Update on Periodicities in Saturn’s Magnetosphere

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1. Latitude variations (presented at MAPS Meeting, April 2017)

2. Correlation of periodicities with solar cycle

3. Update on energetic electron periodicities
   (2016, JGR-SP, 121, doi:10.1002/2016JA023405)

4. High latitude magnetic field periodicities

5. Solar periodicity in low energy (ELS) electrons

6. Recent F-ring observations and periodicities

Annual Periodicities 2015-2016

electrons 27.1–49.5 keV

Peak or main periodicities for each year are noted in each panel, 2005-2016.
Annual Mean Latitudes of Observation

Cassini Latitude Distributions (r>15 Rₚ)

Annual mean latitudes (dashed lines) of Cassini.
Correlation of Mean Latitudes and Main Periods

$cc = 0.79$
Correlation with Higher Energy Electrons

\[ cc = 0.61 \]
\[ cc2 = 0.78 \]
Latitude dependence of periodicities can be an indicator of differential rotation, at least in the magnetosphere. Similar to the Sun’s differential rotation. See proposal by Dessler (1985, GRL, 12, 299-302).
Periodograms such as these were constructed for the entire Cassini mission using 200d sample intervals at a cadence of 30 days. Then they were normalized to the maximum period within the 8-14d spectral window. The normalized periodograms were finally placed into spectrogram format —
The crosses indicate the peak periods. The equinox and GWS event are marked for reference.
Variation in Main Period Compared to Solar Activity

- Main peaks electrons 27.1–49.5 keV
  - Period: $10.16 \pm 0.24$ yrs
  - Amplitude: $0.089 \pm 0.004$ h

- f10.7 radio flux

Graphs show the variation in main period compared to solar activity over the years from 2006 to 2016.
Cross Correlation of Main Peak with Solar Activity

A very good (anti-)correlation of -0.93 is obtained when the C1 electrons lead the solar activity by ~405d.
Comparing the Periodicities over Mission Lifetime

Showing 110-365 keV electrons at top, Bφ in middle, and 100-400 kHz SKR at bottom. All 200-day Lomb periodograms at 30-day cadence, filtered r>15 Rs. Individual periodograms are shown for times A, B, C, D, E, F in next slide.
Individual Periodograms at Selected Times

Sample periodograms electrons 110.0–365.0 keV

A  SNR=21.81

B  SNR= 8.25

C  SNR=13.21

D  SNR= 5.06

E  SNR= 4.81

F  SNR=10.66

With blue lines showing main SKR period and red lines showing main Bϕ period.
Comparison of Main Periods
Limiting Periods

all the periodograms are binned and normalized, the periods tend to lie within a narrow range of ~1/4 hour with two main peaks, regardless of whether they are north or south source. While this is generally agreed upon, nobody has remarked on it. Why do the periods lie within this particular range? Is there structure longward of these limits?
Possible Explanation for Dual Peaks

If the signal is a noisy sinusoid between two limiting periods (i.e., the period varies sinusoidally between limits $T_1$ and $T_2$ as shown in top panels), then a histogram of the signal could readily display two peaks. [Referee suggested this idea.]
Review selection of open-closed field (OCF) boundary. The lack of electrons above ~20 eV in the ELS spectrogram signals the open field region (dashed red lines).
Marking the Open Regions

Gray trace shows entire Cassini trajectory. Red indicates southern open regions, while blue indicates north open regions. OCF boundaries determined by inspection of ELS spectrograms.
Periodograms for North and South Open Regions

Open Regions mainfield subtracted no filters

north Br periodogram

north B\theta periodogram

north B\phi periodogram

south Br periodogram

south B\theta periodogram

south B\phi periodogram

period (h)

period (h)

period (h)
Simulation of Rotating Sources using Cassini Trajectory

North simulation

South simulation
Does Filtering Have an Effect?

Open Regions mainfield subtracted Lanczos filtered

north $Br$ periodogram

north $B\theta$ periodogram

north $B\phi$ periodogram

south $Br$ periodogram

south $B\theta$ periodogram

south $B\phi$ periodogram
Solar Wind Periodicities in ELS Electrons

All pitch angles, three energy regimes, filtered 5 $R_S$ to magnetopause, Titan encounters removed. Periodograms use log(DNF) or log(SKR).
Effects of trajectory can be determined by flying Cassini through the model in top panel (from all ELS data). Resulting periodogram at bottom. Compare to previous.
Some Interesting New Results from F-Ring Orbits

Typical F-ring orbit (blue) shown in cylindrical coordinates. Red lines depict the nominal dipole field of Saturn. Note that at high latitudes, the orbit essentially "skims" one field line that connect approximately with auroral region.
MIMI/LEMMS sampled all pitch angles during this high-latitude interval, by using forward (C4, blue) and backward (E0, red) looking detectors. The resulting distributions indicate outward (upward) flux of electrons away from the auroral zone, with no consequent inward (downward) flow.
Energetic Electron Spectrogram

Notes: “slivers” on either side of equator (EQ) represent crossing of Janus/Epimetheus L shells. Structures on either side of equator are real and seem to be permanent features of inner magnetosphere.
Perhaps surprisingly at these close ranges, the periodicities are clearly evident in both the electrons and ions. This is an ion spectrogram showing one F-ring orbit. Asterisks at flux peaks are 10.79 hours apart.
Geometry for Recent MIMI/INCA Observations

Geometry in XZ plane for recent F-ring orbits. Blue shows one orbit (they’re all the same), and red shows approximate field of view of INCA. The following will show observations from d41 (12hr) to day 44 (12h) when the instrument was operating in the neutral mode.
Recent Periodicity during F-ring orbits

Lomb periodogram generated using energetic electron fluxes for observations made during days 1-50 2017 outside $r = 15 R_s$. Other energies give same period. Secondary periods most likely from Doppler up/down shifts from orbit, so there is only one period observed. NOTE: the period is observed at high as well as low latitudes.
ENA images were corrected for slant-viewing, projected onto the equatorial plane, and averaged into 2x2 Rs bins for d41-44 2017. Double circle near Rhea orbit indicates radial distance at which keograms were made.
Two points to note: ENA intensities are concentrated slightly to the dawnward side of midnight (00 h) and they rotated at essentially the corotation speed (slanted lines), assuming a period of 10.79 h (from previous periodogram). This behavior is quantified by the “midnight flasher” model (from ISSI – October 2015).
Comparison of ENA local time dependence with local time dependences of SKR power (dot-dashed line) and auroral power (dashed line). The SKR and auroral power (Lamy et al., *JGR*, 2009) were re-scaled for direct comparison to ENA median fluxes in 24 local time bins.
**Midnight Flasher Model**

With a period of $T$, $\omega=2\pi/T$, a simple version of this model describes the intensity $F$ at time $t$ position $(r, \phi)$ as:

$$F = Fr(r) \cdot F\phi(t,\phi) \cdot Fm(\phi)$$

Where $Fr(r)$ is a range function (here $r=9$, and $Fr = \text{const}$), $F\phi(t)$ is an angular function,

$$F\phi(t,\phi) = 1 + \cos(\omega t)\cos(\phi) + \sin(\omega t)\sin(\phi)$$

and $Fm(f)$ is the modulation function in local time,

$$Fm(\phi) = 1 + \cos(\phi_o)\cos(\phi) + \sin(\phi_o)\sin(\phi)$$

Here, $\phi = \text{atan}(y,x)$ is the local time angle measured from noon ($\phi=0^\circ$ is noon and $f=180^\circ$ is midnight). The amplitudes of the model are immaterial, but are set to 1 here. For simplicity, the angular dependences are all sinusoidal, but they could also be, for instance, sawtooth or squarewave or something else periodic. See Carbary et al. (2009), *Adv. Space Res.*, 44, 483-493, doi:10.1016/j.asr.2009.04.019.
The model creates the general features of the ENA observations, namely, concentration of the signal near midnight (that can be adjusted to any local time) and the “slant” of the signal to corotation. Secondary or “ghost” signals not reproduced by the model. Compare to previous keogram.
Summary

1. Some evidence for linear change in period as function of latitude, which could indicate differential rotation.

2. Some evidence for correction of long-term variation in period with the solar cycle as indicated by F10.7 index.

3. Periodicities are limited between ~10.55 and ~10.85 hours, with some suggestion of structure between these limits.

4. In open field region, $B\theta$ and $B\phi$ periodicities are “pure”, but the period for $Br$ is not so clear.

5. ELS electrons below ~1 keV show solar wind period of ~26 d, but do not show such a period for higher energies.

6. Periodicity of electrons for ~35 days of F-ring orbits is 10.73 hours.

7. “Midnight-flasher” model explains the gross features of the observations.
C channel electron spectrogram as function of L shell for one pass on d66 2017. L shell is from an offset dipole. BUT beware of fluxes inside L ~5R_S in this energy range as they may have uncorrected background from penetrating radiation.
E-channel (LEMMS back end) observations for pass on d66 2017 in offset L-shell.
Very high energy protons from P-channels (back end) for pass on day 66 2017 in L shell. What will happen inside F-ring? Is there a radiation belt or not?
Detailed fluxes (organized in offset dipole L shell) for one north-to-south F ring orbit on day 9 2017. The fluxes are strongly affected by satellite absorption. Even the tiny Janus and Epimetheus create dropouts in the fluxes.
Scan from d030 2017 at 10:41. Sun to the right. Some interesting features:
1. Multiple aurora features in main oval, including swirl-like structures
2. Airglow layer on dayside
3. Bright spot on horizon in lower left (seems to be real - it’s not a single pixel)
Notable features: dual arc structures (top and bottom) and wavy structure at bottom. Both structures exhibit spatial quasi-periodicity. Observation made on d059 2017 at 1050.
Recent Auroral Images

Scan from d030 2017 1343 showing ray-like structures in main oval.

Scan from d058 2017 0643 showing entire oval. Multiple ovals are apparent. Note center of oval does NOT correspond to pole (according to UVIS registration at least)