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Statistical analysis and multi-instrument overview of the quasi-periodic 1-hour pulsations in Saturn's outer magnetosphere

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ABSTRACT

The in-situ exploration of the magnetospheres of Jupiter and Saturn has revealed different periodic processes. In particular, in the Saturnian magnetosphere, several studies have reported pulsations in the outer magnetosphere with a periodicity of about 1 h in the measurements of charged particle fluxes, plasma wave, magnetic field strength and auroral emissions brightness. The Low-Energy Magnetospheric Measurement System detector of the Magnetospheric Imaging Instrument (MIMI/LEMMS) on board Cassini regularly detects 1-hour quasi-periodic enhancements in the intensities of electrons with an energy range from a hundred keV to several MeV. We extend an earlier survey of these relativistic electron injections using 10 years of LEMMS observations in addition to context measurements by several other Cassini magnetospheric experiments. The one-year extension of the data and a different method of detection of the injections do not lead to a discrepancy with the results of the previous survey, indicating an absence of a long-term temporal evolution of this phenomenon. We identified 720 pulsed events in the outer magnetosphere over a wide range of latitudes and local times, revealing that this phenomenon is common and frequent in Saturn's magnetosphere. However, the distribution of the injection events presents a strong local time asymmetry with ten times more events in the duskside than in the dawnside. In addition to the study of their topology, we present a first statistical analysis of the pulsed events properties. The morphology of the pulsations shows a weak local time dependence which could imply a high-latitude acceleration source. We provide some clues that the electron population associated with this pulsed phenomenon is distinct from the field-aligned electron beams previously observed in Saturn's magnetosphere, but both populations can be mixed. We have also investigated the signatures of each electron injection event in the observations acquired by the Radio and Plasma Wave Science (RPWS) instrument and the magnetometer (MAG). Correlated pulsed signatures are observed in the plasma wave emissions, especially in the auroral hiss, for 12% of the electron injections identified in the LEMMS data. Additionally, in about 20% of the events, such coincident pulsed signatures have been also observed in the magnetic field measurements, some of them being indicative of field-aligned currents. This analysis combined with the multi-instrument approach sets constraints on the origin and significance of the pulsed events. Hence, our results suggest that the acceleration process providing the quasi-periodic relativistic electrons takes place at high-latitudes.

1. Introduction

Short-period pulsations in Saturn's magnetosphere have been reported several times since the flybys by the Voyager probes. During the outbound pass of Voyager-2 in the dawn sector and at intermediate southern latitudes, quasi-periodic enhancements in the energetic electron fluxes have been observed (Schardt et al., 1985). These electron injection events occurred in the energy range from 0.35 to 2 MeV and exhibited a so-called "sawtooth" shape, i.e. a rapid increase in the fluxes followed by a slower decay. Each of the pulses were separated by 40–90 min. These electron pulsations are correlated with sawtooth bursts in the plasma wave measurements in the frequency range from about 500 Hz to 1 kHz,

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this upper limit being just above the electron plasma frequency. Moreover, proton injection events (with an energy of 43–80 keV) and a dip in the magnetic field strength appear lagging the electron injection by several minutes. The magnetic field perturbation could be due to a diamagnetic effect produced by the protons and the beams of electrons are responsible for the wave activity. Besides, time dispersion between the pulses in the different datasets implied the existence of a distant acceleration process near the equator. The authors pointed out that these observations may have been due to the interplanetary configuration between Saturn and Jupiter, the magnetosphere of the former being embedded in the magnetotail of the latter.

Since 2004, the Cassini spacecraft allows a continuous in-situ investigation of Saturn's magnetosphere. Based on Cassini observations, several papers described 1-hour pulsations in several magnetospheric data. Mitchell et al. (2009) found evidence of a ∼1 h quasi-periodic injection of electrons with energy from a few tens of keV to 1 MeV. It appeared in the form of beams accompanied by field-aligned ion conics (with an energy of 30–200 keV). This event was detected when Cassini was at intermediate latitudes in the post-dusk sector of the magnetosphere. Simultaneous pulsed signatures were observed in the broadband electromagnetic whistler mode noise and at frequencies above the electron cyclotron frequency, corresponding to an electrostatic mode. The magnetic field angles exhibited correlated pulses as well. The authors suggested that these coincident observations are associated with downward field aligned current layers in Saturn's auroral zone, as is observed at Earth (Carlson et al., 1998). Such downward current layers, associated with upward electron beams, have been previously identified in Jupiter's magnetosphere by Mauk and Saur (2007) and around Saturn in the predawn and noon sectors (Saur et al., 2006).

A similar event was identified by Badman et al. (2012) when Cassini was around noon at high northern latitudes. During this event, coincident ∼1 h pulsations were observed in the energetic electron (hundreds of keV) and light ions (100–360 keV) fluxes, as well as in the broadband whistler mode waves, propagating upward along the field lines. Correlated fluctuations in the magnetic field measurements are indicative of field-aligned currents, whose the upward part produces auroral arcs poleward of the main emission. They are thought to be triggered by bursts of reconnection at the dayside magnetopause. As suggested by the authors, the quasi-periodic enhancements in the electron intensities may be due to scattering of upward electron beam carrying the downward component of the field-aligned current system. The association between the ∼1 h pulsations and the downward field-aligned currents is in agreement with some observations of quasi-periodic magnetic field pertubations and radio bursts poleward of the polar cap boundary (Jinks et al., 2014).

More recently, analysis of multi-instrument observations of Saturn's cusp region near noon revealed that 1-hour pulsations in energetic electron fluxes are not observed in this open field lines region although they were present in the magnetosphere just outside the cusp (Jasinski et al., 2014). In the magnetosphere, Cassini observed perturbations in the azimuthal component of the magnetic field, indicative of field aligned currents, coinciding with bursts in the whistler mode plasma waves.

Mitchell et al. (2016) reported another pulsed event observed in the post-noon sector at high northern latitudes. During this event, ∼1-hour pulsed field-aligned electron beams were in phase with periodic enhancements in the auroral hiss power and fluctuations in the magnetic field. Moreover, each coincident pulsation is preceded by an intensification of the brightness and a broadening of an auroral arc, similar to the bifurcations of the main auroral emission described by Radioti et al. (2011). The multiple brightenings of the bifurcations are thought to be the signatures of repeated magnetopause reconnection (Badman et al., 2013; Radioti et al., 2013). Thus, the pulsations in auroral features and in in-situ observations described by Mitchell et al. (2016) may be triggered by recurrent reconnection at the magnetopause.

Similar pulsations observed in the prenoon sector may also be explained by Kelvin–Helmholtz instabilities along the dawn flank of the magnetosphere. Indeed, short period pulsations in the intensities of electrons with an energy range from a few tens to a few hundreds of keV have been identified in the prenoon sector when Cassini encountered a plasma vortex associated with Kelvin–Helmholtz waves (Masters et al., 2010). Badman et al. (2016) presented another event exhibiting 1h-pulsations in the magnetic field and plasma wave observed in the northern and southern polar caps. In the same region but at higher latitudes, 20 min quasi-periodic peaks have been also detected.

The aforementioned studies are based on single case events observed in one particular place in the Saturn's magnetosphere. The first global survey of the quasi-periodic electron injections was carried out by Roussos et al. (2016), taking into account most of the observations of ∼1-hour pulsations in the high energetic electron fluxes measured by the Low-Energy Magnetospheric Measurement System (LEMMS), one of the detectors of the Magnetospheric Imaging Instrument (Krimigis, 2004) on board Cassini. The authors analyzed the overall statistical properties of these injections, focusing mainly on their spatial and spectral distribution. They revealed that the quasi-periodic electron injections with a typical interpulse period of 60 min occur at various places in the outer magnetosphere, with however a higher frequency of occurrence in the dusk sector compared to the dawn side. The magnetic mapping of the injections to either the ionophere or the equatorial plane was also performed. According to the mapping, and within the limitation due to the uncertainties inherent to the magnetic field model, the duskside pulsed events are located on closed field lines while most of the dawn events reside on open field lines or near the magnetopause. Several conclusions of Roussos et al. (2016) will be discussed further in this paper.

The long-term stability of the pulsation period of the electron pulses is indicative of the underlying scales of the kronian magnetosphere. In the Earth's magnetosphere, ultra low frequency (ULF) waves and pulsations are able to create very stable periodic phenomena (see the review by Keiling (2009)). These waves, characterized by stable periods, are typically global standing Alfvén waves on magnetic field lines bounded by the ionosphere or field line resonances (FLR) whereby a fast mode wave couples to an Alfvén wave. ULF waves have also been reported at Jupiter and Saturn (e.g. Khurana and Kivelson, 1989; Cramm et al., 1998). Unlike at Earth, these waves are local in scale. The global Alfvén travel times at Saturn being comparable to the planetary rotation rate, such global standing Alfvén waves should be inhibited in the nostationary plasma environment at Saturn. However, Cramm et al. (1998) observed evidence of a FLR in Saturn's magnetosphere using Voyager magnetic field measurements. They interpret their observation as the result of a coupling between a fast mode wave and a propagating Alfvén wave, unlike at Earth where the Alfvén wave is standing. The large size of the kronian magnetosphere allows such resonant mode coupling. This highlights a key difference between ULF phenomena between Saturn and Earth.

Short-period pulsations have been also reported in Jupiter's magnetosphere. Along the outbound trajectory of the Ulysses' flyby in 1992, at intermediate southern latitudes and around dusk, bursts with a quasi-periodicity of ∼40 min have been observed in the electron fluxes at energies from less than 1.5 MeV to beyond 16 MeV (McKibben et al., 1993; Simpson, 1992). These electron pulsations are field-aligned and exhibit the characteristic sawtooth shape with a rise time of only ∼1 min. Some 40-min quasi-periodic increases of the electron intensities have been also detected at lower energies during the Cassini Jupiter flyby in 2001