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# Rotation of the low temperature regions (LTR) at 8 mm

## Abstract

**Background:** In this work, we investigate rotation of the low temperature region (LTR) of the Sun at the radio wavelength of 8 mm. The temperature of these areas is less than the quiet Sun temperature (8200 ± 500 K at 8 mm). We found 100 representative LTR sources. The analyzed data is obtained from solar radio maps (Metsähovi Radio Observatory, Aalto University, Finland). The data is recorded between 1989 and 2014 both during the solar maximum and minimum. Our results show that the rotation rates of LTRs match the best with the coronal holes rotation. Our results also show that the rotation is quite rigid.

**Keywords:** differential rotation, coronal holes, quiet Sun, low temperature region (LTR), solar cycle

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## Introduction

Coronal holes (CH) are the areas of low temperature, density and pressure. They can be seen darker than the quiet Sun area (QSA)[1] at Extreme ultraviolet (EUV) range. CH have been studied very comprehensively,[2] and also at radio wavelengths[3] by using data from Metsähovi Radio Observatory (MRO). CH structures in area of the high brightness temperature regions (HTR) have also studied earlier[4] with MRO data. Behaviour of the solar cycle is not yet understood comprehensively. For instance, some physical unsolved issues are related to the corona. A coronal heating question is still one major problem. The atmospheric rotation rates could help on this. Data series, as presented here, could give new information about the structure of the corona holes. Several investigations have showed that the coronal magnetic field rotates more rigidly than the photosphere.[2,5] This is suggested caused e.g. by the magnetic reconnection at coronal hole boundaries.[6]

LTRs have earlier been used as determining the solar differential rotation at 8 mm.[7] Just recently, there has been an aim to observe one solar radio map each day in MRO (http://www.metsahovi.fi/solar–gallery, 29.05.2018). Thus, compared with the previous studies, we now have more extensively data collection, especially longer observing tracks (5–7 days).

## Instrumentation and observations

The Metsähovi RT–14 telescope at the Metsähovi Radio Observatory (MRO), Aalto University (Helsinki Region, Finland, GPS: N 60 13.04 E 24 23.35) has a Cassegrain type antenna with a diameter of 13.7 meters. The working range of the telescope is 2–150 GHz (13.0 cm–2.0 mm). The antenna provides full disk solar mapping, partial solar mapping and, additionally, the ability to track any selected point on the solar disk. The beam size of the telescope is 2.4 arc min at 8 mm. The receiver is a Dicke type radiometer, thus the radiometer's noise will be filtered out. For the temperature stabilization of the receiver, a Peltier element is used. The noise temperature of the 8 mm receiver is around 280 K, and the temporal resolution during the observations is 0.1 s or less. The obtained data is recorded as intensity. The Quiet Sun temperature at 37 GHz is around 8200 ± 500 K ($T_{b,qsl}$).[8] The radio emission at 8 mm comes from the chromosphere. The temperature resolution is less than 100 K. The full documentation of Metsähovi RT–14 for solar observations can be found from Kallunki et al.[9] As an example, solar radio maps at 8 mm in Figure 1 are presented. The dark areas are the regions of low temperature. In this case minimum temperature is around $97\ \%\ xT_{b,qsl} = 7950\ K$.

We found 100 LTRs between 1989 and 2014, and 23 of them were confirmed as a coronal hole structure. Information of LTRs (latitude, longitude and brightness temperature) is collected from the consecutive solar radio maps. One representative solar map per day is taken to analysis. The analyzed data was selected with following criteria:

a) Each region had a lifetime more than three days

b) All the points were selected longitudes (rel. long.) between −60°and +60° to avoiding possible artifacts near to the solar limb

The brightness temperature of selected areas is between $91.0\ \%\ xT_{b,qsl}$ and $99.5\ \%\ xT_{b,qsl}$.

Totally 100 LTRs were found, which were tracked three days or more. The rotation rates were calculated on the basis of the geometrical center of the LTRs (the red cross in the middle of LTR in Figure 1).

For each data set, the mean rotation rate was calculated. Also the Earth's orbital velocity (0.9865 deg/day) was taken into account in the final results.

## Results

After the mean rotation rates were defined for each data set, they were fitted to the solar differential rotation function: $y = A + Bxsin^2(x)$, where $y$ is a differential rotation rate (deg/day), $x$ is a latitude (deg.) and $A$ and $B$ are solar rotation parameters. Similar analysis methods have been used earlier.[9] The rotation speed profile is presented in Figure 2. The mean speed (equatorial rate) is 13.27 deg/day. Our analysis shows that rotation is very rigidly. Comparison with other speed profiles is presented in Figure 2: Nobeyama (LTR) at 1.76 cm,[10,11] previous 8 mm studies[7,9] and CH studies[5,12,13] as well. More carefully analysis was performed for three LTRs (Figure 3). Beside the geometrical centre point, six other points around the LTR were chosen and the rotation curves were created. The slopes of rotation curves are similar at all events. This confirms that the geometrical centre point of the LTR is usable for the analysis and the structure is rotating as a whole. In addition, this will confirm the interpretation of rigid rotation. In Figure 3, the slopes are similar and they do not depend on the latitude.

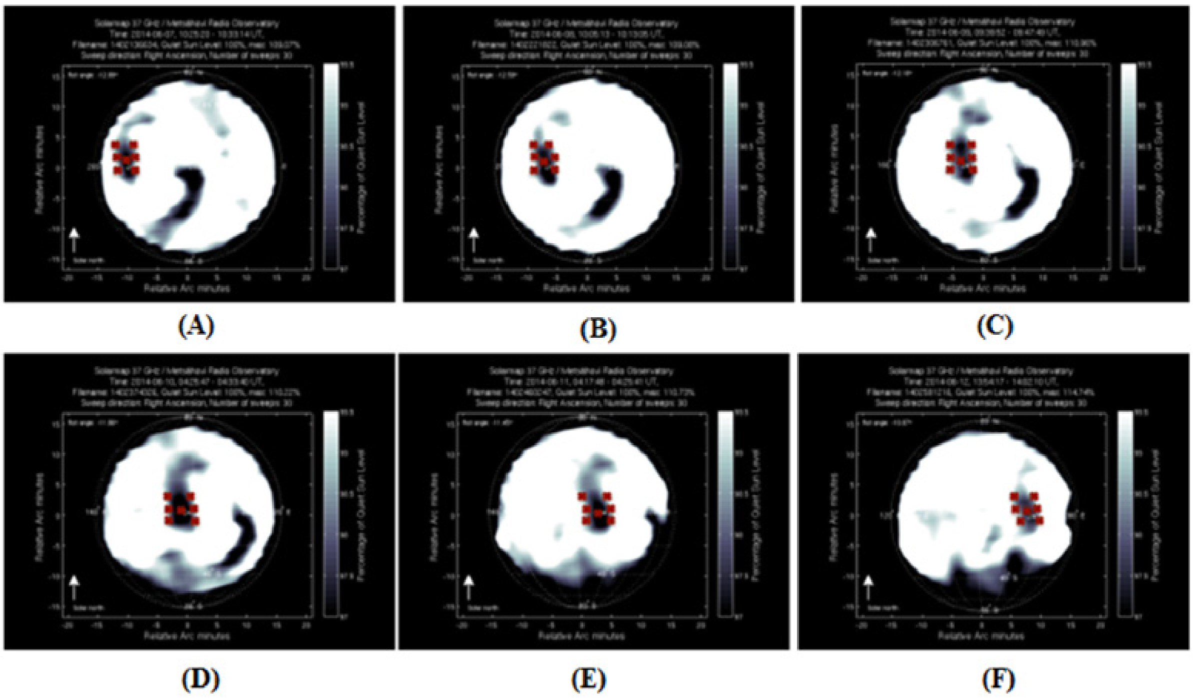


**Figure 1** Six solar radio maps at 8 mm. Maps are observed on six consecutive days between 7 Jun. 2014 (A) and 12 Jun. 2014 (F). Red crosses indicate the object (position), which are under tracking. A black color indicates the areas of LTR.

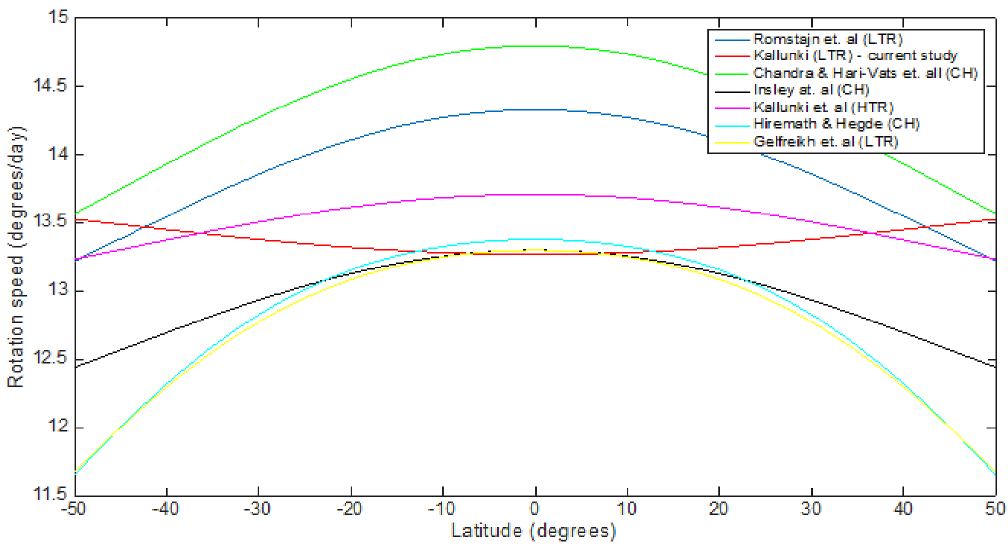


**Figure 2** A comparison between various rotation rate models. The current model matches well with CH models and 1,76 cm results at latitudes close to equator.

## Comparison with previous studies

In Figure 2 rotation rate profiles of LTRs are presented. The mean equatorial rotation rate is 13.27 deg/day (LTR, center). This has some correlation to the other investigations. The study[13] found a rate of 12.6–13.5 deg/day for coronal rotation at He I 10830 Å. However, there is bigger difference between the results obtained by Sheridan[14], 14.8 deg/day at 1.76 cm. It is important to notice that they used coronal (bright) points in their analysis. Our results show that rotation is more rigidly especially compared with the previous radio observations. For the CH,[7] found the equatorial rate 14.33 deg/day.

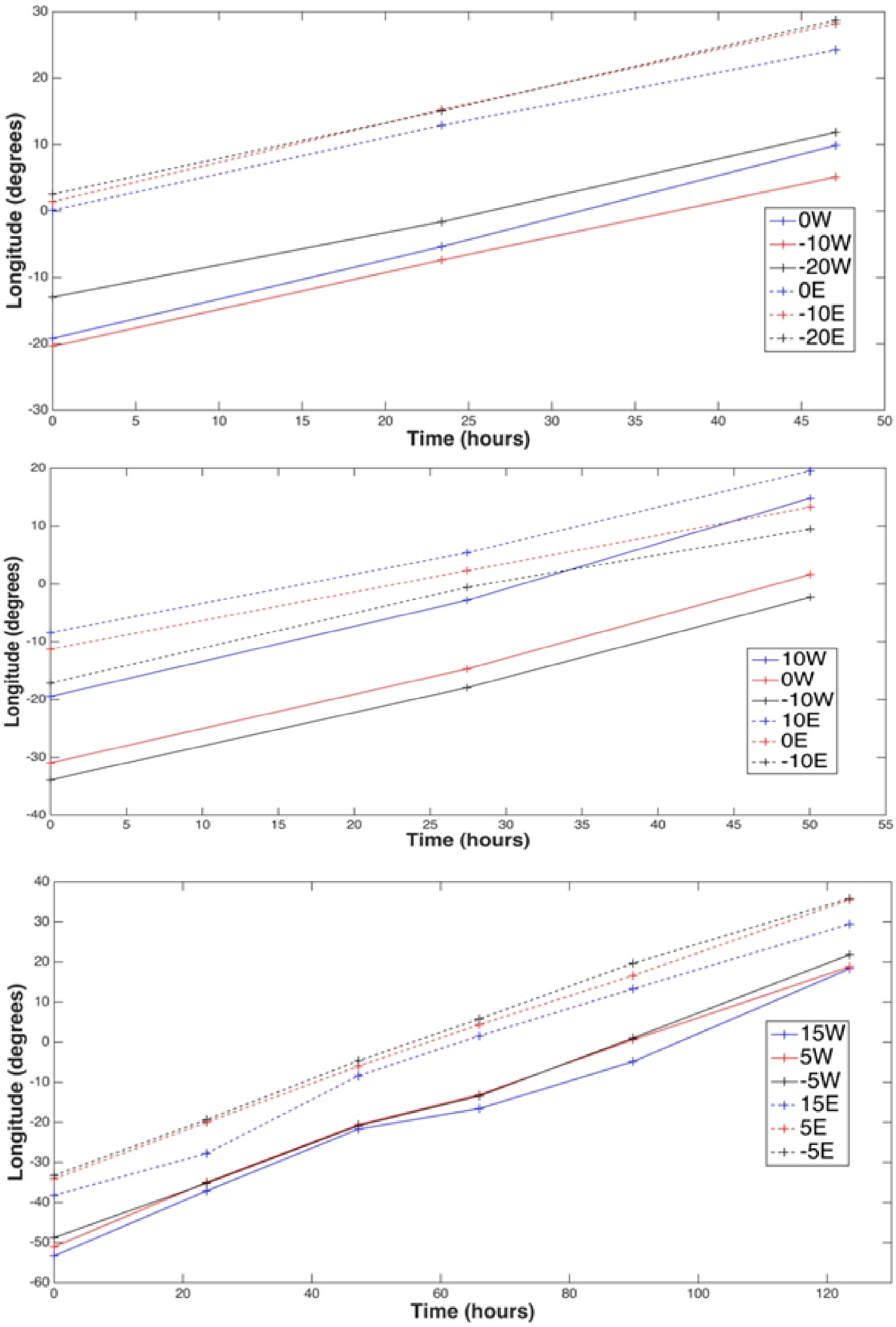


**Figure 3** The rotation of LTRs. Upper panel: track in 2013-04-04 - 2013-04-06, middle panel: track in 2013-08-15 - 2013-08-17 and lower panel: 2014-06-07 - 2014-06-12. E=east and W=west. The number before E or W equals to the latitude value.

## Artifacts and limitations

A limited resolution (beam size is 2.4 arc min) causes some inaccuracies to the results. It is difficult to say an exact effect of this and it also depends on the size of the observed structure. A good approximation is that error in the longitudinal direction cannot be larger than one third of the beam size (2.4 arc min). A low resolution will also might give larger errors close to the limb. However, we do not take into account these data points to the analysis.

The differences for previous studies can also be explained by the relative small amount of samples on high (> +40°) and on low latitudes (<–40°). The model, obtained now is not reliable on high and low latitudes. The height correction was not obtained for the results, thus the comparison would be easier with the previous studies. The height correction could reduce the speed around 0.5 deg/day as was mentioned in[7]. However, it has no significant effect on the final conclusions.

## Discussion and conclusion

The main conclusion to this study is that LTRs are rotating very rigidly compared with HTRs and other atmospheric structures e.g. sunspot. In addition, the rotation of LTR at 8 mm matches quite accurately with CH rotation and rotation at 1.76 cm.[10,11] Main, prevailing emission mechanism in the quiet Sun region (areas of the low magnetic field) is the thermal bremsstrahlung. The electron density of the CHs differs from the QSAs,[14] which can explain the lower brightness temperature. Also several other investigations support the results that the coronal holes (or LTR) are rotating more rigidly than HTRs (or active region and plage).[2,14] It is very difficult to say comprehensively why the rotation rates of the coronal holes and the low temperature regions are rigid in comparison with other structures. Some suggestions have been presented. Our impression is that areas of LTRs are not stable over the track period. Their size will change over the time, which could tell that the magnetic reconnection cannot be only reason for the rigid rotation. The magnetic diffusion can be other physical interpretative process as well.[2] However, the most plausible reason for the rigid coronal hole rotation could be the physical structure of the coronal hole. Hiremath[2] and Navarro–Peralta[16] support the concept that the coronal holes are anchored to the deeper solar interior (even below the convective zone), thus they are not the atmospheric structures in that regard. Further, this can cause more rigid rotation for instance compared with the active regions or sunspots. Our results promote these conclusions. A fully confidence for this would need a detailed analysis of area variation between CHs and LTRs. Our results are almost consistent with[2]. They used data from SOHO / EIT 195 Å (lower corona) which has a relatively good height correlation to the data used here (upper chromosphere at 8 mm). Thus they are also consistent in this respect. If the coronal holes are really deep structure, it will still need more simultaneous observations on the lower atmospheric layers (photosphere and chromosphere) and more helioseismological investigations. In addition, the magnetic structure of LTR's should be studied. One scenario is that LTRs without the connection to CH are slightly magnetic bipolar areas, and vice versa. It is also obvious, based on our results, those CHs and LTRs in 8 mm have some connection to each other. A behind of these must be some similar physical properties and processes. We can conclude on the basis of the results obtained in this study that millimeter wavelength observation could give versatile information about the solar corona. We could not, with this amount of data, study an effect of solar cycle on the rotation rates. We did not study coronal holes in the high temperature regions (HTR), which might be an interesting addition to this analysis. More observations, also at 8 mm, will be needed to fulfill the conclusions presented here.

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## Conflict of interest

Author declares that there is no conflict of interest.

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