rain dynamics

Xia Fang
Centre for mathematical Plasma Astrophysics

Xia Chun, Rony Keppens
Centre for mathematical Plasma Astrophysics

We present the first multidimensional, magnetohydrodynamic simulations which capture the initial formation and the long-term sustainment of the enigmatic coronal rain phenomenon. We demonstrate how thermal instability and catastrophic cooling can induce a spectacular display of in-situ forming blob-like condensations which then start their intimate dynamical ballet on top of initially linear force-free arcades above photospheric neutral lines. Our magnetic arcades host chromospheric, transition region, and coronal plasma, and by following coronal rain dynamics for over 80 minutes physical time, we collect enough statistics to quantify blob widths, lengths, velocity distributions, and other characteristics which directly match with modern observational knowledge. Our virtual coronal rain displays the deformation of blobs into V-shaped like features, interactions of blobs due to mostly pressure-mediated levitations, and gives the first views on blobs which evaporate in situ, or get siphoned over the apex of the background arcade. Our simulations pave the way for systematic surveys of coronal rain showers in true multidimensional settings, to connect parametrized heating prescriptions with rain statistics, ultimately allowing to quantify the coronal heating input.

Session 3

Connection of the different layers of the atmosphere

Posters

S3-1: Non-existence of a cut-off frequency for the propagation of kink-modes on a stratified tube

Jesse Andries
Royal Observatory of Belgium, STCE

We recently (Andries and Cally, ApJ, 743, 164, 2011) provided a fairly general analytic theory for the dispersion and scattering of magnetohydrodynamic waves by longitudinally stratified flux tubes. The theory provides a common framework for, and synthesis of, many previous studies of flux tube oscillations that were carried out under various simplifying assumptions. In particular we illustrated the unifying theoretical framework underlying both the description of waves scattered by flux tubes and the dispersion of waves carried along flux tubes. In the present contribution we will investigate in more detail the propagation of the kink-mode on a slender flux tube in a stratified atmosphere. Spruit (A&A, 98, 155-160, 1981) has studied this situation before and discussed both the appearance of 'buoyancy' terms in the kink-mode and the reduction to a Klein-Gordon equation in the case of an isothermally stratified medium with the associated cut-off frequency preventing the propagation of kink modes towards the corona for low frequencies. We show in convincing detail why the derivation by Spruit (1983) is erroneous and conclude that there is no cut-off frequency for the vertical propagation of kink-modes along a flux tube. The non-existence of the cut-off frequency implies that, regardless of the frequency, kink-modes may propagate along a flux tube from the photosphere towards the corona. How much of the energy is effectively transmitted into the corona, however, remains subject of further study.

S3-2: Evolution of the global temperature structure of the corona during the minimum between solar cycles 23 and 24

Richard Frazin
University of Michigan

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The combination of Differential Emission Measure Tomography (DEMT) with extrapolation of the photospheric magnetic field allows determination of the electron density and electron temperature along individual magnetic field lines. This is especially useful in quiet Sun (QS) plasmas where individual loops cannot otherwise be identified. In Paper I (Huang et al., 2012), this approach was applied to study QS plasmas during Carrington rotation (CR) 2077, at the minimum between solar cycles (SC)-23 and 24. In that work, two types of quiet QS coronal loops were identified: "up" loops in which the temperature increases with height, and "down" loops in which the temperature decreases with height. While the first ones were expected, the latter ones were a surprise and, furthermore, were found to be ubiquitous in the low-latitude corona. In the present work we extend the analysis to 11 CRs around the last solar minimum. We find that the "down" population, always located at low-latitudes, was maximum at the time when the sunspot number was minimum, and the number of down loops systematically increased during the declining phase of SC-23 and diminished during the rising phase of SC-24. Down loops are found to have systematically larger values of β than do up loops. These discoveries are interpreted in terms of excitation of Alfvén waves in the photosphere, and mode conversion and damping in the low corona.

S3-3: Very high resolution structures of an active region: moss cells and filament channels

Serge Koutchmy
Institut d'Astrophysique de Paris- CNRS & UPMC

Leon Golub [1] and Ehsan Tavabi [2]
[1] Smithsonian Institution CFA Cambridge (USA),
[2] Payame Noor Univ. Zanjan (IR Iran)

The best ever resolution of a coronal image was obtained recently during the sounding rocket flight of the Hi-C experiment in 2012 (Cirtain et al. 2013) taking images with a 193 Å Fe XII filter. A rather large portion of the Sun was observed around an active region of the South hemisphere, near the central meridian. Although the pixel size permits a theoretical resolution of 0.2″, as usual the effective resolution is limited by the Signal/Noise ratio. By summing images some improvement can be reached in the visualization of the finest scale features, at the expense of the details of the temporal variations. This is true for quasi-stationary phenomena like confined flows and cell like structures. In addition we used the so-called Madmax algorithm to enhance these features with a presumably coherent spatial behavior. The result from using the processing of 27 frames put together and printed at a poster scale is striking. In particular we pay attention to:

- The cell structure appearing in plage regions called in the past "moss".
- The filament channels with evidence of twisted structure.
- Very fine and extended threads overlying the background.

In addition we substantiate the findings using the magnetic field maps and AIA full disk images from SDO as well as the ground-based observations of much lower resolution.

S3-4: 3D reconstruction of a sigmoidal active region

Marilena Mierla
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A transient sigmoid was observed on 1 January 2009 by XRT on Hinode. Sigmoids are S-shaped structures found in the solar corona (mostly observed in X-ray images). It is known that active regions with sigmoidal morphology are more likely to be eruptive than non-sigmoidal regions. This is why it is important to know the morphology of such structures. Images of the cooler corona from EUVI on STEREO and EIT on SOHO show the loops that overlie the sigmoid for our event. We applied the triangulation method to these features in order to understand the three-dimensional configuration of the the whole region. We used images of the sigmoid region observed from three viewpoints, each separated from each other by 45 degrees. We will present the difficulties in identifying the same features from the three different viewpoints, and also the advantages of multiple spacecraft observations in studying the complexity of such phenomena.

S3-5: MHD modeling of chromospheric flows injected in coronal loops

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[3] NASA Goddard Space Flight Center, USA

It has been recently remarked the possible importance of chromospheric flows for the structure, dynamics and heating of coronal loops. We use a complete MHD model to simulate the injection of a flow from the chromosphere upwards into a coronal loop. The model includes hydrodynamics, thermal conduction, radiative losses and the interaction with an ambient uniform magnetic field. The geometry is 2D cylindrical. The initial speed of the flow is 150 km/s and the density is about 10^{12} cm^{-3}. The flow moves in a coronal magnetic field of a few G. We show the evolution of the flow inside the loop. A 1 MK shock front develops ahead of the flow.

S3-6: Investigation of macrospicules with TESIS/CORONAS-PHOTON EUV telescope

Anton Reva
Lebedev Physical Institute

Sergey Bogachev, Sergey Kuzin
Lebedev Physical Insitute

Macrospicules are small ejections of cool and dense transition region material, which propagate into the corona along magnetic field lines. In TESIS experiment on CORONAS-PHOTON satellite EUV telescope made a series of observation with 3 seconds cadence in 304 Å line. These observations were aimed for investigation of macrospicules. We developed a method of macrospicule velocity diagnostic: the method analyses variations of macrospicule intensity on different altitudes. For 10 macrospicules we measured their velocities on different altitudes.

Macrospicule height is approximately 40 Mm, initial velocity is about 100-200 km/s, and lifetime is about 15 minutes. Observed maximum height of macrospicule is higher than the ballistic height. This means that during macrospicule lifetime some driving force affects macrospicule, and moves it higher than the ballistic height.

S3-7: Solar low-lying cool loops

Clementina Sasso
Inaf-Oac

Vincenzo Andretta [1], Daniele Spadaro [2]
[1] Inaf-Oac,
[2] Inaf-Oact

In the last 30 years, the existence of small and cool magnetic loops has been proposed and debated to explain the increase of the DEM (differential emisson measure) towards the chromosphere. In a previous paper (Sasso et al., 2012), we analysed the general properties of quasi-static cool loops and their conditions of stability and existence showing that stable low-lying cool loops can be obtained through hydrodynamic simulations, also under different and more realistic assumptions on the optically thin radiative losses function with respect to previous works (e.g., Antiochos & Noci 1986, Cally & Robb 1991). In particular, we obtain static cool loops, even for a set of parameters that would prevent the formation of rigorously static loops. In this current work, we decided to explore the effect on the structure and stability of cool loops of a more realistic treatment of hydrogen radiation losses in the lower TR, since the shape of the radiative loss function below 10^5 K is very important for the existence of cool loops. We introduced a new optically thick radiative losses function from the work of Kuin & Poland (1991) and start to analyse the first results. We are able to obtain stable cool loops but the work is still in progress, since we need to explore the whole parameters' space (temperature and pressure).

S3-8: Peristaltic pumping in post-CME supra-arcade current sheets

Roger Scott
Montana State University

Dana Longcope, David McKenzie
Montana State University

Measurements of temperature and density near supra-arcade current sheets suggest that plasma on unreconnected field lines may experience some degree of pre-heating and pre-densification prior to their reconnection. Models of patchy reconnection allow for heating and acceleration of plasma along reconnected field lines but do not offer a mechanism for transport of energy and momentum across field lines. Here we present a model in which a reconnected flux tube retracts, deforming the surrounding layer of unreconnected field. The deformation creates constrictions that act as peristaltic pumps, driving plasma flow along affected field lines. Under certain circumstances these flows lead to shocks that can extend far out into the unreconnected field, altering the plasma properties in the affected region. The shocks may even propagate down to the chromosphere, destabilizing the local thermal equilibrium and driving evaporation, which could subsequently leads to elevated densities and temperatures in the unreconnected coronal magnetic field. These findings have direct implications for observations in the solar corona, particularly in regard to such phenomena as wakes seen behind supra-arcade downflows and high temperatures near current sheets in eruptive solar flares.

S3-9: A model of the chromosphere: heating, structures, and circulation

Paul Song
UMASS Lowell

Vytenis Vasyliunas
Max-Plank Institute

We propose a model of local circulation in the chromosphere, with scale size of supergranules. The strong heating required in order to balance the radiative losses in the chromosphere is provided by strong damping, through plasma-neutral collisions, of Alfvén waves that are driven by motions below the photosphere. On the basis of a self-consistent plasma-neutral electromagnetic one-dimensional model, we derive the vertical profile of wave spectrum and power by a novel method, including the damping effect neglected in previous treatments. The high-frequency portion of the source power spectrum is strongly damped at lower altitudes, whereas the lower-frequency perturbations are nearly undamped and can be observed in the corona and above. As a result, the waves observed above the corona constitute only a fraction of those at the photosphere and, contrary to supposition in some earlier Alfvén-wave-damping models, their power does not represent the energy input. Calculated from parameters of a semi-empirical model for quiet-Sun conditions, the mechanism can generate sufficient heat to account for the radiative losses in the atmosphere, with most of the heat deposited at lower altitudes. When the magnetic field strength varies horizontally, the heating is likewise horizontally nonuniform. Since radiative loss is a strong function of temperature, the equilibrium temperature corresponding to local thermal balance between heating and radiation can be reached rapidly. Regions of stronger heating thus maintain higher temperatures and vice versa. The resulting uneven distribution of temperature drives chromospheric circulation, which produces a temperature minimum in the chromosphere near 600 km altitude and distorts the magnetic field to create a funnel-canopy-shaped magnetic geometry, with a strong field highly concentrated into small areas in the lower chromosphere and a relatively uniform field in the upper chromosphere. The formation of the transition region, corona, and spicules will be discussed.

Session 4

Energy release in the corona: frequency and magnitude of events

Oral presentations

Recent advances in theory and modelling of coronal wave heating (invited)

Ineke De Moortel
University of St Andrews

Pascoe, D.J., Hood, A.W., Wright, A.N.
University of St Andrews

In this talk I will give an overview of current modelling of MHD waves and oscillations, emphasising in particular the process of mode coupling. Can models predict the observed damping rates and energy flux? How reliable are the comparisons between theory and observations? As observations of waves and oscillations become increasingly more detailed, it has become clear that the role of wave heating of the solar atmosphere has to be reassessed. I will highlight some of the recent modelling results as well as try to outline where future efforts are needed.

Statistical analysis of several hours period intensity pulsations in the solar corona over cycle 23 and possible interpretations

Frédéric Auchère
IAS

Karine Bocchialini, Jacques Solomon, Emmanuelle Tison
IAS

We systematically searched for long period intensity pulsations in the whole solar corona using 19.5 nm SOHO/EIT observations from January 1997 to July 2010, i.e the entire solar cycle 23 and the beginning of cycle 24. We did not focus on any particular area or type of structures. We detected 233 events (10 σ detections) whose periods range between 5 and 17 hours with a first maximum around 8 hours and a second maximum around 15 hours. Sixty percent of the pulsations are localized in coronal structures associated with active regions and last several tens of hours. We performed a comprehensive analysis of the possible instrumental artefacts and conclude that the observed signal is of solar origin. We discuss various hypotheses which could explain the behaviour of these pulsations. Neither oscillations due to MHD waves nor condensation cycles in a thermal nonequilibrium process seem able to provide a likely explanation of our observations. We suggest that moderate temporal variations of the heating term in the energy equation, such that one avoids thermal nonequilibrium, could be sufficient to explain those long period intensity pulsations.

Seismological determination of the physical parameters that govern wave dissipation time and spatial scales

Inigo Arregui
Instituto de Astrofisica de Canarias

Andres Asensio Ramos [1], David J. Pascoe [2]
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To quantify the role of wave dissipation in coronal loop plasma heating processes requires the determination of the cross-field density structuring of magnetic waveguides. Nowadays, seismology inversion techniques are unable to fully determine the density contrast and its transverse inhomogeneity length scale. However, recent analyses of the spatial damping of propagating MHD kink waves show the existence of two separate damping regimes for the wave amplitude decay. In this work, we explain how the observational identification of those regimes and the measurement of the associated damping length scales can be used to fully constrain the cross-field density structuring. Our parameter inference is performed in the Bayesian framework, to accommodate a proper propagation of uncertainty. The obtained parameters determine the ideal damping stage, but more importantly, the time and spatial scales that govern the wave energy dissipation and the consequent plasma heating.

A self-consistent model of Alfvén wave phase mixing

Greg Kiddie
University of St Andrews

Ineke De Moortel [1], Peter Cargill [1,2], Alan Hood [1]
[1] University of St Andrews,
[2] Imperial College London

In this work we investigate a basic phase-mixing model which incorporates the mass exchange between the corona and the chromosphere. We use numerical simulations to model Alfvén waves in a low β plasma with a uniform magnetic field, where phase mixing is introduced through a density inhomogeneity. Chromospheric evaporation is approximated by using scaling laws relating heating (by phase mixing of Alfvén waves), density and temperature. By combining this scaling law with our numerical MHD model for phase mixing of Alfvén waves, we investigate the modification of the density profile through the mass upflow. We find a rapid modification of the density profile, leading to drifting of the heating layers.

Toward self-consistent 3D MHD modeling of the heating of a twisted coronal loop

Fabio Reale
University of Palermo, Italy

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[3] University of Turin, Italy,
[4] University of Palermo, Italy

The details of the conversion of magnetic energy into heating is a major topic of solar coronal physics. We investigate a scenario where the energy is obtained from the progressive stressing of the magnetic field lines driven by the motion of the photospheric granulation. The magnetic field is stressed by the progressive twisting due to the rotation of the loop footpoints. Above a certain threshold the magnetic field lines reconnect into less stressed configurations. Turbulent diffusivity triggers a highly non-linear dissipation of the magnetic field into heat. The dissipation destroys the cross-component of the magnetic field as rapidly as it is produced by the motion of the footpoints, reaching a steady state. We model a region including a single coronal loop, described as a straight magnetic flux tube linking two chromospheric layers. The loop model accounts for the reduction of beta and the consequent expansion of the magnetic flux tubes from the chromosphere to the corona. The plasma and magnetic field evolution is described by solving the full 3-D MHD plasma equations including gravity, ohmic and optically thin plasma radiative losses, anisotropic thermal conduction. The thin chromosphere/corona transition region is accurately described with high spatial resolution, down to ≈ 20 km. We present preliminary simulation results that show nearly self-consistent heating and brightening of a coronal loop.

The heating of solar coronal loops (invited)

Adriaan van Ballegooijen
Harvard-Smithsonian Center for Astrophysics

It is generally assumed that the energy for coronal heating originates from interactions of convective flows with kilogauss flux elements in the photosphere, but it is unclear exactly how the energy propagates into the corona and how it is dissipated. Observations of the Sun's corona have not yet advanced to the point where we can clearly identify the physical mechanisms involved in coronal heating. Active region loops have high heating rates and large turbulent velocities (≈40 km/s), but the magnetic field in these loops does not appear to be strongly braided (misalignment angles are only a few degrees). This suggests that much of the action of coronal heating takes place on transverse scales less than 1 Mm, which are presently unresolved. In this talk I review recent advances in modeling coronal heating and its observable consequences. Different scenarios for coronal heating are presented, and the roles of magnetic braiding, waves and turbulence are discussed. 3D MHD models of coronal loops provide predictions of observable quantities: time-averaged heating rates, spatial and temporal variability of the heating, frequency and magnitude of heating events, non-thermal velocities, etc. To obtain accurate heating rates, it is important that the models include the spreading of the coronal field, which expands significantly from the chromosphere to the loop top. Results from an Alfvén wave turbulence of coronal loops are presented. The model predicts that the heating is highly intermittent with "nanoflares" occurring at different sites along the loop.

Heating frequency in active region cores as observed in AIA Fe XVIII images

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We present a study of the frequency and duration of brightenings in the core of solar active regions as observed in the Fe XVIII line component of AIA/SDO 94 A filter images. The Fe XVIII emission was isolated by removing the “warm” emission contribution using as proxy the emission from the AIA 193 and 171 channels. We examined the evolution of loop in cores of several active regions that span a wide range of total magnetic field strengths and at various stages of evolution. Using a newly developed event detector algorithm we find that the typical frequency of occurrence of detectable brightness enhancements is in the order of 20 minutes. Using EBTEL, a 0D hydrodinamical model, we show that a single loop heated a that frequency would be experiencing effectively steady heating. Then we evaluate different heating scenarios with multiple loops along the line-of-sight. Finally, we report on our preliminary efforts to reproduce those characteristic timescales on full active region models where field lines from a non-linear force free extrapolation are populated with EBTEL solutions.

Can long nanoflare storms or uniform steady heating models match the EIS intensity ratios in active region cores?

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All theories that attempt to explain the heating of high temperature plasma observed in the solar corona are based on short bursts of energy. The intensities and velocities measured in the cores of quiescent active regions, however, can be steady over many hours of observation. One heating scenario that has been proposed is the "long nanoflare storm" where short duration heating events occur "infrequently" on many sub-resolution strands; the intensity of the strands are then averaged together to explain the observed steady structures. We examine the intensities predicted by nanoflare storms by modeling an arcade of strands in an active region core. We explore the term infrequently in the nanoflare storms by modeling several storms with various heating rates and magnitudes until the heating is nearly steady. Comparisons of the predicted EIS intensity ratios (Fe XII/Fe XV and Ca XVII/Ca XIV) with recent observations indicate that a long nanoflare storm with a specific heating rate and magnitude can match these intensities while steady heating predicts EIS intensity ratios that are too low to match observations. Furthermore, this study allows us to quantify the term infrequently as these intensity ratios become nearly constant at heating greater than 5 events per 1000 s.

Combining particle acceleration and coronal heating via data-constrained calculations of nanoflares in coronal loops

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We model nanoflare heating of extrapolated active-region coronal loops via the acceleration of electrons and protons in Harris-type current sheets. The kinetic energy of the accelerated particles is estimated using semi-analytical and test-particle-tracing approaches. Vector magnetograms and photospheric Doppler velocity maps of NOAA active region 09114, recorded by the Imaging Vector Magnetograph (IVM), were used for this analysis. A current-free field extrapolation of the active-region corona was first constructed. The corresponding Poynting fluxes at the footpoints of 5000 extrapolated coronal loops were then calculated. Assuming that reconnecting current sheets develop along these loops, we utilized previous results to estimate the kinetic-energy gain of the accelerated particles and we related this energy to nanoflare heating and macroscopic loop characteristics. Kinetic energies of 0.1 to 8 keV (for electrons) and 0.3 to 470 keV (for protons) were found to cause heating rates ranging from 10^{-6} to 1 $\mathrm{erg\,s^{-1}cm^{-3}}$. Hydrodynamic simulations show that such heating rates can sustain plasma in coronal conditions inside the loops and generate plasma thermal distributions which are consistent with active region observations. We concluded the analysis by computing the form of X-ray spectra generated by the accelerated electrons using the thick target approach that were found to be in agreement with observed X-ray spectra, thus supporting the plausibility of our nanoflare-heating scenario.

Session 4

Energy release in the corona: frequency and magnitude of events

Posters

S4-1: Bayesian inference and model comparison for solar atmospheric seismology

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We present recent results form the application of Bayesian inference and model comparison techniques to solar coronal loop seismology. In the first example, quickly damped transverse coronal loop oscillation data are used to obtain estimates for the density contrast, the transverse inhomogeneity length scale, and the Alfvén speed in the loops. In the second example, we use the detection of multiple mode harmonic kink oscillations in coronal loops to obtain information on coronal density stratification and magnetic field expansion. The inference is based on the measurement of period ratios and their deviation due to the hypotheses of either coronal density stratification and magnetic field expansion of the wave guide. We present the first Bayesian model comparison application in coronal seismology, in which the two models are compared to assess how plausible each one is, given our current state of knowledge. In the last example, the spatial damping of propagating waves and the characteristic damping length scales are used to obtain estimates for the cross-field plasma density variation in oscillating waveguides. The three examples show the great promise of Bayesian analysis for seismology of the solar atmosphere.

S4-2: On the nature of damping of slow magneto-acoustic waves

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Propagating slow waves are often observed in polar plume/inter plume regions and active region fan loops. These waves cause periodic disturbances in intensity and are mostly identified from the alternate slanted ridges in the space-time maps. They are observed to have a range of periodicities from 3 to 30 minutes and are found to be rapidly damped. Thermal conduction, compressive viscosity, opacity effects, and area divergence, are believed to be some of the causes for the decay in wave amplitude. From theoretical modeling, it was found that the thermal conduction is the dominant damping mechanism for these waves and others cause a minimal change in the wave amplitude. Using imaging sequence from AIA/SDO, we construct power maps in different period ranges, by summing the power in the individual range above the 99% significance level and found that the power in the long period range is significant up to comparatively farther distances along the structure. This frequency dependence qualitatively supports the damping of these waves due to thermal conduction. However, the exact quantitative relation is needed to search for additional damping sources, if any present. So, we follow the propagating disturbances with different periodicities propagating along open structures like plume/inter plume regions to find a quantitative dependence of the damping length on frequency of the disturbance. If these disturbances are due to waves, then our analysis indicate a significant contribution from sources other than thermal conduction for the damping of these waves.

S4-3: 10 MK slipping loops in an X-class flare observed by SDO/AIA

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We analyze SDO/AIA observations of an X-class flare in a large active region complex. More than an hour before the flare peak, $\approx$ 10 MK loops appear within the pre-existing sigmoid. These loops are visible only in the SDO/AIA 131 and 94 channels and slip on one end with $\approx$ 10 km/s velocities along the co-developing flare ribbons. The ribbons are seen in all SDO/AIA filters and initially correspond to footpoints of the slipping loops. We use DEM analysis of the AIA data to determine individual contributions to different AIA channels. This analysis confirms that the plasma can be heated up to temperatures corresponding to formation of the Fe XXIV. An expanding 10 MK loop system is observed to be involved in the initiation of a CME, while the active region filament located within the flare ribbons stays intact. We discuss individual slipping events observed in EUV with the radio observations.

S4-4: Sausage oscillations of coronal plasma structures

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The dependence of the period of sausage oscillations of coronal loops on length together with the depth and steepness of the radial profile are determined. We performed a parametric study of linear axisymmetric fast magnetoacoustic (sausage) oscillations of coronal loops modelled as a field aligned low-Beta plasma cylinder with a smooth inhomogeneity of the plasma density in the radial direction. The density decreases smoothly in the radial direction. Sausage oscillations are impulsively excited by a perturbation of the radial velocity, localised at the cylinder axis and with a harmonic dependence on the longitudinal coordinate. The initial perturbation results in either a leaky or a trapped sausage oscillation, depending upon whether the longitudinal wavenumber is smaller or greater than the cutoff value respectively. The period of the sausage oscillation was found to always increase with increasing longitudinal wavelength, with the dependence saturating in the long-wavelength limit. Deeper and steeper radial profiles of the Alfven speed correspond to more efficient trapping of sausage modes: the cutoff value of the wavelength increases with the steepness and the density (or Alfven speed) contrast ratio. In the leaky regime, the period is always longer than the period of a trapped mode of a shorter wavelength in the same cylinder. For shallow density profiles and shorter wavelengths, the period increases with wavelength. In the long-wavelength limit, the period becomes independent of the wavelength and increases with the depth and steepness of the radial profile of the Alfven speed. The same qualitative behaviour was also found for the slab geometry, when this work was adapted for a plasma slab as opposed to a cylinder. These results were also found to have a strong agreement with well established analytical results.

S4-5: Distributions of energy of EUV bright points in the solar corona with SDO/AIA

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To explain the high temperature of the corona, much attention has been paid to the distribution of energy in dissipation events. Indeed, if the power-law slope of the dissipated energy distribution is less than -2, the smallest, unobservable events could be the largest contributors to the total energy dissipation in the corona. Observations in EUV and X-rays have actually shown a distribution of event energies extending over 8 decades, with a slope close to -2, but they remain inconclusive about the precise slope. Furthermore, these results rely on a very crude estimate of the (thermal) energy. On the other hand, more detailed spectroscopic studies of events such as coronal bright points do not provide enough statistical information to derive their total contribution to heating.

In this work we aim at getting a better estimate of the distributions of the energy dissipated in coronal heating events, by detecting EUV brightenings at small spatial and temporal scales in high-cadence (one image every fives minutes during three days) multi-chanel SDO/AIA data (94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 335 Å), and using temperature and emission mesure maps derived from the same data to compute the thermal energy associated to these events. We compare these distributions of event energies obtained by this method with previous results.

S4-6: On the cooling of multistranded coronal loops

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Based on the multistranded 1D hydrodynamic loop model developed by Sarkar and Walsh (2008, ApJ, 683, 516), we study the cooling of coronal loops depending of their input energy. We model a 100 Mm loop with 128 strands heated by random short bursts uniformly distributed along the loop. After an equilibrium state has been reached, we turn off the heating and let the loop cool. We impose to the system three different amounts of input energy: 10^{23}, 10^{24} and 10^{25} erg. We first observe that the coronal loop with the largest amount of energy cools faster than the other loops: when the energy input is increased by a factor 10, the cooling time is decreased by about 500 s. We then simulate the intensity of different coronal SDO/AIA channels to deduce how the cooling can be observed with broad-band imagers. Especially, we determine the ordering of the filters during the cooling process, which depends on the energy input: (i) for 10^{23} erg, there is a single peak for each light curves with the order 335 Å-211 Å-193 Å-94 Å-171 Å-131 Å; (ii) the 94 Å and 131 Å channels are varying the most dramatically when increasing the energy input making the cooling more observable in this channel at the start of the cooling; (iii) the double-peaked shape of the temperature response function is responsible for this behaviour. An iterative solver code was used to measure the DEM distribution of the loop as it cooled. In each energy case, the peak position of the DEM very closely matched the true input temperature of the modelled plasma. The peak change over time also closely matched the cooling rate of each energy scenario suggesting that the DEM method can give accurate information regarding the true temperature and energy distribution of a coronal loop.

S4-7: On Alfvenic waves in thread-spicules

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Aims. Hinode/SOT long series observations of spicules in HCaII line show a remarkable dynamical behavior. It might be nothing else than Helical-Kink (HK) mode propagation or Alfvenic waves propagating inside the substructure of multi-component spicules showing a quasi- coherent behavior.

Methods. We compute 2D velocity maps or proper motion maps using the classical technique based on using FFTs and cross-correlation function, and use a 2^{nd}-order accurate Taylor expansion on highly processed images using the popular Madmax algorithm. The location of the peak of the cross-correlation function is obtained with a sub-pixel accuracy. And compute 3D wavelet analysis for on disk correspondence bright points at boundary of networks to find the source for HK modes.

Results. Obtained result on solar coronal hole spicules show surge-like behavior in support of twisting multi-components spicules. We analyzed several long spicules and found (i) the upward and downward flows are similar for lower and middle levels but the rate of upward motion is slightly larger at high levels, (ii) the shearing motion in left and right directions is also equal at all levels, (iii) the medians of the amplitudes are increasing with heights, (iv) the left and right-hand velocity is also increasing, (v) a larger number of multi-component spicules showing the left and right hand shearing motion occur simultaneously and close to each other that might be understood as twisting threads. The twist number depends of the diameter of the whole component and changes from less than 1 turn for very thin structure to more than 2 or 3 turns for surge-like very broad one and the curvature shape due to the low twist number is similar to the transversal kink mode oscillation along the threads.

S4-8: Multiwavelength dynamics of small-scale structures in the quiet solar corona

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We present a multiwavelength study of image sequences registered with the SDO/AIA instrument in December 2010 and February 2011. We propose a simple technique for diagnostics of major plasma parameters (density and temperature). This method allowed to detect a variety of small flare-like events occurring at high rates in the quiet solar corona. We have determined the thermal energies of these events by an increase of EUV emission measure. The corresponding energies range from 10^{23} to 10^{26} erg and hence the found events can be classified as nanoflares. Basing on a statistical approach we derived the frequency distributions of geometric and physical parameters of these events. The research findings point to an important role of low-energy events in the quiet solar corona and favour the nanoflare scenario for coronal heating.

S4-9: Hot reconnection outflows associated to an X-class flare

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The EUV Imaging Spectrometer (EIS) on board the Hinode Mission found hot and fast outflows associated to an X1.4 flare. This flare started near the disk center (S13W04) at 2012 July 12 15:37 UT. Maximum line of sight velocity reached > 600 km s^{-1} in Fe XXIII and Fe XXIV lines formed at temperature of $T_e > 10^7$ K.

One of the neutral lines ran along the boundary of a transient coronal hole created on the north side of AR11520, and the north flare ribbons showed rapid expanding motion in AIA 1600 Å images. Successive magnetic reconnection is considered to take place along the archade of coronal loops over the neutral line.

Hard X-ray sources seen in the RHESSI images of 25–50 keV energy band were so elongated at this time that the east-end of the sources reached the region of the above activity.

Coronal iron lines ($6 < \log T_e < 6.3$) show downflows ($< +30$ km s^{-1}) at the south legs of arcade, while upflows of -30 to -150 km s^{-1} at the north legs. The density sensitive Fe XIV line ratio (Fe XIV 264.8 Å/274.2 Å) is close to its high density limit; $> 10^{11}$ cm^{-3}.

The Fe XXIII and Fe XIV lines formed at log $T_e \approx 7.1$, on the other hand, show two distinctly separated components in their line profiles: One is almost stationary and the other is blue-shifted. The latter increases its velocity linearly toward the direction of the north, and reaches > 600 km s^{-1} at 20″ north from the apices of the archade loops. The east-west width of this "outflow arcade" is about 20,000 km.

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