Sensitivity of solar wind mass flux to coronal temperature


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ABSTRACT

Solar wind models predict that the mass flux carried away from the Sun in the solar wind should be extremely sensitive to the temperature in the corona, where the solar wind is accelerated. We perform a direct test of this prediction in coronal holes and active regions using a combination of in situ and remote sensing observations. For coronal holes, a 50% increase in temperature from 0.8 to 1.2 MK is associated with a tripling of the coronal mass flux. This trend is maintained within active regions at temperatures over 2 MK, with a four-fold increase in temperature corresponding to a 200-fold increase in coronal mass flux.

Key words. Sun: corona – Sun: heliosphere – solar wind – stars: winds, outflows

1. Introduction

The Sun continuously loses mass through the solar wind. Although the rate of this mass loss is small at $2 \times 10^{-14} \, M_\odot \, yr^{-1}$ (Cohen 2011), it plays an important role in transporting angular momentum away from the Sun, controlling the rate at which it spins down (Weber & Davis 1967; Li 1999).

The solar wind mass flux can be predicted with simple hydrodynamic models, where the number density is supplied as a lower boundary condition in the corona and an equation of state relating the temperature and density is assumed (Parker 1958, 1960). For a given base number density and under spherical expansion, the mass flux depends on the temperature profile inside the sonic point via

$$n_0 v_0 = n_0 c_0 \left( \frac{r_c}{r} \right)^2 c_s \exp \left[ -\frac{1}{2} \int_{r_c}^r \frac{c_s^2}{(r^2)^2} dr \right],$$

(1)

where $c^2 \propto T$ is the thermal speed, $w$ is the solar escape velocity, $r$ is radial distance from the centre of the Sun, $n$ is number density, $c$ subscripts are values evaluated at the critical sonic point (where $v = c_s$), and $\circ$ subscripts are values evaluated at the solar surface (Parker 1964, Eq. (25)). An increase in $T$ results in a decrease of the integral, which in turn results in the increase in the mass flux. The exponential dependence of mass flux on temperature means that, under spherical expansion, small variations in coronal temperature should result in large variations in mass flux. However, such large variations are not seen in the solar wind mass flux at 1 AU (Leer et al. 1982; Withbroe 1989; Goldstein et al. 1996).

The resolution of this apparent inconsistency involves two competing effects that cancel each other out: Areas with strong magnetic fields in the corona undergo stronger heating that drives increased mass fluxes, but stronger magnetic fields also undergo more super-radial expansion, resulting in a diluting of the mass over a larger area (Wang 2010). Correcting for radial magnetic field expansion and calculating near-Sun coronal (as opposed to solar wind) mass fluxes can be done routinely using magnetic field models, and it has been shown that the mass flux in the corona spans many orders of magnitude (Wang 1995, 2010; Schwadron & McComas 2008). Correlating these large variations with temperature changes is challenging, however, as coronal temperatures are hard to reliably measure remotely (e.g. Habbal et al. 1993; Esser et al. 1995) and in situ measurements of solar wind temperatures at 1 AU have been significantly distorted from their coronal values (e.g. Marsh et al. 1983; Stansby et al. 2019b; Maksimovic et al. 2020).

In this Letter, we perform such a direct comparison using spectroscopic observations of two active regions and a newly proposed in situ proxy for coronal temperature in three coronal hole streams (Berčić et al. 2020). Section 2 briefly discusses the methods used to calculate coronal mass fluxes, and Sects. 3.1 and 3.2 present the solar wind streams and temperature measurements for coronal holes and active regions, respectively. Section 4 presents the main results, showing that a four-fold increase in coronal temperature is associated with a 200-fold...
increase in coronal mass flux. The results are discussed and put into the context of other studies in Sect. 5, with conclusions provided in Sect. 6.

2. Methods

In order to compare mass fluxes over a wide range of coronal temperatures, data from both coronal holes and active regions were used. To infer coronal mass fluxes, in situ measurements of the solar wind mass flux were scaled back to their coronal values using the frozen-in theorem (e.g. Wang 2010):

\[ n_\odot v_\odot = n_{sw} v_{sw} \left( \frac{B_\odot}{B_{sw}} \right)^2, \]

where \( n \) is the number density, \( v \) is the radial velocity, and \( B \) is the magnetic field. An \( sw \) subscript denotes a quantity measured in the solar wind and an \( \odot \) subscript denotes a quantity evaluated at the base of the corona.

Different methods were used to measure the coronal temperatures of the coronal holes and active regions. For coronal holes, it is hard to reliably determine coronal temperatures with remote sensing data (e.g. Habbal et al. 1993; Wendeln & Landi 2018), so a new method that provides a local in situ proxy for the coronal temperature was used. For active regions, hotter temperatures (and therefore higher ultraviolet emission intensities) allowed the use of remote sensing spectroscopy to estimate the coronal temperature.

3. Data

In this section, the choice of discrete solar wind streams is discussed, along with the data used to estimate coronal mass fluxes and temperatures for each source type. A summary of the data collected for each stream and the various data sources are given in Table 1.

<table>
<thead>
<tr>
<th>Stream</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>1.54</td>
<td>1.10</td>
<td>0.66</td>
<td>0.92</td>
<td>1.13</td>
<td>PSP, HMI, PSP</td>
</tr>
<tr>
<td>S2</td>
<td>1.54</td>
<td>0.99</td>
<td>0.40</td>
<td>0.63</td>
<td>0.93</td>
<td>PSP, HMI, PSP</td>
</tr>
<tr>
<td>S3</td>
<td>1.61</td>
<td>1.61</td>
<td>0.38</td>
<td>0.38</td>
<td>0.79</td>
<td>PSP, HMI, PSP</td>
</tr>
<tr>
<td>AR1</td>
<td>19.2</td>
<td>2.91</td>
<td>0.42</td>
<td>2.66</td>
<td>1.86</td>
<td>WIND, MDI, EIS</td>
</tr>
<tr>
<td>AR2</td>
<td>255</td>
<td>1.47</td>
<td>0.43</td>
<td>69.2</td>
<td>2.28</td>
<td>WIND, MDI, EIS</td>
</tr>
</tbody>
</table>

Notes. The median value is given where a range of values is measured within each stream.

Figure 1 shows an overview of solar wind parameters measured by PSP, with the three streams indicated with coloured bands. The top panel shows the identified coronal hole with an intensity threshold at 50 DN s\(^{-1}\). The y-axis is aligned with solar north in both images, and the colour scale is clipped at 3000 DN s\(^{-1}\). Bottom panel: Carrington map of the same two coronal holes, with the white line showing the trajectory of PSP ballistically backmapped to 2.5 \( R_\odot \). Labelled areas of the trajectory are the in situ data intervals selected for analysis.

was subsequently connected to a second larger equatorial coronal hole (Badman et al. 2020). These are respectively labelled “CHA” and “CHB”, and Fig. 1 shows images of them taken by the Atmospheric Imaging Assembly (AIA, Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO, Pesnell et al. 2012). The top-left panel shows the large coronal hole, and the top-right panel shows the smaller coronal hole. Both were isolated using an intensity contour at 50 DN s\(^{-1}\).

The bottom panel of Fig. 1 shows a synoptic map with the trajectory of PSP ballistically backmapped to 2.5 \( R_\odot \). In this co-rotating Carrington coordinate system, the spacecraft moved from right to left with time, performing a loop at the closest approach. The highlighted portions of the trajectory indicate the three intervals selected for further analysis, labelled S{1,2,3}. The first two intervals were located on either side of the perihelion loop over the small coronal hole, and the third interval was located over the large coronal hole.

Figure 2 shows an overview of solar wind parameters along the orbit of PSP during perihelion 1. Top panel: two coronal holes sampled by PSP, with contours showing the identified coronal hole with an intensity threshold at 50 DN s\(^{-1}\). The y-axis is aligned with solar north in both images, and the colour scale is clipped at 3000 DN s\(^{-1}\). Bottom panel: Carrington map of the same two coronal holes, with the white line showing the trajectory of PSP ballistically backmapped to 2.5 \( R_\odot \). Labelled areas of the trajectory are the in situ data intervals selected for analysis.

The streams marked in Figs. 1 and 2 were selected to have a co-rotating Carrington coordinate system, the spacecraft moved from right to left with time, performing a loop at the closest approach. The highlighted portions of the trajectory indicate the three intervals selected for further analysis, labelled S{1,2,3}. The first two intervals were located on either side of the perihelion loop over the small coronal hole, and the third interval was located over the large coronal hole.

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spatially resolved spectrographic data from Hinode/EUV Imaging Spectrometer (EIS Kosugi et al. 2007; Culhane et al. 2007) to visualise, defined as 

\[ f = \frac{B(r)}{B_{sw}(r)} \]  

The fourth panel of Fig. 2 shows the parallel strahl electron temperature (Berčič et al. 2020). This is defined as the gradient of high energy electrons (the strahl) in velocity space. Under adiabatic expansion, and due to the low collisionality of the high energy electrons, the strahl temperature should be conserved from when the corona was last collisionally dominated to where it is measured the solar wind, giving a proxy for the coronal temperature (Berčič et al. 2020). Although there is a large scatter between individual measurements, there are clear trends visible across the whole interval. During S1, the temperature started relatively high and then gradually declined as the solar wind speed increased until S2. During S3, the measurements were sparser, but on average this interval had lower temperatures than the previous intervals.

### 3.2. Active regions

#### 3.2.1. Choice of streams

Two active regions were analysed, both of which had been previously studied, remotely and in situ by van Driel-Gesztelyi et al. (2012) and Stansby et al. (2020a), respectively. These studies used magnetic modelling and ballistic backmapping to identify the in situ solar wind intervals at 1 AU, corresponding to each active region. In situ data were measured by the Solar Wind Experiment (SWE, Ogilvie et al. 1995) and the Magnetic Field Investigation (MFI, Lepping et al. 1995) on board WIND, from 2008 January 12 14:00 UT to 2008 January 13 12:00 UT for AR1 and 2013 January 24 00:00 UT to 2013 January 25 00:00 UT for AR2.

#### 3.2.2. Coronal magnetic field

To isolate the areas in the corona responsible for feeding the solar wind, open-closed field maps were calculated around each active region by tracing field lines through a potential field source surface (PFSS, Altschuler & Newkirk 1969; Schatten et al. 1969) model. The models were calculated from Global Oscillation Network Group (GONG, Harvey et al. 1996; Plowman & Berger 2020) synoptic photospheric magnetic field maps using the pfsspy software package (Stansby et al. 2020c), with a source surface radius at 2.5 \( R_{\odot} \).

The open-closed field contour for each active region is shown over-plotted in Fig. 3. To measure the coronal magnetic field, the open field regions were isolated on high resolution line of sight field maps from the Michelson Doppler Imager (MDI, Scherrer et al. 1995) for AR1 and from the HMI for AR2. The average photospheric field within the open field contour was calculated as in Sect. 3.1.2.

### 3.2.3. Coronal temperature

Spatially resolved spectroscopic data from Hinode/EUV Imaging Spectrometer (EIS Kosugi et al. 2007; Culhane et al. 2007) and the Solar Wind Experiment (SWE, Ogilvie et al. 1995) and the Magnetic Field Investigation (MFI, Lepping et al. 1995) on board WIND, from 2008 January 12 14:00 UT to 2008 January 13 12:00 UT for AR1 and 2013 January 24 00:00 UT to 2013 January 25 00:00 UT for AR2.

The third panel of Fig. 2 shows coronal magnetic field strengths in context with the in situ data. Dashed red lines show the coronal hole magnetic field strengths, and the solar wind data are scaled by \((r/\text{R}_{\odot})^2\). This allows the expansion factor to be visualised, defined as 

\[ f = \frac{(B_{\text{cor}}r^2)}{(B_{\text{sw}}r^2)} \]  

The open-closed field contour for each active region is shown over-plotted in Fig. 3. To measure the coronal magnetic field, the open field regions were isolated on high resolution line of sight field maps from the Michelson Doppler Imager (MDI, Scherrer et al. 1995) for AR1 and from the HMI for AR2. The average photospheric field within the open field contour was calculated as in Sect. 3.1.2.

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### 3.2. Coronal magnetic field

The magnetic field strength in each coronal hole was calculated from photospheric magnetograms measured by the Heliospheric Magnetic Imager (HMI, Scherrer et al. 2012) on the SDO. Coronal hole boundaries were taken from intensity thresholds at 50 DN \( s^{-1} \) on AIA 193 Å images (shown in Fig. 1), and the mean magnetic field (corrected for projection effects) within these boundaries was calculated using the method from Hofmeister et al. (2017). Taking a single average value assumes a spatially isotropic magnetic field strength with each coronal hole, which is a good assumption at the base of the corona where the plasma beta is \( \ll 1 \) (Peter et al. 2006).
were used to measure electron temperatures in the active regions. The EIS data were prepped and fitted using the SolarSoftWare eis_prep and eis_auto_fit routines. The Fe XIII 202.04 to Fe XII 195.11 Å lines observed by EIS are a temperature-sensitive line pair, with good sensitivity at active region temperatures (Del Zanna & Mason 2018, Sect. 11.1). Using the theoretical ratio of these lines computed in CHIANTI v8 (Del Zanna et al. 2015), temperature maps were calculated for the two active regions. These electron temperature maps are shown in the top two panels of Fig. 3. As an additional check on whether coronal material was flowing into the solar wind (e.g. Harra et al. 2008; Marsh et al. 2008), line of sight Doppler velocity maps were also calculated for the Fe XIII 202.04 Å line, shown in the bottom panels of Fig. 3. The distributions of temperatures within each active region were taken from pixels within the open field contour, which had negative Doppler velocities (i.e. material was flowing away from the Sun).

4. Results

Using Eq. (2), point by point measurements of solar wind mass flux divided by magnetic field strength were multiplied by the average photospheric source magnetic field to give a ratio of magnetic field strength and temperature as a function of height above the solar surface, which reduces Eq. (1) to (see Parker 1964, Eq. (31)):

\[ n_0 B_0 = n_0 c R^2 e^{-2(R/R_\odot - 1)}. \]

where \( R_\odot = r_\odot / r_0 = c^2 / 4r_0^2 \approx (5.8 \text{ MK}) / T \) is the sonic point normalised to the solar radius. Taking a typical observed value of \( n_0 = 2 \times 10^{19} \text{ cm}^{-3} \) (Del Zanna & Bromage 1999), this prediction is shown as the dashed line in Fig. 4. This model agrees qualitatively with the data, in the sense that it predicts the correct order of magnitude and large variations in the mass flux. However, the trend fails to accurately predict mass fluxes for the cool coronal holes and intermediate-temperature active region. This is unsurprising as both the magnetic field strength and temperature profiles are not constant in the corona; more accurate model assumptions need to be considered to understand if fluid models successfully predict mass loss rates.

5. Discussion

The observation that coronal mass flux is extremely sensitive to corona temperature agrees qualitatively with fluid theories of the solar wind, which also predict the correct order of magnitude for the mass flux. To make more accurate quantitative comparisons, observed magnetic field strengths and coronal temperature profiles need to be measured. In the corona, \( |B| \) can only be directly measured below about 1.5 \( r_\odot \), and even then measurement is limited to brighter areas away from coronal holes.

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\footnote{With the reference wavelength (i.e. zero velocity point) set assuming zero average shift over the entire map.}

\footnote{We stress that this is the mass flux at the base of the corona; the solar wind mass flux does not vary by such large orders of magnitude.}
(Wiegelmann et al. 2014; Yang et al. 2020). This could be circumvented by density and velocity measurements (Bemporad 2017) or magnetic field orientation measurements (Boe et al. 2020), which can indirectly infer expansion factors in the corona. Temperature profiles can be estimated using off-limb spectroscopy (e.g. Landi 2008; Crammer 2020) or, again, using density observations to indirectly infer temperatures (Lemaire & Stegen 2016).

In contrast to this study of individual solar wind streams, changes in mass flux and coronal temperatures can be measured over multiple 11-yr solar cycles. In the minimum between cycles 23 and 24, the mass flux in polar coronal holes was lower than the minimum between cycles 22 and 23 (McComas et al. 2008, 2013; Zerbo & Richardson 2015). This reduction was accompanied by a reduction in oxygen charge state ratios, which implies a corresponding reduction in the coronal temperature (Zhao & Fisk 2011; Schadworn et al. 2014). Our study agrees well with, and provides a stream by stream verification of, these long duration statistical variations.

The mass flux carried away from a star controls stellar spin down, with the angular momentum loss rate directly proportional to the mass loss rate (Weber & Davis 1967). Indeed, the reduction in coronal temperatures and therefore solar wind mass flux between cycles 23 and 24 drove a similar reduction in the solar angular momentum loss (Finley et al. 2019a,b). Our results suggest that if there were a way to remotely measure the coronal temperature of the parts of stars in which stellar winds originate, it would be possible to predict the mass loss rate. Unfortunately, only globally integrated observations are available for other stars, which are dominated by closed-loop emission (Cohen 2011; Mishra et al. 2019). However, our observations can be used to place new constraints on the mass fluxes predicted by solar and stellar wind models (e.g. Johnstone et al. 2015; Usmanov et al. 2018; Shoda et al. 2020).

6. Conclusions
We have presented a comparison of solar coronal temperature profiles and mass fluxes across three coronal holes and two active regions. A factor of four increase in coronal temperature results in a more than two orders of magnitude increase in mass flux in the solar wind sources studied, confirming that solar wind mass flux in the corona is extremely sensitive to the plasma temperature. This study provides a new insight into understanding solar mass loss via the solar wind, which in the future can be extended to large statistical studies and detailed theoretical comparisons.

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