An eclipse experiment to study the solar chromosphere and spicules

Draft 1.2, P. G. Judge, 30 Dec 2010.

An experiment is proposed to measure a critical part of the chromospheric flash spectrum during the eclipse which will occur November 13, 2012. The idea is to obtain rapid (30 Hz), high signal-to-noise spectrographic data at at least one chromospheric line, the calcium H line being the most desirable, at a spectral resolution of 15,000 or higher. A small telescope with a small exit pupil can be used to feed a collimated beam, using optical fibers, to a spectrograph, which will record light from the entire chromospheric arc as a function of time. By inverting the time series of data, essentially by differentiating the time series in time, the radially-dependent spectrum of spicules and of the stratified chromosphere will be recorded for posterity, and will shed light on the dynamic and physical links between spicules and the chromosphere. By placing fibers at the exit pupil of the telescope (diameter of a mm or so), one avoids issues of seeing which otherwise would detrimentally affect the time series.

Prof. Shadia Habbal, of the University of Hawaii, will submit proposals to NASA and the NSF in March of 2011, to obtain support for an expedition to the Cairns area of Australia where totality is quite short (2 min). She has invited HAO to join this expedition to perform the experiment outlined here.

Motivations

Recent work with the Hinode spacecraft and with ground-based instruments has re-ignited interest in the role of spicules in controlling the corona, following early work (Beckers 1972, Athay & Holzer 1982). There has been much debate on the nature of spicules, their relationship to the chromosphere and their impact on the corona and solar wind (de Pontieu et al 2007, Judge & Carlsson 2010, Judge, Tritschler & Low 2011). Those spicules that appear to connect to the corona, called “type II” spicules by de Pontieu and colleagues, are not understood at all. In fact, Judge, Tritschler & Low (2011) have questioned the basic nature of such spicules. They argue that it is not yet known if they are straw-like (the classical picture) or if they are warped 2D structures which are expected to form naturally within the chromosphere. The difference is profound, as apparent motions in warped sheets need not correspond to fluid flow, and sheets present a far larger area across which thermal boundary layers can be expected (the transition region). It is important to nail down the nature of the spicules, as a proper understanding will influence our ability to assess the flow of mass and energy into the corona, and also understand the poorly understood solar transition region from which much variable UV emission originates and impacts the earth. It is also important to understand why the chromosphere appears invisible to the Ca II H line in the Hinode NFI instrument, why such broad-band instruments appear to see only spicules and not a stratified chromospheric layer, (Judge & Carlsson 2010), and how spicules form within the stratified chromospheric plasma.

Ground-based work, outside of eclipse, suffers from problems of seeing. Adaptive optics systems are unable to obtain reliable locks across the limb and post-facto image corrections (e.g., Speckle reconstructions) require high signal-to-noise ratios across the whole field of view. Thus even under
exceptional seeing conditions (0.5” or 360 km on the Sun, say), spectra obtained near the solar limb can be sampled and accurately measured relative to the continuum limb only to within a few hundred km. The chromospheric pressure scale height is 150 km or so.

One way to attack the problem, once and for all, is to measure at high cadence the chromospheric flash spectrum. The moon's limb uncovers and covers the chromosphere at a projected speed of 300-400 km/s. The entire stratified chromospheric thickness is about 1500 km, and spicules extend some 5000 km higher. By taking timeseries of spectra at a 30 Hz cadence, we can radially "resolve" length scales of ~13 km. In principle, we can uniquely map out the average radial spectra of the chromosphere with very high radial resolution. It should be noted that no spacecraft instrument can measure the line profiles of chromospheric lines in spicules and the limb chromosphere with the resolution needed to see the essential dynamics change from chromosphere into the spicular flows, if indeed recently found spicules of type II correspond to flows. Coupled with broad band Ca II H line data from Hinode and other data from SDO, eclipse Ca II H line spectra will enable us to study the relationship of spicules to the chromosphere and corona.

Illustration 1: Sketch of the geometry during eclipse

Science requirements

The prime science goal is to obtain spectra with sufficient resolution near the core of the Ca II H line to see the nature of the transition from the stratified chromosphere to spicules. A critical parameter is to determine the change in dynamics of the material from the typically subsonic flows in the chromosphere (< 10 km/s) to supersonic flows in spicules (40 km/s, perhaps extending to > 120 km/s),
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as a well determined function of height above the continuum photosphere. Such a difference is detectable with a spectral resolution corresponding to a spectral FWHM of 20 km/s, or

\[ R \geq 15,000 \]

To resolve one pressure scale height requires spatial sampling of 75 km, which is traversed by the moon's limb in 75/400 \( \sim 0.2 \) sec. Thus the minimum cadence required is

\[ \text{Cadence} \geq 5 \text{ Hz} \]

Data will need to be differentiated in time. Consider the total flux from around the entire unocculted Sun at each wavelength \( \lambda \):

\[ f_\lambda(t) = \int \int d\rho d\phi \, \rho^2/ D^2 \, I_\lambda(\rho,\phi) = 2\pi \int d\rho \, \rho^2/ D^2 \, I_\lambda(\rho), \]

where \( I_\lambda(\rho,\phi) \) is the intensity at wavelength \( \lambda \), heliographic radius \( \rho \) and azimuth \( \phi \), \( D \) is 1AU. Below we propose an instrumental setup measuring \( f_\lambda(t) \) with no imaging information. In this case just an azimuthally-averaged \( I_\lambda(\rho) \) can be recovered, knowing the geometry of eclipse. The integrals depend on time implicitly through the ranges of \( \rho \) and \( \phi \) which are not occulted by the moon. To invert the above equation (going from \( f_\lambda(t) \) to \( I_\lambda(\rho) \)) will require high signal-to-noise measurements of \( f_\lambda(t) \) with high photometric stability. Given this situation, some synthetic calculations have been performed parameterizing \( I_\lambda(\rho) \) and folding it with the required integrals of light passing around the lunar disk for the eclipse of 13 Nov 2012.

Illustration 2: Expected time series of the total flux \( f_\lambda(t) \) in the core and inner wing of the Ca II H line for the eclipse of 13 Nov 2012, as seen from within 10 km of the central line of the shadow track. Vertical dotted lines show second and third contact points.
Figure 2 shows the total flux per square cm at the earth, estimated from known limb darkening (Linsky & Ayres 1976) and typical spicule intensities (Beckers 1972), for Ca II H. The gradients predicted for the chromosphere ($|t| < 60s$, using the line center light curve) yield timescales for $f_\lambda(t)$ changes of 

$$\tau = (d \ln f_\lambda / dt)^{-1} \sim 8 \text{ sec} \ (\equiv 3200 \text{ km at the Sun})$$

To resolve radially $I_\lambda(\rho)$ with 75 km resolution (5 Hz sampling), the changes in $f_\lambda(t)$ would be $f_\lambda = e^{0.2/8} - 1$, or

$$f_\lambda(75 \text{ km resolution}) = 2.5\%,$$

thus 3σ significance requires noise levels in $f_\lambda(t)$ of 0.8%. 

It is likely that the radial dependence is steeper than the 3200 km or so found in the azimuthally averaged spicule data upon which this analysis is based, as the intensities of Ca II H do not depend linearly on the mass density and both the Sun and moon are not radially symmetric (see below). Thus, if one seeks to resolve radially $I_\lambda(\rho)$ at a resolution below 75 km, say by taking video rate (30Hz) data, then we find

$$f_\lambda(13 \text{ km resolution}) = 0.4\%,$$

In this case a 3σ significance requires noise levels in $f_\lambda(t)$ of 0.13%. This radial resolution is not a requirement, but sets a goal by matching to easily available video frame rates.

**Flux budget**

On the solar disk, the intensity contained within the H$_{1\nu}$ and H$_{2\nu}$ minima – i.e. the chromospheric component of the line- is roughly

$$I_{\text{DISK}} \sim 3 \times 10^5 \text{ erg/cm}^2/\text{s/sr}/\lambda$$

The chromospheric component of the line is about 1 Å wide. The following table lists the azimuthally averaged intensities within 1 Å of line center, used to make the time series calculations above:

<table>
<thead>
<tr>
<th>$\cos \theta$</th>
<th>$\mu = 1$</th>
<th>$\mu = 0.2$</th>
<th>-</th>
<th>-</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>distance above limb Mm</td>
<td>-700</td>
<td>-14</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>$I \text{ erg/cm}^2/\text{s/sr}/\lambda$</td>
<td>$3 \times 10^5$</td>
<td>$1.5 \times 10^5$</td>
<td>$6 \times 10^4$</td>
<td>$3 \times 10^4$</td>
<td>$1 \times 10^4$</td>
</tr>
</tbody>
</table>

Looking at Figure 2, we see that $> 10^6$ photons would arrive, unattenuated, per square cm at the earth, per Å, in 1 second. The time series of primary interest is within about 20s after/before second/third contact, respectively, where unattenuated photon fluxes are $> 10^8$. If we assume that the overall efficiency of the combined effects of earth atmospheric absorption/telescope/fiber bundle/
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The spectrograph/camera is on the order of 1%, then there are $10^6$ photons/cm$^2$/s/Å. With an aperture of 10cm, the collecting area is 80 cm$^2$. For a spectrograph of resolution 15,000, camera pixels would need to span just $3968/30,000=0.13$ Å. With an exit pupil sampled by say 100 fibers, we have the total number of photons incident on the camera, per pixel (actually per column of pixels from each fiber), of

$$N \sim 10^6 \times 80 \times 0.13 /100 \sim 10^5$$

photons per second

If the exposure time is say 20 ms, each such “pixel” will acquire

$$n \sim 2000$$

photons,

so shot noise $\sigma \sim 44$ photons, and the noise is 2.2%. There are 100 such fiber images dispersed across the 2D detector, leading to a final noise estimate, per 20 ms exposure, of just 0.2%. This exceeds the requirement of 0.8% for a radial resolution of about 80 km. Flat fields and gain corrections must of course be known to a better precision than the above estimates.

**Preliminary instrument Concept**

From the above discussion, high spectrophotometric precision of a timeseries is critical to the recovery of the flux timeseries $f_\lambda(t)$. Any noise introduced into the time series at the level of 1% or so, seriously affects the results. Now seeing during eclipse is known to be poor. Given the steep gradients in the radial emission in the Ca II H line (particularly the wings), it seems advisable to avoid imaging the chromospheric arc altogether, and simply use a telescope to gather photons to feed a spectrograph to a photometrically stable detector.

The lack of imaging may seem a large price to pay, but consider the following. The seeing is expected to be poor (1” or worse). The telescope angular resolution is 0.8” (10cm aperture, 4000 Å). Spicules are unresolved at this resolution (de Pontieu et al 2007), and seeing-induced image motion removes hope of retrieving useful azimuthal information around the limb of the Sun, beyond what can be obtained from spacecraft such as Hinode and SDO.

A small (< 10cm) refracting telescope and wide-angle eyepiece can produce a collimated exit pupil to feed a fiber optic bundle. A field stop might be used at prime focus to sample just certain regions of the solar limb (a simple rectangular aperture), but this seems undesirable because seeing will induce variations in the observed parts of the sun with time, which are detrimental to the analysis. Thus no field stop is preferable. Indeed it is important that the telescope keep all the light from the pupil on the fiber bundle head–itself physically larger than the pupil size–in order that polarimetric stability be maintained, and that the pupil contain all of the light from the chromosphere and spicules all of the time (field of view should be at least 10% larger than the lunar diameter). If the exit pupil is 1mm (10cm telescope, f/10, 10 mm eyepiece), a bundle of a hundred or so 50 micron diameter optic fibers might be used to feed the entrance slit of an R=15,000 resolution grating spectrograph, observing just the region near the Ca II H line (396.8 nm). A camera running at 30 Hz frame rate (small format, 256x256 pixels would suffice) records spectra, keeping the Sun's disk fixed in the telescope prime focus, from a minute or so before and after second and third contact. The fibers serve to spread the circular pupil light into a slit configuration which is passed to the grating and camera. The 2D spectrum (wavelength vs fiber number) allows for high throughput, high s/n and much flat-fielding accuracy that is needed to differentiate the data with time. The resultant spectra will be flat fielded and...
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gain corrected using the Sun's disk before and after totality.

Illustration 3: schematic instrumental setup

Expected results/risks

The time series contains the spectrum of the entire annulus around the limb of the Sun, as seen in the Ca II H line, and in the absence of a field stop. The moon is 1.037 times the solar diameter at Cairns, i.e. about 26,000 km broader. First the chromosphere at one limb (E) is covered by the moon at 2nd contact, then the W limb chromosphere is uncovered during transition to 3rd contact (figure 2 shows the time series resulting from the eclipse). Thus near each contact just a half annulus will contribute to the spectrum in Ca II H (in the absence of prominences). By differentiating the data wrt time, we will obtain the average spectra as a function of projected radial height with a resolution of 13 km. These data will clearly reveal the switch from spicule to chromospheric plasma and their associated dynamic signatures, as a very accurate function of radius. Such data will address the problems of interpretation of spacecraft data by Judge & Carlsson (2010) and by Judge, Tritschler and Low (2011, in preparation).

Clouds/ variable atmospheric transmission present the most obvious challenges to the experiment. Irregularities in the lunar limb height (departures from a circular disk due to topography) have rms variations of about 5km, corresponding to projected heights of 2Mm at the Sun. Lunar topography is fixed and precisely known from surveyor missions, and can be accounted for in the inversion, and in any case the chromospheric arcs which dominate the emission close to second and third contact extend for a radian or so in azimuth, so that significant averaging will occur. Prominences bright in Ca II H will affect the time series, but their total emission varies on radial scales far larger than that associated with the passage of the lunar disk across the steep chromospheric drop-off, so that just small secular changes to the critical parts of the light curves (within 20s of second/third contact) are expected. The effects of solar and lunar oblateness are negligible.
References


Linsky, J. Ayres, T., 1976. “*The Mg II h and k lines II: Comparison with synthesized profiles and Ca II K*”, ApJ 205, 874