**OBSERVATIONS OF PLUTO'S SURFACE WITH ALMA.** B. J. Butler[1], W. M. Grundy[2], M. A. Gurwell[3], E. Lellouch[4], R. Moreno[4], A. Moullet[5], and L. A. Young[6], [1]National Radio Astronomy Observatory, [2]Lowell Observatory, [3]Harvard-Smithsonian Center for Astrophysics, [4]Observatoire de Paris, [5]SOFIA, [6]SWRI.

**Introduction:** The New Horizons spacecraft flyby of the Pluto/Charon system has revolutionized our knowledge of the dwarf planet and its largest satellite. Pluto's surface varies regionally; some areas appear to be composed primarily of a substrate of non-volatile $H_2O$, others may have a deep overlying deposit of higher hydrocarbons or reddish materials, still others have a veneer of volatile $N_2$, $CH_4$ and CO ices or frosts that may be kilometers deep in specific areas [1-5]. It is clear that the distribution of volatile ices on the surface is influenced by a combination of season (including heliocentric distance), latitude, height and slope, albedo, and thermal properties of the materials, and is intimately involved in the complex geology of the surface.

Recently developed volatile transport models include the thermal inertia, albedos and emissivities of the volatile component and substrate [6-8]. With one set of parameters, they predict the evolution of Pluto's surface appearance and pressure over a full orbit. Comparison with the limited available pre-flyby data, which notably indicate a factor-of-3 pressure increase over the last 25 years, generally favored models with high substrate thermal inertia and a permanent $N_2$ ice cap at Pluto's north pole [9]. However, other models, including one with lower thermal inertia and a smaller volatile inventory, and one with even smaller volatile inventory involving atmospheric collapse, could not be ruled out. Alternate models may explain the lack of $N_2$ at the pole, using Sputnik Planum as a source region [8,10]. Revision of these volatile transport models is underway, but even with all of the information from New Horizons, some parameters in the model are poorly constrained; namely the global subsurface thermal properties. These properties can be determined from Earth-based observations at long (sub-millimeter and longer) wavelengths, if such observations have sufficient resolution. The Atacama Large Millimeter Array (ALMA) telescope provides the requisite resolution (< 0.1 asec).

**New Horizons Thermal Observations:** While the New Horizons flyby has provided amazing data on both Pluto and Charon, surface and subsurface temperature measurements were much more limited. The whole-disk 4.2 cm brightness temperature was measured for both the dayside and nightside of Pluto and Charon on approach and departure, and a few scans across Pluto (both dayside and nightside) were obtained by the Radio Science EXperiment (REX) [11]. At these centimeter wavelengths, because of the low loss tangent of the ices comprising the surface of both Pluto and Charon, measurements from REX likely sample down to a depth > 1 m, making determination of surface temperatures from the data difficult [12]. The $N_2$ ice temperature – expected to be uniform over Pluto due to latent heat exchanges – can be determined from the shape of the 2.15 $\mu$m feature [13] but temperatures of the other ices are poorly constrained. In addition, these measurements are a sample at a single time, in an evolving system; continued Earth-based thermal observations of Pluto and Charon are needed, and shorter wavelengths are preferred as they provide surface temperatures more directly. The ability to resolve not only the two bodies from each other, but each of them individually, is critical in understanding the volatile inventory, and its migration (at least for Pluto), on their surfaces.

**Pre-ALMA Earth-based and Spacecraft Observations:** Thermal measurements with ISO, Spitzer and Herschel indicate that the mean brightness temperature of the Pluto/Charon system decreases considerably with increasing wavelength, from ~52 K near 20 $\mu$m to ~38 K near 500 $\mu$m ([14]). This behaviour likely results from a combination of subsurface sounding and emissivity effects at the longest wavelengths (associated with dielectric constant and/or reflectivity effects), and the fact that there are warmer and colder regions and the warmer regions dominate the emission at shorter wavelengths (because the emission goes like $T^4$ at short wavelengths but goes like $T$ at long wavelengths). Such emissivity effects are seen in millimeter-wavelength measurements of various kinds of ice and snow on Earth [15]. In the submm/mm range, ground-based results are more dispersed, but suggest that the trend might continue. All previous Earth-based thermal measurements – except for SMA observations at 1.35 mm [16] and one VLA observation at 9.1 mm [17] separating Pluto and Charon – have mixed the contribution of the two bodies.

**ALMA Observations:** In 2015 we observed Pluto and Charon with ALMA on June 12 and 13. At that time we did not resolve them individually, but easily separated them on the sky [18]. We observed the system again in 2017 on three dates (September 27 and 29, and October 14), with the intention of getting three separated longitudes to cover as much of the surface as we could with decent resolution. In those observations, the resolution was sufficient to easily resolve Pluto, and marginally resolve Charon (resolutions ranged from 27 to 54 masec). Figure 1 shows the images from those observations [19]. At least one clear brightness temperature enhancement is seen, along with another tentative one, as highlighted in Figure 2. We believe the clear enhancement is associated with Piri Planitia, which is thought to be a region where methane is sublimating, revealing the water "bedrock" below. Analysis of this data is ongoing (with our thermal model [18]), but is hampered by the somewhat limited resolution. We have proposed to use ALMA to observe the system again, but with even higher resolution (as good as 17 masec) during Cycle 7. Images from these observations, should they be approved, should allow for regional temperature contrasts to be determined.

[1] Grundy et al. 2016, *Science*, 351, aad9189. [2] Moore et al. 2016, *Science*, 351, 1284. [3] Cook et al. 2019, *Icarus*, in press. [4] Protopapa et al. 2018, *Icarus*, 287, 218. [5] Schmitt et al. 2017, *Icarus*, 287, 229. [6] Young 2013, *ApJ*, 766, L22. [7] Hansen et al. 2015, *Icarus*, 246-183. [8] Bertrand et al. 2018, *Icarus*, 309, 277. [9] Olkin et al. 2015, *Icarus*, 246-220. [10] Tanguy & Forget, *BAAS*, 47, 210.20. [11] Bird et al. 2019, *Icarus*, 322, 192. [12] Leyrat et al. 2015, *Icarus*, 268, 50. [13] Tryka et al. 1993, *Icarus*, 112, 513. [14] Lellouch et al. 2016, *A&A*, 588, A2. [15] Hewison 1999, *IEEE TGRS*, 37, 1871. [16] Gurwell & Butler, 2010, *BAAS* 42, 1014. [17] Butler et al. 2010, *BAAS*, 42, 1014. [18] Lellouch et al. 2017, *A&A*, 608, A45. [19] Butler et al. 2018, *BAAS*, 50, 502.06. [20] Olkin et al. 2017, *AJ*, 154, 258.

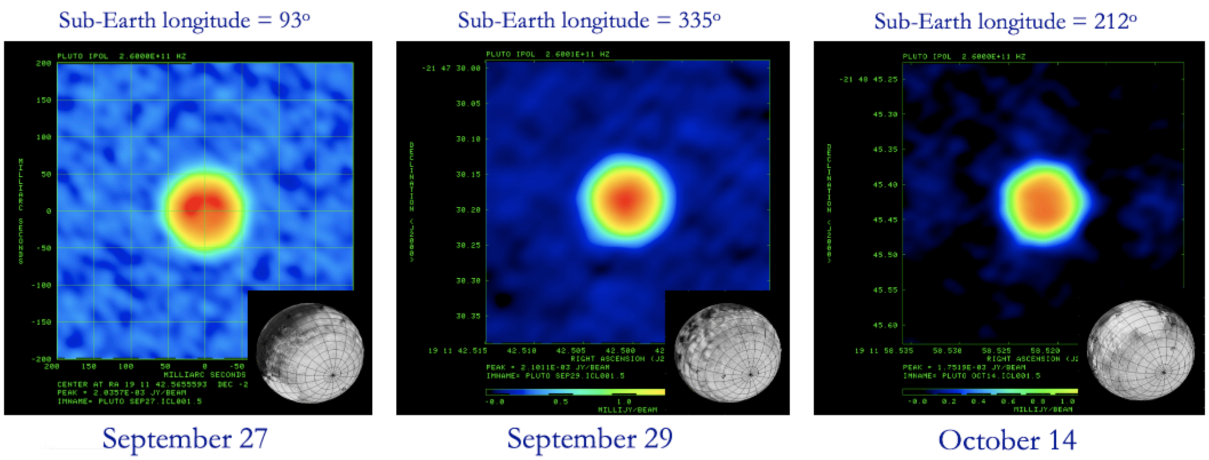


**Figure 1.** Images of Pluto at three longitudes from our 2017 ALMA observations. These are as seen on the plane of the sky. The insets are New Horizons MVIC images, with a cartographic grid of Pluto superimposed.

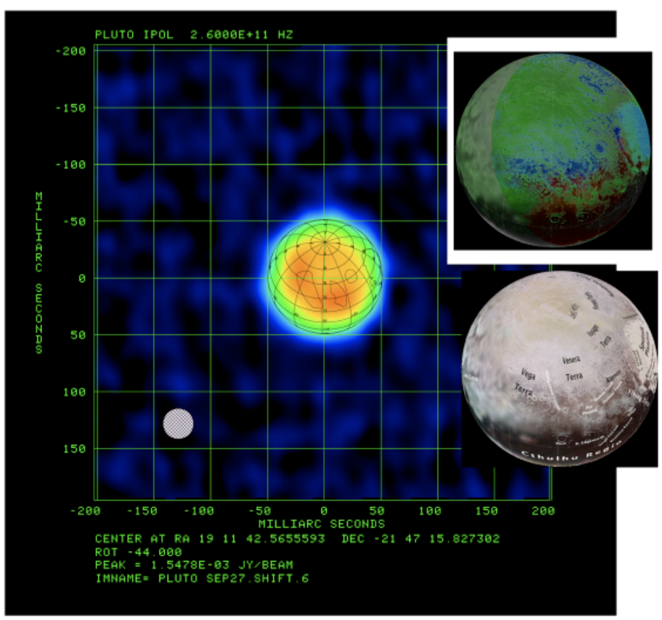


**Figure 2.** The image from Figure 1 for September 27, with the ALMA data rotated so that north is up in the image. The resolution size is shown in the lower left. The lower inset is the color map from [20], with formal and informal-place names. The upper inset is a compositional map, with blue representing $N_2$, red representing $H_2O$, and green representing $CH_4$. The ALMA data has a cartographic grid superimposed, and rough outlines of features.