Available online at www.sciencedirect.com
SciVerse ScienceDirect
Advances in Space Research 49 (2012) 500–508
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Quasi-periodic frequency fluctuations observed during coronal radio sounding experiments 1991–2009

A.I. Efimov [a], L.A. Lukanina [a], L.N. Samoznaev [a], V.K. Rudash [a], I.V. Chashei [b], M.K. Bird [c,d,*], M. Pätzold [d], The MEX, VEX, ROS Radio Science Team [1]

[a] Kotel'nikov Inst. Radio Engg. & Electronics, Russian Acad. Science, 125009 Moscow, Russia
[b] Lebedev Phys. Inst., Russian Acad. Science, 117924 Moscow, Russia
[c] Argelander-Institut für Astronomie, Univ. Bonn, 53121 Bonn, Germany
[d] Rheinisches Institut für Umweltforschung, Univ. Köln, 50931 Köln, Germany

Received 9 February 2011; received in revised form 10 October 2011; accepted 15 October 2011
Available online 21 October 2011

Abstract

Coronal radio sounding experiments were carried out using the dual-frequency signals of the spacecraft Ulysses, Galileo, Mars Express, Venus Express, and Rosetta. The change in differential frequency recorded at the NASA and ESA ground stations, a quantity sensitive only to the plasma along the radio ray path from spacecraft to receiver, has been analyzed in this work. This large volume of observational data provides evidence for the occasional presence of a quasi-periodic component (QPC) in the derived frequency fluctuation spectra. First seen in data from the Mars Express conjunction in 2004, further evidence for the QPC has now been found in data recorded at other solar conjunction opportunities from 1991 to 2009, thereby better defining the statistical characteristics of the QPC. The level of QPC spectral density is a factor of three higher than the expected power-law background level. The characteristic frequency of the spectral density maximum is roughly 4 mHz, corresponding to a QPC fluctuation period of about 4 min. The bandwidth of the spectral line is comparable to the maximum frequency. The QPC are observed at heliocentric distances between 3 and 40 solar radii, both in equatorial regions and at high heliolatitudes. The QPC is detected with an occurrence frequency of about 20% and is occasionally accompanied by its second harmonic. The most likely progenitors of the QPC are quasi-periodic electron density fluctuations associated with magnetosonic waves, which are generated locally from nonlinear interactions of 5-min band Alfvén waves propagating from the coronal base.

Keywords: Coronal radio sounding; Frequency fluctuations; Nonlinear process; MHD waves

1. Introduction

One of the most important properties of the solar wind plasma is its turbulent character: all measurable quantities (magnetic field, density, velocity, etc.) display random fluctuations at virtually all spatial and temporal scales. Solar wind turbulence is most extensively studied by in situ and radio sounding methods in regions at rather large distances from the Sun, where the solar wind is fully developed and its velocity does not depend on heliocentric distance (Tu and Marsch, 1995). Although regions closer to the Sun (heliocentric distances less than 0.3 AU), where the solar wind is accelerated to supersonic and superalfvenic velocities, are still inaccessible to in situ measurements, valuable data have been obtained from coronal radio sounding experiments (Chashei et al., 2007). Information on average solar wind characteristics, turbulence, and their interplay in the region of acceleration is very important for understanding the acceleration mechanism. Turbulence dissipation,

* Corresponding author at: Argelander-Institut für Astronomie, Univ. Bonn, 53121 Bonn, Germany. Tel.: +49 228 731771; fax: +49 228 731775.
E-mail addresses: efimov@ms.ire.rssi.ru (A.I. Efimov), chashey@prao.ru (I.V. Chashei), mbird@astro.uni-bonn.de (M.K. Bird), mpaetzol@uni-koeln.de (M. Pätzold).
[1] MEX, VEX, ROS Radio Science Team: S.W. Asmar, Jet Propulsion Laboratory, California Inst. Tech., Pasadena, CA/USA; B. Häusler, Universität der Bundeswehr München, Germany; M. Hahn; S. Tellman; G.L. Tyler, Stanford University, Stanford, CA/USA.

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doi:10.1016/j.asr.2011.10.013

for instance, may play the role of an additional energy source for the solar wind (Chashei and Shishov, 1983, 1987). It is well established that the flow formation process is closely connected to the thermal regime of the solar corona (Chashei and Shishov, 1987). The fact that the turbulence regime in the acceleration region is different from that in the region of constant velocity is taken as evidence of an effective interaction between turbulence and plasma flow (Chashei et al., 2007).

There has been substantial interest in studying wave disturbances with prominent periods in the corona and solar wind. The widely known 5-min oscillations generated by convective noise in the chromosphere and low corona (Kaplan et al., 1977), which are probably essential agents for coronal heating (Pikel'ner and Lifshitz, 1964), are thus important for the energy balance between corona and solar wind (Chashei and Shishov, 1987, 1988). More recently, McIntosh et al. (2011), using the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) observed outward-propagating Alfvénic waves with amplitudes of the order of 20 km s^{-1} and periods of the order of 100–500 s throughout the quiescent atmosphere. Jess et al. (2009) recorded narrowband high temporal resolution solar disk images across the $H\alpha$ absorption line. They observed oscillations in the bandwidth (FWHM) with significance levels exceeding 99%, but no evidence of periodic trends in either the intensity or the line-of-sight velocity. They interpreted the oscillations as a signature of torsional Alfvén waves with the strongest detected power at periods of 400-to-500-s. According to preliminary estimates, the energy flow connected with these waves is sufficiently large to accelerate the fast solar wind and heat the quiet corona.

Quasi-periodic disturbances in the 5-min band have been associated with isolated trains of Alfvén waves detected at heliocentric distances between 3 and 11 R_S (R_S = solar radius) during coronal sounding experiments with the linearly-polarized signals of HELIOS 1 and HELIOS 2 (Chashei et al., 1999). Sporadic quasi-periodic density oscillations in the inner solar wind were detected in frequency fluctuation spectra recorded during coronal sounding experiments in 2004 with the Mars-orbiting spacecraft MARS EXPRESS (Efimov et al., 2010b). The existence of quasi-periodic fluctuations in Doppler fluctuation spectra has been recently substantiated by an independent wavelet analysis (Efimov et al., 2011)

Following this initial work, we have carried out an analysis of additional radio frequency fluctuation data with MARS EXPRESS (MEX) in 2006 and 2008/2009, VENUS EXPRESS (VEX) in 2006, and ROSETTA (ROS) in 2006. Furthermore, we have reanalyzed earlier differential frequency data obtained in coronal sounding experiments with ULYSSES in 1991 and 1995, as well as S-band frequency fluctuations with GALILEO in 1996/1997. A quasi-periodic component (QPC) was detected sporadically in radio frequency fluctuation (RFF) spectra of all the more recent coronal sounding experiments and the existence of the QPC was verified in the earlier data. In the present paper we discuss the statistical characteristics of the QPC from an analysis of data accumulated during the above mentioned coronal sounding experiments.

2. Measurements and data processing

The spacecraft MEX, VEX and ROS receive and transmit coherent radio signals during solar conjunction using a parabolic High Gain Antenna (HGA). The spacecraft receives an uplink at X-band (7.1 GHz) and transmits simultaneously right-hand circular polarized downlinks at S-band (2.3 GHz) and X-band (8.4 GHz). The X-band uplink carrier frequency is multiplied by the constant transponder ratios 880/749 and 240/749 for coherent transmission at the X-band and S-band downlink frequencies, respectively. The ratio of the downlink frequencies is 880/240 = 11/3. The two-way radio mode takes advantage of the superior frequency stability inherent to the hydrogen maser oscillator at the ground station on Earth (Pätzold et al., 2004). The radio configuration for the ULYSSES solar corona experiment (SCE) was slightly different in that the uplink was at S-band, rather than X-band (Efimov et al., 2010a). Due to the malfunctioning of the HGA on GALILEO, all coronal sounding measurements were taken only with an S-band downlink, driven by the on-board Ultra-Stable Oscillator (USO). Intrinsic frequency fluctuations of this radio signal are much smaller than those induced by propagation through the corona at small solar offset distances (Efimov et al., 2008).

The radio signals were recorded at the 34-m and 70-m tracking stations of the NASA Deep Space Network (DSN) in California, Spain and Australia and at the 32-m ESA ground station at New Norcia, Australia. The signal frequencies at S-band (f_S) and X-band (f_X), as well as the differential frequency $f_D = f_S - (3/11)f_X$, were recorded at a nominal sampling rate of 1 s^{-1}. In order to examine short-lived (sporadic) phenomena, the measurement intervals were divided into segments of duration 2048 s over which temporal fluctuation spectra were calculated for the frequencies f_S, f_X, and the differential frequency f_D. The evolution of the temporal spectra was tracked by shifting the start of each segment by 512 s with respect to the previous segment. A list of the coronal sounding data used for the present analysis is shown in Table 1. Whereas only X-band recordings were used for MEX, VEX and ROS, the ULYSSES and GALILEO analyses used S/X-band and S-band only, respectively. The coronal sounding experiments were performed over the time period from 1991 to 2009 and occurred at different phases of the solar activity cycle. The solar offset distances ranged between 3 and 40 R_S. Most of the experimental data was obtained for low heliolatitudes. An exception was the ULYSSES experiment in 1995, which extended over all heliolatitudes.

Temporal frequency fluctuation spectra over the interval 5×10^{-4} Hz $< \nu < 0.1$ Hz can usually be described by a power-law function with a spectral index α in the interval $0.5 < \alpha < 0.7$ for solar offsets $R > 20$ R_S, and $0 < \alpha < 0.5$