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The stellar occultation by the Centaur (2060) Chiron on November 28, 2018 and the search for rings

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Abstract. Ring systems had not been observed in other bodies besides the giant Planets until recently. However, after the discovery of two narrow and dense rings around the Centaur object Chariklo and the dwarf planet Haumea, we noticed that other objects present similar properties, be it rings, shells, or jets. The second-largest the Centaur object (2060) Chiron has presented secondary events during a stellar occultation observed in 2011 that were interpreted as two narrow and dense rings. In this work, we present the results of a single-chord stellar occultation analysis by the Centaur (2060) Chiron observed at South Africa on 2018 November 28. We have reanalyzed the 2011 event to determine the putative ring properties (width, opacity, optical depth, radius) and explored the 2018 data for short duration events prior and after the occultation by the main body. Our results present a non-central chord with a length of 179.33 ± 0.63 km, and no noticeable secondary events that could be associated with the suggested rings are detected.

Resumo. Sistemas de anéis não haviam sido observados em outros corpos além dos planetas gigantes até recentemente. No entanto, após a descoberta de dois anéis estreitos e densos em torno do Centauro Chariklo e do planeta anão Haumea, notamos que outros objetos apresentam propriedades semelhantes, sejam anéis, cascas ou jatos. O segundo maior Centauro, (2060) Chiron, apresentou eventos secundários durante uma ocultação estelar observada em 2011, que foram interpretados como dois anéis estreitos e densos. Neste trabalho, apresentamos os resultados da análise de uma ocultação estelar pelo Centauro (2060) Chiron observado na África do Sul em 28 de novembro de 2018. Reanalisamos o evento de 2011, para determinar as propriedades do anel proposto (largura, opacidade, profundidade óptica, raio) e exploramos os dados de 2018 em busca de eventos de curta duração antes e depois da passagem corpo principal em frente a estrela. Nossos resultados apresentam uma corda não central com um comprimento de 179, 33±0, 63 km e não detectamos nenhum evento secundário claro que possa ser associado ao perfil dos anéis sugeridos.

Keywords. Minor planets – asteroids: individual: (2060) Chiron

1. Introduction

The asteroid (2060) Chiron (formerly 1977 UB) was first observed by Kowal in November 1^{st}, 1997 using the 122-cm Schmidt telescope located in Palomar (Kowal et al. 1979). The orbit lies between Jupiter and Neptune (from 8.5 to 19 AU). Chiron is the second largest known the the Centaur - the biggest one is (10199) Chariklo. Various diameters have been estimated for Chiron using different techniques. Lebofsky et al. (1984) estimated 173 km, Campins et al. (1994) estimated 182-189 km, Elliot et al. (1995) estimated to be >180 km. Using Herschel Space Telescope the determined diameter was 218 ± 20 (Fornasier et al. 2013) and using ALMA (Atacama Large Millimeter Array) observations the mean diameter was estimated to be 210^{+11}_{-14} km (Lellouch et al. 2017). The last one is used in this work.

This object showed cometary-like activity in observations between 1988 and 1989 (Luu & Jewitt 1990). The possibility of Chiron being a comet arose after the report of unresolved coma (Tholen et al. 1988; Meech & Belton 1990; Hartmann et al. 1990). This explains why the comet designation 95P/Chiron is also adopted. The subsequent observations shows that the brightness variations should occur due to a release of volatile (timescale of hours) and due to a variations on coma density (timescale of decades) (Luu & Jewitt 1990; Bus et al. 1991), respectively.

The stellar occultations by Chiron that occurred in 1993 and 1994 were reported by Bus et al. (1996) and Elliot et al. (1995), respectively. In these events, the presence of dust in the inner coma was detected and features in the light curve were interpreted as collimated jets of material expelled from the nucleus. In 2011, another successful stellar occultation was reported and the lightcurves showed a solid-body detection and symmetric features distant 400 km from the Chiron center. This feature was interpreted as being a near-circular arc or shell of material with 3 km width for the inner and 7 km for the outer collimated jet, separated by 10-14 km. After the discovery of two dense rings orbiting the Centaur Chariklo (Braga-Ribas et al. 2014) and in around a dwarf planet Haumea (Ortiz et al. 2017), the search for other objects with these feature was triggered. The rings detected around Chariklo have width of 7 km and 3 km, with a gap between them of 14 km, distant 400 km from the center. Considering the similarities between Chiron and Chariklo and after a reanalysis of the occultation events mentioned above, a ring system around Chiron was proposed, besides the determination of two possible pole orientation for the rings, where the preferred pole solution could explain the rotational lightcurve variation in several decades (Ortiz et al. 2015).

In this work we present the results of a predicted occultation by (2060) Chiron recorded over South Africa in November 28, 2018. We reanalysed the lightcurve of the 2011 event to determine the properties of the putative rings (width, opacity, optical depth, radius) and explored the 2018 data-set looking for shallow drops in the flux in order to find characteristics compatible with the proposed rings. Sec. 2 shows the general information

Table 1. Observation circumstances for this event.

Site	Longitude Latitude Altitude	Telescope Camera	Exp. Time Dead Time (s)	Observer	Detection
SAAO Sutherland South Africa	20 48 37.8 -32 22 41.88 1760 m	1.0m SHOC	1.5	Amanda Sickafoose	Positive
Boyden Bloemfontein South Africa	26 24 17.0 - 29 02 19.79 1372 m	Alta-U55	10	Pat Van Heerden	Not Detected
ATOM Khomas Region Namibia	16 30 10.2 -23 16 23.4 1800 m	ATOM2 DU888_BV	1 0.00443		Wrong field

about the event and data analysis. Sec. 3 shows the secondary dimming analysis. The results are shown in Sec. 4.

2. Data Analysis

To predict the 2018 event, Version 9 of NIMA (*Numerical Integration of the Motion of an Asteroid*) Ephemeris was used (Desmars et al. 2015). The NIMA V9 (for short) is an update of early versions with observations from OPD (Pico dos Dias Observatory, Brazil) and the results of previously occultations. The candidate star is GAIA DR2 646598228351156352 with magnitude V=17.01 based in catalog NOMAD (Zacharias et al. 2004) and with ICRF/J2000 position:

$$\alpha = 23^h 46^m 04^s.34$$

$$\delta = +02^o 13' 05''.54$$

So, the shadow path was predicted to pass over South Africa and Namibia. The relative velocity of Chiron in this occasion was 5.77km s^{-1}. Three sites attempted to observe, but only one had a positive detection - Amanda Sickafoose in South Africa Astronomy Observatory, using the 1-meter telescope with exposure time of 1.5 seconds made by SHOC camera (see Tab. 1). The event was not detected in Boyden, South Africa, due to a long exposure, but the event geometry shows that the chord could be (a short) positive if the images were acquired with a shorter exposure time. The site in Namibia acquired images without the candidate star, although the projection in the sky plane indicates that the chord would be negative.

This data set was analysed using Platform for Reduction of Astronomical Images Automatically (*PRAIA*) (Assafin et al. 2011) task by differential photometry method. The photometry was made using two reference stars, where we obtained the smallest dispersion (6.02%). The light curve obtained shows a deep drop caused by the pass of the main body (see Fig. 1) but secondary drops were not clearly observed. To fit the occultation by the Chiron's nucleus we used a square-well model, convoluted with a Fresnel diffraction, the star diameter and the finite integration time. Fig. 1 shows the geometric model plotted over data points.

2.1. Model fits

We used the best fit of the rings for (2060) Chiron proposed by Ortiz et al. (2015). In that paper the mean radius of rings is (324 ±10) km. Also the two possible orientations of the pole of this ring are λ = (352 ± 10^o), β = (37 ± 10^o) or λ = (144 ± 10^o),

Table 2. Results from square-well fits to the occultation by main body.

Duration (s)	Length (km)	Ingress (s)	Egress (s)
31.08 ± 0.11	179.33 ± 0.63	75014.817 ± 0.105	75045.887 ± 0.112

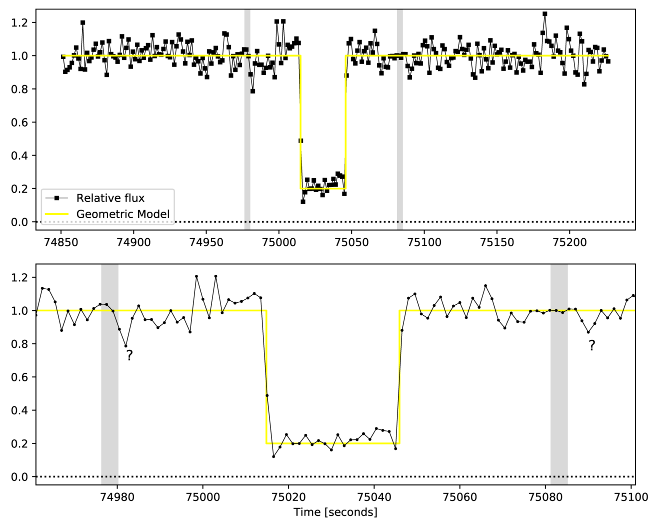

Figure 1. Light curve of (2060) Chiron occultation in November 28, 2018. The black dots shows the midtime in seconds after 2018 November 28 00:00:00.000 for each frame. The yellow curve shows the best fit to square-well model. Gray vertical bars shows the position of the proposed rings by Ortiz et al. (2015)

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β = (24 ± 10^o) where the λ = (144 ± 10^o), β = (24 ± 10^o) solution provide a better match with the amplitude of rotational light curves in literature. Note that this site didn't clearly detect the ring (or jet-like features) perhaps because of the low signal-to-noise ratio, but here we will considered the occultation geometry and search for possible shallow flux drops before and after the main event that could characterize the presence of rings or shell. In this case we have a unresolved ring event, so we search for the best fit of the square-well model using the average values of distance from Chiron center to the ring of (324 ±10) km (Ortiz et al. 2015) and the feature width of (7 ±2) km (Ruprecht et al. 2015). Using a second degree polynomial fit, we calculated the dispersion near the drops in 74981 seconds and 75089 seconds. In these instants, we have shallow drops which can be interpreted as rings or shell. The transmission, equivalent width and opacity for the proposed rings were found from reanalysis of the 2011 November 29 event (Ruprecht et al. 2015).

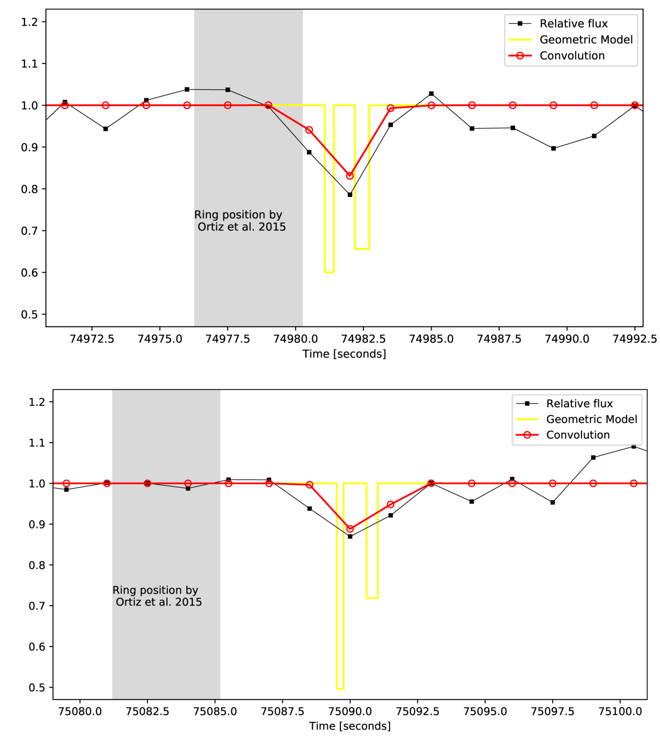

Figure 2. Geometric curve extracted using the ring width and optical depths from reanalysis of the 29 November 2011 event. The red line and circles represent the modelled light curve considering the flux drop promoted by the putative rings.

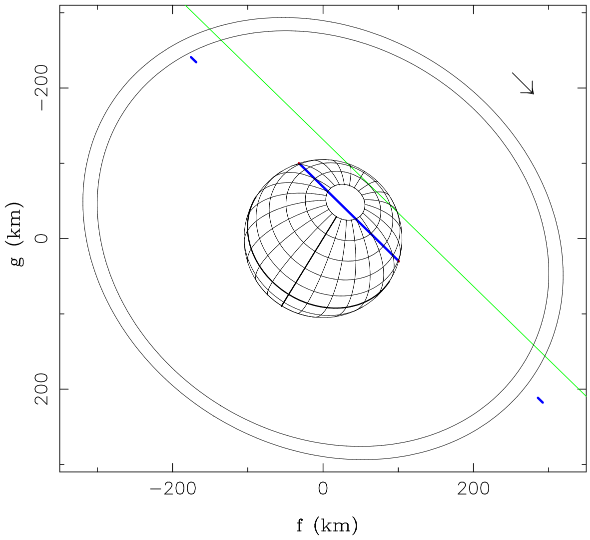

Figure 3. On sky plane plot of the observed chords. The main body is represented by a 105 km sphere in radius (Lellouch et al. 2017). The blue segments are the main body event and possible material detection, the green line is the negative observation. The rings plotted with 324±10 kilometers from Chiron center, as proposed by Ortiz et al. (2015).

3. Results

From the reanalysis of the sharp drops of the 2011 event, we could determine the ring profiles and apply that to search for them in the 2018 light curve. The geometric model in the location of the putative rings can be seen in Fig. 2. The Chiron's diameter could not be obtained as only one site detected the event — this also limits the determination of the shape of the object, which was treated as spherical here. Furthermore, we observed two shallow drops in flux near to 290 km (74980 s) and 360 km (75090 s) from the body center, that could evidence the presence of some material.

4. Conclusion

Using the instants of ingress and egress of the central body and the instants determined in the best fit for the rings, we can plot Chiron and the putative rings in the plane of the sky, as seen in Fig. 3. The center of the rings does not correspond to the center of the Chiron and the instants determined in Fig. 2 don't fit the proposed symmetric rings with 324 ± 10 kilometers as proposed by Ortiz et al. (2015). This can indicate that: i) the observed drops are just a local variation of the noise; ii) the center of the "rings" does not coincide with the center of a circular assumption for Chiron. These observations do not have the required quality to confirm the existence of the proposed rings, but a detection can not be ruled out as they fit the data with a 2σ confidence level.

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