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Active Region Studies with SOHO-CDS

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Abstract. A review is given of some active region observations obtained with the Coronal Diagnostic Spectrometer (CDS) onboard the Solar and Heliospheric Observatory (SOHO). The spectroscopic diagnostic capability of CDS allows the determination of physical parameters (electron density, temperature, elemental abundances), in addition to plasma motions. The relationship between transient brightenings in the transition region emission and the underlying magnetic flux is explored. The structure of sigmoidal active regions has been studied with CDS. Chromospheric evaporation has been found in a small flare.

1. Introduction

The Solar and Heliospheric Observatory was launched in December 1995 and has had six very successful years of operation, except for a short hiccup in 1998, when it was lost for a while. SOHO contains a suite of instruments to study the solar interior, solar atmosphere and solar wind. The two main science goals for the instruments observing the solar atmosphere are:

- *How is the Solar Corona Heated?*
- *Where does the Solar Wind Originate?*

2. Spectroscopic Diagnostics and Occam's Razor

Before diving in to the detailed analyses of the SOHO/CDS spectroscopic data, it is useful to consider some philosophical issues raised by Judge and McIntosh (1999), in particular relating to the non-uniqueness of atmospheric modelling. They ask the question: *"How can we use the emitted photons, with simplified models, to extract objectively meaningful information about the emitting plasma?"* Which, roughly translated means: *"What have spectroscopic diagnostics ever done for us?"*. There are three main approaches which can be followed when trying to match theory and observations:

- **Forward Approach**: the best approach is to start with a theory and take it all the way through to compare with the observations. However, where does one start? There are so many competing theories and variables.

- **Inverse Approach**: starting with the observations and working backwards is not ideal. There are problems with uniqueness and uncertainties introduced by errors in both the observations and the atomic data. However, one can still make some substantial progress.
- **Common Sense or Intuition**: (woman's intuition, of course!). It is possible to make a first shot at the physical parameters, constraints and boundary conditions to get in the right ball park.

Delving yet deeper into the realms of philosophy, Judge and McIntosh invoked Occam's Razor (William of Occam, c. 1285 - 1349).

- *Pluralitas non est ponenda sine necessitate.*

Roughly translated this states *Entries should not be multiplied unnecessarily.* For an early authoritative version from Sir Isaac Newton: *"We are to admit no more causes of natural things than such as are both true and sufficient."* or to quote a famous contemporary Cambridge professor, Stephen Hawking: *"It seems better to employ the principle known as Occam's razor and cut out all the features of the theory which cannot be observed"*. To put it in plain English: *when you have two competing theories which make exactly the same predictions, the one that is the simpler is the better.* This seems eminently sensible, as a rule of thumb and a starting point for a common sense approach.

3. The Coronal Diagnostic Spectrometer

Initial results from the CDS instrument are given in Harrison *et al.* (1997) and Mason *et al.* (1997). The CDS Normal Incidence Spectrometer (NIS) covers two wavelength bands, 307–379 Å and 514–632 Å. The full length of the slit projects to around 4' on the Sun, with a spatial resolution along the slit approximately 5". Rasters of size 4' x 4' of the Sun can be produced at each pointing position. The GIS has a stigmatic slit, covering wavelength ranges: 151–221Å, 256–341Å, 393–492Å and 659-785Å. The unique feature of CDS studies is to allow the simultaneous extraction of both spatial and spectral information, thus enabling quantitative spectroscopic diagnostic analyses to be carried out.

A comprehensive review of spectroscopic diagnostics in the VUV for both solar and stellar atmospheres was provided by Mason and Monsignori Fossi (1994). The Coronal Diagnostic Spectrometer provides the opportunity to study spectroscopic diagnostics:

1. Spectral line profiles: flows and non-thermal broadenings
2. Emission measure distributions
3. Electron density and temperature
4. Elemental abundances

This capability combined with the high cadence and high spatial resolution observations from imaging instruments provides a powerful combination.

4. The CHIANTI atomic database

CHIANTI (Dere *et al*, 1997) is a collaboration between the Naval Research Laboratory (Washington DC, USA), the Arcetri Observatory (Firenze, Italy), and Cambridge University (United Kingdom). The database contains the most up-to-date atomic data (energy levels, oscillator strengths and transition probabilities, electron collisional excitation rates, etc). Various software routines for plasma diagnostics are also provided. An important aspect of this project is that the CHIANTI database and related software are freely available and can be incorporated into other analysis packages. Details can be found on the web:

- http://www.damtp.cam.ac.uk/user/astro/chianti/chianti.html

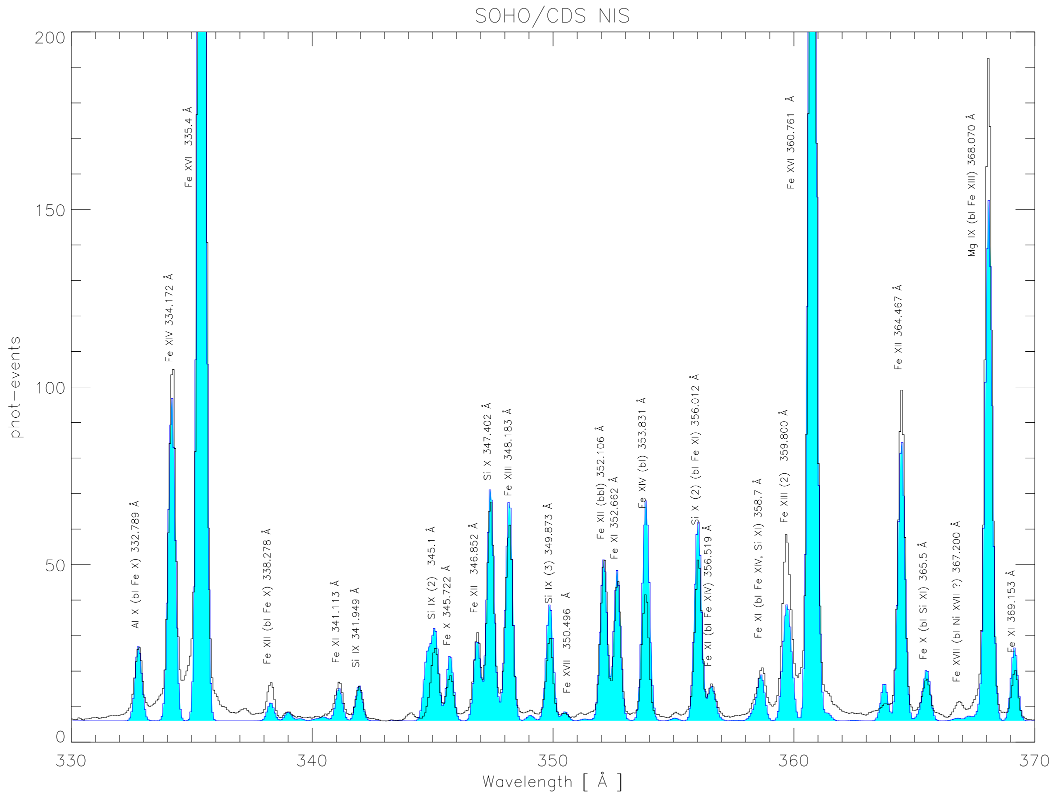

Figure 1. Comparison of CDS and CHIANTI (shaded) spectrum for an active region

The database (CHIANTI version 3) has recently been extended in the 1 - 50 Å wavelength region (Dere et al., 2001). The emission lines from the hydrogen and helium isoelectronic sequences have been included together with innershell transitions and satellite lines. Many other ions have been updated with new atomic data. The comparison of CHIANTI with CDS spectra is excellent (Fig 1).

5. Active Regions: Temperature and Density Structure

An overview of CDS active region observations is given in Fludra *et al.* (1997) and Brekke (1998). Both cool and hot active region loops are seen by CDS high in the corona (Fig 2). Matthews and Harra-Murnion (1997) studied the relationship between the cool structures seen by CDS and the hotter X-ray structures seen by YOHKOH. They found that the cool structures can be found at the same altitude as the hot coronal plasma, but do not seem to be formed by the cooling of the hotter coronal loops (Matthews *et al.*, 1999).

A very interesting and exciting piece of work was carried out by Fletcher and De Pontieu (1999) using both TRACE and CDS observations. They found a coronal feature (10^6 K), which they called 'moss', at the footpoints of hot coronal loops ($\geq 2 \times 10^6$) seen in X-ray emission.

Mason *et al.* (1999) have produced electron density maps of some limb active regions. They find that the densest part of the active region at coronal temperatures is low lying, in the hot core region. This is consistent with work by Falconer *et al.* (1997), who found localised core sites, where the X-ray intensity is persistently brighter than the rest of the active region. These regions are contiguous with strong neutral-line magnetic shear. They inferred that most of the persistent enhanced heating of coronal loops in active regions is controlled by low-lying reconnection accompanying flux cancellation. This manifests itself as X-ray micro-flare activity in the source region.

6. Transition Region Brightenings: Abundance Variations

Short lived brightenings in active regions are frequently observed by CDS in transition region emission (10^5K). Young and Mason (1997) have analysed bright transition region emission in a newly emerging flux region. They determined the relative elemental abundance of magnesium to neon to study the well known FIP effect. They found that two brightenings, only 1' apart, exhibit almost an order of magnitude difference in the Mg/Ne abundance ratio. One region with photospheric abundance and a high electron density seems to be a low lying loop structure, possibly related to emerging flux. The other region with coronal abundance and lower density is at the base of large coronal loop structure. Fletcher *et al.* (2001) find indications that transition region brightenings and elemental abundance variations could be closely related to changes in magnetic topology.

Reviews of elemental abundance studies are provided by Young and Mason (1998) and Mason and Bochsler (1999). A warning is given by Del Zanna *et al.* (2001a, 2001b) that limitations of the analysis method and atomic data can lead to serious errors in elemental abundance determinations. More details can be found in Del Zanna and Mason (2001, this issue).

7. Magnetic Connections: Sigmoids

The sigmoid or 'S-shape' in X-ray emission has been heralded as a precursor to active region eruptions. Gibson *et al* (1999) studied sigmoid features in active regions observed with the CDS. Gibson *et al* (2000, 2001) have carried out

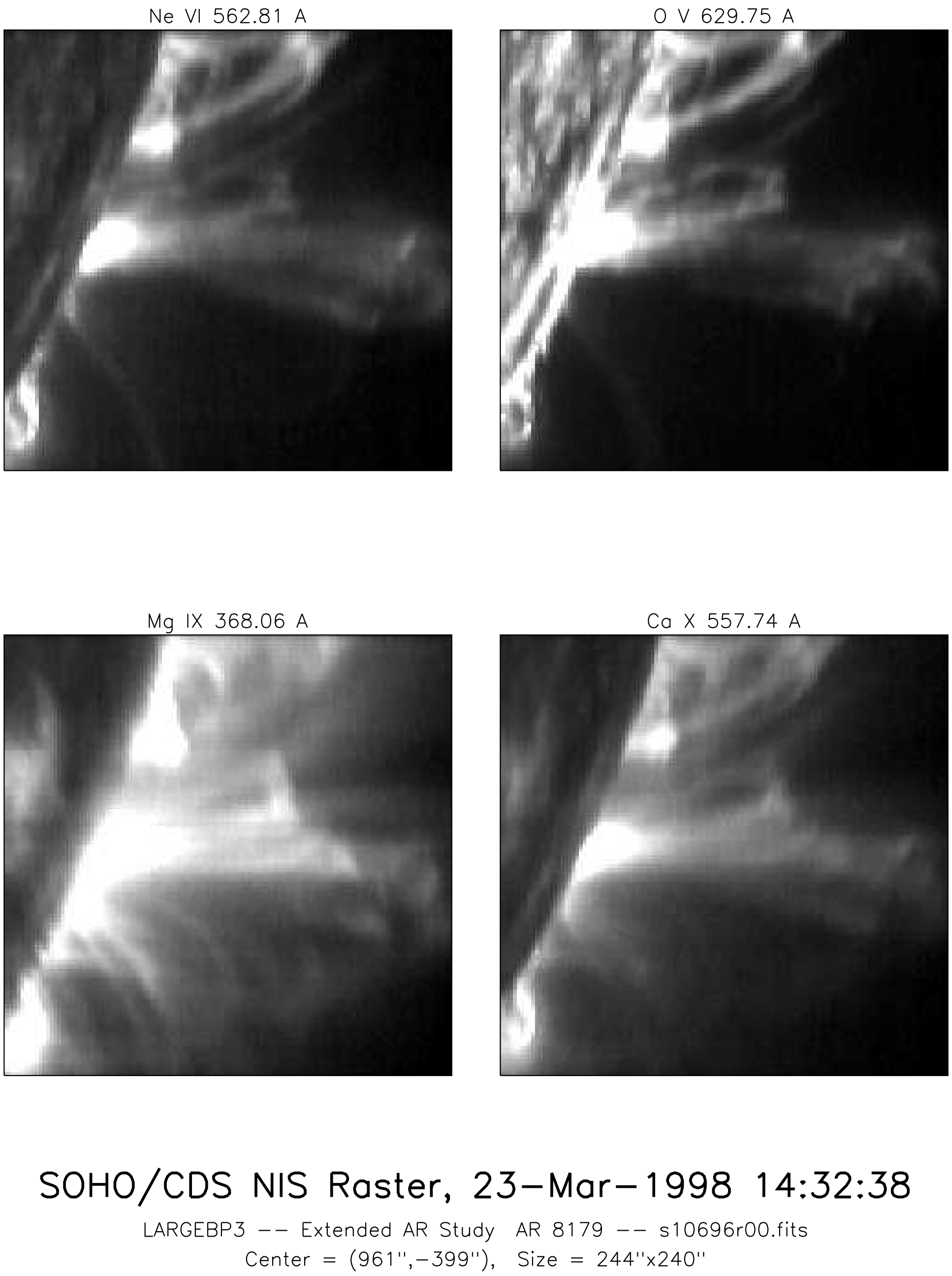

Figure 2. CDS rasters of an active region at the limb, showing cool and hot loops

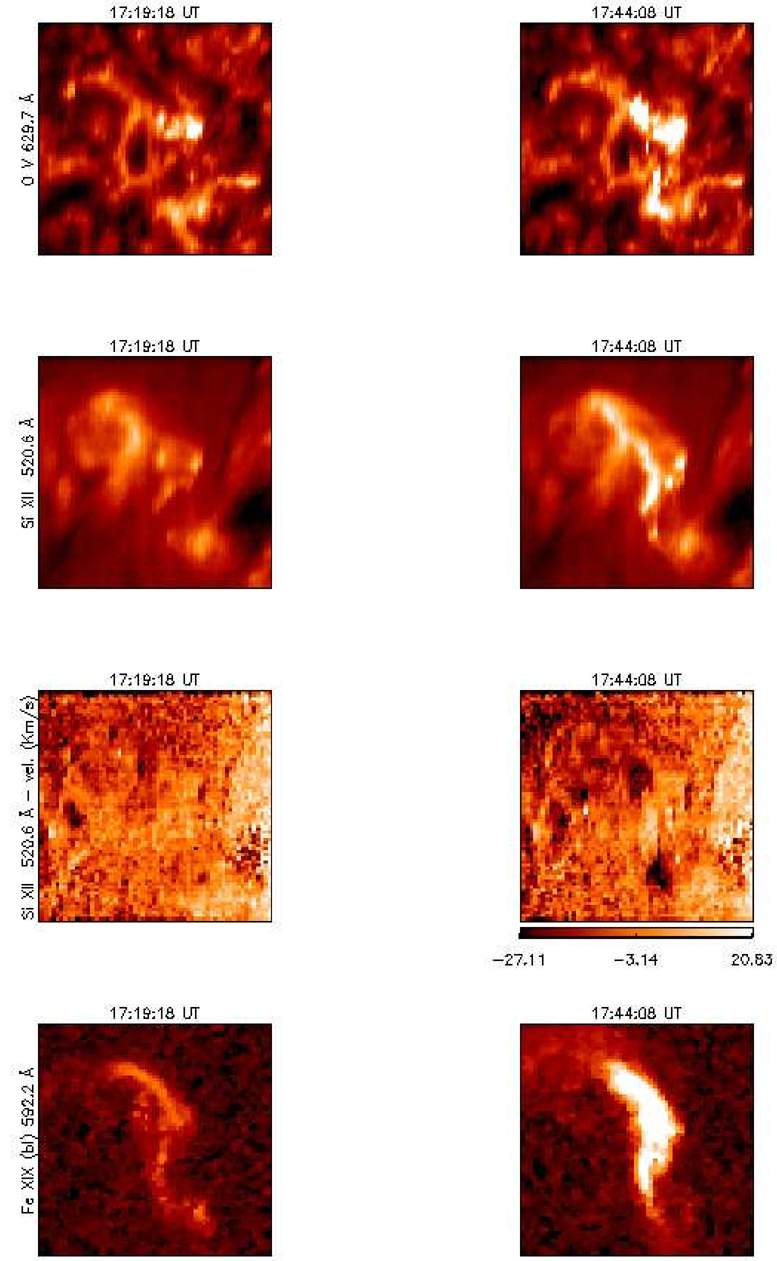

Figure 3. Blueshifted (upflowing) emission (indicated as black in the figure) in SiXII at the footpoints of hot active region structure, seen in FeXIX

SOHO-CDS/TRACE/YOHKOH/GB observations of the structure and evolution of an active region. In particular, they focus on the nature of the sigmoid structure, filament disruptions and a small flare.

8. Solar Flares: Blueshifts

The more active phase of the solar cycle is providing some intreresting flare data. Czaykowska *et al.* (1999) have found evidence for chromospheric evaporation during the gradual flare phase from SOHO-CDS observations. They find blueshifts in the Fe XIX (10^7K) emission indicating upward flows in excess of 100 km s^{-1} at 10^7 K, along the Hα ribbons.

CDS observations of a small flare by Del Zanna *et al* (2001) show blueshifted (upflowing) emission in Si XII (2 x 10^6K) at the footpoints of a very hot Fe XIX (10^7K) structure (Fig 3).

9. Conclusions: The Way Ahead

Imaging instruments can provide high spatial and time resolution observations. They have clearly demonstrated that the solar atmosphere contains dynamic filamentary structures.

Spectroscopic instruments provide good diagnostic capabilities for plasma parameters, and some very interesting results have been obtained.

However, the best way forward in the future is 'forward modelling'. This is non-trivial and requires the close connection between:

- theoretical models,
- atomic physics,
- observations.

An iterative approach is recommended using common sense. CHIANTI is our contribution towards providing the building blocks for this analysis process. It can be integrated with the theoretical models to predict spectral line intensities for comparison with the observations.

10. Acknowledgments

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