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Probing Pluto's underworld: Ice temperatures from microwave radiometry decoupled from surface conditions

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A B S T R A C T

Present models admit a wide range of 2015 surface conditions at Pluto and Charon, where the atmospheric pressure may undergo dramatic seasonal variation and for which measurements are imminent from the New Horizons mission. One anticipated observation is the microwave brightness temperature, heretofore anticipated as indicating surface conditions relevant to surface–atmosphere equilibrium. However, drawing on recent experience with Cassini observations at Iapetus and Titan, we call attention to the large electrical skin depth of outer Solar System materials such as methane, nitrogen or water ice, such that this observation may indicate temperatures averaged over depths of several or tens of meters beneath the surface. Using a seasonally-forced thermal model to determine microwave emission we predict that the southern hemisphere observations (in polar night) of New Horizons in July 2015 will suggest effective temperatures of ~40 K, reflecting deep heat buried over the last century of summer, even if the atmospheric pressure suggests that the surface nitrogen frost point may be much lower.

1. Introduction

Pluto is an object of great topical interest, the largest known Kuiper belt object, and one possessing a massive satellite, Charon. Pluto furthermore has an atmosphere thick enough to be detectable by stellar occultation methods, and one that undergoes significant seasonal change due to Pluto's eccentric orbit and high obliquity. These changes probably cause dramatic variation in surface pressure (see e.g. Spencer et al., 1997; Hansen and Paige, 1996; Young, 2013) and redistribution of surface frosts. Dramatic progress in understanding Pluto and its seasonal changes is expected imminently with the encounter of the New Horizons spacecraft which will measure the atmospheric density profile by several means, image the distribution of surface materials, and measure the microwave brightness temperature of the surface with the high-gain antenna of the Radio Science Experiment.

Interpretation of this latter measurement requires some care, however, in that its circumstances are rather unusual compared with the more familiar terrestrial planet applications of passive microwave remote sensing, in that Pluto surface materials and the seasonal cycle may mean that the measured brightness temperature is not directly relevant for surface–atmosphere equilibrium. In this paper we briefly introduce the dielectric properties of likely Pluto materials, describe the New Horizons Radio Science observation, and use a thermal model to evaluate the seasonal evolution of subsurface temperatures. We then deduce the likely measured effective temperature and discuss its difference with respect to the surface temperature.

2. Dielectric and thermal properties of outer Solar System materials

It is not the purpose of this note to comprehensively review cryogenic ice dielectric properties, but merely to argue that Pluto/Charon surface materials have a reasonable chance of allowing significant microwave penetration (meters to hundreds of meters).

Most microwave remote sensing experience is on terrestrial bodies (e.g., the Moon) whose composition is dominated by silicates, and whose dielectric properties are strongly affected by the presence of even small amounts of liquid water and/or iron oxides (Keihm et al., 1973). Dielectric properties are commonly defined by the dielectric constant and the loss tangent, the latter being representative of the absorption of electromagnetic waves in the considered medium. Unit optical depth in such materials

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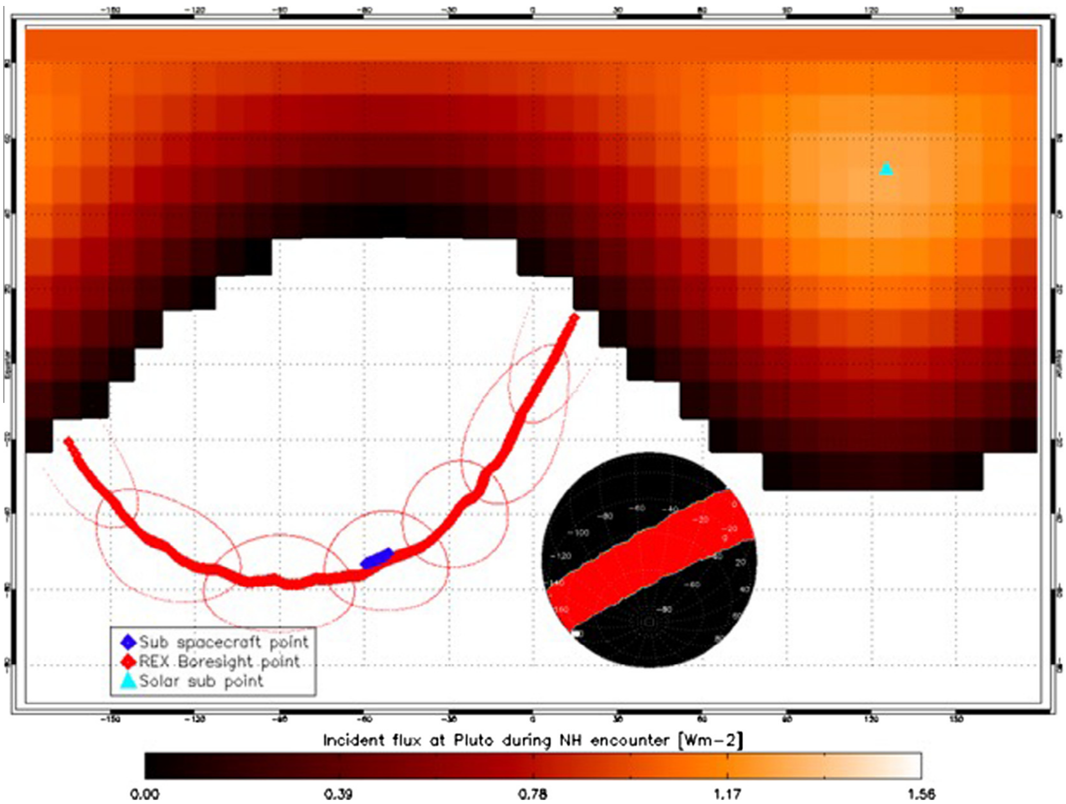

Fig. 1. REX configuration and geometry of observation during NH (New Horizons) encounter of Pluto. Color background is the illumination conditions during the Earth occultation (incident solar flux). The sub-spacecraft, sub-solar and REX beam center points during the REX experiment (between 12h42 UTC and 13h12 UTC) are also shown. An example of the beam size projection at surface is shown on the bottom right thumbnail. Quasi-elliptical shapes represent the beam footprint on the surface every 2 min. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(with loss tangents of ~0.01–0.10 at microwave frequencies) is typically attained within 1–10 wavelengths (thus, centimeters to decimeters) below the surface. However, very cold water ice is much more transparent than rocks or minerals, and the condensed phases of nonpolar materials such as methane and nitrogen have similarly low losses, with loss tangents of the order of 10^{-4} or less (usually only upper limits can be given, as laboratory measurements are challenged to detect losses smaller than this). Cold ice, such as that which forms the bulk of the martian polar cap, can be probed to depths of several km, corresponding to ~100 times the wavelengths of the sounding radars on Mars orbiters (e.g., Plaut et al., 2007).

The most striking demonstration of the microwave transparency of outer Solar System materials (in this instance, condensed methane) is the detection by the Cassini RADAR of a bottom echo at Titan's sea Ligeia Mare (Mastrogiuseppe et al., 2014), the Ku-band signal (2.2 cm) having passed twice through a 160 m column of liquid, i.e. a path of some ten thousand wavelengths. Even impure water ice is somewhat transparent at outer Solar System temperatures: we recently reported (Le Gall et al., 2014) a Cassini observation of Iapetus wherein the electrical skin depth was inferred to be of the order of a few meters, deeper than the diurnal thermal skin depth, such that the seasonal temperature signal was detected.

The X-band (7.8 GHz, 4.2 cm) signal used by the New Horizons Radio Science Experiment, REX, has double the wavelength, and thus crudely twice the penetrating power in water ice, of Cassini Radiometer instrument. Methane and nitrogen ices are also obvious candidate surface materials for Pluto and Charon. Solid methane may be expected to have a similar lack of radio absorption as the liquid (although notionally solid ices could admit more internal scattering at fracture surfaces or grain boundaries). Nitrogen similarly lacks molecular absorptions in the microwave – after all, X-band microwaves are used for spacecraft communication precisely because they are not appreciably attenuated by our 'ocean of air', a column equivalent to 10 m of condensed nitrogen.

Relatively little laboratory data exists on the dielectric properties of materials at Pluto temperatures, although Mathes (1967) reports a loss tangent of nitrogen at its freezing point of 10^{-6} (at 10 kHz). Although the absolute value should not be trusted since such low absorption is difficult to quantify accurately, the qualitative point that solid nitrogen is a low-loss material holds. Thus it seems prudent to consider the implications for such transparent materials on planned Pluto observations at large wavelengths, especially the one performed with the REX experiment onboard the New Horizons spacecraft.

3. New Horizons Radio Science Experiment and expectations

The New Horizons spacecraft was launched in 2006 and is expected to reach Pluto dwarf planet in July 14, 2015. During the

Table 1
Orbital and rotational parameters of Pluto.

Orbital period	247.94 years
Sidereal spin period	6 d 9 h 17 m 36 sec
Excentricity	0.24897
Perihelion	29.656 AU
Aphelion	49.319 AU
Semi-major axis	39.487 AU
Orbit inclination	17.1405 deg
Axial tilt w.r.t. orbit	119.591 deg
Sub-solar latitude in July 2015	51.55 deg