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Note

The UT 7/8 February 2013 Sila–Nunam mutual event & future predictions

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ABSTRACT

A superior mutual event of the Kuiper Belt binary system (79360) Sila–Nunam was observed over 15.47 h on UT 7/8 February 2013 by a coordinated effort at four different telescope facilities; it started ~1.5 h earlier than anticipated, the duration was ~9.5 h (about 10% longer than predicted), and was slightly less deep than predicted. It is the *first full event* observed for a comparably sized binary Kuiper Belt object. We provide predictions for future events refined by this and other partial mutual event observations obtained since the mutual event season began.

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1. Introduction

(79360) Sila–Nunam (preliminary designation 1997 CS_{29}) is a cold Classical Kuiper Belt binary (Luu et al., 1997; Stephens and Noll, 2006) currently undergoing mutual events (Grundy et al., 2012). The binary components are nearly equal brightness, $\Delta m = 0.1$, with a separation (semi-major axis) of 2780 ± 20 km. The components orbit a common center of mass in circular orbits with a period of ~12.5 days; eclipses occur twice per orbit. The rotational period of the combined system is also ~6.25 days, consistent with half the orbital period (Grundy et al., 2012; Rabinowitz, in preparation). Predicted eclipse durations during the 2012–2013 observing season range from 8.2 to 9.1 h. Given the location in the sky of this object, a full event inclusive of baseline observations on either side of occultation could not be observed with a single telescope facility.

The mutual event predicted for UT 7/8 February 2013 was observed in full by combining observations at multiple observatories spaced in longitude. Here we present the results of observations collected from four facilities: the Telescopio Nazionale Galileo (TNG; Canary Islands), the du Pont telescope (Las Campanas Observatory, Chile), the Astrophysical Research Consortium telescope (ARC at Apache Point Observatory) and the NASA Infrared Telescope Facility (IRTF; Mauna Kea, HI).

Data for five additional events are listed in Table 1 to enable updates to future event predictions. Three observations for which attempts were made to collect data are included for completeness, although these datasets are not of sufficient quality for further analysis. We report the observing circumstances, the event mid-times (most are only partial events) and occultation depths for these observations; the constraints required for the predictions. The numbers in the table were provided by the observers listed in Column 7 and reflect a combination of the observing conditions, data sensitivity, and event coverage. Detailed modeling or interpretation of these additional datasets/events are beyond the scope of this Icarus note and are left to other publications.

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Mutual events occur when the components of a binary system occult and eclipse each other as seen from the Earth. A superior event occurs when the primary (Sila) passes in front of the secondary (Nunam) from our perspective on Earth; an inferior event is the reverse. The separation of Sila and Nunam is $a/r_{Sila} \approx 22$, so the apparent angular size of one component from the other is 2.5°. The heliocentric orbital period of Sila–Nunam is ~290 years. Including grazing and shadow events and taking into account the Earth's motion as well, the mutual event season lasts for about 8 years (see Fig. 3 from Grundy et al., 2012) for this particular system. The 2012–2013 observing season has been estimated as the mid-point of the Sila–Nunam mutual events and, as a result, the deepest eclipses and occultations should be measured during this time. As a result of the changing geometry of the system components relative to each other and the Earth, observations throughout the remainder of the mutual event season can provide significant constraints on our understanding of the dynamics within the system and the physical properties of the components.

The duration and depth of the eclipses/occultations allows us to more accurately determine the diameters of the two components. The combined timing of superior and inferior events allows us to better constrain the orbital eccentricity and period of the mutual binary orbit. Observations in multiple filters can allow us to crudely map large scale surface ices. This was done for the Pluto/Charon system between 1984 and 1990 (Buie et al., 1992; Binzel and Hubbard, 1997). Sila is roughly one tenth the diameter of Pluto so we do not expect directly comparable results. However, by observing events over the full duration of the mutual event years in both superior and inferior configurations, we will be able to determine on hemisphere or perhaps tens of degree resolution scales (depending on the size & resolution of telescope/instrument combinations used for the observations), the distribution of surface brightness suggestive of ices or dark patches. Given the distance of these objects from the Sun, this task is more easily accomplished with observations of the mutual events then with high resolution imaging or spectroscopy.

Approximately 81 binaries (see Noll et al., 2008a for a review; Parker et al., 2011) have been discovered since 2002 (Veillet et al., 2002; excluding Pluto/Charon). Of the known objects, only Pluto/Charon (Buie et al., 1992; Binzel and Hubbard, 1997) and Haumea (Ragozzine and Brown, 2010), have had mutual events observed. About half of the known transneptunian binary objects have measured orbits: periods range from a few days (Pluto at 6.38 days, Buie et al., 2006) to years (2001 QW_{322} at 25–30 years, Petit et al., 2008). Mutual orbit eccentricities span a range of phase space from 0 to 0.8 with a concentration around 0.5 (Noll et al., 2008a, 2008b; Grundy et al., 2009, 2011). Separations range from 300 km (Sheppard and Jewitt, 2004; Takahashi and Ip, 2004) to over 100,000 km (Parker et al., 2011) – a few to thousands of diameter ratios. For closer objects mutual events occur more frequently, likewise, objects of similar size exhibit deeper mutual events since they cover proportionally larger areas of each other as they pass in front and behind each other. As more objects are discovered and their orbits determined, additional systems undergoing mutual events can be expected to be identified.

2. Observations

Observations were collected using four coordinated telescopes including the TNG (observations ranged from JD 2456331.4540 to 2456331.7287 and were carried out by A. Doressoundiram, A. Thirouin), a 3.58-m telescope in the Canary Islands, the 100″ du Pont telescope at Las Campanas Observatory (observations ranged from JD 2456331.5938 to 2456331.8202 and were carried out by S. Benecchi), Chile, the ARC 3.5-m telescope at Apache Point Observatory in Sunspot, New Mexico (observations ranged from JD 2456331.57361 to 2456331.90139 and were carried out by A. Verbiscer) and the 3.0-m IRTF on Mauna Kea, HI (observations ranged from JD 2456331.7626 to 2456332.0716 and were carried out remotely by S. Benecchi, K. Noll and E. Ryan with assistance from S. J. Bus). The Device Optimized for the LOw RESolution instrument (DOLORES or LRS) imager, a 2048 × 2048 E2V CCD with a pixel scale of 0.252 arcsec/pixel and a field of view of 8.6 arcmin square, was used at the TNG. The direct CCD camera, a SITe2K chip with a pixel scale of 0.259 arcsec/pixel and a field of view of 8.85 arcmin square, was used at the du Pont. SPIcam, a backside-

Table 1
Observed mutual events.

Minimum light[a]	FWHM	Min. flux	Type[b]	Telescope[c]	Filter	Observers/notes
2012/02/01	–	–	Superior	Perkins, SMARTS	R	W. Grundy, D. Rabinowitz, detection but too low S/N for modeling
2012/02/23	–	–	Superior	SOAR	Sloan_r′	S. Benecchi, no event observed
2012/03/01; 04.09224 ± 0.0532	0.06 ± 0.01	0.55 ± 0.05	Inferior	ARC, Anderson Mesa	R	A. Verbiscer, W. Grundy
2012/04/20		Lower limit 0.63	Inferior	ARC	R	A. Verbiscer/incomplete, confirm event occurrence
2013/01/20; 09.83040 ± 0.101	0.09 ± 0.01	0.60 ± 0.03	Inferior	ARC, Anderson Mesa	Sloan_r′	A. Verbiscer, W. Grundy
2013/02/08; 03.84000 ± 0.0462	**0.19 ± 0.02**	**0.60 ± 0.01**	**Superior**	**ARC, TNG, du Pont, IRTF**	**Sloan_r′**	**A. Verbiscer, S. Benecchi, A. Doressoundiram, K. Noll, E. Ryan, A. Thirouin**
2013/0214; 10.55760 ± 0.0137	0.18 ± 0.01	0.55 ± 0.01	Inferior	du Pont, IRTF	Sloan_r′	S. Benecchi, W. Grundy
2013/03/05; 04.54464 ± 0.0470	0.11 ± 0.01	0.61 ± 0.02	Superior	ARC, VATT	Sloan_i′ (ARC); Sloan_r′ (VATT)	A. Verbiscer, R. Beaton
2013/03/11; 11.29440 ± 0.0784	0.11 ± 0.01	0.65 ± 0.02	Inferior	IRTF	Sloan_r′	W. Grundy

Note: time of minimum light and minimum fluxes are derived from applying the Gaussian model described in the text to the dataset for each event. Most observations were of partial eclipses. The parameters and their accuracy reflect on the completeness and sensitivity of the individual datasets. The bolded line is the event for which the data itself is presented in this paper.

[a] "Minimum light" in UT is given in year, month, day and decimal hour, or UT date of the predicted event if an event was attempted but the data were not of sufficient quality to warrant modeling.

[b] "Superior" events are when Sila appears in front of Nunam and "inferior" events are when Nunam is in front of Sila.

[c] Telescopes include: ARC is the Astrophysical Research Consortium 3.5-m telescope at Apache Point Observatory in Sunspot, New Mexico. Anderson Mesa is the 72″ Perkins Telescope at Lowell Observatory west of Flagstaff, Arizona. The du Pont is the 100″ telescope located in Chile at Las Campanas Observatory. IRTF is the NASA Infrared telescope located on Mauna Kea. SOAR is the 4.1-m telescope situated on Cerro Pachón in Chile. TNG is the Telescopio Nationale Galileo in the Canary Islands. VATT is the Vatican Advanced Technology Telescope at Mount Graham International Observatory, Arizona.

illuminated SITe 2048 × 2048 CCD with a pixel scale of 0.14 arcsec/pixel and a 4.78 arcmin field of view, was used on ARC in a 2 × 2 binned mode. MIT Optical Rapid Imaging System (MORIS), an Andor iXon^{EM+} DU-897 camera co-mounted with SPEX (which we did not use) was used in conventional readout mode at the IRTF. MORIS has a pixel scale of 0.11 arcsec and a field of view of 1 arcmin square (Gulbis et al., 2011; Bus et al., 2011).

Seeing ranged from 1 to 1.5 arcsec at the four observatories: ~1.5 arcsec at the TNG, ~1.2 arcsec at the du Pont, ~1.2 arcsec at ARC and ~1.0 arcsec at the IRTF. Data at the TNG were collected for 900 s alternating in the Sloan r′ and Sloan g′ filters. At the du Pont and IRTF telescopes data were collected using the Sloan r′ filter for a duration of 300 s per exposure with alternating Bessel V and I filters at the du Pont; we only report on the V result in this paper. Observations from ARC were collected in the Sloan r′ filter at 300 s intervals and co-added in pairs increments to improve the signal-to-noise (S/N). Similarly the du Pont and IRTF datapoints were also co-added to improve the S/N.

The data for the other events listed in Table 1 include additional data collected using ARC, the IRTF and the du Pont as previously described. The 72″ Perkins Telescope at Lowell Observatory west of Flagstaff, Arizona, SOAR, a 4.1-m telescope situated on Cerro Pachón in Chile and the Vatican Advanced Technology Telescope (VATT) at Mount Graham International Observatory, Arizona were also used. At each facility an imaging camera with a large enough field of view for the Sila–Nunam and multiple comparison field stars was employed. Where available the Sloan_r′ filter was used, otherwise an R filter sufficed. The parameters and their accuracy reflect on the completeness and sensitivity of the individual datasets.

3. Data reduction and analysis

3.1. Image processing

In all cases images were bias subtracted and flatfielded. One benefit of this particular mutual event was the proximity of two comparison stars about one magnitude brighter than Sila–Nunam that fit within the limited MORIS field of view on the IRTF. A combination of aperture and PSF photometry was extracted on all three objects using a combination of IDL and IRAF routines. Absolute photometry was also collected using overlapping transneptunian Object-like colored Landolt (1992) and Sloan (Smith et al., 2002) standard stars: Rubin 149, PG1528+062, PG1047+003, SA95-142 and SA101-207. The APO data were not absolutely calibrated relative to standard stars, so the APO measurements outside of the event were shifted vertically to match the calibrated magnitude baseline outside of the event.

3.2. Lightcurve fitting

A single lightcurve is not enough to obtain unique results for fully constraining orbital or physical properties (like the object diameters) of the binary system. However, we can use this event to demonstrate the value of coordinating observations across multiple observing facilities and to improve predictions for future events. We use the event timings and astrometry to provide an updated set of predictions for the second half of the mutual event season for this binary system.

To be consistent in our timing interpretation for each mutual event observed, each individual event is fit with a Gaussian model of the form: $f(x) = Ae^{(x-x_c)^2}/\sigma^2$, where A is the amplitude of the curve, x_c is the location of the center of the Gaussian, and σ measures the width of the curve. We recognize that the light curve cannot be fully modeled by a Gaussian, however, it does effectively allow us to consistently calculate the timing of the minimum light and depth of each event. For the full event on UT February 7/8 (Fig. 1), the mid-point of the event was found to be at 3.84 ± 0.05 h. This is offset early from the predicted mid-point of 4.72 h by 52.8 min. The event start was ~1.5 h earlier than anticipated and the event duration was ~9.5 h, about 10% longer than predicted by Grundy et al. (2012). The implication is that there are limb effects not yet considered in our simplistic fit or that Sila and Nunam are not identical in size and/or albedo. We save this analysis for a future paper in which we will combine all the mutual event datasets to fit for component sizes, albedos, and mutual orbit inclination. The depth of the event was slightly less than expected, 0.54 ± 0.01 magnitudes; the predicted depth was 0.69 magnitudes. The slopes between the ingress and egress sides of the curve are consistent within 1 sigma, therefore we do not believe there is significant asymmetry in this lightcurve.

3.3. Lightcurve color

While the Sloan r′ filter was used across all facilities for consistency, color observations were acquired at the TNG and du Pont telescopes in different filters. At the TNG Sloan g′ filter observations were alternated with Sloan r′. At the du Pont the rest of the

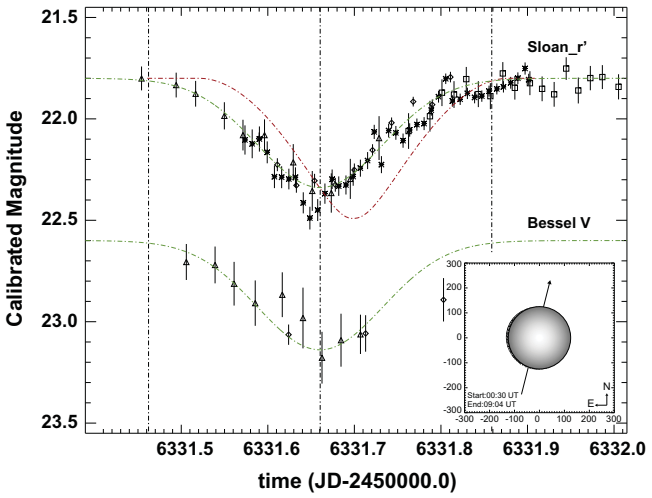

Fig. 1. Combined lightcurve for the UT 7/8 February 2013 mutual event in the Sloan r′ and Bessel V filters. Triangles are observations collected with the TNG, diamonds are observations collected using the du Pont, asterisks are observations collected using the ARC at APO, and squares are observations collected using the IRTF. The red dashed line is the event prediction (Grundy et al., 2012), while the green curve is a Gaussian fit to the data points. The vertical dashed lines indicate the locations of the first contact, minimum light and last contact. The actual event start was ~1.5 h earlier than anticipated and the event duration was ~9.5 h, about 10% longer than predicted. The depth of the event was slightly less than expected, 0.54 ± 0.01 magnitudes; the predicted depth was 0.69 magnitudes, a difference of ~20%. The slopes between the ingress and egress sides of the curve are consistent within 1 sigma, therefore we do not believe there is significant asymmetry in our result. At the TNG the Sloan g′ filter was alternated with the Sloan r′ filter. In the figure, the Sloan g′ data have been shifted to the Bessel V filter using the IRAF *synphot* routine. At the du Pont, the rest of the Sloan filter set was not available so a Bessel V filter was used (comparable to the Kron–Cousins V filter) to get a crude color lightcurve at alternating intervals. The green curve is the fit to the full Sloan r′ dataset from the top panel. The V curve is reasonably consistent with the Sloan r′ curve and the data on egress are sparse. We interpret this to mean that there are not large color variations on the objects in their current configuration. The insert on the lower right is a schematic diagram of the event showing the motion of Nunam relative to Sila and the location of the shadow of the foreground object at the distance of the more distant object (scale in km relative to the primary center). The model assumes spherical shapes and Lambertian scattering behavior. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Predicted UT dates of mutual events during the 2013–2014 apparition.[a]

First contact, UT (Y/M/D and decimal hours)		Min. light, UT (Y/M/D and decimal hours)		Last contact, UT (Y/M/D and decimal hours)		Duration[b] (decimal hours)	Event type[c]	Min. flux
2013/10/16	3.900	2013/10/16	8.450	2013/10/16	12.717	8.82	Superior	0.57
2013/10/22	10.783	2013/10/22	15.100	2013/10/22	19.133	8.35	Inferior	0.55
2013/10/28	16.100	2013/10/28	20.650	2013/10/29	0.900	8.80	Superior	0.57
2013/11/03	22.983	2013/11/04	3.283	2013/11/04	7.333	8.35	Inferior	0.56
2013/11/10	4.300	2013/11/10	8.833	2013/11/10	13.083	8.78	Superior	0.58
2013/11/16	11.183	2013/11/16	15.500	2013/11/16	19.517	8.33	Inferior	0.56
2013/11/22	16.500	2013/11/22	21.050	2013/11/23	1.267	8.77	Superior	0.58
2013/11/28	23.400	2013/11/29	3.600	2013/11/29	7.700	8.30	Inferior	0.57
2013/12/05	4.700	2013/12/05	9.183	2013/12/05	13.467	8.77	Superior	0.59
2013/12/11	11.617	2013/12/11	15.850	2013/12/11	19.900	8.28	Inferior	0.57
2013/12/17	16.933	2013/12/17	21.417	2013/12/18	1.650	8.72	Superior	0.59
2013/12/23	23.850	2013/12/24	4.083	2013/12/24	8.100	8.25	Inferior	0.58
2013/12/30	5.200	2013/12/30	9.583	2013/12/30	13.850	8.65	Superior	0.59
2014/01/05	12.117	2014/01/05	16.267	2014/01/05	20.300	8.18	Inferior	0.58
2014/01/11	17.450	2014/01/11	21.867	2014/01/12	2.033	8.58	Superior	0.60
2014/01/18	0.367	2014/01/18	4.450	2014/01/18	8.500	8.13	Inferior	0.59
2014/01/24	5.750	2014/01/24	10.067	2014/01/24	14.250	8.50	Superior	0.60
2014/01/30	12.683	2014/01/30	16.717	2014/01/30	20.700	8.02	Inferior	0.59
2014/02/05	18.033	2014/02/05	22.283	2014/02/06	2.450	8.42	Superior	0.60
2014/02/12	0.933	2014/02/12	5.000	2014/02/12	9.017	8.08	Inferior	0.57
2014/02/18	6.283	2014/02/18	10.600	2014/02/18	14.850	8.57	Superior	0.58
2014/02/24	13.167	2014/02/24	17.317	2014/02/24	21.383	8.22	Inferior	0.55
2014/03/02	18.533	2014/03/02	23.000	2014/03/03	3.233	8.70	Superior	0.56
2014/03/09	1.433	2014/03/09	5.633	2014/03/09	9.750	8.32	Inferior	0.53
2014/03/15	6.750	2014/03/15	11.317	2014/03/15	15.583	8.83	Superior	0.54
2014/03/21	13.667	2014/03/21	17.983	2014/03/21	22.117	8.45	Inferior	0.51
2014/03/27	19.000	2014/03/27	23.650	2014/03/28	3.933	8.93	Superior	0.53
2014/04/03	1.917	2014/04/03	6.317	2014/04/03	10.433	8.52	Inferior	0.50
2014/04/09	7.267	2014/04/09	12.000	2014/04/09	16.267	9.00	Superior	0.53
2014/04/15	14.183	2014/04/15	18.567	2014/04/15	22.717	8.53	Inferior	0.49
2014/04/21	19.517	2014/04/22	0.233	2014/04/22	4.550	9.03	Superior	0.53
2014/04/28	2.433	2014/04/28	6.817	2014/04/28	11.017	8.58	Inferior	0.49
2014/05/04	7.783	2014/05/04	12.517	2014/05/04	16.833	9.05	Superior	0.53

Note: $1-\sigma$ uncertainties on the event times are on order 15 min and times are computed for the best current orbit solution, assuming object radii of 125 km for Sila and 118 km for Nunam.

[a] Updates and 2015 event predictions posted online at http://www2.lowell.edu/~grundy/tnbs/79360_1997_CS29_Sila-Nunam.html.

[b] Duration is defined as the time between "first contact" and "last contact".

[c] "Superior" events are when Sila appears in front of Nunam and "inferior" events are when Nunam is in front of Sila.

Sloan filter set was not available so a Bessel V was used (comparable to the Kron–Cousins V filter) instead to get a crude color lightcurve at alternating intervals: Sloan r′–V–Sloan r′. In the bottom panel of Fig. 1 we show the sparsely sampled color observations in comparison with the densely sampled Sloan r′ observations. We offset the Sloan g′ magnitudes to Bessel V by 0.48 magnitudes using the IRAF *synphot* routine.[1] The V curve is reasonably consistent with the Sloan r′ curve, especially when considering the uncertainties and the lack of data during egress, indicating that there are not likely large color variations on the objects in their current configuration.

4. Event predictions

Observations of many individual occultation events enable us to improve our knowledge of the orbital parameters of Sila and Nunam's mutual orbit, and thus provide improved predictions for the timing of future events. In order to make use of the available observations to improve future predictions, the two objects were taken to have astrometric separations of zero at each occultation midtime listed in Table 1. The astrometric uncertainty we assigned to each of these points was the estimated sum of the radii of the two bodies (243 km, projected to the distance of the Sila–Nunam system at the time of each event) in the East–West direction. In the North–South direction, where most of the relative motion during an event occurs, we assigned an uncertainty equal to the relative sky plane distance traveled during the sum of the event mid-time measurement uncertainty plus the time difference between predicted occultation and eclipse maxima.

Using the relative astrometry reported by Grundy et al. (2012) plus these occultation-derived positions, we re-fit the orbit, using the same procedures as described in the 2012 paper. The latest astrometric observation used in the 2012 paper was from May 2010. By including mutual event observations from 2012 and 2013, we extended the time base over which the system has been observed. The greater temporal coverage primarily benefited the determination of the orbital period, from the earlier value of 12.50995 ± 0.00036 days to an improved value of $12.510061 \pm 1.81361 \times 10^{-5}$ days. The eccentricity determination also improved modestly, shrinking from 0.020 ± 0.015 to 0.025 ± 0.006, thanks to the symmetry of timing between superior and inferior events. We use the improved orbital parameters to predict events for the 2014 apparition as listed in Table 2 and online at http://www2.lowell.edu/~grundy/tnbs/79360_1997_CS29_Sila-Nunam.html. These predictions were based on a model of the system where Sila and Nunam are taken to be equal-albedo spheres with radii of 125 and 118 km, respectively. We report times of first and last contact, along with the time and magnitude dip at the lowest point in the lightcurve, assuming Lambertian scattering behavior.

[1] In *synphot* we use the Kurucz solar model as our reference standard and a reddening function (ebmv) of 0.1 which corresponds to a color term of ~0.55 magnitudes in V–R (Benecchi et al., 2011).

5. Conclusions

Using telescopes in Europe, Chile and the US (mainland and Hawaii) we successfully observed the first full mutual event for the Kuiper Belt binary (79360) Sila–Nunam. The event start was ~1.5 h earlier than anticipated and the event duration was ~9.5 h, about 10% longer than predicted, possibly due to non-Lambertian limb darkening, differences in the albedo and size of the components from the baseline model, and/or remaining uncertainties in the mutual orbit. The depth of the event was slightly less deep than expected, 0.54 ± 0.01 magnitudes; the predicted depth was 0.69 magnitudes. We present a list of events in 2014 and 2015 (online) for this mutual binary system and encourage others to help us obtain observations to better characterize this system. The timing for events should now be accurate to a few tens of minutes.

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