SEARCHING FOR SUBSURFACE OCEANS ON THE MOONS OF URANUS USING MAGNETIC INDUCTION. B. P. Weiss, J. B. Biersteker[1], V. Colicci[1], A. Couch[1], A. Petropoulos[2], T. Balint[2], [1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge MA, USA [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA.

Introduction: Some of the most common potentially habitable environments in the solar system may be those of ocean worlds, planetary bodies with large-scale subsurface bodies of liquid water [1]. In particular, subsurface oceans have been confidently identified amongst the icy moons of Jupiter and Saturn and perhaps beyond. The icy moons of the ice giants are likely to be next major targets of Discovery, New Frontiers or flagship-class missions [e.g., 2, 3]. Here we explore the possibility of detecting and characterizing subsurface oceans among the 27 moons in the Uranus system using spacecraft magnetometry measurements from flybys and orbiters. We consider the approach of magnetic induction whereby a spacecraft magnetometer senses magnetic fields from electrical currents in the oceans generated by Uranus's time-varying magnetic field. Our goal is to assess whether a spacecraft magnetometry investigation could detect and even characterize subsurface oceans on the moons of Uranus.

Major Moons: We focus on the five major moons: Miranda, Ariel, Umbriel, Titania, and Oberon. The surfaces of all of these bodies, with the possible exception of Oberon, show geomorphological evidence for resurfacing following accretion in the form of possible diapiric coronae, grabens, and cryovolcanism [4]. The ages of these surfaces are uncertain but could be as young as 0.1-0.4 billion years (Ga) for Ariel and Miranda [5]. The heat for these endogenic processes may have been supplied by the gravitational energy of formation, radiogenic elements, and/or tides [6]. Although the major moons are not currently in mutual resonances, they are thought to have previously passed through one or more low-order mean motion resonances [7-9]. As such, it is conceivable that one or more of the major moons harbors a subsurface ocean today.

Driving Field: We employ the classic technique of magnetic induction to search for conducting subsurface saltwater oceans [10, 11]. Time-varying fields inside a conducting body generate currents by Faraday's law of induction. These currents in turn generate a secondary magnetic field by Ampere's Law that can be sensed by a magnetometer.

Uranus's magnetic field is well described by a dipole offset by ~0.3 of Uranus's radius along the spin axis toward the north pole and tilted by 59° [12]. The wobbling of this dipole due to the 17.2 h rotation period of Uranus, combined with amplitude modulation due to the ~33.6-323 h period orbital motions of the moons and from higher order multipole contributions to the field,

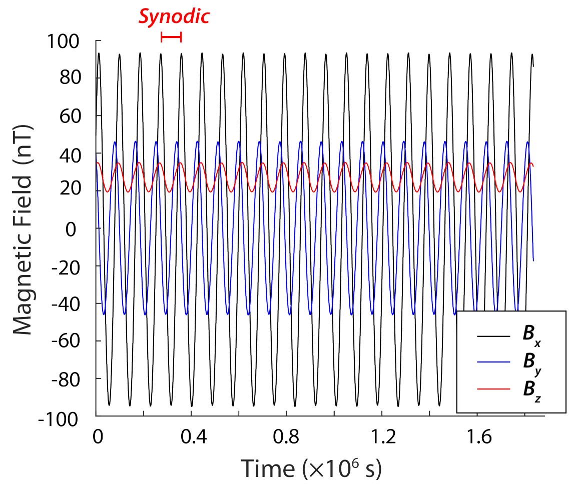

Fig. 1. Uranus's time variable magnetic field as experienced by Miranda. Shown are the intensities of three field components, where the *x* points toward Uranus, *y* points opposite the orbital velocity of the moon, and *z* completes the triad. The 24 h synodic period is labeled.

collectively produce time variable fields in the reference frames and locations of the moons (Fig. 1). In particular, using the internal hexadecapole AH5 magnetic field model from Voyager 2 data [13], we find that the dominant frequency at the major moons is the synodic frequency (i.e., time required for a moon to return to the same longitude above Uranus's surface). The periods and amplitudes of the synodic fields range from ~35 h and ~330 nT at the innermost major moon Miranda to ~18 h and ~3.6 nT at the outermost moon, Oberon. These frequencies have skin depths of ~80-100 km for oceans with conductivities like that of terrestrial seawater (~2.8 S m^{-1}). Furthermore, the major moons experience a rich range of other driving frequencies at harmonics of the synodic frequency, their orbital frequencies, beating between the synodic and orbital frequencies, and harmonics of these frequencies (Fig 2).

Induced Field: These driving fields can be used to probe for subsurface oceans as part of two major stages of exploration. First, detection of induced fields from a small number of close (i.e., <1 moon radius) flybys could identify the existence of an ocean by measuring the induction response at a single frequency. However, degeneracies between the ocean thickness, ice thickness, and ocean conductivity make it challenging to determine these parameters separately from single-frequency sounding. This is what the Galileo mission achieved for Europa [11]. Second, repeated, long-term

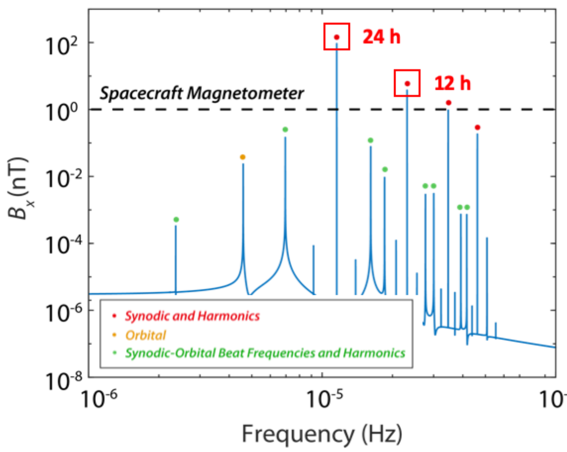

Fig. 2. Periodogram of the *x*-component of Uranus's magnetic field as experienced by Miranda. There is a rich spectrum of frequencies including the synodic and its harmonics (red), Miranda's orbital frequency (orange), beats between the synodic and orbital frequency and harmonics of these beats (green). Red boxes denote synodic frequency (24 h) and its second harmonic (12 h).

(e.g., lasting for tens of moon orbital periods or more) field measurements at a given moon could enable multi-frequency sounding (Fig. 2). For sufficiently thick and conductive oceans, these data could enable separate determination of the ocean thickness, ice thickness, and ocean conductivity. This is the goal of the Europa Clipper mission [14].

To assess these possibilities, we calculated the induced field at each moon assuming a spherically symmetric body with a nonconducting rocky interior overlain by conducting ocean and capped with a nonconducting ice shell [e.g., 11]. For a single flyby within <0.7 moon radii of the surface, we find that if these bodies contain oceans with sufficient depths (≳10-100 km) and conductivities (greater than or equal to that of Earth's oceans), the induced surface fields should have amplitudes exceeding the typical ~1 nT sensitivity of spacecraft magnetometry investigations (Fig. 3). A trajectory developed for a flagship-class mission to Uranus involves several such flybys for each of the moons [2]. We also find that multi-frequency sounding of at least Ariel and possibly also Miranda may enable separate determination of ocean thickness, ice thickness and ocean conductivity for conductivities > 1-10 S m^{-1} and ocean thicknesses > 20-100 km. This could be enabled by multiple (≳ 10-20) flybys of each moon and/or dedicated moon orbiters or landers.

Conclusions: The multipolar, nonaxially symmetric magnetic field of Uranus could produce substantial induced magnetic fields in subsurface oceans of the five major moons that could be detected by a close flyby of a typical spacecraft magnetometry experiment. As such,

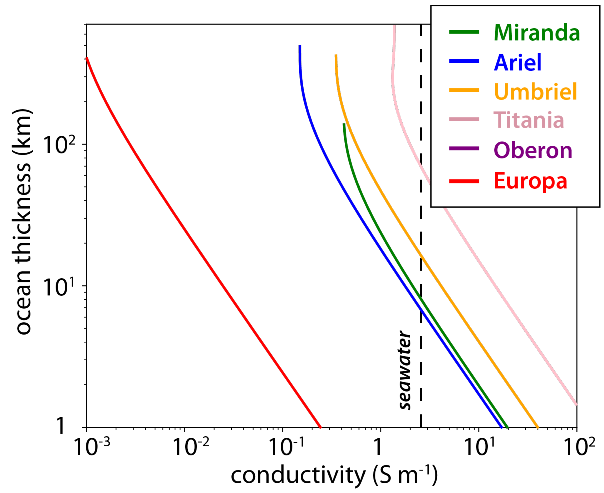

Fig. 3. Detection thresholds for oceans on icy moons. Curves denote the combinations of ocean thickness and conductivity for producing an induced field of amplitude 1 nT at 1.7 moon radii above the pole of the induced dipole from the surface of each of the five major moons of Uranus (green, blue, orange, pink and purple) and Europa (red). These models assume an ice thickness of 1 km. Dashed black line denotes the conductivity of seawater. For this conductivity, minimum ocean thicknesses of ~6-80 km would be detectable by a flyby at this altitude.

searching for subsurface oceans on the major moons using magnetic induction should be a key science objective of future Uranus missions. The central payload element for enabling this is a magnetometer, but an instrument for measuring plasma density and velocity would also be valuable.

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