Evidence for Super-adiabatic Heating and Cooling of Alfvénic Solar Wind

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ABSTRACT

Alfvénic fluctuations are widespread and crucial in various physical processes of space & astrophysical plasma. However, their role in heating and work done remains unexplored. Here, we have used Wind spacecraft's data situated at 1 AU distance to examine 12 distinct Alfvénic regions using polytropic analysis. The study finds an average polytropic index value $\alpha = 2.64$, which is consistent with a super-adiabatic behaviour for plasma particles with three effective degrees of freedom ($f = 3$). Moreover, this study examines several scenarios for plasma particles with different degrees of freedom. We noted that the investigated Alfvénic region could be adiabatic only for plasma particles with $f = 1.26$ degrees of freedom. In addition to this, for $\alpha = 2.64$, the ratio of work done to the total heat supply within the system is $\frac{\delta w}{\delta q} = -0.68$, indicating that 68 per cent of the total supplied heat is utilized to accomplish work by the system on the surrounding (expansion phenomena), and the remaining is used to increase the internal energy of the system. As a result, we hypothesized that the Alfvénic plasma region is cooling more than the adiabatic expectation, resulting in super-cooling phenomena. Thus, we propose that the discovered possible super-adiabatic process would be critical in understanding the energy transfer from the Alfvénic zone to the surrounding plasma.

Key words: Solar Wind – Alfvén wave – Heating – Cooling – Thermodynamics

1 BACKGROUND AND MOTIVATION

A thermodynamic process that happens without heat or mass transfer between the system and its surroundings is known as an adiabatic process (Carathéodory 1909; Tisza 1966). It is a crucial thermodynamic process that underpins the first rule of thermodynamics. Unlike an isothermal process, an adiabatic process only distributes energy to the environment as work (Lewis et al. 2020). In general, heating and cooling of the ideal gas is associated with adiabatic compression and expansion respectively. This process is prevalent in nature i.e. from diesel engines to the Earth's atmosphere. The adiabatic cooling causes moisture or salinity to condense in meteorology and oceanography (Houghton 2002); the rising magma is cooled adiabatically before an eruption (Kavanagh & Sparks 2009). The temperature of the Earth's convecting mantle under the lithosphere is nearly adiabatic (Turcotte & Schubert 2002); In fact, an expanding universe can be characterized to first order as an adiabatically cooling fluid. However, various physical mechanisms regulating plasma entail heat transfer, thus the adiabatic assumption is no longer valid.

The heating and cooling of space and astrophysical plasma is one of the most difficult problems facing the scientific community. 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 . In order to explore the space plasma from a thermodynamics standpoint, a polytropic technique was adopted (Baumjohann & Paschmann 1989; Livadiotis 2019b). It provides macroscopic relationships between plasma moments that can be utilized to investigate the transition of plasma from one state to another state under constant specific heat. The polytropic process is concerned with a quasi-static change in physical condition where the specific heat remains constant. For an ideal gas, the polytropic equations written as (Livadiotis 2019a,b; Nicolaou et al. 2020);

$$P \propto N^{\alpha} \quad or \quad T \propto N^{\alpha-1} \quad or \quad N \propto T^{\nu} \tag{1}$$

where, P, T, N, and α ($\nu = 1/(\alpha - 1)$) are the pressure, temperature, number density, and effective polytropic index (henceforth polytropic index) of the system respectively. It's vital to remember that α is not to be confused with the specific heat ratio $\gamma = \frac{c_p}{c_v}$ (an adiabatic process). In case of polytropic process, the ratio of the energy transferred in the system as heat over the energy transferred as work remains constant, whereas, in adiabatic case, there is no heat transfer in the system during the transition. In case of adiabatic plasma, the γ is related with the particle's effective degree of freedom f as; $\gamma = 1 + \frac{2}{f}$. In addition, the α value provides information on the different thermodynamic processes that occur within the system such as (Nicolaou et al. 2014b; Livadiotis 2019b); (i) $\alpha = 0$ implies isobaric process (constant pressure), (ii) $\alpha = 1$ correspond to isothermal process (constant temperature), (iii) $\alpha = \infty$ implies an isochoric process (constant density, i.e, incompressible region), (iv) $\alpha = \gamma = \frac{c_p}{c_v}$ corresponds to an isentropic process, which implies adiabatic reversible process, (v) $\alpha < 0$ implies a process where work and heat flow simultaneously in and out of the system (i.e., an explo-

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sive behaviour), (vi) $1 < \alpha < \gamma$: sub-adiabatic state, suggest heat and work flow go in same directions, (vii) $\gamma < \alpha < \infty$: super-adiabatic state, means heat and work go in the opposite direction.

The polytropic behaviour has been seen in a variety of plasma regimes, including: solar wind protons ($\alpha = 1.46 - 1.67$) (Livadiotis & Desai 2016), solar wind electrons ($\alpha = 1$) (Livadiotis & Desai 2016), solar flares ($\alpha = 1.66 - 1.64$) (Wang et al. 2015), planetary bow-shocks ($\alpha = 1.85$) (Tatrallyay et al. 1984), interplanetary coronal mass ejections (ICMEs) between 0.3 and 20 AU ($\alpha = 1.3$) (Liu et al. 2006), magnetic clouds ($1.1 < \alpha < 1.3$ (Osherovich et al. 1993)), coronal plasma ($\alpha = 1.04 - 1.58$) (Prasad et al. 2018), solar corona ($\alpha = 1.10$) (Van Doorsselaere et al. 2011)), upper-chromospheric sunspot ($\alpha = 1.12$) (Houston et al. 2018), hot flare loop ($\alpha \sim 1.64$) (Wang et al. 2015), Earth's plasma sheet ($\alpha \sim 1.67$ (Zhu 1990), $\alpha \sim 4/3 - 5/3$ (Goertz & Baumjohann 1991)), Saturn's magnetosphere ($\alpha \sim 1.25$ for H^+; and 0.95 for O^+) (Dialynas et al. 2018), galaxy clusters (e.g., $\alpha \sim 1.2 - 1.3$) (Markevitch et al. 1998), galaxy superclusters (e.g., $\alpha \sim 1.16$) (Ettori et al. 2000), etc. Moreover, Mishra & Wang (2018) proposed that α value decreases from 1.8 to 1.35 as the CME propagates away from the Sun, thus CME released heat and reached into adiabatic state. Recently, Teh (2021) showed that the small-scale flux-ropes accompanied with torsional Alfvén waves has average effective $\alpha = 1.68 \pm 0.43$, whereas, flux-rope without torsional Alfvén waves has average effective $\alpha = 1.52 \pm 0.40$. Furthermore, there are cases, where, we observe $\alpha < 1$, e.g., inner heliosheath (Livadiotis & McComas 2013), outer-heliosphere (Livadiotis 2021), Earth's magnetosphere; central plasma sheet (Pang et al. 2015), bow shock (Pang et al. 2020), Saturnian inner magnetosphere (Dialynas et al. 2018), Jovian magnetosheath (Nicolaou et al. 2014a), etc.

In the present paper, we focus on the solar wind plasma, which are generally dominated by the Alfvén wave (AW) or Alfvénic fluctuations (Belcher & Davis Jr 1971). The AWs are the most fundamental oscillation in a magnetised plasma and crucial in both astrophysical and laboratory plasmas (Cramer 2001). They have significant impact on magnetised turbulence phenomenologies, large-scale magnetic structure interaction, solar corona heating, solar and stellar interiors, cosmic ray transport, astrophysical accretion disk, slow recovery of geomagnetic storms, etc., (De Pontieu et al. 2007; Jess et al. 2009; Shaikh et al. 2019). The in-situ observations suggest that the solar wind is superposed by the large-amplitude, outward-propagating AWs in the interplanetary medium (Bruno & Carbone 2013). The remote observation of AWs in the low corona also supports solar wind energisation (De Pontieu et al. 2007). Moreover, several theoretical studies have been conducted to determine how AWs could potentially heat and accelerate the solar wind (see Hansteen & Velli (2012) and references therein). It is also hypothesised that Alfvén wave dissipation heats the chromospheric plasma (Grant et al. 2018). It is worth noting that large-wavelength AWs once released from photospheric motions are unable to transfer their energy to plasma near the Sun until it becomes turbulent. Turbulence causes energy to cascade from broad wavelengths to small wavelengths, which increases the dissipation rate of AWs (Bruno & Carbone 2013). The sun is the primary source of AWs suggesting that most of these waves are propagating outward (Liu et al. 2020). It is hypothesised that radial variations in the Alfvén speed cause AW reflection, which could result in inward-propagating AWs (Cranmer & Van Ballegooijen 2005; Chandran & Hollweg 2009). The interaction of counter-propagating AWs is one of the main causes of AW turbulence (Iroshnikov 1963; Kraichnan 1965). The numerical simulations in fast solar wind further suggest that reflected AWs cause a robust turbulent cascade (e.g., Perez & Chandran (2013)).

Solar wind can be energized with the work done by the AW pressure force and being heated by AWs cascade and dissipation (Hollweg 1973). However, the interconnection between AW heating and work is poorly explored. Thus, we examine the heating and cooling process in the Alfvénic region from a thermodynamic point of view. The most fundamental thermodynamic process that can be assessed using in-situ plasma data is the polytropic process, which provides information on the quasi-static change of state. The goal of the current study is to analyse the link between heat and work on the Alfvénic intervals using a polytropic method.

2 METHODOLOGY AND EXAMPLE EVENT

We used data from the Solar Wind Experiment (SWE; Ogilvie et al. (1995)) and Magnetic Field Investigation (MFI; Lepping et al. (1995)) instruments on board the Wind satellite with a temporal resolution of 92 seconds. MFI provides magnetic field data (B_x, B_y, B_z), whereas SWE provides plasma properties (proton velocity vector V_p, density N_p, also temperature T_p components (in terms of the component of the thermal speed)). For polytropic analysis, we examined the Alfvénic intervals, which have been thoroughly investigated in the literature and are listed in Table 1. This ensures that the chosen interval minimizes the mixing of distinct plasma regimes required for reliable polytropic index estimation. While choosing the Alfvénic region, we have selected Alfvén region irrespective of their existence into the slow and fast solar wind. We have used Eq. 1 for the investigation of polytropic process into the Alfvénic region. To do so, we have taken natural logarithms to Eq. (1), which gives;

$$logP_{th} = \alpha \; logN_p + logF \tag{2}$$

Thus, for each Alfvénic region, we apply a linear fit model to the scatter plot of $logP_{th}$ vs. $logN_p$. The slope of the fitted line provides the value of α, and the y-intersection determines the equation's constant, i.e., $logF$. We have also estimated other physical parameters, such as; entropy $S = \frac{3}{2}k_B ln(P_{th}/N_p^{\alpha})$; and plasma beta $\beta_P = \frac{P_{th}}{P_{mag}} = \frac{N_p k_B T_p}{B^2/2\mu_0}$, here, k_B is the Boltzmann constant, and μ_0 is permeability of free space. We have demonstrated the calculated entropy in k_B units as; $S/k_B = \frac{3}{2}ln(P_{th}/N_p^{\alpha})$. The value of entropy indicates randomness associated with the studied region, i.e., low value of entropy suggesting system is more ordered. The β_P value suggest contribution of thermal and magnetic pressure in the region (Nicolaou et al. 2020).

3 RESULT

We analyse all 12 Alfvénic intervals as show in Table 1, based on the methodology described in Section 2. Figure 1 shows plots of $logP_{th}$ vs $logN_p$ for four out of the 12 intervals we examine. Table 1 shows the derived key parameters for all of the 12 cases. These parameters are total interplanetary magnetic field (B_{mag}), plasma speed (Vp), plasma temperature (T_p), plasma density (N_p), plasma beta β_p, magnetic pressure P_{mag}, thermal pressure P_{th}, dynamic pressure P_{sw}, Alfvén speed V_A, Alfvénic Mach number M_A, and Magnetosonic Mach number M_{ms}) for each studied regions. Here, we will focus our discussions on a the typical Alfvénic interval that crossed the Wind spacecraft on March 04, 1998, 20:21:25 to March 05, 1998, 00:23:12, studied thoroughly by Li et al. (2017). The top left Figure 1 shows polytropic estimation for the given Alfvénic interval. The analysis indicates high Pearson correlation coefficient (0.93), while

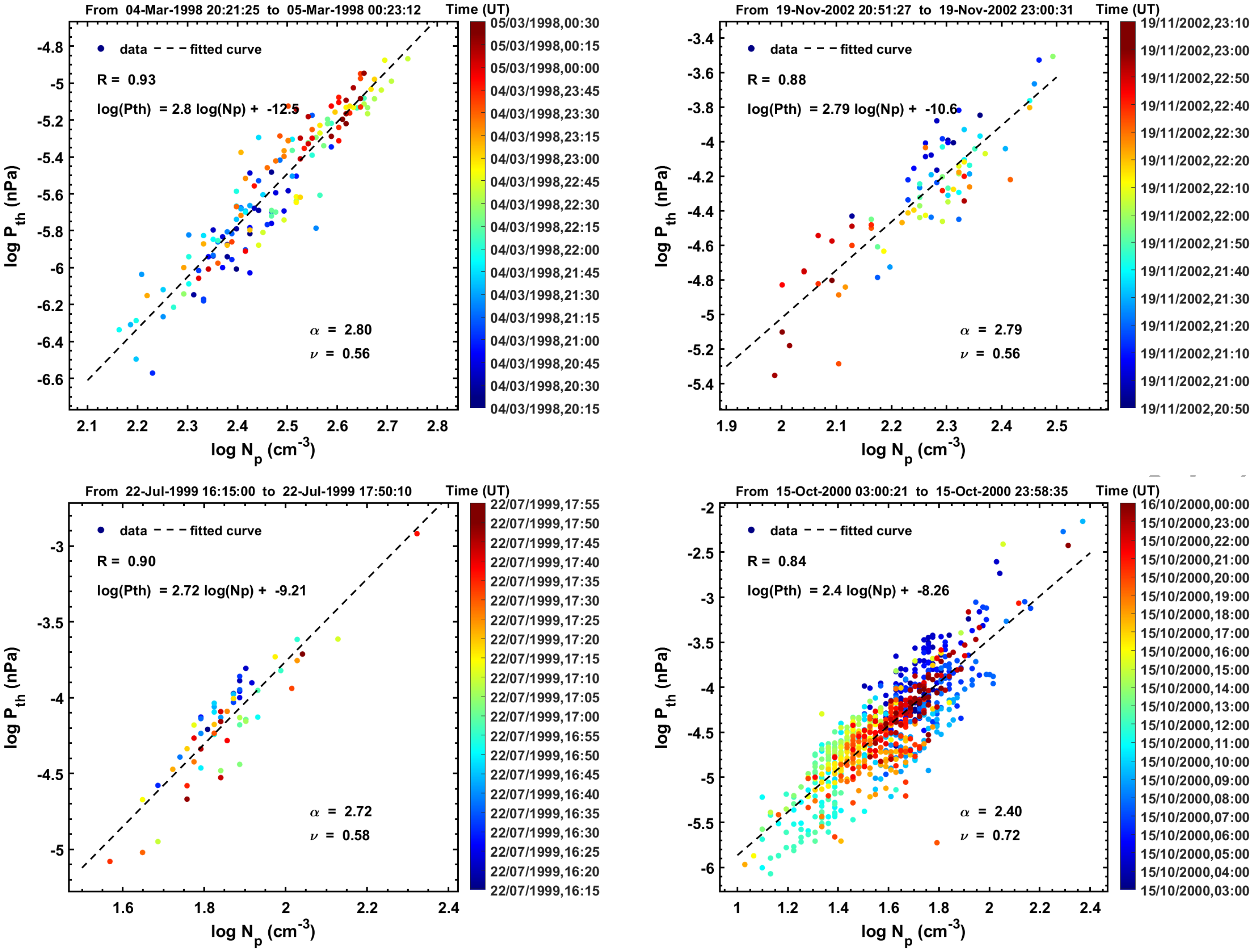


Figure 1. Variation of $log P_{th}$ vs $log N_p$. The coloured circles represents data points (time evolution) and black dash line gives linear fitting value.

linear fit provides slope, i.e., $\alpha = 2.80$ and intercept $log F = -15.6$. Similar analyses were done for the remaining 11 Alfvénic intervals.

4 DISCUSSION

This study looked at a polytropic analysis of twelve different solar wind intervals dominated by Alfvénic fluctuations. The polytropic index for all occurrences is $2 < \alpha < 3$ range, with an average value of 2.64. Generally, the solar wind plasma near Earth is adiabatic i.e., $\alpha = 5/3$. If we assume adiabatic plasma, then the particles have $f = 1.26$ effective degrees of freedom and thus, highly anisotropic velocity distribution and/or existence of heterogeneous correlations among particle velocity components (see e.g., (Livadiotis & Nicolaou 2021)). On the other hand, if we assume $f = 3$, then the plasma is super-adiabatic and thus, governed by a mechanism that involves heat transfer. As a result, the only method to enhance the system's internal energy is to work on it, and vice versa. We see that the average entropy for all regions is -100.03 (in units of k_B). A drop in entropy suggests that the region's chaos has lessened. It's possible that an increase in α correlates to a drop in the entropy.

4.1 Heating & Cooling Process

In a polytropic process, the pressure-volume work (w) done by the system can be calculated by integrating the pressure $P(V)$ function:

$$\delta w = \int_{V_1}^{V_2} P(V)\,\Delta V \tag{3}$$

If you know the system's initial state P_1 **and** V_1, any subsequent state 2 inside P and V can be described as $P_1 V_1^{\alpha} = P V^{\alpha}$, thus; $P(V) = (P_1 V_1^{\alpha})/V^{\alpha}$, As a result of substituting into the above equation and integrating, we get:

$$\delta w = \frac{P_1 V_1}{1-\alpha}\left[\left(\frac{V_2}{V_1}\right)^{1-\alpha} - 1\right] \tag{4}$$

since, $TV^{\alpha-1} = constant$, and ideal gas law is $PV = nR_sT$ (n = amount of substance, $R_s = c_p - c_v$ is universal gas constant), the work will reduce in the form of;

$$\delta w = \left[\frac{\gamma - 1}{1-\alpha}\right] c_v n(T_2 - T_1) \tag{5}$$

where, $\gamma = \frac{c_p}{c_v}$. According to the first law of thermodynamics,

$$\delta q = \delta u + \delta w \tag{6}$$

Table 1. List of Alfvénic intervals and associated average plasma parameters such as; IMF magnitude (B_{mag}, nT), plasma proton speed (V_p, km/s), plasma temperature (T_p, Kelvin), and plasma density (N_p, per cc), proton plasma beta (β_p), pressures such as; magnetic (P_{mag}, nPa), thermal (P_{th}, nPa), dynamics (P_{sw}, nPa), Alfvénic speed (V_A, km/s), Alfvénic (M_A) and Magnetosonic Mach number (M_{ms}). Further columns demonstrates thermodynamics related parameters as described into the texts. Note that the value of f is calculated with the assumption that studied region is adiabatic, i.e., $\frac{\delta q}{\delta w} = 0$.

Start Time	End Time	B_{mag}	Vp	Tp	Np	β_p	$Pmag$	Pth	Psw	V_A	M_A	M_{ms}	α	ν	$logF$	f	S_{kb}	Reference
4th May 2008 11:29	5th May 2008 11:30	5.18	589.19	1.81E+05	3.11	0.84	0.01	0.01	2.09	64.82	9.34	6.33	2.14	0.88	-7.32	1.75	-86.39	
2nd Jun 1998 15:29	2nd Jun 1998 15:50	8.84	389.68	5.36E+04	9.51	0.23	0.03	0.01	2.80	62.72	6.24	5.37	2.33	0.75	-10.21	1.5	-94.70	Yang et al. (2016)
15th Oct 2000 03:00	15th Oct 2000 23:58	8.84	509.66	1.86E+05	4.96	0.42	0.03	0.01	2.50	86.97	5.91	4.67	2.40	0.72	-8.26	1.42	-93.18	Shaikh et al. (2019)
3rd Jun 1998 07:05	3rd Jun 1998 07:20	6.64	400.55	6.37E+04	9.67	0.50	0.02	0.01	3.01	46.78	8.60	6.53	2.49	0.67	-10.43	1.34	-98.29	Yang et al. (2016)
29th Jan 1995 20:22	29th Jan 1995 20:55	12.46	591.21	3.25E+05	8.45	0.62	0.06	0.04	5.74	93.70	6.32	4.56	2.52	0.66	-8.65	1.32	-96.27	Chao et al. (2014)
14th Oct 2002 18:16	14th Oct 2002 18:52	15.59	388.31	2.24E+05	10.03	0.33	0.10	0.03	2.94	107.68	3.62	2.97	2.52	0.66	-9.31	1.32	-97.37	Liu et al. (2020)
22nd Jul 1999 16:15	22nd Jul 1999 17:50	10.14	457.62	1.83E+05	6.43	0.41	0.04	0.02	2.62	87.67	5.24	4.14	2.72	0.58	-9.21	1.16	-101.33	Shi et al. (2015)
19th Nov 2002 20:51	19th Nov 2002 23:00	11.03	400.77	1.05E+05	9.58	0.30	0.05	0.01	2.99	78.12	5.15	4.29	2.79	0.56	-10.61	1.12	-104.85	Zhang et al. (2014)
16th Jun 2002 16:00	16th Jun 2002 19:52	8.02	404.11	8.51E+04	7.31	0.36	0.03	0.01	2.32	65.02	6.31	5.08	2.80	0.56	-10.34	1.11	-104.60	
04th Mar 1998 20:21	05th Mar 1998 00:23	10.01	360.99	2.41E+04	11.94	0.10	0.04	0.00	3.02	63.60	5.71	5.31	2.80	0.56	-12.49	1.11	-107.88	Li et al. (2017)
3rd Feb 1995 09:00	3rd Feb 1995 10:00	5.89	557.70	1.08E+05	3.31	0.36	0.01	0.01	2.01	70.79	7.89	6.37	3.04	0.49	-8.97	0.98	-107.58	Chao et al. (2014)
17th Oct 2002 17:39	17th Oct 2002 22:00	8.87	564.21	1.70E+05	3.16	0.24	0.03	0.01	1.97	109.31	5.19	4.44	3.09	0.48	-8.51	0.96	-107.89	Liu et al. (2020)
- -	**Average**	**9.29**	**467.83**	**1.42E+05**	**7.29**	**0.39**	**0.04**	**0.01**	**2.83**	**78.10**	**6.29**	**5.01**	**2.64**	**0.63**	**-9.53**	**1.26**	**-100.03**	

where, δq is the total heat transferred into the system and δu is the change in internal energy which is associated with the temperature change of the system;

$$\delta u = c_v n(T_2 - T_1) \tag{7}$$

Thus, transferred heat can be calculated as;

$$\delta q = \left[\frac{\gamma - \alpha}{1 - \alpha}\right] c_v n(T_2 - T_1) \tag{8}$$

Dividing Eq. 5 by Eq. 8 , we get;

$$\frac{\delta w}{\delta q} = \left[\frac{\gamma - 1}{\gamma - \alpha}\right] \tag{9}$$

This is the same equation derived by Livadiotis (2019a) (see Eq. 4a). Furthermore, the relation between γ and degree of freedom is given as $\gamma = \frac{2}{f} + 1$. Therefore, substituting this into above Equation, we will get following relation;

$$\alpha = \frac{2}{f}\left(1 - \frac{\delta q}{\delta w}\right) + 1 \tag{10}$$

This is exactly the same Equation mentioned in the Nicolaou et al. (2020). It quantifies the plasma heating or cooling based on thermodynamic variables which relates α, f, and $\frac{\delta q}{\delta w}$.

Figure 2 shows the relation of $\frac{\delta q}{\delta w}$ with f for different value of α (Eq. 10). The red ($\frac{\delta q}{\delta w} > 0$) and cyan ($\frac{\delta q}{\delta w} < 0$) shaded region represent the heating and cooling mechanisms for an expanding plasma, respectively. It is associated with different parameters that either supply or retain heat from the expanding plasma region. In Figure 2, we show variation for different α values, such as; 2.64 (average value found in our work), 2.7 for region close to the Sun (Nicolaou et al. 2020), 5/3 for the stream interaction region (Newbury et al. 1997), and 1.46 for solar wind between 0.3 and 1 AU (Totten et al. 1995). In addition, we also shows the variation for $\alpha = 0.01$ (nearly isobaric process), $\alpha = 1$ (isothermal process), and $\alpha = 3$ (extreme super-adiabatic process). In the present study $\alpha = 2.64$, and from Eq. 10 if we assume that $\frac{\delta q}{\delta w} = 0$ (i.e., adiabatic plasma), it leads to $f = 1.26$; indicating that the region cannot gain or lose energy with the surrounding medium at this point. The heating process occurs as f decreases below 1.26 this makes $\frac{\delta q}{\delta w} > 0$, which could be attributed to some physical processes that heated the plasma protons in the examined location. Cooling phenomena are observed if $f > 1.26$ in some way which makes $\frac{\delta q}{\delta w} < 0$.

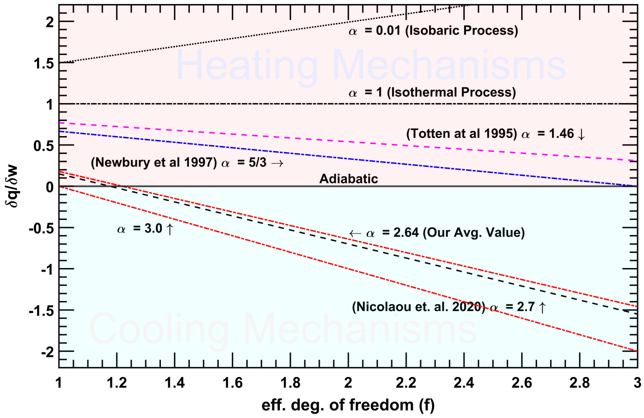


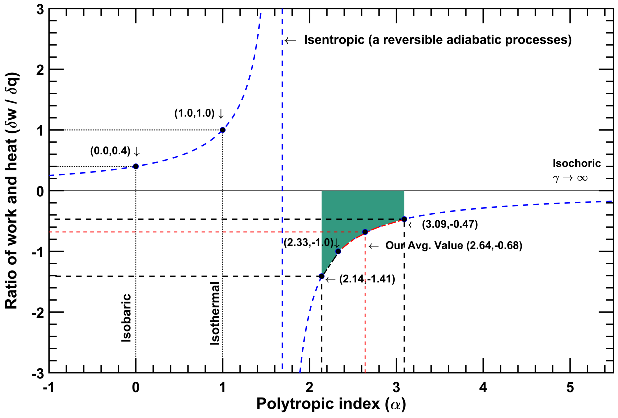
Figure 2. Relation between $\frac{\delta q}{\delta w}$ and f for different value of α. The red- and cyan-shaded regions represent the heating and cooling mechanisms. It is associated with different parameters that either supply or retain heat from the expanding plasma region. In plot, we show variation for different α values, such as; 2.64 (average value in this work), 2.7 (Nicolaou et al. 2020), 5/3 (Newbury et al. 1997), 1.46 (Totten et al. 1995), $\alpha = 0.1$ (isobaric process), $\alpha = 1$ (isothermal process), and $\alpha = 3$ (highly super-adiabatic), respectively.

Figure 2 also demonstrates the following points; Totten et al. (1995) reported average $\alpha = 1.46$, indicating that expanding solar wind plasma protons are heated for any given value of f between 1 and 3. They also noticed that α does not depend on the solar wind speed, suggesting it is independent to the origins of solar wind streams. Whereas, Newbury et al. (1997) found $\alpha \sim 5/3$; in this case, for $f = 3$, there is no heat loss or gain by the proton, but as f decreases, there is some process that heat the plasma proton. Nicolaou et al. (2020) studied the polytropic process of the solar wind plasma close to the Sun, in a heliocentric distance ranging from $\sim$ 0.17 AU to $\sim$ 0.80 AU using Parker Solar Probe (PSP) data. They discovered an average value of $\alpha =\sim 2.7$ with an associated $f \sim 1.2$ near the Sun. At this point, the system switches from heating to cooling process. They found that for $\alpha =\sim 2.7$ the system characterizes an adiabatic plasma only if $f \sim 1$. Further, they suggested that their findings align with the kinetic description of plasma ions interacting with slow waves, in which the ions behave as if they were a one-dimensional adiabatic fluid with temperature fluctuations limited along the magnetic field. (Gary & Gary 1993; Verscharen et al. 2017). Whereas, in case of

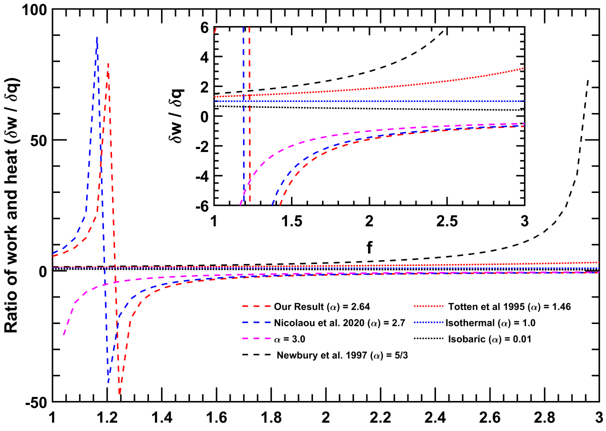
$f > 1$ (greater than 1.2), there exist some cooling mechanisms for plasma protons, at least in the direction of phase space density. Since, our average value of $\alpha = 2.64$ which is very close to the finding of (Nicolaou et al. 2020), therefore, we believe that in our studied Alfvénic regions at 1 AU, similar processes might be taking place. In addition, a detailed investigation is required to pinpoint the usual physical processes that contribute to the heating or cooling of plasma protons close to the Sun and at 1 AU.

Nicolaou et al. (2014b) estimated α values, particularly from 1995 to 2006 at 1 AU distance using OMNI data base, which includes data obtained from several spacecraft at 1 AU. They observed that a κ-Gaussian distribution with a mean of ~ 1.8 best describes the distribution of the α. Moreover, Livadiotis (2018a) estimated the $\alpha = 1.86 \pm 0.09$ for the solar wind proton plasma at 1 AU over the last two solar cycles (years 1995–2017). It also suggest that value of α independent of the plasma flow speed. Furthermore, Livadiotis (2018b) shows the connection between polytropic index and kappa indices of solar wind proton at 1 AU and its relation with the particle potential energy. Nicolaou & Livadiotis (2019) shows that during last two solar cycles the average α value per year lies near by -1.68. They also shows relationship with κ, the magnetic field strength, and the solar activity. Nicolaou et al. (2019) estimated the α of the solar wind protons over 2002, and found that average value is -1.9. Thus, at 1 AU distance several studies has been performed which gives average α of the solar wind proton ranges from 5/3 to 1.9 value.

The adiabatic index of hydrogen is $\gamma = C_p/C_v = 5/3$ for temperatures $T \sim 8000K$ and $T \geq 5 \times 10^4 K$ (De Avillez et al. 2018). The solar wind has a very high temperature and is dominated by hydrogen, and we will assume that the solar wind-related hydrogen ion has $\gamma = 5/3$. Therefore, we examine the typical case for monoatomic gas with $\gamma = 5/3$ in Eq. 9 to determine the relationship between change in internal energy and work/heat, which is equivalent as using $f = 3$ in Eq. 10. The Figure 3a depicts the link between the work/heat ratio and the polytropic index (α). For an isobaric process with $\alpha = 0$, we notice that $\frac{\delta w}{\delta q} = 0.40$, implying that 40% of the provided total heat will be utilized to produce work. In contrast, the remaining heat will increase the system's internal energy. Whereas at $\alpha = 1$ (isothermal process), $\frac{\delta w}{\delta q} = 1$, indicating that total heat given into the system is used to perform work. Therefore internal energy of the system will not change, implying that the temperature of the system will remain constant. When the process is adiabatic, then $\frac{\delta w}{\delta q} = 0$. It is worth noting that when $\alpha = 5/3$, the system enters an isentropic state.



(a) $\frac{\delta w}{\delta q}$ vs α.



(b) $\frac{\delta w}{\delta q}$ vs f.

Figure 3. Ratio of work and heat supplied as a function of effective (a) polytropic index and (b) degree of freedom. In plot (a), we have shown different data-points on the curves associated with different thermodynamics processes. Whereas, the plot (b) is similar to the Figure 2. We have also zoomed the plot to get better visibility of the curves trend.

According to our findings, the value of α spans from 2.14 to 3.09, with an average of 2.64. As a result, the investigated regions have super-adiabatic properties. For $\alpha = 2.64$, we found that $\frac{\delta w}{\delta q} = -0.68$, indicating that the system is expanding (cooling), with 68 percent of the total energy translated into work and the remaining 32 percent increasing the internal energy of the system. As a result, the system's temperature drops, and we can say that heat is being taken from the system. Similarly, we can understand the different situations of α and corresponding $\frac{\delta w}{\delta q}$ ratio. Overall, the Alfvénic region exhibits super-adiabatic expansion behaviour, which causes the system to cool down. It is true if we observe the overall plasma expansion. But here, we examine fluctuations within a structure governed by waves. So, the examined plasma is not monotonically expanding. So, the plasma is compressing and expanding within the observed fluctuations. During the compression process, the energy used to squeeze the gas turns into heat and increases its temperature to the point where the gas is superheated at the end of compression. Thus, if we accept $f = 3$, the super-adiabatic result means that an expanding plasma (doing work) is cooling more than the adiabatic expectation (heat emitted by the gas to the surrounding environment). Figure 3b is analogous to Figure 2 which demonstrates the variation of $\frac{\delta w}{\delta q}$ with respect to f for different values of α. Thus, it provides information on the heating and cooling processes of the system for different values of f. Figure 3b demonstrate similar finding of the previous studies which I discussed earlier in the previous subsection. Thus, the f in addition to α value, plays a substantial role in plasma proton heating and cooling processes.

5 CONCLUSION

We argue that Alfvénic regions at 1 AU exhibit super-adiabatic properties based on polytropic processes (Livadiotis & Nicolaou 2021). We hypothesize that the presence of small-scale fluctuations caused by turbulence may contribute to following $\alpha = 2.64$ trend. The $\frac{\delta w}{\delta q} = -0.68$, suggests that the system accomplished work on the surrounding medium so that system expands and significantly cools the plasma protons. So, there will be two possibilities; (1) region squeezed rapidly by an external force, system's energy will grow (heating phenomena, e.g., plasma's in ICMEs sheath or Planetary Magnetosphere, and CIR regions), and (2) if the region expands, the system's energy will drop (cooling phenomena, e.g., expanding plasma-like solar wind, interstellar plasma).

Surprisingly, our results are consistent with the observation of solar wind polytropic behaviour near the Sun (Nicolaou et al. 2020). Thus, we believed that the solar wind flow connects the processes close to the Sun to 1 AU away. However, we should not overlook any distinct process responsible for our observation at 1 AU such as anisotropic distribution of solar wind proton or existence of heterogeneous correlations (see e.g., Livadiotis & Nicolaou (2021) and references therein). The common plasma process that regulates the effective degree of freedom deserves further exploration close to the Sun and at 1 AU. The discovered super adiabatic process would be critical in understanding the energy transfer from the Alfvénic zone to the surrounding plasma, such as the solar wind, planetary magnetosphere, large-scale structures (ICMEs, CIRs, etc.), and so on. The process might be applicable to any astrophysical media superposed with Alfvén fluctuations, such as the interstellar medium, intergalactic medium, and so on. This super-adiabatic process in Alfvénic plasma might, in fact, be a contender for universal expansion.

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DATA AVAILABILITY

We have utilised Wind spacecraft's data which is publicly available at `https://wind.nasa.gov/data.php`, and (2) Coordinated Data Analysis Web (CDAWeb) `https://cdaweb.gsfc.nasa.gov/pub/data/wind/`. We have used MATLAB 2020a software for the data analysis and visualisation.

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