

WIND, WAVES, AND MAGIC ISLANDS AT TITAN'S LARGEST SEA: KRAKEN MARE A. G. Hayes¹, J. M. Soderblom², J.W. Barnes³, J. D. Hofgartner⁴, V. Poggiali¹, M. Mastrogiuseppe⁵. ¹Cornell University, Ithaca NY 14853, ²Massachusetts Institute of Technology, Cambridge MA 02139, ³University of Idaho, Moscow ID 83844, ⁴Jet Propulsion Laboratory, Pasadena CA 91109, ⁵Sapienza University of Rome, 00185 Roma, Italy

Introduction: For the majority of the Cassini Mission, Titan's hydrocarbon lakes and seas were observed to be quiescent and remarkably calm, with vertical deviations of less than a millimeter[1,2,3,4,5]. This lack of observable surface roughness has been attributed to a seasonal effect in which polar winds were too weak to create waves or other dynamic features[6]. As northern spring approached, the previous series of non-detections began to give way to indications of potential activity. Specifically, apparent sunglints offset from the geometric specular points were observed in several lakes and seas[7] and a transient bright radar signature, known as Titan's Magic Island, was observed to both appear and disappear over the surface of Ligeia Mare[8,9]. Herein, we report the observation of a new Magic Island (Fig. 1), in addition to an isolated patch of transient surface roughness (Fig. 2/3), observed within Titan's largest sea Kraken Mare. The data were acquired during flyby T104 (08/21/2014) and included nearly coincident observations by the radar and Visual and Infrared Mapping Spectrometer VIMS).

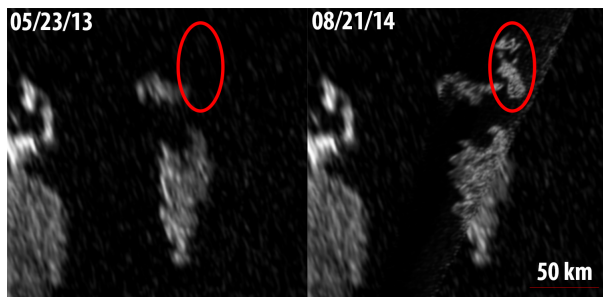


Figure 1: SAR data acquired in May 2013 (HiSAR) and August 2014 (strip) over Kraken Mare showing the Kraken Magic Island (right). The red circle depicts an area of anomalous backscatter observed during the T104 flyby that is similar in morphology and size to the Ligeia Magic Island.

Kraken Magic Island: The primary objective of the T104 flyby was a radar altimetry observation over Kraken Mare in order to look for surface activity and measure the depth of the sea. While shallow (~30 m) bottom detections were observed over Moray Sinus, the majority of Kraken was too deep to detect the seafloor[10,11]. During the observation, the radar was cycled between the nadir beam and two adjacent beams with incidence angles of 3–5°. These off-nadir beams were processed into a Synthetic Aperture Radar (SAR) strip that revealed transient bright features similar to the Magic Island observed at Ligeia Mare (Fig. 1)[8,9]. These features have been dubbed the Kraken Magic Island and are located in an area that was previous observed to be quiescent sea. The Kraken Magic Island has an average backscatter (σ_0) of 3.6 ± 1.7 dB at 5.3° incidence. The nearby physical island has an average σ_0 of -1.2 ± 2.9 dB at 5.1° and the surrounding sea has an average 5° incidence σ_0 of -15.4 ± 2.9 dB, which is well below the noise-equivalent σ_0 of -11.5 dB and consistent with no detectable signal.

In a fortuitous circumstance, VIMS spectra of Kraken Mare were collected ~2 hours after the radar swath during a ride-along observation. Furthermore, the geometric specular point (location of the specular reflection of the Sun from a flat surface on Titan as viewed by Cassini) was located within the sea, and only $\sim 0.5^\circ$ (as viewed by Cassini) from the Kraken Magic Island. At the position of the Kraken Magic Island, an anomalous 5- μ m bright signal was detected that is

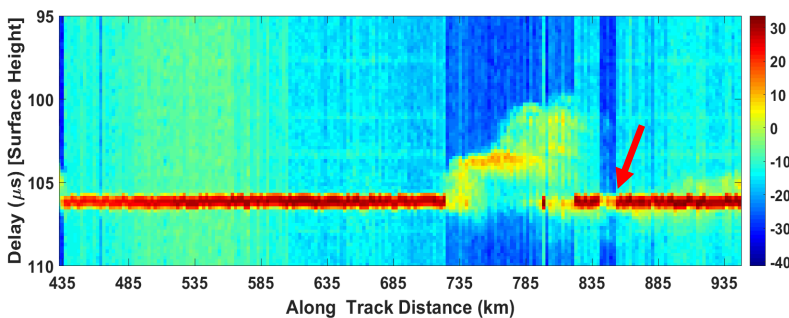


Figure 3: Radargram (position vs. time delay / height, colored by returned reflection strength) of a portion of the T104 altimetry pass over Kraken Mare. The red arrow depicts the location of an anomalous 20 dB reduction in backscatter. Note that the anomalous return occurs at the same elevation as the sea, while the physical land from 725–820 km shows returns from elevations above the sea surface Color represents returned backscatter intensity in dB..

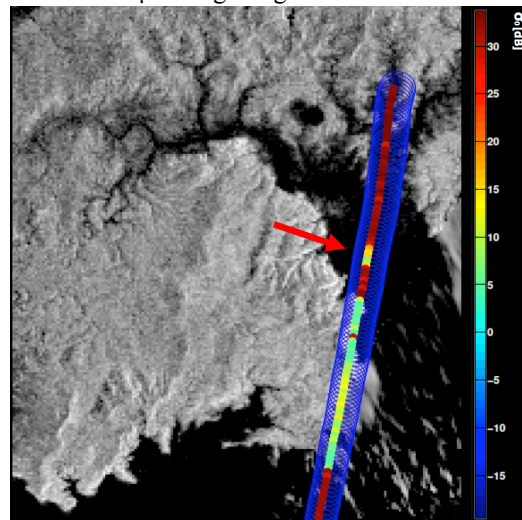


Figure 2: Position and reflection strength of a portion of the T104 altimetry pass over Moray Sinus in Kraken Mare. The red arrow depicts the location of a 20 dB drop in backscatter over the liquid surface.

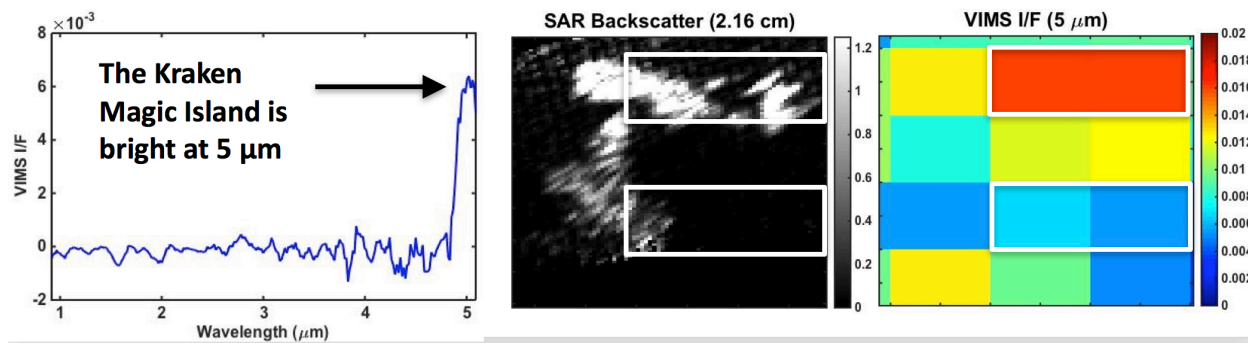


Figure 4: VIMS I/F spectrum (left) of the Kraken Magic Island. The region shows a bright return at 5- μ m in VIMS pixels that overlap the transiently bright radar feature (middle). Compared to its surroundings, the feature is also bright in VIMS (right).

consistent with offset sunglints and similar to previous observations at Punga Mare that were interpreted as wind-waves (Fig 4)[7]. The co-detection of the Kraken Magic Island in both radar and VIMS can constrain formation hypotheses. Hypotheses consistent with the Ligeia Magic Island include waves, floating solids, suspended solids, and bubbles[8,9]. VIMS would not see suspended solids. Floating solids would require micron-smooth facets in a specular orientation, although the Kraken Magic Island (at 5° inc.) is 3X brighter in radar than the nearby non-transient islands (perhaps wet surfaces?). Solids would also need to refrain from disbursing over the 2 hours between observations. While detail models are still being developed, preliminary analysis suggests that bubbles would struggle to produce the observed brightness in both the microwave (requiring bubbles in a liquid column) and infrared (coming from surface bubbles only). Bubbles would also need to persist between observations. Therefore, we prefer waves (liquid surface roughness) as the best explanation for the Kraken Magic Island.

When VIMS observes a specular reflection, or sunglint, offset from the geometric specular point, the intensity reflects the fraction of the surface that is oriented in a particular direction (incidence \pm the VIMS IFOV/2) relative to the surface normal[see 12]. This quantity is known as the specular area fraction (SAF) and, if the roughness is the result of wind-waves, can be compared to the output of wave models to constrain surface winds[see 6,7]. The SAF required to produce the VIMS returns from the Kraken Magic Island is 5×10^{-8} . Using the Universal Wave and Stress Model (UNIWSM)[13], appropriately adapted for the Titan environment[see 6,10], an SAF of 5×10^{-8} at an offset of 0.5° corresponds to a wind speed of 0.4–1.0 m/s over methane-dominated liquids, depending on the azimuth of the wind vector relative to the VIMS boresight.

Isolated Rough Patch: In addition to the Kraken Magic Island, a region of anomalous roughness was detected in the T104 nadir-pointed altimetry dataset (Fig 2). When observed in altimetry mode, smooth hydrocarbon liquid surfaces produce strong specular reflections of ~ 30 dB. While traversing the liquid surface in Moray Sinus, however, several footprints returned

nadir reflections of ~ 10 dB, suggesting a significant roughness compared to adjacent 30 dB reflections (footprints are all offshore and SAR images show no evidence for islands). The reduced intensity returns came from the same elevation as the sea and are not consistent with reflections from the elevated topography of nearby dry land (see Fig. 3). Doppler spectra of the anomalous returns have larger pulse width, consistent with increased small-scale surface roughness.

Assuming returns adjacent to the anomalous patch are from a perfectly flat surface, a minimum roughness for can be derived using a coherent scattering model (i.e., physical optics: $\sigma \propto \exp[-4k^2\sigma_h^2]$, where k is the wavenumber and σ_h is the RMS surface roughness). For a 20 dB drop in signal, this corresponds to a minimum surface roughness of 3.7 mm. An RMS roughness of > 3.7 mm corresponds to wave fields driven by > 0.5 m/s winds over methane-dominated liquids using the UNIWSM-Titan wave model[6,13]. Similar to winds that could drive wave fields consistent with the VIMS brightness of the Kraken Magic Island, these wind speeds are close to the predicted threshold for wave generation[5].

Summary: The T104 observation of Kraken Mare has revealed a transient bright feature, known as the Kraken Magic Island. Unlike the Ligeia Magic Island, the Kraken feature was observed by VIMS within 2 hours of the radar observation. In addition, a ~ 10 km patch of liquid in Moray Sinus was rough during the observation. Both the rough patch and the Kraken Magic Island are consistent with wind-waves generated by 0.4–1.0 m/s winds. These features demonstrate the dynamic nature of Titan's methane-based hydrologic cycle and may mark the beginning of a more active summer season for Titan's northern lakes and seas.

References: [1] Barnes et al. (2011) *Icarus* 211 [2] Stephan et al. (2010) *GRL* 37 [3] Wye et al. (2009) *GRL* 36 [4] Zebker et al. (2014) *GRL* 41, [5] Grima et al. (2017) *EPSL* [6] Hayes et al. (2013) *Icarus* 225 [7] Barnes et al. (2014) *Plan. Sci.* 3 [8] Hofgartner et al. (2014) *Nat Geo* 7 [9] Hofgartner et al. (2016) *Icarus* 271 [10] Hayes (2016) *AREPS* [11] Mastrogioseppe et al. (2018) *Icarus* 300 [12] Soderblom et al. (2012) *Icarus* 220 [13] Donelan et al. (2012) *JGR* 114.