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Observations of the solar chromosphere at millimeter wavelengths

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Abstract. Millimeter wavelengths provide a powerful tool to study the thermal structure of the solar chromosphere and its response to dynamic processes. We present initial studies of chromospheric fine structure and its dynamics obtained from observations of the quiet Sun with BIMA at 3.5 mm with a resolution of 12″. The two-dimensional millimeter maps of the solar chromosphere reveal brightness features corresponding to supergranular network boundaries and bright points within cells. Significant intensity oscillations with frequencies of 1.5 – 8.0 mHz with a tendency toward shorter-period oscillations in the internetwork and longer periods in network regions are found in the data. However, higher spatial resolution is required for a more detailed study. We discuss the requirements imposed on observations in the millimeter domain that might provide an insight into the fundamental questions of solar physics. We also review the capabilities of the current and future millimeter-wave interferometers, including the CARMA and ALMA arrays.

Key words. Sun: chromosphere – Sun: radio radiation

1. Introduction

The Sun is a strong radio source and radio observations can provide information on different structures throughout the solar atmosphere. As every frequency becomes optically thick at various points in the solar atmosphere, radio frequencies probe different atmospheric layers. Moreover, radio images continuum intensity can often be interpreted directly as temperature maps without the complications of non-equilibrium line formation that have to be taken into account when analyzing visible and UV line observations of the chromosphere. At submillimeter wavelengths we can probe the temperature minimum region and at millimeter wavelengths we get access to the chromospheric layers. At these wavelengths the Sun radiates due to the thermal free-free mechanism, which is well understood, and its opacity is provided by collisions of electrons with ions and neutral atoms. Since collisional opacity depends on the square of density, this mechanism is also a density diagnostic.

2. Observations

2.1. Single-dish observations and comparison with model simulations

Observations and mapping of the Sun at mm/submm wavelengths with single-dish tele-

Send offprint requests to: M. Loukitcheva scopes has a long history since the initial observations in the 1960s, but they have always suffered from the limited angular resolution of the single–dish technique: for typical dish sizes in the range of 10 – 15 m the resulting resolution is of the order 1′ at λ = 3 mm (Loukitcheva et al. 2004). The problem of frustratingly low resolution can be overcome by observing at shorter wavelengths (submillimeter), which is possible with the James Clerk Maxwell Telescope (JCMT) and Caltech Submillimeter Telescope (CSO) on Mauna Kea, Hawaii. These telescopes have been able to make images of the solar disk at submillimeter wavelengths with a spatial resolution as small as 20″ (e.g., Lindsey et al. 1995). Another solution is to observe the Sun with bigger antennas. Thus, the Nobeyama 45 m-telescope has been able to achieve a similar resolution of 20″ at 3 mm for solar observations (Irimajiri et al. 1995).

Loukitcheva et al. (2004) used a collection of quiet-Sun brightness measurements at mm and submm wavelengths from the literature and compared them with the output of the classical semi-empirical models (FAL, Fontenla et al. 1993) and dynamical models of Carlsson & Stein (1995, hereafter CS). The dynamic picture of the solar non-magnetic chromosphere, described in the simulations of CS, was found to be consistent with single-dish (low-resolution) millimeter and submillimeter brightness observations. However, a combination of FAL models also reproduced the (low-resolution) data relatively well.

Analyzing millimeter emission from a dynamic chromosphere, we found that the brightness temperatures are extremely time-dependent at millimeter wavelengths. Dynamic effects such as shock wave propagation can considerably change the height at which the dominant contributions to emission occur. We identified the 0.8 – 5.0 mm wavelengths as the most appropriate one to look for the clearest signatures of dynamic effects. Our analysis demonstrates that spatially and temporally resolved observations should clearly exhibit the signatures of the strong shock waves found in the dynamic models, if they are truly present in the quiet Sun.

2.2. Interferometric observations

Spatially and temporally resolved solar images can be obtained by using interferometric mapping methods. Interferometer observations of the (non-flaring) Sun at millimeter wavelengths have been carried out since the 1970s, but generally not with a sufficient number of telescopes. The 10-element Berkeley-Illinois-Maryland Array (BIMA, Welch et al. 1996) operating at a wavelength of 3.5 mm (frequency of 85 GHz) for a long time offered the largest number of dishes of any existing millimeter interferometer, and was the telescope best suited for such observations.

3. Results

3.1. First interferometric observations of the chromosphere

In 2003 – 2004 we obtained two sets of time-resolved images of the Sun at a wavelength of 3.5 mm with the BIMA array. After extensive analysis of interferometric image reconstruction issues we demonstrated that it is possible to map the solar chromosphere with a millimeter interferometer and, furthermore, provided the first observations of spatially-resolved chromospheric oscillations at mm wavelengths (White et al. 2006; Loukitcheva et al. 2006), opening up a new method for studying heating in the Sun's atmosphere. The mm maps were constructed using a maximum entropy deconvolution method (MEM) and restored with a Gaussian beam of 12″, which represents the highest spatial resolution achieved so far at this wavelength for non-flare solar observations.

Figure 1 depicts the quiet solar chromosphere at two wavelengths representing different conditions in the atmosphere. The UV image from TRACE in the 1600 Å channel (top) and the BIMA image at 3.5 mm (bottom) correspond to the temperature minimum region and the height of the middle chromosphere, respectively. The mm image has a spatial resolution of 12″, while the resolution of the UV image is about 1–2″. The similarity of the brightness structures, which is very prominent, implies that the BIMA resolution is not adequate to resolve the fine structure at millimeter wave-

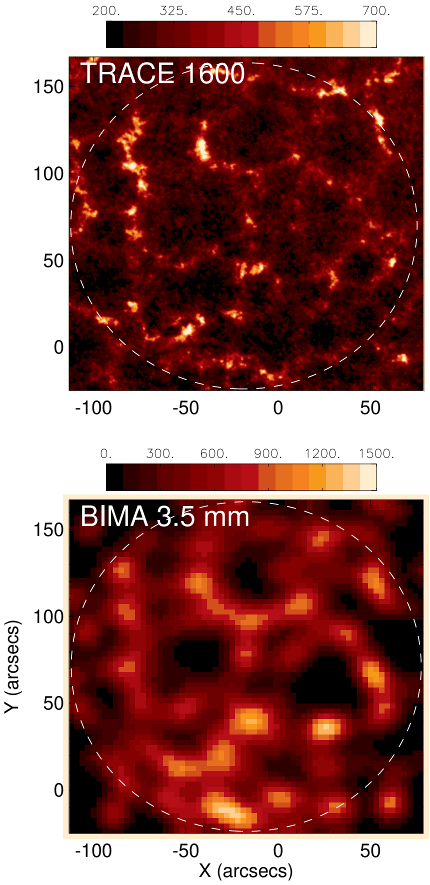

Fig. 1. Portrait of the solar chromosphere at two different heights. *From top to bottom*: UV image from TRACE in the 1600 Å channel and the BIMA image at 3.5 mm. Dashed circles mark the 96″ radius BIMA FOV where we regard fluxes to be reliable. *X* and *Y* axes are in arcsec from the disk center, which is located at (0, 0).

lengths. With the current resolution the contrast of the brightness structures is observed to be up to 30% of the quiet-sun brightness. The mm image shows the classical network structure in the chromosphere with a high degree of correlation with other chromospheric intensity maps (UV at 1600 Å and Ca II K-line intensities) and the photospheric magnetic field from MDI magnetograms.

The time-series analysis of the BIMA data revealed the presence of intensity oscillations with typical amplitudes less than 150 K (2% of quiet-Sun brightness) in the range of periods from 120 to 700 seconds (frequency range 1.5 – 8.0 mHz). We found a tendency toward short period oscillations in internetwork and longer periods in network regions of the quiet Sun, which is in good agreement with the results obtained at other wavelengths. At 3 mm, the inner parts of the chromospheric cells exhibit behaviour typical of the internetwork with the maximum of the Fourier power in the 3-minute range. However, most of the oscillations are not in the form of steady harmonic waves but wave trains of finite duration lasting for typically 1–3 wave periods.

The chromospheric observations done with BIMA demonstrate the potential that we can expect of solar observations with more powerful millimeter telescopes. Processing of the BIMA data has also revealed a number of peculiarities of chromospheric observations with an interferometer, which should be taken into account in the future observations (e.g., White et al. 2006). Due to the dynamic nature of the chromosphere, it was not clear *a priori* that millimeter interferometer imaging observations of the quiet Sun would be successful. The solar chromosphere is the toughest possible target for an interferometer, since it completely fills the field-of-view with low-contrast but time-varying features. We found that for such a target the best method for making snapshot maps is to use maximum-entropy deconvolution with a default image based on a long integration that contains enough information to reconstruct the spatial brightness distribution. Deconvolution from snapshot images without a default model did not work. We carried out extensive tests of the sensitivity of the data w.r.t. oscillation power and find that this method can see sources with intensity variation amplitudes less than 10% of the brightest feature in the field, as long as the source is located where there is significant flux in the default image. We explain this result as an artifact of the positivity constraint employed in many maximum-entropy algorithms: the zero level in the default image is set by the darkest feature in the field of view, and an oscillating source located in a region of weak emission that becomes negative can cause the effective zero level of the brightness distribution to change.

We would like to mention two important observational constraints that are set by the chosen method of image restoration. First of all, our results for weaker internetwork features, located in the regions of low flux, are at the limit of data accuracy and should be taken with caution. The image restoration procedure can lead to underestimation of the flux in the internetwork since the dynamical behavior in regions of low flux is not as well recovered as in regions of high flux. On the other hand, the spatial resolution of the BIMA images is not adequate to resolve bright internetwork features within dark areas and many of them carry an admixture from the neighboring brighter locations. The solution lies in better antenna spacing (to completely sample the spatial structure within the field of view at any instant), which means more elements in an array and more configurations than BIMA can provide.

The second concern is that the analysis of time-resolved data found significant low-frequency power with periods longer than 10 minutes. Part of these low-frequency fluctuations can be seen in the antenna total power and may be due to atmospheric effects, such as clouds affecting the sky opacity enough to distort the total power. BIMA did not provide real-time correction for such total power variations. In general, the low-frequency power is not to be trusted because of the positivity-constraint issue that moves the whole image up and down. This happens because the interferometer is insensitive to the total flux, and we need accurate single-dish measurements to restore it. We conclude that using of MEM for image restoration is appropriate for chromospheric observational data as it is the only method that can deal with large – scale flux, but the positivity constraint limits the applicability of the results and alternative versions of MEM are needed for future applications.

3.2. Requirements for the chromospheric observations

Here we summarize the requirements for the chromospheric observations that might be able to uncover the nature of the chromosphere taking into account prior observations, results of model simulations (Loukitcheva et al. 2008) and lessons taught by the first interferometric data analysis (White et al. 2006).

Frequency coverage: The appropriate range of mm wavelengths to look for the observational signatures of the shock waves dissipating in the solar chromosphere is 0.8 – 5.0 mm. Multiband observing capability is valuable for the study of the wave mode propagation.

Precise imaging at high ($0''.1$) resolution: The ability to image with $0''.1$ resolution will allow us to obtain solar data with a resolution on the order of other existing instruments operating in the UV or optical. It will provide access to the fine millimeter brightness structure associated with the shocks in a dynamic chromosphere. However, observations must always retain information on short-spacing flux or imaging will be unsuccessful.

Temporal resolution: Chromospheric fine structure is known to evolve on the timescale of several tens of seconds, which implies that a temporal resolution of about one second is required. Shorter timescales may be present in flares and dynamic filaments.

High fidelity imaging: The chromospheric thermal structure should be imaged with high dynamic range, fidelity and spatial- resolution, with good sensitivity to both compact and extended sources. The instrument must be capable of producing high-quality images on a time scale of seconds.It is also important to have the ability to observe in total-power mode, and thereby derive the short-spacing information necessary for absolute temperature measurements.

Accurate calibration: In addition to general calibration procedures, attention must be paid to calibration of solar observations that are in a different power regime than normal cosmic observations, as well as successful calibration of the time-variable contribution of the sky.

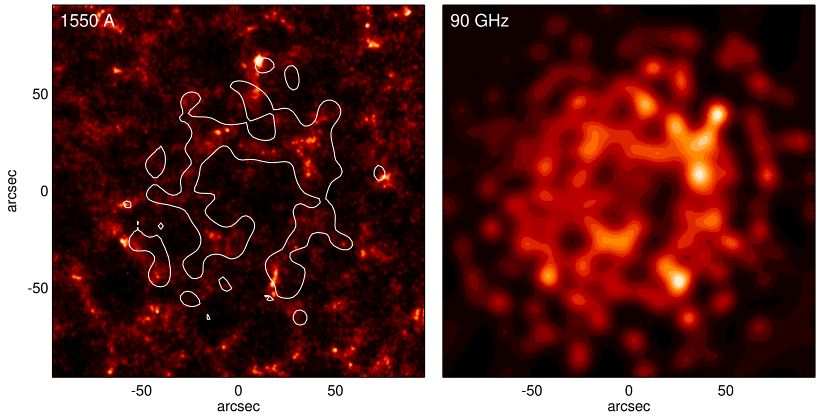

Fig. 2. Images of the solar chromosphere, taken on September 26, 2008. *left:* TRACE image at 1550 Å with the overlaid radio contours; *right:* CARMA image at 90 GHz.

Deconvolution techniques: More development is needed in the area of techniques used for deconvolution and image restoration, potentially combining the advantages of the MEM and CLEAN methods without the problem of the positivity constraint.

3.3. Present day and future mm-submm interferometric arrays

Among several radio interferometers that are under development or recently constructed, there are two that are worth detailed consideration: the CARMA and ALMA arrays.

3.3.1. CARMA

The Combined Array for Research in Millimeter-wave Astronomy (CARMA, Beasley 2004) was created through the merger of the Owens Valley Radio Observatory (OVRO) Millimeter Array and the Berkeley-Illinois-Maryland Association (BIMA) Array, and eventually including the Sunyaez–Zeldovich Array (SZA). CARMA consists of six 10.4-meter, nine 6.1-meter, and (potentially) eight 3.5-meter antennas, that are used in several combinations. The angular resolution is as high as $0\farcs15$ at 230 GHz in its A-configuration. Due to the larger number of antennas, observations with CARMA can result in better maps of the chromosphere than those available from BIMA. Moreover, CARMA provides real-time correction for total power variations which was missing in BIMA observations. Imaging using CARMA data is not straightforward as the instrument antennas each have a different field of view (FOV); the array consists of 9 dishes with a 120″ primary beam and 6 dishes with a 70″ beam at $\lambda = 3$ mm. Several attempts at mapping of the solar chromosphere with CARMA, have failed at the deconvolution stage when using the same technique (MEM) that worked well for the BIMA data. However in September 2008 we obtained data which have been successfully reconstructed. In Fig. 2 we show the chromospheric map of the QS region, obtained with CARMA at 90 GHz, together with a TRACE image at 1550 Å with the overlaid millimeter contours to stress the similarities in brightness. Absolute amplitude calibration of the CARMA data remains uncertain, but CARMA data have the potential to be a powerful tool for chromospheric studies.

3.3.2. ALMA

The Atacama Large Millimeter/submillimeter Array (ALMA, Brown et al. 2004) is an inter-

Table 1. Basic characteristics of the ALMA frequency bands which are most useful for chromospheric studies.

Band	λ range (mm)	resolution range [″]	continuum sensitivity [mJy]	primary beam [″]
3	2.6 – 3.6	3.0 – 0.034	0.060	56
4	1.8 – 2.4	2.1 – 0.023	0.070	48
5	1.4 – 1.8	1.6 – 0.018	1.3	35
6	1.1 – 1.4	1.3 – 0.014	0.14	27
7	0.8 – 1.1	1.0 – 0.011	0.25	18

national radio telescope under construction in the Atacama Desert of northern Chile. ALMA is situated on a dry site at 5 000 m elevation, allowing excellent atmospheric transmission over the instrument wavelength range of 0.3 to 10 mm. The instrument will provide both interferometric and total-power measurements. ALMA consists of two parts; the "12-m array", which is an array of 12-m diameter antennas, with up to 64 antennas (baselines extend from 20 m to 15 km). There is also the ALMA Compact Array (ACA) which consists of four 12-m antennas. usually used in single-dish mode, and twelve 7-m antennas, which might be operating separately or together with the 12-m array. A summary of the ALMA specifications referring to the frequency bands that are important for the solar studies can be found in Table 1. In the most compact configurations, which will be used during the Early Science stage, spatial resolution will range from 0.″4 to 2.″8 depending on wavelength. ALMA will be able to measure circularly polarized signals, which is very important for solar studies since it permits measurements of the chromospheric magnetic field that have not previously been available in the millimeter range. Commissioning and Science Verification of the ALMA project will be done throughout 2010 and the Early Science will start in the second half of 2011 with at least 16 antennas and 4 receiver bands.

4. Summary

Millimeter and submillimeter observations provide a powerful tool to study the solar chromosphere. The time when we will be able to obtain millimeter images of the chromosphere that would be directly comparable with the images from other spectral domains is radidly approaching. We can look forward to improved CARMA data and the start of ALMA operations, which finally will allow the mapping of the three-dimensional thermal structure of the solar chromosphere.

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