Icarus 314 (2018) 265–273

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

K2 precision lightcurve: Twelve days in the Pluto-Charon system

S.D. Benecchi[a,*], C.M. Lisse[b], E.L. Ryan[c], R.P. Binzel[d], M.E. Schwamb[e,f], L.A. Young[g], A.J. Verbiscer[h]

[a] Planetary Science Institute, 1700 East Fort Lowell Rd., Suite 106, Tucson, AZ 85719, USA
[b] JHU-APL, 11100 Johns Hopkins Road, Laurel, MD 20723, USA
[c] NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA
[d] Massachusetts Institute of Technology, Cambridge, MA, England, United Kingdom
[e] Gemini Observatory, Northern Operations Center, 670 North A'ohoku Place, Hilo, HI 96720, USA
[f] Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 10617,Taiwan
[g] Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, CO 80302, USA
[h] University of Virginia, Department of Astronomy, PO Box 400325, Charlottesville, VA 22904, USA

ARTICLE INFO

Article history:
Received 16 March 2018
Revised 7 May 2018
Accepted 18 May 2018
Available online 15 June 2018

Keywords:
Kuiper Belt
Photometry
Kepler
K2

ABSTRACT

The *Kepler* spacecraft's imaging photometer monitored the Pluto system from October–December 2015 during Campaign 7 of the K2 extended mission. *Kepler* obtained an unprecedented and fortuitous nearly continuous 12-Pluto day lightcurve from measurements acquired every 30 min using long cadence sampling. This 3-month-long baseline anchors the Pluto+Charon lightcurve near the time of the *New Horizons* July 2015 encounter, observing at solar phase angles between 1.16° and 1.74°. Long-term modeling of Pluto's lightcurve will ultimately reveal its long-term seasonal variation. K2's combined Pluto+Charon lightcurves measured at this epoch have an average total amplitude of 0.120 ± 0.006, 0.07 magnitudes smaller than the amplitude predicted by a static frost model (Buie and Tholen, 1989) projected from *Hubble Space Telescope* surface maps (Buie et al., 1992). Subtracting a static Charon lightcurve from the Pluto+Charon K2 lightcurve produces the same results. Likewise, we subtract each rotation model from the model for the first full rotation and find that the average difference of all variations is 0.017 ± 0.008 magnitudes. Moreover, the difference between the first and last K2 rotation is 0.005 magnitudes, implying that there are no significant changes in the lightcurve during the 3 months of K2 observations. These results are consistent with seasonal transport on Pluto's surface and the predictions of Buratti et al. (2015a). However, a detailed understanding of the surface-atmosphere interactions associated with these phenomena requires decades of monitoring.

1. Introduction

Discovered in 1930, Pluto is a dwarf planet in the Kuiper Belt, a disk containing ~130,000 objects 100 km–2400 km in diameter and many more smaller bodies (e.g., Petit et al., 2011). As remnants of planet formation, the composition, surfaces and dynamical evolution of Kuiper Belt objects (KBOs) inform our understanding about how the terrestrial and giant planet cores may have interacted and formed. Unlike the smaller KBOs, Pluto is large enough to host volatile ices and experience surface weathering (Schaller, 2010). In July 2015 the *New Horizons* spacecraft flew past this icy world and its five satellites, providing a once-in-a-lifetime opportunity to link our Earth-based view of Pluto with 'ground truth' provided by in situ measurements (Stern et al., 2015). This encounter was a short-lived fly-by compared to other planetary voyages, so studies from Earth-based or Earth-orbit facilities prior to and after the *New Horizons* encounter still provide valuable long time baseline information. Fortuitously,[1] the *Kepler* spacecraft (Borucki et al., 2010) is in an Earth-trailing orbit and therefore was able to observe the Pluto-Charon system for three months shortly after the *New Horizons* flyby at times when Pluto was not visible from Earth and for durations not feasible from ground-based observatories. From October-December 2015 *K2* obtained an unprecedented 12 Pluto-day continuous lightcurve during Campaign 7 of the K2 extended

* Corresponding author.
E-mail addresses: susank@psi.edu, susank@alum.mit.edu (S.D. Benecchi), carey.lisse@jhuapl.edu (C.M. Lisse), erin.l.ryan@nasa.gov (E.L. Ryan), rpb@mit.edu (R.P. Binzel), mschwamb@asiaa.sinica.edu.tw (M.E. Schwamb), layoung@boulder.swri.edu (L.A. Young), verbiscer@virginia.edu (A.J. Verbiscer).

[1] The K2 field-of-view is 0.25 ° and only 20 fields (a few partially overlapping) around the entire sky have been observed over the duration of the mission (2014–2018).

https://doi.org/10.1016/j.icarus.2018.05.015
0019-1035/

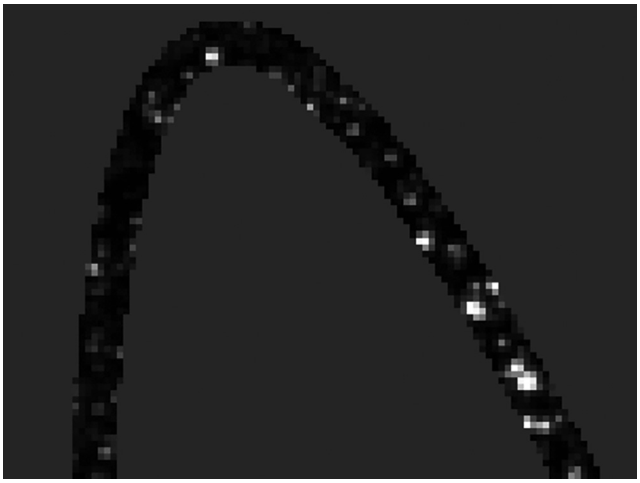

Fig. 1. Animation of Pluto as it moves through the K2 field. The white, mostly fixed objects are background stars in the field though which Pluto transverses, deviant points in the lightcurve found in Fig. 3 map time-wise to when Pluto travels near these stars. Changes in the resolution of these stars indicate variability due to spacecraft motion during the observations. Video generated by Geert Bernstein, Director, Kepler/K2 Guest Observer Office (https://Keplerscience.arc.nasa.gov/images/release-notes/c7/k2c7-pluto.gif).

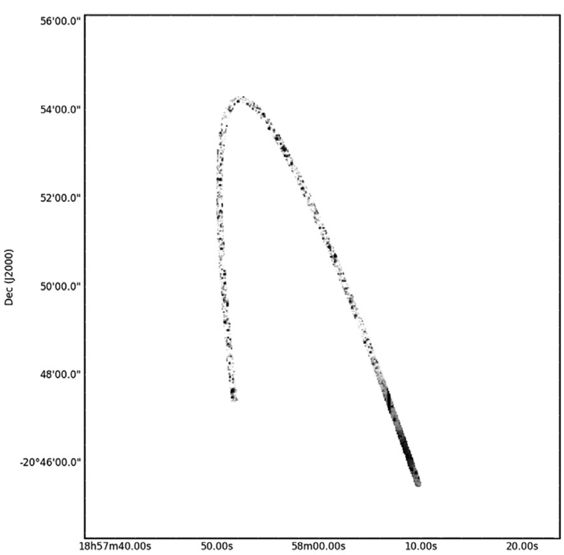

Fig. 2. Extent of the Pluto tracklet, or Pluto trajectory, on the *Kepler* channel 65 imager. The stored pixels are presented in inverted greyscale with a arcsinh stretch. The darkness at the right hand bottom of the tracklet is due to a bright star. Additional dark points within the tracklet indicate other background field sources (seen as white pixels in Fig. 1). Because this *Kepler* campaign pointed near the galactic center, there are a large number of sources in this frame.

mission (Howell et al., 2014; Fig. 1). These observations enabled uninterrupted monitoring of the Pluto+Charon lightcurve as the system recedes from the Sun to monitor long-term seasonal variations on the surface of Pluto.

1.1. Pluto-Charon lightcurve throughout history

Owing to significant variations in incident solar energy (∼2%/year) due to its highly eccentric orbit, Pluto is a constantly changing world. Pluto's surface and atmospheric ices include N_2, CO and CH_4 which are all in vapor-pressure equilibrium (Owen et al., 1993; Hansen and Paige, 1996). The orientation of Pluto's spin axis and the sub-solar latitude (the height of the "midday Sun") changes by more than 1° per Earth year, bringing 100,000 square kilometers of new surface area into sunlight for the first time in ∼100 years, while casting an equal and opposite polar area into a century-long arctic winter (Earle and Binzel, 2015; Earle et al., 2017; Earle, 2018). The pole orientation should produce significant seasonal transport of volatiles (Stern and Trafton, 1984; Hansen and Paige, 1996; Young, 2013; Hansen et al., 2015) and therefore variation in the amplitude of Pluto's lightcurve on top of the longitudinal variations measurable over the course of Pluto's 6.3874 +/− 0.0002-day rotation period (Neff et al., 1974).

The lightcurve of the Pluto+Charon system has been monitored since its discovery, and technology developments in the last ∼20 years now allow for resolved imaging of Pluto and Charon (Binzel 1989; Buie et al., 1992, 1997), as well as decomposition of unresolved lightcurves of the combined system. Buie (1984) carried out spectrophotometry of Pluto, decoupled from Charon, at various points on its lightcurve to investigate the absorption depths of methane and to produce the first surface model for Pluto. At the time, two dark spots, both at a latitude of −23° and separated by 134° in longitude were found on the surface and two terrains were modeled using Hapke scattering theory (Hapke, 1981). Between 1984 and 1990, Pluto and Charon's orbital plane was edge-on as seen from Earth, enabling observations of mutual events as they eclipsed and occulted each other approximately every 3.2 days, coinciding with their synchronously locked mutual orbit and rotation period. The duration of these mutual events ranged from minutes to 4.5 h between immersion to emersion in the middle of the six-year-long mutual event season. Observations of these events during the entire season enabled the first detailed mapping of Pluto's surface ices. Buie et al. (1992) produced a model including all the data available from 1954 through 1990 during which Pluto's northern pole came into view after ∼100 years of darkness as Pluto moved from solar insulation at a sub-solar latitude of −55° (south latitude) to 0° latitude (equatorial). Their final result showed that the north polar region was brighter than the equatorial region with the south polar region being brighter still.

In 1994 (Buie et al., 1997), and later in 2002 (Buie et al., 2010), the *Hubble Space Telescope* (HST) obtained high resolution, spatially resolved surface maps of Pluto and Charon through lightcurve observations. During the 1994 campaign, which used the Faint Object Camera in High Resolution mode (at a sub-solar latitude of 12.7°), Pluto's north pole became fully observable while Pluto's south pole transitioned to a century-long winter. During the 2002 campaign, Buie et al. (2010) used HST's Advanced Camera for Surveys/High Resolution Camera (at a sub-solar latitude of ∼30°) as Pluto's southern pole moved into permanent darkness. The biggest change from the Buie et al. (1992) map was a significant brightening of the north polar region which led to a better understanding of seasons on Pluto and its surface-atmospheric interactions.

From the large archive of time-based observations of Pluto, there are a variety of methods one can use to map Pluto's surface-atmosphere interactions over time: simple photometry, spectroscopy or high resolution imaging. Perhaps the simplest method from an observational approach is to monitor Pluto's lightcurve which records the combined effects of geometry and surface changes. Fundamentally, the geometric changes can be calculated and removed from the lightcurve, resulting in what we will refer to in this paper as a "reduced lightcurve" at a given time and the results compared to reduced lightcurves taken at other times. Because Pluto is in vapor-pressure equilibrium, changes in the reduced lightcurve over time should, therefore, be a reflection of the surface-atmosphere interaction due to volatile transport as a result of Pluto's orbit and motion towards or away from the Sun. Early modelers predicted that Pluto's atmosphere would collapse onto its surface (potentially around 2013–2016) during its 248 year orbit (Stern and Trafton, 1984; Hansen and Paige, 1996), however, more recent observations and models demonstrate that