Schumann resonance: a tool for investigating planetary atmospheric electricity and the origin and evolution of the solar system

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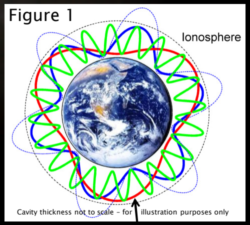
Abstract

Investigation of Extremely Low Frequency (ELF) electromagnetic waves produced by lightning activity has been used to assist the characterization of a variety of phenomena related to atmospheric electricity, namely lightning climatological studies. Detection of Schumann Resonance (SR) spectral features of the earth-ionosphere cavity from outside the cavity offers new remote sensing capabilities to assess tropospheric-space weather connections. A link between the water mixing ratio and atmospheric electrical conductivity makes SR a suitable tool to assess volatile abundance of the outer planets, offering new capabilities to constrain thermodynamic parameters of the protosolar nebula from which the solar system evolved. In this work we discuss a new technique and associated instrumentation to detect SR signatures of planetary environments and subsequently to infer the fraction of volatiles in the gaseous envelopes of the giant planets.

Schumann Resonance

Schumann resonances are ELF electromagnetic oscillations of the earth-ionosphere cavity, and are produced by lightning activity.

Figure 1



$$\omega_n = \frac{c}{R}\sqrt{n(n+1)}$$

SR varies mainly with:

Lightning activity

- Daily variation (maximum in late afternoon LT)
- Seasonal variation
- Local enhancement due to mesoscale convective systems

Ionosphere dynamics

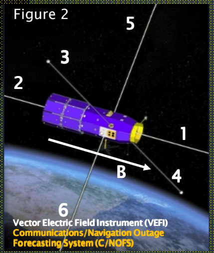
- Solar cycle
- Solar particle events
- Magnetospheric storms
- Anthropogenic activities

Boundary Conditions (Earth cavity):

- ✔ Surface is static and a perfect reflector
- ! Ionosphere is dynamic (!) and a perfect reflector (?)
  - ✔ Propagation inside the cavity
  - ✖ Cavity leakage – anisotropy plays a key role

C/NOFS Satellite

Figure 2



VEFI – includes 3 electric field dual probes to perform low frequency measurements

Boom size: 10 m
Dipole effective length: ~ 20 m
Sampling: 512 s^{-1}
Sensitivity: ~10 $nVm^{-1}Hz^{-1/2}$ (ELF range)
E12 is 'parallel' to B
E34, E56 are 'perpendicular' to B

Altitude: 400–850 km
Inclination: 13°
Orbit period: ~97 min

Concerning VEFI ELF measurements, only E34 and E56 waveforms are available in a regular basis

VEFI also includes two optical lightning detectors

Highlights:
C/NOFS detected Schumann resonance features in the Earth equatorial ionosphere.

Figure 3 shows typical VEFI electric field data recorded on 31 May 2008. Spectrogram (left) and mean spectrum computed all through the orbit (right). The top and bottom panels refer to meridional (vertical) and zonal (east-west) components, respectively. The fuzzy horizontal lines seen mostly during nighttime in the left panels and the spectral peaks on the right-hand side correspond to Schumann resonance eigenmodes (Simões et al., 2011). The black (satellite eclipse) and gray (sunset-sunrise) bars identify nighttime measurements.

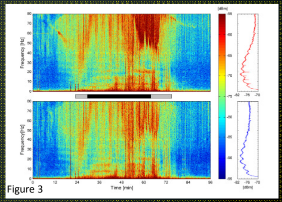


Figure 3

References

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Simões, F., et al. (2008), The Schumann resonance: a tool for exploring the atmospheric environment and the subsurface of the planets and their satellites, *Icarus*, 194, 30–41, doi:10.1016/j.icarus.2007.09.020.
Simões, F., R. F. Pfaff, and H. Freudenreich (2011), Observation of Schumann resonances in the Earth's ionosphere, *Geophys. Res. Lett.*, 38, L22101, doi:10.1029/2011GL049668.
Simões, F. et al. (2012), Using Schumann resonance measurements for constraining the water abundance on the giant planets – implications for the solar system's formation, Astrophys. J., 750:85, doi: 10.1088/0004-637X/750/1/85.

Wave Propagation Model

We use a finite element algorithm to model ELF electromagnetic wave propagation in planetary cavities. The domain and code implementation are 3D, but sometimes the model is simplified considering a spherically symmetric parameterization of the medium and 2D axi-symmetric approximations. The key parameters of the medium are (Simões et al., 2008):

- *Inner boundary (0.5 R, where R is the radius of the planet);*
- *Outer Boundary (2 R for eigenmode or 10 R for time-harmonic propagation);*
- *Atmospheric conductivity and collision frequency profiles;*
- *Radio wave atmospheric refractivity;*
- *Magnetic field to address contribution of medium anisotropy;*
- *Permittivity and conductivity of the interior;*
- *Hertz dipole to emulate the source.*

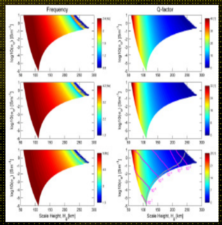

Figure 4

Figure 4 shows typical modeling results of (left) eigenfrequencies and (right) *Q*-factors of (from top) the three lowest eigenmodes as function of interface conductivity (σ_0) and scale height (*Hd*) of the Uranus cavity. In the bottom right panel, the magenta curves represent mean water contents in the gaseous envelope; cavity parameterizations near the gray curve represent the most plausible conductivity profiles.

Electrical Conductivity Connection With Volatiles

Since the ionization energy of helium is significantly higher than that of molecular hydrogen (see Table 1 for details), electrical conductivity of the interior of the giant planets is mainly due to hydrogen and driven by thermodynamic parameters such as temperature, pressure, and density as a function of depth. Several processes contribute to increase the electrical conductivity depending on distribution and nature of impurities. The ionization energy of water, methane, and ammonia is significantly lower, providing a direct contribution to conductivity increase.

The composition of the giant planets gaseous envelopes is mainly hydrogen and helium.

The fraction of volatiles in the gas giants remains largely unknown. See Figure 5 for more information.

Table 1

Molecule	Ionization Energy [eV]
He	**24.6**
H_2	**15.6**
H_2O	12.6
CH_4	12.6
NH_3	10.1

Solar System Evolution Connection With Volatiles

The formation and evolution of the solar system is closely related to the abundance of volatiles, namely water, ammonia, and methane in the protoplanetary disk. the distribution of rocky, icy, and gaseous bodies resulting from the protosolar nebula is linked to volatiles' abundance and to the location of the "snow line". Accurate measurement of volatiles in the solar system is therefore important for understanding not only the nebular hypothesis and origin of life but also planetary cosmogony as a whole. Schumann resonance detection can be potentially used for constraining the uncertainty of volatiles of the giant planets, mainly Uranus and Neptune, because such ELF wave signatures are closely related to the electric conductivity profile and water content. Figure 5 shows conductivity profiles for a few water contents (dry envelope, 0.01, and 0.1) for the gaseous envelopes of Uranus and Neptune (Liu, 2006). Compared with those of a dry envelope, the eigenfrequencies of the cavity decrease by ~50 % when the fraction of volatiles is 0.1. Unlike in situ and other remote sensing techniques , SR measurements provide the average properties of the whole envelope down to hundred, possibly thousands of kilometers.

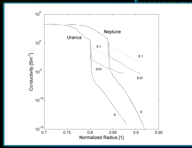

Figure 5: Conductivity profile of Uranus and Neptune as a function of normalized radius, R, where R = 1 corresponds to an atmospheric pressure of 1 bar. The solid, dashed, and dotted lines correspond to 0, 0.01, and 0.1 water content, respectively. The sharp increase of conductivity corresponds to the solid-gas or liquid-gas interface predicted by models. For the same depth, a water mixing ratio of 0.1 might increase the conductivity by as much as 10 orders of magnitude compared to that of a dry envelope, a fact that clearly illustrates the extreme sensitivity of ELF wave propagation conditions to the gaseous envelope water mixing ratio. The conductivity profiles are adapted from Liu (2006).

Future Work

- Improve chemistry models to provide better estimates of the conductivity profile;
- Estimate ELF wave leakage of Saturn's cavity to determine whether Cassini could detect SR features close to the planet;
- Understand the connection between electrical conductivity and volatiles and constrain the snow line location.

Summary

- Schumann resonances can be detected from orbit;
- Schumann resonance features are defined mainly by the radius of the planet and the conductivity of the gaseous envelope;
- The conductivity profile is affected by the content of volatiles in the atmosphere;
- Investigation of the fraction of volatiles (H_2O, CH_4, NH_3) in the cavity is useful to assess the location of the "snow line" in the protosolar nebula from which the solar system evolved (see sketch in Figure 6).

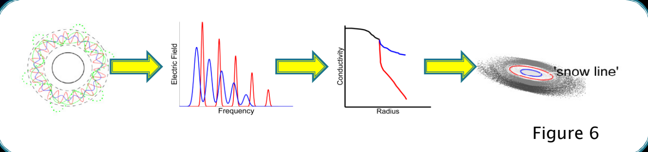

Figure 6