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Co-rotating Solar Wind Disturbances in Radio Sounding Data and Local Measurements

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Abstract—In this paper, we present the results of two series of experiments on radio sounding of near-solar plasma by the signals of the Mars Express and Venus Express spacecraft in 2006 and Mars Express in 2008. The radio sounding data are compared with measurements of the proton concentration near the Earth's orbit on the Wind satellite. This analysis shows that the general nature of the temporal dynamics of disturbances observed in two series of measurements is qualitatively similar. The sequence of amplifications of fluctuations in the frequency and density of protons indicates that the observed disturbances are associated with co-rotating regions of interaction of solar wind flows of various velocities.

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1. INTRODUCTION

Numerous studies of near the Sun plasma by radio sounding using spacecraft (SC) signals made it possible to obtain a significant amount of information related to the formation and acceleration of the solar wind. Using plasma instruments installed on board the Wind, ACE, and other satellites, measurements provided systematic data on the solar wind plasma parameters near the Earth's orbit. Comparison of two arrays of measurements can be used to study the relationship between events occurring near the Sun and disturbances in near-Earth space.

The first study in this direction was performed at Kotelnikov IRE, RAS and was published in 2019–2021. (Efimov et al., 2019, 2020, 2021). In 2006, for the first time, two-position radio sounding of the solar wind was performed based on the simultaneous use of signals from two satellites for radio sounding, one of which moves relative to the Sun from west to east (Venus's satellite Venus Express) while the other (the Mars Express Mars's satellite) moved in the opposite direction (Efimov et al., 2021). This radio-sounding scheme is an effective tool for studying disturbances generated in selected regions of the solar corona that rotate together with the Sun. In the experiments, frequency fluctuations of sounding radio signals were measured; the variance of frequency fluctuations is proportional to the variance of plasma concentration and velocity approximately near the line of sight proximate point (Armand, 2003). The purpose of this communication is to analyze the relationships between fluctuation processes in near-solar space and their reflection in near-Earth outer space using the example of two events.

2. OBSERVATION OF DISTURBANCES IN 2006

In 2006, a disturbance with increased turbulence was detected for the first time on October 6 (the day of the year is DOY 279, UT = 1600, $t = 279.7$) on the eastern limb when probing the near-solar plasma with the signals of the Mars Express Martian satellite that set behind the Sun. The outflow of disturbed plasma flows on the eastern limb manifested itself both in several interconnected processes in the circumsolar space and near the Earth's orbit. Disturbed plasma flows when crossing the Mars Express–Earth radio sounding path caused an increase in radio wave frequency fluctuations on October 6, 2006 (DOY 279.7). The increase in frequency fluctuations σ reached two times with respect to the unperturbed conditions σ_b (Fig. 1a). During the rotation of the Sun, the coronal source of disturbance from the east side passes to the west side of the Sun, and on October 21 (DOY 294, UT = 0030, the total time was 294.02), this region is in the center of the western limb while the disturbance is observed at the minimum heliocentric distance of $R = 7.54R_S$, where R_S is the Sun radius. At this time, when sounding near-solar plasma with signals from another spacecraft (the Venus Express satellite), a strong increase in frequency fluctuations, which exceeded the background level by four times and exceeded the fluctuations on the east-

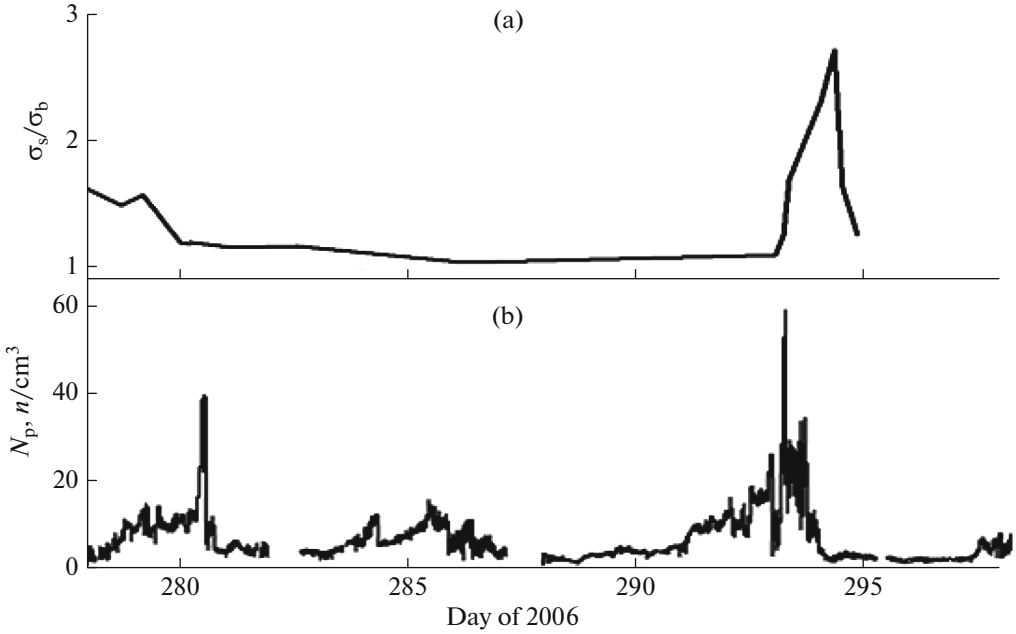

Fig. 1. (a) The frequency variations of the X-band signals of the MEX and VEX SC when probing the near-solar plasma and (b) the time dependences of the proton concentration in the near-Earth space plasma according to Wind satellite data in the period from October 5 to 25, 2006.

ern limb by more than two times (DOY 279.7), was recorded. In the latter case, the radio sounding path was at a significantly greater distance (R = 20.3R_S) from the Sun. It should be noted that the time interval between two maxima of fluctuations in the frequency of probing plasma radio signals is 14 days, which is close to half of the nominal period of the Sun's rotation (T = 27 days).

As follows from Fig. 1b, the background value of the proton concentration does not exceed four particles per cubic centimeter (days of the year: 280–282, 288–290, 294–298). On October 11, 2006 (DOY 285, UT = 1200, t = 285.5), i.e., 5.8 days after the first observation of strong frequency fluctuations, a fourfold increase in the N_p proton concentration was recorded on the eastern limb. It should be kept in mind that the frequency fluctuations are proportional to the absolute level of fluctuations in the electron concentration. The time of movement of plasma flows from the place of generation (t_1 = 279.7) to the Earth's orbit (t_2 = 285.5) corresponds to the velocity of V = 300 km/s, which was measured at that time on board the Wind artificial Earth satellite (AES) (Efimov et al., 2021).

A coronal source of increased turbulence moved towards the central meridian with respect to the Earth in one-quarter of the solar rotation period after the first registration on October 6, 2006 (i.e., near DOY 285.5).

The compressed area of the disturbance reached the Earth in the DOY's interval of 291–292, i.e., 2–3 days before the time of registration of the maximum frequency fluctuations on the western limb: DOY 294, UT = 0030. The second maximum concentration of charged particles in the near-Earth orbit corresponds to an increase in frequency fluctuations on the western limb, while the Np max first maximum proton density at DOY 285.5 that was produced by disturbed plasma flows can be conditionally called a precursor of a stronger disturbance created by the region of increased turbulence on October 21, 2006. The advance time is $t_{advance}$ = 294 – 285.5 = 8.5 days, which is close to one-quarter of the rotation period.

3. CONDITIONS FOR RADIOSONDING EXPERIMENTS IN 2008

The geometric picture of radio occultation experiments with the Mars Express Martian satellite, which set behind the Sun, is shown in Fig. 2, which for each day of 2008 shows the position of the projections of the spacecraft–Earth ray lines onto the pattern plane for the Mars Express satellite. The horizontal axis shows the R distances from the central meridian in units of the R_S solar radius, while the vertical axis shows the distances from the equatorial plane. Most of the time, areas located south of the equator were sounded.

The general geometric picture of radio sounding experiments is characterized by a Table 1 in which the dates of the experiments are indicated by the days of the year (DOY).

The closest approach of the line of sight to the center of the Sun was achieved on December 5, 2008 at the site that the SC set behind the Sun (eastern limb),

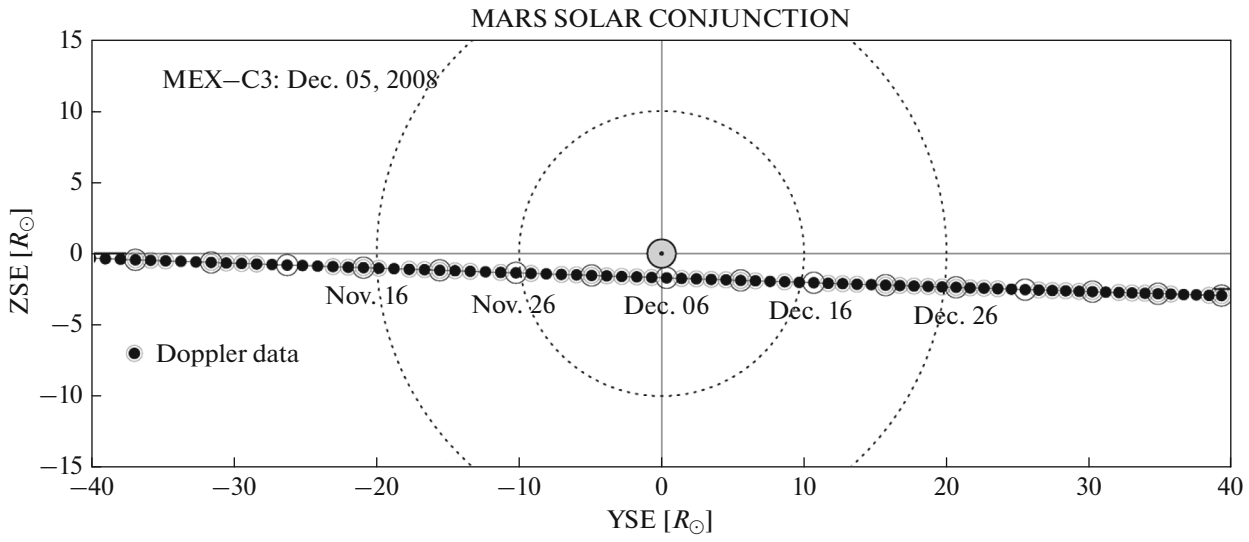

Fig. 2. The trajectory of the Mars Express in the pattern plane from October 29, 2008 to January 15, 2009.

while the R impact distance was equal to $2.95R_S$. The minimum distance at the phase of when the spacecraft exited from behind the Sun (its western limb) was reached on December 7 and was equal to $2.4R_S$.

4. OBSERVATIONS OF DISTURBANCES IN THE NEAR-SOLAR PLASMA IN RADIOSONDING EXPERIMENTS IN 2008

During the experiments on radio sounding of the circumsolar plasma in 2008, the region of increased turbulence was observed twice. For the first time this was during the setting of the Mars Express behind the Sun when the supercorona regions located to the east of the Sun's center were probed on November 29, 2008 (UT = 1200, DOY 335.4). The second time was on December 13, 2008 (UT = 0000, DOY 348) when the area of increased turbulence due to the rotation of the Sun after 13.5 days (half of the rotation period of T = 27 days) moved to the western limb while the MEX–Earth radio line passed at a small distance of $R = 5.6\ R_S$ from the center of the Sun. At this small distance of the propagation path of sounding radio signals from the region of increased turbulence, the increase in the level of frequency fluctuations σ_S/σ_b reached large values relative to the background value of q_m = 5.1 (Fig. 3a). When sounding the eastern region, the gain of frequency fluctuations was significantly less ($q_m = 2.5$), since the radio sounding path was distant from the Sun at a significantly greater distance from the center of the Sun ($R = 12R_S$).

5. DISTURBANCES IN THE EARTH'S ORBIT ACCORDING TO THE DATA OF LOCAL MEASUREMENTS IN ADJACENT PERIODS

The time variations in the level of frequency fluctuations that were recorded during the sounding of near-solar plasma by the signals of the Mars Express were compared with the measurements of the N_p proton density, the V velocity of the plasma fluxes, and magnetic field induction B that were performed by the onboard instruments of the Wind satellite in adjacent time periods.

Figure 3b shows the time dependences of the concentration of protons recorded in the Earth's orbit by instruments of the Wind satellite. They were formed under the influence of processes that took place on the eastern limb of the Sun. When the disturbed plasma flows propagate in radial directions from their source starting from DOY 335.4, the first proton density maximum of $N_{p\,max1} \approx 30\ cm^{-3}$ was formed at $t_3 = 338.5$ (Fig. 3b), i.e., 3.1 days after the start of their generation, which corresponds to the velocity of the dis-

Table 1. The conditions for radio sounding of near-solar plasma by signals from the Mars Express in 2008

Days of 2008		Proximate distance R/R_S	
sunset (Ingress)	exit (Egress)	sunset (Ingress)	exit (Egress)
306–338 November 1–December 3	342–384 December 7, 2008–January 18, 2009	37.51–2.95	2.40–40.83

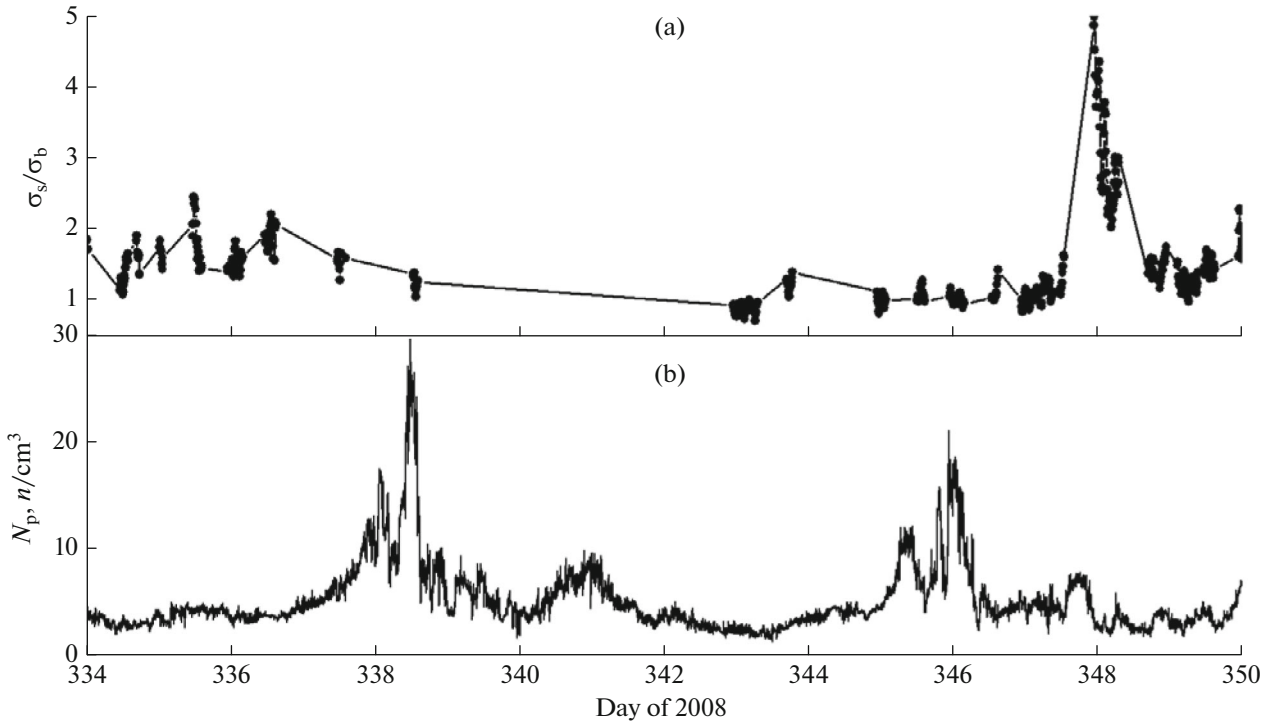

Fig. 3. (a) The frequency variations σ_f of the X-band signals of the Mars Express when probing the near-solar plasma and (b) time dependences of the proton concentration of the near-Earth space plasma according to Wind satellite data in the period from November 29 to December 15, 2008.

turbed plasma flows of $V = 500$ km/s. The background value of the proton concentration was, on average, three particles per cubic cm, i.e., 10 times less than the maximum proton concentration $N_{p\,max1} \approx 30$ cm^{-3}.

The second proton concentration maximum was observed on December 11, 2008 (DOY 346), and its value reached $N_{p\,max2} \approx 20$ cm^{-3}; 7 times higher than the background value. The first maximum of the proton concentration was ahead of the second maximum of frequency fluctuations by 9.5 days. The shift between these events was determined with a small error ($\pm$ 0.2 days) and can be considered as a precursor of the second amplification. The time shift between increases in the proton concentration, as follows from Figs. 3b, was ~7 days, which is close to one-quarter of the solar rotation period.

6. CONCLUSIONS

Two series of observations performed in 2006 and 2008 reveal a similar picture of the temporal dynamics of disturbances in the solar wind. First, the disturbance is observed by the amplification of the frequency fluctuations of sounding radio signals in the supercorona on the eastern limb. Then, after a time exceeding one-quarter of the rotation of the Sun, a significant increase in the concentration of protons near the Earth's orbit is recorded. A second increase in the proton concentration occurred in the near-Earth plasma after approximately one-quarter of a rotation, while after a time of less than one-quarter of a rotation, frequency fluctuations intensified on the western limb. Such dynamics indicates that the observed disturbances were due to long-lived structures of the SIR (stream interaction regions) type, in which plasma density enhancements are associated with the regions of interaction of slow and fast solar wind flows. When SIR regions exist for two rotations they are called CIRs (co-rotating interaction regions). Compressed SIR/CIR regions can cause geomagnetic storms; their contribution to the statistics of geoeffective disturbances during periods of low solar activity significantly exceeds the contribution from propagating flare disturbances such as coronal mass ejections (Ermolaev et al., 2017; Chashei et al., 2021). The detection of amplifications of frequency fluctuations on the eastern limb in radio sounding experiments can be considered as a precursor of the arrival of an SIR/CIR to the Earth with an advance time of 7–8 days. The correlated nature of the variations in the supercorona and near-Earth plasma indicates that shorting structures are formed at heliocentric distances of less than 10 solar radii and that the absolute level of concentration fluctuations in the compressed regions significantly exceeds the background values. Additional data on the validity of this statement were presented in (Efimov et al., 2016).

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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