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Quasi-periodic injections of relativistic electrons in Saturn's outer magnetosphere

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ABSTRACT

Quasi-periodic, short-period injections of relativistic electrons have been observed in both Jupiter's and Saturn's magnetospheres, but understanding their origin or significance has been challenging, primarily due to the limited number of in-situ observations of such events by past flyby missions. Here we present the first survey of such injections in an outer planetary magnetosphere using almost nine years of energetic charged particle and magnetic field measurements at Saturn. We focus on events with a characteristic period of about 60–70 min (QP60, where QP stands for quasi-periodic). We find that the majority of QP60, which are very common in the outer magnetosphere, map outside Titan's orbit. QP60 are also observed over a very wide range of local times and latitudes. A local time asymmetry in their distribution is the most striking feature, with QP60 at dusk being between 5 and 25 times more frequent than at dawn. Field-line tracing and pitch angle distributions suggest that most events at dusk reside on closed field lines. They are distributed either near the magnetopause, or, in the case of the post-dusk (or pre-midnight) sector, up to about 30 R_S inside it, along an area extending parallel to the dawn–dusk direction. QP60 at dawn map either on open field lines and/or near the magnetopause. Both the asymmetries and varying mapping characteristics as a function of local time indicate that generation of QP60 cannot be assigned to a single process. The locations of QP60 seem to trace sites that reconnection is expected to take place. In that respect, the subset of events observed post-dusk and deep inside the magnetopause may be directly or indirectly linked to the Vasyliunas reconnection cycle, while magnetopause reconnection/Kelvin–Helmholtz (KH) instability could be invoked to explain all other events at the duskside. Using similar arguments, injections at the dawnside magnetosphere may result from solar-wind induced storms and/or magnetopause reconnection/KH-instability. Still, we cannot exclude that the apparent collocation of QP60 with expected reconnection sites is coincidental. given also the large uncertainties in field line tracing with the available magnetic field models. The intensity of the QP60 spectrum is strong enough such that if transport processes allow, these injections can be a very important source of energetic electrons for the inner saturnian magnetosphere or the heliosphere. We also observe that electrons in a QP60 can be accelerated at least up to 6 MeV and that the distribution of QP60 appears to trace well the aurora's local time structure, an observation that may have implications about high-latitude electron acceleration and the connection of these events to auroral dynamics. Despite these new findings, it is still unclear what determines the rather well-defined 60 to 70-min period of the electron bursts and how electrons can rapidly reach several MeV.

1. Introduction

Relativistic electrons have been detected in all planetary magnetospheres of our Solar System with the highest intensities

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observed within the boundaries of the stable charged particle trapping regions, that is the radiation belts (Mauk and Fox, 2010). The source (or seed) electron population of the belts resides typically within the middle or outer magnetosphere and its energy spectrum extends up to few hundred keV or several MeV, depending on the planet. Acceleration of this population by one or more processes (adiabatic transport, wave–particle interactions, flux-tube interchange, solar-wind transients) may give rise to the high intensities of MeV electrons observed within the belts (Shprits et al., 2012; Paranicas et al., 2010; Gannon et al., 2005; Horne et al., 2005; de Pater, 1981; Lyons and Thorne, 1973).

What is, however, less clear is how the high numbers and energies of the seed electrons are derived. At Earth, dipolarization associated injections and convection changes have been shown to be sufficient to supply the MeV electron population in the outer belt, at least on certain instances. Similarly at Saturn, it is believed that dipolarizations play a key role in supporting the at least part of the seed electron population, but it has not yet been demonstrated if their occurrence fully justifies the large energies and/or intensities in the middle magnetosphere. For example, Mitchell et al. (2015b) discusses several examples of Cassini observations with recently injected energetic particle populations in the middle magnetosphere of Saturn. Peak electron energies in one such example (day 301/2004) are at about 200 keV on a background population that extends at least up to 800 keV in this specific case or to about 1 MeV on average (Kollmann et al., 2011). It is therefore important to evaluate the relative importance of additional sources in providing energetic electrons to the middle magnetosphere and, eventually, the radiation belt.

One such source may be a type of quasi-periodic energetic electron injections, first reported by Schardt et al. (1985) using Voyager-2 observations in the dawn sector of Saturn's magnetosphere and at intermediate latitudes (-29°). The signature of each of these injections was a sudden increase of energetic electron intensities (by 1–2 orders of magnitude) in the energy range of 100 keV to several MeV, followed by a slower, exponential decay that lasted between 30 and 60 min ("sawtooth" structure). Each injection involved two or more of these sawteeth repeated at quasi-regular intervals of 40–80 min. As Voyager-2 was a flyby mission it remained unclear how common such events where or what their spatial distribution was, despite the authors noting the highly unusual interplanetary conditions during the flyby.

Quasi-periodic injections have also been reported in recent publications based on Cassini observations. Mitchell et al. (2009) described such an event from day 269 of 2006, highlighting also how the coincident signatures in energetic ion, plasma wave and magnetic field measurements are similar to those of downward sheet currents in Earth's auroral zone. This event took place at intermediate latitudes, but at the post-dusk sector of the magnetosphere, far from the location of the Voyager-2 observations. Its position also mapped relatively deep inside the magnetopause. Badman et al. (2012) reported a similar event from day 320 of 2008, where the recurrent electron injections extended down to energies of few tens of keV. This observation took place around local noon and at high, north latitudes. The authors attributed the enhanced electron intensities to scattered electrons in downward current regions that map into transient structures in Saturn's aurora that are triggered by reconnection. Masters et al. (2010) observed also a quasi-periodic electron signature coincident with a vortex structure in the pre-noon sector of Saturn's outer magnetosphere. This vortex was associated to the growth of the Kelvin–Helmholtz (KH) instability at the magnetopause, a flow-shear instability that can also trigger reconnection in planetary magnetospheres.

While both aforementioned Cassini and Voyager-2 studies focused on single case events, it is evident that these sawtooth electron injections may be taking place globally in Saturn's magnetosphere. Besides being a potentially important source of relativistic electrons, the evidence suggesting that they may be originating at reconnection sites may also make them an important tracer of that process. What is also interesting is that strikingly similar type of quasi-periodic electron injections were seen during Ulysses's flyby of Jupiter with a period in the 40–80 min range. Radio emissions that appear to have a common origin with the aforementioned electron injections at Jupiter (McKibben et al., 1993; MacDowall et al., 1993; Zhang et al., 1995) were also detected. This suggests that quasi-periodic electron injections may be connected to fundamental dynamical processes in corota tion-dominated magnetospheres.

Here we take advantage of Cassini's extended tour of the saturnian system to derive for the first time statistical properties of these quasi-periodic electron injections in an outer planet's magnetosphere. While numerous aspects of these injections can be investigated, for this initial study we will focus mostly on their spatial nature. Spectral, angular electron distribution characteristics and the response of the magnetic field is also explored briefly. We will use these data in order to constrain the physical origin of the injections and to understand their relation to trapped electron populations in Saturn's middle magnetosphere. This work also provides important context for a series of studies that report, similar, short period quasi-periodic pulsations in in-situ and auroral data obtained during the 2013 Saturn Aurora Campaign (Badman et al., 2015; Mitchell et al., 2015a).

2. Instrumentation and analysis tools

Most of the data presented in this study are from Cassini's MIMI/LEMMS energetic charged particle detector (Krimigis et al., 2004). LEMMS has two telescopes pointing in opposite directions, called the Low Energy and the High Energy Telescope (LET/HET respectively). Each telescope contains different type of channels for separating the species (ions/electrons) and for constraining the energy of the measured particles with different time and energy resolution.

The channel types used here are the "rate" and the "pulse-height-analysis (PHA)" channels. The former have the advantage of a good geometric factor for both the keV and the MeV range, a wide energy coverage (electron energies from about 20 keV to greater than 10 MeV) and the use of coincidence techniques which can partly suppress penetrating particles and light contamination. The disadvantage of the rate channels is the moderate or poor energy resolution at the MeV range ($\Delta E/E > 1$). The PHA channels achieve an energy resolution between 0.06 and 0.07 for the energy range of 25 keV and 1.6 MeV at the expense of a lower sensitivity and the lack of coincidence measurements. For these reasons, the use of rate and PHA channels is complementary.

More specifically, we analyzed data from electron rate channels C0–C7 (LET: 18–532 keV) and E0–E7 (HET: >95 keV). Although the magnetospheric structures analyzed appear in electrons, we also review energetic ion data for the context, since also Mitchell et al. (2009) and Zhang et al. (1995) report coincident field-aligned structures in proton intensities. Ion rate channels considered here are A0–A7 and P2 (27—4920 keV). Regarding the electron PHA channels, we mostly use the ones above 250 keV (PHA-F1 detector) in order to constrain the energy spectral shape beyond about 1 MeV, where energy resolution is poor. The signal from lower energy PHAs (PHA-E detector) can be very sensitive to light contamination, affecting the results of spectral form fits to the data. The LEMMS signal is corrected for the instrumental background as described in previous papers (Roussos et al., 2011;