Investigating the latitudinal-dependent solar differential rotation rate using SDO/HMI Dopplergrams

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Abstract. The solar photospheric differential rotation rate has novel implications for the structure of the heliospheric magnetic field. The rotation period at the solar poles is $\sim$35 days and $\sim$25 days at the equator. In this study, the Doppler shift of 116 Dopplergrams from the Helioseismic and Magnetic Imager instrument on board the Solar Dynamics Observatory are investigated to experimentally determine the photospheric differential rotation rate at different solar latitudes. A model is developed to describe the variation of surface speed with solar latitude. The results align with trends and behaviours reported in historical models from the literature, demonstrating consistency across studies. The findings confirm the latitudinal differential rotation of the Sun. The developed model of this study shows a deviation of 8. 45% slower compared to the Newton and Nunn model, 8. 38% slower compared to the Snodgrass model and 4. 33% slower compared to the Howard and Harvey model. This result is worth noting considering the difference in time scales, with the models in the literature using data spanning more than a decade, compared to the model developed in this study using 1.5 hours of collected data. The study not only confirms the theoretical expectations regarding solar rotation but also demonstrates the effectiveness of time-saving Doppler spectroscopic analysis and space-based solar observations in studying solar dynamics. The results contribute to a broader understanding of solar behaviour.

1 Introduction

The rotation of the Sun has long been known to reflect some of the defining features of its nature and overall internal dynamics. Depending on the observer's frame of reference, the rate at which the Sun rotates can be distinguished by the synodic and sidereal rotation rates. The synodic rotation rate describes how fast the Sun appears to rotate relative to an observer on Earth. In contrast, the sidereal rotation rate refers to the rotation of the Sun relative to the fixed distant stars [1]. The photospheric rotation rate of the Sun is dependent on solar latitude [2],[3],[4],[5]. Over the past few decades, scientists have investigated the photospheric differential rotation rate of the Sun and different ways in which it shapes the basic understanding of the heliospheric magnetic field (HMF) [1],[6],[7].

Different models have been developed to characterise the photospheric solar differential rotation rate. Among these models, Newton and Nunn [3], Howard and Harvey [4], and Snodgrass [5] are of particular interest, as they provide reliable and detailed measurements for this study. It is worth noting that each of these models mentioned uses different techniques to determine the photospheric rotation rate. The Newton and Nunn model [3] traced sunspots across the solar disk for 11 years. In contrast, the Howard and Harvey model [4] was developed using Doppler shifts from spectral lines over a 2-year observational period, and the Snodgrass model [5] used both sunspot data and Doppler shift analysis over a 20-year observational period.

The differential rotation rate varies according to the methods implemented in studying this phenomenon [8]. The general expression that relates the rotation rate to the latitude is

$$w(\theta) = A + B\sin^2(\theta) + C\sin^4(\theta), \tag{1}$$

where A represents the equatorial rotation rate, while B and C govern the differential rate [8].

Newton and Nunn [3], Howard and Harvey [4], and Snodgrass [5] reported the mathematical relation between the differential rotation rate and latitude as follows:

$$w(\theta) = 2.904 - 0.492\sin^2(\theta)\ \mu\text{rad/s}, \tag{2}$$

$$w(\theta) = 2.779 - 0.351\sin^2(\theta) - 0.442\sin^4(\theta)\ \mu\text{rad/s}, \tag{3}$$

and

$$w(\theta) = 2.902 - 0.464\sin^2(\theta) - 0.328\sin^4(\theta)\ \mu\text{rad/s}. \tag{4}$$

Equations (2), (3), and (4) represent the Newton and Nunn model [3], the Howard and Harvey model [4], and the Snodgrass model [5], respectively. The graphical representation that relates these models mentioned above is shown in Figure 1. This study aims to use recent satellite data from the Solar Dynamics Observatory to better understand the latitudinal dependence of the solar photospheric rotation rate.

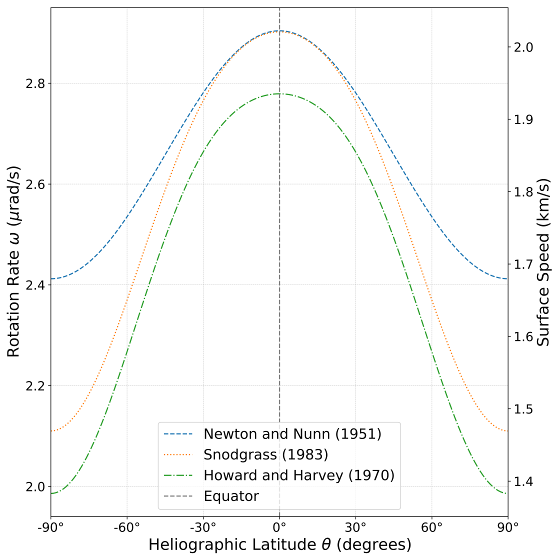


Figure 1: Solar differential rotation profiles of Newton and Nunn[3], Snodgrass [5], and Howard and Harvey[4]. The left y-axis indicates the rotation rate in μrad/s, while the right y-axis indicates the rotation rate in km/s. To guide the eye, the equator is shown by a vertical dashed line at $0°$.

2 Data

The Dopplergrams are acquired from the Virtual Solar Observatory (VSO)[1]. The VSO is connected to the Joint Science Operations Centre (JSOC)[2], which, in turn, is linked to the Solar Dynamics Observatory (SDO)[3]. Data from the Helioseismic and Magnetic Imager (HMI)[4] instrument are accessed from the SDO, from which the Dopplergrams are obtained. These Dopplergrams are in Flexible Image Transport System (FITS) file format. The observation date is 1 July 2012, and the observational window spans 1.5 hours from 15:00 to 16:30 UTC. This data set includes 116 Dopplergrams with 45-seconds cadence. The open source software package, Sunpy, is used for the analyses [9].

[1]VSO: `https://sdac.virtualsolar.org/cgi/search`

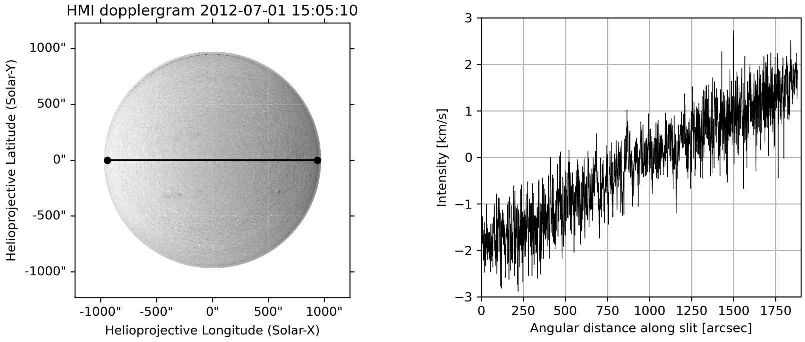
[2]JSOC: `http://jsoc.stanford.edu/`

[3]SDO: `https://sdo.gsfc.nasa.gov/data/`

[4]HMI: `http://hmi.stanford.edu/`

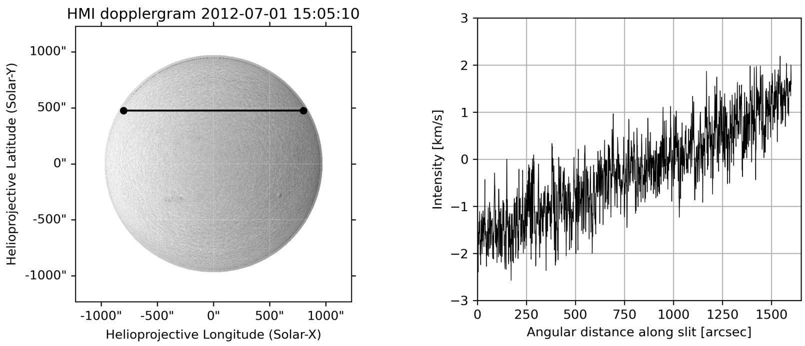
3 Results

Figures 2-6 show examples of Dopplergrams obtained from the SDO, indicating the Dopplergram intensity at different solar latitudes.



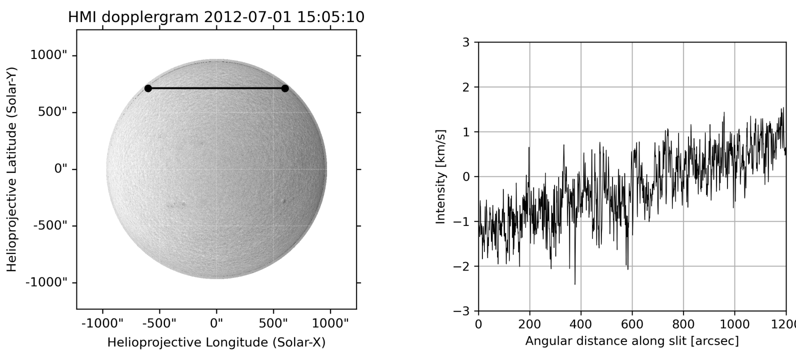
(a) (b)

Figure 2: (*a*) HMI Dopplergram observed at 15:05:10 on 1 July 2012. The solid indicates the equator (0°). (*b*) HMI Dopplergram intensity along the equator (from left to right).



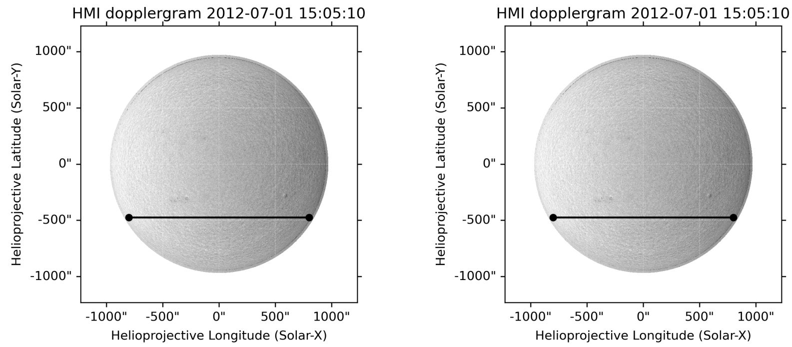
(a) (b)

Figure 3: (*a*) HMI Dopplergram observed at 15:05:10 on 1 July 2012. The solid line refers to the $45°$ latitude. (*b*) HMI Dopplergram intensity along the $45°$ solar latitude line (from left to right).



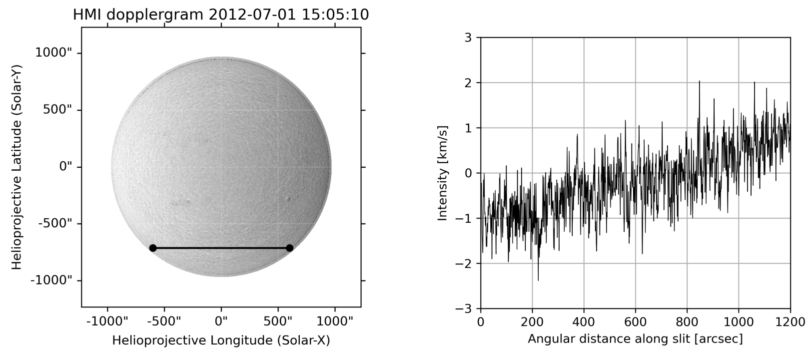
(a) (b)

Figure 4: (*a*) HMI Dopplergram observed at 15:05:10 on 1 July 2012. The solid line now indicates the $72°$ latitude. (*b*) HMI Dopplergram intensity along the $72°$ solar latitude line (from left to right).



(a) (b)

Figure 5: (*a*) HMI Dopplergram observed at 15:05:10 on 1 July 2012. The solid line now indicates the $-45°$ latitude. (*b*) HMI Dopplergram intensity along the $-45°$ solar latitude line (from left to right).



(a) (b)

Figure 6: (*a*) HMI Dopplergram observed at 15:05:10 on 1 July 2012. The solid line now indicates the $-72°$ latitude. (*b*) HMI Dopplergram intensity along the $-72°$ solar latitude line (from left to right).

Figure 2a and 2b shows the full-disk Dopplergram and Dopplergram intensity profile, respectively, along the solar equator (0 degrees). The Dopplergram intensity profile is notably noisy, as a result of omitting any smoothing or averaging techniques during processing; instead, only a single Dopplergram was considered. The differential rotation rate at the equator ranges between -1.9 km/s and 1.9 km/s. The negative sign signifies that the east limb approaches the observer, whereas the positive sign shows that the west limb recedes from the observer. Note that, at the central meridian region of the Dopplergram, the line-of-site (LOS) differential rotation rate is zero relative to the observer. Figures 3-6 explain the same as Figure 2 with the differential rotation rates ranging between -1.5 km/s and 1.5 km/s in Figure 3b, -1.1 km/s and 1.1 km/s in Figure 4b, -1.5 km/s and 1.5 km/s in Figure 5b, and -1.1 km/s and 1.1 km/s in Figure 6b. A comparison across different latitudes of the Sun reveals a decrease in solar rotation further away from the equator. Moreover, the results also show a rotation rate symmetry across the solar equator.

Figure 7 shows the plot of the resulting model developed using SDO data compared to the three models in the literature. The SDO data is indicated by red dots, with accompanying error bars. A trend is fitted to the SDO data, shown as a solid blue line. Note that, for the construction of the SDO model, the SDO data was converted from a synodic period to a sidereal period [10].

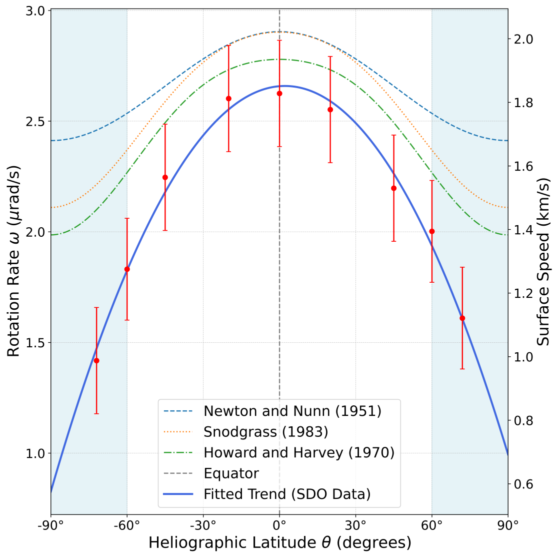


Figure 7: Comparison between the Newton and Nunn [3] model, the Snodgrass [5] model, the Howard and Harvey [4] model, and model from the SDO data.

The model fitted using SDO data demonstrates the solar rotation profile. The model shows that the Sun's rotation rate is latitude dependent and is fastest at the equator with a surface speed of 1.83 km/s. In particular, the solar photospheric rotation rate decreases farther away from the equator. To determine the error bars, the expression $\sigma_\mu = \frac{\sigma}{\sqrt{N}}$ [11] is used. Where σ_μ represents the standard error, σ represents the standard deviation and N represents the number of data points used. These error bars indicate the uncertainty in the SDO data. Note that the data within the shaded region of Figure 7, i.e., between $-90°$ & $-60°$ (southern hemisphere), and $90°$ & $60°$ (northern hemisphere), are not reliable due to projection challenges close to the solar limb.

4 Conclusion

The SDO results presented in this study indicate an underestimated differential rotation rate, likely due to the relatively short observational window of 1.5 hours. By contrast, the models by Newton and Nunn, Howard and Harvey, and Snodgrass are based on 11 years, 2 years, and 20 years, respectively, of data collection, enabling more robust characterization. The error bars in Figure 7 suggest an uncertainty of approximately 0.24 radians/s in the SDO measurements. Despite this, the study confirms the photospheric latitudinal differential rotation rate using SDO Dopplergrams. The Dopplergrams, however, exhibit considerable noise, potentially due to the lack of averaging across the full set of 116 observations. Future work will aim to extend the observational window to one year to improve measurement accuracy and reliability.

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