Super-Adiabatic Cooling of Small Scale Magnetic Flux-Ropes in Inner Heliosphere: PSP Observation

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Abstract

Small scale magnetic flux-rope (SSMFR) is ubiquitous in space plasma and contributes to several plasma processes such as; plasma transport, wave activity, acceleration, etc. Here, we have investigated the thermodynamics of three SSMFRs close to the Sun. The polytropic indices for all three SMFRs were greater than two, suggesting that the plasma shows super-adiabatic properties. Additionally, the SSMFRs' work-to-heat-supply ratios are greater than -0.6. It shows that more than 60% of the heat delivered to the system is used to carry out work, while the remaining is used to boost internal energy. Thus, the discovered super-adiabatic process would be critical in understanding the energy transfer from the SSMFR to the surrounding plasma.

1. Introduction

A magnetic structure that twists, spins, and produces helical lines is known as a small-scale magnetic flux rope (1, 2). The in-situ observation points to the following characteristics of SSMFRs: (1) the constant rotation and twisting of the magnetic field components in time-series data. (2) The structure is convected with the solar wind and in quasi-static equilibrium. It is observed that the duration of SSMFRs ranges from a few minutes to several hours (3, 4). Regarding the origin of SSMFRs, several hypotheses have been put forth, including the following: (1) SSMFRs are manifestations of small coronal mass ejections that are produced during solar eruptions (3,5); (2) magnetic reconnection across the Heliospheric current sheet (HCS) (4); and (3) SSMFRs can be produced by both solar processes and interplanetary space (11). SSMFRs' origin is still up for debate, but we are certain that their occurrence is influenced by the solar corona and the interplanetary medium. Additionally, several simulations and observations show that 2D magnetohydrodynamic (MHD) turbulence may produce SSMFRs (6, 7, 8, 9, 10).

The role of SSMFRs may be crucial for particle acceleration (12, 27, 28, 29, 30). They suggested merging or first-order Fermi energization via contracting SSMFRs, leading to charged particle energization. Shi et al., 2021 observed Alfvénic waves and ion-cyclotron waves in a SSMFRs (13). The reconnection signature is also observed at the boundary of SSMFRs (11). Tang et al. 2018 observed Kelvin-Helmholtz wave within the ion scale flux-rope (14). The polytropic study of 59 SSMFRs at 1AU was recently researched by Teh 2021 (15). They suggested that for flux ropes with torsional Alfvén waves, as opposed to those without, they discovered that the mean and median of the polytropic index (α) are closer to 5/3, i.e., adiabatic. Osherovich, Farrugia, & Burlaga (1993) showed that when the $\alpha < 1$, the cylindrical flux rope expands self-similarly (31). In contrast, Shimazu and Vandas (2002) showed that a cylindrical flux rope could be expanded self-similarly when $\alpha > 1$ (32). Moreover, it has also been shown that ICME magnetohydrodynamic (MHD) modelling produces an expanding flux-rope for $\alpha > 1$ (e.g., 33). Furthermore, Liu et al. (2005) statistically obtained $\alpha = 1.15$ for the expansion of ICMEs, while at 20 AU, $\alpha = 1.3$ (25). The behavior of the polytropic state of a variety of plasma regions was reported; solar wind (1.46 to 1.67; see e.g., 22); solar flare (1.66 to 1.64; see e.g., 23); bow-shock (1.85; see e.g., 24); ICME (1.3; e.g., 25); Earth's plasma sheet (1.67; e.g., 26), and so on. Recent research by Teh 2021 on SSMFRs suggests that the average α within the SSMFR with torsional Alfvén waves is 1.68, whereas the value without them is 1.52 (15). As a result, adiabatic behavior is seen in the SSMFRs. Recently, Shaikh et al., 2022 shows heating and cooling of super-adiabatic Alfvén region at 1 AU (34). Here, for the first time we are investing the thermodynamic properties of SSMFRs close to the Sun using Parker Solar Probe (PSP) data. Moreover, we also investigated the heating/cooling phenomena within the SSMFR from thermodynamic point of view.

2. Data

Data from the PSP spacecraft's magnetic field and plasma characteristics were used. Data were gathered via the FIELDS (MAG; 36) flux-gate magnetometer and the Solar Probe Cup (SPC; 35). The FIELD (4Hz FGM data in RTN coordinate) and SWEAP PSP instrument data utilized in our research are accessible at https://cdaweb.gsfc.nasa.gov/pub/data/psp/. The data have a temporal precision of 0.25 sec for the magnetic field vector and 0.874 sec for plasma moments. Moreover, we have selected three SSMFRs events from the catalogue available at http://fluxrope.info/index.html. The selected SSMFRs are (1) 4th Apr 2019, (2) 22nd Aug 2019, and (3) 27th Aug 2019. The observed SSMFRs was situated at distance of 36, 73, and 50 solar radius from the Sun, respectively.

3. Methodology

Investigating how plasma changes states while being subjected to continuous specific heat requires the use of the macroscopic relationships between plasma moments provided by the polytropic approach. The polytropic process deals with a quasi-static change in a physical state when the specific heat does not vary. The polytropic equations for an ideal gas: (see e.g., 17, 31, 34)

$$P_{th} \propto N_p^{\alpha} \qquad \dots 1$$

Here, P_{th}, N_p, and α are the system's pressure, number density, and effective polytropic index (henceforth polytropic index). We have taken natural logarithms to Eq. (1), which gives; log(P_{th}) = alpha log(N_p) + log (F). Thus, we apply above linear fit model to the observed scattered data plot of P_{th}, N_p. The slope of the Eq. will give value of effective polytropic index, while the y-intercept gives equations constant. The different alpha values suggest different thermodynamic processes within the investigation region, such as; (1) $\alpha = 0$ implies isobaric process (constant pressure), (ii) $\alpha = 1$ correspond to isothermal process (constant temperature), (iii) $\alpha = 1$ implies an isochoric process (constant density, i.e., incompressible region), (iv) $\alpha = \gamma$ corresponds to an isentropic process, which implies adiabatic reversible process, and (v) $\alpha > \gamma$ means super-adiabatic process. Note that we should not confused with the specific heat ratio $\gamma = \frac{c_p}{c_v}$, which indicate an adiabatic processes. In an adiabatic plasma the $\alpha = \gamma$ and the particle effective degree of freedom (f) is; $\gamma = 1 + \frac{2}{f}$.

4. Observation and Discussion

The Figure 1 shows an SSMFR observed on 22nd August 2019 from 23:02:51 UT to 23:08:28 UT. The observed SSMFRs was with PSP spacecraft at distance of 73 solar radius. The top to bottom panels in the Fig. 1 are total magnetic field, magnetic field vector, elevation and azimuth angle of magnetic field, plasma speed, plasma density, plasma temperature, plasma thermal pressure, and magnetic pressure. The average magnetic field is 31 nT, plasma speed 340 km/s, number density 45 cc, and plasma temperature 150000 K, respectively. We observed that the magnetic pressure is higher compared to thermal pressure.

Furthermore, we performed polytropic analysis for the SSMFR. The Fig. 2 demonstrate the polytropic plot, where we observed that Pearson correlation coefficient between plasma thermal pressure and plasma density is 0.88. It suggest that both the parameters highly depends on each other. Moreover, we fitted polytropic equation to this scattered data. We observe the slope is 2.44 and y-intercept is -11.6. Thus, polytropic index of this SSMFR is 2.44, which indicate that plasma has super-adiabatic characteristics. If we assume adiabatic system, than the degree of freedom of plasma proton is $f = 1.39$. We performed similar analysis for the remaining two SSMFRs (Figures not shown here); 04th April 2019 from 05:55:25 UT to 06:05:41 UT, and 27th August 2019 from 19:19:32 UT to 19:29:48 UT. In former case, the polytropic index is 2.72 while for later case it is 2.39, respectively. Again, it suggest that these two SSMFRs also has super-adiabatic characteristic. Moreover, in case of adiabatic assumption, the effective degree of freedom for these SSMFRs are $f = 1.16$ and $f = 1.44$, respectively.

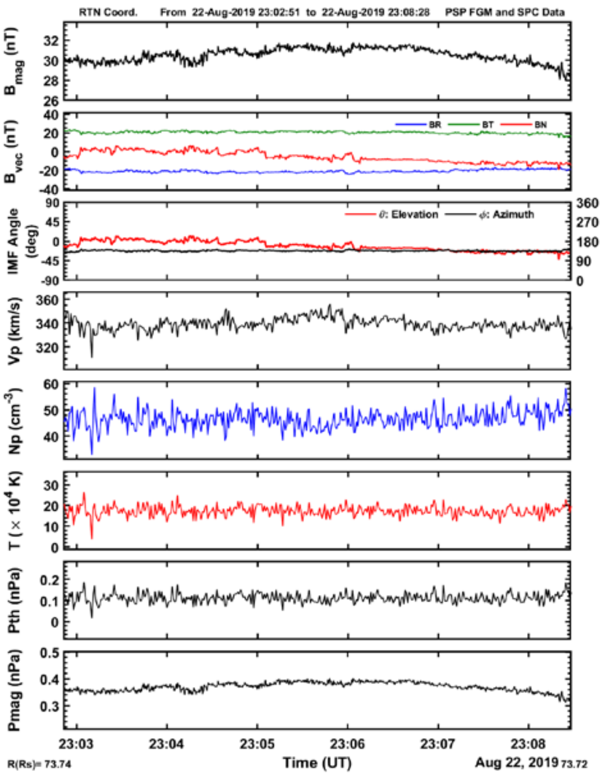

Figure 1. Temporal profile of plasma parameters and magnetic field variation for an example event of SSMFR observed by the PSP spacecraft dated August 23, 2019. The top panels (first, second, and third) represents total IMF ($\boldsymbol{B_{mag}}$), IMF components ($\boldsymbol{B_{vec}} = (\boldsymbol{B_x}, \boldsymbol{B_y}, \boldsymbol{B_z})$), and IMF azimuth ($\boldsymbol{\phi}$) \& elevation ($\boldsymbol{\theta}$) angles, respectively. The fourth, fifth, and sixth panels show the variation of plasma speed (Vp), proton density (Np), and plasma temperature (T), respectively. The last two panels represent variation of thermal (Pth) and magnetic (Pmag) pressures.

5. Heating and Cooling Process

In a polytropic analysis, the relationship between work done and heat supply is given as (see detailed mathematics in 34);

$$\frac{\delta w}{\delta q} = \frac{\gamma - 1}{\gamma - \alpha} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 2$$

Where, the γ *and* α are specific heat ratio and polytropic index. Since the solar wind has major proton composition and high temperature, it is proposed that the value of $\gamma = 5/3$. So, substituting this value and calculated α values into the Eq. 2, we will get the information about the $\frac{\delta w}{\delta q}$ ratio. The Figure 3 shows the analysis of heating/cooling of the system i.e., SSMFRs. We found that for 4th Apr 2019 event it is -0.63, It suggest that 63% of the supplied heat will be used to perform work by the system on the surrounding whereas the remaining will be utilized to increase internal energy of the system. For 22nd Aug 2019 it is -0.86, and for the 27th Aug 2019 the value is -0.92, respectively. These outcome suggest that system is doing more work on the surrounding. Hence the system will cool down eventually.

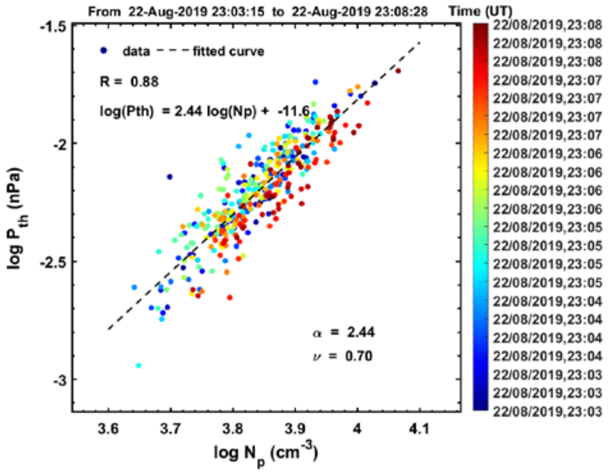

Figure 2. Variation of $\log(P_{th})$ vs $\log(N_p)$. The coloured circles represent data points (time evolution), and the black dash line gives a linear fitting value.

5. Conclusion

The heating and cooling of space and astrophysical plasma are among the scientific community's most challenging problems. In this regard, magnetic reconnection (Yamada et al., 2010), wave-particle interaction (Tsurutani & Lakhina, 1997; Wang et al., 2006), temperature anisotropy (Maruca et al., 2011), etc., have all been investigated. Here, we have investigated the heating and cooling of space plasma from thermodynamic point of view within the SSMFRs. Based on polytropic analysis, we found that the examined SSMFRs near the Sun exhibit a super-adiabatic property (16, 34). The polytropic behavior of solar wind plasma near the Sun (17) and processes in the Alfvenic region at 1 AU are in agreement with our findings. We also noted that plasma within the SSMFRs performs work on the surrounding medium so that plasma expands and significantly cools the plasma proton. We also observe that in the adiabatic plasma, it controls effective particle degree of freedom. We proposed that the observed cooling of plasma protons within the SSMFRs manifest expansion processes, e.g., expanding plasma-like solar wind and interstellar plasma). Furthermore, we believe that we should not overlook the other processes that might be taking place with the SSMFRs, such as; the anisotropy, turbulent phenomena, wave-particle interaction, Etc. Thus, we believe that our results will be very useful to understand the heating and cooling phenomena in space plasma. In future we will performer similar analysis for the statistically large dataset of SSMFRs for concrete understanding of thermodynamics of plasma.

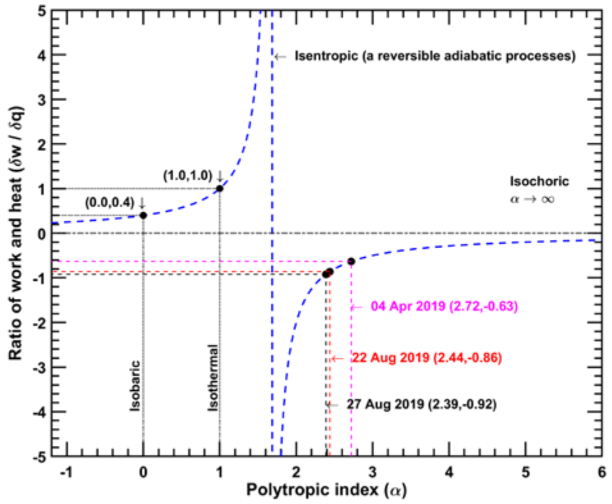

Figure 3. The work and heat ratio is a function of the effective polytropic index. We have shown different data points on the curves associated with different thermodynamics processes in the plot.

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7. References

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