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Timescales and radial lengthscales of quasi-periodic density structures observed by the Helios probes

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Summary. — Quasi-periodic density structures are important mesoscale structures that constitute the slow solar wind. The associated periodicities play a fundamental role in the understanding of the release processes of solar coronal plasma and provide important constraints on models trying to understand the origin of the slow solar wind. However, observational restrictions have limited their study to coronagraph images near the Sun and in situ measurements at 1 AU, preventing a clear connection between in situ structures to their coronal sources. A first step toward a better understanding of this problem is the analysis of Helios measurements to probe the solar wind between 0.3 and 0.6 AU. Three instances of quasi-periodic density structures have been identified showing characteristic timescales of ≈31-33 minutes and ≈112-120 minutes. Using the mean radial bulk speed corresponding to the time intervals of the structures, the related radial lengthscales are derived showing a characteristic value of ≈120-150 R_E.

1. – Introduction

The understanding of the release process of coronal plasma forming the slow solar wind (SW) streams is still under debate. Different source regions of slow SW have been identified: (I) boundaries between coronal holes and streamers, (II) the current sheets near the top of helmet streamers cusps, and (III) the low latitude active regions in the rising phase of solar activity. While the current SW models are able to reproduce the SW features at long timescales (more than several hours), that is not the case for smaller timescales. An important way to address this problem is the study of mesoscale structures with timescales of tens of minutes to several hours, such as the quasi-periodic density structures discussed here. They have been already observed in the high solar corona by coronagraph images [1-3] and at 1 AU by in situ measurements [4-6]. In both cases, the quasi-periodic density fluctuations have been related to the advection of structures formed by release processes of solar coronal plasma. Unfortunately, the enormous observational gap between the sites of observations makes the relationship of in situ structures to their coronal sources controversial, even though some successful examples have been presented [5]. Observations from coronagraphs show that the plasma blobs emanating from coronal streamers occur at periodicities from many hours down to many minutes, with ≈90 minutes being one characteristic timescale [2]. Interestingly, a case study at 1 AU unambiguously showed quasi-periodic structures, with a period of ≈90 minutes, in a slow SW stream [6]. Structures on even smaller timescales can be also released from the Sun into the SW [3]: indeed, previous statistical investigations at 1 AU have revealed characteristic periodicities of ≈5, ≈10, and ≈30 minutes that occurred more often than others [7, 8]. Here, three instances of quasi-periodic density structures observed by the Helios probes between 0.3 AU and 0.6 AU are discussed. The unique position of the spacecraft allows studying the timescale and the radial lengthscale of the structures only a short time after their release from the Sun, therefore close to their pristine state.

2. – Data, Methods, and Observations

The Helios1 and Helios2 probes orbit around the Sun on highly eccentric, elliptical orbits that ranged in distance from the Sun from 0.3 AU and 1 AU. For this study, we use the revisited Helios plasma measurements obtained by fitting bi-Maxwellian function to the original 3D ion distribution functions [9]. The proton number density n_p and the velocity components, expressed in the Heliographic Radial-Tangential-Normal (HGRTN or RTN) coordinate system, are sampled every 40.5 s. The magnetic field measurements, obtained at a higher cadence, are averaged over the 40.5 s plasma measurements and are expressed in the Spacecraft Solar Ecliptic (SSE) coordinate system converted in spherical coordinates: B is the intensity of the interplanetary magnetic field while its direction is identified by $\theta_B = \arcsin(B_Z/B)$ and $\phi_B = \arctan(B_Y/B_X)$. We identified in Helios measurements three instances of periodic n_p fluctuations associated to the transit of density structures. The corresponding SW parameters are reported in figure 1 in which the boundaries of the structures (dashed lines) and their substructures (dotted lines) can be identified by visual inspection as local minima in n_p and the simultaneous variations of the magnetic field strength or direction. In a similar way to [4], we determined the radial lengthscales (L) of the observed quasi-periodic density structures. For each structure and substructure we evaluated the duration (T) and the mean ($\langle v_r \rangle$) and standard deviation (σ_r) of the SW radial velocity. Next, we derive the corresponding lengthscale and uncertainty as $L \pm \Delta L = (\langle v_r \rangle \pm \sigma_r) * T$, which are expressed in Earth radii (R_E). Figure 1a shows an event from when the Helios1 spacecraft located at ≈0.59 AU from the Sun between ≈16:30 UT and ≈22:40 UT on 18 October 1975. The first four structures have durations of ≈26, ≈35, ≈64, and ≈35 min, respectively, corresponding to $L = 100 \pm 1$, 136 ± 1, 252 ± 3, and $137 \pm 1\,R_E$. The fifth one (≈65 min and $243 \pm 5\,R_E$) manifests two substructures of ≈35 min ($133 \pm 2\,R_E$), and ≈ 30 min ($110 \pm 1\,R_E$). The last structure (≈57 min and $209 \pm 2\,R_E$) can be separated in three substructures respectively of ≈15, ≈20, and ≈22 min corresponding to $L = 55 \pm 1$, 75 ± 1, $80 \pm 1\,R_E$. Figure 1b shows an event from when the Helios1 spacecraft located at ≈0.37 AU from the Sun between ≈5:00 UT and ≈13:00 UT on 14 April 1977. Together with an initial region of ≈11 min ($35 \pm 1\,R_E$), the first two structures of ≈132 min ($450 \pm 10\,R_E$) and ≈116 min ($421 \pm 8\,R_E$) seem to be part of a single stream whose radial velocity slowly rises from ≈350 km/s to ≈390 km/s. These structures are respectively made up of five

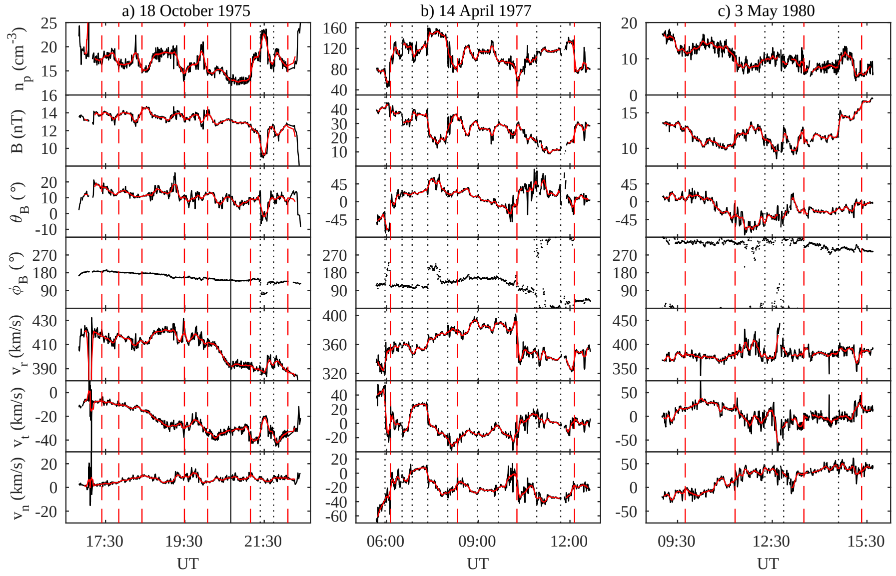

Fig. 1. – The SW parameters as measured by Helios on: a) 18 October 1975; b) 14 April 1977; c) 3 May 1980. From the top to the bottom: the proton number density; the magnetic field strength; the θ_B and ϕ_B angles; the velocity components in RTN coordinate system. The overlapping red lines are the corresponding 11 point running averages to guide the eye.

substructures of ≈23 min ($77 \pm 1\,R_E$), ≈20 min ($66 \pm 1\,R_E$), ≈31 min ($102 \pm 1\,R_E$), ≈39 min ($L = 137 \pm 2\,R_E$), ≈19 min ($69 \pm 1\,R_E$), and three substructures of ≈39 min ($140 \pm 3\,R_E$), ≈41 min ($150 \pm 2\,R_E$), and ≈36 min ($131 \pm 2\,R_E$) substructures. The third structure of ≈113 min ($365 \pm 10\,R_E$) consists of three substructures respectively of ≈39 min ($128 \pm 3\,R_E$), ≈47 min ($151 \pm 3\,R_E$), and ≈27 min ($85 \pm 2\,R_E$) with v_r fluctuating around ≈340 km/s. Figure 1c shows an event from when the Helios1 spacecraft located at ≈0.58 AU from the Sun between ≈8:30 UT and ≈16:15 UT on 3 May 1980. The number density has three main enhancements with ≈95 min ($334 \pm 5\,R_E$), ≈131 min ($480 \pm 25\,R_E$), and ≈110 min ($390 \pm 10\,R_E$). The second structure, characterized by the high variability of v_r, can be divided in three parts of ≈57 min ($209 \pm 8\,R_E$), ≈36 min ($131 \pm 7\,R_E$), and ≈39 min ($137 \pm 3\,R_E$). The third structure can be divided in two substructures of ≈66 min ($237 \pm 5\,R_E$) and ≈44 min ($159 \pm 6\,R_E$). Figure 2a-2c shows the radial lengthscales with the associated errorbars of each structure and substructure identified in the three instances of quasi-periodic density fluctuations. Their distribution, reported in figure 2d, shows a clear enhancements in the interval $\approx 120 - 150\,R_E$. Indeed, this scale size appears in all of the three events. Additionally, three other enhancements occur, though with lower occurrence, at $\approx 65 - 80$, $\approx 185 - 285$, and $\approx 350 - 430\,R_E$.

3. – Discussion and Conclusions

The timescales and lengthscales of periodic density structures observed by the Helios probes have been identified. For each event, the structures with similar timescales can be grouped to evaluate an average periodicity for each of them. In this way, we obtained for the 18 October 1975 event ≈ 31 min, for the 14 April 1977 event two periodicities of ≈ 33 min and ≈ 120 min, and for the 3 May 1980 event ≈ 112 min. While the longer timescale

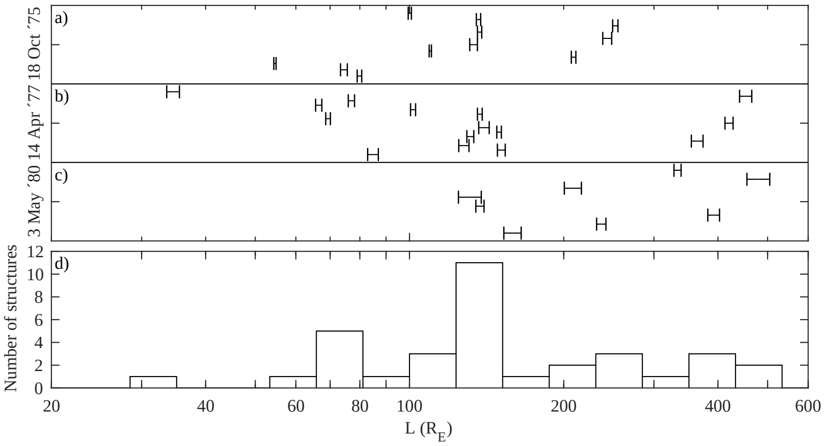

Fig. 2. – The radial lengthscale of structures and substructures identified on: a) 18 October 1975; b) 14 April 1977; c) 3 May 1980. d) Lengthscales distribution.

$\approx 112 - 120$ is close to the ≈ 90 min periodicity which have been shown in coronagraph images to be a characteristic timescale of plasma release at the helmet streamer [2], the shorter ones fall in the range of the periodic density structures of ≈5, ≈10, and ≈30 min identified by statistical investigations at 1 AU [7, 8]. Regarding the radial lengthscales of the quasi-periodic structures, previous investigations at 1 AU showed typical values at $\approx$ 23, 30, 45 and 80−100 R_E [4], and $\approx$ 11, 19, 21, and 28 R_E [10]. We found some similarity only with the shorter lengthscale identified in our events at $\approx 65-80\, R_E$. More importantly, a characteristic scale size of $L \approx 120 - 150\, R_E$ appears in all our events. The timescales and scale sizes associated with these structures play a fundamental role in the understanding of the release processes of solar coronal plasma. A more extended analysis is needed to clearly identify the characteristic scales of the quasi-periodic density structures. New data from recent (Parker Solar Probe) and upcoming (Solar Orbiter) missions will give the opportunity to investigate these structures giving a new insight on their role in the origin of the solar wind.

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