Fast UV Spectro-imagery for Solar Physics

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The needs of UV solar physics in terms of fast spectro-imagery

In order to diagnose the plasma in the solar atmosphere, in 3 spatial dimensions and time, physical quantities such as temperature, densities, ionization degree, abundance, along with magnetic and velocity fields must be known. In the remote-sensing approach, these quantities are derived from the measurements of the radiation field. The high chromosphere, corona and the transition region emit essentially in the VUV and EUV, which imposes some constraints upon the instrumentation.

The velocity field is crucial for the determination of the momentum and the kinetic energy in the solar plasma. The prime candidate for this measurement is the Doppler effect which allows access to the field component along the line of sight. This requires a rather high spectral resolution (see below) and in some cases, the combination of measurement of apparent motions (in a time-dependent imaging mode) and Doppler velocity field can provide the full velocity vector.

With the advent of the SOHO, TRACE, STEREO, Hinode and now SDO missions, exceptional sequences of images have been obtained in the UV and EUV. They show important dynamics at all spatial and temporal scales. For instance, the so-called EIT waves have been observed with EIT on SOHO at a scale which can reach a solar radius, but the lack of spectral information hampers the identification of these waves. Spectrographs have attempted to identify them: CDS on SOHO observed blue shifted profiles (Harra & Sterling, 2001), which is the possible signature of outflowing material in a coronal mass ejection. But because of the limited field of view (FOV) and the duration of the observing sequence, the measurement has not been confirmed.

At a smaller scale (let us say twice the size of an average active region, 200″×200″), rapid events such as mini or micro-flares can be completely missed: a typical CDS scan lasts 10 minutes while the event front lasts about two minutes. The same is true for the dynamics within coronal loops at high and intermediate temperatures (see the debate about the steady vs. burst heating which cannot be resolved because of the lack of combined spatial, spectral and temporal resolution). At even small scales (a few arc seconds), the solar atmosphere is highly dynamic (e.g. Wang et al., 2000) and a limited spatial scan does not allow us to put the small events in a more general picture.

This means that the combination of imaging and spectral capabilities is necessary. Note that the need of fast spectro-imagery for the study of the transition region is discussed in Gary et al. (2008).

Fast spectro-imagery in the visible

This has been recognized for a long time and many attempts have been made, until now in the visible domain (see Mein 1977 and more recently Mein 1995, for reviews). Starting with the Hα line and later extended, e.g. to the Ca II triplet, the Multi-Channel Subtractive Double Pass spectrograph (MSDP) has obtained important performance (bandpass = 0.13nm @ 656.3nm, FOV 30″ × 250″, spectral resolution = 0.025 nm) and various observatories have implemented it (Meudon, Themis, VTT, Wroclaw, Pic du Midi). The reason for its success lies in the fact that this instrument provides a good compromise between FOV and spectral/spatial/temporal resolutions. (Note that the importance of this instrumentation has been demonstrated by the publication of about 280 papers related to the MSDP). In particular, the various monochromatic images are obtained simultaneously. But this instrument can "only" observe the photosphere and the lower chromosphere.

Other instrumentation has been implemented earlier, such as the UBF at Sac Peak or IPM at THEMIS. Let us recall that they have (as all Fabry-Perots) very interesting properties in the case of narrow

bandpasses and isolated lines and benefit from excellent spectral resolution (e.g. IBIS at Sak Peak). But they have a limited field of view and are definitely limited to visible lines, i.e. to the study of the photosphere and low chromosphere.

Fast spectro-imagery in the UV

The SIMURIS proposal (Damé et al. 1994) included an Imaging Fourier Transform Spectrometer (FTS) with a beam splitter supposed to work above 115 nm. In the EUV, recently, Kankelborg et al. (2006) developed the MOSES concept which flew on 8 February 2006, the instrument, working in He II (30.4nm). It seems that the intensity image was easily recovered but the precise spectral information and the derived velocity field appeared to be more difficult to recover (see section 3.4 of Fox et al. 2010) but was recovered. Let me quote the conclusion of the authors of the paper : "Our observation of this event's three-dimensional structure and dynamics is only possible because of the simultaneous imaging and spectroscopy provided by *MOSES*. With an imager only, we would not know this is a transition region EE. With a slit spectrometer, we would have missed pieces of the full event, perhaps only seeing one of the jets, or only the core, depending on slit alignment, and would not have observed the peculiar, non-collinear geometry of the jets."

In between the EUV and the FUV range, no fast spectro-imaging instrumentation has been proposed (see however Millard 2005, Millard et al. 2006 & Ruiz de Galarreta Fanjul et al. 2010). In particular, the need for a fast spectro-imaging device working in the VUV (say, between 60 nm and 140 nm) has still not been fulfilled, probably because this range extends below 121.5 nm (and in particular 102.5 nm), precluding the use of MgF2, LiF or other dielectrics which could have been potential candidates for use in filters, especially Fabry-Perots.

However, note that Gary et al. (2007, 2008) report very positive results on the development of a Fabry-Perot Interferometer (FPI) dedicated to the C IV doublet around 155nm.

So we are left with all-reflective optics schemes with the further constraint of a minimal number of reflections in order to optimize the throughput. We propose to focus on two different all-reflection optical architectures based on interferometric techniques: Spatial Heterodyne Spectroscopy (SHS), with and without Integral Field Unit (IFU); and Imaging Transform Spectrometer (IFTS). In order to properly compare the pros and cons of these two types, it is important to select a wavelength range and the expected performance in terms of spectral, spatial and temporal resolutions and size of the FOV.

Lyman α

A first step from both observational and instrumental standpoints could be devoted to the Lyman α line at 121.67 nm. The Hydrogen Lyman α doublet is, in some respect, the UV "workhorse" for the hot solar atmosphere, equivalent to the Hα line in the visible. There are many reasons for that: it is the strongest solar UV emission line, it has a large absorption coefficient and H is the most abundant element. It is also a solid tool for diagnostic and a strong contributor to radiation losses in many solar features. But the conditions of its formation are not easy to handle. Lyman α is very optically thick: at a temperature of about 10^4K, the absorption coefficient is about 4.2×10^{-14}cm^{-1}, which means that a layer with a density of about 10^{10}cm^{-3} and a thickness of 1000 km has an opacity of about 4×10^4. Actually this drawback can be turned into an advantage, since each part of the line profile corresponds to a given depth in the atmosphere: Lyman α is formed all through the chromosphere and the bottom of the transition region.

In the case of the solar chromospheres(s) and transition region (TR), profiles are rather broad (at least 0.1 nm wide with very extended wings a few nm away) and, when observations take place at low spatial and temporal resolution, this only requires a rather low spectral resolution (about 0.01 nm) to resolve the reversed profile (see e.g. profiles obtained in coronal holes by Hui Tian et al. 2010). But in the case (e.g.) of prominences, profiles obtained at high spatial resolution (Vial et al. 2007) display features at the scale

of the SUMER resolution (0.005 nm); unfortunately, because of the slit-mode observation, they were difficult to localize in the overall prominence. As for the beautiful VAULT images they don't have any spectral information (Korendyke et al. 2001).

A comparison between two candidates : (I)FTS vs (I)SHS

One can summarize the comparison as follows (for more details, see Ruiz de Galarreta Fanjul et al. 2010) : since detectors are bi-dimensional, the three dimensions cannot be recorded simultaneously. FTSs acquire a panchromatic image and scan through the interferogram in the temporal domain. This can limit the temporal resolution in the study of solar activity. Spectral Heterodyne Spectroscopy (SHS) is an alternative solution, based on the Fourier Transform which simultaneously records all optical path differences. Compared to a conventional FTS, it is insensitive to a change in the intensity of the incoming light (e.g. Damiani 2009). In order to run it in an imaging mode (since it is a slit device), at least one of the spatial dimensions of the data cube must be sequentially acquired over time. One could think of an Integral Field Unit (IFU) which works very well in the VIS-IR and for moderately large FOV. But the mirror slices should have a micron width which is technically unfeasible.

One is left with an IFTS being – as far as we know – the only realistic candidate, and whose supplementary advantage lies in its flexibility: variable resolution enables either moderate-resolution wide spectral range or very accurate line profile acquisition (Millard 2006), a feature which could even be used in on-board operations.

In the case of Lyman α, a preliminary study (Ruiz de Galarreta Fanjul et al. 2010) shows that a 200″ × 200″ field can be measured with a 0.01 nm and 10s resolution. Such performance is rather similar to the performances of the above-mentioned MSDP working in the visible.

Other candidate lines :

We have focused on the study of the Lyman α line, because of its importance and its high output. Of course, an all-reflection IFTS could work on a large bandpass (actually, FTSs were designed essentially for this use), e.g. in the Lyman continuum, the Lyman series (from Lyman β down to 91.2 nm) or windows including optically thin lines representative of the Transition Region. Close to the Lyman β line, one could record the O VI lines between 103 and 104 nm. Above the Lyman α line, SUMER has observed a large variety of emission lines (e.g. N V at 124 nm, Si IV at 139 nm or C IV at 155 nm) emitted at temperatures around 10^5 K. A spectral resolution of about 0.005 nm would be sufficient to build velocity maps with a cadence depending on the effective bandpass. This "free spectral range" could be limited with the help of dedicated selective multilayer mirrors (see e.g. Welsh et al. 1996). With the same type of selective multilayers, still lower wavelengths (< 40 nm) could be reached (Delmotte et al. 2005, Ménesguen et al. 2009).

Technical feasibility of an IFTS in the UV

The concepts have been proposed as early as 1972 by the Wisconsin group (Kruger et al. 1972) and later on by Thorne et al. (1987) but working in the VUV requires special designs and techniques ("all-reflective mirrors") which have hampered major successes until recently. With the advent of ultra-polishing techniques, efficient coatings and multilayers, space-qualified PZT and better UV detectors, it is now possible to build a realistic and space-qualified UV instrument (see e.g. Thorne 1998). In physics laboratories (such as the SOLEIL Synchrotron ring), VUV (non-imaging) FTS are routinely used (de Oliveira et al. 2009). In terms of the (difficult) metrology and stabilization, one can think of transposing the techniques used "on the ground" to instrumentation designed to fly in space. Before envisaging such a possibility, it is necessary to test the feasibility on mock-ups, to test the performance (especially in terms of stability of the optical path difference) and design a flyable instrument.

We think that such an effort is worth the effort, in view of its astrophysical benefits.

Some references

N.B. This note is not comprehensive about the various past efforts. It simply relies upon some work that I am more familiar with.

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