Kepler K2 Precision Lightcurve Observations of Pluto: Preliminary Results

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Introduction. Pluto is a key object located in the third zone out from our Sun, a region which hosts the Kuiper Belt, a disk of ~130,000 objects 100 km - 2400 km in diameter, and many more smaller bodies [1] that are the remnants of planet formation. These objects provide important insight to formation and collisional processes that were at work in the original solar nebula. The composition and surface evolution of these objects inform our understanding about how the terrestrial and giant planet cores may have formed. Unlike the smaller Kuiper Belt objects (KBOs), Pluto is large enough to host volatiles ices and experience surface weathering, in particular as it recedes from the Sun.

In 2015 the New Horizons (NH) spacecraft encountered this small, dark, icy world & 5 moons (Charon, Nix, Hydra, Kerberos and Styx) that orbit it [2], providing a once-in-a lifetime opportunity to directly link our Earth-based view of Pluto with 'ground truth' provided by *in situ* measurements. From late May to early July 2015 the New Horizons spacecraft monitored the Pluto system using ***clear filter imaging from the LORRI camera*** [3]. However, this first encounter was a short-lived flyby because it was infeasible to brake the s/c into orbit within the Pluto system while keeping the mission duration & cost modest.

Pluto is known to be a constantly changing world due to the solar energy being received decreasing by ~2% per year on account of its eccentric orbit now carrying it rapidly away from perihelion. It is also known to have surface and atmospheric ices N_2, CO and CH_4 which are in vapor-pressure equilibrium. What is more, the orientation of Pluto's spin axis and the sub-solar latitude (the height of the "midday Sun") changes by more than 1^o per Earth year, bringing 100,000 square kilometers of new surface area into sunlight for the first time in a century (while casting an equal and opposite polar area into a century-long arctic winter). These orbit-related effects on the atmosphere and surface of Pluto are on top of the well-known longitudinal variations measurable over the course Pluto's 6.387 day rotation. Observations of Pluto one year prior-to and post-flyby will allow us to identify evolving trends in the system which could be missed if we focused on only the flyby dataset. Our ultimate goal is to better understand Pluto, its family of satellites and their evolution since formation.

K2 Observations. We thus obtained K2 extended Kepler mission (K2) observations of the Pluto system

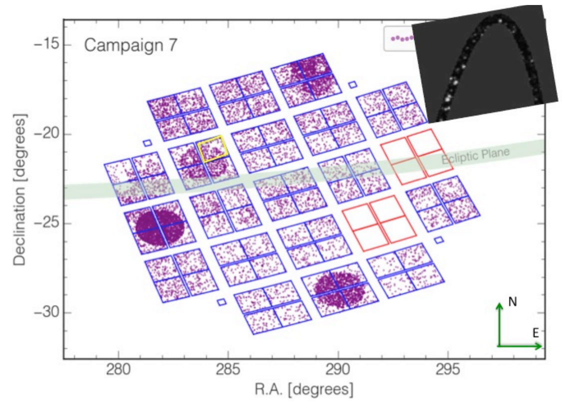

Fig 1. - The K2 array and the location of the "arch" of pixels Pluto moved through in Campaign 7.

[4-5], which was fortuitously "on silicon" throughout the duration of the K2 Campaign 7 field focused on the galactic center. With these observations, we continued to monitor the Pluto system from ***October-December 2015*** using the Kepler spacecraft's clear filter imaging photometer, providing a key baseline of photometric observations that were not available from NH or ground-based observatories because of Pluto's position near the Sun as seen from the Earth during the timeframe of the campaign.

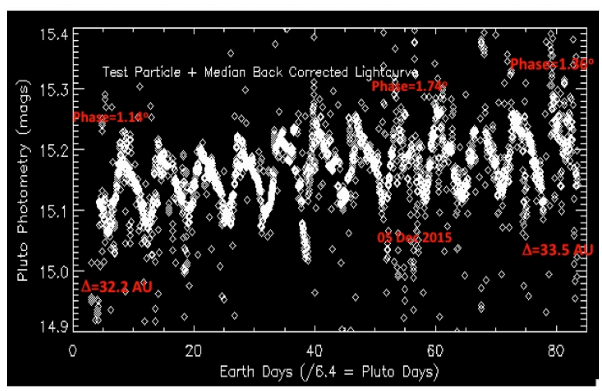

Fig. 2 - Preliminary K2 Pluto Oct - Dec 2015 lightcurve.

Using K2's long cadence sampling, we obtained an ***83-day continuous lightcurve with measurements every 30 minutes***. The result was 3,980 discrete, unresolved measurements of the combined Pluto system over 12 mutual rotations where the 6.387 day periodicity of the Pluto-Charon rotation can be easily seen (Fig. 2). The 3-month baseline (04 Oct - 26 Dec 2015) allowed us to sample ***solar phase angles ranging from 1.1°-1.7°***

during the period of observation. The continuous 30-minute sampling interval provided a time resolution (which translates into high resolution photometry ***every 1.2^o in longitude on Pluto***) not possible from any other observatory.

Monitoring Pluto, which moved only a few arcmin/night, required designing a target pixel mask over its path on the K2 FOV; fortunately the K2 pointing was accurate enough that the Pluto system stayed within the designed pixel mask throughout the 3 months of observation. Throughout the observations, Pluto was relatively bright, [V]~14.2, in the middle of the brightness distribution of K2 Campaign 7 observed objects, so it was an ideal object for the K2 set-up. Because Pluto was bright and continuously monitored, locating Pluto on the K2 chip in each cadence observation and removing the observational background was time intensive, but relatively straightforward.

Discussion. The positional uncertainty of Pluto over a 30 min observing period, less than a Kepler pixel, provided star-like PSFs in a single K2 observation. Our main current challenge in reducing and analyzing the K2 Pluto lightcurve data, however, is that we are utilizing K2 to study Pluto in a fashion totally wrong compared to Kepler's original design - rather than a star fixated on 1 pixel for 3 months, Pluto moves in an arch across a K2 CCD and samples many different pixel gains and effective PSF's. K2 also slews on the sky in a cyclical fashion every 6 hours. Studying the lightcurves of background stars scattered across the Pluto pixel mask/track, we see the form of their curves change nonlinearly as we move along Pluto's track.

Another complication for interpreting the dataset arises from the large pixel scale of Kepler (~2"). Thus within 1 Kepler pixel both Pluto and Charon (with radii of 1189 and 603 km, respectively, and separated by ≤0.94" [6]) reside and produce measurable flux as they synchronously rotate about their common barycenter every 6.387 days. However, Charon's lightcurve is known [7], and was refined with NH, and while Pluto has an atmosphere which drives the motion of surface ices and changes Pluto's lightcurve over time, Charon is does not have any measurable atmosphere [2,8] so the lightcurve is more stable and can be easily subtracted from the sum to monitor the changes in Pluto's lightcurve directly.

Despite these hindrances, we can make an important preliminary statement. As Pluto recedes from the Sun we expect most, if not all, of Pluto's atmosphere to collapse onto its surface [9]. This collapse could result in an overall brightening of Pluto as new frost forms a bright, reflective global layer, or the atmosphere could only recondense "statically" at the currently bright icy regions, or something between these 2 extremes could happen. Comparing our new ***lightcurve amplitude to predictions of the "static" model [10], we find good agreement*** (Fig. 3).

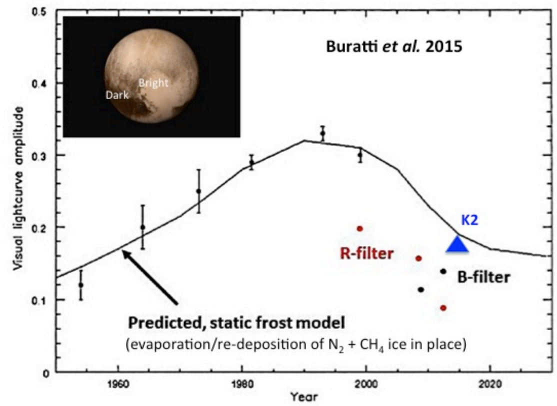

Fig. 3 - Historical observations of the amplitude of Pluto's lightcurve compared to a static frost model (solid line). Observations prior to 2000 were taken in the V-filter, like the *LORRI* & *K2* measurements. The amplitude of Pluto's lightcurve should be largest when we are viewing the maximal amount of equatorial regions near equinox, circa ~1990.

Conclusions. Our K2 Pluto analysis is very much a work in progress. Nevertheless, we can already show that a simple "static, in place" atmospheric collapse due to Pluto's cooling as it recedes from the Sun after perihelion passage seems to be currently in effect. Our K2 lightcurve observations come at a time in Pluto's orbit that will not be seen for observed again for ~247 years, thus this dataset is critical for our continued study of Pluto's evolving surface-atmosphere interaction as it occurs. Also, our observations represent the highest time resolution Earth-centered dataset of the Pluto system ever collected and provide critical long time baseline photometry for tying the NH sub-disk photometry to disk integrated observations. By extension, Pluto will provide insight for interpretation of other dwarf planets and Kuiper Belt objects in the third zone of our Solar System.

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