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Observations of the solar chromosphere with ALMA and comparison with theoretical models

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Abstract

In this work we use solar observations with the ALMA radio telescope at the wavelength of 1.21 mm. The aim of the analysis is to improve understanding of the solar chromosphere, a dynamic layer in the solar atmosphere between the photosphere and corona. The study has an observational and a modeling part. In the observational part full-disc solar images are analyzed. Based on a modified FAL atmospheric model, radiation models for various observed solar structures are developed. Finally, the observational and modeling results are compared and discussed.

1 Introduction

The Atacama Large Millimetre/submillimetre Array (ALMA)[1] is currently the world largest ground-based astronomical facility, capable of observing almost all types of celestial objects including the Sun (Kobelski *et al.*, 2016; Bárta *et al.*, 2017; Bastian *et al.*, 2018). The main advantage of solar observations with ALMA is mapping of the solar chromosphere with an unprecedented spatial, temporal, and spectral resolution in the wavelength range between 0.3 mm and 8.6 mm (Wedemeyer *et al.*, 2016; Shimojo *et al.*, 2017; White *et al.*, 2017). Solar measurements are currently limited to two observing bands centered at 1.3 mm (239 GHz, Band 6) and 3 mm (100 GHz, Band 3) (Brajša *et al.*, 2018).

A valuable and unique property of solar ALMA measurements is its capability to be used as an approximately linear thermometer of plasma in the solar atmosphere (Wedemeyer *et al.*, 2016). So, the measured brightness temperature (the intensity of radiation) is directly proportional to the gas temperature of the observed structure or layer in the solar atmosphere. The formation height of the continuum radiation increases with increasing observing wavelength which enables very accurate measurements of the solar chromosphere's temperature as a function of height. The topic is important for solar physics, but it is important for stellar physics too, since the Sun is representative for the whole class of solar-like and other late-type stars (Aschwanden *et al.*, 2008; Liseau *et al.*, 2016).

[1]http://www.almaobservatory.org

This study has an observational and a modeling part. In the observational part, data reduction is performed on Commissioning and Science Verification (CSV) data taken during several test campaigns in previous years and made publicly available in 2017. Models of various observed solar structures were developed and compared with actual ALMA observations. Radiation models are based on modified FAL atmosphere models with thermal bremsstrahlung as the dominant mechanism responsible for the emission at ALMA wavelengths. A comparison of observations and models enables precise constraints on plasma properties in the solar atmosphere.

2 Solar ALMA observations and measurements of the brightness temperature

In present analysis we use fast-scan single-dish mapping of the Sun. The observing method, calibration, calculation of the brightness temperature and producing full-disc solar images are described in detail by White *et al.* (2017).

Many Commissioning and Science Verification (CSV) data of solar observations with ALMA were released to the scientific community in 2017[2]. We have used an image of the whole solar disc from December 18th, 2015 taken with a 12 m single dish total power ALMA antenna at a frequency of 248 GHz corresponding to $\lambda = 1.21$ mm in a double circle pattern (Brajša *et al.*, 2018). The measurement frequency/wavelength is in Band 6. The beam size amounts to 26 arcsec and the

[2]https://almascience.eso.org/alma-data/science-verification

ALMA solar map used here is presented in Fig. 1 in the paper by Brajša *et al.* (2018) compared with corresponding full-disc solar images in EUV (AIA-SDO data) and Hα and with the solar magnetogram (HMI-SDO data).

In the full-disc solar ALMA image at 1.21 mm (Fig. 1a in Brajša *et al.* (2018)) several regions of interest were identified. They correspond to the quiet Sun areas, active regions, sunspots, filaments (prominences on solar disc), magnetic inversion lines and coronal holes. The areas of typical representatives of those solar structures were reduced, so that their average brightness temperature could be measured.

We performed a qualitative and a quantitative analysis of the solar ALMA image. Qualitatively we concluded that at 1.21 mm active regions are bright, but a sunspot within the active region appears dark. The inversion lines of the large scale magnetic field are dark at 1.21 mm and the ALMA structures outline also the shape of these objects. Finally, filaments and coronal holes can be barely visually discerned from the quiet Sun background.

Quantitatively we found following results: the brightness temperature of the quiet Sun region at the solar disc centre was measured to be 6040 K at 1.21 mm. This is fully consistent with the central brightness temperature determined by White *et al.* (2017) for the 2015 data: $T_b = 6040 \pm 250$ K. Further, a limb brightening of quiet Sun regions, up to 10% was measured, in general agreement with some previous results for this wavelength range. The measured active region (Table 1 in Brajša *et al.* (2018)) had a higher brightness temperature than surrounding areas by about 1000 K. In the sunspot 90 K depression relative to the quiet Sun intensity at the same radial distance from the solar disc centre was measured. The magnetic inversion lines, filaments and coronal holes all had smaller brightness temperatures compared to the quiet Sun levels at their corresponding radial distances from the disc centre. Their relative intensities were: $\Delta T_b = -170$ K (magnetic inversion line), $\Delta T_b = -110$ K (filament), and $\Delta T_b = -50$ K (coronal hole).

Finally, we studied the small bright isolated structures in the ALMA 1.21. mm solar image (Brajša *et al.*, 2018). These are the so called ALMA bright points and they have a high overlapping rate with coronal bright points (AIA-SDO 19.3 nm), He I 1083 nm dark points (NSO-SOLIS), and small-scale magnetic features (SDO-HMI). Presently we do not have a quantitative analysis of ALMA bright points and this work is in progress.

3 Modeling of the brightness temperature for various solar structures

Thermal bremsstrahlung is the dominant radiation mechanism assumed in present analysis. With decreasing wavelengths the optical depth $\tau = 1$ is reached at lower heights in the solar atmosphere with lower temperatures. Our investigation is based on the models of Fontenla *et al.* (1993), describing average models that agree reasonably well with radio observations (Bastian *et al.*, 1996). The average model is then disturbed to find the necessary deviations for the observed structures yielding the physical parameters differing from the characteristics of the quiet solar atmosphere.

The calculation was performed using a program that computes the brightness temperature for a defined wavelength and stores the increase in brightness temperature per unit height in an array. Then, the program integrates these contributions and yields the total brightness temperature for the given wavelength. Finally, the procedure is repeated for all wavelengths under consideration.

Our starting model of the solar chromosphere and corona is the *FAL model A* (Fontenla *et al.*, 1993), combined with the Baumbach-Allen coronal model at high altitudes using an electron temperature $T_e = 1.2 \cdot 10^6$ K (Benz *et al.*, 1997). This model roughly describes the structure of a coronal hole (Brajša *et al.*, 2007), and we use it in the present analysis as a model of the quiet Sun (Model QS).

3.1 Active regions

The higher brightness temperature in active regions is primarily a consequence of enhanced density in the chromosphere and corona. This shifts the $\tau = 1$ point to higher altitudes where the temperature is higher. Above active regions, at the heights from 100 km to 80 000 km, the solar atmosphere has density and temperature values which are different from those above the quiet Sun regions. Three active region models were developed and in all three cases the temperature is higher by factor of 2, while the density is larger by the factors of 5, 7, and 10. All three active region models have significantly higher brightness temperatures than the quiet Sun in the whole ALMA wavelength range. Thus, active regions should appear very bright at ALMA wavelengths.

The preliminary results are presented in Fig. 2b in the paper by Skokić *et al.* (2017). We can see that the brightness temperature of all three active region models at the wavelength of about 1 mm are higher by about 7000 K than the quiet Sun level.

3.2 Prominences on solar disc (filaments)

Taking into account the physical parameters of prominences (Engvold *et al.*, 1990; Tandberg-Hanssen, 1995) we develop six prominence models. Prominences are denser and cooler structures in the solar atmosphere. The prominence models assume hydrostatic equilibrium and thus pressure is conserved at a given altitude. So, the values of the density, n, are multiplied by a factor f and the values of the temperature, T, are divided by the same factor f (Parenti, 2014). This factor f amounts to f=80, f=120, f=160, f=200, f=240, f=280, for the six prominence models, at the prominence heights from 40 000 km to 50 000 km, which are typical prominence heights, see, e.g., Bastian *et al.* (1993) and Brajša *et al.* (2009).

The calculated brightness temperatures for the six prominence models are presented as a function of wavelength in Fig. 3a in the paper by Skokić *et al.* (2017). We see that for some models there are two radiation regimes: absorption and emission, dependent on the wavelength. At some specific wavelength, depending on the model, filaments become invisible against the background radiation of the quiet Sun and a transition from absorption to emission takes place. At the wavelength of about 1 mm the curves (the brightness temperature vs. wavelength) converge and some models predict a small excess in intensity, while one model remains slightly below the quiet Sun level.

3.3 Coronal holes

Our starting model of the quiet Sun describes the conditions similar to the coronal hole atmosphere. We now construct deviations from the coronal hole model by changing the values of the density and temperature towards the structure of the quiet non-hole chromosphere and corona. These models which simulate various non-hole structures will be referred to as non-hole models. We develop four quiet non-hole solar atmosphere models taking into account that coronal holes are regions of lower temperature and density in the solar corona. For the non-hole atmosphere, the hybrid network model of Gabriel (1992) is used. Temperature and density parameters used for constructing these models are based on various studies from the literature.

The resulting brightness temperatures for all models (coronal hole and 4 non-hole models) are shown in Fig. 3b in the paper by Skokić *et al.* (2017). It can easily be seen that there is no significant difference in predicted intensity between the quiet Sun and coronal holes for the main ALMA wavelength range (wavelengths from 3 mm to 0.3 mm, corresponding to bands 3 to 10). The difference becomes smaller with decreasing wavelength and the curves converge in the mm wavelength range.

Finally, we note that the modeling part of this work is performed within the SSALMON[3] international scientific network (Wedemeyer *et al.*, 2015a,b). Modeling efforts so far, relevant for the present analysis, are described in a preliminary form by Skokić *et al.* (2017) and further work is currently underway.

4 A comparison of observational and theoretical results, discussion and concluding remarks

In the present analysis we calculated also the brightness temperature of the quiet Sun for the ALMA wavelength range, but we note that the determination of the absolute quiet Sun level is not an easy task, both theoretically and experimentally (White *et al.*, 2017). So, we will make a comparison between the observed and calculated results only relatively, as differences from the quiet Sun level. We now summarize these results for the three analyzed structures in the solar atmosphere: active regions, prominences on the disk and coronal holes, for the wavelength of 1.21 mm.

The observed active region had a brightness temperature higher than the quiet Sun level by about 1000 K. However, the calculated value is much higher, about 7000 K. This indicates a qualitatively correct result, but of a much larger calculated value than the measured one. The model could be improved by taking smaller values of temperature and density increase and by checking how the range of integration (which corresponds to the height and position of the active region in the solar atmosphere) influences the calculated brightness temperature.

For prominences on the disc the measured value indicates a slight absorption (a negative difference to the quiet Sun level of about 100 K) which is consistent with only one (out of six) prominence models with the highest factor for increasing the density and decreasing the temperature. One possible interpretation is that the observed prominence has the parameters which put into the model reproduce the measurements in the best way. The possibility that other prominences would behave differently can not be excluded and further observations are needed.

Coronal holes have a very small negative difference between the measured values inside the hole and the surrounding quiet Sun areas. This is fully consistent with theory as we have seen that all models (coronal hole and non-hole) converge at mm wavelengths. It should also be noted that it is not always trivial to determine the borders of coronal holes from observations, in spite of huge improvement of modern detection techniques. Special care should be taken to avoid possible misidentifications. Moreover, coronal holes are rarely fully homogeneous structures. Small localized brightennings often appear within them (Brajša *et al.*, 2007; Selhorst *et al.*, 2017) which should be taken into account in ALMA image analysis and comparison with other data, as well as in modeling efforts.

In present work we have described observational and modeling efforts to reconstruct and interpret full-disc solar images at the wavelength of 1.21 mm recorded with ALMA. The work will be continued by including other observing bands, adding the interferometric analysis and refining theoretical models.

[3]https://www.ssalmon.uio.no

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References

Aschwanden, M. J., Stern, R. A., & Güdel, M. 2008, ApJ, 672, 659.

Bárta, M., Skokić, I., Brajša, R., & Czech ARC Node Team 2017, In *Ninth Workshop 'Solar Influences on the Magnetosphere, Ionosphere and Atmosphere', proceedings of the conference held 30 May-3 June, 2017 in Sunny Beach, Bulgaria. Edited by K. Georgieva, B. Kirov and D. Danov. ISSN 2367-*

7570, 2017, p. 127-132, edited by K. Georgieva, B. Kirov, & D. Danov, pp. 127–132.
Bastian, T. S., Bárta, M., Brajša, R., Chen, B., Pontieu, B. D., *et al.* 2018, The Messenger, 171, 25.
Bastian, T. S., Dulk, G. A., & Leblanc, Y. 1996, ApJ, 473, 539.
Bastian, T. S., Ewell, M. W., Jr., & Zirin, H. 1993, ApJ, 418, 510.
Benz, A. O., Krucker, S., Acton, L. W., & Bastian, T. S. 1997, A&A, 320, 993.
Brajša, R., Benz, A. O., Temmer, M., Jurdana-Šepić, R., Šaina, B., *et al.* 2007, SoPh, 245, 167.
Brajša, R., Romštajn, I., Wöhl, H., Benz, A. O., Temmer, M., *et al.* 2009, A&A, 493, 613.
Brajša, R., Sudar, D., Benz, A. O., Skokić, I., Bárta, M., *et al.* 2018, A&A, 613, A17.
Engvold, O., Hirayama, T., Leroy, J. L., Priest, E. R., & Tandberg-Hanssen, E. 1990, In *IAU Colloq. 117: Dynamics of Quiescent Prominences*, edited by V. Ruzdjak & E. Tandberg-Hanssen, *Lecture Notes in Physics, Berlin Springer Verlag*, vol. 363, p. 294.
Fontenla, J. M., Avrett, E. H., & Loeser, R. 1993, ApJ, 406, 319.
Gabriel, A. 1992, In *NATO Advanced Science Institutes (ASI) Series C*, edited by J. T. Schmelz & J. C. Brown, *NATO Advanced Science Institutes (ASI) Series C*, vol. 373, p. 277.
Kobelski, A., Bastian, T. S., Bárta, M., Brajša, R., Chen, B., *et al.* 2016, In *Coimbra Solar Physics Meeting: Ground-based Solar Observations in the Space Instrumentation Era*, edited by I. Dorotovic, C. E. Fischer, & M. Temmer, *Astronomical Society of the Pacific Conference Series*, vol. 504, pp. 327–329.
Liseau, R., De la Luz, V., O'Gorman, E., Bertone, E., Chavez, M., *et al.* 2016, A&A, 594, A109.
Parenti, S. 2014, Living Reviews in Solar Physics, 11, 1.
Selhorst, C. L., Simões, P. J. A., Oliveira e Silva, A. J., Giménez de Castro, C. G., Costa, J. E. R., *et al.* 2017, ApJ, 851, 146.
Shimojo, M., Bastian, T. S., Hales, A. S., White, S. M., Iwai, K., *et al.* 2017, SoPh, 292, 87.
Skokić, I., Brajša, R., Sudar, D., Kuhar, M., & Benz, A. O. 2017, In *Ninth Workshop 'Solar Influences on the Magnetosphere, Ionosphere and Atmosphere', proceedings of the conference held 30 May-3 June, 2017 in Sunny Beach, Bulgaria. Edited by K. Georgieva, B. Kirov and D. Danov. ISSN 2367-7570, 2017, p. 121-126*, edited by K. Georgieva, B. Kirov, & D. Danov, pp. 121–126.
Tandberg-Hanssen, E. (ed.) 1995, *The nature of solar prominences*, *Astrophysics and Space Science Library*, vol. 199.
Wedemeyer, S., Bastian, T., Brajša, R., Barta, M., Hudson, H., *et al.* 2015a, Advances in Space Research, 56, 2679.
Wedemeyer, S., Bastian, T., Brajša, R., Barta, M., & Shimojo, M. 2015b, In *Revolution in Astronomy with ALMA: The Third Year*, edited by D. Iono, K. Tatematsu, A. Wootten, & L. Testi, *Astronomical Society of the Pacific Conference Series*, vol. 499, p. 341.
Wedemeyer, S., Bastian, T., Brajša, R., Hudson, H., Fleishman, G., *et al.* 2016, SSRv, 200, 1.
White, S. M., Iwai, K., Phillips, N. M., Hills, R. E., Hirota, A., *et al.* 2017, SoPh, 292, 88.