EPSC Abstracts
Vol. 13, EPSC-DPS2019-735-1, 2019
EPSC-DPS Joint Meeting 2019

EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

The landscape of Saturn's magnetic field from the Cassini Grand Finale

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Abstract

Saturn's magnetic field continues to offer surprises since the first in-situ measurements made during the Pioneer 11 Saturn flyby. Here we will report features of Saturn's magnetic field revealed by the magnetometer measurements from the Cassini Grand Finale phase, and discuss their implications on the interior structure and dynamics of Saturn.

1. Introduction

The intrinsic magnetic field not only is a critical factor determining the electromagnetic environment of a planet, it also serves as a key diagnostic of the interior structure and dynamics of the host planet [1]. Saturn's magnetic field has been measured in-situ by four space missions, Pioneer 11, Voyager 1, Voyager 2, and Cassini.

The Cassini mission entered the Grand Finale phase in April. 2017 and executed 22.5 highly inclined, close-in orbits around Saturn before diving into the planet on September 15th 2017. During the Cassini Grand Finale, the fluxgate magnetometer (MAG) onboard the spacecraft [2] made continuous in-situ measurements of Saturn's magnetic field [3]. Here we present our analysis of the full dataset of Cassini Grand Finale MAG measurements.

2. Dataset

The periapsis distance of the Cassini Grand Finale orbits varied between 1.064 R_S and 1.02 R_S (1 R_S = 60268 km) from the center of Saturn, the periapsis latitude was -6°±1° except that of the dive-in orbit which was 10°, and the periapsis local time were ±1 hour around local noon. Figure 1 shows the characteristics of the magnetic field measurements along a typical Cassini Grand Finale orbit (shown here is Rev 291). All four dynamical ranges of the fluxgate magnetometer [2] were activated during one orbit, with the measured total field amplitude ranging from < 2 nT to > 20,000 nT.

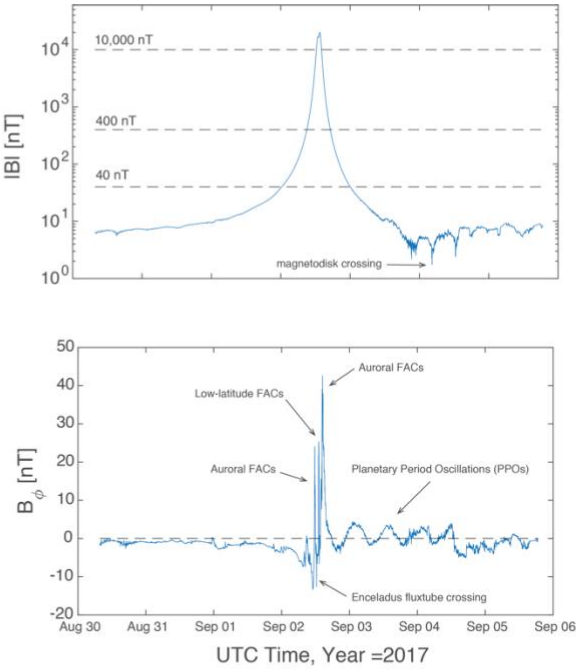

Figure 1: Characteristics of the magnetic field measurements along a typical Cassini Grand Finale orbit (shown here is Rev 291). The top panel shows the total amplitude of the magnetic field, and the bottom panel shows the azimuthal component, which exhibits various magnetospheric features.

3. Results

The north-south asymmetry of Saturn's internal magnetic field was directly measured with a northward offset of Saturn's magnetic equator by ~ 0.0468 R_S (2820.5 km). The measurements further demonstrated that the northward offset of Saturn's magnetic equator varies with cylindrical radial distance from Saturn. Limited “longitudinal” variation of Saturn’s magnetic equator revealed that Saturn's internal magnetic field is exceptionally axisymmetric, with a dipole tilt less than 0.01 degrees. The azimuthal magnetic field measured near the periapsis arise from a low-latitude field-aligned current system confined to magnetic field lines inside Saturn's tenuous D-ring [3, 4].

Although almost perfectly axisymmetric, Saturn's internal magnetic field exhibits features on many characteristic length scales in the latitudinal direction. In addition to the spherical harmonic analysis, we employed the Green's function to construct new internal field models for Saturn. Expressed using Gauss coefficients, Saturn's internal magnetic field features prominent dipole, quadrupole, and octupole terms, while the degree 4 to degree 11 terms are on the order of 100 nT or less. Examining B_r at 0.75 R_S, the degree 4 to 11 contributions correspond to latitudinally banded structure with characteristic width similar to the off-equator zonal jets observed in the atmosphere of Saturn. Saturn's internal magnetic field beyond 60°, the small-scale features in particular, are less well constrained by the available measurements. This is mainly due to incomplete spatial coverage in the polar region.

4. Implications on Saturn’s interior

The almost perfect alignment between Saturn’s magnetic axis and spin-axis is challenging for dynamo theory, since the Cowling’s theorem precludes the possibility of a perfectly axisymmetric magnetic field being generated by MHD dynamo action. A stably stratified layer near the top of the deep dynamo with strong zonal motion but no large-scale radial motion could axisymmetrize the dynamo-generated magnetic field [5]. This stable layer most likely results from extensive helium de-mixing and rainout from metallic hydrogen. From the upper bound on the magnetic dipole tilt, we estimated that this stably starfield layer must be at least 3000 km thick.

The small-scale axisymmetric magnetic bands suggest the existence of a secondary magnetic field generation process in the semi-conducting region of Saturn, in addition to the main magnetic field generation process in the highly conducting metallic hydrogen layer of Saturn. This secondary magnetic field generation process is enabled by the existence of the background magnetic field, deep differential rotation (zonal flow), and local small-scale helical fluid motion.

Acknowledgements

We acknowledge support from the Cassini Project. Work at Imperial College London was funded by Science and Technology Facilities Council (STFC) consolidated grant ST/N000692/1. M.K.D. is funded by Royal Society Research Professorship RP140004. H.C. is funded by NASA Jet Propulsion Laboratory (JPL) contract 1579625.

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