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Coronal Radio Sounding: An Ingenious technique for Investigating Solar Wind Dynamics in the Inner-Middle Corona

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Abstract

The Coronal radio sounding techniques have been instrumental in providing information in parts of the near Sun coronal medium where in-situ plasma measurements are quite challenging. In this summary paper, we have shared the methodology adopted and results shared from our analysis of coronal radio sounding experiment performed by Akatsuki mission during oct-Nov 2022, 'Smiley Sun' event. This presented a unique opportunity to delve into plasma turbulence within the inner corona and explore the mechanisms responsible for energizing and accelerating high-speed streams emanating from these trans-equatorial coronal holes. The analysis consistently unveiled a shallow turbulence spectrum and flow speeds ranging from 180 to 400 km/s at heliocentric distances of 3 - 9 $R_{\odot}$. This study proposes interesting insights into how solar wind properties near the coronal regions can be investigated using the radio-sounding method, which is an effective method to study complex coronal physics.

1 Introduction

A deeper understanding of solar wind generation and acceleration mechanisms in inner-middle coronal regions is crucial for improving our ability to predict space weather events. One of the recent discussions pertinent in the space physics community is the mechanism behind origin and energization of solar wind streams and their impact on the space weather near-Earth environment. Both of these mechanisms are coupled to each other, as the orientation and energy input by various sources on solar corona ultimately decides the geo-effectiveness of the incident solar wind stream [1]. However, the complex conditions in the solar corona, including high temperatures and frozen-in magnetic fields, make the in-situ observations quite challenging. In this context, active coronal radio sounding techniques, using spacecraft signals, have proven invaluable for obtaining information about the plasma turbulence process, velocities, densities, magnetic field fluctuations, and particle acceleration near Suns coronal medium, in the region as close as 3 $R_{\odot}$ to 20 $R_{\odot}$ (1 $R_{\odot}$ = 1 Solar Radii = 696340 Km) from the Sun's surface [2, 4, 6, 7, 8] where primarily direct plasma measurements are difficult.

Active radio sounding techniques involves transmitting radio waves towards the corona and analyzing the signals that have been propagated through the coronal medium, reflected or scattered. This technique is similar to radar, where an external transmitter emits a signal and a receiver detects the return signal. The radio signals that are used to probe solar corona can be the spacecraft radio beacons, that are transmitted by interplanetary spacecraft when they are in the Solar conjunction configuration. Solar Conjunction is the period when a planet is on the opposite side of the Sun than the Earth. During this time, if there is a spacecraft that is orbiting around the planet, the radio signals transmitted by that spacecraft will travel through the solar corona and then will be received at the ground station. It is known that the dispersion relation of plasma is a function of electron density of medium and frequency of incident electromagnetic wave. Since the solar corona is an ionized plasma, with the inherent turbulence, dispersive effects gets registered in the parameters of the on the emergent radio waves. The spectral inversion of these signals assists in understanding various coronal properties like plasma turbulence, velocity, density, magnetic field fluctuations, and solar wind acceleration [3, 4]. The active Coronal Sounding technique utilizes this principle to study features and dynamics of the near Sun region using radio signals transmitted by spacecrafts. Active radio sounding experiments helps us to derive the information about the density fluctuations, flow speed of inhomogenities, and turbluence in the intervening medium. In our work we have studied the downlink radio signals from two spacecraft, the Indian Mars Orbiter Mission (MOM) and JAXAs Venus Climate Orbiter mission (Akatsuki), which conducted coronal-radio sounding experiments during their solar conjunction periods, to investigate the properties of solar wind plasma in the inner-middle coronal regions [7, 8, 9].

In this summary paper, we will share the analysis and results obetained from one such experiment that was conducted by the Akatsuki spacecraft, also known as the Venus Climate Orbiter (VCO) mission during Venus-Solar conjunction in 2022. The experimental period spanned from October 11, 2022, to November 7, 2022, within the ascending phase of solar cycle 25. Serendipitously, this period coincided with the appearance of a distinct trio of trans-equatorial coronal holes on the solar disk named as Smiley

Sun event. This event provided us with a unique opportunity to track velocities of solar wind originating from the trans-equatorial coronal holes at various heliocentric distances closer to the solar surface all the way up to the L1 point in the near-Earth space environment. The detailed discussion can be referred from Jain et.al. 2024 [9].

2 Data and Methodology

The experiments were conducted using X-band radio signals transmitted by the Radio Science (RS) payload onboard the Akatsuki (JAXA Venus Climate Orbitor) spacecraft. The signals were recorded at UDSC (Usuda Deep Space Newtork), Japan ground station as shown in Figure 1. The work here reports the analysis of radio signals recorded at the UDSC station in the period between 20th October to 1st November, 2022. This experiment was performed in open-loop format and the sampling frequency was 1 Hz. As the received signal traveled across the charged Coronal medium a doppler shift in the phase of received signal was expected. The received signals were processed to find the observed Doppler shift using the standard technique as adopted in radio occultation experiments [8, 9]. The geometrical expected Doppler was calculated using relative ephemeris data (position and velocity) provided by the MOM mission team. Their difference gives the values of Doppler frequency residuals. In order to take into account errors arising from systematic sources such as oscillator drifts, imperfections in trajectory, and the effect of terrestrial ionosphere and atmosphere, a linear regression was estimated and subtracted from frequency residuals [8, 9] . This gave fluctuations in the residual values around zero mean value. These observables are termed as doppler frequency fluctuations and these fluctuations arise from the propagation of radio waves in the medium that has intrinsic fluctuations in its refractive index values due the turbulence plasma densities. Using the Fast Fourier Transform (FFT) algorithm these values were spectrally analyzed to give the frequency fluctuation spectrum. The closest point of the radio ray path from the solar surface (solar offset) in terms of heliocentric distances is evaluated from the spacecraft and planetary body ephemeris with the assistance of NASA SPICE tool. We were able to probe the heliocentric distances as close as 3-9 $R_{\odot}$. (Figure 1).

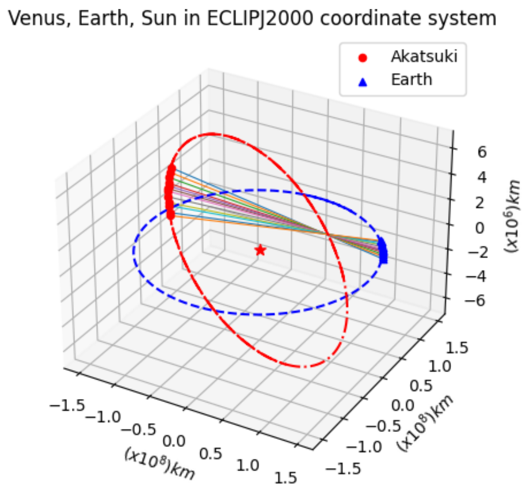

Figure 1. Akatsuki -solar conjunction geometry during 20th Oct - 1st Nov 2022. The colored straight lines represent the ray path of the radio signals transmitted by the spacecraft (Red circle) and received on the ground station on Earth (blue triangle) (taken from [9]).

3 Results and Discussions

3.1 Spectral density spectrum for the frequency fluctuations

Frequency fluctuation spectra were approximated by fitting a straight line (in log-log plot), in the frequency range v_{lo} and v_{up}. The lower-frequency cutoff $v_{lo} = 10^{?3}$ Hz is the length of the processed interval and the upper cutoff vup = 0.05Hz is one-tenth of the Nyquist frequency , considering that sample rate is 1Hz, and beyond Nyquist frequency systems noise begins to dominate the signal [5, 7, 8]. The slope then can be estimated directly by the linear fit on the log-log plot. The slope (red straight line) denotes the value of spectral index α_f [8]. The detailed steps on data analysis and parameters estimation are given in [8, 9].

Figure 2 shows the temporal spectra of frequency fluctuations during three different experiment days. F with each day representing the different solar proximate distance and varying patterns in the appearance of the smiley sun on the solar surface. At closer heliocentric distances (Fig 2(a), when R = 3.92Rs with the slope being 0.37), the spectrum is flatter. After two days, as the Sun rotates, we observe on 26 October, the smiley sun pattern was at the front side of the solar disk, the solar proximate distance of the radio signals was about 4.5 Rs and the spectrum slope was 0.275 as shown in the middle panel of Figure 2. Two days later, when R = 5.80Rs, the slope was still 0.285. It was observed that the slopes during this period of observation (i.e. from 20th October - 1st Nov), were in the ranges of 0.2-0.4, and the spectrum appeared shallow.

3.2 Solar Wind Turbulence

The above results are interpreted according to the solar wind turbulence theories [2, 3] , which consider that solar wind turbulence is driven by the interaction of Magnetohydrodynamic (MHD) waves with the solar plasma particles. This turbulence sets up the energy transfer in the coronal region, heats the coronal medium and leads to the supersonic acceleration of the solar wind plasma propagating in the interplanetary medium.

It is found that the turbulence power spectrum at smaller heliocentric distances ($< 10R_{\odot}$) displays flattening with a spectral index α_f ($\sim 0.2?0.3$), which corresponds to a solar

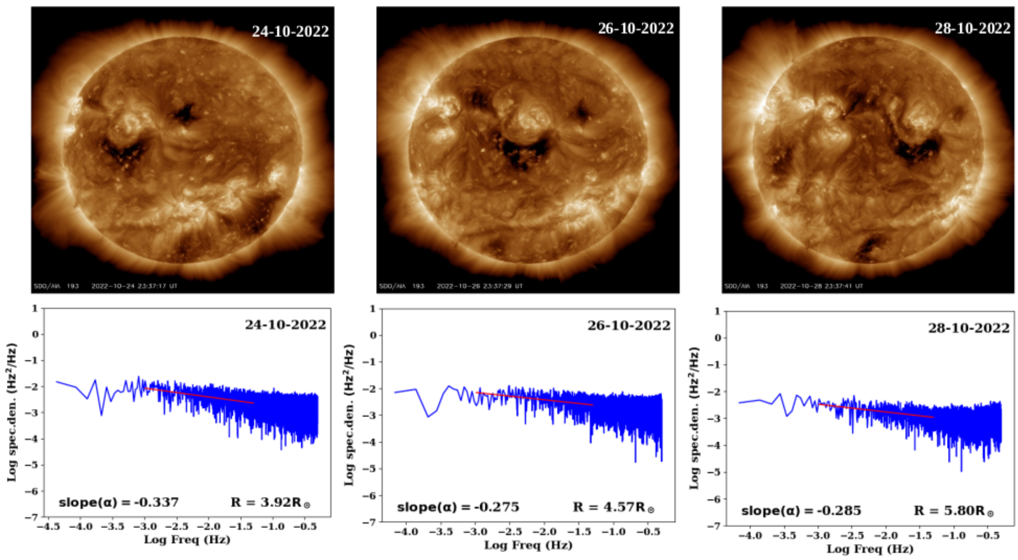

Figure 2. Coronal holes (upper panel) and frequency fluctuations (FF) power density spectrum (lower panel) on the given experiment days. 26th October pattern is adoringly christened as "Smiling Sun" [9].

wind acceleration region. At larger heliocentric distances ($> 10-15R_{\odot}$), the curve steepens, with a spectral index α_f ($\sim 0.7?0.8$), which is closer to the value 2/3 indicative of a developed Kolmogorov-type turbulence spectrum [2]. This range signifies a developed turbulence phase where energy is transferred from larger wavelength to shorter wavelength through cascading, eventually leading to dissipation in the medium, heating of medium and acceleration of solar wind.

Previous studies [4, 5] have shown that the turbulence spectrum is expected to be underdeveloped near the regions of stronger magnetic fields such as the coronal holes, and is indicated by the flatter slopes. The change in the turbulence regime takes place at farther distances from the solar surface for the fast solar wind emanating from the coronal hole than for the slow solar wind from active regions [4, 7, 8]. We observed the presence of the shallow turbulence spectrum in our data on all experiment days, indicates that the radio ray path is embedded under the influence of coronal holes.

3.3 Flow speed estimates in inner-middle Corona

To better understand the presence of these transequatorial coronal holes and their impact on the plasma turbulence in the coronal medium, we estimated the flow speeds using the approach developed by [6, 8]. It is based on the formalism derived by Armand-Efimov [3], isotropic quasi-static turbulence in solar wind plasma. It is based on the theory of propagation of electromagnetic waves in the turbulent plasma medium. It assumes that plasma fluctuations are frozen-in and propagate outward with the solar wind velocity (Vsw) across the line of sight of radio waves [2, 4, 6]. The extensive details, formalism used, estimation of the above parameters, and data analysis steps can be found in [8, 9].

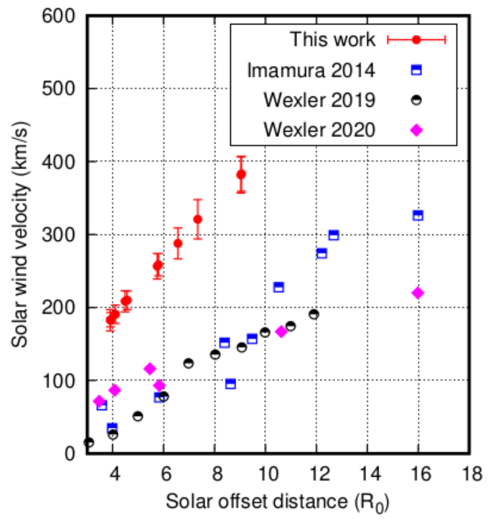

Figure 3. Plasma flow velocities (red dots) in inner-middle corona, as derived in this work. And when compared with previously reported values. The relatively higher speeds indicate that, our radio ray was embedded in the region of coronal holes that are source of high speed solar plasma streams (taken from [9]).

Figure 3 denotes the flow speeds at varying heliocentric distances during the experiments conducted between 24 Oct-1Nov 2022. It can be seen that plasma flow speeds increase from 180 Km/s to 400 Km/s from heliocentric distances $3to9R_{\odot}$. It can be noticed that solar wind at increasing heliocentric distances were higher, when compared with the slow solar wind speed that usually prevails in these regions [7, 8]. This observation indicates that there is a stronger particle acceleration that generally occurs in the coronal holes leading to higher flow speeds.

4 Concluding remarks

In this study, we investigated the flow of solar winds emanating from a trans-equatorial trio of coronal holes from a region spanning heliocentric distances from 3 to 9 solar radii using Akatsuki radio sounding experiment. The turbulence spectrum was flatter and flow speeds in the inner-middle corona came out to be 180 to 400 km/s, which are attributed to the fast speed stream, whose arrival was recorded after two-three in near Earth space. This information can be used to improve the forecast from space weather prediction models.

The application of simple yet ingenious radio sounding technique helped us to understand the inner coronal region which is the least probed area and holds immense potential for explaining the several arcane heliophyiscs phenomenon such as generation and acceleration of solar wind, locus of alfvenic surface, energy transfer at transition region etc. It can help us to predict the properties of the ambient solar wind as well transient events which can give birth to the space weather events that utlimately travel across interplanetary medium to effect near-Earth environment.

The methodology developed by us in this work not only advances our understanding of the coronal region; but it also demonstrates the potential use of radio science systems, already planned for future interplanetary missions, to conduct valuable studies of solar wind dynamics without requiring additional instrumentation. Consequently, coronal radio sounding technique can be employed as a robust and resource-efficient method for investigating the heliosphere.

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