SCHUMANN RESONANCE: A TOOL FOR INVESTIGATING PLANETARY ATMOSPHERIC ELECTRICITY AND THE ORIGIN AND EVOLUTION OF THE SOLAR SYSTEM. F. Simões[1], R. F. Pfaff[1], M. Hamelin[2], C. Béghin[3], J.-J. Berthelier[2], P. Chamberlin[4], W. Farrell[5], H. Freudenreich[1,6], R. Grard[7], J. Klenzing[1], J.-P. Lebreton[3,8], S. Martin[1,6], D. Rowland[1], Y. Yair[9], [1]NASA/GSFC, code 674, Greenbelt, Maryland, USA, [2]LATMOS/IPSL-UPMC, Paris, France, [3]LPC2E, Orléans, France, [4]NASA/GSFC, code 671, Greenbelt, Maryland, USA, [5]NASA/GSFC, code 695, Greenbelt, Maryland, USA, [6]ADNET Systems, Inc, Rockville, Maryland, USA, [7]ESA/ESTEC-RSSD, Noordwijk, Netherlands, [8]LESIA, Observatoire de Paris-Meudon, France, [9]Open University of Israel, Raanana, Israel (fernando.a.simoes@nasa.gov).

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 Theory: SRs are electromagnetic oscillations of the earth-ionosphere cavity produced by lightning activity. Earth can be regarded as a nearly perfect conducting sphere, wrapped in a thin dielectric atmosphere that extends to the lower edge of the ionosphere where the conductivity is also substantial, nesting the earth-ionosphere cavity similar to a waveguide. Propagation of ELF electromagnetic waves within the cavity formed by two, highly conductive, concentric, spherical shells, such as those formed by the surface and the ionosphere of Earth, was first studied by Schumann [1], and the resonance signatures of the cavity subsequently were observed in ELF spectra by Balser and Wagner [2]. The eigenfrequencies, f_n, of a homogeneous cavity with losses can be approximately computed from

$$f_n \approx \frac{c}{2\pi R}\sqrt{n(n+1)\frac{1-\frac{d}{R}}{\varepsilon_r\left(1+i\frac{\sigma}{\varepsilon_r\varepsilon_o\, 2\pi f_n}\right)}}, \qquad (1)$$

where c is the velocity of light in vacuum, R and d are the radius and thickness of the cavity, ε_r and σ are the relative permittivity and conductivity of a uniform medium, ε_o is the permittivity of vacuum, and n=1,2,3,… is the corresponding order of the eigenmode (see Table 1). Although sctrictly valid when the cavity is thin and losses are small, i.e., $h \ll R$ and $\sigma \ll \omega_n \varepsilon_o$, Equation (1) is nevertheless useful to estimate SR eigenfrequencies. The range of the SR spectral features is determined by the radius of the planet and, to a lesser extent, by the cavity thickness and medium losses.

Physical Quantity	Value[2,3,6]
Frequency (ground)	7.8, 14.3, 20.8, 27.3, 33.8 Hz,…
Q-factor (ground)	~5
Q-factor (ionosphere)	~5
Electric field (ground)	~0.3 $mVm^{-1}Hz^{-1/2}$
Electric field (ionosphere)	~0.25 $\mu Vm^{-1}Hz^{-1/2}$
Magnetic field (ground)	~ 1 pT

Table 1: Typical SR characteristics of the earth-ionosphere cavity.

Ground-Based Measurements: On Earth, SR ground-based measurements are driven by three major research fields related to atmospheric electricity, specifically the global electric circuit and transient luminous events such as sprites, tropospheric weather and climate change, and space weather effects [3,4,5]. For decades, continuous monitoring of ELF waves from multiple stations around the world has been used to investigate lightning-thunderstorm and tropospheric-ionospheric connections, because SR signatures are mostly driven by lightning activity and ionosphere variability. A major interest of SR studies is concerned with the processes linking lightning and thunderstorm activity to the global electric circuit. For example, SR may be used as a global tropical thermometer to infer thunderstorm-related activity in equatorial regions [4]. Variability of SR is associated with changes of not only electromagnetic sources but also properties of the atmosphere and the upper boundary of the cavity. Disturbances of the lower ionosphere originate from electrodynamic and hydrodynamic processes such as

magnetospheric activity, energetic electron precipitation, gravity waves and tides, lightning and transient luminous events. The interaction between the solar wind and the magnetosphere/ionosphere distorts and modulates the upper boundary of the cavity, modifying the SR spectral signatures, thus making it a good proxy for solar activity-induced geomagnetic storms and space weather [5].

Satellite Measurements: The Vector Electric Field Instrument (VEFI) on the Communications/ Navigation Outage Forecasting System (C/NOFS) satellite detected SR signatures well beyond the upper boundary of the cavity [6]. C/NOFS is a 3-axis stabilized satellite inserted in to a 13° inclination orbit to investigate electrodynamic processes of the equatorial ionosphere. Figure 1 shows typical VEFI measurements of the two components (zonal and meridional, i.e., roughly in the vertical and east-west directions) perpendicular to the geomagnetic field. The lowest five SR peaks are observed at about 7.9, 14.1, 20.6, 26.8, and 32.9 Hz and match those of ground measurements (cf. Table 1).

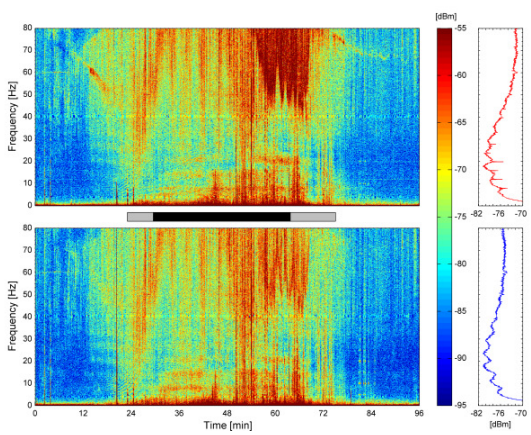

Figure 1: VEFI electric field data recorded on 31 May 2008 during orbit 667 (starts at 16:21:47 UT). (left) Spectrogram and (right) mean spectrum computed all through the orbit. The top and bottom panels refer to the meridional and zonal components, respectively. The fuzzy horizontal stripes better seen during nighttime and the spectral peaks on the right-hand side correspond to SR eigenmodes. The gray and black stripes define nighttime on the ground and satellite eclipse, respectively.

The electric field amplitude of the first mode is about 3 orders of magnitude lower than on the ground. The SR signatures are typically detected by C/NOFS during nighttime and are observed routinely in the altitude range of C/NOFS (perigee and apogee are ~400 and ~850 km, respectively). Additionally, SR signatures are not detected in the component of the electric field parallel to the geomagnetic field; for the perpendicular direction, the electric field amplitude of the zonal (east-west) and meridional (vertical) components is similar.

Planetary Context: Following the discovery of lightning activity on other planets, the excitation of SR in other environments has been conjectured in various planets and moons, from Venus to Neptune, including Titan, Saturn's largest moon (Table 2). The key elements contributing to SR generation are the presence of electromagnetic sources and wave reflection in the ionosphere as well as suitable propagation conditions in the atmosphere. We emphasize a few relevant results but the interested reader can find more details elsewhere (e.g., see review [7]).

Planetary body	Frequency [Hz]	Q-factor
Venus	8-9.5	5-10
Mars	7.5-14	2-4
Jupiter	0.6-0.75	5-10
Saturn	0.75-0.8	3.5-7
Titan	18-22	4-6
Uranus	1-2.5	5-20
Neptune	1.2-2.6	2-16

Table 2: Estimated frequencies and Q-factors of the first eigenmode of planetary cavities [7,8].

The value of SR as a probe for studying planetary electrical properties is evident. For example, the detection of SR signatures in the Martian environment is relevant for investigating dust electrification processes in the atmosphere and the hypothetical global electric circuit [9]. For example, SR measurements would contribute for investigating a key subject of the Mars Atmosphere and Volatile Evolution Mission (MAVEN), which aims the study the causes of Martian atmospheric loss (particluarly H_2O), altering the climate and rendering it inhospitable to life. The observation of SR on Venus could resolve the debate on the presence of significant lightning activity there; detection of lightning remains unclear because whistlers attributed to lightnign discharges have not been confirmed by detection of optical emmissions [10]. On Titan, because ground conductivity is low, ELF waves can propagate below the surface and are useful to constrain the depth of the water-ammonia ocean predicted by theoretical models; the proposed excitation mechanism is also

different than that operating on Earth [11]. In the giant planets, detection of SR spectral features would be useful for inferring the electric conductivity profile [12] and the abundance of volatiles (water, ammonia, and methane) [13]. This would be particularly useful for improving the solar system volatile abundance and constraining thermodynamic parameterization of the protosolar nebula from which the solar system evolved [8]. Establishing a more accurate location of the solar system snow line would be valuable for investigating protoplanetary disk accretion models and the formation and dynamics of planetary bodies. The accurate assessment of the water content in the giant planets could also contribute to the understanding of the formation and dynamics of outer solar system objects, from the Kuiper Belt to the Oort cloud.

SR Connection to Volatiles: The gaseous envelopes of the giant planets are composed primarily of hydrogen and helium. Although progress has been made in the investigation of the atmosphere of the gas giants, mostly via remote sensing techniques, the fraction of volatiles in their gaseous envelopes remains unknown. Since the ionization energy of helium is considerably higher than that of molecular hydrogen (25 vs. 15 eV), 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 increasing the electrical conductivity depending on the distribution and nature of impurities. The ionization energy of water, methane, and ammonia is about 12.6, 12.6, and 10.1 eV, respectively, and provides a direct contribution to conductivity increase. In addition to a stoichiometric contribution, composition also plays indirect roles in conductivity, mainly in the atmosphere, as a consequence of enhancement of aerosol-cloud interactions, electrophilic species chemistry, phase changes, droplet formation, ion attachment, etc. The reaction mechanisms in the environment of giant planets are markedly different from those taking place on Earth. The dielectric properties of water, for example, are remarkably diverse in the solid, liquid, and gas phases and can drive nucleation and clustering, as well as condensation and freezing, thus modifying charged particles mobility and recombination rates. Unlike the Jovian planets where measurements provided some atmospheric composition constraints, the water content uncertainty in the fluid envelopes of Uranus and Neptune is large, implying electric conductivity profiles possibly differing by several orders of magnitude. Conductivity may vary significantly, depending on the water ice mixing ratio in the gaseous envelope (Figure 2).

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, illustrating the extreme sensitivity of ELF wave propagation to conditions within the gaseous envelope water mixing ratio [8, and references therein].

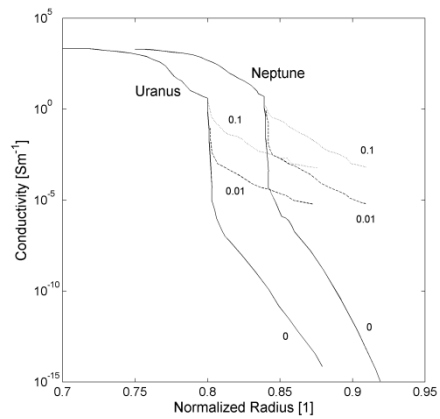

Figure 2: Theoretical conductivity profile of Uranus and Neptune as a function of normalized radius, $\hat{R}$, where $\hat{R}$=1 corresponds to an atmospheric pressure of 1 bar. The solid, dashed, and dotted lines correspond to 0, 0.01, and 0.1 water content, respectively [8].

Space Instrumentation Heritage: Assessment of volatile mixing ratios in the gaseous envelopes of the giant planets may involve in situ and remote sensing techniques. Whereas in-situ measurements are more accurate though less versatile, remote sensing offers recurrent examinations but less accuracy and spatial resolution. On the other hand, direct methods involving spectroscopic techniques are more accurate but possess restricted depth range, e.g., limited to the atmosphere. The indirect method proposed here using SR measurements can be applied to higher depths, possibly hundreds or thousands of kilometers. Direct methods measure the water content directly and indirect methods require subsequent modeling to infer the content of volatiles. We briefly discuss the suitability and the technology readiness level of a few relevant instruments used for atmospheric electricity and water content investigations.

The most accurate way of evaluating the water content in the giant planets is employing in situ techniques for measuring the water mixing ratio in the gaseous envelope. This approach was used by the Galileo Probe Mass Spectrometer (GPMS) during the descent through the atmosphere of Jupiter down to ~20 bar

[14]. Other solutions involve Earth-orbiting observatories or dedicated spacecraft around the planets, e.g., Cassini at Saturn, employing infrared, optical, or ultraviolet spectrometry to infer atmospheric composition [15,16]. The microwave radiometer part of the Juno spacecraft en route to Jupiter may provide accurate water content estimates, possibly down to about 200 bars [17]. Although measurements of the water content in the atmosphere of Jupiter and Saturn have been made by various spacecraft, the generalization to the entire fluid envelope of the two planets is not possible; for example, measurements made by the Galileo Probe in Jupiter's atmosphere found less water than expected [14]. However, it is not clear whether models have to be revised or those in-situ measurements misrepresent the global abundance and cannot be generalized to the entire atmosphere, much less to gaseous envelope.

The Radio and Plasma Wave Science (RPWS) instrument onboard Cassini was developed to investigate Saturn kilometric radiation, lightning, and plasma-related interactions between the ionosphere and magnetosphere of Saturn and its satellites, mainly Titan. The instrument measures low frequency electric and magnetic fields but is not optimized for the ELF range. Three 10 m beryllium-copper tubes and a magnetic search coil are used to measure vector electric and magnetic fields, respectively. The sensitivity of the electric and magnetic field sensors at 10 Hz and 10 kHz is approximately 1 and 0.01 $\mu Vm^{-1}Hz^{-1/2}$ and 1 and 0.05 $pTHz^{-1/2}$ [18]. RPWS cannot measure SR signatures at the present location of Cassini, but attempts to their detection are strongly recommmended when the spacecraft approaches Saturn during the final phase of the mission.

The Permittivity, Wave, and Altimetry (PWA) analyzer, an element of the Huygens Atmospheric Structure Instrument (HASI) flown onboard the Huygens Probe, was designed to measure in-situ the electric properties of the atmosphere and surface of Titan, namely atmospheric conductivity and ground permittivity and low frequency electromagnetic waves [19,20]. PWA consists of six electrodes mounted on two ~0.5 m deployable dielectric booms. For conductivity measurements, the sensitivity of the mutual impedance probe is ~10 pSm^{-1} and that of the two relaxation probes is in the order of 10 and 0.1 pSm^{-1}. The sensitivity of the PWA dipole antenna in the ELF range is about 0.5 $mVm^{-1}Hz^{-1/2}$.

The VEFI package onboard C/NOFS is suited to perform DC and AC electric field measurements. In addition to electric field double probes, VEFI also includes a flux-gate magnetometer, a fixed-bias Langmuir probe, and a lightning detector [21]. The main component of VEFI is the 3-axis electric field sensor that records DC and AC electric fields employing the double probe technique [22]. The instrument includes six 9.5 m booms with 12 cm diameter spherical sensors with embedded pre-amplifiers. The booms are oriented to provide three orthogonal 20 m tip-to-tip double probes. The sensitivity of VEFI in the ELF range is approximately 10 $nVm^{-1}Hz^{-1/2}$ for a nominal sampling of 512 s^{-1}. The estimated accuracy for magnetic field measurements in the ELF range is 0.1 nT for a sampling of 8 s^{-1}.

Rationale and Instrument Requirements: Since remote sensing or in-situ measurements involving spectroscopic techniques may not be representative at a global scale, utilization of SR spectral features offers a complementary approach to estimate the fraction of volatiles in the gas giants. Therefore, we discuss instrumentation relevant for detecting low frequency electromagnetic waves. Table 3 presents the sensitivity and frequency range instrument requirements to perform SR measurements in terrestrial planets and gas giants. Performing both electric and magnetic field measurements contributes to extend our knowledge of atmospheric electricity, e.g., lightning activity, and cavity leakage mechanisms related to ELF electromagnetic wave propagation in the ionosphere. Compared to other techniques, the approach proposed here has the following advantages: (i) it can be performed from orbit or in-situ; (ii) it is sensitive down to depths of hundreds or thousands of kilometers; (iii) it provides global estimates of volatiles; (iv) it is not very sensitive to local heterogeneities induced by weather patterns. The major disadvantage is the fact that since it is an indirect measurement, the interpretation is highly dependent on electric conductivity modeling.

Physical Quantity	Range
Electric field sensitivity	Better than 10 nV m^{-1} $Hz^{-1/2}$
Magnetic field sensitivity	Better than 0.1 pT $Hz^{-1/2}$
Frequency range	0-100 Hz for terrestrial planets
	0-10 Hz for giant planets
Frequency resolution	0.1 Hz for terrestrial planets
	0.01 Hz for giant planets
Amplitude resolution	16 bits

Table 3: Instrument requirements for SR measurements in planetary environments.

Remote sensing and in-situ techniques used on Earth to investigate SR patterns can be adapted to other

planets, onboard orbiters, landers, balloons, blimps, and descent probes. Platforms aiming at performing in-situ measurements also allow for assessment of the electrical conductivity in the cavity, providing additional data to constrain the conductivity profile locally. The Huygens Probe is a good example where wave and particle measurements were combined in the cavity of Titan. In addition to constraining the water content in the gaseous envelopes, combination of wave and particle measurements may also contribute to addressing a variety of subjects related to atmospheric electricity, aeronomy, and weather patterns. Several phenomena related to propagation of Alfvén waves, e.g., ionospheric Alfvén resonator and geomagnetic pulsations, also fall in the frequency range used to investigate SR spectral features.

Summary: Detection of SR from orbit offers new remote sensing capabilities to investigate atmospheric electricity on Earth; it serves as proof of concept for planetary environments as well. A link between the water mixing ratio and atmospheric conductivity makes SR a suitable tool to assess volatile abundance of the outer planets. The best set of electromagnetic sensors currently available for investigating SR in the outer planets would combine the 3-axial VEFI dual probe and the RPWS magnetic search coil for electric and magnetic field measurements, respectively. Although improvements are necessary, these sensors present high technology readiness level and offer a practical solution to start with, both for remote sensing and in-situ measurements. These sensors would also be valuable for investigating atmospheric electricity in the outer planets. The same set of sensors is useful to confirm previous claims of detection of SR on Mars and Titan, and reconcile the dispute about lightning activity on Venus. Most significantly, these sensors are invaluable for assessing the electric conductivity profiles of the gaseous envelopes of the giant planets and, indirectly, for constraining the fraction of volatiles, namely water, in those environments. This specific set of electromagnetic sensors is pertinent to bring together several fields of research, from Earth's tropospheric and space weather connections to planetary atmospheric electricity, heliophysics sciences, and astronomy and astrophysics.

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