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Energy Transfer from the Chromosphere to the Corona Using Oxygen as a Trace Element

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Summary

The complete set of oxygen ions, from neutral to hydrogen-like, can be used to trace energy flow from the photosphere to the corona, allowing coronal heating mechanisms to be tested. All of the ions can be observed by combining a single **ultraviolet imaging spectrometer** with an **X-ray imaging spectrometer**.

Science justification

Most coronal heating theories invoke the source of energy for coronal heating to be in the photosphere, with energy transferred to the corona through, for example, Alfven waves or field line braiding. A fundamental goal of UV spectroscopy has been to use emission lines formed at different temperatures to track the flow of energy into the corona, yet previous instruments have always lacked a complete set of emission lines to do this. Even where line coverage has enabled partial coverage of a section of the solar atmosphere, puzzling mismatches between ions belonging to different elements have been observed, usually interpreted as abundance anomalies.

In addition, non-equilibrium ionization is becoming increasingly recognized as a complicating factor in the interpretation of solar spectra due to the highly dynamic nature of the solar atmosphere. By tracking all of the ions of an element, it is much easier to identify when non-equilibrium conditions apply: for example, if O IV is moved to lower temperature regions by advection (Olluri et al. 2013) then morphologically the emission distribution should be closer to O II or O III, which can be directly checked with observations. Having all oxygen ions available also means that modeling of the non-equilibrium plasma can be directly targeted to an individual species.

Oxygen is the only element for which it is practical to observe all ions (in this case with two instruments), yet still retain good temperature coverage:

- its abundance is high enough that good quality, optically thin emission lines are available for all ions;
- for ions O I through VI, the lines lie reasonably close together between 700 and 1040 Å and so can easily be observed with a single instrument; and
- the strong lines of O VII and O VIII also lie close together, within 19-22 Å.

Here it is proposed to have a combined UV and X-ray instrument package that will enable strong lines of all eight oxygen ions to be observed simultaneously. The temperature coverage provided by the ions is shown in Figure 1.

Specific science goals that will be addressed are:

1. Propagation of Alfvén waves and magnetoacoustic waves from the chromosphere to the corona. Waves can be identified in intensity, Doppler shift or line width, and then tracked through the atmospheric layers to determine the extent to which damping is occurring.
2. Sunspot and fan loops, and coronal plumes are clearly identified in the upper transition region and corona, yet the connection to the lower transition region and chromosphere has not been made due to a lack of temperature coverage. Current ideas favor small-scale reconnection at the loop/plume footpoints (Wang et al. 2016, Raouafi & Stenborg 2014, Régnier et al. 2014). The oxygen lines will enable the connection between the source chromospheric structures (small-scale bipoles), reconnection signatures (flows, line-broadening), and the flow of high temperature plasma into the loops to be unambiguously made.

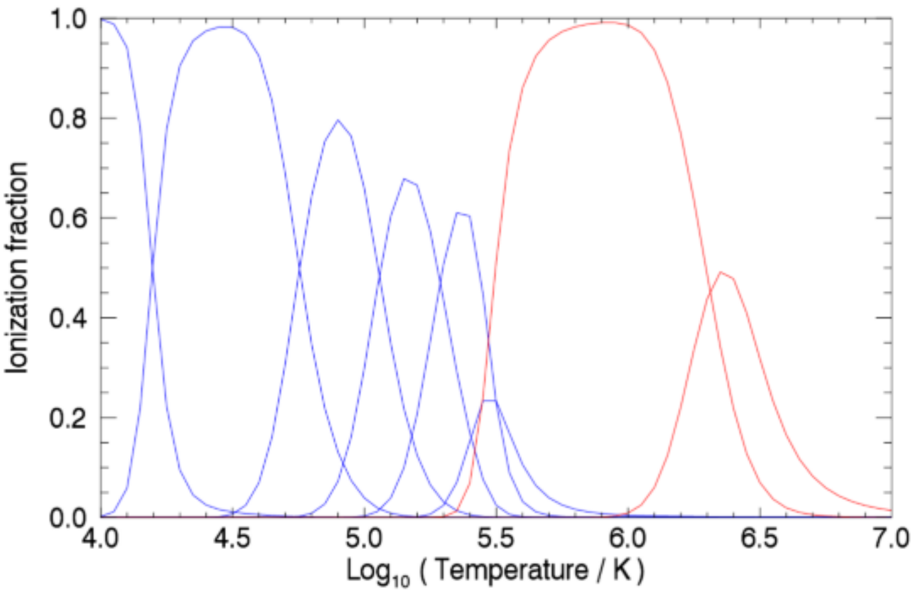

Figure 1. Ionization fraction curves for the oxygen ions, from CHIANTI. Blue curves are for the UV ions, and red curves for the X-ray ions.

Table 1. Oxygen emission lines.

Ion	**Wavelength**	**Transition**
O I	1025.762	$2s^22p^4\ {}^3P_2 - 2s2p^5\ {}^3D_3$
O II	834.466	$2s^22p^3\ {}^4S_{3/2} - 2s2p^4\ {}^4P_{5/2}$
O III	835.289	$2s^22p^2\ {}^3P_2 - 2s2p^3\ {}^3D_3$
O IV	790.201	$2s^22p\ {}^2P_{3/2} - 2s2p^2\ {}^2D_{5/2}$
O V	760.448	$2s^2\ {}^3P_2 - 2s2p\ {}^3P_2$
O VI	1031.912	$2s\ {}^2S_{1/2} - 2p\ {}^2P_{3/2}$
O VII	21.602	$1s^2\ {}^1S_0 - 2s2p\ {}^1P_1$
O VIII	18.967	$1s\ {}^2S_{1/2} - 2p\ {}^2P_{3/2}$

Instrument requirements

Table 1 identifies strong, clean lines from each of the oxygen ions. As can be seen, the ultraviolet lines can be observed with two relatively narrow wavelength bands from 760 to 840 Å and 1020-1040 Å. Since the transition region is critical for understanding energy transfer through the atmosphere, we consider the **primary objective** to be to obtain measurements of the UV lines. Since the wavelength ranges are close to those of the LEMUR/EUVST instrument (Teriaca et al. 2012) and the SPICE instrument for Solar Orbiter (Fludra et al. 2013) then the UV instrument is clearly feasible.

We also highlight that the 760-840 Å wavelength band contains the important Ne VIII 770.40 Å emission line, giving access to the low temperature boundary of the corona. In addition, extending the long wavelength channel down to 970 Å yields the very strong C III 977.03 Å line, together with the hydrogen Lyman-beta and gamma lines, and the Fe XVIII 974.86 Å hot coronal line.

To continue coverage of the atmosphere into the corona and flare temperatures with oxygen requires observation of lines of O VII and O VIII, for which the strongest lines are in the 18-22 Å range and thus a completely different instrument is required. An imaging spectrometer such as MAGIX will be suitable, and we note the oxygen lines are key observables for current rocket experiment.

If an imaging X-ray spectrometer is not feasible, then we note the following:

- Ne VII 770.43 and 780.39 will be available to the UV spectrometer giving access to hotter temperatures than O VI;
- The 170-210 Å range would give temperature diagnostics from a continuous sequence of iron ions from Fe VII to Fe XIV (logT=5.6 to 6.3), extending the oxygen sequence, and providing a viable alternative to the X-ray oxygen lines. The LEMUR/EUVST design demonstrated that this channel can be observed by the same instrument that observes the longer UV wavelengths.

IRIS has demonstrated the need for high spatial resolution when observing the chromosphere and transition region, and a resolution of 0.3” or better is *essential*. This is probably not feasible in the X-ray wavelength region, however.

Complementary instrumentation

Imaging in the transition region and corona is critical for placing the spectroscopic data in context, and a slit-jaw camera for the UV instrument similar to that for IRIS is preferred. For the corona, a separate EUV imager similar to AIA is preferred.

High resolution magnetic field measurements are critical for understanding energy transfer, but the data from DKIST or other ground-based telescopes should be sufficient. However, a magnetograph with spatial resolution matching the UV instrument would provide valuable baseline data that is available for all data-sets, irrespective of ground-based seeing or operations restrictions.

References

Fludra et al., 2013, Proc. of SPIE, 8862, 88620F
Olluri et al., 2013, ApJ, 767, 43
Raouafi & Stenborg, 2014, ApJ, 787, 118
Teriaca et al., 2012, Exp. Ast., 34, 273
Wang, Warren & Muglach, 2016, ApJ, 818, 203