A PYTHON PACKAGE FOR MODELLING THE PHOTOMETRIC SIGNATURES OF EXOPLANETARY RINGS/SATELLITES

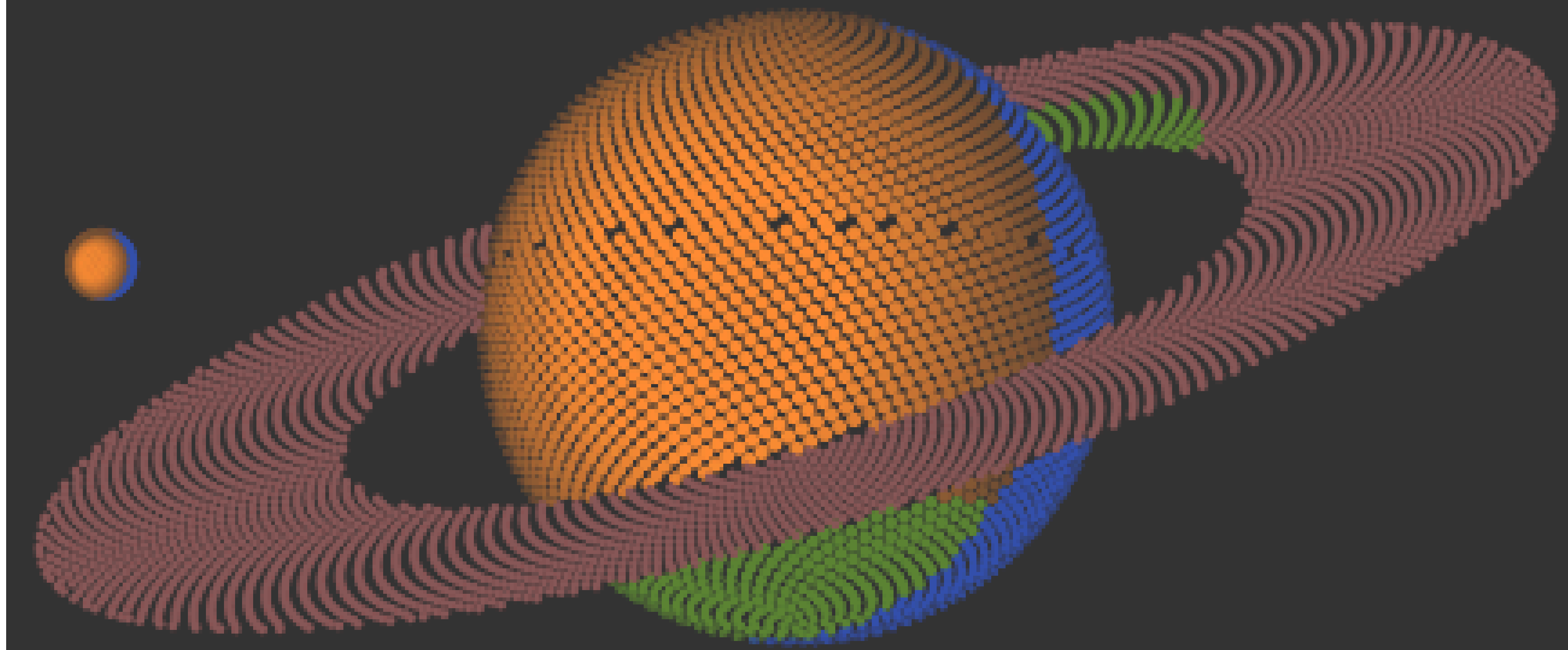
SEBASTIÁN NUMPAQUE - SEAP/FACom
INSTITUTO DE FÍSICA, UNIVERSIDAD DE ANTIÓQUIA

TUTOR:
Dr. JORGE I. ZULUAGA - SEAP/FACom
INSTITUTO DE FÍSICA, UNIVERSIDAD DE ANTIÓQUIA

seap-udea/
pryngles-public

PlanetaRY spanGLES

Solar, EArth & Planetary Physics SEAP
FACom Grupo de Física y Astrofísica Computacional
UNIVERSIDAD DE ANTIOQUIA



PRYNGLES 0.9.10 (C) 2022
HTTPS://GITHUB.COM/SEAP-UDEA/PRYNGLES-PUBLIC

JORGE I. ZULUAGA, MARIO SUCERQUIA & JAIME A. ALVARADO-MONTES
WITH CONTRIBUTIONS OF ALLARD VEENSTRA

ANILLOS/SATÉLITES EXOPLANETARIOS ¿DÓNDE ESTÁN?

→ PRESENCIA TÍPICA DENTRO DEL SISTEMA SOLAR

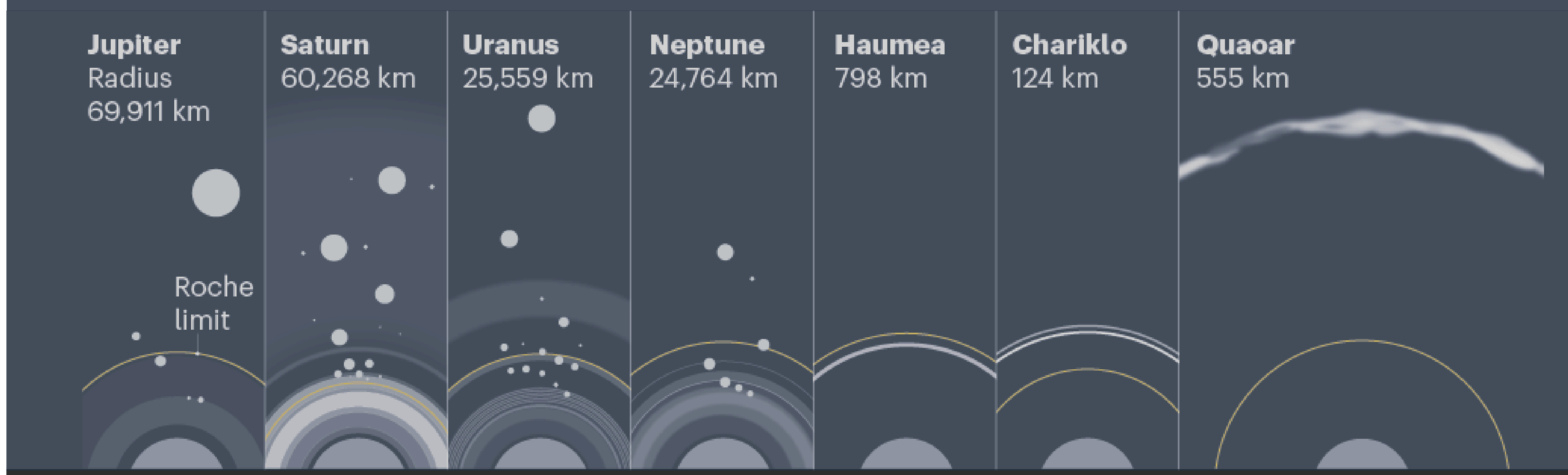
RESULTADO DE:

- FORMACIÓN Y EVOLUCIÓN PLANETARIA
  PDS 70c - A. ISELLA, ET AL. 2019
- IMPACTOS Y COLISIONES
  ORIGIN OF THE MOON - R. CANUP, 2012
- DISRUPCIONES DE MAREA
  SATURN'S RINGS - J. WISDOM, ET AL. 2022

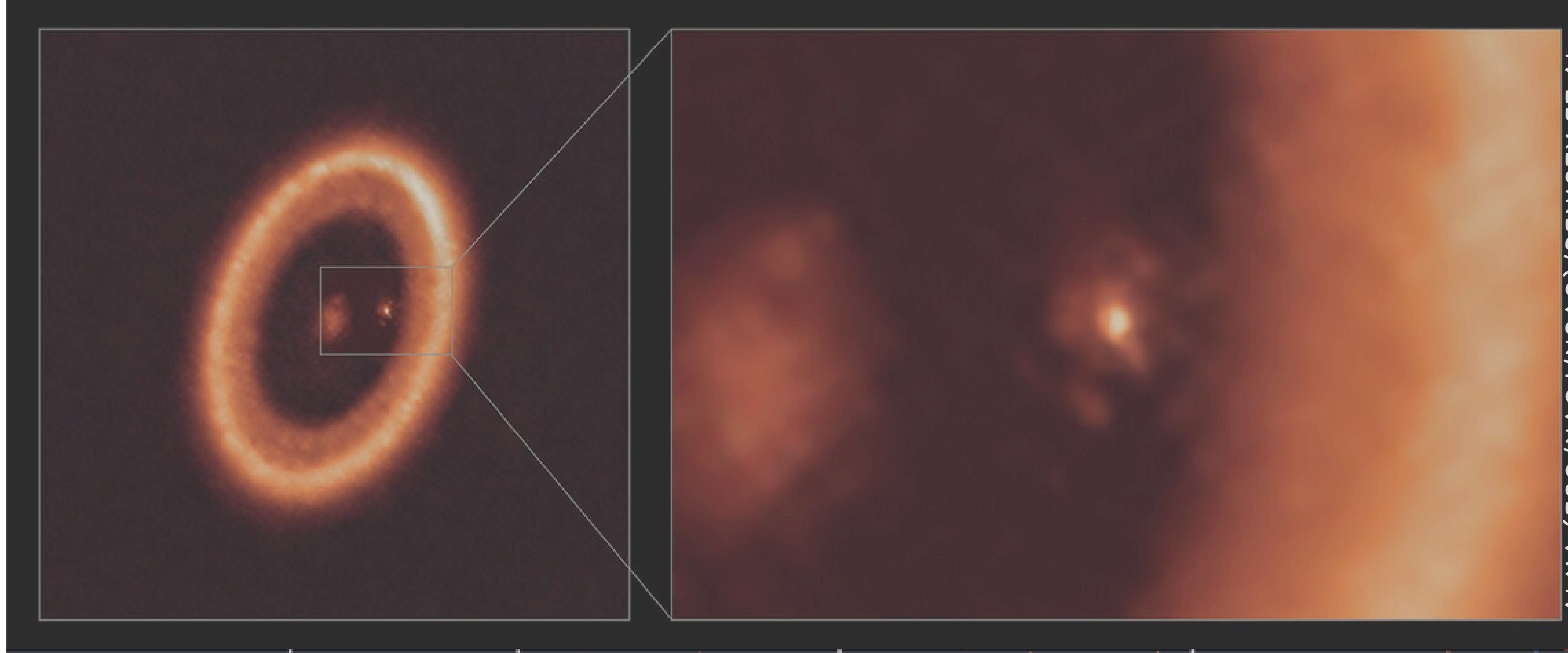
→ ¿QUÉ TAN COMUNES Y ABUNDANTES SON ESTAS ESTRUCTURAS?

→ ¿SON ESTRUCTURAS ESTABLES O TRANSITORIAS?

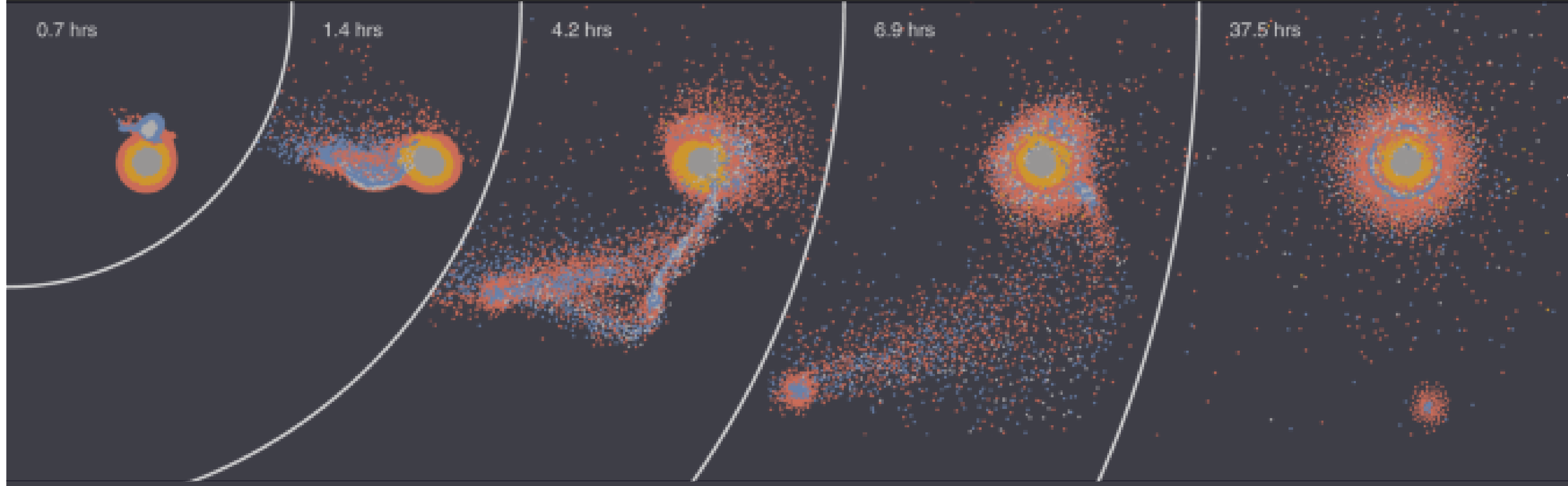
→ ¿CUÁLES SON SUS CARACTERÍSTICAS Y DIVERSIDAD?



HEDMAN, M. (2023)



ALMA (ESO/NAOJ/NRAO)/BENISTY ET AL.



MELOSH, H. (2019)

ANILLOS/SATÉLITES EXOPLANETARIOS ¿DONDE ESTÁN?

¿SEÑALES DÉBILES PARA DISCERNIR DEL RUIDO?
⟶ R. HELLER. 2018

SUB-MERCURY EXOPLANET KEPLER 37b
⟶ T. BARCLAY, ET AL. 2023

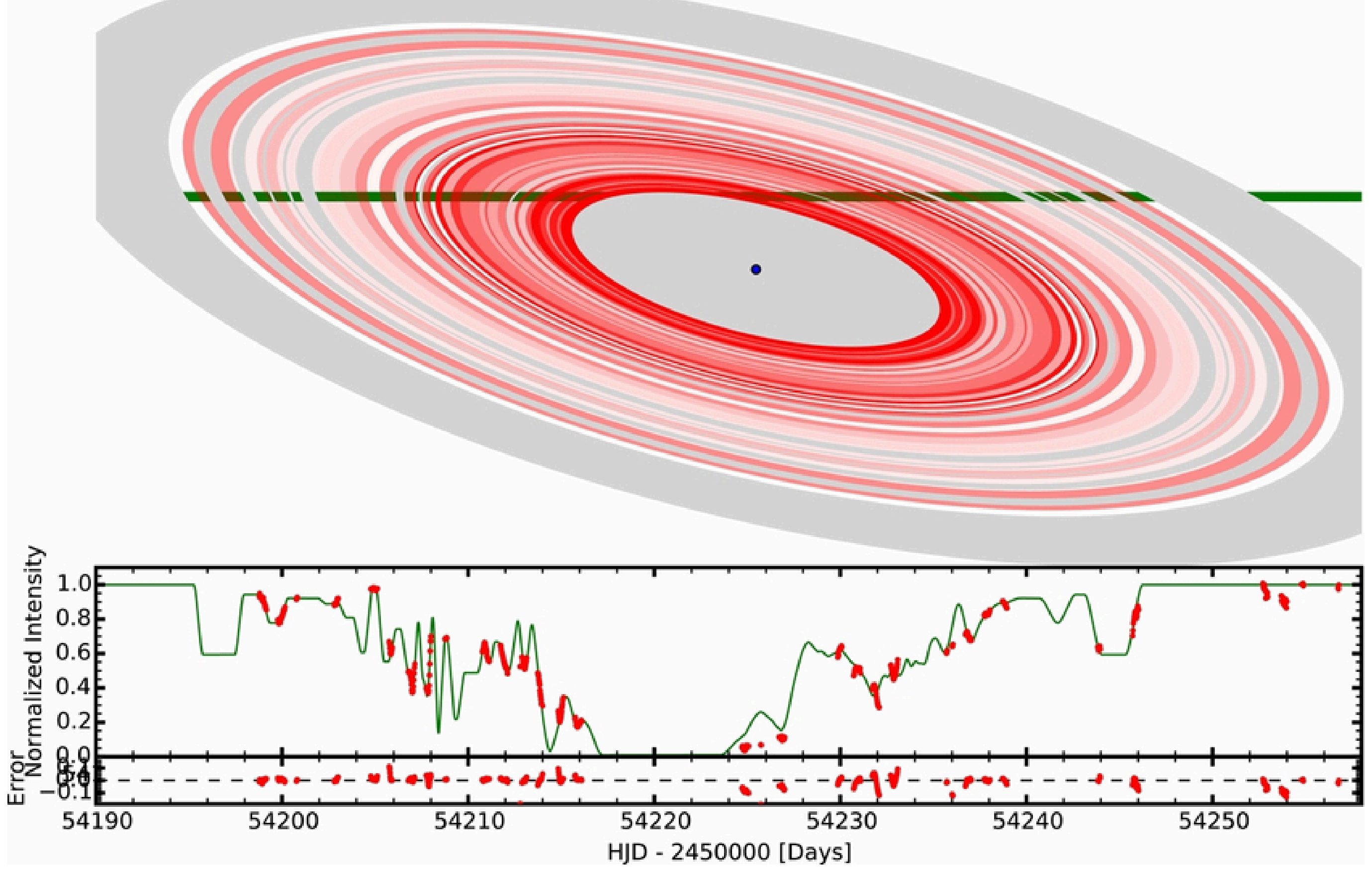
LUZ REFLEJADA POR ANILLOS KRONIANOS $\sim 10^2$ppm
⟶ J. I. ZULUAGA, ET AL. 2020

POSIBLES CANDIDATOS:

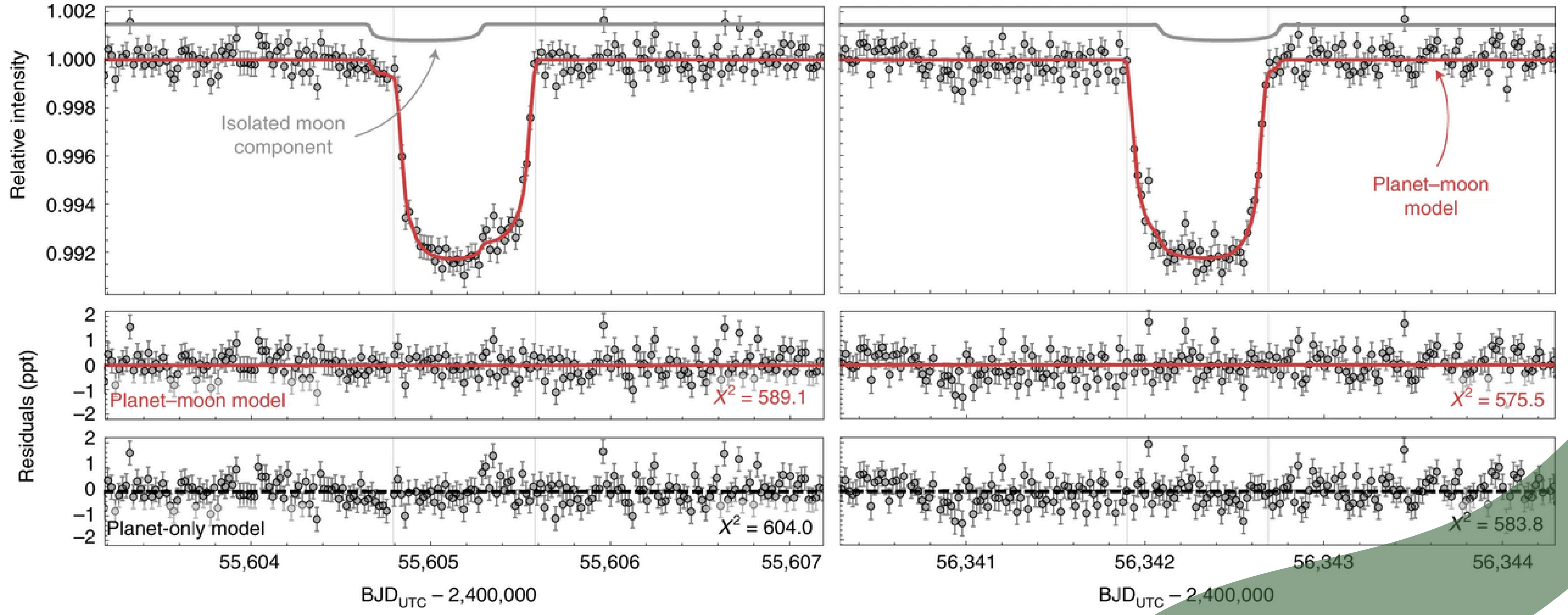
- EXORING - J1407 B
  (M. A. KENWORTHY & E. E. MAMAJEK. 2015)

- EXOMOON - KEPLER 1708 B
  (KIPPING, D., BRYSON, S., BURKE, C. ET AL. 2022)

M. A. KENWORTHY & E. E. MAMAJEK



KIPPING, D., BRYSON, S., BURKE, C. ET AL.



PRYNGLES[1]
DISCRETIZANDO SUPERFICIES...

→ [1]HTTPS://GITHUB.COM/SEAP-UDEA/PRYNGLES-PUBLIC python™

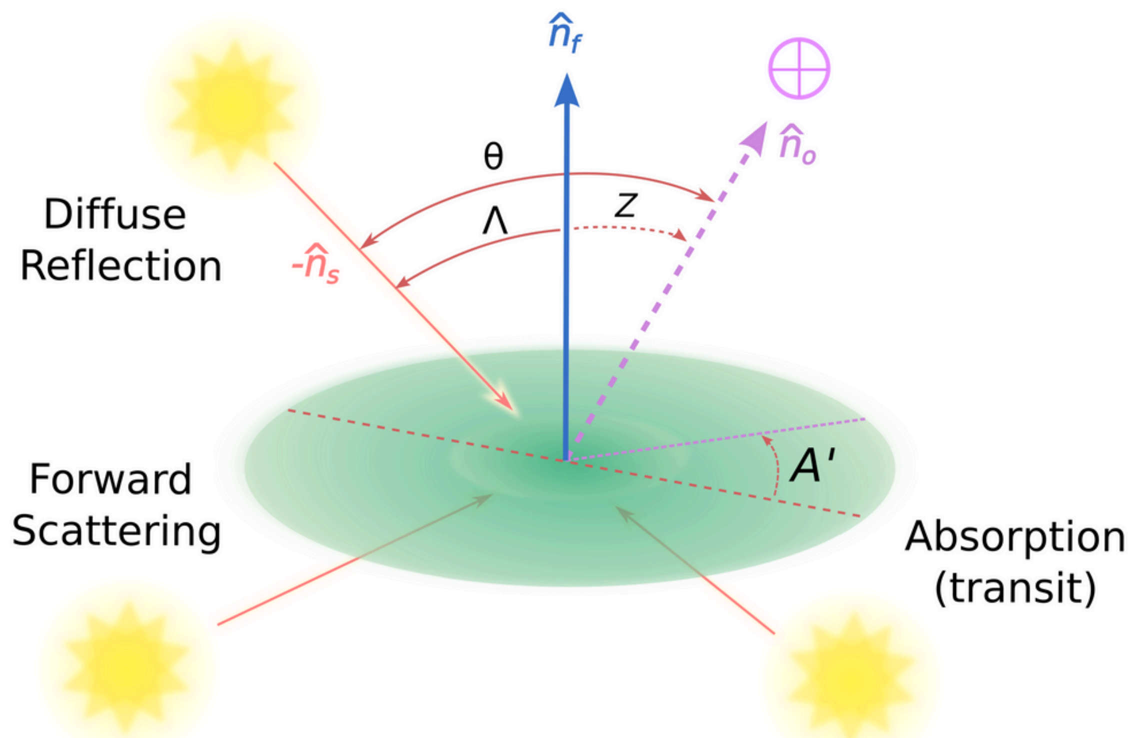
→ [1]J. I. ZULUAGA, M. SUCERQUIA & J. A. ALVARADO-MONTES
WITH CONTRIBUTIONS OF A. VEENSTRA

ATRIBUTOS DE SPANGLES:

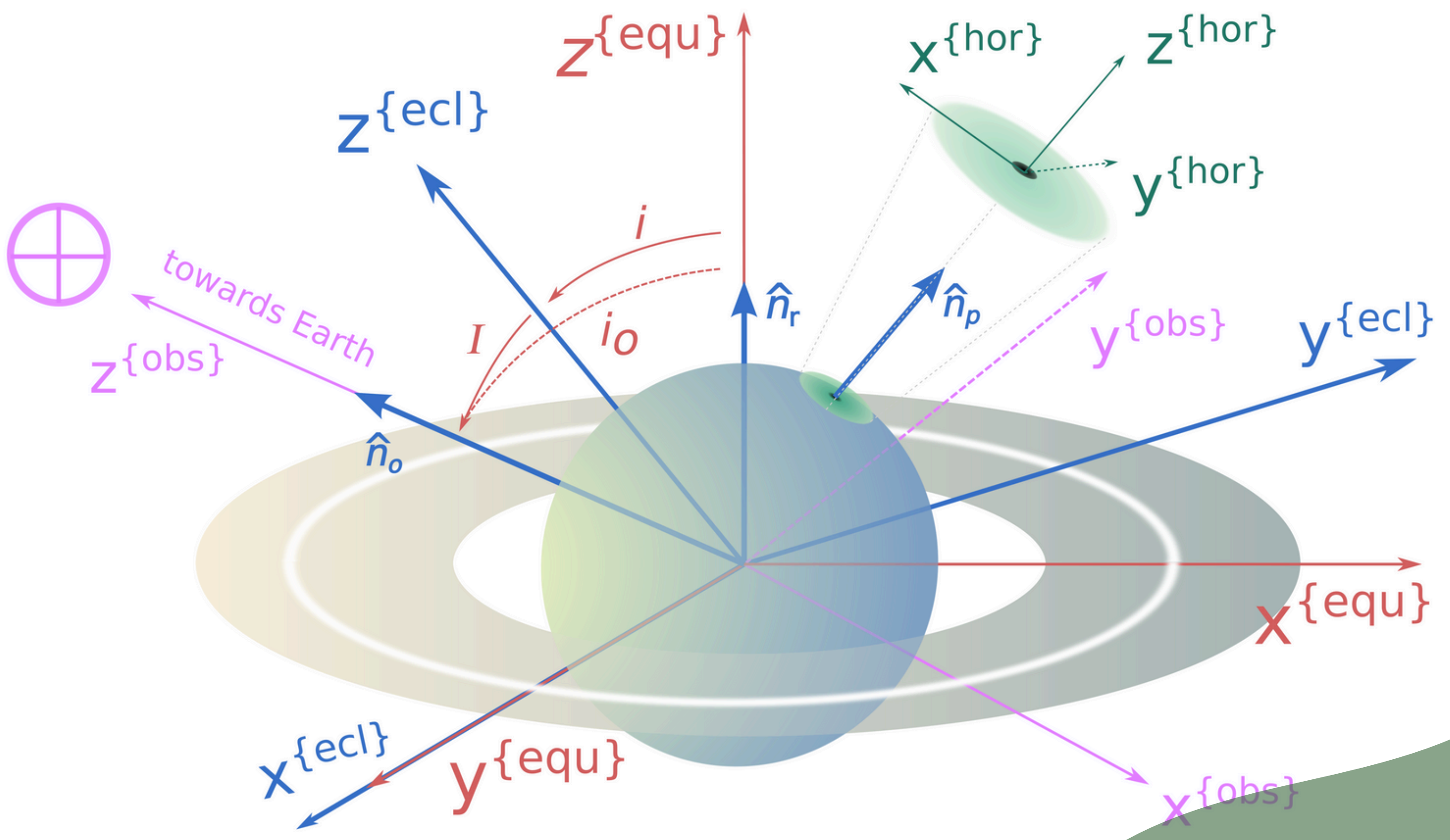
1. ESTADOS
   (ILUMINADO, VISIBLE, OCULTO, TRÁNSITO, ETC.)
2. COORDENADAS
   (FUENTE, OBSERVADOR, EQU, ECL, ALT-AZ, ETC.)
3. PARÁMETROS FÍSICOS
   (ALBEDO, OPACIDAD, EMISIVIDAD, ETC.)

MODELAMIENTO DE EFECTOS ÓPTICOS:

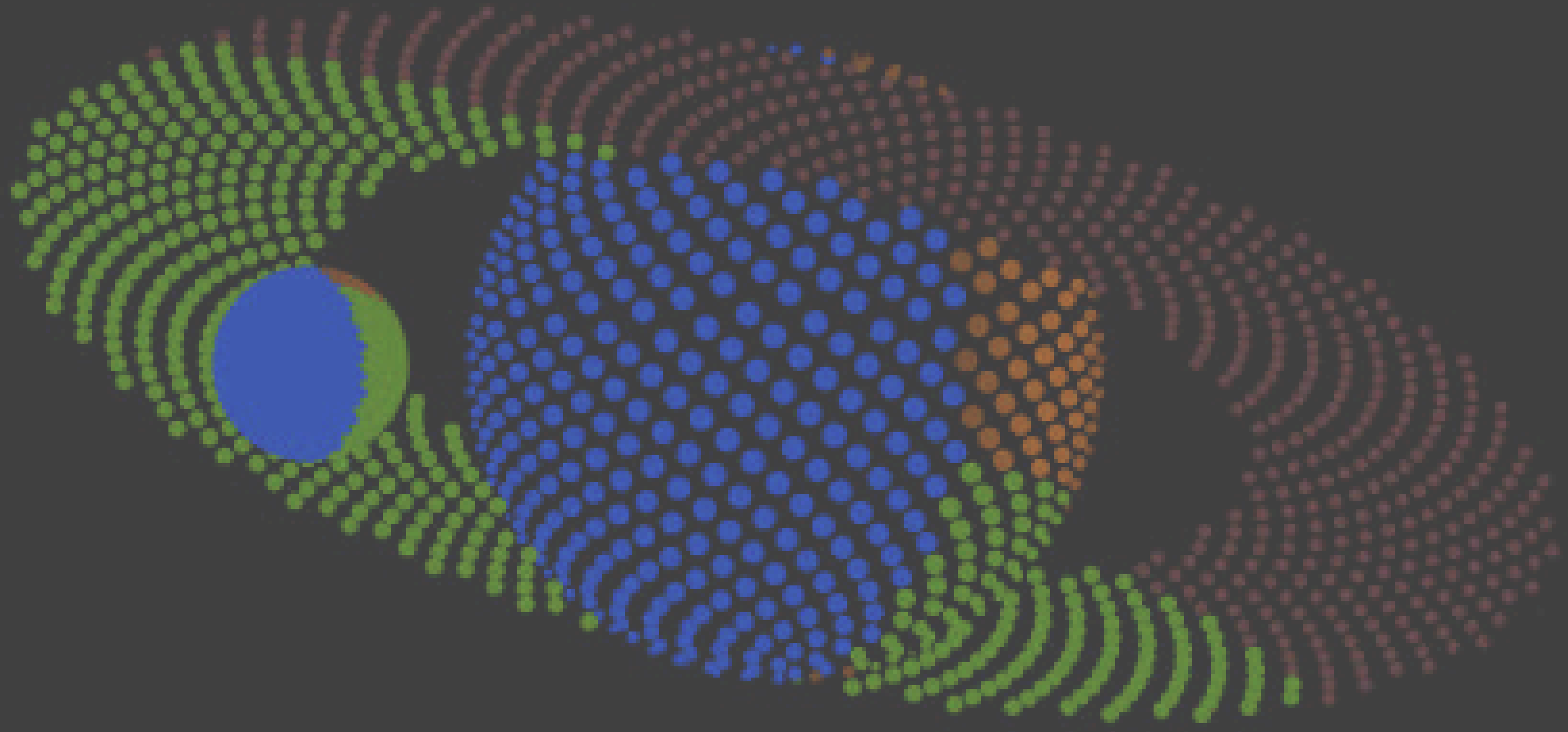
→ TRÁNSITO
→ SCATTERING
→ POLARIZACIÓN (ADAPTADO DE ***PyMieDAP***)



ZULUAGA J. I; SUCERQUIA M & ALVARADO-MONTES J. A.



PRODUCCIÓN CIENTÍFICA



Pryngles 0.9.10
https://github.com/seap-udea/pryngles-public

Scattered light may reveal the existence of ringed exoplanets

Mario Sucerquia[1,2]★, Jaime A. Alvarado-Montes[3,4], Jorge I. Zuluaga[5], Matías Montesinos[1,2,6] and Amelia Bayo[2,1]

[1] Núcleo Milenio Formación Planetaria - NPF, Universidad de Valparaíso, Av. Gran Bretaña 1111, Valparaíso, Chile
[2] Instituto de Física y Astronomía, Facultad de Ciencias, Universidad de Valparaíso, Av. Gran Bretaña 1111, 5030 Casilla, Valparaíso, Chile
[3] Department of Physics & Astronomy, Macquarie University – Sydney, NSW 2109, Australia.
[4] Centre for Astronomy, Astrophysics, and Astrophotonics, Macquarie University – Sydney, NSW 2109, Australia.
[5] SEAP, Instituto de Física - FCEN, Universidad de Antioquia, Calle 70 No. 52-21, Medellín, Colombia.
[6] Chinese Academy of Sciences South America Center for Astronomy, National Astronomical Observatories, CAS, Beijing 100012, China

The bright side of the light curve: a general photometric model of non-transiting exorings

Jorge I. Zuluaga[a,*], Mario Sucerquia[b,c] and Jaime A. Alvarado-Montes[d,e]

[a] SEAP/FACom, Instituto de Física - FCEN, Universidad de Antioquia, Calle 70 No. 52-21, Medellín 050026, Colombia
[b] Universidad de Valparaíso, Av. Gran Bretaña 1111, Valparaíso , Chile
[c] Núcleo Milenio Formación Planetaria - NPF, Valparaíso , Chile
[d] School of Mathematical and Physical Sciences, Macquarie University, Sydney NSW 2109, Australia
[e] Research Centre for Astronomy, Astrophysics and Astrophotonics, Macquarie University, Sydney NSW 2109, Australia

ARTICLE INFO

Keywords:
planets and satellites: rings
techniques: photometric
methods: numerical
planets and satellites: detection

ABSTRACT

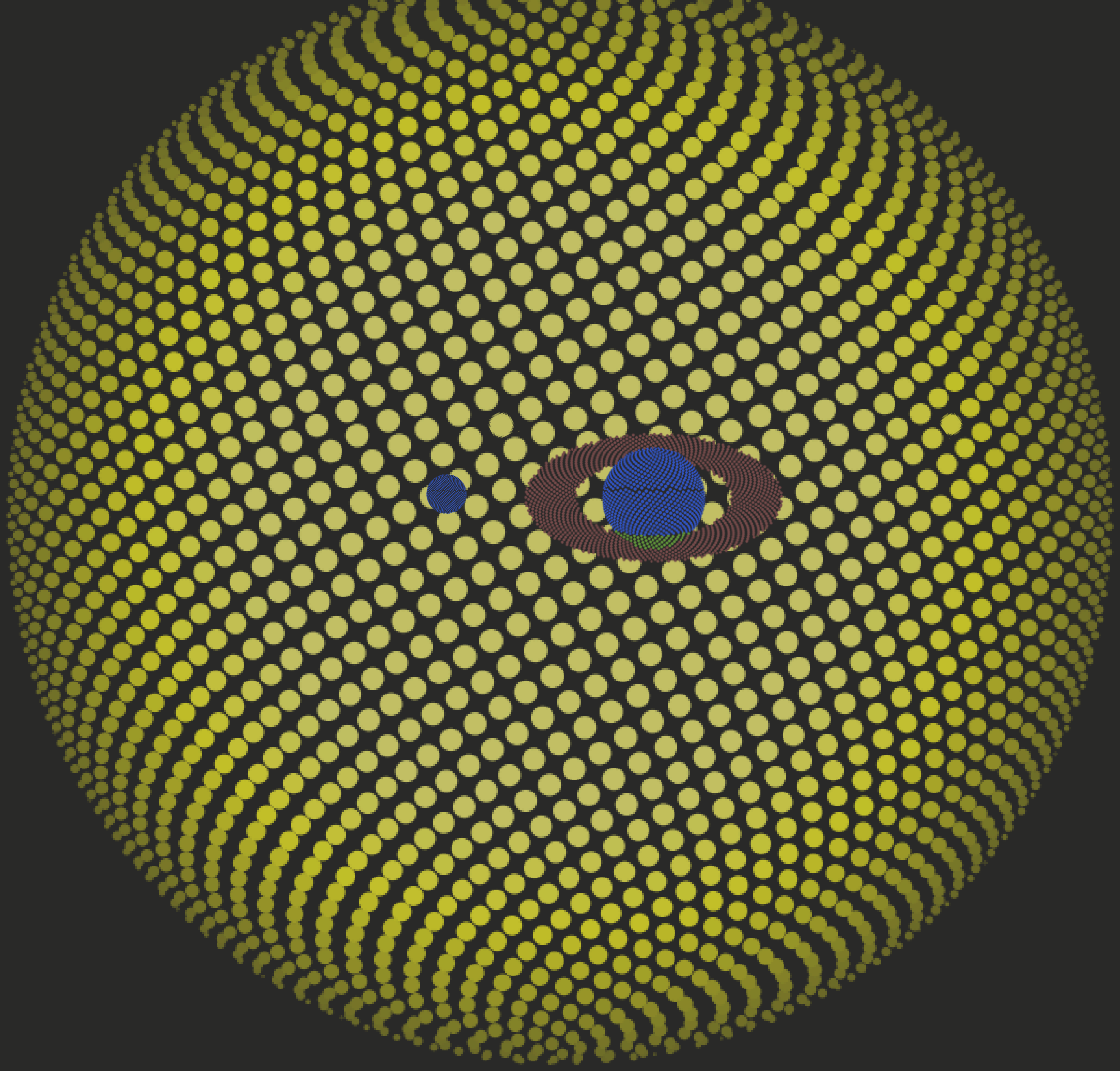
Rings around exoplanets (exorings) are one of the most expected discoveries in exoplanetary research. There is an increasing number of theoretical and observational efforts for detecting exorings, but none of them have succeeded yet. Most of those methods focus on the photometric signatures of exorings during transits, whereas less attention has been paid to light diffusely reflected: what we denote here as the bright side of the light curve. This is particularly important when we cannot detect the typical stellar flux drop produced by transiting exoplanets. Here, we endeavour to develop a general method to model the variations on the light curves of both ringed non-transiting and transiting exoplanets. Our model (dubbed as `Pryngles`) simulates the complex interaction of luminous, opaque, and semitransparent objects in planetary systems, discretizing their surface with small circular plane discs that resemble sequins or spangles. We perform several numerical experiments with this model, and show its incredible potential to describe the light curve of complex systems under various orbital, planetary, and observational configurations of planets, moons, rings, or discs. As our model uses a very general approach, we can capture effects like shadows or planetary/ring shine, and since the model is also modular we can easily integrate arbitrarily complex physics of planetary light scattering. A comparison against existing tools and analytical models of reflected light reveals that our model, despite its novel features, reliably reproduces light curves under common circumstances. `Pryngles` source code is written in `Python` and made publicly available.

A general polarimetric model for transiting and non-transiting ringed exoplanets

Allard. K. Veenstra[1], Jorge I. Zuluaga[2], Jaime A. Alvarado-Montes[3,4], Mario Sucerquia[5,6,7], and Daphne M. Stam[1]

[1] Faculty of Aerospace Engineering, Technical University Delft, Kluyverweg 2, 2629 HS Delft, The Netherlands
e-mail: a.k.veenstra@tudelft.nl
[2] SEAP/FACom, Instituto de Física - FCEN, Universidad de Antioquia, Calle 70 No. 52-21, Medellín, Colombia
e-mail: jorge.zuluaga@udea.edu.co
[3] School of Mathematical and Physical Sciences, Macquarie University, Balaclava Road, North Ryde, NSW 2109, Australia
[4] The Macquarie University Astrophysics and Space Technologies Research Centre, Macquarie University, Balaclava Road, North Ryde, NSW 2109, Australia
e-mail: jaime-andres.alvarado-montes@hdr.mq.edu.au
[5] Instituto de Física y Astronomía, Facultad de Ciencias, Universidad de Valparaíso, Av. Gran Bretaña 1111, 5030 Casilla, Valparaíso, Chile
[6] Departamento de Ciencias, Facultad de Artes Liberales, Universidad Adolfo Ibáñez, Av. Padre Hurtado 750, Viña del Mar, Chile.
[7] Núcleo Milenio Formación Planetaria - NPF, Universidad de Valparaíso, Av. Gran Bretaña 1111, Valparaíso, Chile
e-mail: mario.sucerquia@uv.cl

PRYNGLES
GENERALIZANDO EL PROBLEMA...



INTERFAZ R*ingedPlanet* (2022):

1. SISTEMAS ESTRELLA-PLANETA-ANILLO
2. MARCO DE REFERENCIA PLANETOCÉNTRICO,
3. DINÁMICA ANALÍTICA ⟶ PROBLEMA DE KEPLER

⟶ EFECTOS TESTEADOS $\varepsilon \lesssim 10^{-4}$:

1. PAQUETES EXTERNOS ⟶ ***batman & PyPplusS***
2. MODELOS ANALÍTICOS ⟶ M. SUCERQUIA, ET AL. 2020

INTERFAZ *System* (DEV):

1. SISTEMAS ARBITRARIOS
2. MARCO DE REFERENCIA BARICÉNTRICO
3. INTEGRACIÓN NUMÉRICA ⟶ REBOUND
4. REESTRUCTURACIÓN DE ARQUITECTURA MODULAR
5. GESTION CENTRALIZADA DE SPANGLES ⟶ PANDAS

⟶ EFECTOS TESTEADOS $\varepsilon \lesssim 10^{-5}$:

1. INTERFAZ *RingedPlanet*
2. PROXIMAMENTE PAQUETES EXTERNOS
   ⟶ *Pandora, LUNA, Gefera*

PRYNGLES
MODELANDO FOTOMETRÍA...

REFLEXIÓN DIFUSA ⟶ $$\frac{F}{F_0} = \sum_i \frac{a_{S_i}\cos\Lambda_i}{4\pi d_i^2} A_{L_i}(\Lambda_i)\cos Z_i$$

ATMOSFERAS ⟶ (SOBOLEV V.V. 1975)

$$A_{L_i}(\Lambda_i) = 2\int_0^1 \cos Z\,\rho(\gamma,\Lambda_i,Z)\,d(\cos Z)$$ ⟶ ALBEDO LAMBERTIANO

1. SEMI-INFINITA $\tau \to \infty$
2. ISOTRÓPICAMENTE GRIS

$$\rho(\gamma,\Lambda,Z) = \frac{\gamma}{4}\frac{f(\gamma,Z)f(\gamma,\Lambda)}{\cos\Lambda+\cos Z}$$ ⟶ COEFICIENTE DE REFLEXIÓN

$$A_S = 4\int_0^1\int_0^1 \cos\Lambda\cos Z\,\rho(\gamma,\Lambda,Z)\,d(\cos\Lambda)\,d(\cos Z)$$ ⟶ ALBEDO ESFÉRICO

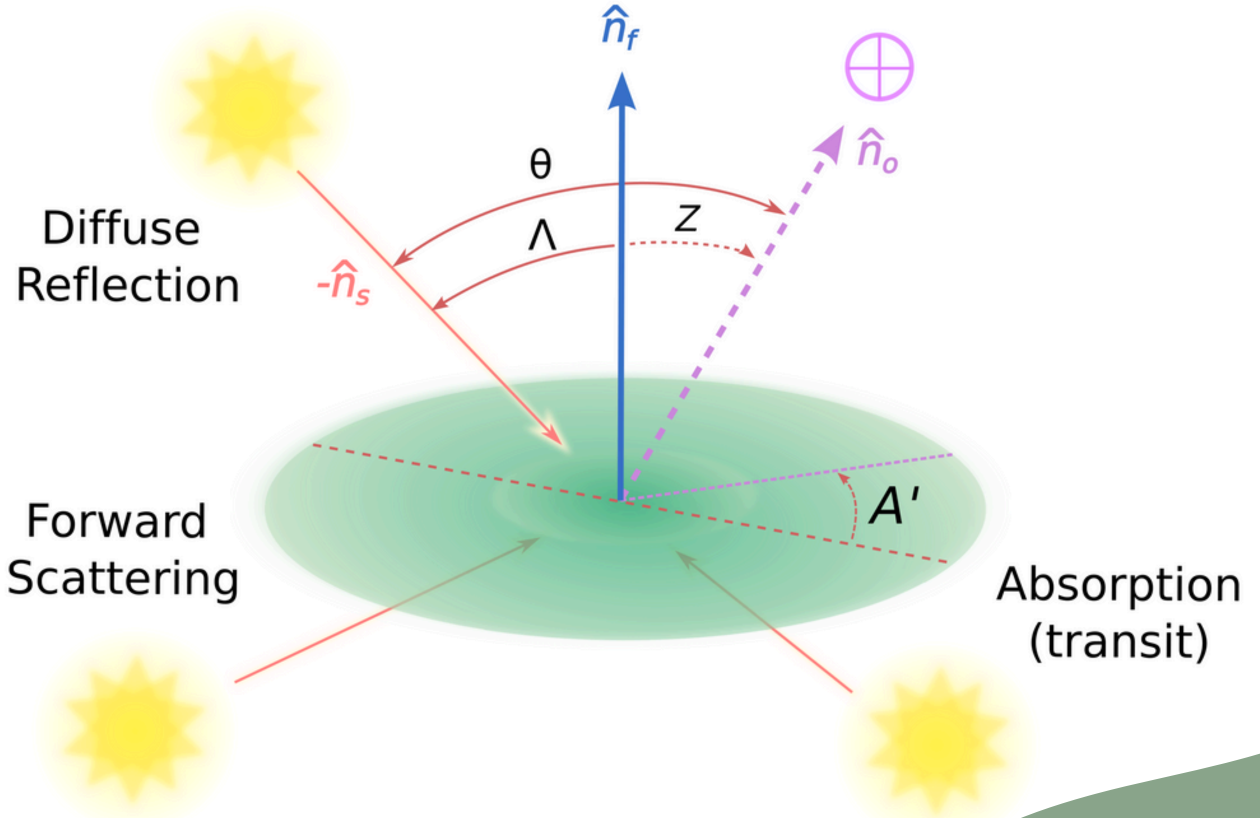
SUPERFICIES ⟶ (RUSSEL H. N. 1916):

$$A_{L_i}(\Lambda_i) = 2\pi\gamma\int_0^1 \frac{f(\Lambda_i,Z)}{\cos\Lambda}d(\cos Z)$$ ⟶ ALBEDO LAMBERTIANO

LEY DE REFLEXIÓN DIFUSA:

1. LEY DE LAMBERT
2. LEY DE LOMMEL-SEELIGER

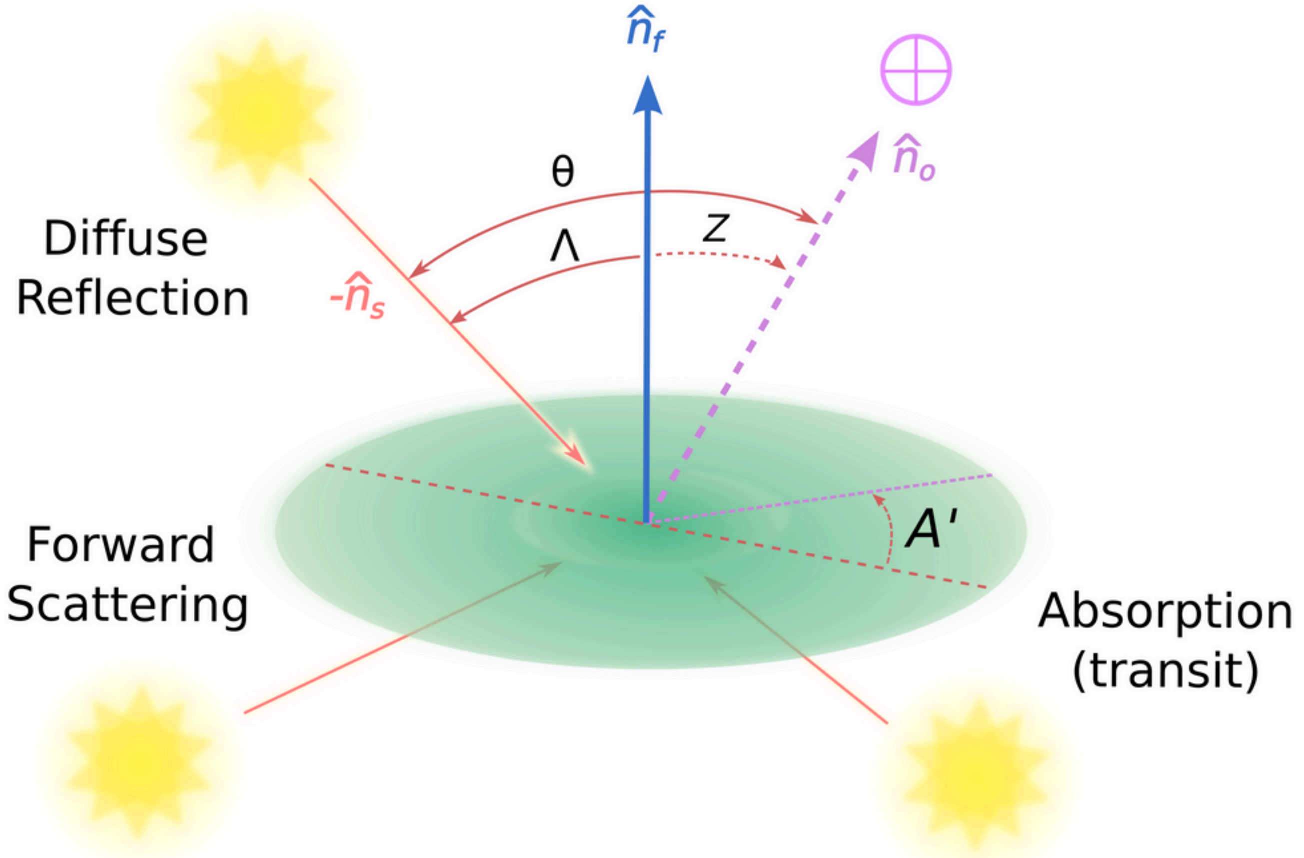
⟶ $$f(\Lambda,Z) = \begin{cases} \cos\Lambda \\ \dfrac{\cos\Lambda\cos Z}{\cos\Lambda+\cos Z} \end{cases}$$



ZULUAGA J. I; SUCERQUIA M & ALVARADO-MONTES J. A.

PRYNGLES
MODELANDO FOTOMETRÍA...

ABSORCIÓN (TRÁNSITO) ⟶ $\frac{F}{F_0} = \sum_i a_{S_i} \cos Z_i \, \beta_i(Z_i) \frac{I(\mu)}{I(0)}$



ZULUAGA J. I; SUCERQUIA M & ALVARADO-MONTES J. A.

LEY DE OSCURECIMIENTO DEL LIMBO - NO LINEAL
⟶ (CLARET A. 2000)

$$\mu = \sqrt{1 - \frac{R^2}{R_*^2}}$$

$$\frac{I(\mu)}{I(0)} = 1 - \sum_n C_n (1 - \mu^{n/2})$$

1. TEMPERATURAS ⟶ (2e3 < T < 5e4)
2. INDICE DE METALICIDAD ⟶ (-5 < log Fe/H < 1)l

FACTOR DE ATENUACIÓN
⟶ (FRENCH, R.G. & NICHOLSON, P.D. 2000)

CONSIDERA EFECTOS DE ABSORCIÓN Y DIFRACCIÓN

$$\beta_i(Z_i) = 1 - \frac{\tau}{2 \cos Z_i} e^{-\frac{\tau}{\cos Z_i}}$$

1. SPANGLE OPACO - SUPERFICIE
2. SPANGLE SEMITRANSPARENTE - ANILLO/ATMOSFERA

PRYNGLES
ESTRUCTURAS DETECTABLES...

CORRELACIÓN DE MAGNITUDES FOTOMÉTRICAS:

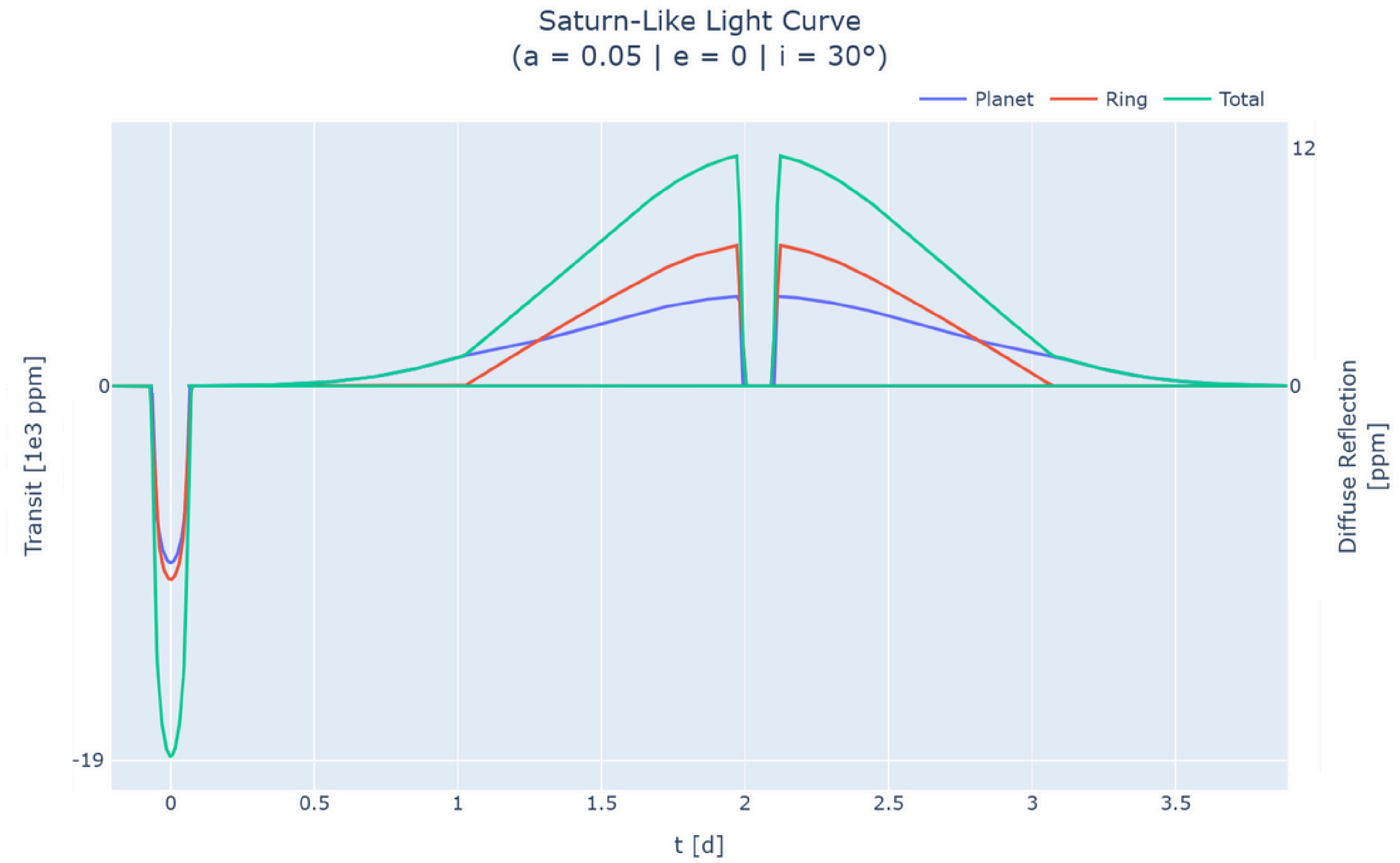
1. TAMAÑO DEL CUERPO
2. DISTANCIA A LA ESTRELLA
3. NATURALEZA DE LA ÓRBITA
4. ORIENTACIÓN DE LINEA DE VISIÓN

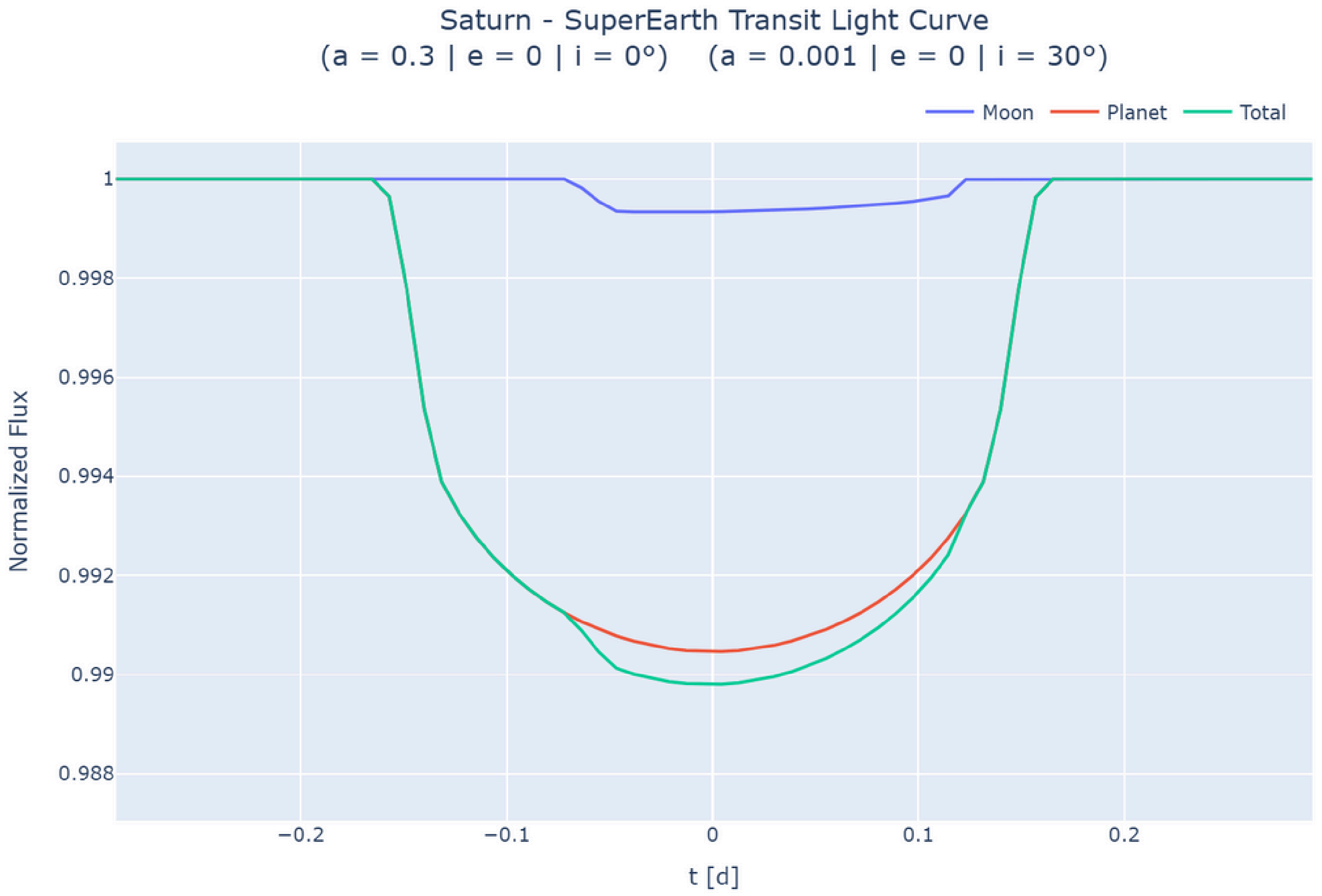
TRÁNSITO:

⟶ SUBESTIMACIÓN DE DENSIDADES
⟶ RESOLUCIÓN DE OBJETOS ADICIONALES
⟶ ANÁLISIS DE VARIACIONES DE TRÁNSITO

REFLEXIÓN DIFUSA:

⟶ TRAZAS OBSERVABLES EN TRÁNSITO PRIMARIO/SECUNDARIO





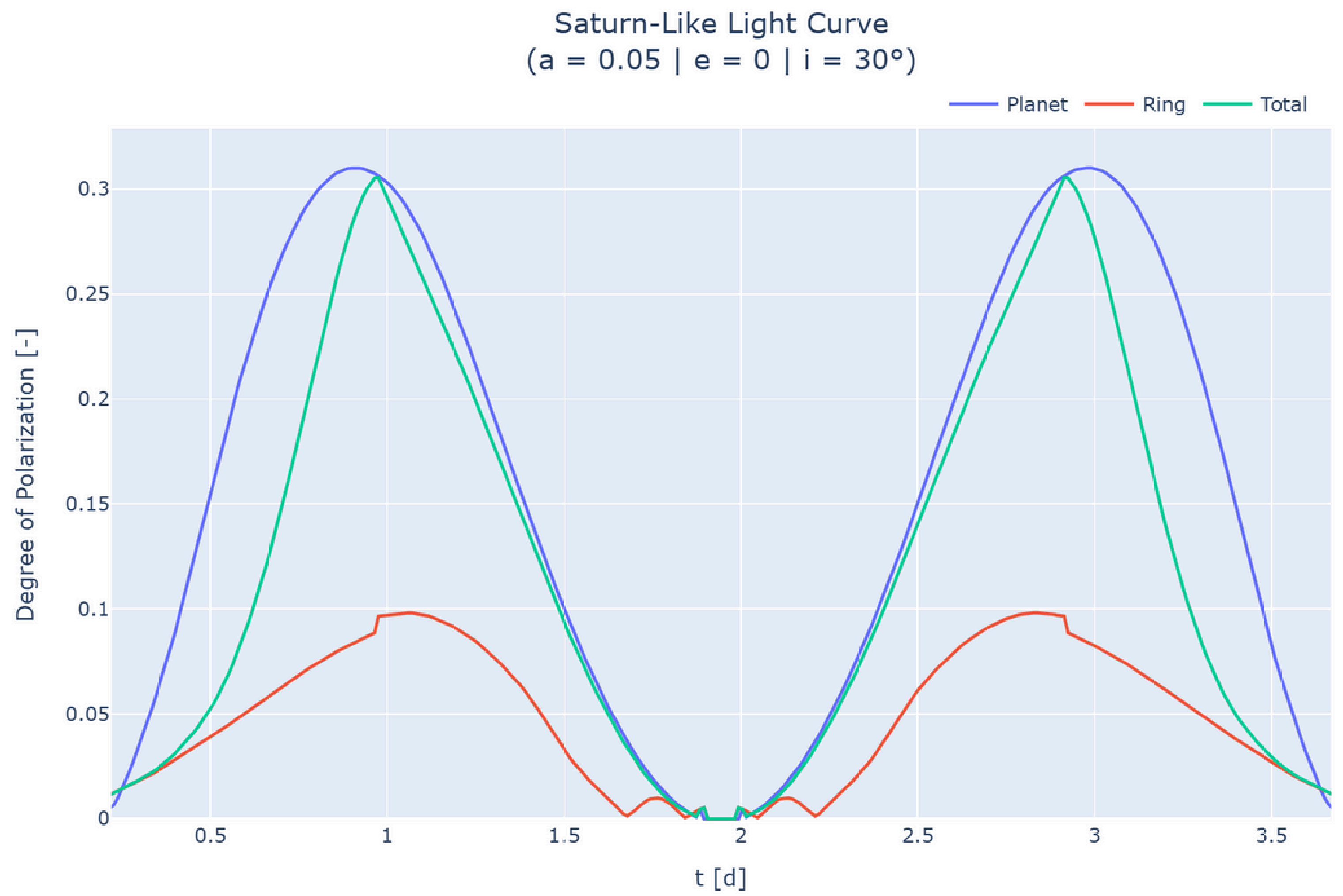
PRYNGLES
ESTRUCTURAS DETECTABLES…

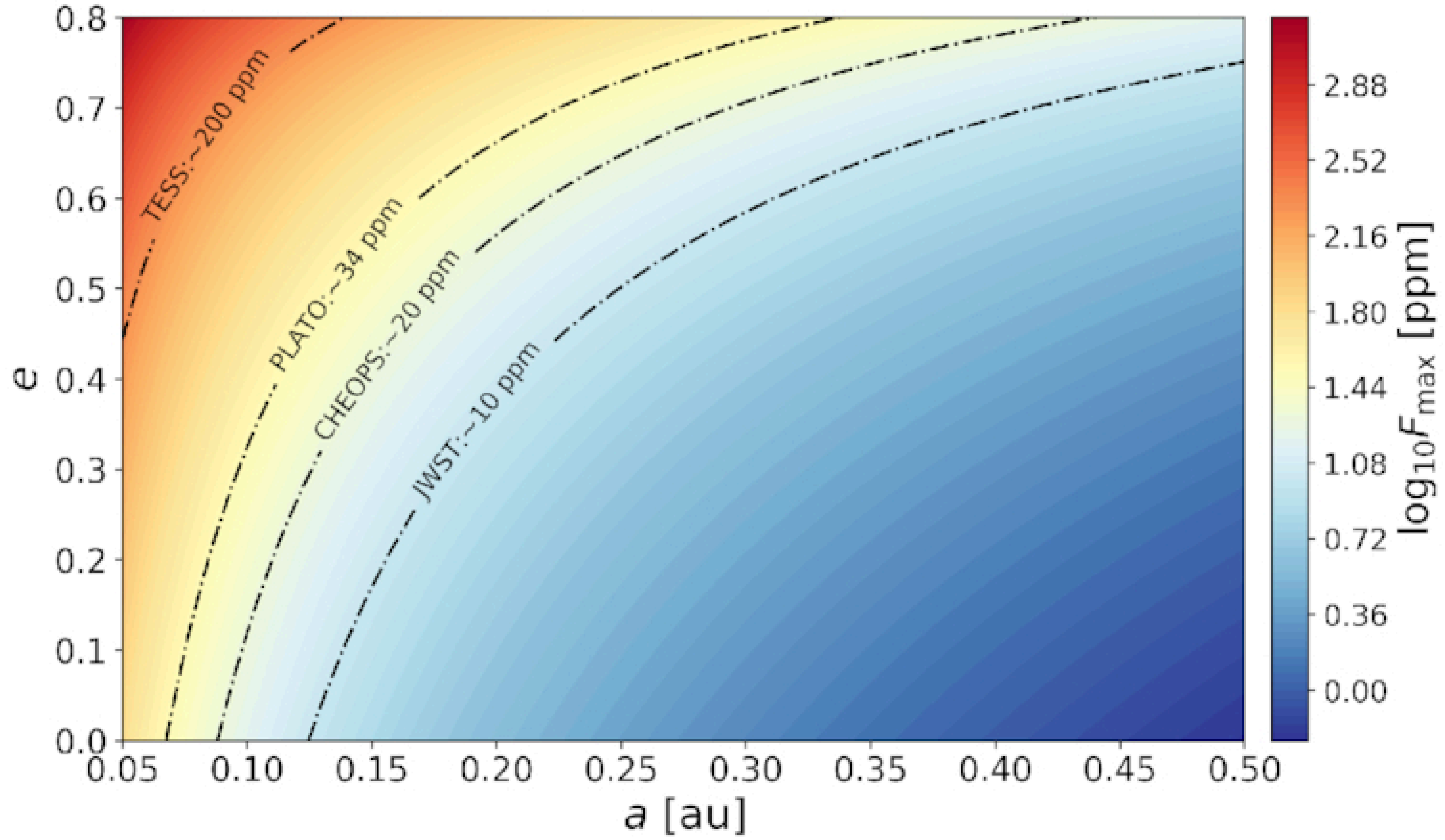
CAPACIDAD OBSERVACIONAL:

1. ESPACIO DE PARÁMETROS RESTRINGIDO
2. LIMITACIÓN EN TIEMPOS DE OBSERVACIÓN
3. MENOR VARIEDAD DE SISTEMAS RESOLUBLES
4. PRECISIÓN INSTRUMENTAL REQURIDA Y FUTURA

SCATTERING:

⟶ REDUCCIÓN EN EL GRADO DE POLARIZACIÓN
⟶ TRAZAS OBSERVABLES EN TRÁNSITO PRIMARIO





M. SUCERQUIA, ET AL. 2020

PRYNGLES
UN FUTURO PROMETEDOR...

⟶ REVISIÓN, REPRODUCCIÓN Y MOTIVACIÓN DE OBSERVACIONES

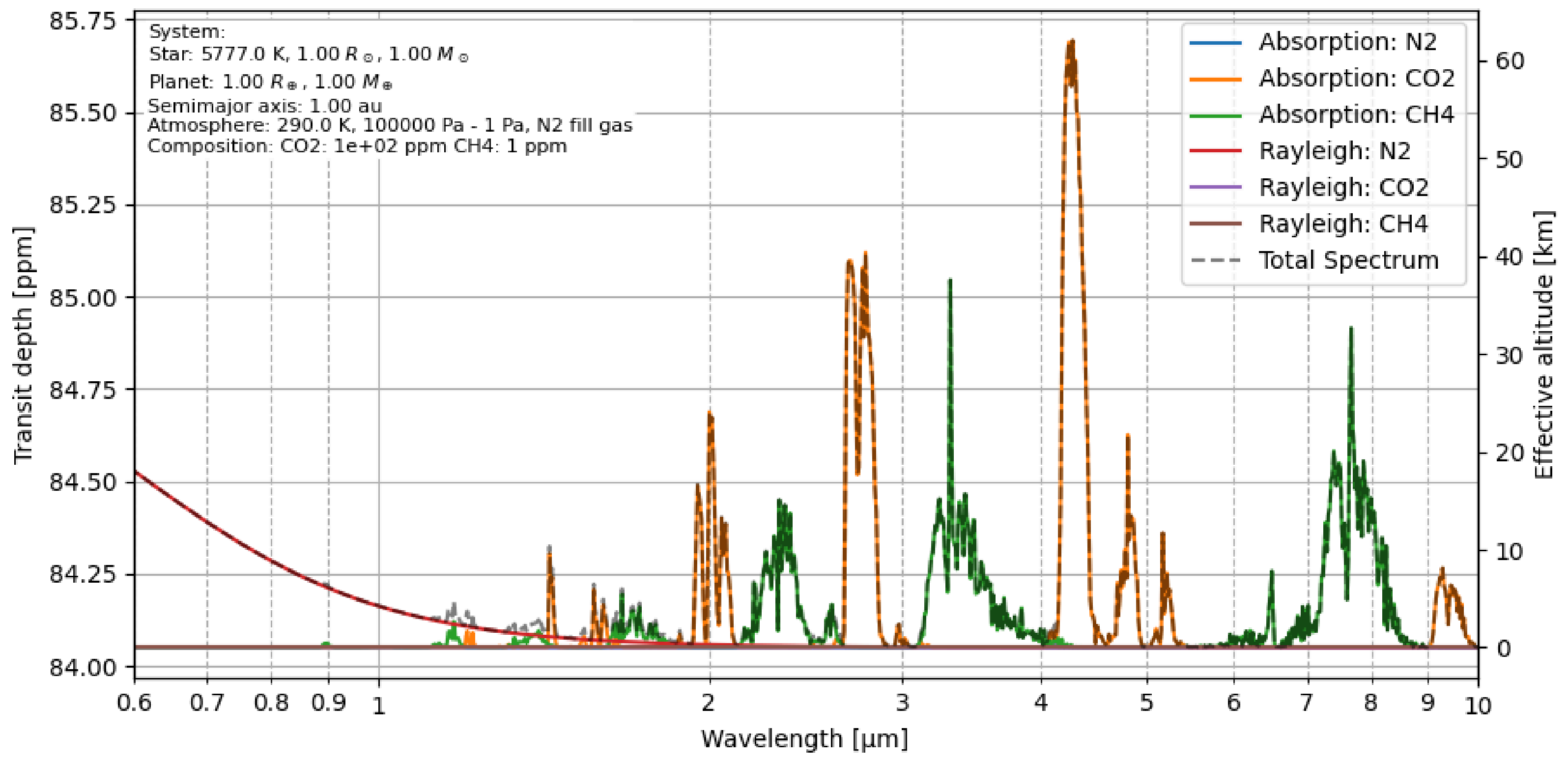
PROSPECTOS:

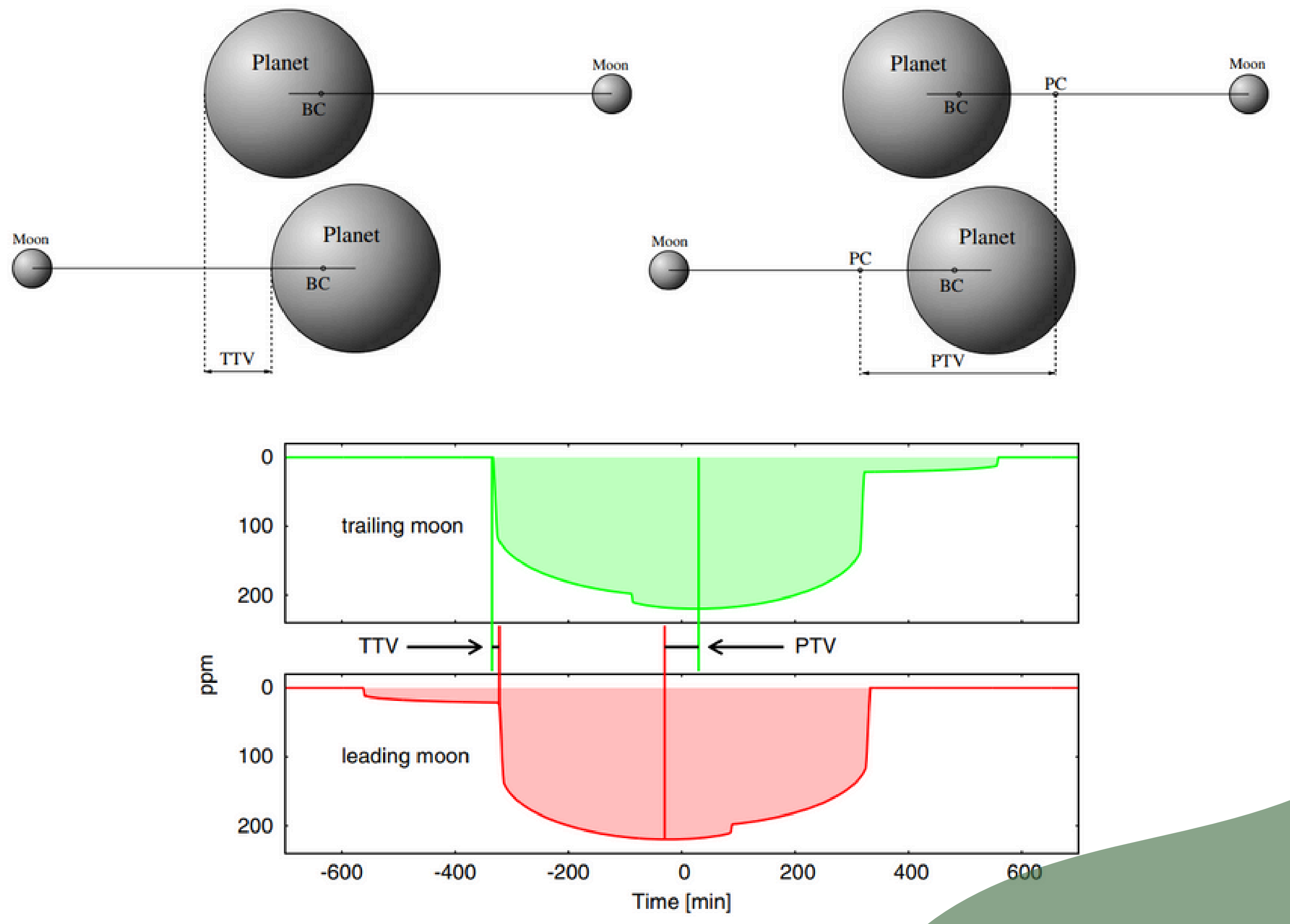
1. TÉCNICAS DE TTV/TDV
2. MAPEO DE SUPERFICIES/ATMOSFERAS
3. ANÁLISIS DE DIVERSIDAD Y ESTABILIDAD
4. IMPLEMENTACIÓN DE MODELOS MULTIBANDA
5. AJUSTES A MODELOS DE COMPOSICIÓN Y DINÁMICA INTERNA

OTRAS APLICACIONES:

⟶ ASTROFÍSICA ESTELAR (BINARIAS ECLIPSANTES)

D. S. DUQUE-CASTAÑO, J. I. ZULUAGA & L. FLOR-TORRES. 2024





R. HELLER. 2018

NOS MANTENEMOS EXPECTANTES DE LA PRIMER DETECCIÓN EN ANILLOS Y SATÉLITES EXOPLANETARIOS

REFERENCIAS

1. A. ISELLA,, ET AL. DETECTION OF CONTINUUM SUBMILLIMETER EMISSION ASSOCIATED WITH CANDIDATE PROTOPLANETS, 879, L25 (2019), ARXIV:1906.06308 [ASTROPH.EP].
2. ROBIN M. CANUP. FORMING A MOON WITH AN EARTH-LIKE COMPOSITION VIA A GIANT IMPACT.SCIENCE338,1052-1055(2012).DOI:10.1126/SCIENCE.1226073
3. JACK WISDOM ET AL. LOSS OF A SATELLITE COULD EXPLAIN SATURN'S OBLIQUITY AND YOUNG RINGS.SCIENCE377,1285-1289(2022).DOI:10.1126/SCIENCE.ABN1234
4. HELLER, R. (2018). DETECTING AND CHARACTERIZING EXOMOONS AND EXORINGS. HANDBOOK OF EXOPLANETS, 835–851. DOI:10.1007/978-3-319-55333-7_35
5. T. BARCLAY, ET AL. (2013). A SUB-MERCURY-SIZED EXOPLANET. NATURE, 494(7438), 452–454. HTTPS://DOI.ORG/10.1038/NATURE11914
6. ROSSI, L., BERZOSA-MOLINA, J., & STAM, D. M. (2018). PYMIEDAP: A PYTHON–FORTRAN TOOL FOR COMPUTING FLUXES AND POLARIZATION SIGNALS OF (EXO) PLANETS. ASTRONOMY & ASTROPHYSICS, 616, A147. ARXIV:1804.08357
7. D. S. DUQUE-CASTAÑO, J. I. ZULUAGA, AND L. FLOR-TORRES (2024), MACHINE-ASSISTED CLASSIFICATION OF POTENTIAL BIOSIGNATURES IN EARTH-LIKE EXOPLANETS USING LOW SIGNAL-TO-NOISE RATIO TRANSMISSION SPECTRA, SUBMITTED TO MNRAS, ARXIV:2407.19167
8. BARNES, J.W., FORTNEY, J.J., 2004. TRANSIT DETECTABILITY OF RING SYSTEMS AROUND EXTRASOLAR GIANT PLANETS. APJ 616, 1193–1203. DOI:10.1086/ 425067, ARXIV:ASTRO-PH/0409506.
9. SOBOLEV, V.V., 1975. LIGHT SCATTERING IN PLANETARY ATMOSPHERES
10. RUSSELL, H.N., 1916. ON THE ALBEDO OF THE PLANETS AND THEIR SATELLITES. APJ 43, 173–196. DOI:10.1086/142244.
11. CLARET, A., 2000. A NEW NON-LINEAR LIMB-DARKENING LAW FOR LTE STELLAR ATMOSPHERE MODELS. CALCULATIONS AT SEVERAL SURFACE GRAVITIES. A&A 363, 1081– 1190.
12. FRENCH, R.G., NICHOLSON, P.D., 2000. SATURN'S RINGS II. PARTICLE SIZES INFERRED FROM STELLAR OCCULTATION DATA. ICARUS 145, 502–523. DOI:10. 1006/ICAR.2000.6357.
13. KIPPING, D., ET AL., 2022. AN EXOMOON SURVEY OF 70 COOL GIANT EXOPLANETS AND THE NEW CANDIDATE KEPLER-1708 B-I. NATURE ASTRONOMY 6, 367–380. DOI:10.1038/S41550-021-01539-1, ARXIV:2201.04643.
14. KENWORTHY, M.A., MAMAJEK, E.E., 2015. MODELING GIANT EXTRASOLAR RING SYSTEMS IN ECLIPSE AND THE CASE OF J1407B: SCULPTING BY EXOMOONS? APJ 800, 126. DOI:10.1088/0004-637X/800/2/126, ARXIV:1501.05652.
15. TEACHEY, A. (2024). DETECTING AND CHARACTERIZING EXOMOONS AND EXORINGS (HANDBOOK OF EXOPLANETS, 2ND EDITION). ARXIV E-PRINTS. HTTPS://DOI.ORG/10.48550/ARXIV.2401.13293
16. SUCERQUIA, M., ALVARADO-MONTES, J.A., ZULUAGA, J.I., MONTESINOS, M., BAYO, A., 2020A. SCATTERED LIGHT MAY REVEAL THE EXISTENCE OF RINGED EXOPLANETS. MNRAS 496, L85–L90. DOI:10.1093/MNRASL/SLAA080, ARXIV:2004.14121.
17. ZULUAGA, J. I., SUCERQUIA, M., & ALVARADO-MONTES, J. A. (2022). THE BRIGHT SIDE OF THE LIGHT CURVE: A GENERAL PHOTOMETRIC MODEL OF NON-TRANSITING EXORINGS. ASTRONOMY AND COMPUTING, 40, 100623. HTTPS://DOI.ORG/10.1016/J.ASCOM.2022.100623
18. VEENSTRA, A. K., ZULUAGA, J. I., ALVARADO-MONTES, J. A., SUCERQUIA, M., & STAM, D. M. (2024). A GENERAL POLARIMETRIC MODEL FOR TRANSITING AND NON-TRANSITING RINGED EXOPLANETS. ARXIV E-PRINTS. HTTPS://DOI.ORG/10.48550/ARXIV.2404.16606