INVESTIGATING THE INTERIORS OF SMALL BODIES AND OCEAN WORLDS WITH SPACECRAFT SWARMS AND SCHUMANN RESONANCES T. Marshall Eubanks[1], Charles F. Radley[2], [2]Asteroid Initiatives LLC, Clifton, VA 20124 USA; [2]Leeward Space Foundation, Palm Bay, Florida 32907 USA; tme@asteroidinitiatives.com;

Introduction: A Schumann Resonance is an electromagnetic oscillation excited in a closed waveguide formed by multiple reflecting layers at or near the surface or interior of a planetary body. The waveguide, for spherical bodies with uniform reflecting layers, is a resonant cavity with a fundamental wavelength $\sim$ the circumference of the body. The terrestrial Schumann Resonance, predicted by W.O. Schumann in 1952 [1], is formed by the cavity between the ionosphere and the surface of the Earth, with a fundamental frequency $\sim$7 Hz and the resonance primarily being excited by lightning. A Schumann Resonance was detected on Titan at $\sim$36 Hz by the *Huygens* probe [2], with the resonant cavity being formed by Titan's and subsurface ocean and the excitation thought to result from currents in the ionosphere induced by the advected Saturnian magnetic field [3]. The same mechanisms should apply to Europa, leading to a prediction of a Schumann resonance between near-surface charged particles and the subsurface ocean which can be used to explore the subsurface of that ocean world. Similar considerations lead to the possibility of full-body Schumann-type resonances on small bodies (asteroids and comets), with the reflecting layer being provided by photo-disassociated electrons at the surface. Such resonances and reflecting layers could be used by small spacecraft swarms on small bodies, allowing a new means of investigation of the interior of these bodies and also of communication between landers not within the line of sight on the surface.

Schumann Resonances on Ocean Worlds: The eigenfrequencies, f_n, of a homogenous non-conducting cavity of a radius R and thickness d are given by

$$f_n = \frac{c}{2\pi\, R} \sqrt{n(n\ +\ 1)\, \frac{1 - \frac{d}{R}}{\epsilon_r}} \qquad (1)$$

where c is the speed of light in a vacuum and ϵ_r is the relative permittivity of the material in the waveguide. Equation 1 assumes that the ice has negligible conductivity; brine inclusions could cause an effective conductivity in the shell and thus give the eigenfrequencies complex components. For the Earth, observations reveal a complicated modal structure with many excited eigenfrequencies, while for Titan only the f_2 mode, at a frequency $\sim$36 Hz, was detected in the *Huygens* data.

An ocean world in orbit about a gas giant should have charged particles at either its surface or at the top of its atmosphere and thus should be able to support Schumann resonances if the plasma frequency, f_p, of the surrounding plasma is $>$ the Schumann resonance frequency. As even the free electron density of the solar wind corresponds to $f_p > 10$ kHz, orders of magnitude larger than the predicted ocean world resonance frequencies, Schumann resonances should be common in the ocean worlds in the outer solar system.

Schumann Resonances on Europa: Observations by the *Galileo* spacecraft reveal that Europa has a charged particle ionosphere, with particle densities being as high as 10^4 cm^{-3}. This density is comparable to the densities observed in the ionosphere of Titan, but in the case of Europa this plasma is present immediately above the surface due to the lack of any significant neutral particle Europan atmosphere. A Schumann Resonance should thus exist on Europa, with the resonant cavity consisting of the ice between the ionosphere and the surface of the buried ocean, and the excitation arising from currents induced by changes in the Jovian magnetic field.

The Europan Schumann Resonance should thus be detectable by European landers with the appropriate radio receivers. For Europa, with a total radius of 1560.8 km, if the ice shell is assumed to be pure ice with a 30 km thickness and $\epsilon_r \sim$3.15 , f_n would be $\sim$ 24, 42 and 59 Hz for n = 1, 2 and 3, respectively. Observations of the Schumann Resonance could be used, as for Titan, to determine the thickness, effective permittivity and conductivity of the ice shell of the moon and confirm the existence of its buried ocean. On the Earth, interferometric observation of the Schumann resonances from multiple sites is used to locate the excitation of the resonance [4]. Regional variations in these properties should cause mode splitting and broadening of modal frequencies on Europa. A network of small femtospacecraft with simple dipole receivers deployed on Europa could thus provide information on the variations in the depth and dielectric properties of the ice shell surrounding the ocean, complementing the return from a single lander.

Ionospheres on Small Bodies: Some comets and small asteroids may also support Schumann resonance type radio responses. Small body normal mode frequencies will not follow Equation 1, as radio waves with sufficiently low frequencies can pass entirely through small dielectric bodies, as was demonstrated at 90 MHz by the CONSERT bistatic radar experiment conducted by Rosetta and its lander Philae [5]. Small dielectric bodies should be able to support full-body resonances, as was also anticipated by Schumann [1]. A spherical small body would have vector spherical harmonic normal modes with fundamental frequencies of order c / (R

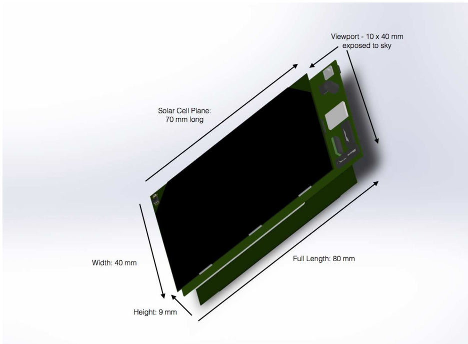

Figure 1: The Asteroid Initiatives Pixie Femtospacecraft (without insulation).

$\sqrt{\epsilon_r}$), or ∼60 kHz for a 500 meter body with the dielectric properties of Vesta [6]. While small bodies in the solar system are rarely spherical, this can be taken as a rough approximation of the possible resonance frequencies if an outer reflecting layer is available from nearby charged particles.

A combination of numerical modeling [7, 8] and *in situ* observations [9] have substantially improved the knowledge of the near-surface charging environment for small bodies. [7] simulated the charged particle environment around a 200 m long asteroid and found two primary processes dominated its charging; solar radiation energizes a large number of photoelectrons in the sunlit regions, causing a positive surface charge and a small Debye length, while shaded regions collect electrons from the solar wind, causing negative charging with a larger Debye length. At the sunlit surface, the simulated photoelectron density can be 10^8 e^- m^{-3}, which corresponds to a plasma frequency ∼90 kHz, while the shaded regions will have much lower plasma frequencies, comparable to that of the solar wind, or ∼30 kHz at a distance of 1 AU from the Sun.

Dielectric bodies with effective radii $\gtrsim$ 6 km (r / 1 AU)^2, with r being the distance from the Sun, are thus candidates for full body Schumann-type resonances, with the trapped solar wind providing a reflecting layer on the night-side. These resonances could be excited by a transmitter located on a single lander, providing a news means of exploring the small body interiors.

The Pixie Femtospacecraft: In order to meet the requirements of operation in deep space and to create true spacecraft swarms to meet various operational goals Asteroid Initiatives developed the Pixie femtospacecraft (see Figure 1). A Pixie is 80 x 40 x 9 mm with a mass $<$ 50 grams, includes a battery and a variety of instruments, and is intended to operated in a swarm with other spacecraft nodes (Pixies or otherwise) within communication range. The current Pixie design was intended to carry a number of different instruments to the surface of a small Near-Earth asteroid and was developed for deployment on the secondary body of the Didymos system (the “Didymoon”), first as part of the now-canceled Asteroid Impact Mission (AIM) [10], and then as a possible stand-alone mission in support of the DART impactor [11].

Although there are probably not strong sources of excitations at frequencies near 100 kHz, the ”day-side ionosphere” - the reflecting layers of photoelectrons present within a meter or so of sunlit regions - could with suitable transmitters be used by swarms small spacecraft to explore the interiors of these bodies, either through bistatic radar between a swarm of receivers and one or more transmitters, or by a single spacecraft reflecting a 50 - 100 kHz signal from a sunlit region on the opposite site of the body. As software radios for frequencies around 100 kHz can be made very small and low-mass, this technique lends itself to use by a femtospacecraft swarm deployed on a small body.

In order to operate as a single unit spacecraft swarms must be able to perform clock synchronization and coordinated data collection and distribution, and in many cases may need to perform internal swarm positioning as well. Even assuming the presence of orbiting relays these requirements are difficult for swarms deployed on small bodies, where lines of site can be irregular and short. The ability to transmit *through* the body and use reflecting layers to bounce a communications signal to every member of a landed spacecraft swarm would greatly enhance distributed sensor networks on small bodies. For a body such as the Diddymoon, 100 mW transmitters at 50 kHz with small antennas and software radios should make it possible to provide 10 kbps communications between node members in either a multicast or unicast fashion. Use of these photoelectron ionospheres on a small body mission would provide a major advance in the technical capabilities of small swarm spacecraft such as the Pixies.

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