Turbulent Proton Heating Rate in the Solar Wind from 5–45 $R_{\odot}$

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Abstract

Various remote sensing observations have been used so far to probe the turbulent properties of the solar wind. Using the recently reported density modulation indices that are derived using angular broadening observations of Crab Nebula during 1952–2013, we measured the solar wind proton heating using the kinetic Alfvén wave dispersion equation. The estimated heating rates vary from $\approx 1.58 \times 10^{-14}$ to $1.01 \times 10^{-9}$ erg cm$^{-3}$ s$^{-1}$ in the heliocentric distance range of 5–45 $R_{\odot}$. Further, we found that heating rates vary with the solar cycle in correlation with density modulation indices. The models derived using in situ measurements (for example, electron/proton density, temperature, and magnetic field) that the recently launched Parker Solar Probe observations (planned closest perihelia 9.86 $R_{\odot}$ from the center of the Sun) are useful in the estimation of the turbulent heating rate precisely. Further, we compared our heating rate estimates with the one derived using previously reported remote sensing and in situ observations.

Unified Astronomy Thesaurus concepts: Solar wind (1534); Radio occultation (1351)

1. Introduction

Even after decades of intense research, we do not know the precise solar wind heating mechanism and its acceleration. The in situ observations confirm that solar wind undergoes extended nonadiabatic heating (Freeman 1988; Gazis et al. 1994; Matthaeus et al. 1999; Richardson & Smith 2003). More details on turbulent heating and solar wind acceleration are given by Cramer et al. (2007, 2013), Chandran & Hollweg (2009a), Verdini et al. (2010), Woolsey & Cramer (2014), and Zank et al. (2018). Interaction between counter-propagating Alfvén waves causes the wave energy to cascade to small scales. When the scale sizes which are perpendicular to the background magnetic field direction ($\lambda_\perp$) are comparable to the proton gyroradius ($\rho_p$), the wave energy begin to dissipate and thereby heats the plasma. It is known that when $\lambda_\perp \gg l_i = v_A/\Omega_p$, where $l_i$ is the proton inertial length, $v_A$ is the Alfvén speed, and $\Omega_p$ is the proton cyclotron frequency, the Alfvén waves are non-compressible. But there is a considerable evidence that when the scale sizes are in the range of $\rho_p \lesssim \lambda_\perp \lesssim l_i$, they are compressive (e.g., Harmon 1989; Hollweg 1999; Chandran et al. 2009b). Also, the waves become dispersive and damp for the scales $\lambda_\perp \gtrsim \rho_p$.

In order to estimate the heating rates in the solar wind, we used the recently reported density modulation indices ($\epsilon_N = \delta N / N$, where $\delta N$ is the rms density fluctuations and “$N$” is the ambient background density) derived using the Crab Nebula occultation observations carried out during 1952–2013 (Machin & Smith 1952; Slee 1959; Hewish & Wyndham 1963; Erickson 1964; Blesing & Dennison 1972; Dennison & Blesing 1972; Sastry & Subramanian 1974; Armstrong et al. 1990; Anantharamaiah et al. 1994; Subramanian 2000; Ramesh et al. 2001; Sasikumar Raja et al. 2016, 2017, 2019b). In this technique, when a radio point source (in this study Crab Nebula), observed through the foreground solar wind (in June of every year), we can obtain the following observations: (i) the radio sources angular broadening increases due to the turbulent medium’s scattering, (ii) since we observe the radio sources whose flux density is constant over a long time, the peak flux density decreases as the source size increases, but the integrated flux density remains constant, (iii) the radio sources broaden anisotropically for the heliocentric distance below 10 $R_{\odot}$, and thus we can measure the parameter anisotropy (i.e., the ratio between the major to the minor axis of radio source) (Blesing & Dennison 1972; Dennison & Blesing 1972; Sasikumar Raja et al. 2017), and (iv) the position angle of the major axis of the source (measured from the north through the east). With such observations, Sasikumar Raja et al. (2016) have derived the density modulation indices in the heliocentric distance 5–45 $R_{\odot}$. In this article, we use those density modulation indices to measure the proton heating rate ($\epsilon_N$) by making use of kinetic Alfvén wave dispersion equations (see Section 3.4) and compared the results with the recent reports that are measured using angular broadening (Sasikumar Raja et al. 2017) and interplanetary scintillation observations (Bisoi et al. 2014; Ingale 2015a). We also compare our results with the recently reported heating rates derived using the in situ observations of Adhikari et al. (2020) and Bandypadhyay et al. (2020). Further, we report the way heating rates vary with the heliocentric distance and the way they vary with the solar cycle.

2. Observations

The angular broadening of the Crab Nebula is first observed by Machin & Smith (1952). Since then, many authors have reported similar observations, as previously mentioned (see Section 1). In this article, we present results derived using data obtained by the Gauribidanur radioheliograph (GRAPH) during 2011–2013 (Ramesh et al. 1998; Ramesh 2011, 2014) and other historical observations carried out during 1952–1963 (Machin & Smith 1952; Hewish 1957, 1958; Hewish & Wyndham 1963; Sasikumar Raja et al. 2016). For instance, Figure 1 shows the observation of GRAPH carried out at 80 MHz over an interferometer baseline of 1600 m. The top panel shows the schematic of the Crab Nebula occultation...
technique. The red and green circles indicate the Sun and location of the Crab Nebula on different days of 2011 and 2013 June. The bottom panel shows the decrement in flux density as the Crab Nebula ingresses and becomes invisible during June 12–18 and then increments as it egresses. The flux density during 2013 is lower (compared to 2011) as it corresponds to the solar maximum. We note that the latter observations are carried out over interferometer baselines in the range of 60–1000 m and the frequency range of 26–158 MHz. Therefore, Sasikumar Raja et al. (2016) have scaled these structure functions to the largest baseline of GRAPH (1600 m; before the extension) and its routinely observed frequency 80 MHz using the general structure function (see Section 3). For the sake of completeness, we summarize a method using the way in which Sasikumar Raja et al. (2016) derived the density modulation indices (see Figure 2) and the way we measured proton heating rate in the following sections.

3. Results and Discussions

In the solar wind, turbulent density inhomogeneities play a vital role in scattering of the radio waves (Coles & Harmon 1989; Yamauchi et al. 1998; Biso et al. 2014; Mugundhan et al. 2017; Kruper et al. 2018, 2020; Sasikumar Raja et al. 2019a). Such inhomogeneities are represented by a spatial power spectrum. It comprises a power law together with an exponential turnover at the inner scale. In the case of isotropic medium, the turbulent spatial power spectrum \( P_{SN}(k, R) \) is defined as (Bastian 1994; Ingale et al. 2015b)

\[
P_{SN}(k, R) = C_N^2(R)k^{-\alpha} \times \exp\left(-l_i(R)/2\pi\right)^2,
\]

where \( k \) is the wavenumber, \( l_i \) is the inner/ dissipation scale, and \( C_N^2 \) is the amplitude of density turbulence. It is worth mentioning that the injected large-scale energy in the solar wind breaks up into smaller scales until it is dissipated by heating the protons via gyro-resonant interactions. Also, note that the scales at which the energy is injected are called outer scales, and the scales at which the dissipation happens are called inner scales (Kulsrud 2005). Using remote sensing observations, it is found that, at large scales, the density spectrum follows the Kolmogorov scaling law with \( \alpha = 11/3 \) (Coles & Harmon 1989; Spangler 2002). However, at small scales, the spectrum flattens to \( \alpha = 3 \) (Coles & Harmon 1989). In this article, since we are interested in the density fluctuations and proton heating rate near the dissipation scales, we have used \( \alpha = 3 \). We note here that \( C_N^2 \) are measured for both the proton inertial scale model (Coles & Harmon 1989; Leamon et al. 1999, 2000; Smith et al. 2001; Bruno & Trenchi 2014; Chen et al. 2014; Sasikumar Raja et al. 2019b) and the proton gyroradius model (Bale et al. 2005; Sahraoui et al. 2013; Biso et al. 2014; Chen et al. 2014; Sasikumar Raja et al. 2019b). Note that Sasikumar Raja et al. (2016) measured the \( C_N^2 \) for two cases of proton temperatures \( T_i = 10^5 \) K and \( T_i = 10^6 \) K.

3.1. Measurement of Phase Structure Function

A plane wave from a distant radio point source observed through the solar wind experiences loss of spatial and temporal coherence due to the refraction and scattering caused by the density inhomogeneities. The spatial coherence of the plane
wave observed through the scattering medium (i.e., solar wind) is described by the mutual coherence function \( \Gamma(s) \), which is in turn related to the phase structure function \( D_F(s) \). We note that \( D_F(s) \) provides the information to the extent to which an ideal point source is broadened and it contains information about the spectrum of density turbulence. In general, the phase structure function is defined as (Coles & Harmon 1989; Bastian 1994; Ingale et al. 2015b),

\[
D_F(s) = \langle (\phi(r) - \phi(r+s))^2 \rangle,
\]

where, \( \langle \cdot \rangle \) indicates the time average, \( s \) is the baseline of an interferometer, and \( \phi(r) \) and \( \phi(r+s) \) are the geometric phase delays in the line-of-sight direction through a turbulent medium at positions \( r \) and \( r+s \).

Using the Crab Nebula occultation observations we measure \( \langle \Gamma(s) \rangle \), using

\[
\Gamma(s) = \frac{V(s)}{V(0)},
\]

where \( V(s) \) is the peak flux density of the Crab Nebula observed through the scattering medium over a baseline \( s \), and \( V(0) \) is the flux density over a zero-length baseline. The quantity \( V(0) \) is measured when the Crab Nebula is far from the solar disk and is unresolved; \( V(0) \approx 2015 \text{ Jy at } 80 \text{ MHz} \) (Braude et al. 1970; McLean & Labrum 1985; Sasikumar Raja et al. 2017).

By knowing the \( \Gamma(s) \), we measured the density structure function \( D_F(s) \), using (Prokhorov et al. 1975; Ishimaru 1978; Coles & Harmon 1989; Armstrong et al. 1990)

\[
D_F(s) = -2 \ln \Gamma(s) = -2 \ln \left[ \frac{V(s)}{V(0)} \right].
\]

### 3.2. The Amplitude of Density Turbulence Spectrum (\( C_N^2 \))

By knowing the structure functions, we measured the amplitude of the turbulence \( C_N^2 \) using the general structure function (GSF) (Ingale et al. 2015b; Sasikumar Raja et al. 2016, 2017). The GSF...
is defined as follows:
\[
D_p(s) = \frac{8\pi^2 r_e^3 \lambda \Delta L}{\rho^2 \pi^2 (\alpha - 2)} \left(1 - \frac{\alpha - 2}{2}\right) \left(1 - f_p^2(R) \frac{f_k^2(R)}{f^2}\right) \times \left\{iF_1\left[-\frac{\alpha - 2}{2}, 1, -\left(\frac{s}{l_i(R)}\right)^2\right] - 1\right\} \text{rad}^2,
\]

(5)

where \(iF_1\) is the confluent hyper-geometric function, \(r_e\) is the classical electron radius, \(\lambda\) is the observing wavelength, \(R\) is the heliocentric distance (in units of solar radii), \(\Delta L\) is the thickness of the scattering medium \((\approx (\pi/2)R_0\) where \(R_0\) is the impact parameter related to the projected heliocentric distance of the Crab Nebula), \(f_p\) and \(f\) are the plasma and observing frequencies, respectively, and the quantity \(l_i\) is the inner scale.

In order to evaluate the inner scales, we used the following two prescriptions that are widely used in the literature. The first prescription envisages proton cyclotron damping by Alfvén waves. The inner scales measured using this mechanism are called proton inertial lengths. The density fluctuations \(\delta N_e\) at the inner scale and spatial power spectrum (Equation (1)) are related as follows (Chandran et al. 2009b):
\[
\delta N_e^2(R) \sim 4\pi k_i^2 P_{\delta N}(R, k_i) = 4\pi C_N^2(k_i^3 - 1)e^{-1},
\]

(12)

where \(k_i \equiv 2\pi/l_i\).

By knowing the \(\delta N_e\) and the background electron density \((N_e; \text{ Section 3.1})\), the density modulation index \((\epsilon_N)\) can be measured using
\[
\epsilon_N(R) \equiv \frac{\delta N_e(R)}{N_e(R)}.
\]

(13)

For the sake of completeness, the measured density modulation indices and its variation with heliocentric distance are shown in Figure 2 (Sasikumar Raja et al. 2016). Similarly, the solar cycle dependence of the density modulation indices is shown in the upper panel of Figure 4 (Sasikumar Raja et al. 2016). Further, assuming the kinetic Alfvén wave dispersion equation, we derived the heating rate.

### 3.4. Solar Wind Heating Rate

In this paper, we used the density modulation indices \((\epsilon_N)\) derived using the above method (see Section 3.3) to measure the heating rates. Following Chandran et al. (2009b) and Sasikumar Raja et al. (2017), we assume that density fluctuations at small scales are manifestations of low frequency, oblique \((k_l \gg k_i)\), Alfvén wave turbulence, which are often referred to kinetic Alfvén waves. Here, the quantities \(k_l\) and \(k_i\) are the components of the wavevector \(k\) in the perpendicular and parallel directions to the background large-scale magnetic field, respectively.

As previously discussed, we envisage a situation where the balanced counter-propagating Alfvén waves (i.e., with zero helicity) cascade and resonantly damp the protons at the inner scale and thereby heat the solar wind. Because of the passive mixing of the Alfvén waves with other modes at the inner scale, our proton heating rate measurements provide an upper limit. The proton heating rate (i.e., the turbulent energy cascade rate) at inner scales is (Hollweg 1999; Chandran et al. 2009b; Ingale 2015a)
\[
\epsilon_k(R) = c_0 \rho_p k_i(R) \delta v_k^3(R) \text{ erg cm}^{-3} \text{ s}^{-1},
\]

(14)

where \(\rho_p = m_p N_e(R)\) g cm\(^{-3}\) with \(m_p\) the proton mass (in grams), and \(k_i = 2\pi/l_i\) and \(\delta v_k\) are the wavenumber and magnitude of the turbulent velocity fluctuations at inner scales, respectively. The dimensional less quantity \(c_0\) is assumed to be 0.25 (Howes et al. 2008; Chandran et al. 2009b; Sasikumar Raja et al. 2017).

By knowing the \(\epsilon_N\), we calculated \(\delta v_k\) using the kinetic Alfvén wave dispersion relation (Howes et al. 2008; Chandran et al. 2009b; Ingale 2015a; Sasikumar Raja et al. 2017)
\[
\delta v_k(R) = \left(1 + \frac{\gamma k_i^2(R)\rho_p^2(R)}{k_i(R)\rho_p(R)}\epsilon_N(R, k_i)\nu_A(R)\right)\epsilon_N(R, k_i)\nu_A(R),
\]

(15)

\(\nu_A(R)\) is the proton gyrofrequency (Williams 1995)
\[
B(R) = 3.4 \times 10^{-5} R^{-2}(1 + R^2)^{1/2} \text{ Gauss}.
\]

(11)
where the adiabatic index $\gamma_i$ is taken to be 1 (Chandran et al. 2009b; Sasikumar Raja et al. 2017).

The Alfvén speed ($v_A$) in the solar wind is measured using

$$v_A(R) = 2.18 \times 10^{11} \mu^{-1/2}N_e^{-1/2}(R)B(R) \text{ cm s}^{-1}. \quad (16)$$

The magnetic field strength ($B$) is estimated using the Parker spiral magnetic field in the ecliptic plane using (Williams 1995)

$$B(R) = 3.4 \times 10^{-5}R^{-2}(1 + R^2)^{1/2} \text{ Gauss}, \quad (17)$$

where $R$ is the heliocentric distance in units of astronomical units.

The derived proton heating rates in different years are shown in Figure 3 and we found that heating rates vary from $\approx 1.58 \times 10^{-14}$ to $1.01 \times 10^{-8} \text{ erg cm}^{-3} \text{ s}^{-1}$ over the heliocentric distances of 5–45 $R_\odot$. The circles and squares indicate proton heating rates derived assuming different inner scale models—proton inertial length and proton gyroradius model, respectively.

At 5 $R_\odot$, in the coronal holes (i.e., in the fast solar wind), the estimated proton heating rates range from $2 \times 10^{-10}$ to $1.4 \times 10^{-8} \text{ erg cm}^{-3} \text{ s}^{-1}$ (Chandran et al. 2009b). Similarly, at 1 au the estimated heating rate is $5 \times 10^{-16} \text{ erg cm}^{-3} \text{ s}^{-1}$ (Chandran et al. 2009b). The heating rates derived assuming density fluctuations are due to the kinetic Alfvén waves in the heliocentric distance range of 2–174 $R_\odot$ using interplanetary scintillation observations (Hewish & Wyndham 1963; Manoharan et al. 2000; Janardhan et al. 2011; Sasikumar Raja et al. 2019a) are $3 \times 10^{-8} \text{ erg cm}^{-3} \text{ s}^{-1}$ (during solar maximum) and $\approx 10^{-15} \text{ erg cm}^{-3} \text{ s}^{-1}$ (during solar minimum) consistent with our estimates (Ingale 2015a). Using two-dimensional imaging angular broadening observations of Crab Nebula, the measured heating rates vary from $2.2 \times 10^{-13}$ to $1.0 \times 10^{-11} \text{ erg cm}^{-3} \text{ s}^{-1}$ in the projected heliocentric distance range of 9–20 $R_\odot$ (Sasikumar Raja et al. 2017). The
recently reported heating rates in the heliocentric distance range of $1.5 - 4.0 \, R_\odot$ varied from $\approx 3.31 \times 10^{-10}$ to $4.5 \times 10^{-7} \, \text{erg cm}^{-3} \text{s}^{-1}$ (Cranmer 2020). Further, the author extrapolated these heating rates to the distances of $0.3 - 0.6 \, \text{au}$ and they range from $\approx 10^{-15}$ to $10^{-14} \, \text{erg cm}^{-3} \text{s}^{-1}$ and at $1 \, \text{au}$, the extrapolated heating rates are a few times $10^{-16} \, \text{erg cm}^{-3} \text{s}^{-1}$.

Using in situ measurements by the Parker Solar Probe, Bandyopadhyay et al. (2020) estimated energy transfer rates of $8.7 \pm 0.3 \times 10^{-13} \, \text{erg cm}^{-3} \text{s}^{-1}$ at $36 \, R_\odot$ and $5.8 \pm 1.3 \times 10^{-14} \, \text{erg cm}^{-3} \text{s}^{-1}$ at $54 \, R_\odot$. They originally quoted numbers in units of joules per kilogram per second. We multiplied their numbers by $N_p m_p$ (where $N_p$ is the solar wind density derived using the Leblanc model (Leblanc et al. 1998) and $m_p$ is the proton mass) to arrive at heating rates in units of erg per cubic centimeter per second. By comparison, the proton heating rate at $36 \, R_\odot$ from our results (see Figure 3) range from $\approx 2.8 \times 10^{-10}$ to $7.4 \times 10^{-13} \, \text{erg cm}^{-3} \text{s}^{-1}$. Similarly, Adhikari et al. (2020) reported that heating rates due to quasi-2D turbulence in the heliocentric distance of $\approx 1.6 - 100 \, R_\odot$ range from $1.06 \times 10^{-4}$ to $1.73 \times 10^{-14} \, \text{erg cm}^{-3} \text{s}^{-1}$. Authors also reported that the heating rate due to the nearly incompressible/slab turbulence in the heliocentric distance of $\approx 1.3 - 100 \, R_\odot$ range from $4.24 \times 10^{-7}$ to $1.11 \times 10^{-14} \, \text{erg cm}^{-3} \text{s}^{-1}$. A summary of these proton heating rates is given in Table 1.

As the density modulation indices (see Figure 2) and heating rates (see Figure 3) are weakly dependent on heliocentric distance, we averaged the observations that are carried out in different years and plotted them in Figure 4. The upper and middle panels of Figure 4 are the averaged density modulation indices and proton heating rates for different inner scale models, respectively. The lower panel shows the yearly averaged sunspot number. Figure 4 shows that the derived density modulation indices and heating rates closely follow the solar cycle. During solar maximum, the slow solar wind drives in all the directions and hence Sasikumar Raja et al. (2016) justified the lower modulation index in 1958 (also refer to the upper panel of Figure 4). Following the lower density modulation indices, heating rates are lower during the solar maximum.

4. Summary and Conclusions

In this article, we have used recently reported density modulation indices $\varepsilon_N$ derived using angular broadening observations of Crab Nebula (Sasikumar Raja et al. 2016). The authors have studied the way $\varepsilon_N$ vary with heliocentric
Table 1

| S.No | R (R☉) | Proton Heating Rate (erg cm⁻³ s⁻¹) | References |
|------|--------|----------------------------------|------------|
|      | 1      | 5–45 | 1.58 × 10⁻¹⁵–1.01 × 10⁻⁸ | Present work |
|      | 2      | 5    | 2 × 10⁻¹⁰–1.4 × 10⁻⁸ | Chandran et al. (2009b) |
|      | 3      | 215  | 5 × 10⁻¹⁶          | Chandran et al. (2009b) |
|      | 4      | 2–174| 3 × 10⁻⁹–10⁻¹⁵    | Ingale (2015a) |
|      | 5      | 9–20 | 2.2 × 10⁻¹³–1.0 × 10⁻¹¹ | Sasikumar Raja et al. (2017) |
|      | 6      | 1.5–4.0 | 3.31 × 10⁻¹⁰–4.5 × 10⁻⁷ | Cranmer (2020) |
|      | 7      | 64.5–129 | 10⁻¹⁰–10⁻¹⁸      | Cranmer (2020) |
|      | 8      | 215  | 10⁻¹⁶                  | Cranmer (2020) |
|      | 9      | 36   | 8.7 ± 0.3 × 10⁻¹³   | Bandypadhyay et al. (2020) |
|      | 10     | 54   | 5.8 ± 1.3 × 10⁻¹⁴  | Bandypadhyay et al. (2020) |
|      | 11     | 1.6–100 | 1.06 × 10⁻⁴–1.73 × 10⁻¹⁴ | Adhikari et al. (2020) |
|      | 12     | 1.3–100 | 4.24 × 10⁻⁷–1.11 × 10⁻¹⁴ | Adhikari et al. (2020) |

In situ

|      | 15     | 5–45 | 1.58 × 10⁻¹⁵–1.01 × 10⁻⁸ | Present work |

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