An in-depth view of Chariklo and its rings

Analysis of stellar occ. observed between 2013 and 2020

B. Morgado et al.,

About myself

1. Grad. in Physics (IF/UFRJ): 2009-2013
2. Msc. in Astronomy (OV/UFRJ): 2013-2015
3. PhD in Astronomy (ON): 2015-2019
   a. One-year stay at Paris Observatory (2016-2017)
4. ERC Postdoc at Paris Observatory (2019-2020)
5. CNPq Postdoc at Observatório Nacional (2020- current)

Main interests

- Astrometry and Dynamics of Solar System Objects
- Stellar Occultations and Observational Techniques
- Minor Bodies of the Solar System.

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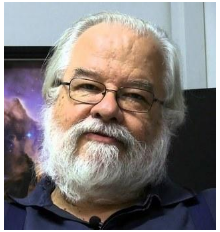
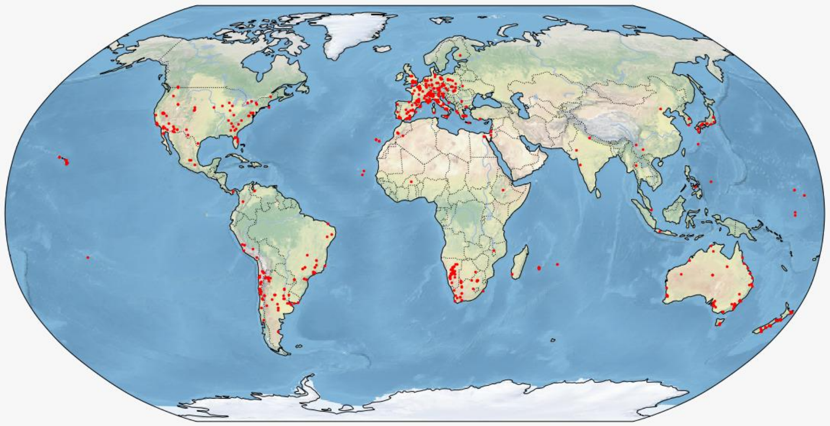
About LuckyStar

1. ERC projects that aims is to study the solar system beyond Neptune with stellar occultations. The project is led by Bruno Sicardy in collaboration with groups from Paris, Meudon, Granada and Rio.

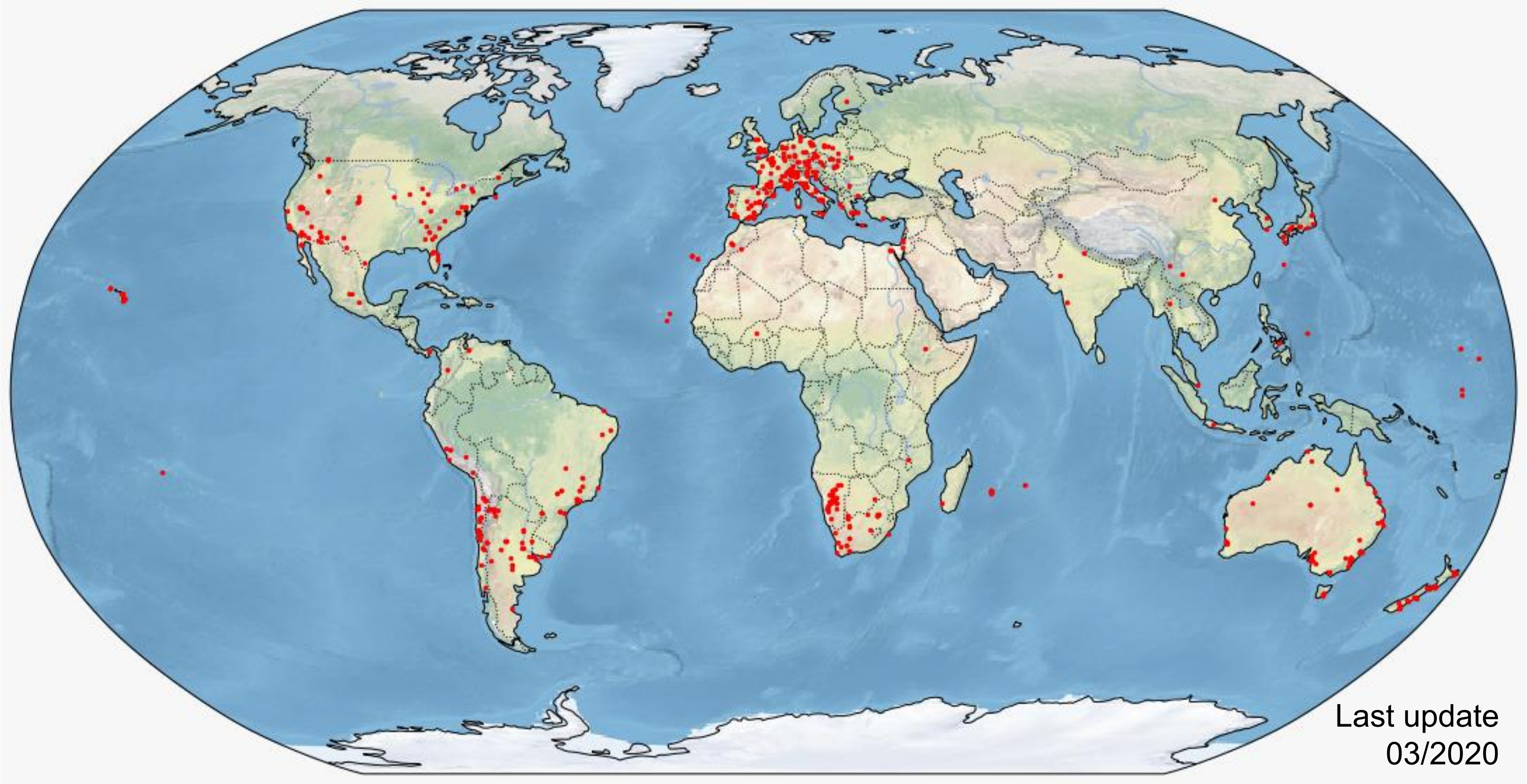




- Paris Group:
  - Led by Bruno Sicardy
- Rio Group:
  - Led by Roberto Vieira Martins
- Granada Group:
  - Led by José Luiz Ortiz



And a global collaboration with researchers and observers around the globe

About LuckyStar



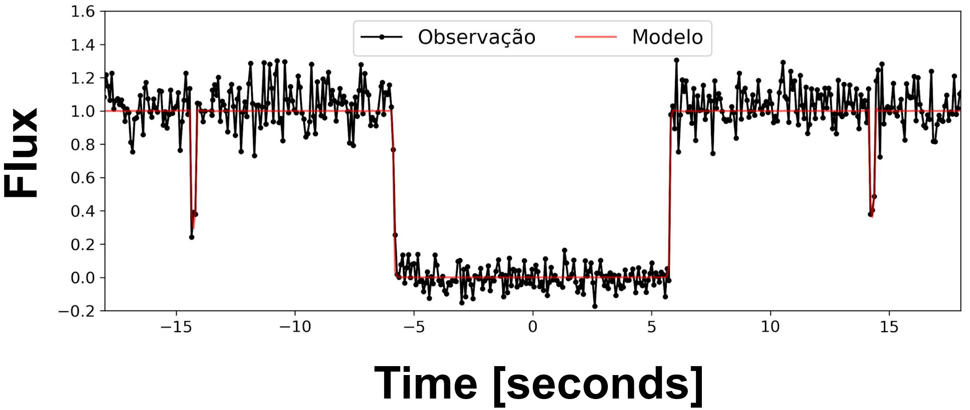
Last update
03/2020

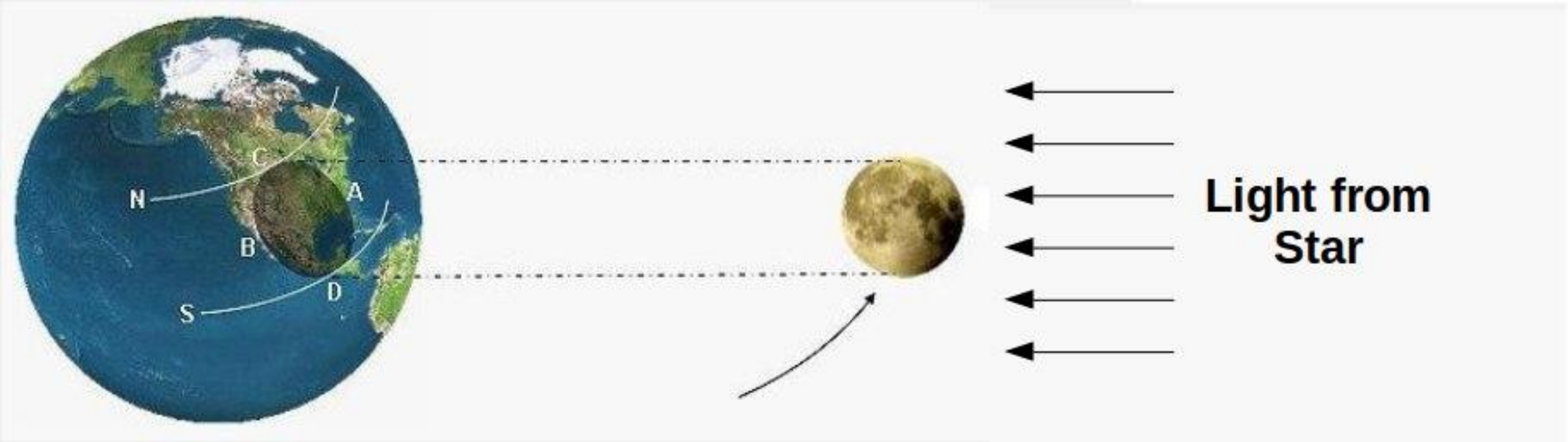
Stellar Occultations:

1. Stellar Occultations occurs when a Solar System Object cross in front of a star for an observer on Earth.

2. Each observer will obtain a light curve, showing a flux drop (event).

3. Allows the convert between time resolution to spatial resolution.





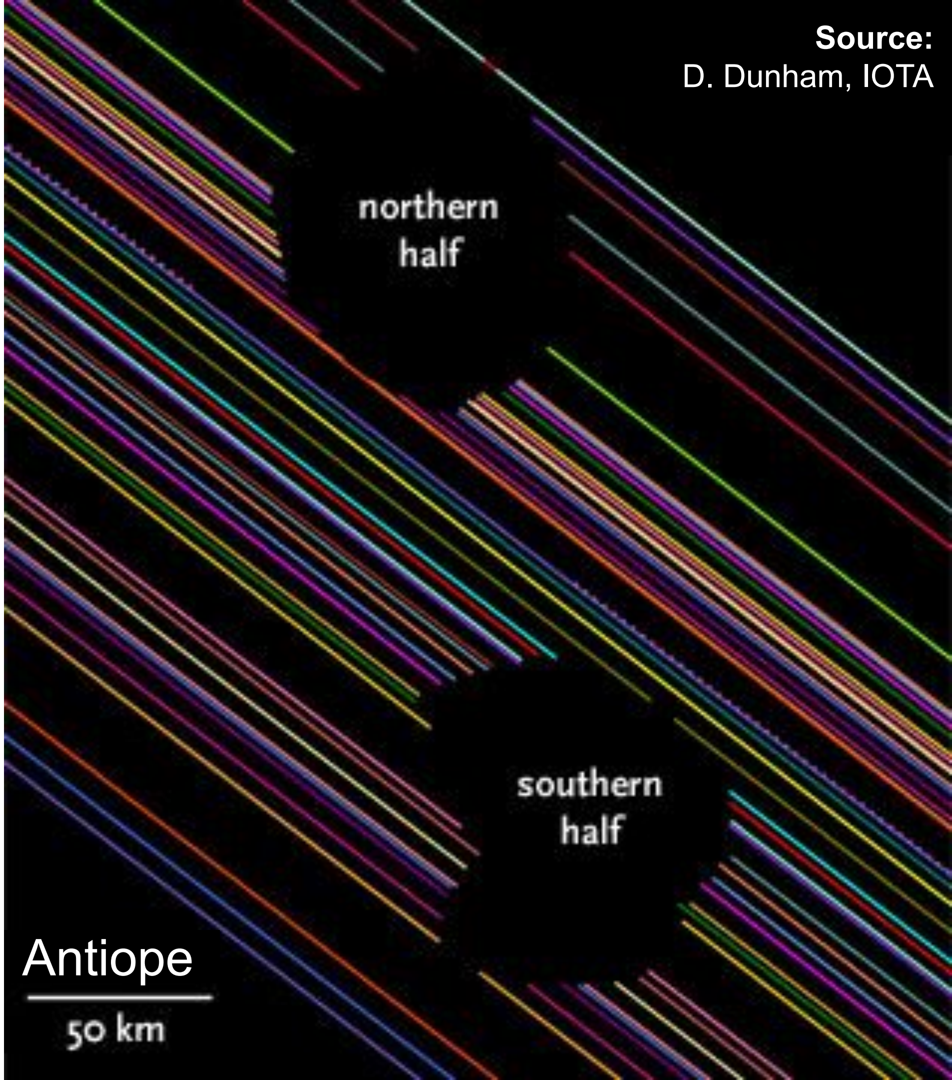
Stellar Occultations:

4. Allows the determination of 2D apparent shapes and sizes with km level uncertainties.

5. Allows probing the vicinity of objects in the search of material (rings, dust shell, etc), or even atmospheres in the nanobar level.

6. Allows the detection of contact binaries, topographic features (craters, chasms, etc)

7. Provides km level astrometric positions, allowing improved orbits and even the detection of non gravitational forces (for example the Yarkovisky Effect).



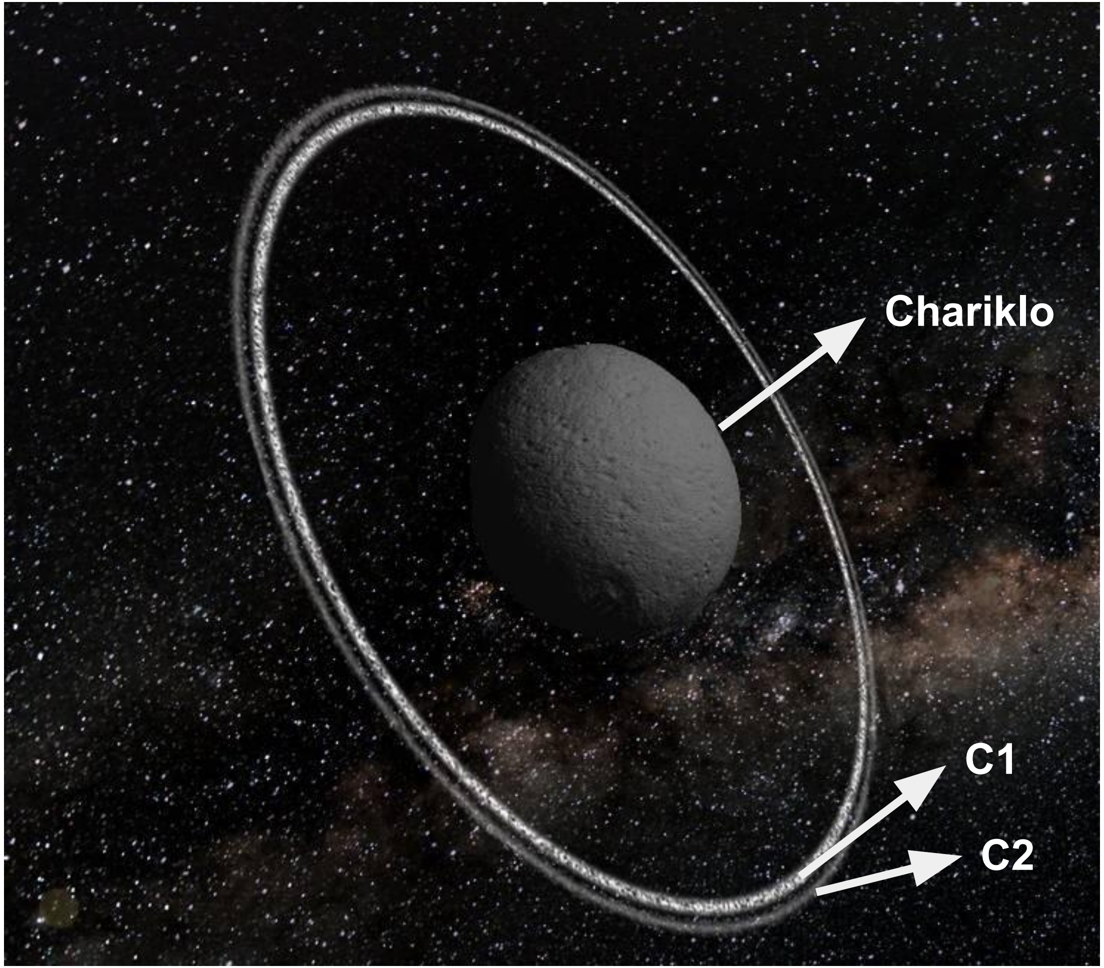
Chariklo:

1. Chariklo is a Centaur orbiting the sun at ~15.8 AU.

2. Discovered on 1997, is the largest known Centaur (~125 km of radius. **(Ticha et al., 1997 MPEC)**

3. Has the first ring's system discovered around a small body. It has two dense rings with radius of 391 and 405 km **(Braga-Ribas et al., 2014)**.

4. The rings system also explains some photometric and spectroscopic evidence **(Duffard et al., 2014)**.



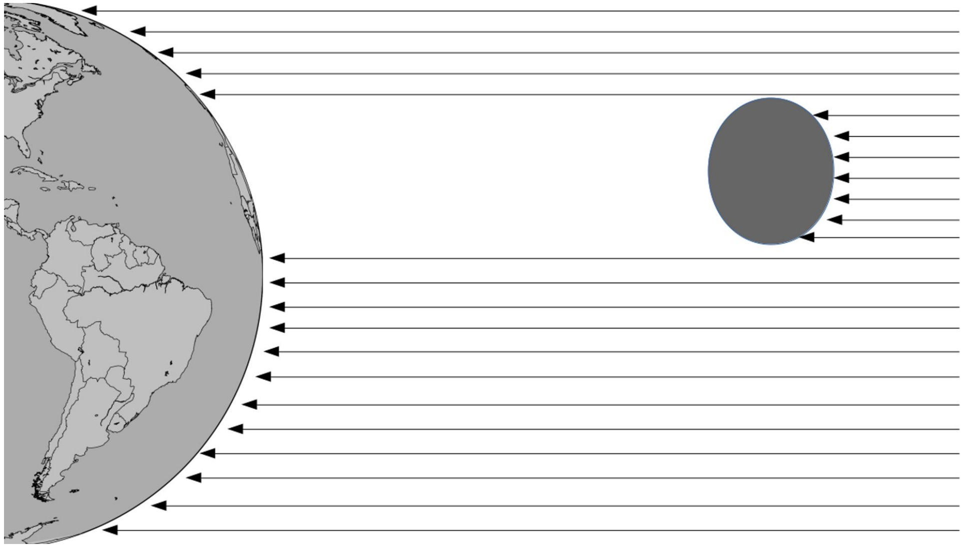
Maquet L., 2014

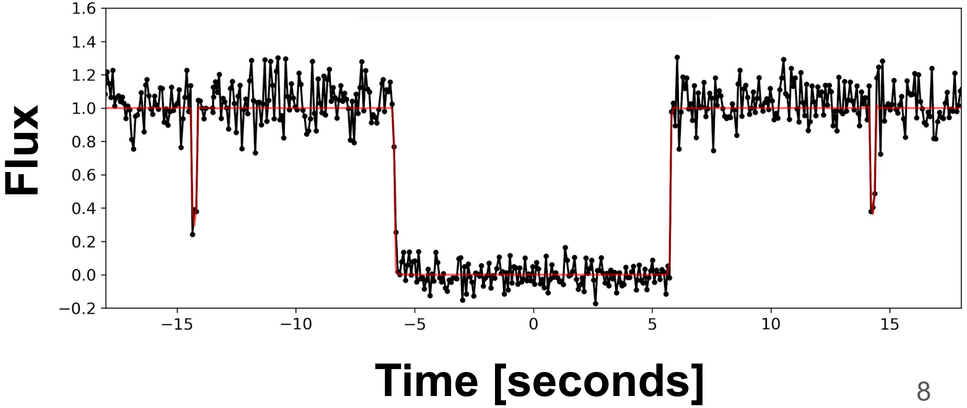
Chariklo and Stellar Occultations:

1. In 2013, Chariklo rings were discovered using the Stellar Occultation technique. **(Braga-Ribas et al., 2014)**

2. Between 2014 and 2016, 12 Stellar Occultation were observed. However all of them are single or double-chord events. **(Berard et al., 2016; Leiva et al., 2016)**

3. With Gaia DR2, these positive detection and NIMA, Chariklo ephemeris was improve and it had uncertainties smaller than 5 mas (~50 km) **(Desmars et al., 2017, DPS)**





Motivation:

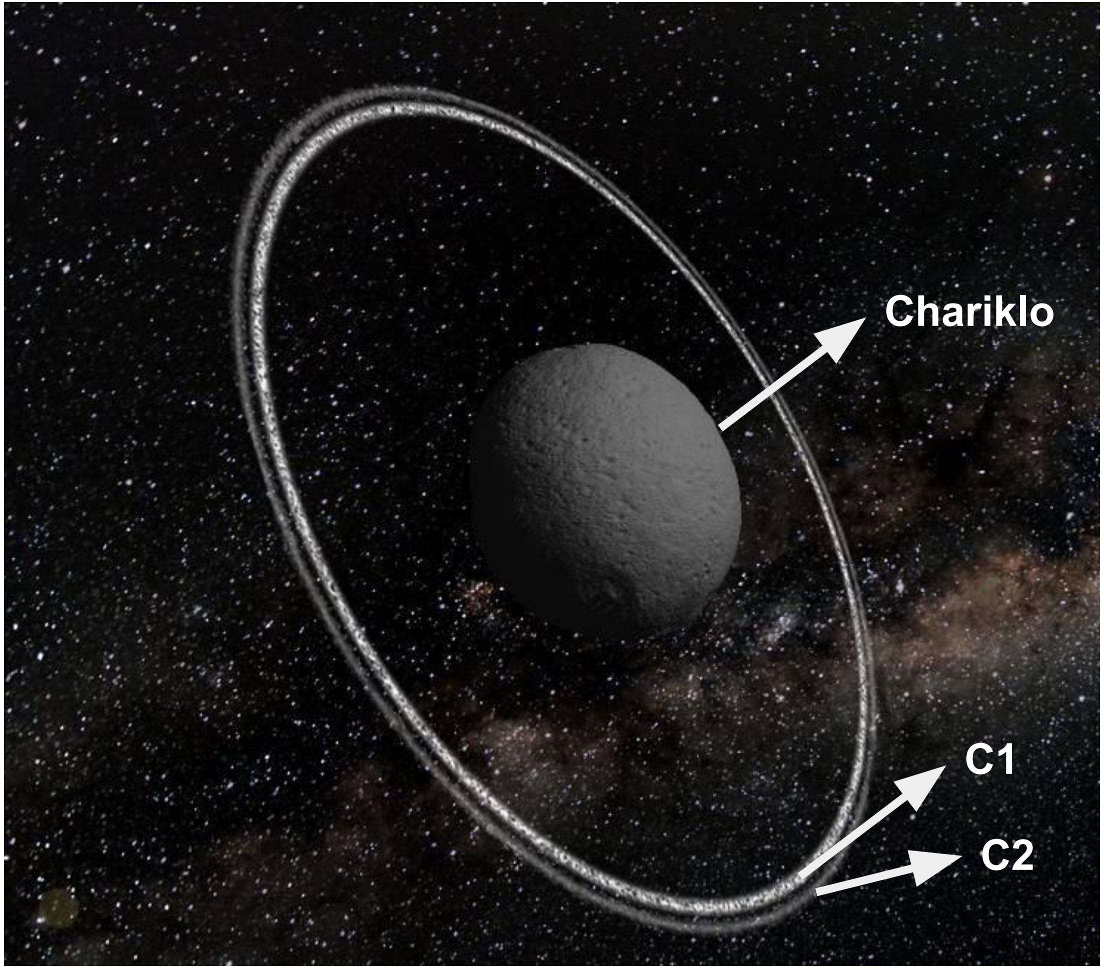
1. Questions we want to answer:

➔ What are the general shapes of the rings (C1 and C2) ?

➔ What is Chariklo's shape and density?

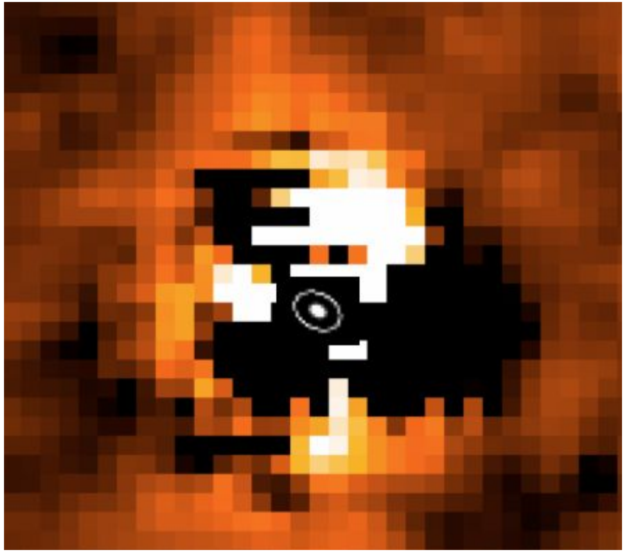
➔ There are inner structures in the rings ?

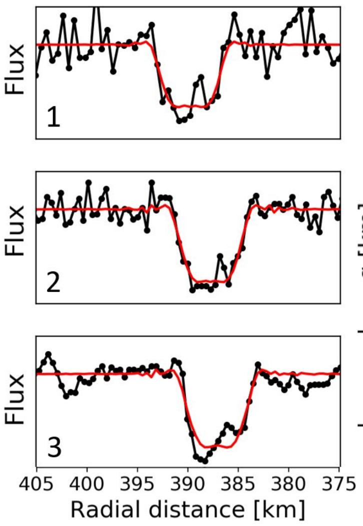
2. These results should be useful for constraining dynamical models of Chariklo and its rings, and provide new insights into the formation and evolution of this system.

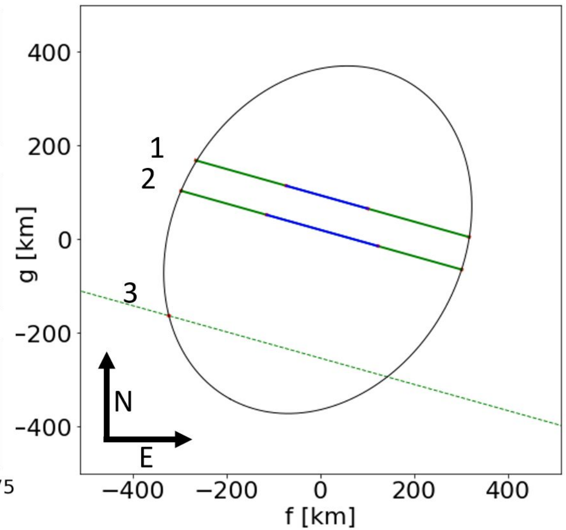


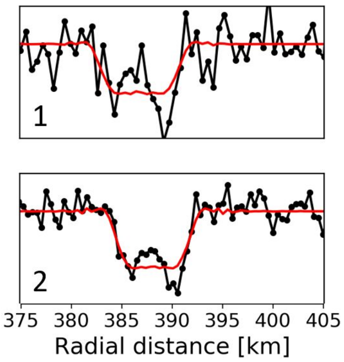
Maquet L., 2014

Why keep doing Stellar Occultations by Chariklo?









- HST PSF (30 mas)
- SPHERE @VLT PSF(30-40 mas)
- Chariklo in scale for comparison
- 10 mas → 100 km @ Chariklo's dist.

Is not possible to detect Chariklo's rings using HST [Sicardy et al., 2015, DPS]

X

- Small Telescopes: 30 - 50 cm
- Exposure times: ~0.1 seconds
- Event velocity: 5 km/s
- Resulting in ~0.5 km per data point

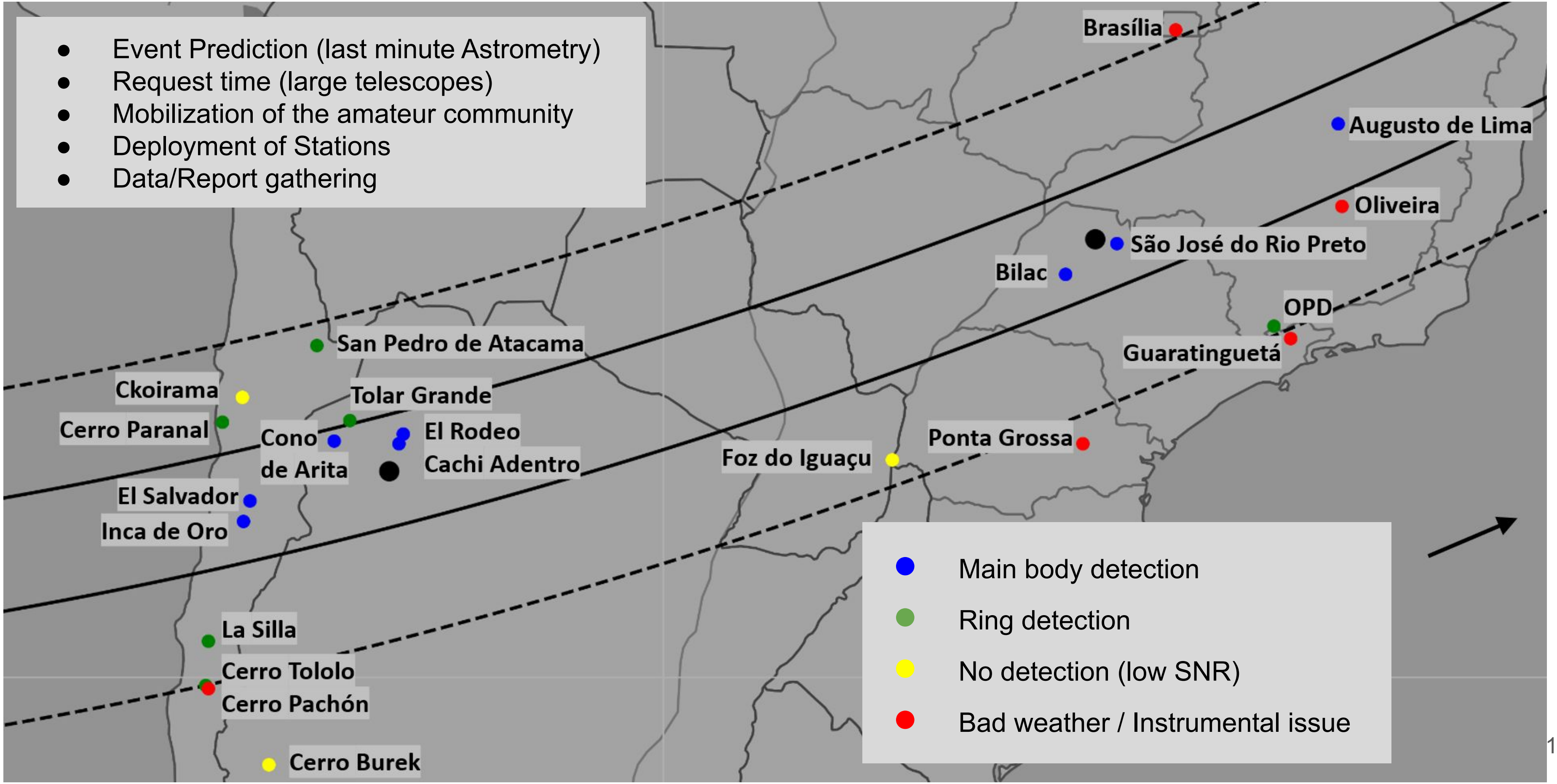
We can detect details in Chariklo C1R

Observation and Reduction Process

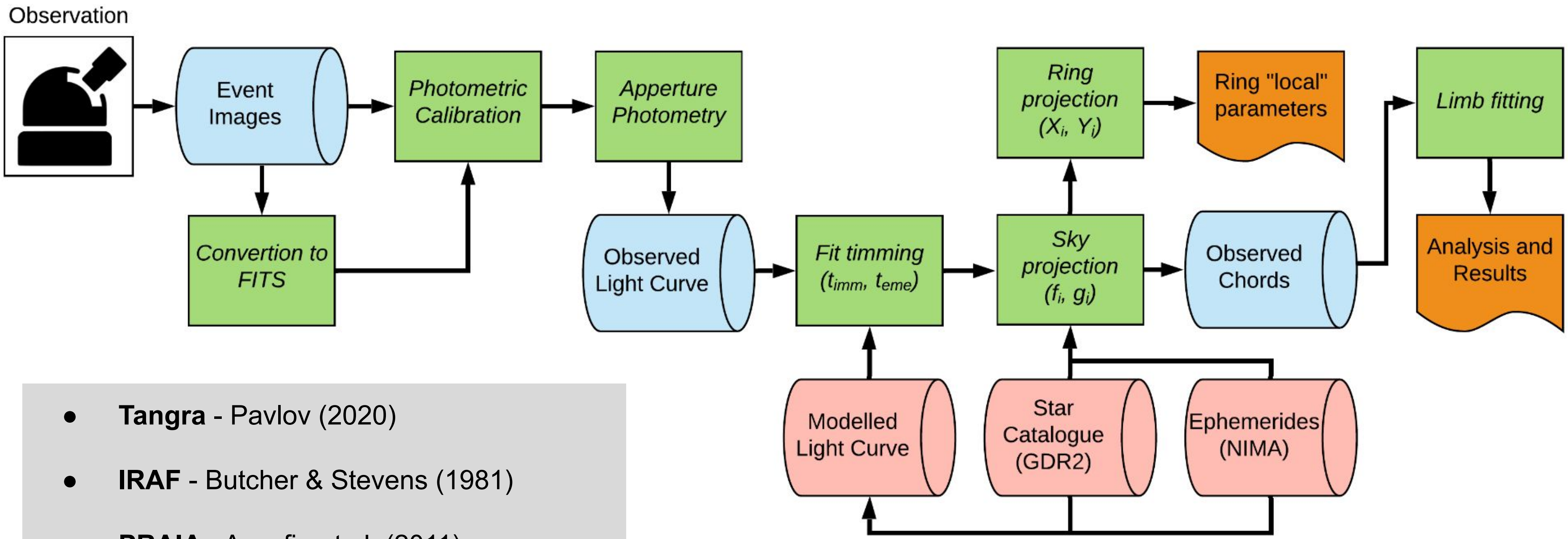
Overview

Observational Campaign: (2017-07-23)

- Event Prediction (last minute Astrometry)
- Request time (large telescopes)
- Mobilization of the amateur community
- Deployment of Stations
- Data/Report gathering



Reduction Process



- **Tangra** - Pavlov (2020)
- **IRAF** - Butcher & Stevens (1981)
- **PRAIA** - Assafin et al. (2011)
- **SORA** - Gomes-Júnior et al. (in prep) (http://sora.readthedocs.io)

Results

Ring's structure and parameters

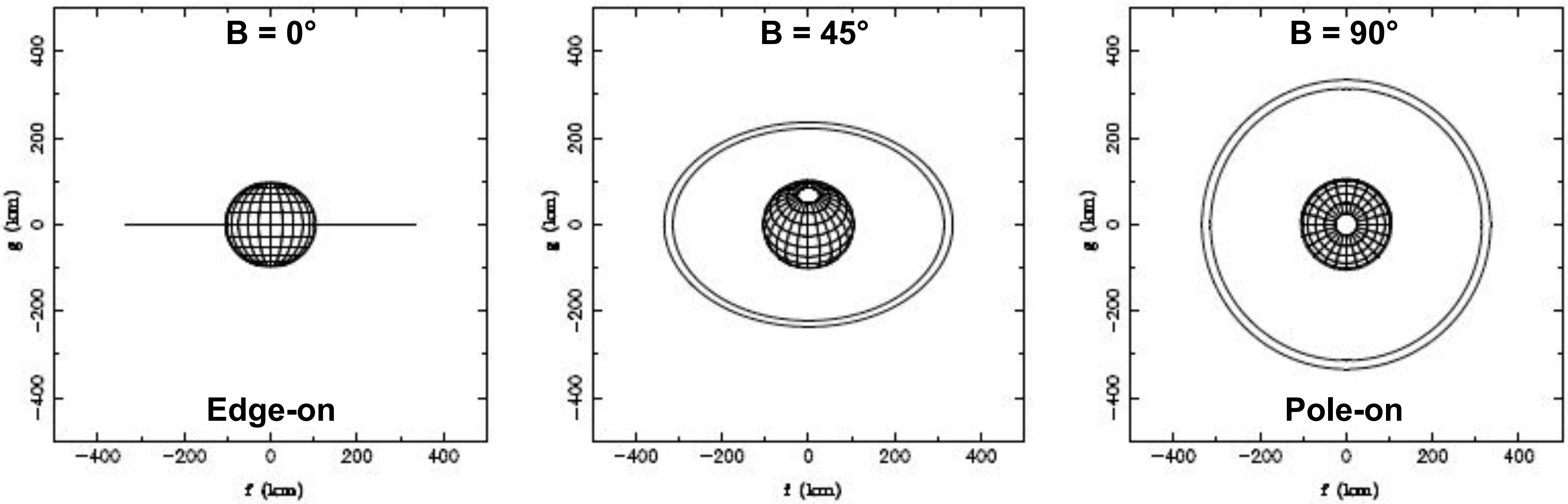
C1 - Ring radius and Pole position

C1 - Global ring parameters:

1st step: Fitting an ellipse on the project ring's times and getting the five main parameters: (f_c, g_c, ε', a', P).

2st step: Compute the pole position, considering that the rings are circular and all oblateness is due to geometry,.

Pereira C. L., 2020 (Dissertation)



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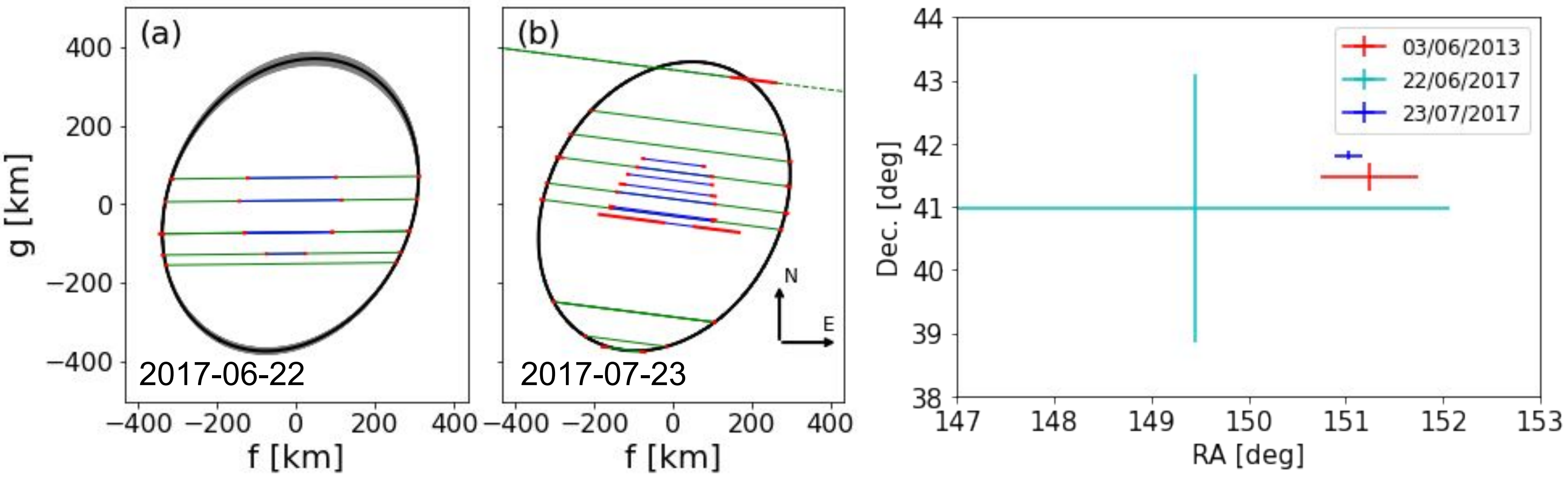
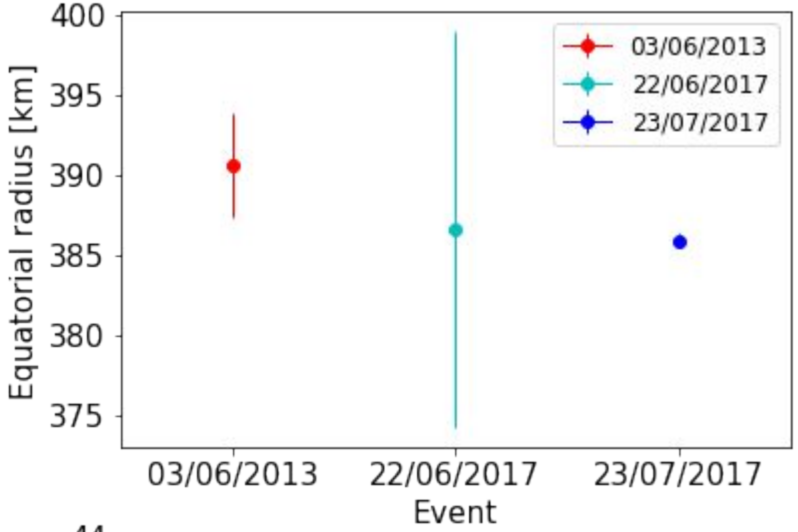
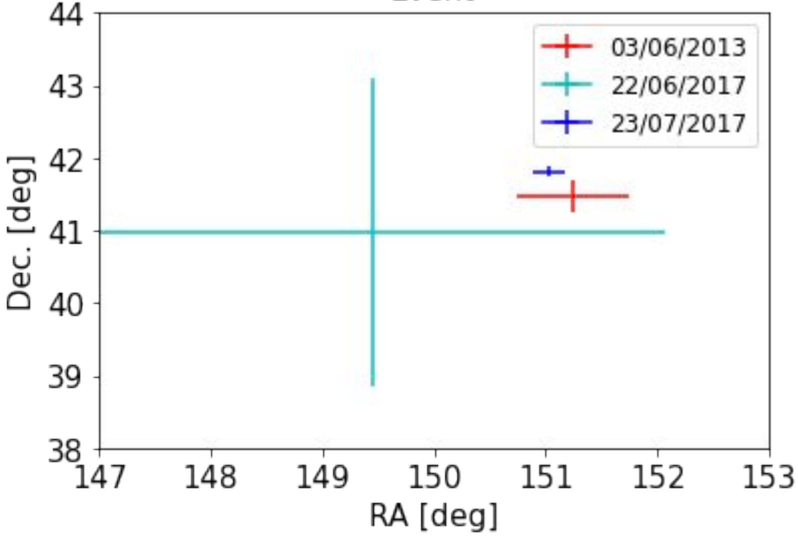


C1 - Global ring parameters:

Conclusions:

1. Ring radius in an ~1-σ agreement
2. Pole position in an 1-σ agreement
3. We can not discard the possibility of Chariklo's rings to be circular. Was not possible to measure any differences with a high level of confidence (more than 3-σ).





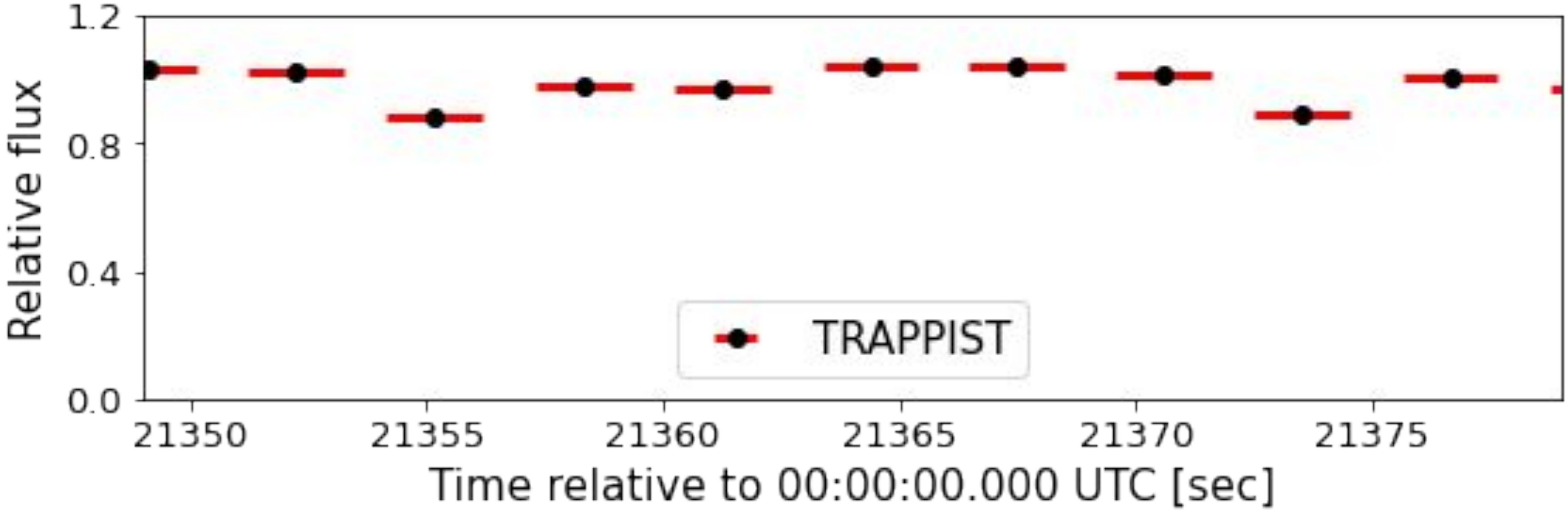
Ring's structure and parameters

C1 - Structures and radial width

C1 - Structures and Ring width

1st step: Fit resolved detection ($t_{immersion}$, $t_{emersion}$, opacity).

exptime = 2.000 seconds



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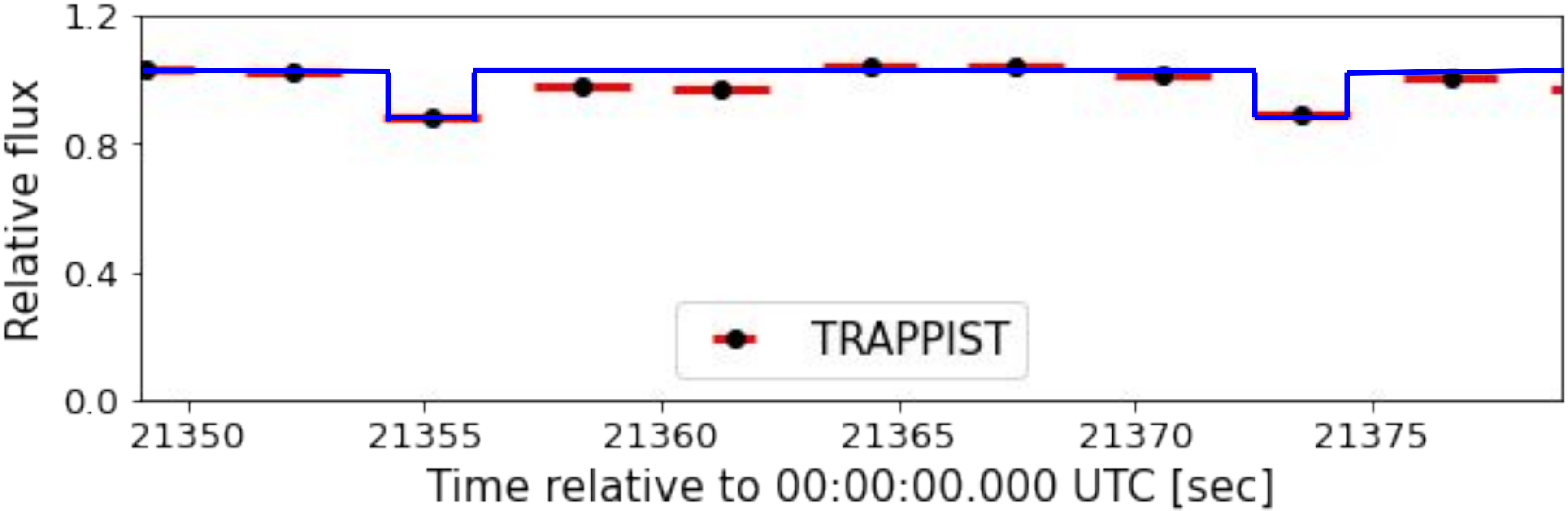

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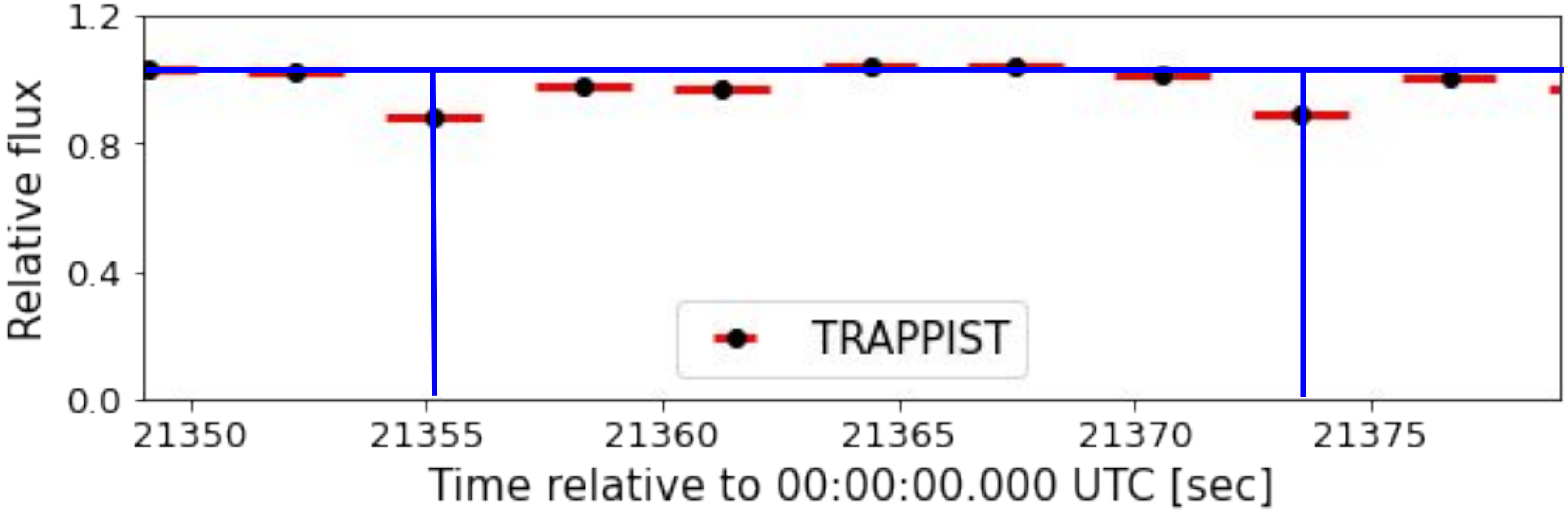
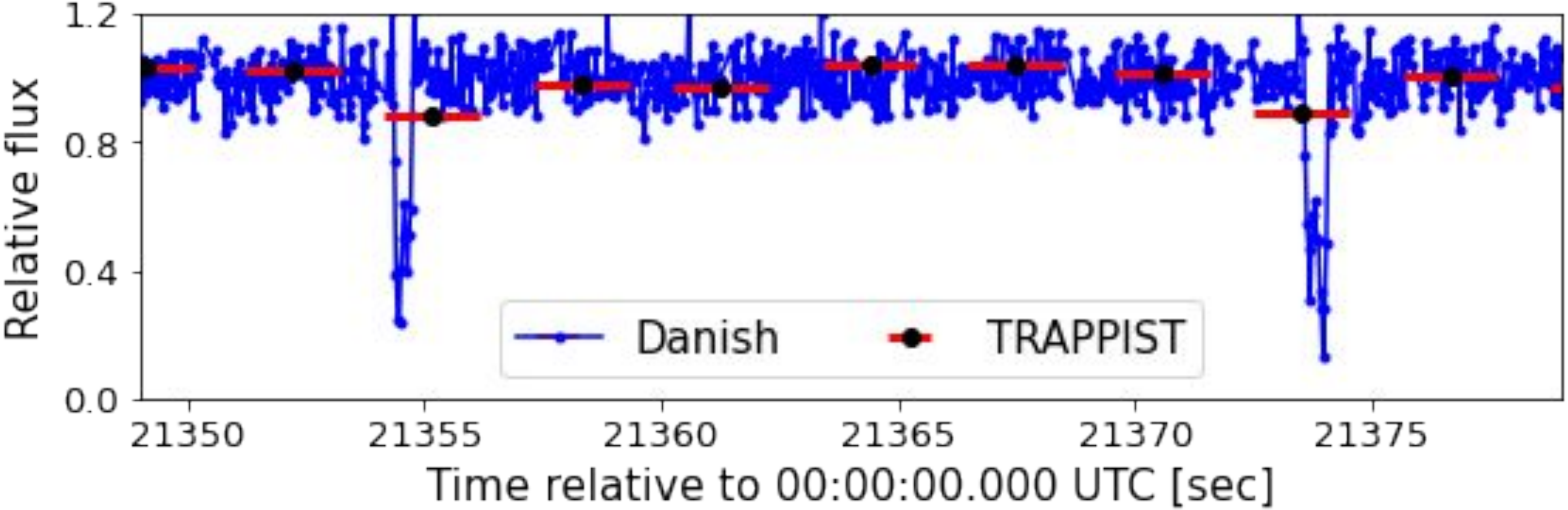


C1 - Structures and Ring width

1st step: Fit resolved detection ($t_{immersion}$, $t_{emersion}$, opacity).

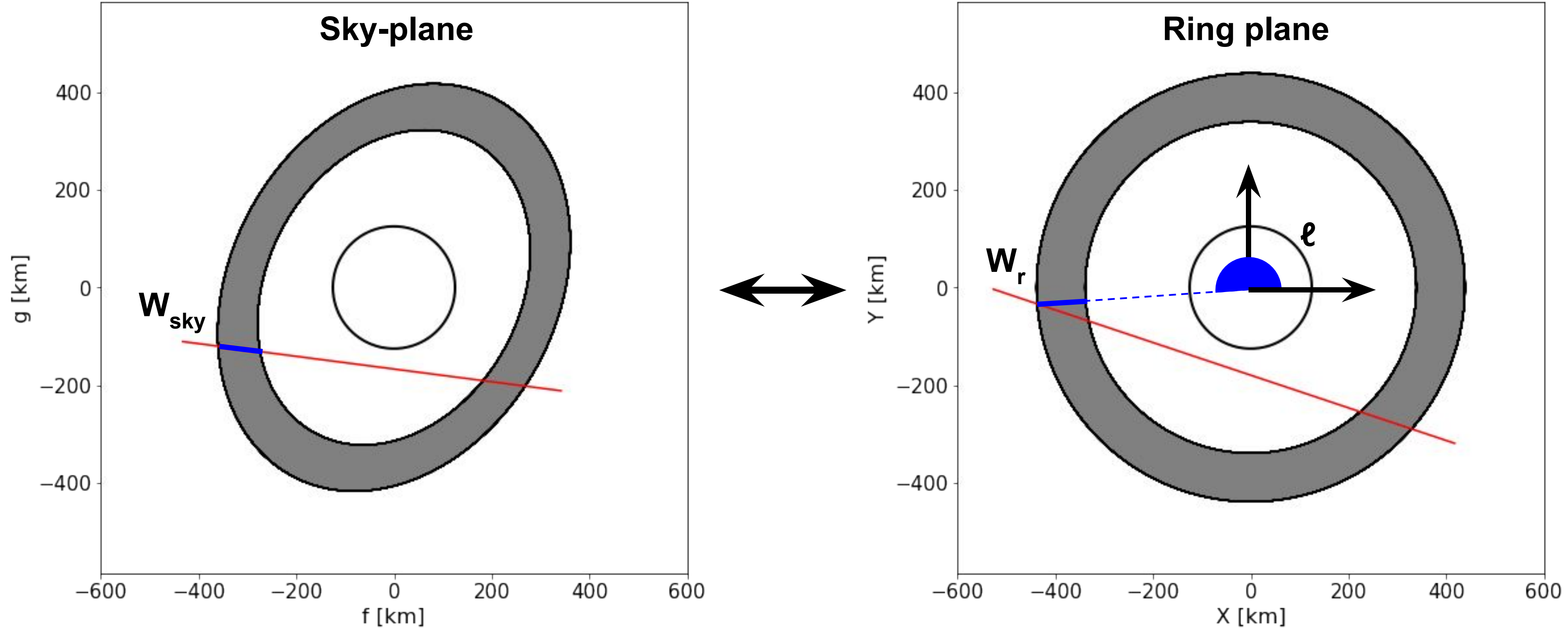
exptime = 0.034 seconds



C1 - Structures and Ring width

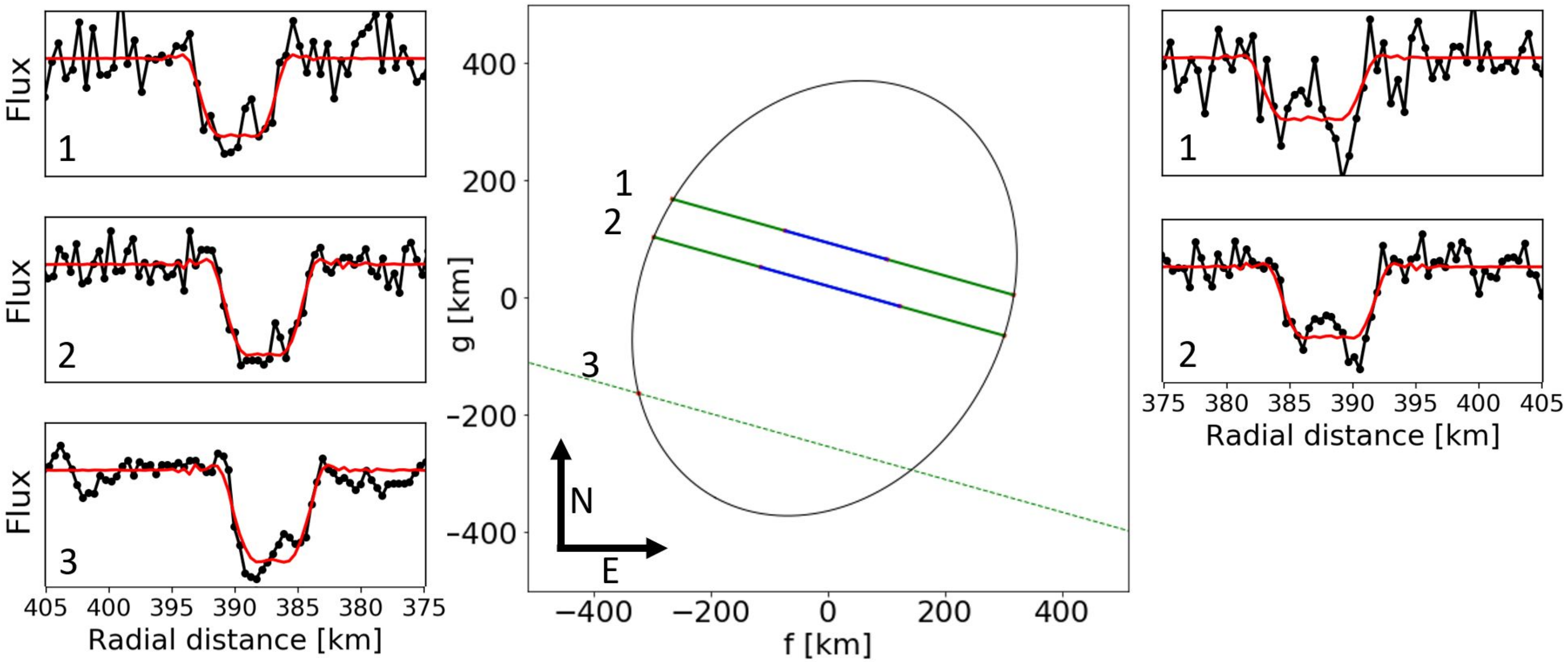
2nd step: Considering the ring pole and centre (f_0, g_0) reproject in the ring plane

3th step: Calculate parameters in the ring plane (radial width and true longitude)



C1 - Structures and Ring width

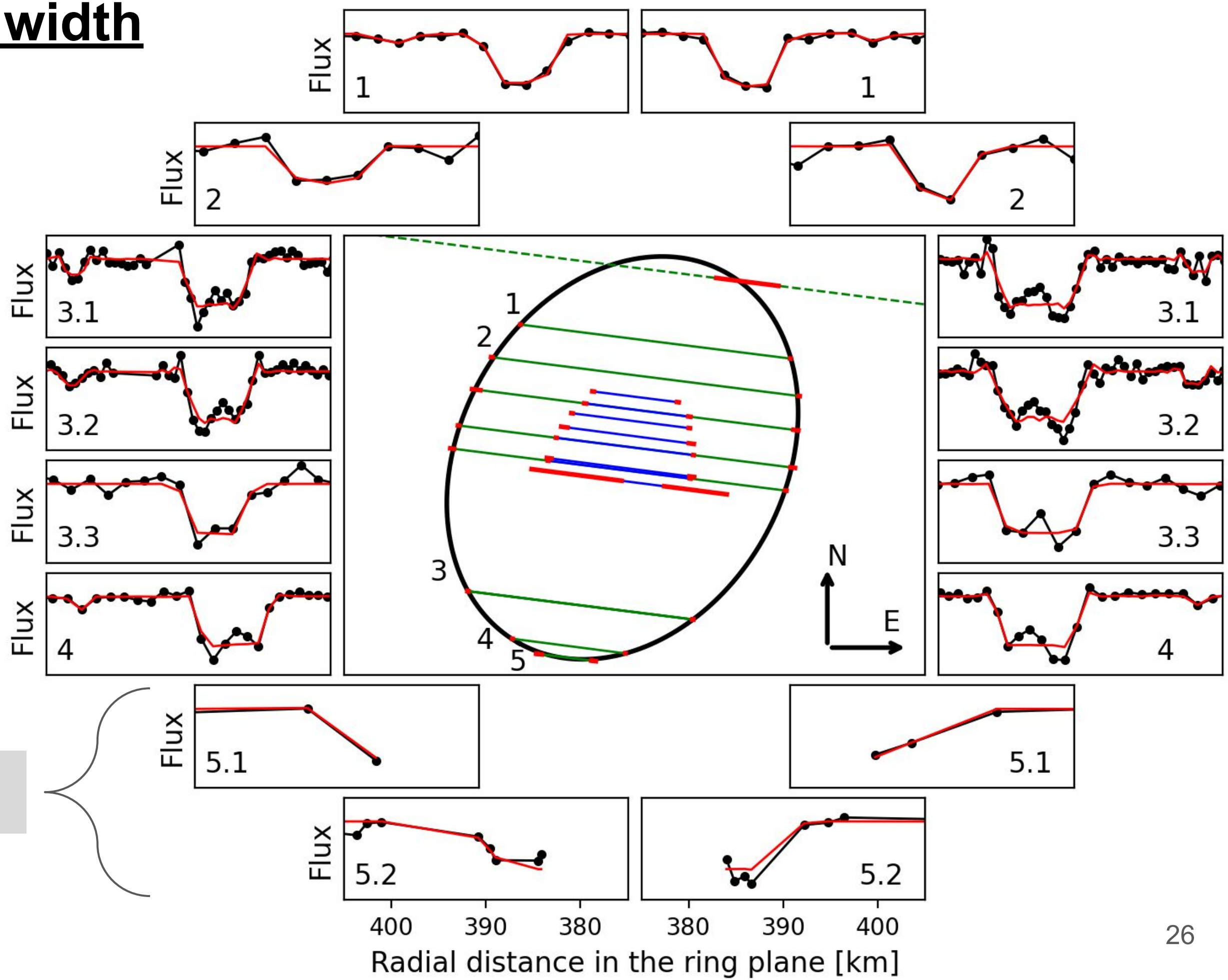
2017-04-09



C1 - Structures and Ring width

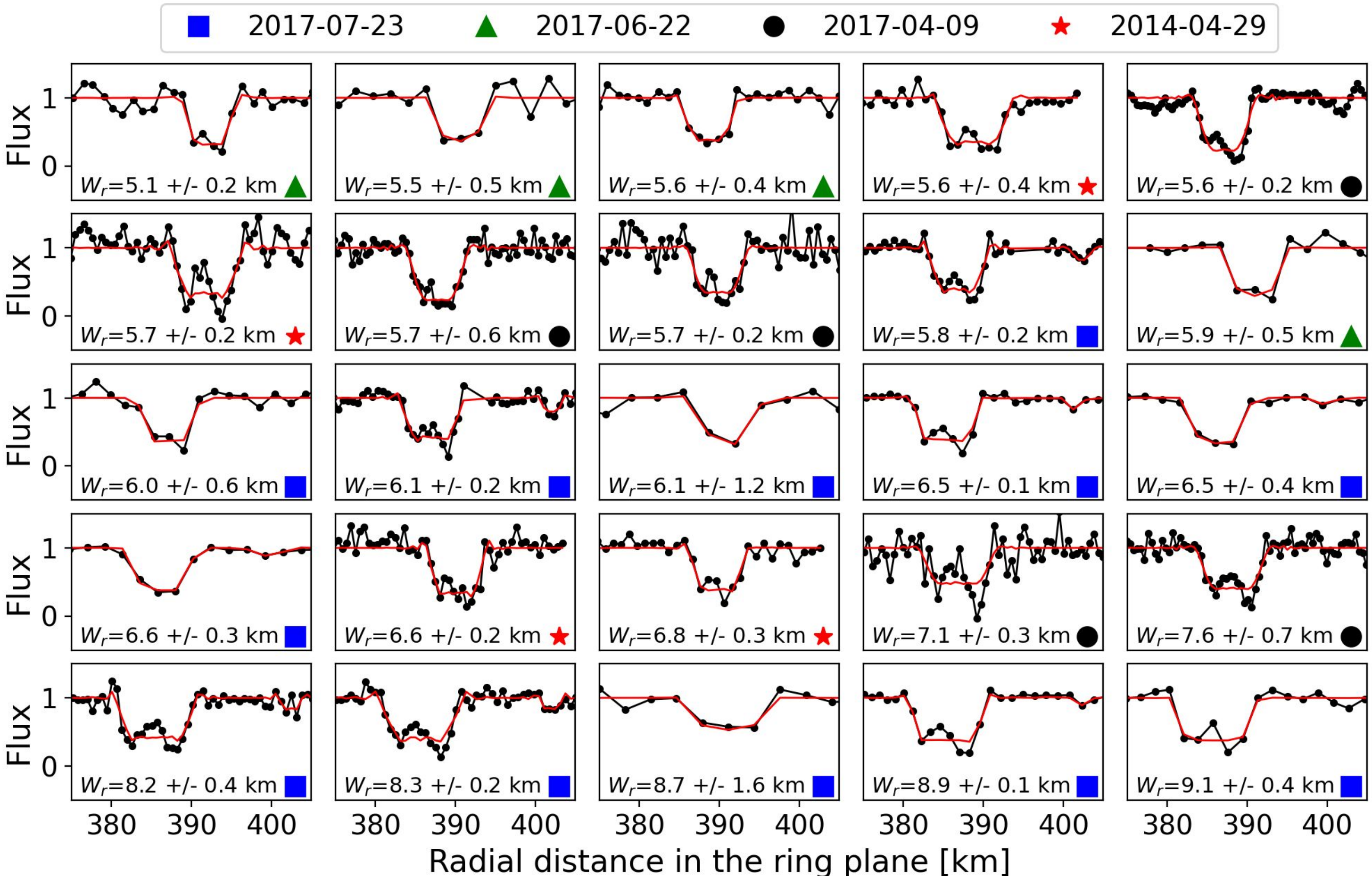
2017-07-23

Grazing occultations!

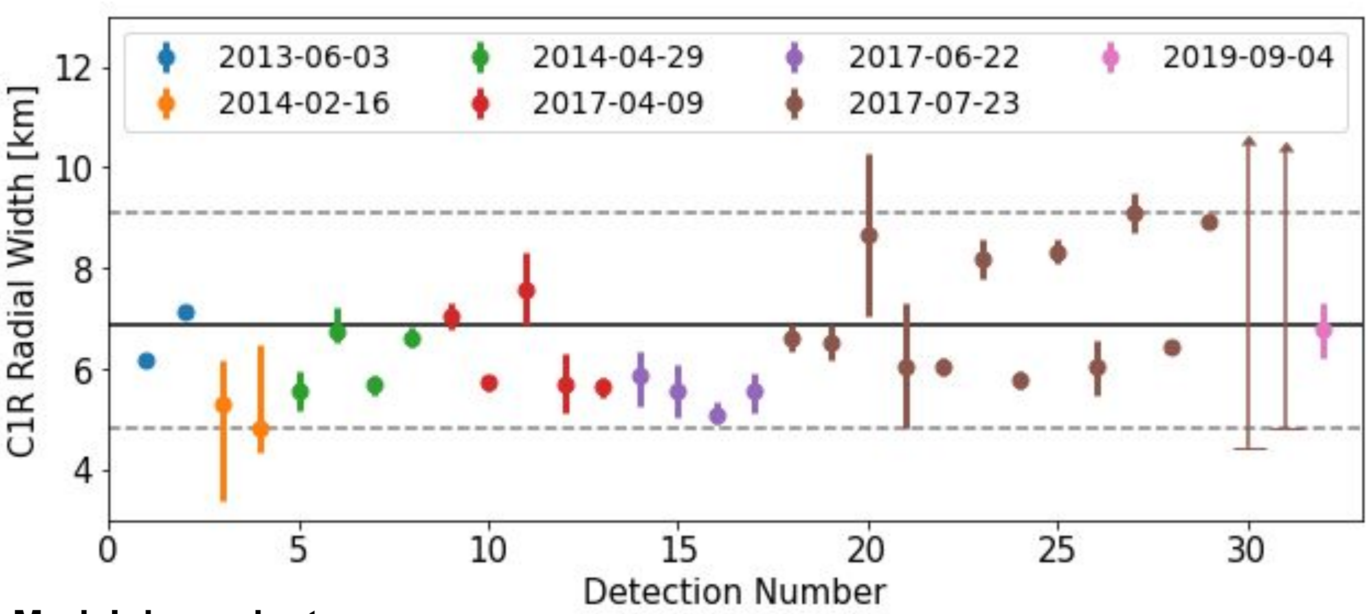


C1 - Structures and Ring width

All



C1 - Structures and Ring width



- mean = 6.9 km
- max = 9.1 km
- min = 4.8 km

Model dependent:

For a solidly precessing ring, i.e. a ring with a m=1 azimuthal number normal mode:

e ≫ □e

□e ~ ΔW_r / a

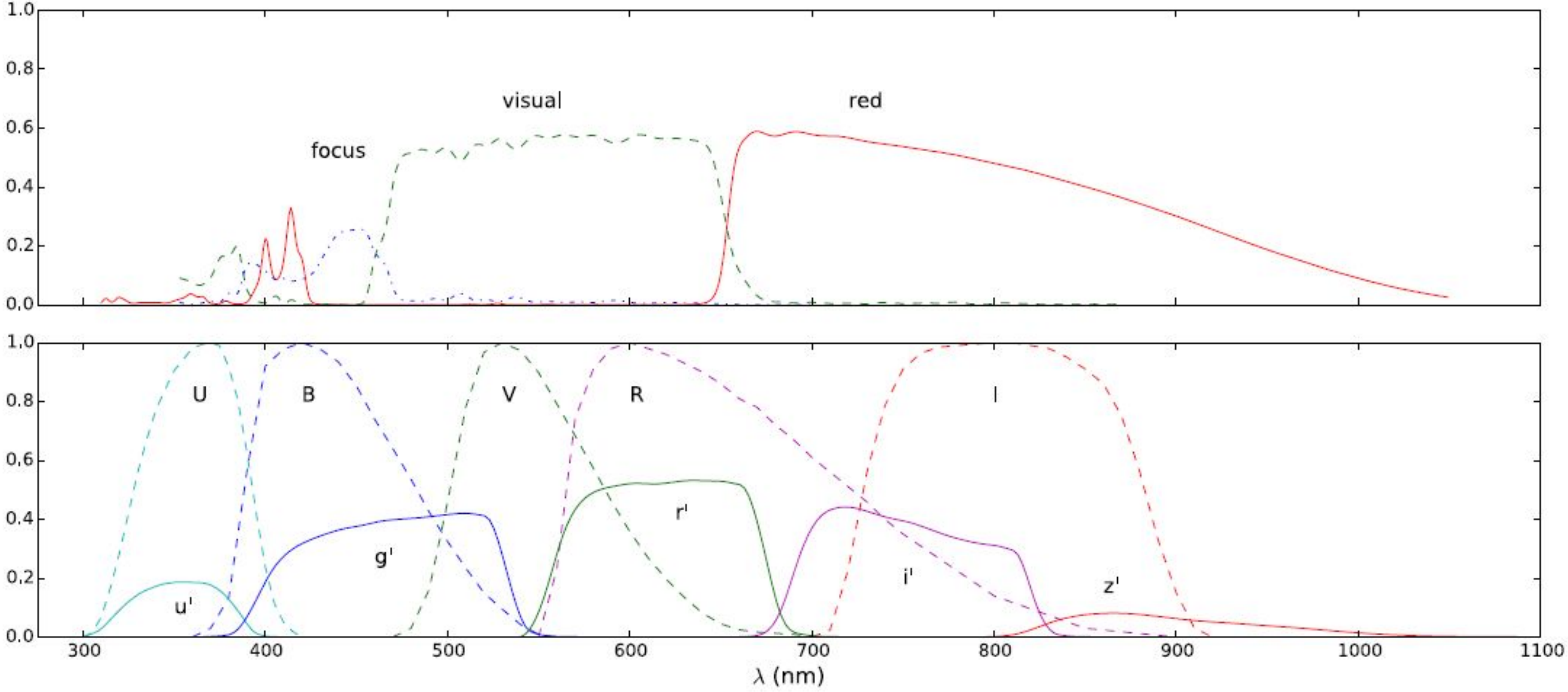
- ΔW_r = 3.9 km
- a = 385.6 km
- e ≫ 0.005

Ring's structure and parameters

C1 - Two-band resolved profiles of C1R

C1 Ring in different wavelengths

Danish telescope (1.54 m) using V and R filters.



C1 Ring in different wavelengths

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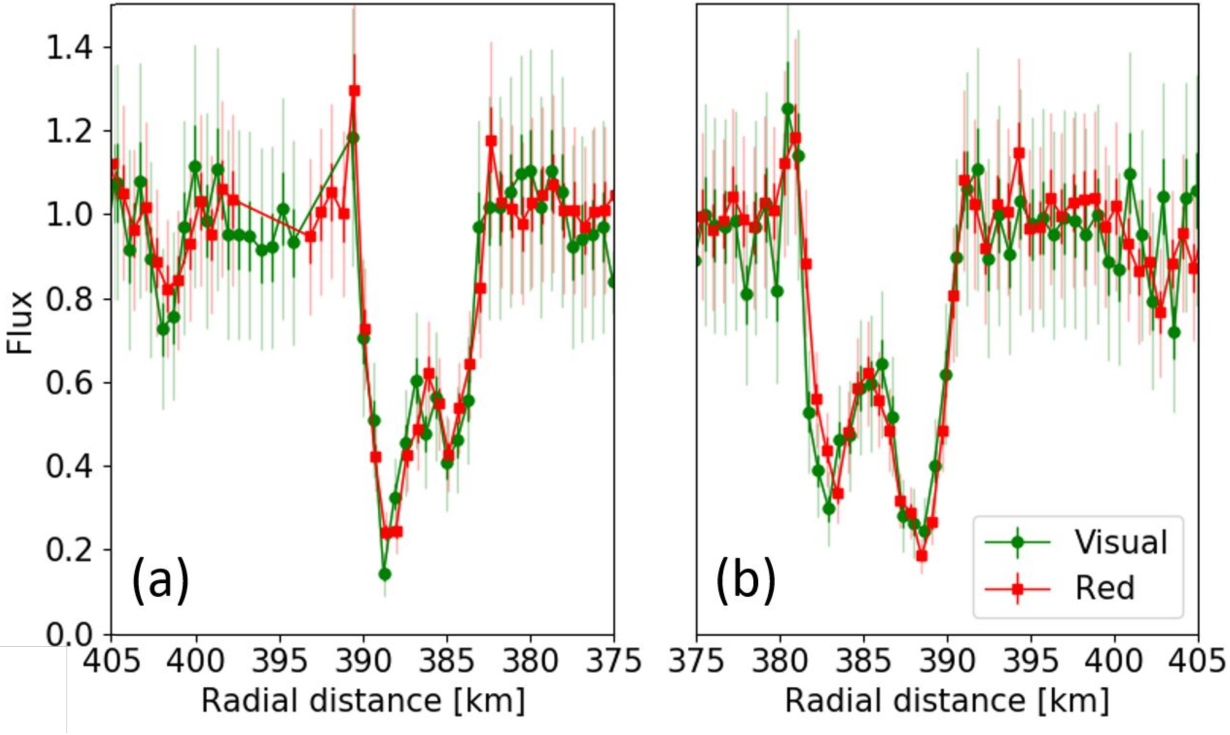


There is no significative difference between both detection (including within the W-shaped structure)

Ring particles larger than the wavelength (~1 micron)

C1 - Structures and Ring width

Conclusions:

1. Clear detections of W structures in 13 detections.

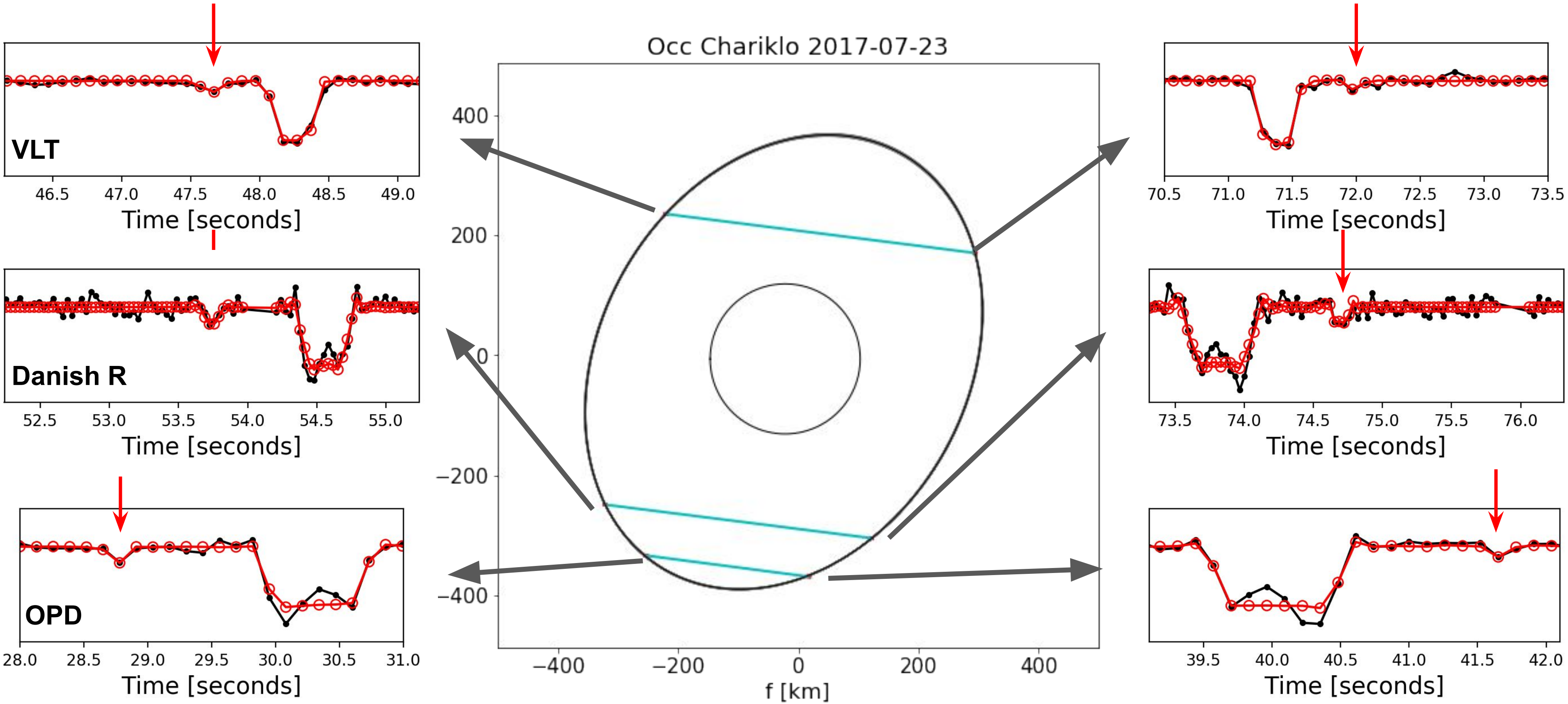
2. Mean radial width of ~6.9 km, varying between ~4.8 and ~9.1 km.

3. There is **no** significant difference between observations in Visual and Red bands. Meaning that the ring particles should be larger than 1 micron.

Ring's structure and parameters

C2 structure

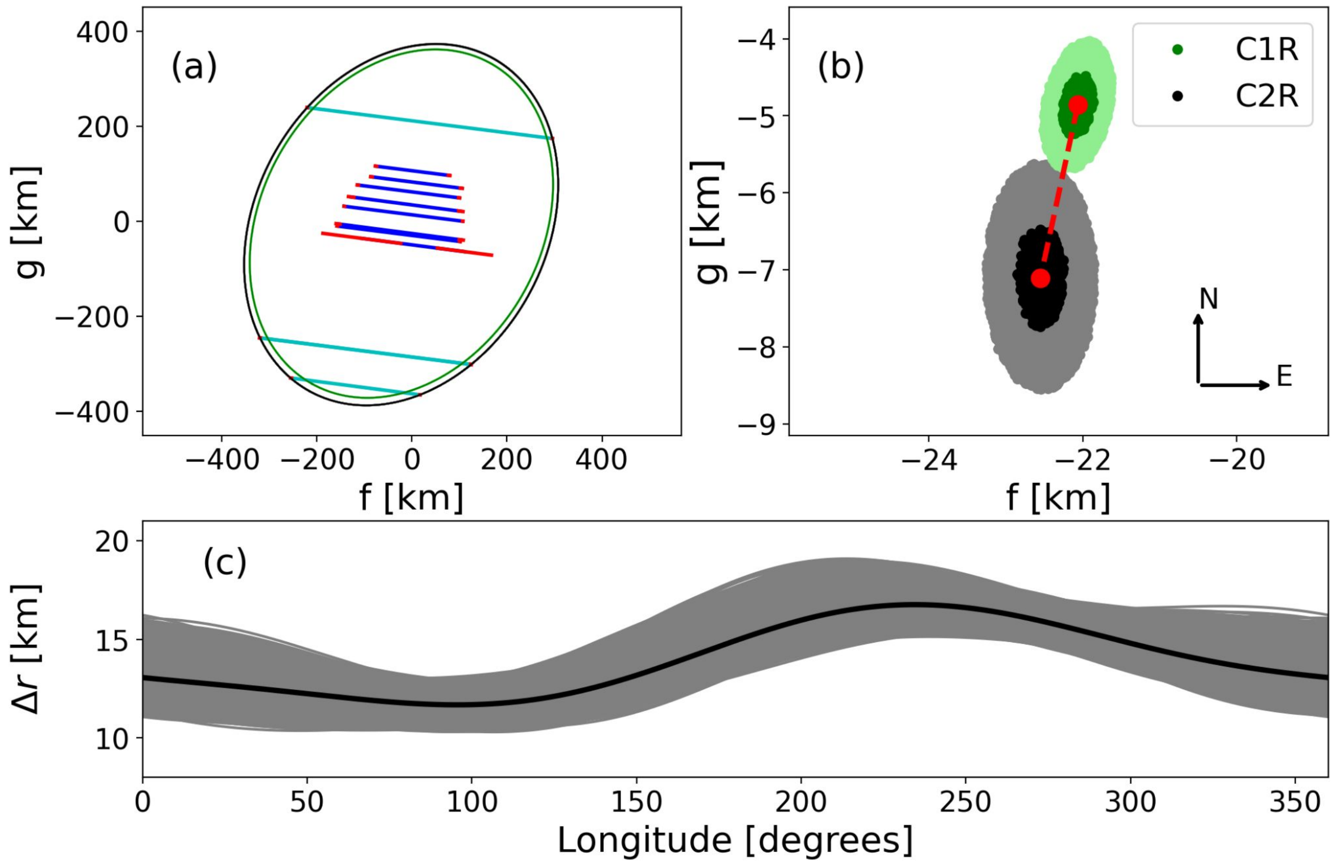
C2 detections - 2017-07-23



Equivalent Width

- $E_p = W_r \cdot p_N$ = **0.117 +/- 0.080 km**

Chariklo C2 x C1:



- r_{c1c2} = **2.28 km**
- Δe_{c1c2} **~ 0.006**

- **mean** = 13.9 km
- **max = 19.1 km**
- **min = 10.5 km**

Chariklo C2 pole:

Conclusions:

1. 1-σ Agreement between the poles determined with C1 and C2.

2. Less than 3-σ agreement between the centre position of C1 and C2

3. Was not possible to determine the width and the opacity of C2, but it has an equivalent width of **0.117 +/- 0.080 km**

4. Global radial difference between C1 and C2 is **13.9 km** (1-sigma between **10.5** and **19.1 km**).

Chariklo’s size and shape

Fitting a 3D ellipsoidal model

Assumptions:

1) Chariklo pole position is constant and the same as Chariklo rings.
   RA_{pole} = 10 05 12.0
   Dec_{pole} = +41 28 48.0

2) Chariklo's main body centre is the same as Chariklo's rings centre.

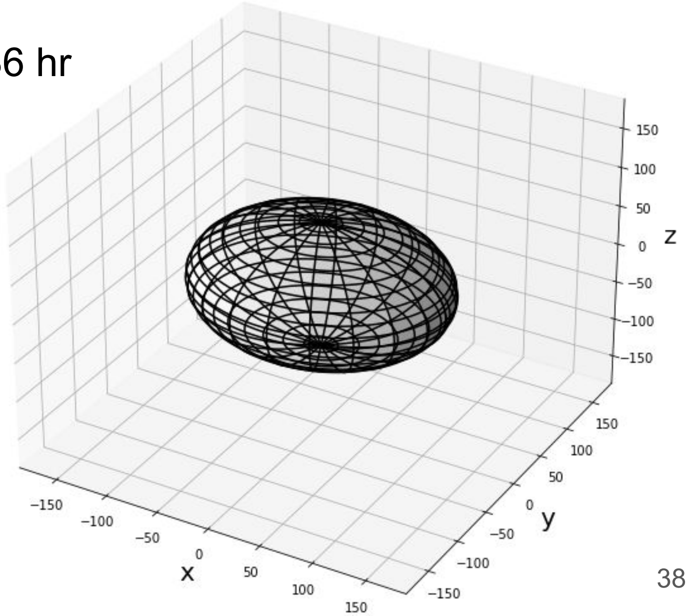
3) Chariklo rotational period is know an equals to 7.004 ± 0.036 hr
   $\partial w = 360° / \text{period}$ (Fornasier et al. 2014)

4) Chariklo is a triaxial ellipsoid with axis a > b > c

5) $\lambda_c = w_0 + \partial w * \Delta t$

6) Δt also considers the light time for each occultation.

7) Parameters to be fitted: a , b , c , w_0



Initial guess:

- a = 125 +/- 50 km
- b = 125 +/- 50 km
- c = 125 +/- 50 km
- a > b > c

- w_0 = 0 ~ 360 degrees
- ∂w = 1233.5808110 +/- 12.7465296 degree/day

- Occultations considered:
  - ★ 2020-06-19
  - ★ 2019-08-08
  - ★ 2017-08-24
  - ★ 2017-07-23
  - ★ 2017-06-22
  - ★ 2017-04-09
  - ○ 2016-10-01
  - ○ 2016-08-08
  - ○ 2014-06-28
  - ○ 2014-04-29
  - ○ 2013-06-03

- Runned in part in SDumont supercomputer @ LNCC

$$\chi^2 = \sum_i^N \frac{(r_i - r'_i)}{\sigma_i^2 + \sigma_{model}^2}$$

σ_{model} = 3 km

→ Center offset;
Topographic features;

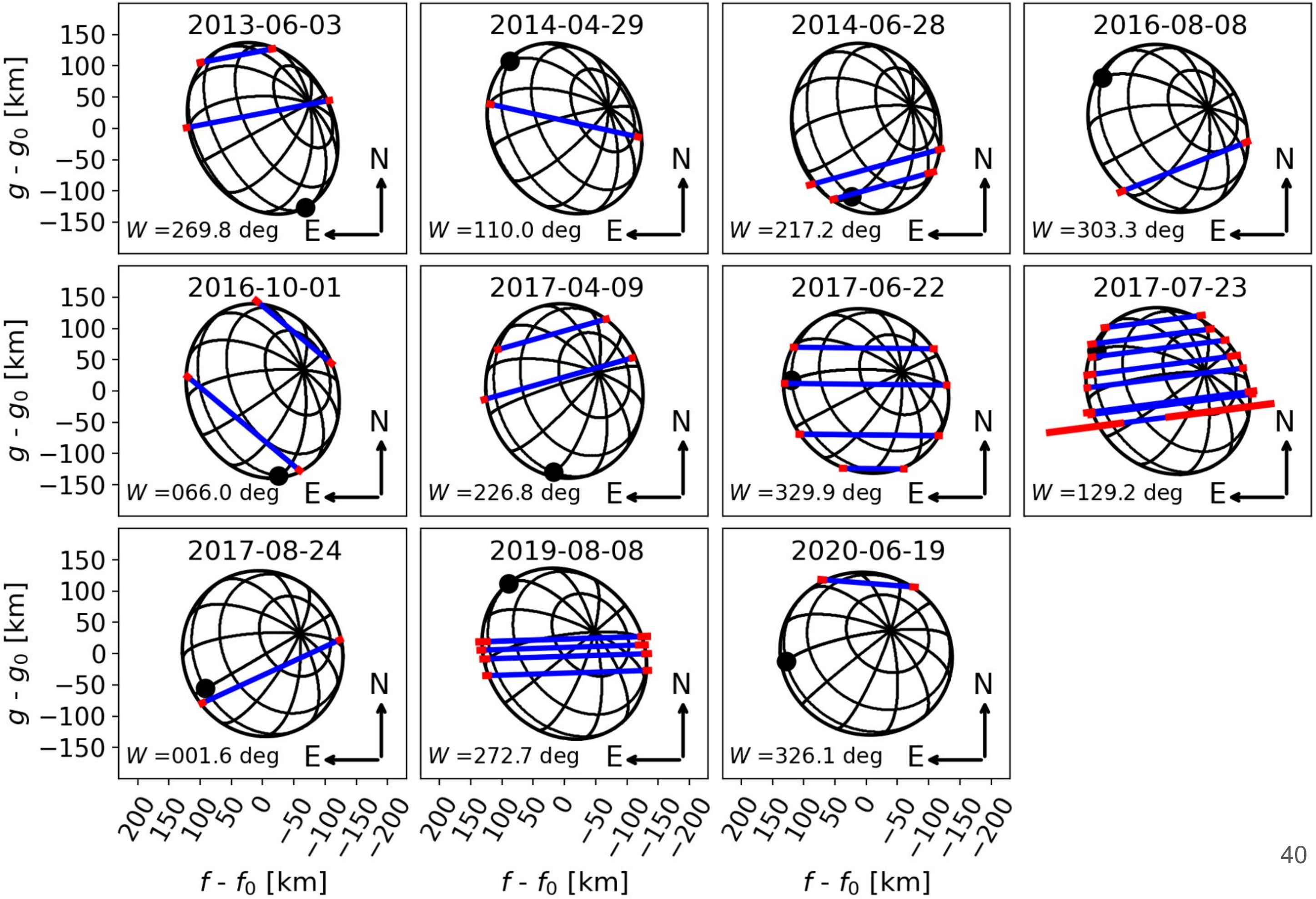
3D fitting

a = 143.8 $^{+1.4}_{-1.5}$ km

b = 135.2 $^{+1.4}_{-2.8}$ km

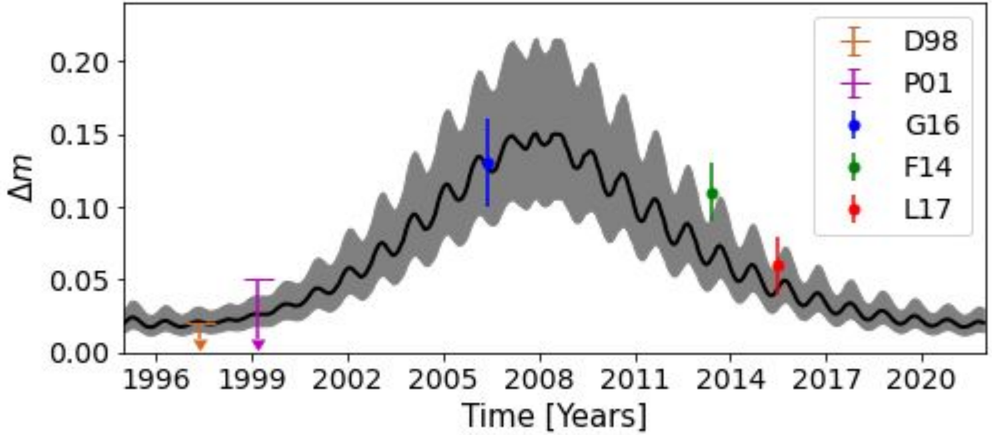
c = 99.1 $^{+5.4}_{-2.7}$ km

Residues: ~4.1 km



Chariklo’s rotational light curve amplitude

Date	Δmag	B°	Reference
1997-05	< 0.02	-56	Davies et al. (1998)
1999-03	< 0.05	-53	Peixinho et al. (2001)
2006-06	0.13 ± 0.03	-13	Galiazzo et al. (2016)
2013-06	0.11 ± 0.02	34	Fornasier et al. (2014)
2015-07	0.06 ± 0.02	42	Leiva et al. (2017)



$$\Delta mag = -2.5 \log \frac{A_{min}\rho_b + A_r(I/F)}{A_{max}\rho_b + A_r(I/F)}$$

Fernández-Valenzuela et al., 2017

(*) Do not consider solar phase angle

- For Chariklo it is smaller than 3.5 degrees

Ellipsoid (Best fit)

a = 143.8 km   b = 135.2 km   c = 99.1 km

Ring

R_{CR1} = 385.9
W_R = 6.5
(*) C2R is not considered

Chariklo's density:

Obtained ellipsoidal shape:

$a = 143.8^{+1.4}_{-1.5}$ km

$b = 135.2^{+1.4}_{-2.8}$ km

$c = 99.1^{+5.4}_{-2.7}$ km

$$\Omega = \frac{2\pi}{G\rho T^2} = \beta\gamma \int_0^\infty \frac{u}{(1+u)(\beta^2+u)\Delta(u,\beta,\gamma)} du \,,$$

$$\Delta(u,\beta,\gamma) = \sqrt{(1+u)(\beta^2+u)(\gamma^2+u)} \,,$$

Known Rotational Period of 7.004 +/- 0.036 hr (Fornasier et al., 2014)

(1) Considering that Chariklo is a Jacobi ellipsoid, its density should be:

$\rho = 1.55^{+0.05}_{-0.08}$ g/cm^3

$\Omega = 0.191$

A stable Jacobi ellipsoid should have Ω between 0.284 and 0.374 (Tancredi & Favre, 2008). Rotating with a 7h period, its density would range between 0.79 and 1.04 g/cm^3.

Conclusion: Chariklo 3D shape is not consistent with a Jacobi equilibrium figure. Also, meaning that it is not an homogeneous body in hydrostatic equilibrium.

Chariklo Size and Shape

Conclusions:

1. Chariklo is consistent with an triaxial ellipsoid.

2. The residuals suggested topographic features with a mean value of ~3 km

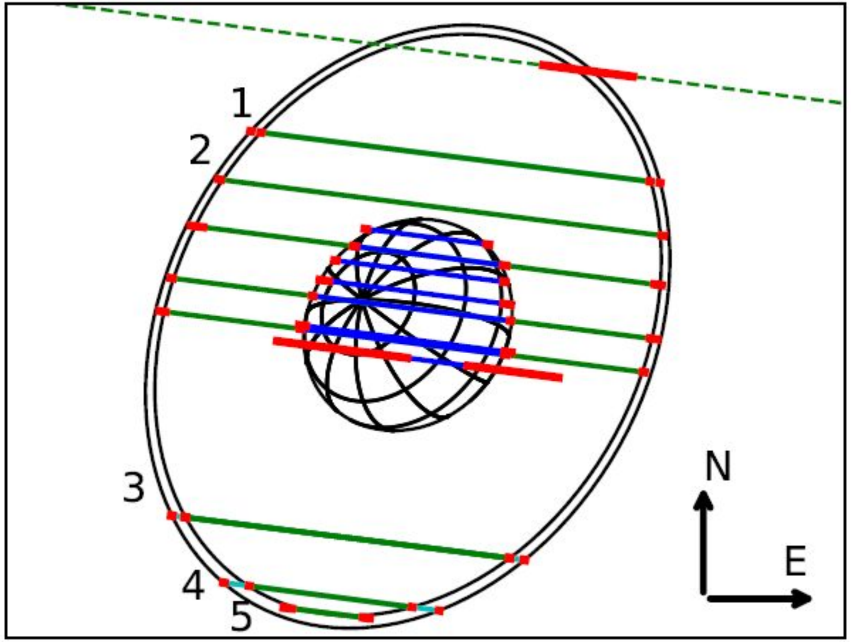
3. The ellipsoidal shape is consistent with the rotational light curves observed

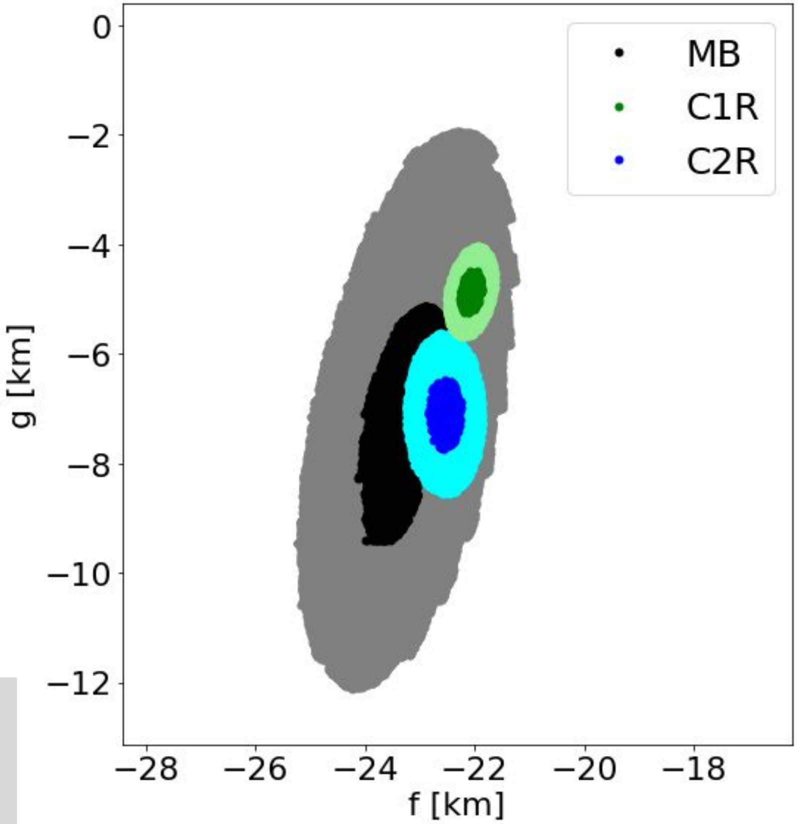
4. Chariklo 3D shape is not consistent with a Jacobi equilibrium figure. Also, meaning that it is not an homogeneous body in hydrostatic equilibrium.

Chariklo’s size and shape

Centre position and ring excentricities

Chariklo’s system





MB x C1R = 0.00 ~ 5.35 km (8.55) → 0.000 ~ 0.014 (0.022)

MB x C2R = 0.00 ~ 3.27 km (6.84) → 0.000 ~ 0.008 (0.017)

Astrometrical positions

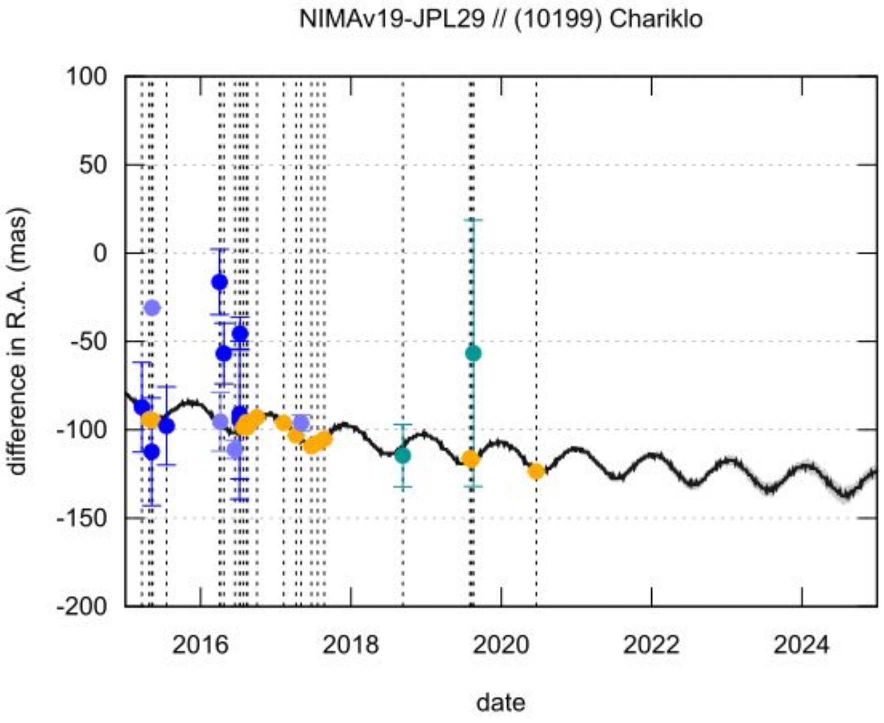
Improving Chariklo's orbit

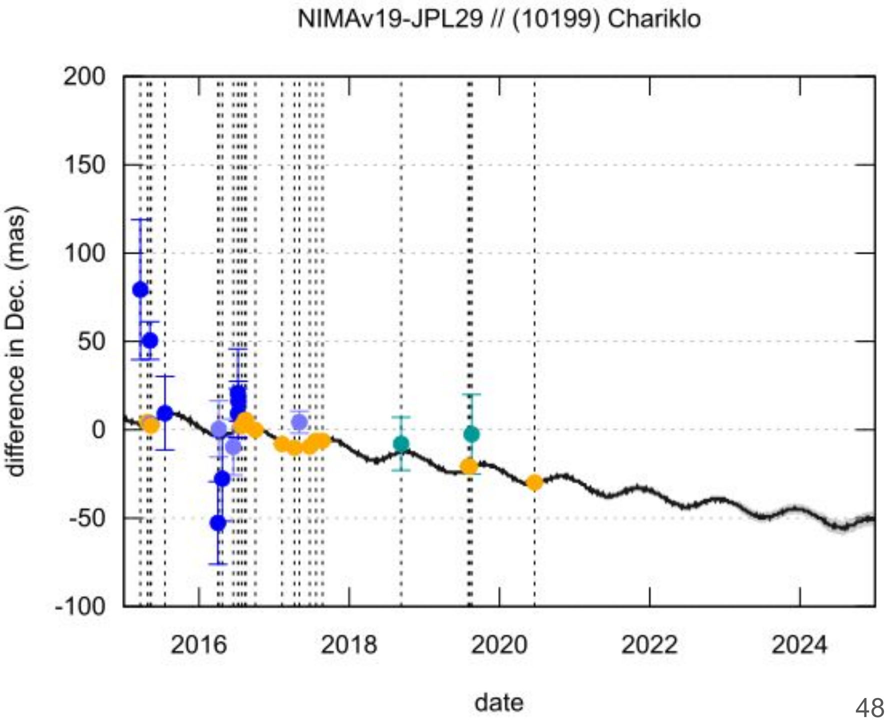
Chariklo’s astrometrical position:

Date and time UTC	Right Ascension[a]	Declination[a]
2020-06-19 15:51:00.000	$20^h\ 02^m\ 32^s.0002322 \pm 0.339$ mas	-22° 20’ 41”.488487 ± 0.227 mas
2019-08-08 21:41:00.000	$19^h\ 31^m\ 49^s.7910264 \pm 0.227$ mas	-25° 34’ 26”.785014 ± 0.544 mas
2019-08-02 10:02:00.000	$19^h\ 33^m\ 07^s.4812764 \pm 0.872$ mas	-25° 34’ 42”.519146 ± 1.187 mas
2017-08-24 02:59:00.000	$18^h\ 42^m\ 35^s.2371826 \pm 0.426$ mas	-31° 09’ 50”.561462 ± 0.432 mas
2017-07-23 05:58:00.000	$18^h\ 48^m\ 09^s.2288885 \pm 0.103$ mas	-31° 26’ 32”.437598 ± 0.096 mas
2017-06-22 21:18:00.000	$18^h\ 55^m\ 15^s.6602082 \pm 0.116$ mas	-31° 31’ 21”.621802 ± 0.110 mas
2017-04-09 02:24:00.000	$19^h\ 04^m\ 03^s.6255610 \pm 0.129$ mas	-31° 17’ 15”.257638 ± 0.127 mas

Chariklo’s astrometrical position:

NIMA v.19





Chariklo's astrometrical position:

NIMA v.19

Date	σ_α (arcsec)	σ_δ (arcsec)	
2021-01	0.001	0.001	
2021-07	0.002	0.002	
2022-01	0.002	0.002	→ **~20 km**
2022-07	0.003	0.002	
2023-01	0.003	0.002	→ **~30 km**
2023-07	0.004	0.003	
2024-01	0.003	0.003	
2024-07	0.005	0.004	

Conclusions

Conclusions

Chariklo has been observed by stellar occultations since 2013.

For the first time we had multiple detection over C1R, C2R and Chariklo main body.

These results should be useful for constraining dynamical models of Chariklo and its rings

2013	2014-2016		2017-2020	
Braga-Ribas et al., 2014	**Berard et al., 2016** **Leiva et al., 2016**		**Morgado et al., 2021**	
2013-06-03 - Ring discovery	2014-02-16	2014-03-16	2020-06-19	2019-09-04
	2014-04-29	2014-06-28	2019-08-08	2019-08-02
	2015-04-26	2015-05-12	2017-08-24	2017-07-23
	2016-07-26	2016-08-10	2017-06-22	2017-04-09
	2016-08-10	2016-08-15		
	2016-10-01			

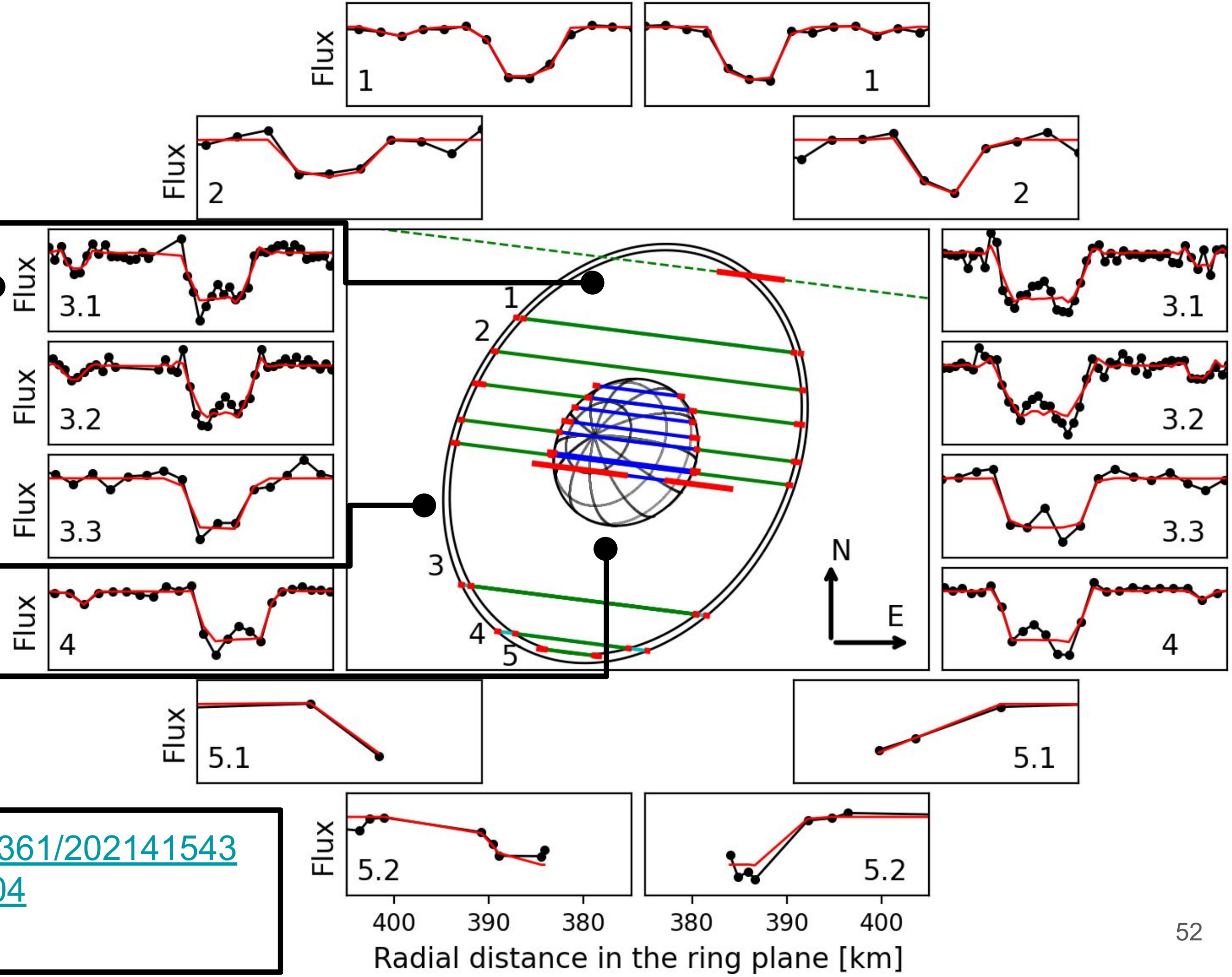
Take away message:

C1R: Global shape

C1R: Local structure

C2R: Global shape

Chariklo 3D shape



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https://arxiv.org/abs/2107.07904

Summary: Morgado et al., (2021) A&A

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Refined physical parameters for Chariklo's body and rings from stellar occultations observed between 2013 and 2020

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Thanks