



## THE FIRST HIGH-PHASE OBSERVATIONS OF A KBO: *NEW HORIZONS* IMAGING OF (15810) 1994 JR<sub>1</sub> FROM THE KUIPER BELT

SIMON B. PORTER<sup>1</sup>, JOHN R. SPENCER<sup>1</sup>, SUSAN BENECHCHI<sup>2</sup>, ANNE J. VERBISCHER<sup>3</sup>, AMANDA M. ZANGARI<sup>1</sup>, H. A. WEAVER<sup>4</sup>,  
TOD R. LAUER<sup>5</sup>, ALEX H. PARKER<sup>1</sup>, MARC W. BUIE<sup>1</sup>, ANDREW F. CHENG<sup>4</sup>, LESLIE A. YOUNG<sup>1</sup>, CATHY B. OLKIN<sup>1</sup>,  
KIMBERLY ENNICO<sup>6</sup>, AND S. ALAN STERN<sup>1</sup>

(THE NEW HORIZONS SCIENCE TEAM)

<sup>1</sup> Southwest Research Institute, Boulder, CO, USA; [porter@boulder.swri.edu](mailto:porter@boulder.swri.edu)

<sup>2</sup> Planetary Science Institute, Tucson, AZ, USA

<sup>3</sup> University of Virginia, Charlottesville, VA, USA

<sup>4</sup> Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA

<sup>5</sup> National Optical Astronomy Observatory, Tucson, AZ, USA

<sup>6</sup> NASA Ames Research Center, Moffett Field, CA, USA

Received 2016 May 16; revised 2016 July 22; accepted 2016 July 25; published 2016 September 1

### ABSTRACT

NASA's *New Horizons* spacecraft observed (15810) 1994 JR<sub>1</sub>, a 3:2 resonant Kuiper belt object (KBO), using the LORRI on 2015 November 2 from a distance of 1.85 au and again on 2016 April 7 from a distance of 0.71 au. These were the first close observations of any KBO other than Pluto. Combining ground-based and *Hubble Space Telescope* (*HST*) observations at small phase angles and the LORRI observations at higher phase angles, we produced the first disk-integrated solar phase curve of a typical KBO from  $\alpha = 0^\circ\text{--}58^\circ$ . Observations at these geometries, attainable only from a spacecraft in the outer solar system, constrain surface properties such as macroscopic roughness and the single particle phase function. 1994 JR<sub>1</sub> has a rough surface with a  $37^\circ \pm 5^\circ$  mean topographic slope angle and has a relatively rapid rotation period of  $5.47 \pm 0.33$  hr. 1994 JR<sub>1</sub> is currently 2.7 au from Pluto; our astrometric points enable high-precision orbit determination and integrations that show that it comes this close to Pluto every 2.4 million years ( $10^4$  heliocentric orbits), causing Pluto to perturb 1994 JR<sub>1</sub>. During the November spacecraft observation, the KBO was simultaneously observed using *HST* in two colors, confirming its very red spectral slope. These observations have laid the groundwork for numerous potential future distant KBO observations in the *New Horizons*–Kuiper belt extended mission.

**Key words:** Kuiper belt: general – Kuiper belt objects: individual (15810) – space vehicles

### 1. INTRODUCTION

NASA's *New Horizons* spacecraft launched on 2006 January 19, flew past Jupiter to obtain a gravity assist in 2007 February, and passed within 13,700 km of Pluto on 2015 July 14 (Stern et al. 2015). Kuiper belt objects (KBOs) form the larger and more primordial of the solar system's two circumstellar disks. KBOs can only be observed from Earth within a few degrees of solar opposition, and a spacecraft is required to observe them at any higher solar phase angle. The 2003 planetary science decadal survey “New Frontiers in the Solar System” (Space Studies Board 2003) recommended that a “Kuiper Belt–Pluto Explorer” (which became *New Horizons*) investigate several KBOs, and that the value of those investigations would be increased commensurately with the number of KBOs observed.

After the Pluto flyby, NASA approved a thruster burn sequence to redirect *New Horizons* to the KBO 2014 MU<sub>69</sub>, with the final burn on 2015 November 4. This trajectory allows the spacecraft to reach 2014 MU<sub>69</sub> on 2019 January 1 (Porter et al. 2015). On 2016 July 1 NASA approved the *New Horizons* extended mission to 2014 MU<sub>69</sub>.<sup>7</sup> In addition to the 2014 MU<sub>69</sub> flyby, the planned extended mission also includes distant observations of about 20 KBOs at viewing geometries impossible from the Earth, allowing close satellite and ring searches, measurement of surface properties, and precision orbit determination.<sup>8</sup>

<sup>7</sup> <https://www.nasa.gov/feature/new-horizons-receives-mission-extension-to-kuiper-belt-dawn-to-remain-at-ceres>

<sup>8</sup> [http://pluto.jhuapl.edu/News-Center/PI-Perspectives.php?page=piPerspective\\_04\\_14\\_2016](http://pluto.jhuapl.edu/News-Center/PI-Perspectives.php?page=piPerspective_04_14_2016)

(15810) 1994 JR<sub>1</sub> (hereafter JR<sub>1</sub>) is a Kuiper belt object in a 3:2 mean motion resonance with Neptune. It was discovered in 1994 with the Isaac Newton Telescope at the Roque de los Muchachos Observatory (Irwin et al. 1995), making it the 13th KBO discovered (including Pluto–Charon) and the first resonant KBO after Pluto with a multi-year arc (Marsden 1996). JR<sub>1</sub> is currently 2.7 au from Pluto and, like all 3:2 objects, is in a 1:1 resonance with Pluto. de la Fuente Marcos & de la Fuente Marcos (2012) proposed that this makes JR<sub>1</sub> a quasi-satellite of Pluto, an object that spends an extended amount of time close to Pluto but is not gravitationally bound.

Here, we present new observations of JR<sub>1</sub> obtained with *New Horizons* and *Hubble Space Telescope* (*HST*) on 2015 November 2 and by *New Horizons* on 2016 April 7. These observations enabled the first rotational period determination, an improved orbit fit, and a much extended solar phase curve. These observations demonstrate the capability of *New Horizons* to explore similarly distant Kuiper belt objects in its proposed extended mission.

### 2. OBSERVATIONS

#### 2.1. *New Horizons* Observations

The primary astronomical imager on *New Horizons* is the LORRI, which consists of a spacecraft-body-mounted 20.8 cm aperture Ritchey-Chretien telescope feeding a triplet field-flattening lens assembly, and on to an unfiltered back-illuminated CCD (Cheng et al. 2008). The CCD has  $1024 \times 1024$  illuminated

pixels, with an average plate scale of  $4.963571 \pm 0.000038$   $\mu\text{rad}/\text{pixel}$ .<sup>9</sup> However, *New Horizons* does not have reaction wheels, and all pointing must be done with reaction control thrusters, which can only actively maintain pointing to within 4 arcsec. Thus, for exposures longer than 0.3 s, LORRI images are binned  $4 \times 4$  on the spacecraft to  $256 \times 256$  pixels. These  $4 \times 4$  images are much easier to downlink to Earth and have minimal loss of spatial precision for long exposures. All the  $4 \times 4$  images presented here used an exposure time of 9.967 s.

LORRI first observed JR1 on 2015 November 2 in four sets of ten  $4 \times 4$  images, spaced one hour apart, and designated “JR1\_LORRI\_306.” At the time of the observation, *New Horizons* was 1.85 au from the KBO, and seeing it at a solar phase angle of  $26^\circ.7$ . LORRI observed JR1 again on 2016 April 7, at a distance of 0.71 au and solar phase angle of  $58^\circ.5$ . The observation sequence began with two “JR1\_LORRI\_DEEP” stacks of twenty-four  $4 \times 4$  images, with the second starting 30 minutes after the first. This was followed 30 minutes later by “JR1\_LORRI\_LIGHTCURVE\_01,” a sequence of nine sets of three  $4 \times 4$  images, spaced 30 minutes apart. Finally, “JR1\_LORRI\_LIGHTCURVE\_02” was another nine sets of three  $4 \times 4$  images, but spaced one hour apart. During the April encounter, *New Horizons* also obtained “JR1\_LORRI\_CLOSE,” an experimental sequence of non-binned  $1 \times 1$  images with only the central  $512 \times 512$  pixels returned. Here, we only present results of the  $4 \times 4$  observations, as JR1 did not appear to be visible in the  $1 \times 1$  s. All LORRI observations will be archived in NASA’s Planetary Data System.

Our first step was to build up a new delta-bias/hot pixel map to correct for bias drift (see Figure 10 in Cheng et al. 2008). After subtracting this bias, we then extracted the point-like sources in the images and matched them to stars in the USNO UCAC4 catalog (Zacharias et al. 2013). This allowed us to map the pointing of each image to a World Coordinate System (WCS) with a typical accuracy of 0.1 pixels (0.4 arcsec). Since JR1 was typically nearer the center of the field, we did not incorporate higher-order distortion coefficients. Next, we reprojected each image into a common sidereal projection, and then median-combined the reprojected images to produce high signal-to-noise star stacks for both the November and April epochs. This was especially important for the November epoch, as it had a much higher star density. We next extracted windows from each original image, centered on the predicted location of the KBO using NAIF SPICE (Acton 1996), scaled up by a factor of eight (i.e., twice the original pixel resolution), and rotated to the mean position angle for that set of observations. We suppressed the stars by reprojecting the star stacks to the projection of each individual window and subtracting. We median-combined each set of subtracted windows, which suppressed cosmic rays and other artifacts. Between the star subtraction and the apparent sky motion of the KBO, we were able to suppress all but the brightest stars, leaving just the KBO in the center of each stacked window. Finally, we fit an elliptical two-dimensional Gaussian to each stacked window, minimizing the  $\chi^2$  residuals. A non-circular form was needed because the spacecraft was not fully settled after each small slew for the light curve observations, causing the effective PSFs to be smeared in many cases. We converted the pixel  $x/y$  location of the Gaussian to sky coordinates with the image’s WCS and measured the integrated DN/second by

summing our model source. We converted the DN/second to  $V$  magnitude with the calibrated  $4 \times 4$  zero point determined shortly after the Pluto flyby:

$$V = 18.91 - 2.5 * \log_{10}(\text{DN/second}) + \text{CC} \quad (1)$$

where CC is the color correction. Of the objects with calibrated LORRI photometry, (5145) Pholus has the most similar spectral slope ( $V - R = 0.78$ ; Tegler & Romanishin 1998), and so we used its LORRI color correction of  $\text{CC} = 0.213$  mag (Cheng et al. 2008). Note that this zero point is only valid for  $4 \times 4$  LORRI images. The reduction pipeline and the orbit determination were repeated several times until the predicted location of the KBO matched the actual, meaning the KBO was centered in the windows. This pipeline made extensive usage of the Astropy Python package (Astropy Collaboration et al. 2013).

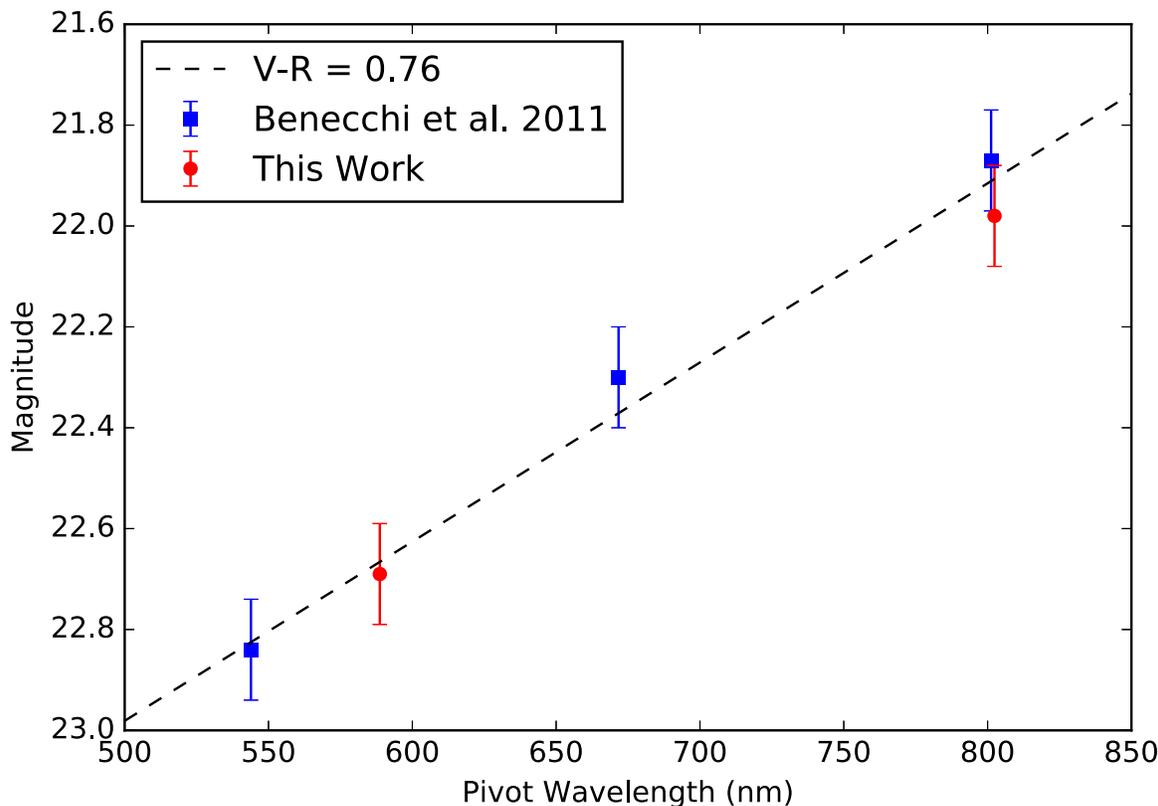
## 2.2. HST Observations

In addition to the *New Horizons* observations, the *Hubble Space Telescope* (Program #14092; PI: S. Benecchi) observed JR1 on 2015 November 2, starting just over a minute before the first LORRI observation (light-time corrected) and continuing for the following half hour. With this observation, the Wide Field Camera 3 (WFC3/UVIS) obtained five images, two with the F606W (wide  $V$ ) filter and three with the F814W (wide  $I$ ) filter. The exposure time for the F606W images was 348 s, and 396 s for the F814W. We performed the photometry for the *HST* observations using the same methodology as Benecchi et al. (2011). This method matches the KBO’s PSF with a synthetic model generated by Tiny Tim (Krist et al. 2011), fitting for  $x$  and  $y$  positions, flux, and sky background. We converted the  $x$  and  $y$  positions to sky coordinates with xytsky and used it in our orbit fits. This was the first time a KBO (other than Pluto and Charon) was simultaneously observed from two extremely distant locations in the solar system, and allowed us to very precisely constrain the present location of JR1. The measured magnitude in F606W was  $22.69 \pm 0.04$ , and the magnitude in F814W was  $21.98 \pm 0.02$ . These colors and complementary observations from *HST*/WFPC2 (Benecchi et al. 2011) are shown in Figure 1. Differencing the November observations gives  $F606W - F814W = 0.71$ , while Figure 1 shows an approximate  $V - R$  slope of  $0.76 \pm 0.09$ . In either case, JR1 is a very red object. The mean  $V - R$  (Johnson  $V$ , Cousins  $R$ ) for the 12 3:2 resonant objects in Benecchi et al. (2011) is 0.62, and JR1 is redder than 2/3 of those objects, while Pluto’s mean  $V - R$  is 0.56–0.60 (Buratti et al. 2015). Dalle Ore et al. (2015) showed that the surfaces of similarly red KBOs and Centaurs are composed of irradiated  $\text{CH}_4$ ,  $\text{CO}$ ,  $\text{CO}_2$ , and  $\text{H}_2\text{O}$  ices, producing a coating of longer-chain hydrocarbons.

## 3. PHOTOMETRY

After its discovery in 1994, JR1 was observed a number of times in the 1990s. The best-calibrated photometry of this period was obtained in both  $V$  and  $R$  in 1995 and published in Green et al. (1997). Benecchi et al. (2011) obtained additional color photometry with *HST*/WFPC2 in 2001 and *HST*/ACS in 2002. After a 13 year gap, JR1 was recovered by D. Tholen (MPS 610223) in 2015 June with the University of Hawaii 2.2 m telescope. This was followed by the colors presented above obtained in November 2015 with *HST*/WFC3. As

<sup>9</sup> [http://naif.jpl.nasa.gov/pub/naif/pds/data/nh-j\\_p\\_ss-spice-6-v1.0/nhsp\\_1000/data/ik/nh\\_lorri\\_v201.ti](http://naif.jpl.nasa.gov/pub/naif/pds/data/nh-j_p_ss-spice-6-v1.0/nhsp_1000/data/ik/nh_lorri_v201.ti)

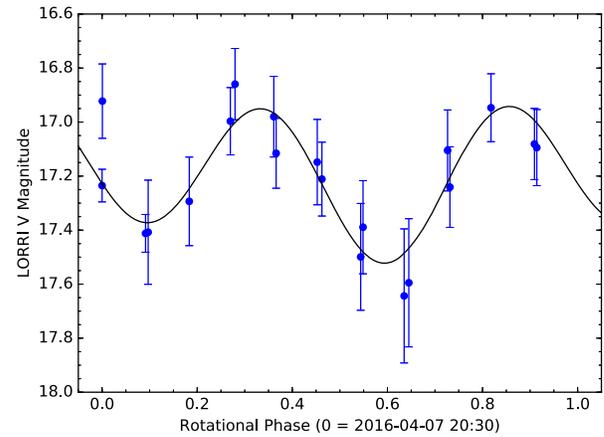
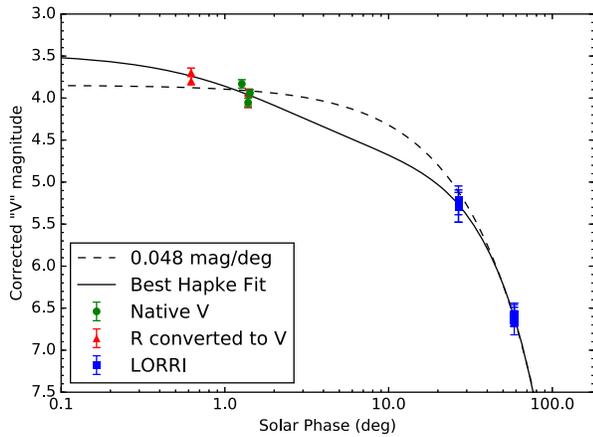


**Figure 1.** Measured colors for (15810) 1994 JR<sub>1</sub> with *HST*. Blue squares are observations by WFPC2 in F555W, F675W, and F814W published in Benecchi et al. (2011). Red circles are new WFC3 observations in F606W and F814W. The 0.1 mag error bars are an estimate of the light curve variation; actual measurement uncertainties are lower (see Table 1). The dashed line corresponds to a spectral slope with  $V - R = 0.76$ . These data have not been corrected for light curve variation.

**Table 1**  
LORRI Photometry of (15810) 1994 JR<sub>1</sub>

Observation Mid-time	Number of Observations	R.A.	Decl.	V Magnitude	Solar Phase
2015-11-02 00:45:49	10	17 <sup>h</sup> 14 <sup>m</sup> 29 <sup>s</sup> .45	-9:21:29.5	18.04 ± 0.17	26°715
2015-11-02 01:45:49	10	17 <sup>h</sup> 14 <sup>m</sup> 28 <sup>s</sup> .93	-9:21:21.6	18.17 ± 0.20	26°718
2015-11-02 02:45:49	10	17 <sup>h</sup> 14 <sup>m</sup> 28 <sup>s</sup> .34	-9:21:14.1	18.01 ± 0.18	26°721
2015-11-02 03:45:49	10	17 <sup>h</sup> 14 <sup>m</sup> 27 <sup>s</sup> .80	-9:21:06.9	18.35 ± 0.19	26°725
2016-04-07 19:01:40	24	15 <sup>h</sup> 41 <sup>m</sup> 03 <sup>s</sup> .77	12:12:24.3	17.24 ± 0.06	58°210
2016-04-07 19:31:40	24	15 <sup>h</sup> 41 <sup>m</sup> 01 <sup>s</sup> .88	12:12:49.1	17.41 ± 0.07	58°220
2016-04-07 20:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 58 <sup>s</sup> .21	12:13:37.4	17.00 ± 0.12	58°240
2016-04-07 21:00:15	3	15 <sup>h</sup> 40 <sup>m</sup> 56 <sup>s</sup> .31	12:14:02.5	16.98 ± 0.15	58°251
2016-04-07 21:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 54 <sup>s</sup> .42	12:14:27.2	17.15 ± 0.16	58°261
2016-04-07 22:00:15	3	15 <sup>h</sup> 40 <sup>m</sup> 52 <sup>s</sup> .53	12:14:51.9	17.50 ± 0.20	58°271
2016-04-07 22:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 50 <sup>s</sup> .65	12:15:16.7	17.64 ± 0.25	58°282
2016-04-07 23:00:15	3	15 <sup>h</sup> 40 <sup>m</sup> 48 <sup>s</sup> .73	12:15:41.1	17.10 ± 0.15	58°292
2016-04-07 23:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 46 <sup>s</sup> .87	12:16:06.4	16.95 ± 0.13	58°302
2016-04-08 00:00:15	3	15 <sup>h</sup> 40 <sup>m</sup> 44 <sup>s</sup> .95	12:16:31.3	17.08 ± 0.13	58°312
2016-04-08 00:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 43 <sup>s</sup> .09	12:16:55.9	16.92 ± 0.14	58°323
2016-04-08 01:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 39 <sup>s</sup> .29	12:17:45.7	17.29 ± 0.16	58°343
2016-04-08 02:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 35 <sup>s</sup> .48	12:18:35.8	17.12 ± 0.13	58°364
2016-04-08 03:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 31 <sup>s</sup> .72	12:19:25.6	17.39 ± 0.17	58°385
2016-04-08 04:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 27 <sup>s</sup> .87	12:20:15.1	17.24 ± 0.15	58°405
2016-04-08 05:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 24 <sup>s</sup> .10	12:21:05.3	17.09 ± 0.14	58°426
2016-04-08 06:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 20 <sup>s</sup> .27	12:21:55.2	17.41 ± 0.19	58°447
2016-04-08 07:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 16 <sup>s</sup> .50	12:22:45.2	16.86 ± 0.13	58°467
2016-04-08 08:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 12 <sup>s</sup> .66	12:23:34.9	17.21 ± 0.14	58°488
2016-04-08 09:30:15	3	15 <sup>h</sup> 40 <sup>m</sup> 08 <sup>s</sup> .83	12:24:25.2	17.59 ± 0.24	58°509

**Note.** Astrometric uncertainty is 0.6 arcsec for all points.



**Figure 2.** LORRI photometry of (15810) 1994 JR<sub>1</sub>. The left panel shows the best-fit phase curve and points from LORRI, Green et al. (1997), Benecchi et al. (2011), and D. Tholen. *R*-band photometry was converted to *V*-band with  $V - R = 0.76$  (see Figure 1). The right panel shows the 2016 April LORRI points phase-folded over a period of 5.47 hr, with median *V* magnitude 16.9 and peak-to-peak amplitude of 0.8 mag.

described above, *New Horizons* obtained four photometric points on 2015 November 2 at a cadence of one hour. The spacecraft obtained 20 additional photometric points on 2016 April 7, the first 11 at a cadence of 30 minutes and the last 9 at a cadence of one hour. These points are shown in Table 1.

### 3.1. Solar Phase Curve

JR1 was an ideal first post-Pluto target for *New Horizons*, given both its proximity to Pluto and that it was bright enough to be seen by the spacecraft at phase angles of  $27^\circ$  and  $58^\circ$ . The ground-based observations of Green et al. (1997) and *HST* observations in Benecchi et al. (2011) and this work are all in the solar phase angle range  $\alpha = 1^\circ$ – $2^\circ$ . The lowest solar phase photometry we considered were D. Tholen’s 2015 June observations at  $\alpha = 0^\circ.6$ . Future ground-based photometry closer to opposition are necessary to constrain the opposition surge fully.

Using the ground-based, *HST*, and LORRI observations, we generate JR1’s disk-integrated solar phase curve (Figure 2) and fit the Hapke (2012) photometric model. The LORRI observations acquired in 2015 November and 2016 April have been corrected for rotational light curve variation to the mean of the double-peaked light curve shown in Figure 2. The best-fit photometric parameters are summarized in Table 2. While we do not have a constraint on the size of JR1 (as no occultations or thermal measurements have been reported), we assume a mean diameter of 250 km, which gives a geometric albedo of 0.04, typical for a resonant KBO of this size (Stansberry et al. 2008). The phase integral is 0.22, estimated using Russell’s Rule (Verbiscer & Veverka 1988), giving a spherical, or Bond albedo of 0.01. A linear fit to these points gives a phase coefficient of  $0.0475 \pm 0.0007$  magnitudes/degree. This is smaller than most of the larger KBOs listed in Belskaya et al. (2008, pp. 115–127), but similar to smaller Centaur (2060) Chiron. The Hapke (2012) parameters are then single-scattering albedo  $w = 0.025$ , surface roughness (mean topographic slope angle)  $\bar{\theta} = 37^\circ \pm 5^\circ$ , and the Henyey–Greenstein (Henyey & Greenstein 1941) single particle scattering asymmetry parameter (mean cosine of the scattering angle)  $\xi = -0.38$ . This is a moderately backscattering  $\xi$ , typical for icy objects in the outer solar system (Verbiscer et al. 2013). The opposition surge is characterized by angular widths and amplitudes contributed from both shadow hiding

**Table 2**  
Orbit and Physical Properties of 1994 JR<sub>1</sub>

Mean and Standard Deviation of $\pm 10$ Myr Barycentric Orbit		
Semimajor Axis	39.41	$\pm 0.11$ au
Eccentricity	0.1244	$\pm 0.0058$
Inclination to Invariant Plane <sup>a</sup>	3.48	$\pm 0.60$
Physical Properties		
<i>V</i> – <i>R</i> Color	0.76	$\pm 0.09$
Rotational Period	5.47	$\pm 0.33$ hr
Assumed Diameter	250 km	...
Geometric Albedo	0.04	...
Phase Integral <i>q</i>	0.22	...
Phase Coefficient	0.0475	$\pm 0.0007$ mag/deg
Single-scattering Albedo <i>w</i>	0.025	$\pm 0.005$
Surface Roughness $\bar{\theta}$	37	$\pm 5^\circ$
Henyey–Greenstein $\xi$	–0.38	$\pm 0.05$
Opposition Surge		
	Width	Amplitude
Shadow Hiding	0.029	0.89
Coherent Backscatter	0.026	0.73

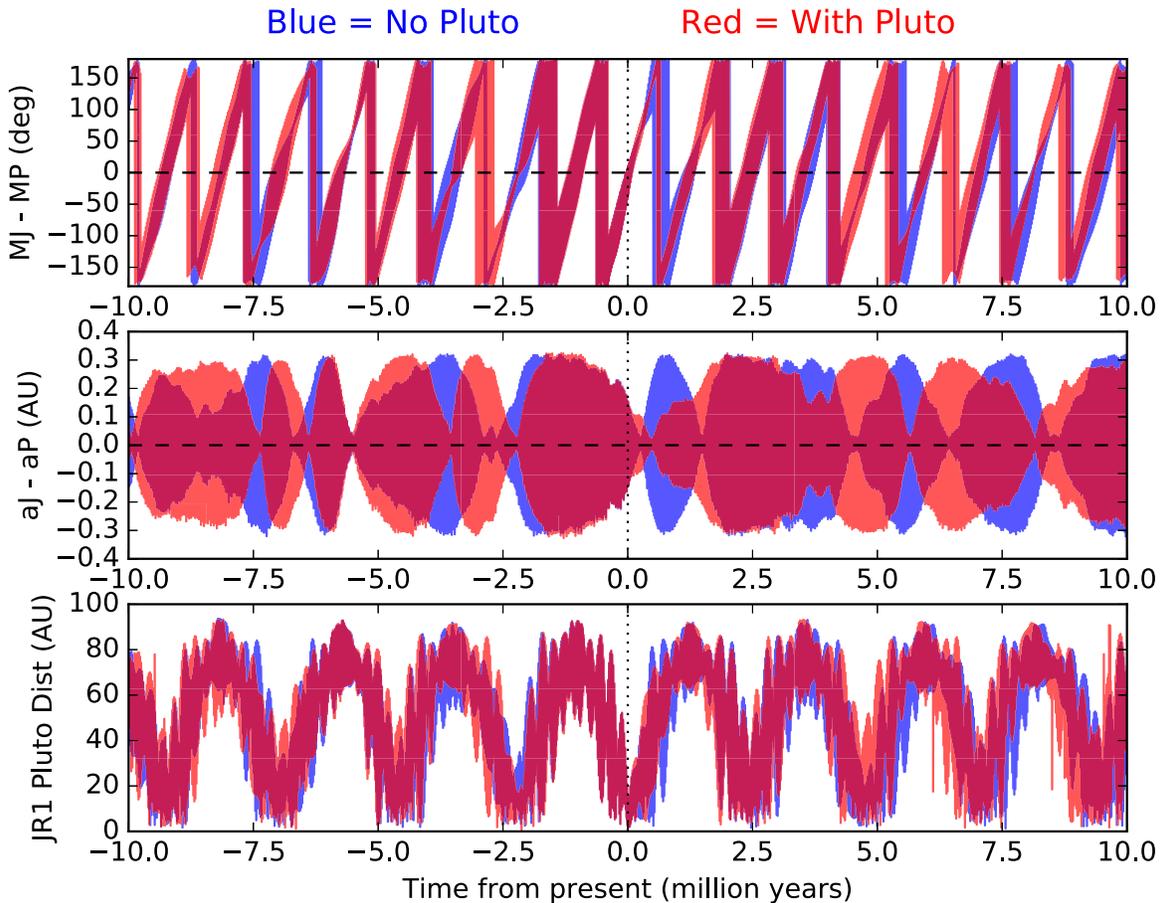
**Note.**

<sup>a</sup> Assumed Invariant Pole: R.A.  $23^{\text{h}}00^{\text{m}}31^{\text{s}}.9$ , decl.  $-3:51:09.4$ .

and coherent backscatter. The angular width of the shadow hiding opposition surge is 0.029 and the amplitude is 0.89; the angular width of the opposition surge due to coherent backscatter is 0.026 and the amplitude is 0.73. The LORRI observations at the larger phase angles place constraints on the surface roughness and the single particle phase function. This surface roughness is even higher than Saturn’s dark, similarly sized moon Phoebe ( $\bar{\theta} = 32^\circ$ ; Simonelli et al. 1999). This indicates that like Phoebe (which is thought to have originated in the Kuiper belt; Johnson & Lunine 2005), JR1 may have a very heavily cratered surface.

### 3.2. Rotational Period

Because of its infrequent cadence, the ground-based photometry of JR1 never showed a discernible periodicity. The two light curve observations by *New Horizons* were designed to measure any high-frequency variation by sampling



**Figure 3.** Relative orbital evolution for 1994 JR<sub>1</sub> and Pluto. The top panel shows the difference in their mean longitudes, the middle shows the difference in their semimajor axes, and the bottom shows the physical distance between the objects. When Neptune perturbations bring the two objects close to each other every 2.4 million years, Pluto does perturb JR<sub>1</sub>'s orbit.

at 30 minute and one hour cadences. The 30 minute observations were downlinked first, and immediately displayed a periodic variation of around five hours (double-peaked). When the rest of the April data were down, we fit an initial period using just the April photometry, as it was all at roughly the same distance and solar phase angle. We iteratively phased the light curve between 3 and 14 hr, with steps of 2.88 s. For each potential period, we derived a minimized  $\chi^2$  two-term Fourier series, and selected the period with the lowest  $\chi^2$  value. Our best fit to just the April photometry has a period of  $5.47 \pm 0.33$  hr and amplitude of 0.8 mag and is shown in Figure 2. This period is consistent with the variation in brightness seen in the four November spacecraft observations, though the period is uncertain enough to allow the two epochs to be combined. A period of 5.47 hr is faster than the average period of 7.5 hr for 29 KBOs and Centaurs in Thirouin et al. (2010), but well within their range of 3.56–12 hr for sub-dwarf-planet-sized objects. Future ground-based high-cadence photometry (sampling several times over the period) would be very useful to reduce the uncertainty in the period and allow preliminary estimates of JR<sub>1</sub>'s rotational pole and shape.

#### 4. ORBIT

We combined our astrometry of JR<sub>1</sub> from *New Horizons* with the previous Earth-based astrometry and our 2015 November *HST* observations to produce an astrometric set that spanned almost 22 years and observer distances of

43–0.7 au. For the observer location from *New Horizons*, we used the spacecraft trajectory solution OD124, which includes the burn to 2014 MU<sub>69</sub> in 2015 November. For Earth and *HST* observer locations, we used JPL DE433 ephemeris and *HST* kernels, respectively.

We then used emcee (Foreman-Mackey et al. 2013) to create a discretely sampled probability distribution cloud of 100,000 orbital solutions by modeling all the available astrometric data (using appropriate uncertainties) with fully perturbed ephemerides. To do this, we propagated the orbits with a high-precision *N*-Body integrator<sup>10</sup> based on the 12/13 order Runge–Kutta–Nystrom integrator of Brankin et al. (1989). We used planetary masses and initial states from JPL DE433, substituting the more accurate Pluto mass from Brozović et al. (2015). The uncertainty in our orbit solution is very low, due both to the unique observational location of *New Horizons* and the exceptionally long orbital arc for a KBO. The major advantage of observing JR<sub>1</sub> from the Kuiper belt was in restricting the object's distance from the Sun, 35.50 au at the time of these observations. We were able to reduce the  $1\sigma$  radial uncertainty in the position of JR<sub>1</sub> from  $10^5$  km with just Earth-based observations to less than  $10^3$  km with the *New Horizons* points. In addition, because of JR<sub>1</sub>'s early discovery and thus very long data arc for such a small KBO, we can also place tight constraints on its motion. This then allowed us to run high-

<sup>10</sup> <https://github.com/ascendingnode/PyNBody>

precision orbital integrations to test its past and future interactions with Pluto.

#### 4.1. Long-term Orbital Evolution

JR1 is currently 2.7 au away from Pluto and on a very similar orbit. Because they are both in 3:2 resonant orbits with Neptune, both Pluto and JR1 are primarily perturbed by Neptune. However, the combined Pluto system (Pluto and its five satellites) is by far the most massive 3:2 resonant KBO system. We therefore sought to test what influence, if any, Pluto would have on JR1 during this future period of interactions. We first selected 250 random state vectors from our unbiased cloud of orbits. Using the same  $N$ -Body integrator and planetary initial states/masses as we used for fitting, we integrated those state vectors first back and then forward 10 million years from the present, saving the barycentric orbits for JR1 and Pluto along the way. We then re-ran the same simulations, but for a control case with the mass of Pluto set to zero.

JR1 is primarily perturbed by Neptune, though it is not trapped in a Kozai resonance, as its perihelion circulates. Pluto's argument of perihelion librates every 3.8 million years (Malhotra & Williams 1997 and references therein), while JR1's argument circulates every 0.83 million years. This combines with the nodal regression of the two bodies to be in conjunction every 2.4 million years ( $\approx 10^4$  orbits). Because of Pluto's eccentric and inclined orbit, the Pluto-JR1 distance at one of these conjunctions is highly variable, but can be as close as 0.5 au. During the conjunctions, Pluto does perturb JR1, as can be seen in Figure 3. But because the close approach distance is variable, Pluto's perturbation on JR1 is effectively chaotic. While this could be described as Pluto quasi-satellite behavior (and has been: de la Fuente Marcos & de la Fuente Marcos 2012), since JR1's orbit is still primarily controlled by Neptune, a more precise description would be a series of periodic Pluto scattering events, one of which JR1 is currently experiencing. Regardless of semantics, JR1 is certainly a case of Pluto exerting its gravitational influence over a fellow 3:2 resonant object.

#### 5. SUMMARY

(15810) 1994 JR<sub>1</sub> has a  $V - R$  of 0.76, making it a very red KBO. Unique *New Horizons* observations showed that JR1 has a high surface roughness of  $37^\circ \pm 5^\circ$ , indicating that it is potentially very cratered. They also showed that the rotational period of JR1 is  $5.47 \pm 0.33$  hr, faster than most similar-sized KBOs, and enabled a reduction of radial uncertainty of JR1's position from  $10^5$  to  $10^3$  km. Neptune perturbations bring Pluto and JR1 close together every 2.4 million years, when Pluto can perturb JR1's orbit. Future ground-based photometry of JR1 would be useful to better constrain the period and opposition surge and to allow preliminary estimates of JR1's shape and pole. These proof of concept distant KBO observations demonstrate that the *New Horizons* extended mission will indeed be capable of observing dozens of distant KBOs during its flight through the Kuiper belt.

Special thanks to David Tholen for recovering JR1 after a 13 year gap, enabling all the observations in this Letter, and to Paul Helfenstein for the use of photometric modeling software. This work was supported by NASA's *New Horizons* Project. This work uses observations made with the NASA/ESA *Hubble Space Telescope*, and associated with program #14092. Support for this program was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

*Facility:* HST(WFC3).

*Software:* AstroPy, emcee, Matplotlib, NAIF SPICE, IDL.

#### REFERENCES

- Acton, C. H. 1996, *P&SS*, **44**, 65
- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, **558**, A33
- Belskaya, I. N., Levasseur-Regourd, A.-C., Shkuratov, Y. G., & Muinonen, K. 2008, in *Surface Properties of Kuiper Belt Objects and Centaurs from Photometry and Polarimetry*, ed. M. A. Barucci et al. (Tucson, AZ: Univ. Arizona Press), 115
- Benecchi, S. D., Noll, K. S., Stephens, D. C., Grundy, W. M., & Rawlins, J. 2011, *Icar*, **213**, 693
- Brankin, R. W., Gladwell, I., Dormand, J. R., Prince, P. J., & Seward, W. L. 1989, *ACM Trans. Math. Software*, **15**, 31
- Brozović, M., Showalter, M. R., Jacobson, R. A., & Buie, M. W. 2015, *Icar*, **246**, 317
- Buratti, B. J., Hicks, M. D., Dalba, P. A., et al. 2015, *ApJL*, **804**, L6
- Cheng, A. F., Weaver, H. A., Conard, S. J., et al. 2008, *SSRv*, **140**, 189
- Dalle Ore, C. M., Barucci, M. A., Emery, J. P., et al. 2015, *Icar*, **252**, 311
- de la Fuente Marcos, C., & de la Fuente Marcos, R. 2012, *MNRAS*, **427**, L85
- Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, *PASP*, **125**, 306
- Green, S. F., McBride, N., O'Ceallaigh, D. P., et al. 1997, *MNRAS*, **290**, 186
- Hapke, B. 2012, *Theory of Reflectance and Emittance Spectroscopy* (Cambridge: Cambridge Univ. Press)
- Heney, L. G., & Greenstein, J. L. 1941, *ApJ*, **93**, 70
- Irwin, M., Tremaine, S., & Zytlow, A. N. 1995, *AJ*, **110**, 3082
- Johnson, T. V., & Lunine, J. I. 2005, *Natur*, **435**, 69
- Krist, J. E., Hook, R. N., & Stoehr, F. 2011, *Proc. SPIE*, **8127**, 81270J
- Malhotra, R., & Williams, J. G. 1997, in *Pluto's Heliocentric*, ed. S. A. Stern & D. J. Tholen, (Tucson, AZ: Univ. Arizona Press), 127
- Marsden, B. G. 1996, in *Proc. IAU Symp. 172, Dynamics, Ephemerides, and Astrometry of the Solar System*, ed. S. Ferraz-Mello, B. Morando, J.-E. Arlot et al. (Dordrecht: Springer), 153
- Porter, S. B., Parker, A. H., Buie, M., et al. 2015, *LPSC*, **46**, 1301
- Simonelli, D. P., Kay, J., Adinolfi, D., et al. 1999, *Icar*, **138**, 249
- Space Studies Board 2003, *New Frontiers in the Solar System* (Washington, DC: The National Academies Press)
- Stansberry, J., Grundy, W., Brown, M., et al. 2008, in *Physical Properties of Kuiper Belt and Centaur Objects: Constraints from the Spitzer Space Telescope*, ed. M. A. Barucci et al. (Tucson, AZ: Univ. Arizona Press), 161
- Stern, S. A., Bagenal, F., Ennico, K., et al. 2015, *Sci*, **350**, 1815
- Tegler, S. C., & Romanishin, W. 1998, *Natur*, **392**, 49
- Thirouin, A., Ortiz, J. L., Duffard, R., et al. 2010, *A&A*, **522**, A93
- Verbiscer, A. J., Helfenstein, P., & Buratti, B. J. 2013, in *The Science of Solar System Ices*, ed. M. S. Gudipati & J. Castillo-Rogez (New York: Springer), 47
- Verbiscer, A. J., & Veverka, J. 1988, *Icar*, **73**, 324
- Zacharias, N., Finch, C. T., Girard, T. M., et al. 2013, *AJ*, **145**, 44