THE MYSTERIOUS SOLAR CHROMOSPHERE

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During the eclipse of August 16, 1868, Pierre JANSSEN first used a spectrometer and revealed unknown yellow line D3 587.6 nm in the spectrum of the solar chromosphere.

Later at the same year independently Joseph LOCKYER observed this line with his spectrometer out of eclipse. He suggested that this line would be the signature of a new and unknown element which he called “helium”.
“The chromosphere is the least-well understood layer of the Sun’s atmosphere. Until recent years, it could only be detected fleetingly during a solar eclipse. Now it has become more accessible with radio observations, birefringent filters, and ultraviolet observations from space. However, each one of these has shortcomings which has left much of its behavior a mystery.”

Studying of the chromosphere and corona demands inexhaustible optimism

van de Hulst
General Observational Data and Constraints

• In the chromosphere the temperature rises from 4000K in the temperature minimum to 1000000K in the corona.

• The chromosphere has a bright network structure in resonance lines, radio and UV. Enhanced vertical diverging magnetic fields occur in the network and lead to an excess of heating. Size of the network cell is 20-40 arcsec (15-30 Mm) and its interior has not any temperature increase. Higher up, the magnetic field is expected to expand and form a magnetic canopy when it connects with neighboring network field.

• The chromosphere is especially important because here the plasma changes its parameter \( \beta \) (ratio of gas and magnetic pressure) from being gas dominated to being dominated by the magnetic field.

• In chromosphere the apparent scale height of 1000 km far exceeded that in hydrostatic equilibrium.
• The height of the chromosphere in $H\alpha$ is about 5000 km, for Calcium H,K is the same, but sometimes these lines are seen up to 12000 km. And the height in $He\,D3$ and 1083 nm is much lower, about 1500 – 2000 km. But the $He$ excitation potential is so high and for $H$ and $Ca$ – much lower. Excitation of $He$ is difficult problem: either chromosphere is quite hot (more than 20000 K) or another mechanism, for example, coronal back-radiation. It is important to note that in the chromosphere there are strong non-LTE conditions. Observations of $CO$ near 4.7 micron show that the low-chromosphere contains a substantial amount of cool (3800 K) material.

• The thermal radio emission from the chromosphere covers wavelengths from 0.3 mm near the temperature minimum to about 4.5 mm near temperature step into the corona. The radio brightness temperature is between 6000 K to 8000 K. No limb brightening is seen.

• Oscillating behavior was first found in the chromosphere in the emission peaks of the Calcium H,K resonance lines. Such behavior of these lines in the inernetwork cells can only be explained by the effects of upward propagating acoustic waves that shock 1-1.5 Mm above the photosphere.

International Symposium on Chemical Physics of Low Temperature Plasmas in honour of Prof Mario Capitelli on the occasion of his 70th Birthday
Dynamics of the chromosphere: chromosphere network

Part of the “quiet Sun” chromosphere in CaII-K2 line:

left – snapshot, right – long exposed photo
Models of the solar chromosphere

Standard (stationary)


Semi-empirical, one-dimensional, static plane-parallel stratified non-magnetic atmosphere. Based on the observed temporally and spatially averaged continuum and resonance lines intensities in UV domain, where the intensity is not good measure of the local temperature in non-LTE conditions since the source function is deviated from Planck.

Dynamical


Non-static and non-magnetic chromosphere with upward propagating acoustic waves steepening into shocks at a height of about 1000 km where they produce temperature difference as great as 10000 K. But high temperature material exists only relatively briefly, so that the mean atmosphere in the CS model is a relatively constant 5000 K throughout most chromosphere. 1D-radiation hydrodynamics calculation with non-LTE radiative transport.
Solar chromosphere (VAL)


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Solar eclipse 1991, July 11 (La-Paz, Mexico)
RT-0.6, $\lambda 3.4$ mm, central phase

This result as well as other radio data convincingly gives the value of chromosphere height much more than from VAL model.
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In contrast with UV and optic emission the solar millimeter continuum is formed in LTE conditions with Planck source function in Rayleigh-Jeans approximation, so the intensity depends linearly on temperature and is due to bremsstrahlung (free-free emission). Thus the thermal mm radio emission is a very suitable to use thermometer for chromosphere and may be able to provide an independent test of models.

Comparing observational and calculated for various FAL models millimeter wavelengths spectra we conclude that UV data require a warmer model than the microwave data.
Mm-radio emission is very sensitive to the dynamic processes in the chromosphere if they are spatially and temporally resolved.

Emission in the range of 0.5-8 mm is most sensitive to the propagation of acoustic waves through the atmosphere.

Dynamic picture of the solar internetwork chromosphere is consistent with mm-wave brightness observations. The temporally average spectrum from CS-simulation provides a good fit to observed mm data.
We proposed a new diagnostic that is highly sensitive to dynamic effects (sampling both the hot and the cool gas in the chromosphere) and may be provided by observations at mm wavelengths with an acceptable angular resolution.

We carried out unique observations of chromospheric oscillations with the only interferometer till recently worked in the mm range which was used for solar observations – 10-elements Berkeley-Illinois-Maryland Array (BIMA) operated at 3.5 mm wavelength.

With BIMA data we have constructed 2D-maps of the quiet chromosphere with the highest angular resolution of 10 arcsec achieved so far at this wavelength for solar observations. We compared them with the intensity variations expected from CS-model.
The solar chromosphere at the center of the solar disk at 4 different wavelengths on May 18, 2004.

From top left to bottom right:
- MDI longitudinal photospheric magnetogram,
- TRACE 1600A image,
- CaII K-line center image from BBSO and
- BIMA image at 3.5 mm.

The images are created by averaging over the 3.5h period of the BIMA observation.
Fourier and wavelet analyses of the BIMA data revealed the presence of intensity oscillations with RMS brightness temperature amplitudes of 50-150 K in the frequency range 1.5-8 mHz. We were able to distinguish between the properties of network and cell interiors.

**Derived periods of max power N(P), P – period**

- **QS**: $P = 200-350$ s
- **IN**: $P = 210-270$ s
- **NW**: $P = 270-330$ s, $P = 510-570$ s

Chromospheric Oscillations from Quiet Sun Millimeter Observations
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Histograms of the period of maximum power for the quiet Sun internetwork (solid line) and network (dashed line).
Oscillations at the internetwork location:

a) the histogram of observed brightness.

b) Fourier power spectrum as a function of frequency.

c) wavelet power spectrum as a function of time and period (grey scale).

Cross-hatched regions indicate the cone of influence, where the nearby boundary affects the reliability of the results. Thin solid lines in b) and c) represent the 99% significance level of oscillations.

Significant oscillations are found at the frequencies of 4.5 mHz (220 s), 6.0 mHz (167 s), 2.5 mHz (400 s).
Conclusion

Our results point out the need for further millimeter interferometric observations with longer sequences and higher angular resolution, which are a promising diagnostic of chromospheric structure and dynamics. Particularly exciting are the prospects of observing with ALMA – Atacama Large Millimeter Array, - which will provide angular resolution in the range 0.015-1.4 arcsec for 0.3 -5 mm domain. This would be better than any existing facility for solar observations. ALMA will be able to observe at wavelengths where the CS model predicts that the largest observable effects will be seen.

The development of realistic three-dimensional radiation magneto-hydrodynamic simulations is also highly desirable.
They plan to link three antennas by early 2010, and to make the first scientific observations with ALMA in the second half of 2011.

ALMA

66 antennas 12 m diameter, placed on the Atacama plateau (Chili), 5000 m above see
Thank you
My hot congratulations to Professor Mario CAPITELLI!