Doppler signatures in EVE spectra, and flares

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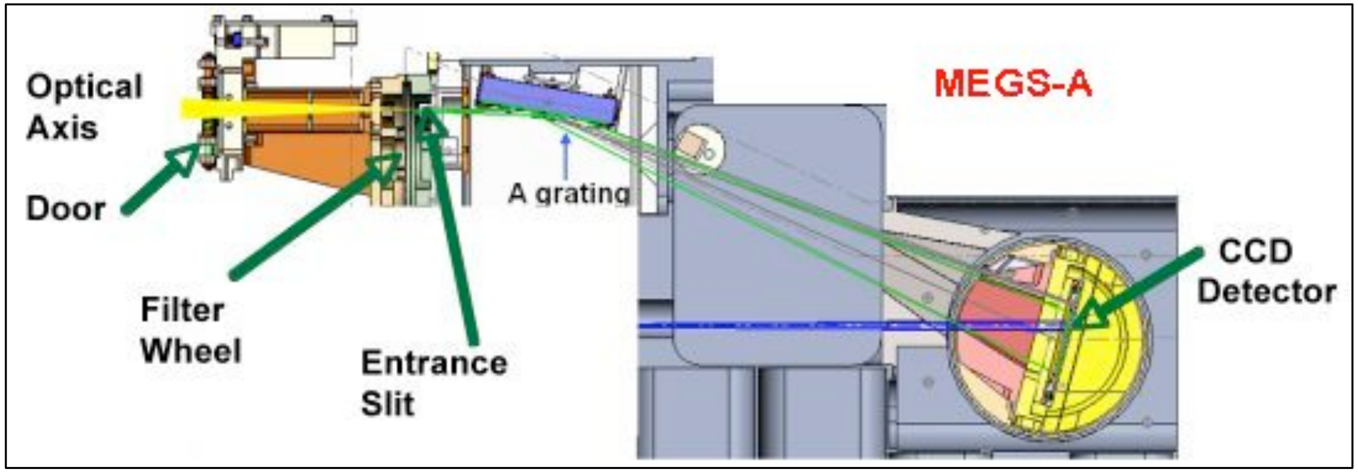
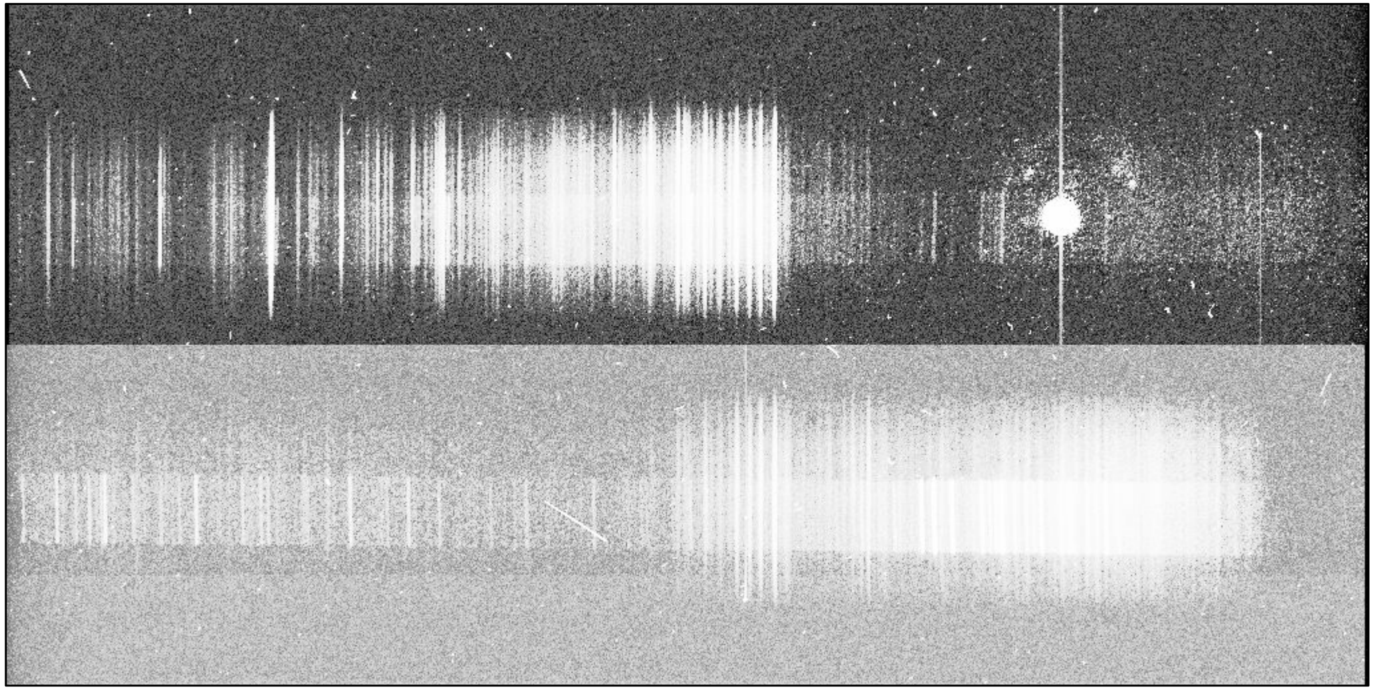
The Extreme-ultraviolet Variability Experiment (EVE) on SDO is providing a comprehensive set of EUV spectra of the Sun as a star. The routine sampling is with 10 s integrations at a resolution of 0.1 nm. Although this resolution corresponds to only some 1000 km/s in velocity space, we demonstrate that the instrument is stable enough to detect the SDO orbital motion of a few km/s readily in the bright He II line at 30.4 nm via MEGS-A. We find the random error in the centroid location of this line to be less than one pm (less than 1 km/s) per 10 s integration. We also note systematic effects from a variety of causes. For flare observations, the line centroid position depends on the flare position. We discuss the calibration of this effect and show that EVE can nonetheless provide clear Doppler signatures that may be interpreted in terms of flare dynamics. This information has some value in and of itself, because of EVE's sensitivity, but we feel that it will be of greatest importance when combined with imagery (e.g., via AIA) and modeling. We discuss flare signatures in several events, e.g. the gamma-ray flares SOL2010-06-12 and SOL2011-02-16T:07:44, taking advantage of AIA image comparisons. We also discuss the non-gamma-ray events SOL2011-02-15 and SOL2011-03-07T19:43 for comparison.

EVE/MEGS-A

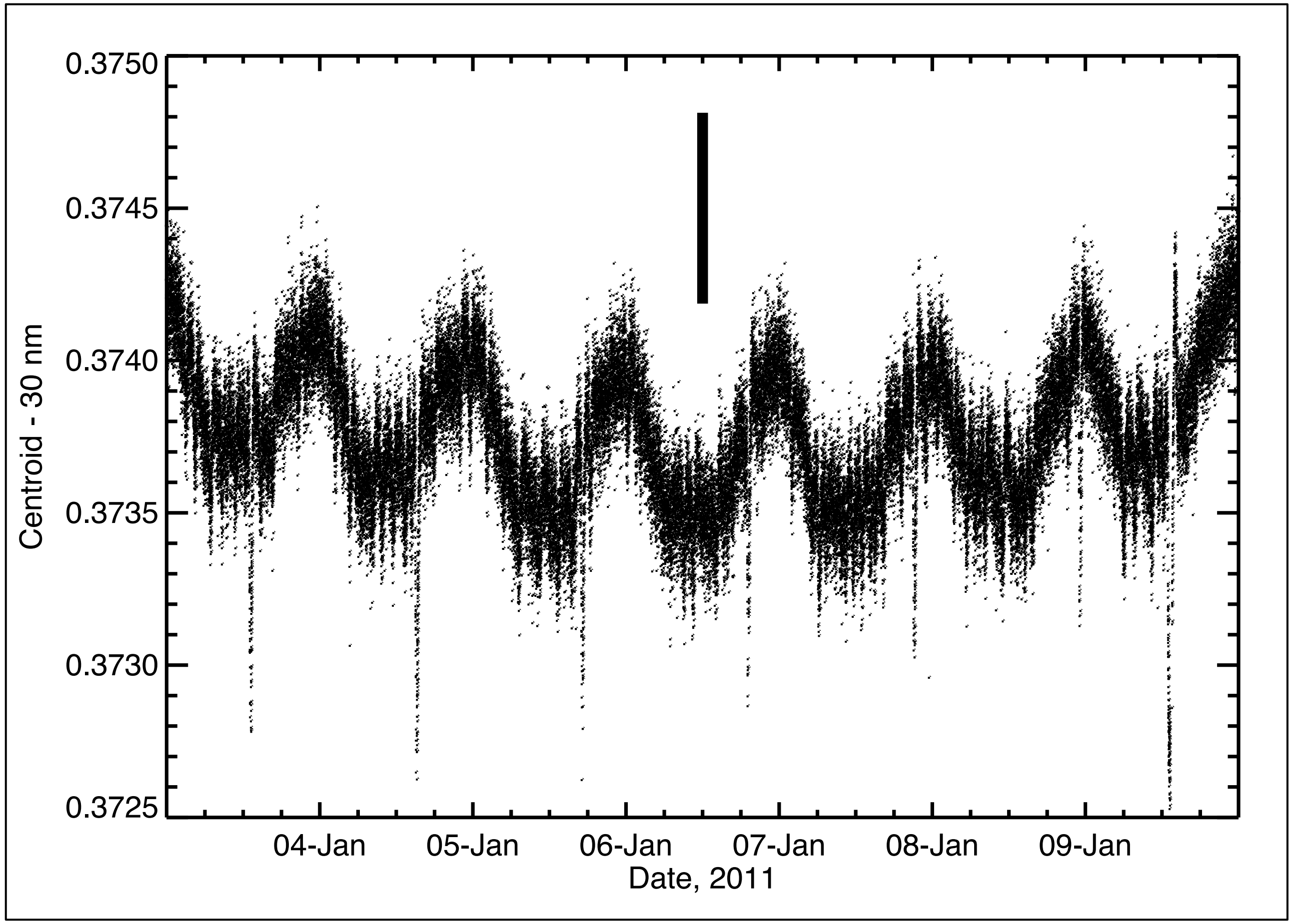


Instrument



Raw flare data

Redshift analysis for MEGS-A



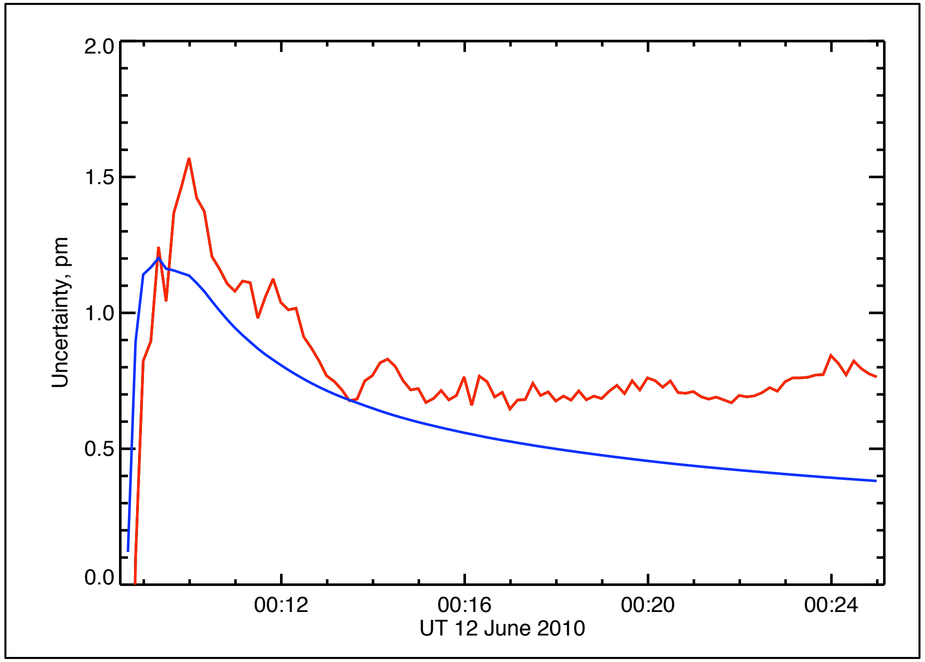
We have used standard tools (Gaussian fits via IDL *gaussfit*; mean wavelengths) to characterize line centroid positions. The figure shows the Gaussian centroid for one week of observation at 30.4 nm. The heavy bar shows a displacement equivalent to 6.14 km/s.

Interpretation of redshifts

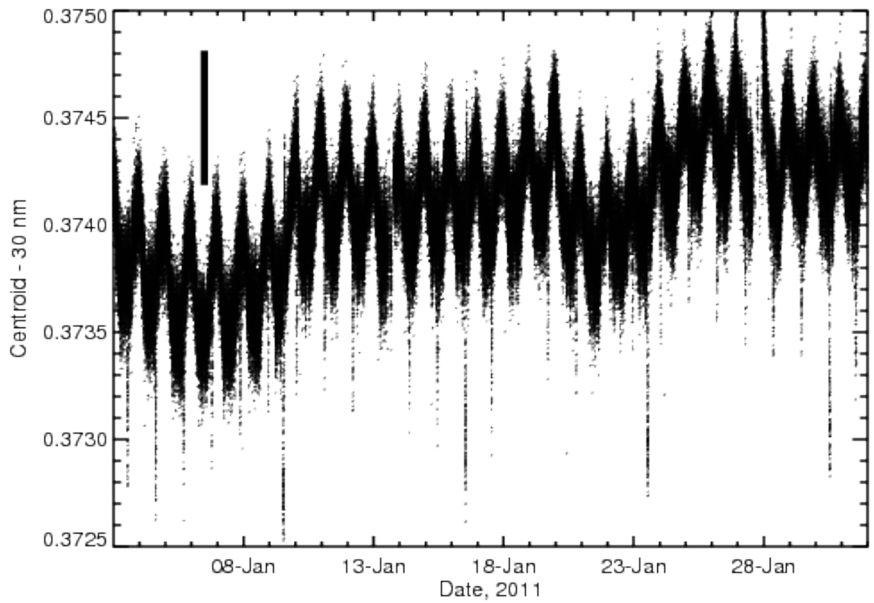
- The centroid determination is stable for week-long intervals, and during quiet solar conditions the redshifts are dominated by a sinusoidal term with period one day, amplitude about 3 km/s, and minima at the anti-Earth point in the SDO orbit.
- There are many artifacts also present, most notably (a) effects of the daily calibrations, and (b) a quasi-periodic variation at tens of minutes' period that we currently cannot explain
- The data justify estimation of a random error, and it is of order 1 pm for the Gaussian fits; for simple mean-wavelength analysis ($\Sigma S_i \lambda_i / \Sigma \lambda_i$) the random error is of order 100 fm for the He II 30.4 nm line.
- Such small uncertainties and good stability make the data interesting for flare observations, since 1 pm corresponds to about 10 km/s.

Measurement of random error

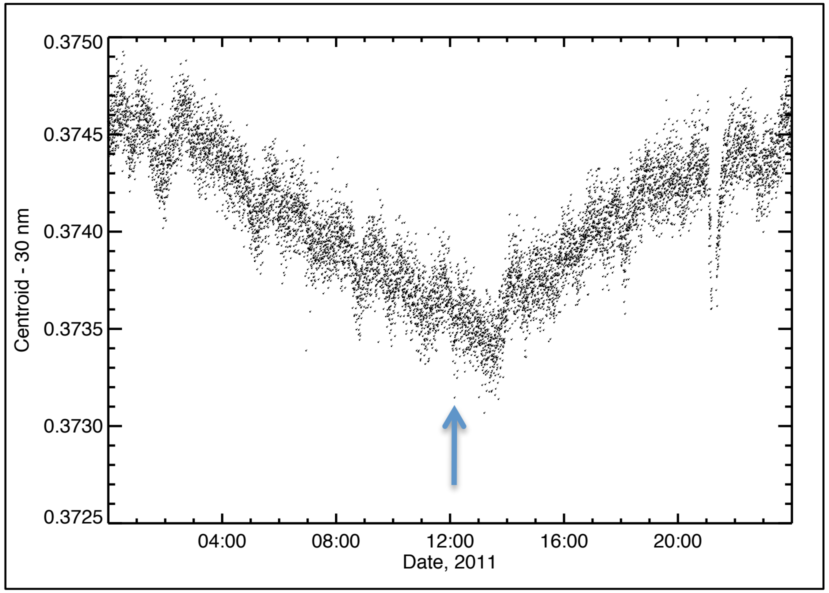
• We make Gaussian fits to each 10-s frame of EVE/MEGS-A data, as shown on the figures for the SOL2010-06-12 flare.
• The figure shows cumulative error estimates for a quiet period:
  - errors of single-component Gaussian fit (red)
  - standard deviation of centroids (blue)
• The difference is understood to be the extra variance due to the model (a single Gaussian is not right)

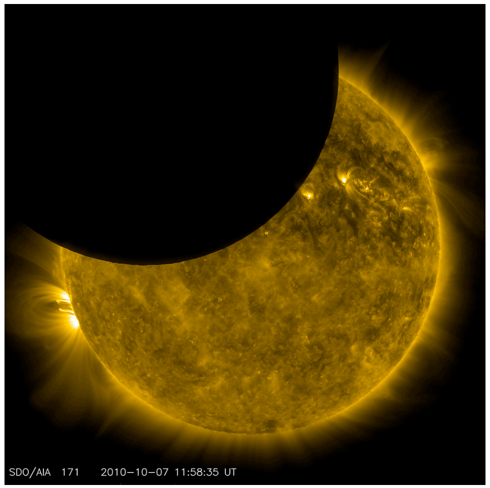


Other non-flare redshifts



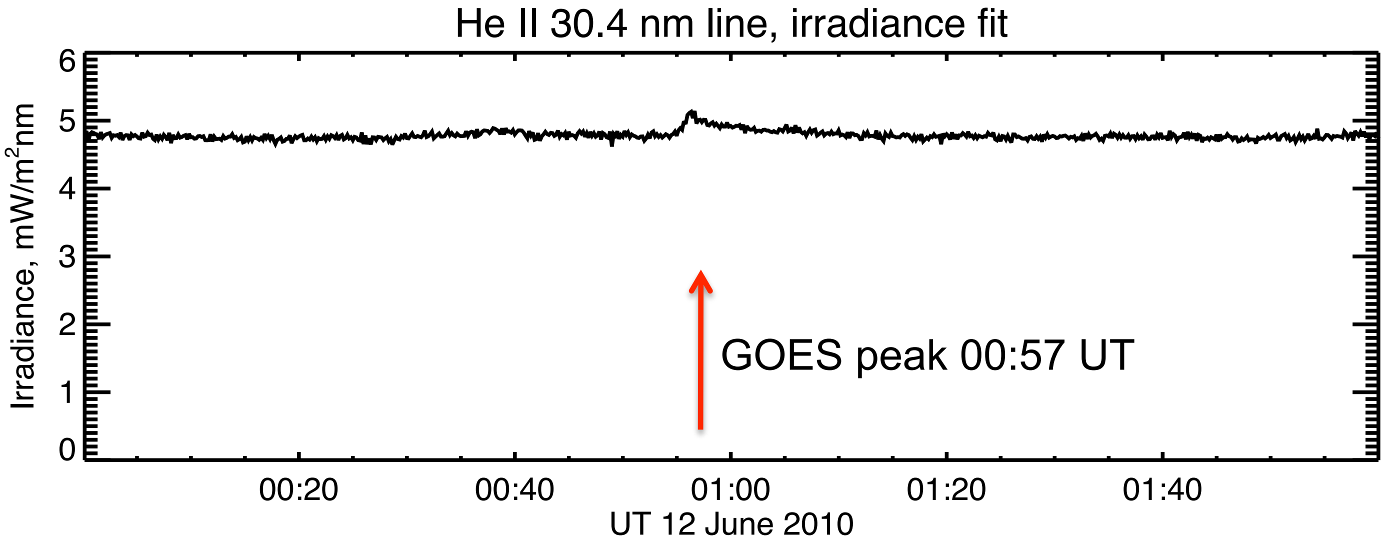
One month of data – no obvious lunar term in the redshift variation

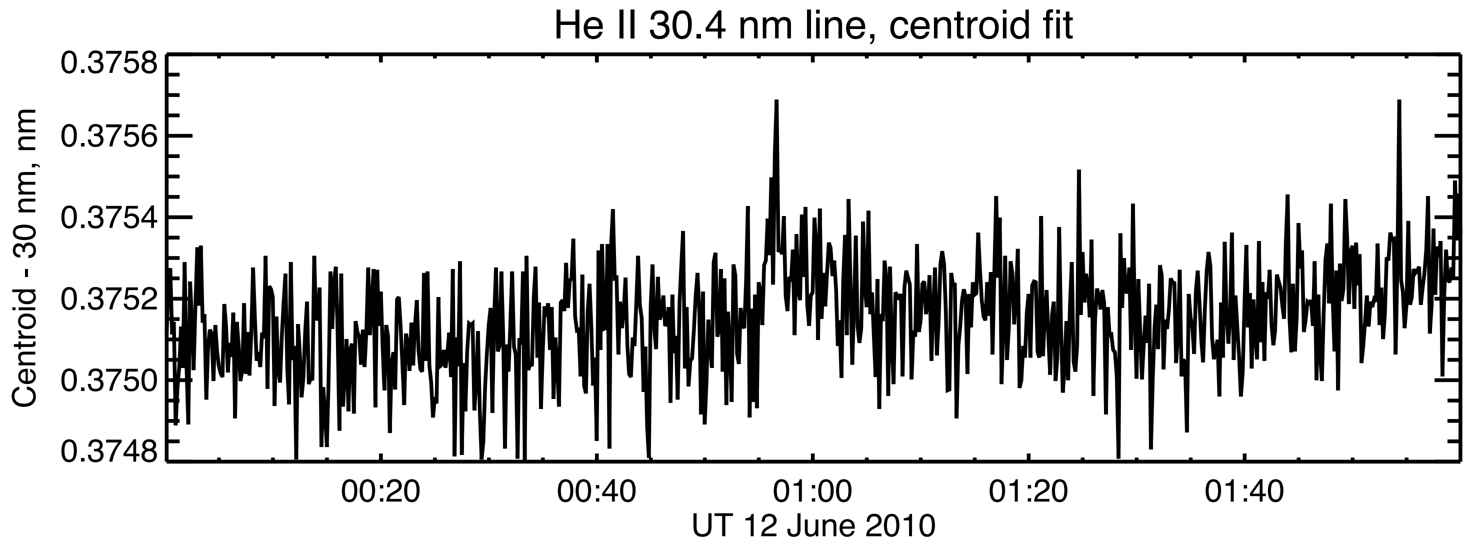




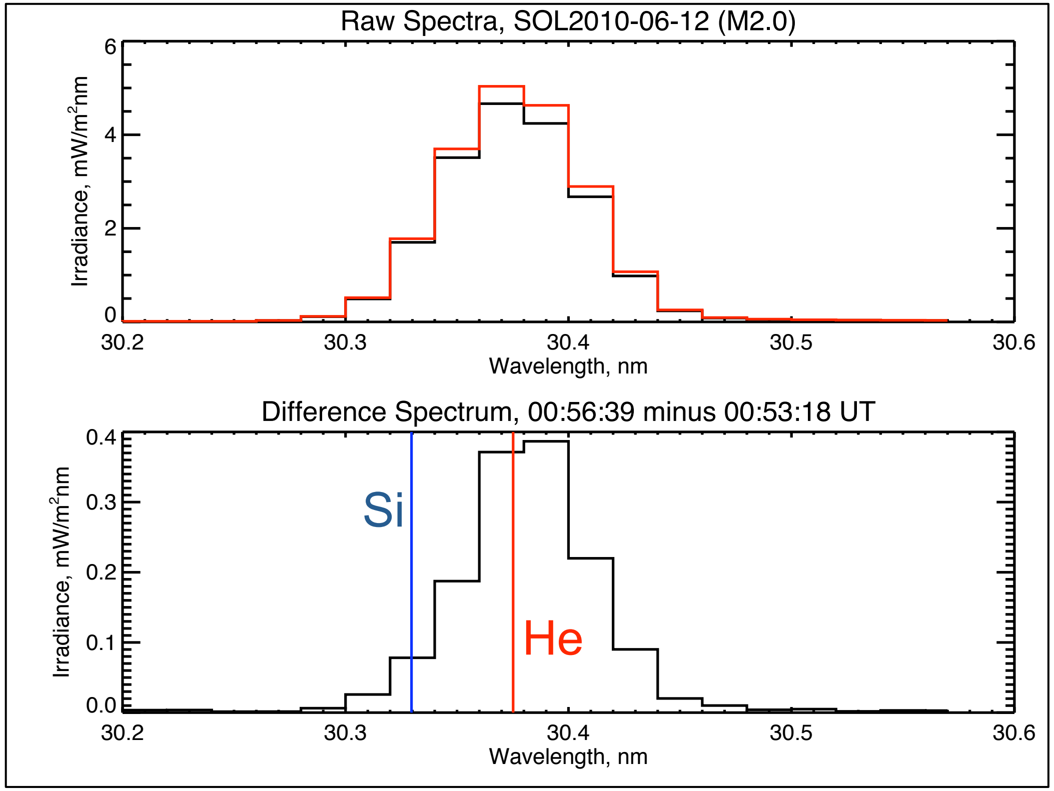
Redshifts during an SDO eclipse (7 Oct. 2010), showing a possible thermal effect

Flare SOL2010-06-12 (M2.0)





He II and Si XI lines



- The wavelengths shown have a -3.09 pm offset to match the MEGS-A scale
- The He wavelength shown is the weighted mean of the two lines
- The well-known Si XI blend may be present at this epoch
- The data will certainly support multi-line fits
- Is Chianti complete enough?

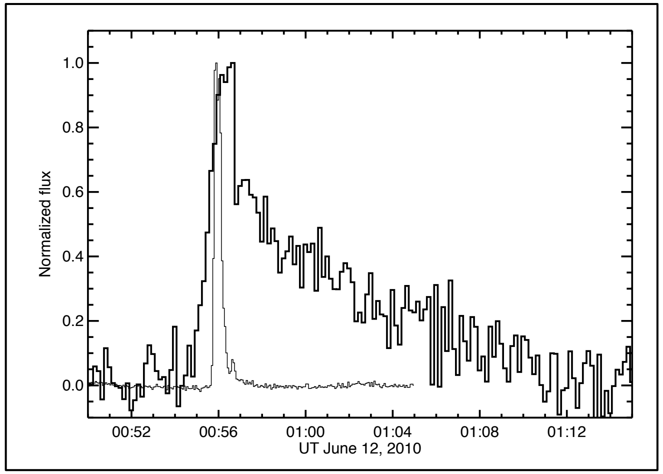
Differential spectral analysis for SOL2010-06-12

Flare Phase	Time range	Irradiance mW/m^2	Centroid nm	Width nm	Redshift km/s
Preflare	00:50:09-00:54:29	4.26	30.3751	0.0312	
Impulsive	00:55:59-00:56:49	4.45	30.3754	0.0313	
Gradual	00:56:59-00:58:09	4.40	30.3753	0.0312	
Impulsive excess		0.197	30.3801	0.0322	48.88±2.49[a]
Gradual excess		0.137	30.3784	0.0305	32.05±5.33[a]
Impulsive-gradual					16.8±5.9[a]

[a]Statistical uncertainty

Lessons learned:

- The random redshift errors are small
- If one assumes that the flare is compact, a differential measurement of evaporation may be possible
- Image comparisons with AIA are essential

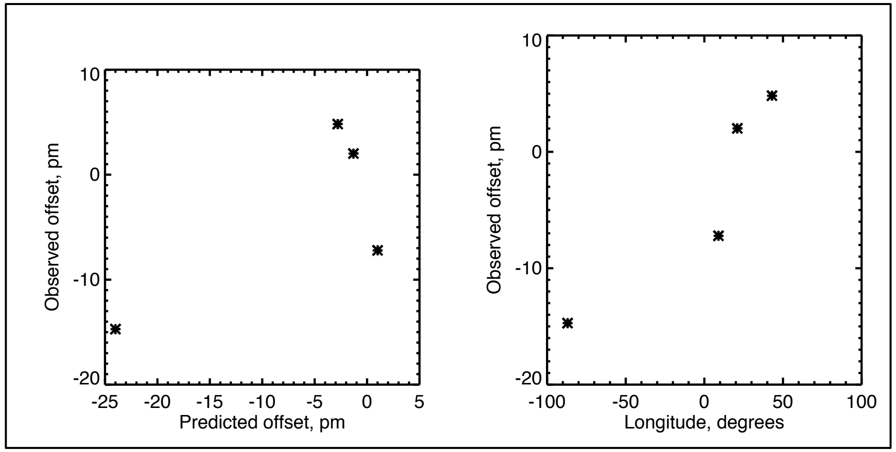


Absolute vs. Relative wavelengths

• MEGS-A makes precise measurements of spectral irradiance and has a stable wavelength calibration.
• With assumptions, our flare observation suggests a wavelength offset of -3.09 pm, around 3%.
• There are many known and unknown effects determining the wavelength calibration; among the former is the optical effect resulting from angle-dependent illumination of the CCD. Pre-launch calibration of this effect suggests that

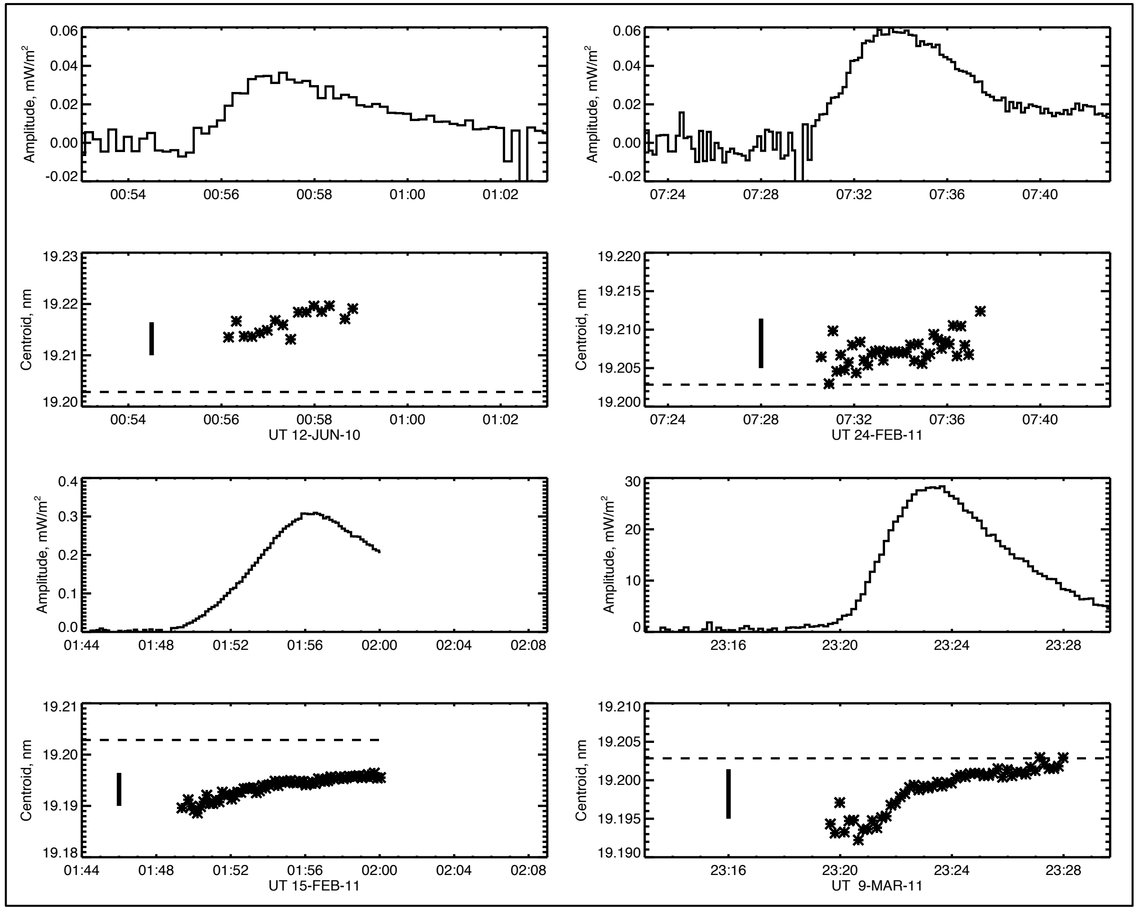
$$|\Delta\lambda \approx 6.5\ \sin\theta - 18.5\ \sin^2\theta + 3.5\ \sin\phi \quad \text{pm},$$

Where (θ, ϕ) are the heliographic longitude and latitude.



A first look for this dependence, based on four flares only – we can probably achieve an in-flight calibration check in this way!

Four flares in Fe XXIV 19.2 nm



- Upper two sets for the two SDO γ-ray flares; lower two for the two SDO X-class events
- The fits are to the flare excess signal via simple subtraction
- In each case the line shifts systematically redwards, as expected from evaporation
- Statistical uncertainties for the X-class events are small (calibration bar 100 km/s)

Conclusions

- EVE/MEGS-A has excellent properties that contain clear Doppler signatures
- Although there is no imaging, the time series is complete
- There is imaging from AIA, of course, so combining the data sets bearing the simulations in mind should allow us to study flare dynamics with these data.
- There is a caveat regarding simple background subtraction in ignorance of the imaging: see Bornmann, ApJ 356, 733 (1990)