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Research paper

Spacecraft radial alignments for investigations of the evolution of solar wind turbulence: A review☆

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ABSTRACT

With the launch of the Parker Solar Probe, BepiColombo, and Solar Orbiter missions in the three-year period 2018 – 2020, the investigation of the evolution of solar wind turbulence, dynamics, and structures in the inner heliosphere has become more readily feasible, thanks to the increasing availability of orbital configurations suitable for multi-point observations of the Sun and the processes it drives in interplanetary space. Specifically, data analysis, models, and numerical simulations based on multi-spacecraft coordinated studies have been allowing scientists to address still unsolved questions, such as how turbulence and plasma heating evolve with the heliocentric distance. A few instances of spacecraft radial alignments have been used, even before the advent of the three most recent heliospheric missions, to track the evolution of the solar wind plasma throughout interplanetary space, leading to major advances in understanding the mechanisms underlying magnetohydrodynamic turbulence and the physical processes involved in dissipating the energy transferred along the turbulent cascade to heat the plasma. This paper aims to review the different works carried out so far on these issues, describing the diagnostics adopted and discussing the most important achievements in the field of solar wind turbulence evolution.

1. Introduction

Solar physicists are truly experiencing a golden age. In fact, for the first time in the era of space exploration of the Solar System within Earth's orbit, three spacecraft (s/c), namely Parker Solar Probe (PSP, Fox et al., 2016), Solar Orbiter (SO Müller et al., 2020) and BepiColombo (BC, Benkhoff et al., 2010), are studying the heliospheric dynamics and how the Sun interacts with its surroundings through the solar wind. This is a turbulent flow of weakly collisional charged particles that originates in the outermost layer of the Sun's atmosphere, the solar corona, and expands radially, defining the Sun's region of influence, the heliosphere (Hundhausen, 1972). The latter extends to the heliopause, where the pressure of the solar wind is counterbalanced by that of stellar winds, marking the boundary with the interstellar medium. The solar wind is highly inhomogeneous in space, non-stationary in time, as well as perturbed by transient events of solar origin, such as Coronal Mass Ejections (CMEs, Webb and Howard, 2012). It follows that single-spacecraft measurements only cannot capture the complex magnetohydrodynamic (MHD) properties of the interplanetary plasma, let alone the spatiotemporal evolution of the solar wind. This limited perspective of ongoing processes thus precludes a complete understanding of how the magnetic structure of the Sun and of the solar corona drive the solar wind and its various processes throughout the heliosphere. These include turbulence, transient events, particle energization, and energy transport across the interplanetary space. This major obstacle is in general not easy to overcome, due to the challenge of designing costly multi-probe missions for the simultaneous investigation of spatial and temporal variations of the fields, as well as the evolution of the solar wind as it expands from the outer corona. Despite the prohibitive costs and technological difficulties intrinsic in multi-spacecraft missions, the international heliospheric community is moving in precisely this direction for next-generation solar missions. While specific missions will be soon launched (HelioSwarm, https://www.lpl.arizona.edu/missions/helioswarm) or have been recently proposed (Magnetic Topology Reconstruction Explorer, MagneToRE, Maruca et al., 2021) for the study of inertial-range fluctuations, multi-spacecraft missions are being considered for large-scale heliospheric structure investigation (see, e.g., the SQUARE^2 mission concept in Telloni, 2022), e.g., responding to a call for white papers for the NASA decadal survey (4π-HeliOS, L. Harra, private communication). However, such space missions, whether approved and funded by international space agencies, take decades to be conceived, scientifically and technologically defined, built and finally launched.

In the meantime, a valuable option remains to exploit quadratures and alignments among existing spacecraft (i.e., orbital configurations in

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which the s/c #1 – Sun – s/c #2 angle is ~ 90° and ~ 0°, respectively). However, these are quite rare and require a rigorous selection of the plasma samples to analyze (Telloni et al., 2021b,a). The alternative is performing statistical studies using large datasets collected by the same probe at different distances from the Sun during its journey around it (e.g., Chen et al., 2020; Alberti et al., 2020). However, this does not seem to be a viable approach to characterizing the four-dimensional dynamics of heliospheric processes and to exploring the evolution of solar wind turbulence. Indeed, such observations would involve solar wind samples coming from different coronal sources, thus precluding a certain level of homogeneity/stationarity required for these surveys. As a result, it would be impossible to decouple the evolution of turbulence dynamics from any external phenomena, whose contribution would not be ponderable. This would prevent a rigorous assessment of the evolution of solar wind turbulence within the inner heliosphere. It follows that coordinated studies between two or more probes represent the best possible way to rigorously explore how the solar wind, and in particular turbulence, evolves during its expansion (see Velli et al., 2020; Hadid et al., 2021). The concurrent presence of PSP, SO, and BC in the inner heliosphere (with different orbits, payloads, and characteristics), along with the flotilla of probes orbiting near Earth around the Lagrangian point L1, thus represents a phenomenal multi-point, multi-instrumental observatory for the Sun and the dynamical evolution of the solar wind processes. More precisely, their synergy makes it possible to link the local properties of the solar wind measured in situ with its solar sources observed remotely.

Launched from Cape Canaveral on August 12, 2018, PSP is a NASA solar mission tasked with flying through the extended solar corona. It will get closer to the solar surface than any spacecraft before it in the next few years, at a distance of only 6.2 million kilometers from the Sun. Its payload consists mainly of in-situ instruments for measuring particles and electric and magnetic fields. In fact, the extreme heat and radiation conditions that PSP has to face preclude the possibility of having remote-sensing instruments for direct observation of the Sun from so close. The NASA-ESA SO mission, also launched from Cape Canaveral on February 10, 2020, has somewhat complementary characteristics to PSP. Though approaching the Sun at a distance nearly 7 times greater than that reached by PSP (it has a perihelion just under one-third of the Earth–Sun distance, or 42 million kilometers), the potential of SO lies in its payload and orbit (Zouganelis et al., 2020). In fact, of the 10 instruments on board, as many as 6 are for remote observations of the Sun, its atmosphere and heliosphere. In addition, SO will gradually rise above the ecliptic plane (up to 33° above solar equator) and, for the first time, observe remotely the Sun's North and South poles, thus providing new information about both the solar corona at higher latitudes and the source regions of the fast solar wind. Not specifically designated to study the Sun, but rather Mercury and its magneto/atmosphere, BC (an ESA-JAXA mission launched from the Guiana Space Centre on October 20, 2018) is not equipped with instruments for remote sensing of the Sun. Nevertheless, the in-situ instruments onboard are collecting a large volume of local measurements of the solar wind at distances very close to the Sun, i.e., within the Mercury's orbit. While still in its cruising phase, BC plays a key role in this multi-messenger approach to solar physics. Before the advent of PSP, SO, and BC, and besides the near-Earth space observatories and the twin spacecraft of the Solar TErrestrial RElations Observatory (STEREO, Kaiser et al., 2008, traveling on Earth's orbit ahead - STEREO-A - and behind - STEREO-B -it), the inner heliospheric missions useful for radial alignment purposes are the pair of German-US probes Helios 1 and Helios 2 (launched in the 1970s and first to approach the Sun at a distance of 0.29 au, Leinert, 1976), and the MErcury Surface, Space ENvironment, GEochemistry and Ranging (MESSENGER, Solomon et al., 2007) and Venus Express (VEX, Svedhem et al., 2007) spacecraft that studied in the first decade of the 2000s Mercury and Venus, respectively.

In spite of this unprecedented opportunity for multi-spacecraft studies of the Sun and its environment thanks to PSP, SO, and BC, it is worth noting that these probes, and especially their orbits, were not designed to maximize their synergy in coordinated studies, i.e., the number of orbital configurations useful for the investigations described above. Nor was this the case for past heliospheric missions, such as MESSENGER and VEX. As a result, the number of radial alignments between past and present heliospheric missions is limited. A complete list is provided in Table 1 (where the space missions orbiting around L1 are labeled as "Earth"). Mainly due to the difficulties of identifying the same plasma parcel crossing two aligned probes during its outward propagation, the number of studies based on radial alignments aiming to explore the evolution of solar wind turbulence is even more limited: a handful of papers has been carried out so far since the launch of the twin Helios missions. This Review aims at comprehensively summarizing in a single paper the results obtained from such works, describing in the next section the followed methodological approaches and presenting the major scientific achievements, while illustrating in which direction the heliospheric community is moving in the context of multi-spacecraft studies of the evolution of the solar wind and its turbulence characteristics.

2. Evolution of solar wind turbulence

Schwartz and Marsch (1983) first exploited a radial alignment between two spacecraft. This occurred in March 1976 between Helios 1 and 2 at 0.51 and at 0.72 au, respectively (see Table 1). Their aim was to address the evolution of the thermodynamic properties of the solar wind during its expansion throughout interplanetary space. In the framework of double adiabatic equations for a multi-species plasma and based on measured particle three-dimensional distribution functions, the authors studied the adiabatic invariants (i.e., magnetic moment and longitudinal invariant) and energetics of the same high-speed stream plasma at two different evolution stages. They found that, for the analyzed intervals, the particle adiabatic conservation is violated. In other words, the solar wind was observed to cool more slowly than predicted by purely adiabatic expansion, suggesting that some mechanism was at work to heat the plasma. This motivated a major effort in an attempt of identifying the sources of solar-wind heating. A second key finding by the authors was the evidence that Alfvénic fluctuations are strongly damped as the solar wind expands, much more quickly than expected from the Wentzel–Kramers–Brillouin (WKB) prediction for linear, non-interacting modes. This first suggested Alfvén wave dissipation as a possible source of energy for solar wind heating. Additionally, Schwartz and Marsch (1983) found significant proton and alpha particle drifts, which may serve as a viable alternative energy source for protons (Verscharen et al., 2015). Alpha particles, in fact, carry considerable fractions of solar-wind momentum and energy, being heavier and typically both faster and hotter than protons. It is now well known that a number of candidate mechanisms may participate in the observed decay of Alfvénic fluctuations with heliocentric distance, such as nonlinear interactions, a trend toward more balance between outwardly and inwardly propagating Alfvén waves, generation of transverse shear with solar wind expansion, parametric instabilities (see the review by Tu and Marsch, 1995). As for the heating sources of the solar wind, there is no doubt today that turbulence transfers the required energy down to the small scales where it is dissipated into heat. What, on the other hand, are the mechanisms that actually dissipate this energy, finally heating the particles, is still a matter of strong debate (see in this regard Smith et al., 2001; Kiyani et al., 2015; Sorriso-Valvo et al., 2019; Chen et al., 2019; Matthaeus et al., 2020; Carbone et al., 2022; Squire et al., 2022, and references therein).

In spite of the pioneering results found by Schwartz and Marsch (1983), the evolution of turbulence was not addressed in that work. The first study of the radial evolution of solar wind turbulence based on a rare radial alignment between two probes was performed, almost 30

Table 1
List of radial alignments between past and current inner heliospheric missions. Line-ups with a radial separation of less than about 0.05 au are not reported, as rather considered satellite conjunctions. Pay attention to radial alignments with SO starting February 2025, since the spacecraft will periodically lift off the ecliptic plane, potentially thereby precluding the line-up (Elliott et al., 2003, showed, however, that as long as the latitude separation of aligned probes is less than 15°, they usually observe the same flow structures). "Earth" stands for L1-orbiting space observatories.

Date	Spacecraft #1	Spacecraft #2	Notes
1976/03/08	Helios 1	Helios 2	Schwartz and Marsch (1983)
1976/05/02	Helios 1	Helios 2	
1976/09/19	Helios 1	Helios 2	
1976/10/31	Helios 1	Helios 2	
1977/04/02	Helios 1	Helios 2	
1977/04/30	Helios 1	Helios 2	
1977/10/18	Helios 1	Helios 2	
1977/10/25	Helios 1	Helios 2	
2005/10/22	MESSENGER	Earth	
2007/08/14	MESSENGER	Earth	
2008/02/07	MESSENGER	Earth	
2008/10/06	MESSENGER	Earth	
2009/02/26	MESSENGER	Earth	
2009/09/20	MESSENGER	Earth	
2010/01/24	MESSENGER	Earth	
2010/07/07	MESSENGER	Earth	Bruno and Trenchi (2014), Bruno et al. (2014), Telloni et al. (2015)
2010/11/28	MESSENGER	Earth	
2011/04/09	MESSENGER	Earth	Bruno and Trenchi (2014)
2011/08/16	MESSENGER	Earth	
2011/12/04	MESSENGER	Earth	
2012/03/21	MESSENGER	Earth	
2012/07/28	MESSENGER	Earth	
2012/11/17	MESSENGER	Earth	
2013/03/04	MESSENGER	Earth	
2013/07/09	MESSENGER	Earth	
2013/11/01	MESSENGER	Earth	
2014/02/15	MESSENGER	Earth	
2014/06/19	MESSENGER	Earth	
2014/10/16	MESSENGER	Earth	
2015/01/30	MESSENGER	Earth	
2006/06/01	MESSENGER	VEX	
2007/08/13	MESSENGER	VEX	
2008/06/06	MESSENGER	VEX	
2009/02/19	MESSENGER	VEX	
2009/10/16	MESSENGER	VEX	
2010/05/09	MESSENGER	VEX	
2010/12/02	MESSENGER	VEX	
2011/06/03	MESSENGER	VEX	
2011/10/16	MESSENGER	VEX	
2012/03/07	MESSENGER	VEX	
2012/08/11	MESSENGER	VEX	
2012/12/18	MESSENGER	VEX	
2013/05/17	MESSENGER	VEX	
2013/10/20	MESSENGER	VEX	
2014/02/23	MESSENGER	VEX	
2014/07/28	MESSENGER	VEX	
2014/12/27	MESSENGER	VEX	
2007/08/19	MESSENGER	STEREO-A	
2008/02/18	MESSENGER	STEREO-A	
2008/10/14	MESSENGER	STEREO-A	
2009/04/04	MESSENGER	STEREO-A	
2009/10/03	MESSENGER	STEREO-A	
2010/02/17	MESSENGER	STEREO-A	
2010/08/10	MESSENGER	STEREO-A	
2010/12/17	MESSENGER	STEREO-A	
2011/05/24	MESSENGER	STEREO-A	
2011/09/10	MESSENGER	STEREO-A	
2011/12/31	MESSENGER	STEREO-A	
2012/05/12	MESSENGER	STEREO-A	
2012/08/28	MESSENGER	STEREO-A	
2012/12/21	MESSENGER	STEREO-A	
2013/05/01	MESSENGER	STEREO-A	
2013/08/16	MESSENGER	STEREO-A	
2013/12/12	MESSENGER	STEREO-A	
2014/04/20	MESSENGER	STEREO-A	
2014/08/05	MESSENGER	STEREO-A	
2014/12/03	MESSENGER	STEREO-A	
2007/08/09	MESSENGER	STEREO-B	
2008/01/31	MESSENGER	STEREO-B	
2008/09/26	MESSENGER	STEREO-B	
2009/02/14	MESSENGER	STEREO-B	
2009/08/22	MESSENGER	STEREO-B	
2010/01/12	MESSENGER	STEREO-B	
2010/05/19	MESSENGER	STEREO-B	
2010/11/05	MESSENGER	STEREO-B	
2011/03/16	MESSENGER	STEREO-B	
2011/07/03	MESSENGER	STEREO-B	
2011/11/06	MESSENGER	STEREO-B	
2012/02/24	MESSENGER	STEREO-B	
2012/06/09	MESSENGER	STEREO-B	
2012/10/07	MESSENGER	STEREO-B	
2013/02/03	MESSENGER	STEREO-B	
2013/05/19	MESSENGER	STEREO-B	
2013/09/07	MESSENGER	STEREO-B	
2014/01/10	MESSENGER	STEREO-B	
2014/04/29	MESSENGER	STEREO-B	
2014/08/13	MESSENGER	STEREO-B	
2006/01/12	VEX	Earth	
2007/08/17	VEX	Earth	
2009/03/28	VEX	Earth	
2010/10/29	VEX	Earth	
2012/06/05	VEX	Earth	
2014/01/11	VEX	Earth	
2007/09/14	VEX	STEREO-A	
2009/06/19	VEX	STEREO-A	
2011/03/25	VEX	STEREO-A	
2012/12/30	VEX	STEREO-A	
2014/10/07	VEX	STEREO-A	
2007/08/02	VEX	STEREO-B	
2009/01/11	VEX	STEREO-B	
2010/07/07	VEX	STEREO-B	
2011/12/12	VEX	STEREO-B	
2013/05/28	VEX	STEREO-B	
2018/10/24	PSP	Earth	
2019/04/07	PSP	Earth	
2020/01/28	PSP	Earth	
2020/06/15	PSP	Earth	
2021/01/17	PSP	Earth	
2021/05/01	PSP	Earth	
2021/11/19	PSP	Earth	
2022/02/25	PSP	Earth	
2022/06/04	PSP	Earth	
2022/12/10	PSP	Earth	
2023/03/18	PSP	Earth	
2023/06/27	PSP	Earth	
2023/12/28	PSP	Earth	
2024/03/30	PSP	Earth	
2024/07/05	PSP	Earth	
2024/08/29	PSP	Earth	
2024/09/18	PSP	Earth	
2024/12/24	PSP	Earth	
2025/03/23	PSP	Earth	
2025/06/22	PSP	Earth	
2018/10/24	PSP	BC	
2019/04/09	PSP	BC	
2020/01/27	PSP	BC	
2020/06/14	PSP	BC	
2020/08/09	PSP	BC	
2020/09/24	PSP	BC	Alberti et al. (2022a,b)
2021/01/20	PSP	BC	
2021/03/05	PSP	BC	
2021/04/28	PSP	BC	

(continued on next page)

Table 1 (*continued*).

Date	Spacecraft #1	Spacecraft #2	Notes
2021/08/11	PSP	BC	
2021/09/27	PSP	BC	
2021/11/21	PSP	BC	
2022/02/23	PSP	BC	Telloni et al. (2022)
2022/09/08	PSP	BC	
2022/10/11	PSP	BC	
2022/12/12	PSP	BC	
2023/02/10	PSP	BC	
2023/03/18	PSP	BC	
2024/04/01	PSP	BC	
2024/04/29	PSP	BC	
2024/07/01	PSP	BC	
2024/08/19	PSP	BC	
2024/09/30	PSP	BC	
2024/11/15	PSP	BC	
2024/12/24	PSP	BC	
2025/02/09	PSP	BC	
2025/03/23	PSP	BC	
2025/05/07	PSP	BC	
2025/06/19	PSP	BC	
2025/08/04	PSP	BC	
2020/09/27	PSP	SO	Telloni et al. (2021b)
2021/04/29	PSP	SO	
2021/08/11	PSP	SO	
2021/09/18	PSP	SO	
2021/11/19	PSP	SO	
2022/02/25	PSP	SO	
2022/04/06	PSP	SO	
2022/05/31	PSP	SO	
2022/09/06	PSP	SO	
2022/10/21	PSP	SO	
2022/12/10	PSP	SO	
2023/03/17	PSP	SO	
2023/04/17	PSP	SO	
2023/06/21	PSP	SO	
2023/09/28	PSP	SO	
2023/10/12	PSP	SO	
2023/12/28	PSP	SO	
2024/03/31	PSP	SO	
2024/06/29	PSP	SO	
2024/12/23	PSP	SO	
2025/03/23	PSP	SO	
2025/04/05	PSP	SO	
2025/06/18	PSP	SO	
2019/04/01	PSP	STEREO-A	
2019/09/16	PSP	STEREO-A	
2020/01/21	PSP	STEREO-A	
2020/06/08	PSP	STEREO-A	
2021/01/14	PSP	STEREO-A	
2021/04/29	PSP	STEREO-A	
2021/08/19	PSP	STEREO-A	
2021/09/20	PSP	STEREO-A	
2021/11/16	PSP	STEREO-A	
2022/02/25	PSP	STEREO-A	
2022/06/03	PSP	STEREO-A	
2022/12/10	PSP	STEREO-A	
2023/03/18	PSP	STEREO-A	
2023/06/26	PSP	STEREO-A	
2023/09/01	PSP	STEREO-A	
2023/09/16	PSP	STEREO-A	
2023/12/28	PSP	STEREO-A	
2024/03/30	PSP	STEREO-A	
2024/09/27	PSP	STEREO-A	
2024/12/24	PSP	STEREO-A	
2025/03/23	PSP	STEREO-A	
2019/07/16	BC	Earth	
2020/07/15	BC	Earth	
2021/10/08	BC	Earth	
2022/04/14	BC	Earth	
2022/10/27	BC	Earth	
2023/03/27	BC	Earth	

(*continued on next page*)

Table 1 (*continued*).

Date	Spacecraft #1	Spacecraft #2	Notes
2023/10/05	BC	Earth	
2024/02/16	BC	Earth	
2024/08/18	BC	Earth	
2024/12/06	BC	Earth	
2025/03/23	BC	Earth	
2025/07/29	BC	Earth	
2025/11/20	BC	Earth	
2020/03/02	BC	SO	
2020/04/25	BC	SO	
2021/10/04	BC	SO	
2022/07/09	BC	SO	
2023/03/14	BC	SO	
2023/03/29	BC	SO	
2023/06/27	BC	SO	
2024/02/10	BC	SO	
2024/04/03	BC	SO	
2024/05/19	BC	SO	
2024/12/04	BC	SO	
2025/05/27	BC	SO	
2025/11/23	BC	SO	
2021/09/28	BC	STEREO-A	
2022/03/13	BC	STEREO-A	
2022/10/24	BC	STEREO-A	
2023/03/20	BC	STEREO-A	
2023/10/06	BC	STEREO-A	
2024/02/19	BC	STEREO-A	
2024/08/26	BC	STEREO-A	
2024/12/11	BC	STEREO-A	
2025/04/06	BC	STEREO-A	
2025/08/13	BC	STEREO-A	
2025/11/29	BC	STEREO-A	
2020/04/30	SO	Earth	
2021/11/09	SO	Earth	
2022/03/07	SO	Earth	
2023/03/28	SO	Earth	
2024/03/20	SO	Earth	
2025/03/13	SO	Earth	
2025/10/07	SO	Earth	
2026/08/29	SO	Earth	
2027/07/07	SO	Earth	
2028/04/25	SO	Earth	
2028/11/03	SO	Earth	
2029/08/19	SO	Earth	
2030/05/27	SO	Earth	
2021/09/18	SO	STEREO-A	
2023/03/24	SO	STEREO-A	
2024/03/23	SO	STEREO-A	
2025/03/23	SO	STEREO-A	
2026/02/21	SO	STEREO-A	
2027/01/25	SO	STEREO-A	
2027/07/31	SO	STEREO-A	
2028/05/19	SO	STEREO-A	
2029/03/03	SO	STEREO-A	

years later, by D'Amicis et al. (2010). Those authors indeed investigated the Earth – Ulysses[1] line-up occurred at the end of August 2007. Their aim was exploring the evolution of turbulence of the same fast wind stream from 1 to 1.4 au, using magnetic field and plasma data from the Advanced Composition Explorer (ACE, Stone et al., 1998) and Ulysses, respectively. In doing this, a standard diagnostic for spectral features, Alfvénic content, and intermittency of the solar wind fluctuations was performed on ACE and Ulysses measurements. The results showed that the low-frequency break that marks the transition from the energy-containing to the inertial range shifts to lower frequencies as the wind expands from 1 to 1.4 au. Being this break related to the correlation

[1] Ulysses (Wenzel et al., 1992) orbits on a wide polar trajectory out of the ecliptic, hence its radial alignments with close-in spacecraft are even rarer. Since, in these exceptional cases, Ulysses is outside Earth's orbit, these events are not listed in Table 1, which is limited to line-ups in the inner heliosphere.

length, the results were consistent with the growth of this quantity moving away from the Sun (Matthaeus and Goldstein, 1982b; Bruno and Dobrowolny, 1986). Comparison at the two heliocentric distances of the normalized cross-helicity σ_c and residual energy σ_r estimate,s[2] at the typical 1-hour Alfvénic scale, allowed the authors to find that while ACE observations showed a prominent Alfvénic population ($\sigma_c \sim 1$ and $\sigma_r \sim 0$), magnetically dominated structures ($\sigma_c \sim 0$ and $\sigma_r \sim -1$) were predominant at Ulysses' distance. This clearly indicates that the Alfvénic content (i.e., Alfvénicity) of the interplanetary magnetic field fluctuations is degraded during the wind evolution (as first pointed out by Schwartz and Marsch, 1983). D'Amicis et al. (2010) also investigated the radial evolution of solar wind intermittency. This feature characterizes solar wind turbulence and is linked to an inhomogeneous energy transfer along the turbulent cascade (Kolmogorov, 1962; Oboukhov, 1962; Frisch, 1995). It determines the presence of active and quiescent intervals in turbulent fluctuations, which cause the system to deviate from scale invariance. As a result, the Probability Distribution Functions (PDFs) of solar wind fluctuations at different scales are not self-similar. Rather, the PDFs become more peaked as smaller scales are considered (Sorriso-Valvo et al., 1999). The scaling of the flatness (i.e., the fourth-order moment of the increments of a given parameter) quantifies the deviation of a PDF from a Gaussian distribution and is therefore commonly used as a tool to measure intermittency (e.g., Marsch and Liu, 1993; Frisch, 1995). It is found to increase with distance from the Sun (see, e.g., Bruno et al., 2003). D'Amicis et al. (2010) found that intermittency increased from Earth to Ulysses. Based on the observed depletion of Alfvénic fluctuations (which tend to decrease intermittency due to their stochastic nature) with heliocentric distance, the authors argued that this was probably due to the emergence of magnetic structures, which may become predominant at large heliocentric distances.

In a series of papers carried out in 2014 – 2015, R. Bruno, D. Telloni, and L. Trenchi moved their attention from the MHD fluid scales to those above the high-frequency break separating the inertial and dissipative regimes. In those works, they exploited a number of radial alignments between MESSENGER and Wind (orbiting around L1, Acuña et al., 1995) for the inner heliosphere (as reported in Table 1) and the Wind – Ulysses line-up of August 2007 (previously analyzed by D'Amicis et al., 2010, see above) for the outer heliosphere. Specifically, Bruno and Trenchi (2014) studied the radial evolution of the ion spectral break when moving from 0.42 to 5.3 au. They found that it shifts toward lower and lower frequencies with increasing the heliocentric distance as $r^{-1.1}$.[3] In addition, the authors showed that its radial dependence is consistent with expectations based on cyclotron resonance conditions (e.g., Marsch, 2006), pointing to a crucial role for resonant wave-particle mechanisms in dissipating the energy transferred along the turbulent cascade (as first suggested by Leamon et al., 1998). Bruno et al. (2014) dealt instead with the scaling exponent associated with the frequency range above this spectral break. The authors found robust evidence for a link between the power of the inertial-range magnetic field fluctuations and the spectral slope at proton scales: as the power increases the spectrum becomes steeper. The overall picture thus outlined predicts the existence of a background spectrum for solar-wind magnetic field fluctuations, extending from fluid to kinetic scales (Bruno et al., 2017). Superimposed on this are the Alfvénic fluctuations, which generally carry most of the inertial range-associated power. Therefore, the larger the Alfvénic fluctuations (it has been shown that there is a limit of their maximum amplitude, Bruno et al., 2017), the more the inertial-scale spectrum lifts from the background level. It follows that for this to connect to the kinetic-scale spectrum (common to all solar wind samples), the ion-scale spectrum must be steeper in those solar wind plasma intervals that have a higher content of Alfvénic fluctuations. This result strongly suggests that the dissipation mechanisms are somehow regulated by the amount of wave-carried energy available at fluid scales, supporting previous analyses (Smith et al., 2006). In the context of an evolving solar wind turbulence, Telloni et al. (2015) explored the kinetic range just above the high-frequency spectral break, to search for waves and study their radial evolution. The authors used the normalized magnetic helicity σ_m[4] and its dependence on the angle between velocity and magnetic field vector orientations at different scales, as diagnostics for revealing the presence of waves in the analyzed solar wind samples (see also He et al., 2011; Podesta and Gary, 2011). They found clear evidence for the presence of left-handed Ion Cyclotron Waves (ICWs) and right-handed Kinetic Alfvén waves (KAWs) at both 0.56 and 0.99 au. These wave populations were found to evolve with distance from the Sun. Specifically, their spectral position was observed to shift toward lower frequencies according to the radial evolution of the high-frequency break (Bruno and Trenchi, 2014). This finding strongly relates the spectral steepening right after the proton gyrofrequency and the concurrent presence of ICWs and KAWs, leading the authors to argue that the generation of these wave families is more efficient the more energy is available in the inertial range. This insight was later confirmed by Bruno and Telloni (2015), who showed that as the amplitude of the Alfvénic fluctuations decreases, the kinetic-range spectrum becomes shallower and the two wave populations weaker and weaker until they disappear. All these results concurred in drawing a scenario in which the proton cyclotron instability is the most likely mechanism for the generation of ICWs in solar wind turbulence (later statistically proven by Telloni et al., 2019).

The first studies based on spacecraft alignment involving BC (at 0.58 au) are due to Alberti et al. (2022a,b). In both papers, the authors exploited BC's September 2020 line-up with PSP, which was orbiting closer to the Sun at 0.17 au, to characterize the evolution of turbulence (Alberti et al., 2022a) and magnetic helicity (Alberti et al., 2022b) moving away from the Sun. Specifically, in Alberti et al. (2022a) the assumption of universal scaling (i.e., self-similarity) intrinsic to the Kolmogorov description of MHD turbulence (K41, Kolmogorov, 1941) was relaxed to explore the magnetic field topology of the same solar wind plasma as it expands into the inner heliosphere. The K41 theory actually predicts that the rate of energy transfer is preserved along the turbulent cascade. This implies that the high-order statistics (i.e., the high-order structure functions) should be governed by a single scaling exponent of either 1/3 or 1/4 in the Kolmogorov or Iroshnikov–Kraichnan picture of turbulence (Iroshnikov, 1963; Kraichnan, 1965), respectively. However, such scaling universality is mostly absent in the solar wind, reflecting the aforementioned intermittent nature of the nonlinear turbulence (e.g., Frisch, 1995; Bruno and Carbone, 2013). Abasing on recently developed tools in the field of decomposition methods and statistical approaches (see Huang et al., 1998, 2008, for more details), Alberti et al. (2022a) examined the solar-wind magnetic field scaling properties at two different distances from the Sun. This allowed the authors to disentangle the role of different mechanisms in distributing energy across the inertial scales of turbulence. Two major results were found. One is that the energy seems to be much more

[2] Cross-helicity and residual energy measure the imbalance between inward and outward Alfvénic modes and between kinetic and magnetic energy, respectively (pure Alfvén waves being identified with $\sigma_c = \pm 1$ and $\sigma_r = 0$).

[3] Incidentally, since the radial evolution the low-frequency break is faster ($r^{-1.5}$, D'Amicis et al., 2010; Bruno and Carbone, 2013), it results that the range of inertial scales widens during the solar wind expansion (Telloni et al., 2015). Since the frequency extension of the inertial range can be used to infer the magnetic Reynolds number R_m (Matthaeus et al., 2005), it follows that R_m increases with heliocentric distance: this indicates that the Alfvénic solar wind evolves towards a more turbulent state as it expands outward.

[4] The magnetic helicity is one of the invariants in ideal MHD equations (along with cross-helicity and total energy) and measures the polarization state of magnetic field fluctuations: $\sigma_m = \pm 1$ denote right- and left-handed waves, respectively.

efficiently transferred, via nonlinear interactions, across the turbulent scales the farther away from the Sun. The other one is that the role of large versus small gradients in dissipating energy to heat the plasma appears to be different at PSP's and BC's orbit. More specifically, close to the Sun, energy transfer seems indeed to occur mainly through large magnetic field gradients. On the other hand, small fluctuations are still predominant in the nonlinear energy cascade far from the Sun. In Alberti et al. (2022b) companion paper, the authors studied the evolving magnetic helicity spectra. As mentioned above, magnetic helicity can provide very important information on the presence of waves at near kinetic scales (see also Telloni et al., 2019, in this regard). By investigating the helical content of turbulence in the frequency domain, Alberti et al. (2022b) were able to draw the following evolution scenario for magnetic helicity. The large-scale magnetic helicity appears to be advected by the solar wind, as suggested by the presence of a coherent major peak at the lowest spectral frequency both at 0.17 and 0.58 au.[5] The amplitude of the magnetic helicity fluctuations associated with the inertial range dampened moving away from the Sun. The authors interpreted this observational evidence as due to the different mechanisms underlying the cascade energy transfer at PSP and BC locations (according to Alberti et al., 2022a), which may reflect in different helical properties. In this regard, the reader is referred to Bieber et al. (1996), who first studied the magnetic helicity content in the dissipation range (see also Markovskii et al., 2015). The absence of signatures of ICWs and KAWs (being the magnetic helicity around zero at near kinetic scales) at both heliocentric distances finally suggests that such waves were not generated, in that case study, during the propagation of the solar wind from 0.17 to 0.58 au.

Telloni et al. (2021b) studied the first PSP – SO alignment of September 2020, analyzing the evolution of turbulence properties (i.e., spectral power, Alfvénicity and intermittency of the solar-wind magnetic field fluctuations) from 0.1 au (PSP) to 1 au (SO). As usual, they applied flatness and magnetic compressibility[6] to estimate the level of intermittency and Alfvénicity. PSP measurements showed a power-law spectrum with a scaling index close to 3/2 (thus indicative of Iroshnikov–Kraichnan weak turbulence, Iroshnikov, 1963; Kraichnan, 1965), very low magnetic compressibility (i.e, high Alfvénicity), and slowly increasing flatness (i.e., reduced level of intermittency). Conversely, at SO's orbit, the turbulence resembled the Kolmogorov-like fashion (Kolmogorov, 1941): the spectral exponent of the field fluctuations scaling-law behavior was indeed close to 5/3. Additionally, since both magnetic compressibility and power-law increase of flatness were higher, SO observations exhibited lower Alfvénicity and enhanced intermittency. In agreement with the results outlined by Schwartz and Marsch (1983) and D'Amicis et al. (2010), it thus appears that due to the depletion of Alfvénic fluctuations during solar wind propagation, the magnetic structures advected by the wind acquire a more important role in the turbulence dynamics, thereby making the plasma more compressive and intermittent. As a final result, turbulence evolves from a weak, less-developed to a strong, fully developed state in the transition from 0.1 to 1 au. Such evolution actually occurs well before Earth's orbit. Indeed, in Telloni et al. (2022) it was found, exploiting the close alignment to the Sun between PSP and BC of February 2022 (both probes were within Mercury's orbit), that the solar wind plasma evolves towards a highly turbulent and intermittent state already before 0.3 au. These results confirm Helios observations from the 1970s that showed that at one-third of the Earth–Sun distance the turbulence is already well developed (see, e.g., Tu and Marsch, 1995), but extend them significantly by a theoretical description of the turbulence evolution based on the transport equations in the framework of the Nearly Incompressible (NI) MHD model advanced by Zank et al. (2017). While not ruling out the possibility that other mechanisms (such as those mentioned above) may play a role in driving the development and evolution of turbulence in the solar wind, the excellent agreement between PSP/BC observations and NI MHD model found in Telloni et al. (2022) strongly suggests that turbulence evolution may be governed by 2D fluctuations and their coupling with the minority slab component (see Zank et al., 2017, for much more details on the 2D+slab theory).

3. Concluding remarks

In spite of the significant advances achieved in studying the evolution of solar wind turbulence based on spacecraft radial alignments, the multi-messenger approach to interplanetary space physics is still largely unexploited. After more than half a century of in-situ spacecraft measurements, exploration of the Solar System's plasma still relies primarily on near-Earth and/or single point-and-time observations. The result is a largely incomplete understanding of the solar wind and its underlying processes and a severe undersampling of the complex space–time dynamics of the heliosphere.

In an effort of overcoming this major limitation, the international heliospheric community is exploring the possibility of multi-spacecraft solar missions. A more readily available option is to exploit the orbital configurations between past and current space missions. Obviously, the question arises as to the statistical significance of a scenario outlined from a single radial alignment event, such as those reviewed in this paper. For this reason, a complete list of all probe line-ups occurred in the inner heliosphere since the 1970s (about 250) has been provided in Table 1: a statistical analysis, performed on the basis of two-point observations of the same solar plasma, at different distances from the Sun, during different phases of the solar cycle, and under different solar source conditions, would indeed allow a scenario to be drawn that could be used as a reference model, crucial in theoretical modeling of the evolution of solar wind turbulence.

CRediT authorship contribution statement

Daniele Telloni: Conceiving the review paper, Searching for radial alignments between past and current inner heliospheric missions, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data gathered by the space missions mentioned in this review are publicly available at NASA's Space Physics Data Facility(https://cdaweb.gsfc.nasa.gov/index.html/).

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[5] This feature is more likely related to the presence of large-scale magnetic flux tubes roughly aligned with the Parker's spiral (see, e.g., Matthaeus and Goldstein, 1982a). In that case it has nothing to do with the advection of a highly helical component by the solar wind.

[6] As the ratio between the power spectra associated with magnetic field intensity and vector fluctuations, the magnetic compressibility is a measure of the contribution of compressive over directional fluctuations (Bavassano et al., 1982).

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