

7th IAA Planetary Defense Conference

26-30 April 2021, Online Event

Hosted by UNOOSA in collaboration with ESA



Session 6b: NEO Characterization

Chairs: Marina Brozovic | Stephen Lowry

Presenters: J. Masiero | M. Devogele | V. Reddy |
D. Dunham | J. Roa Vicens

Characterization of Near-Earth Asteroids from NEOWISE survey data

Joseph Masiero (Caltech/IPAC)

27-Apr-2021

Co-authors: A. Mainzer, J.M. Bauer, R.M. Cutri,
T. Grav, J. Pittichová, E. Kramer, E.L. Wright



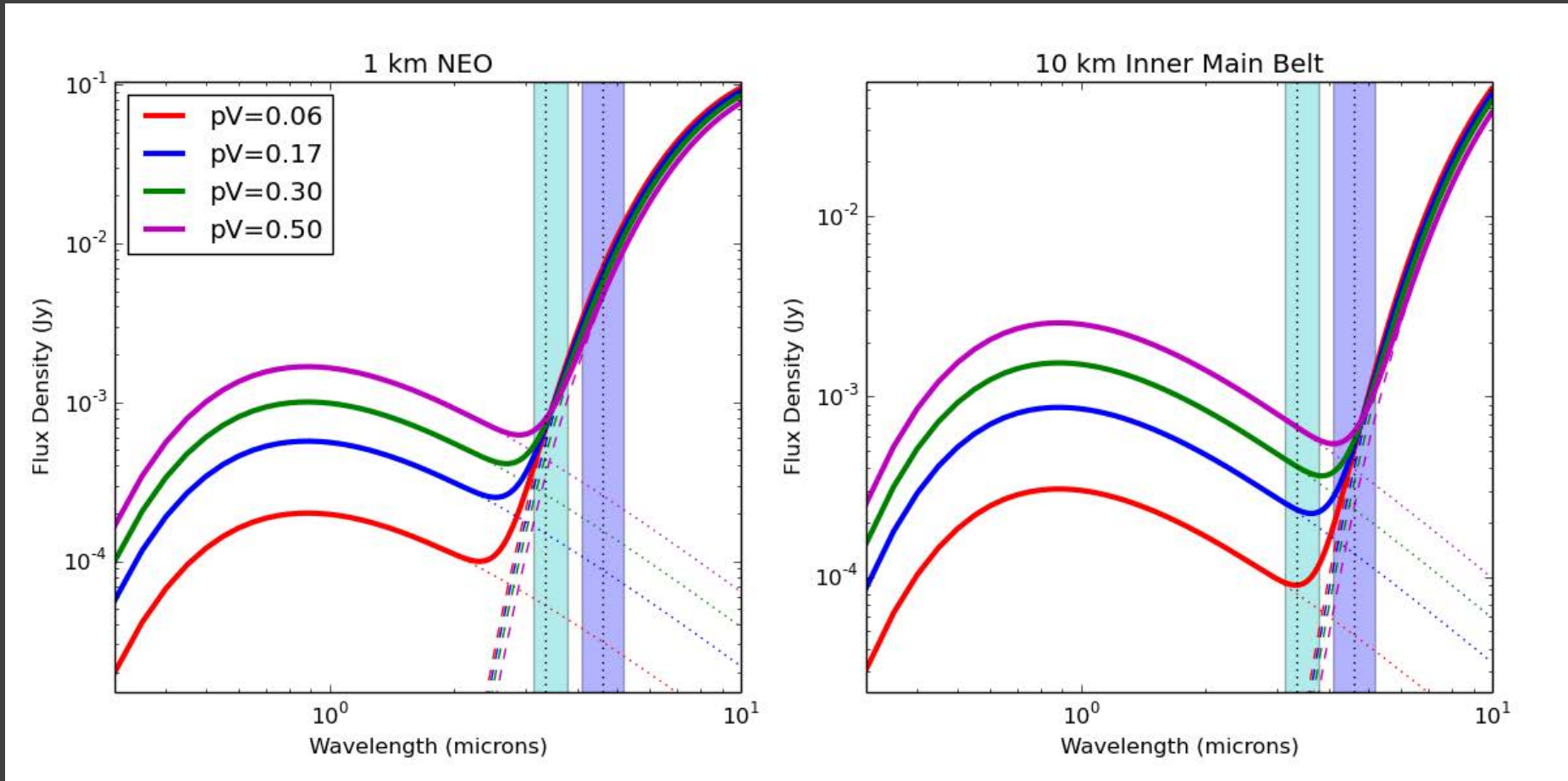
NEOWISE mission overview

- PI-led (PI: Amy Mainzer, U Arizona) under NASA PDCO Program (Lindley Johnson, Planetary Defense Officer)
- Utilizes WISE spacecraft brought out of hibernation in October 2013, following same survey pattern
- 3.4 and 4.6 μm bands (W1 and W2) at $\sim 77\text{K}$
- Terminator-following pole-to-pole orbit
- Surveys entire sky roughly every 6 months
- Mission goals:
 - Expand survey of NEOs at mid-infrared wavelengths using W1 and W2 channels
 - Obtain physical characterization (including diameters and albedos) of NEOs detected by NEOWISE
 - NEOWISE observations a key component to future mission planning (both human and robotic) as well as planetary defense preparation

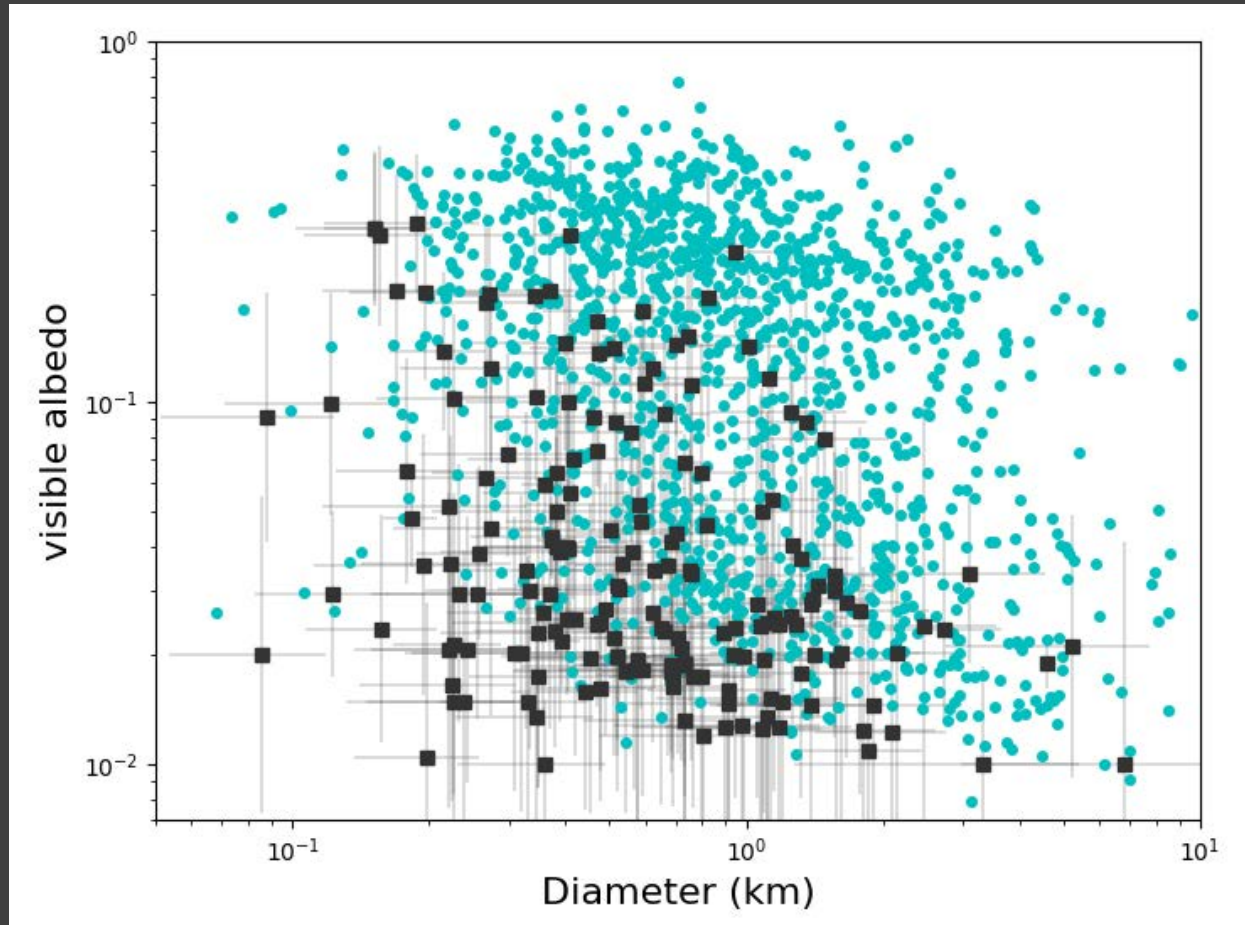


NASA JPL / Caltech

Sizes from Thermal Infrared

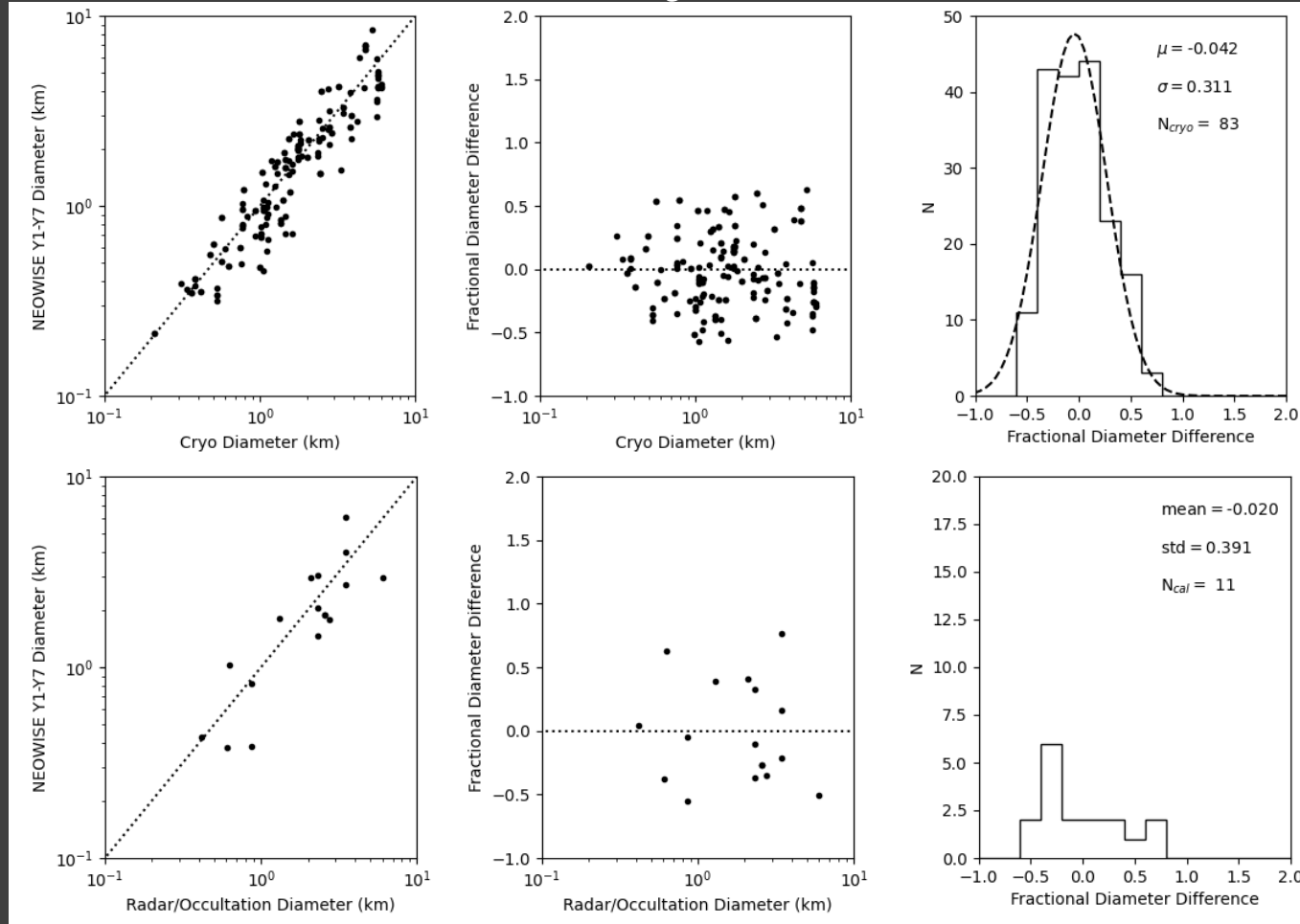


Seven years of NEOWISE survey



Masiero et al. in prep

NEO size accuracy

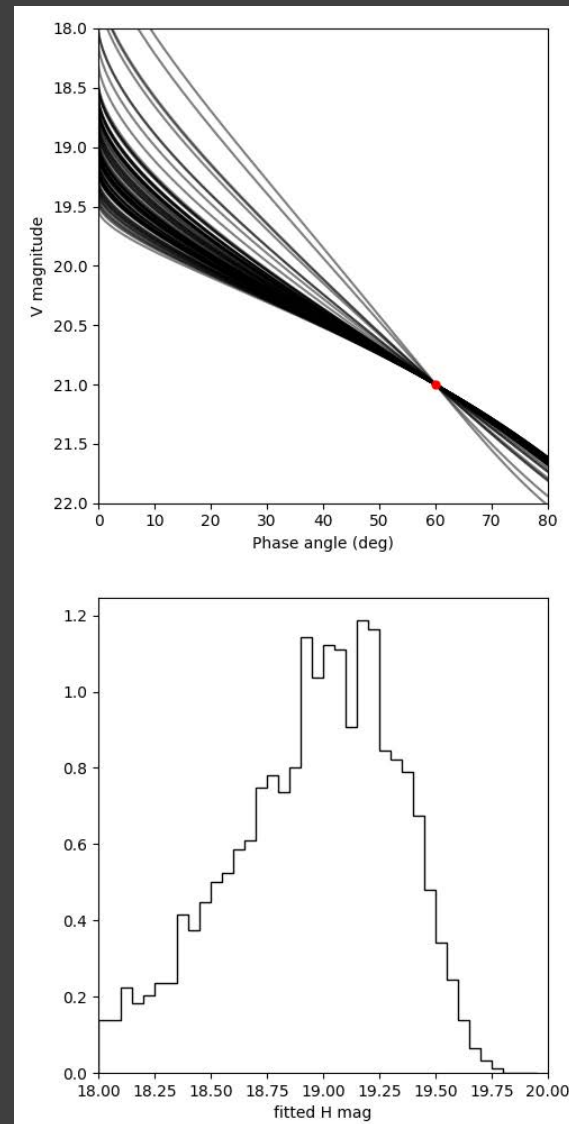


- Sizes from NEATM are spherical equivalent diameters
- Using only 3.4 and 4.6 microns, NEO diameter accuracy is ~30-40%
- This is due to uncertainty in the beaming parameter for NEOs
- When thermal peak is observed and beaming can be fit (e.g. cryogenic WISE mission) diameter accuracy improves to ~10-15%

Masiero et al. in prep

Albedo Uncertainty

- Albedos derived by combining thermal IR diameters with optical measurements
- Uncertainties from both components drive final albedo uncertainty
- For NEOs, observations made at high phases result in large H mag uncertainties unless G slope parameter is constrained
- This drives the uncertainty on albedo
- For the Main Belt, optical observations are at low phase angles, so uncertainty on H much smaller, and not comparable to NEOs
- Caution needed when relating albedo to physical properties
- See Masiero et al. 2021, PSJ, 2, 32 for discussion



Observations of Exercise Object 2021 PDC

- NEOWISE would not detect 2021 PDC in regular survey operations
- However, a survey replan would allow NEOWISE to follow it for ~3 weeks in June 2021
- This would allow for 300 exposures of 2021 PDC, which could be coadded to increase sensitivity
- Trade off would be increased heat load on the telescope potentially reducing sensitivity by the end of the observing campaign
- Data would be sufficient for a 3σ detection of a 100m size object

INFORMATION ON THIS SLIDE REFERS ONLY TO A THEORETICAL PLANNING EXERCISE

Size constraints on 2021 PDC

- Using an assumed 3σ detection, NEATM thermal model fit gives a diameter of 2021 PDC of 160 ± 80 m
- Large uncertainty a result of unknown beaming parameter
- Based on this, NEOWISE would be able to provide a 3σ upper limit of $D < 240$ m to mitigation planners by early July 2021
- As data came in over June, upper limit could be calculated and would steadily decrease, with largest sizes being rejected in mid June

INFORMATION ON THIS SLIDE REFERS ONLY TO A THEORETICAL PLANNING EXERCISE

Conclusions

- NASA has requested that the NEOWISE team plan to continue survey through June 2023
- Orbital evolution will be monitored as sun comes out of Solar minimum
- NEOWISE continues to perform well
- No significant degradation in sensitivity anticipated during this time, rate of NEO characterization expected to continue at current level
- NEOWISE offers a unique capability to provide thermal IR observations of a large number of NEOs in support of hazard assessment and planetary defense

Polarimetry as a tool for physical characterization of potentially hazardous NEOs

Maxime Devogèle¹ & Nicholas Moskovitz²

¹Arecibo Observatory/University of Central Florida

²Lowell Observatory

Planetary Defense Conference 2021

April 27, 2021

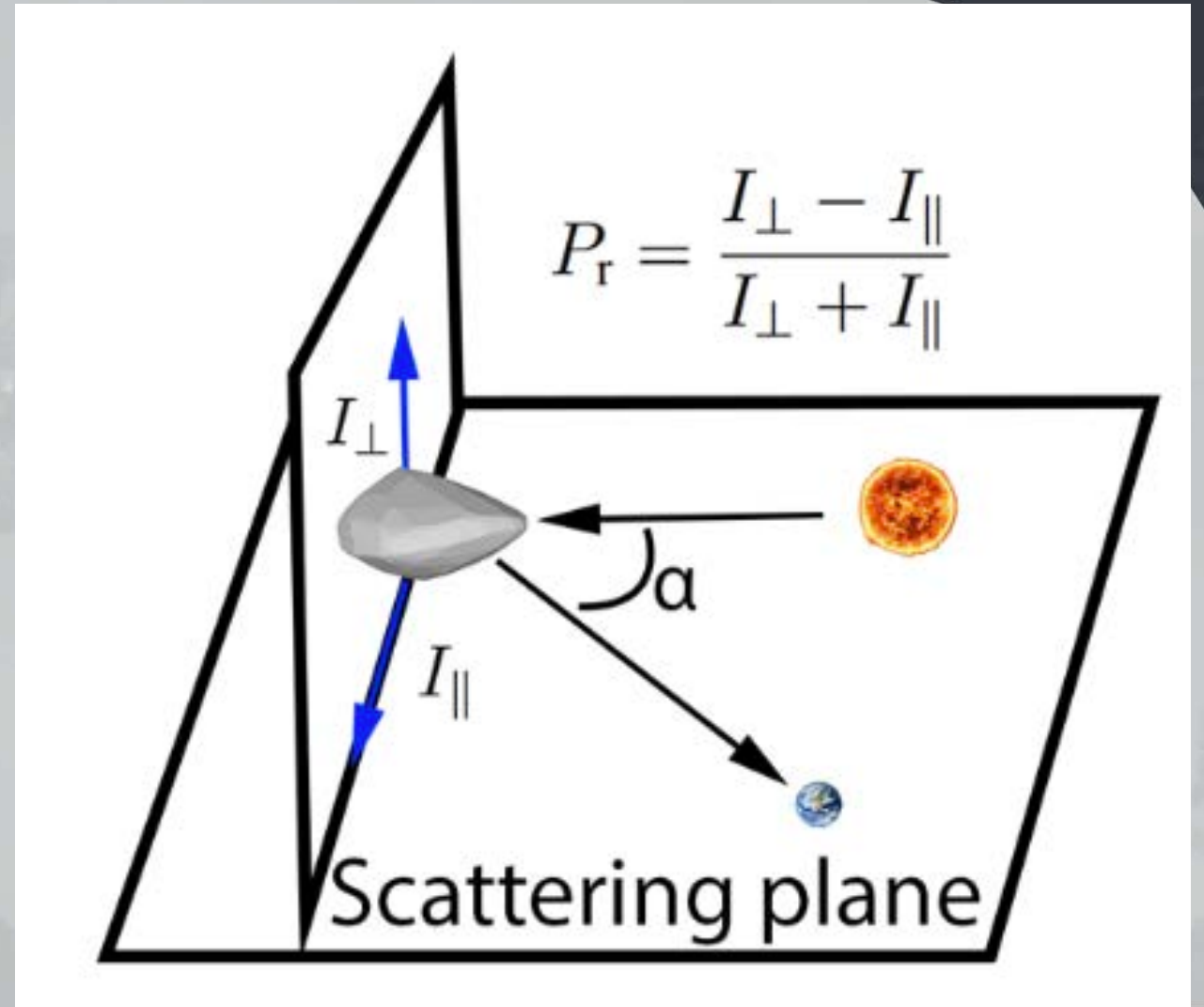


Image credit: Israel Cabrera Photography



What is polarimetry?

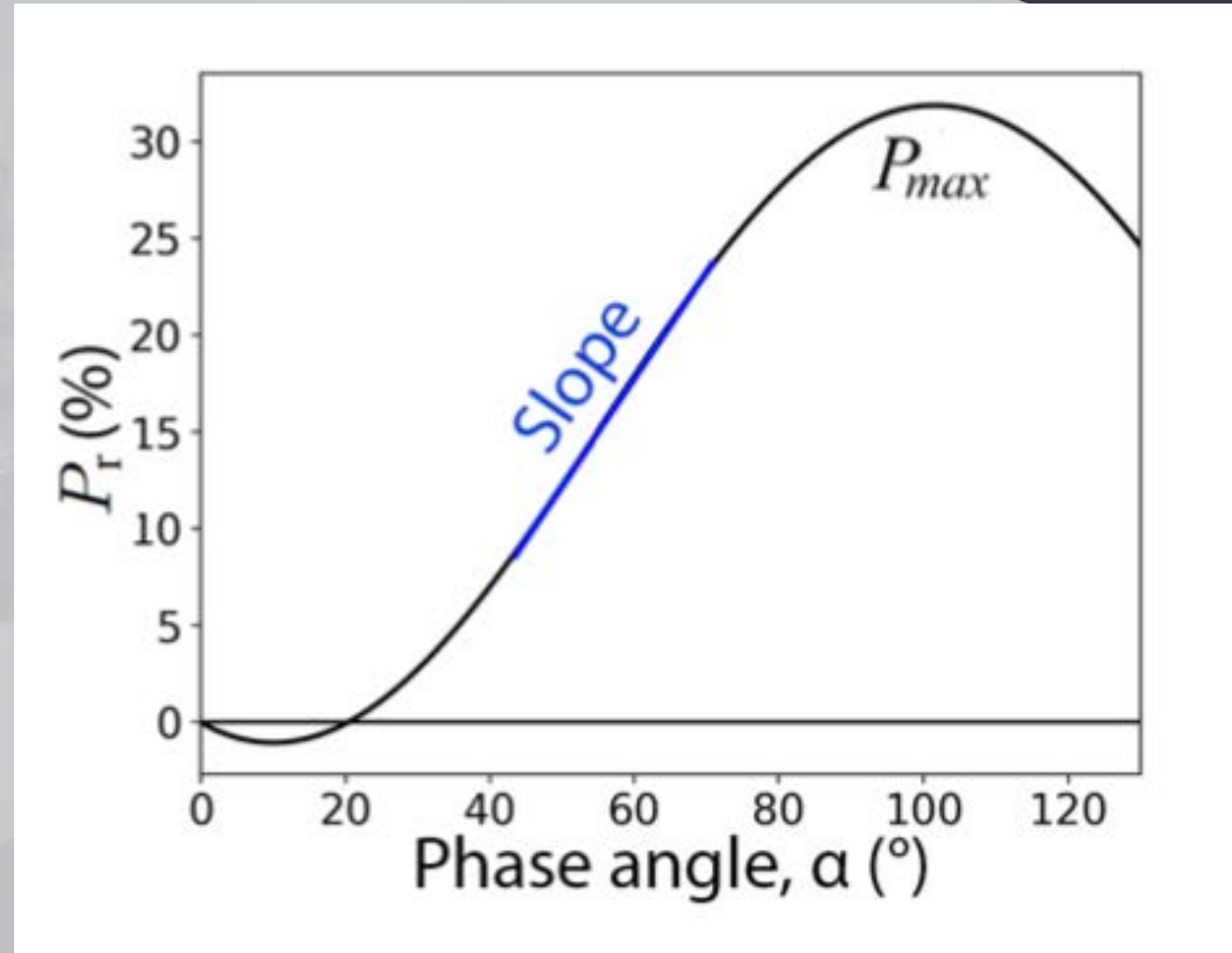
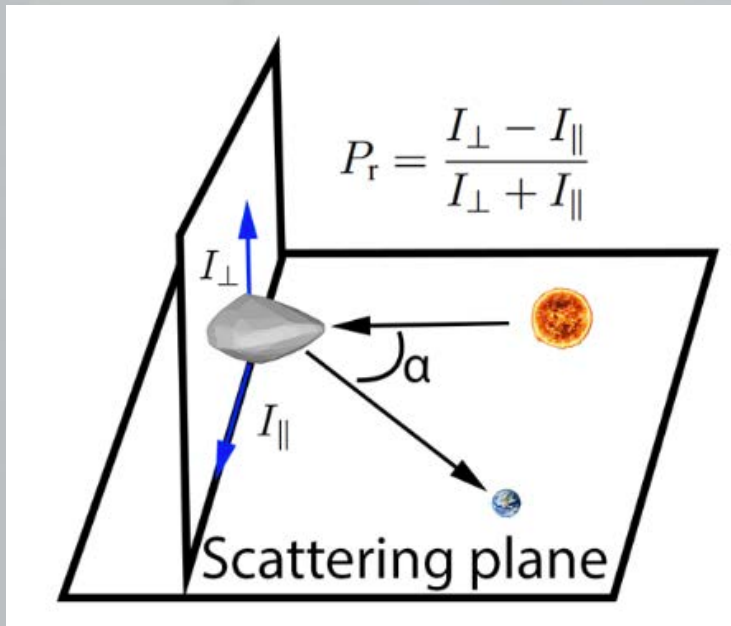
Measure of the linear polarization of the sunlight scattered by the surface of an asteroid



What is polarimetry?



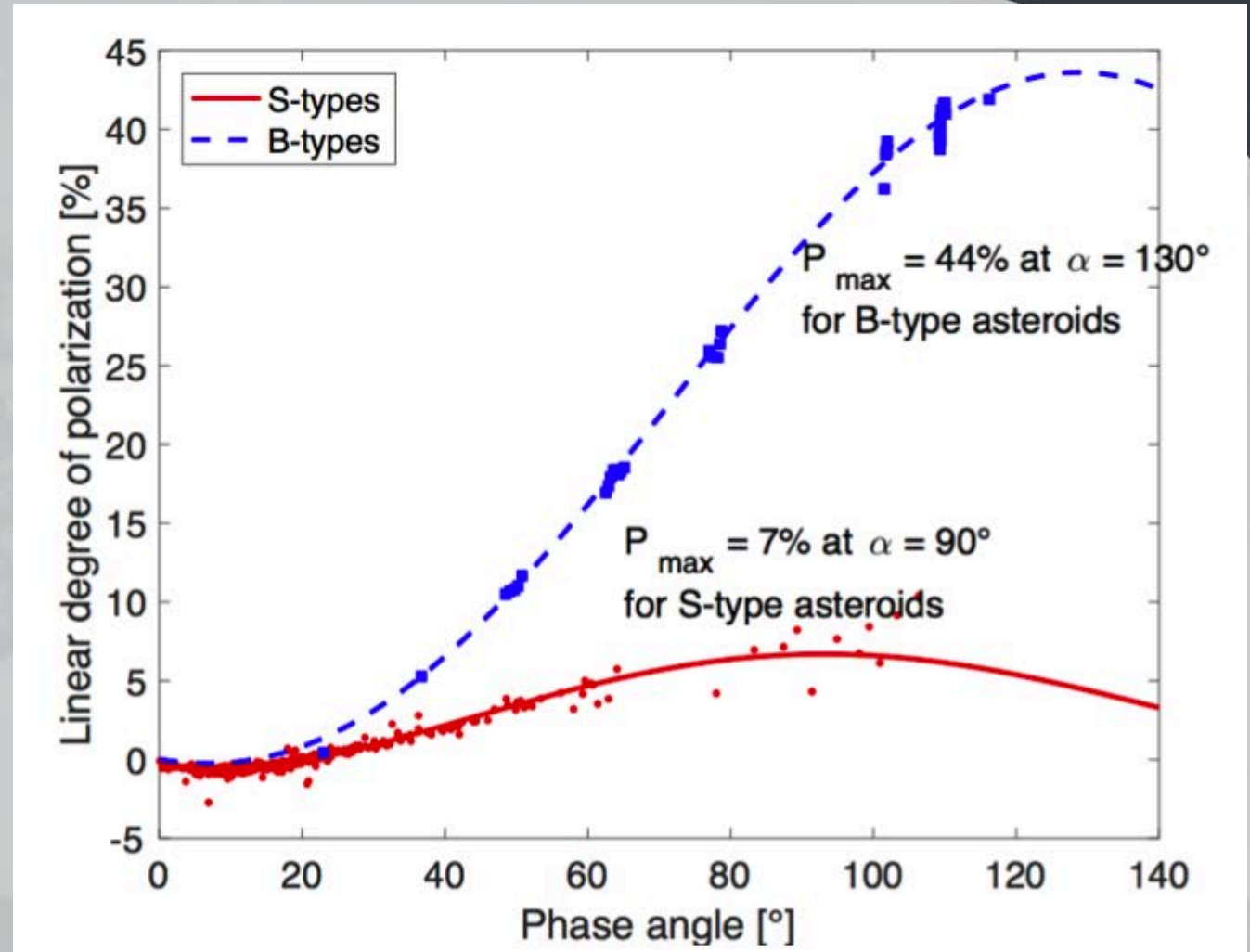
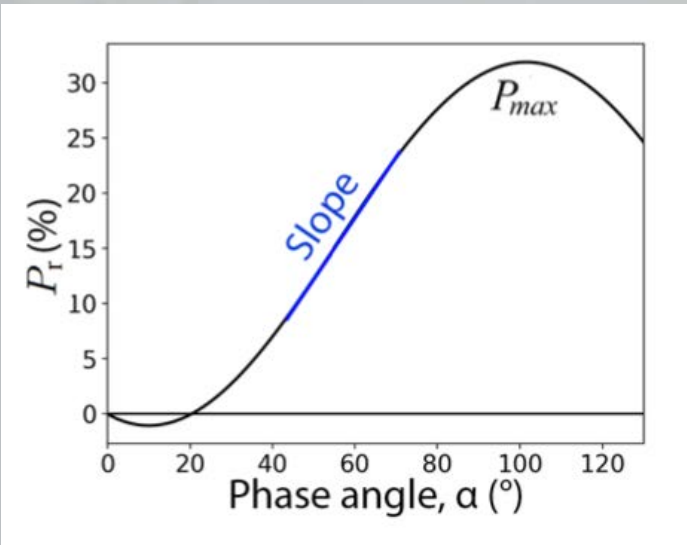
Polarimetry is mainly dependent on the phase angle

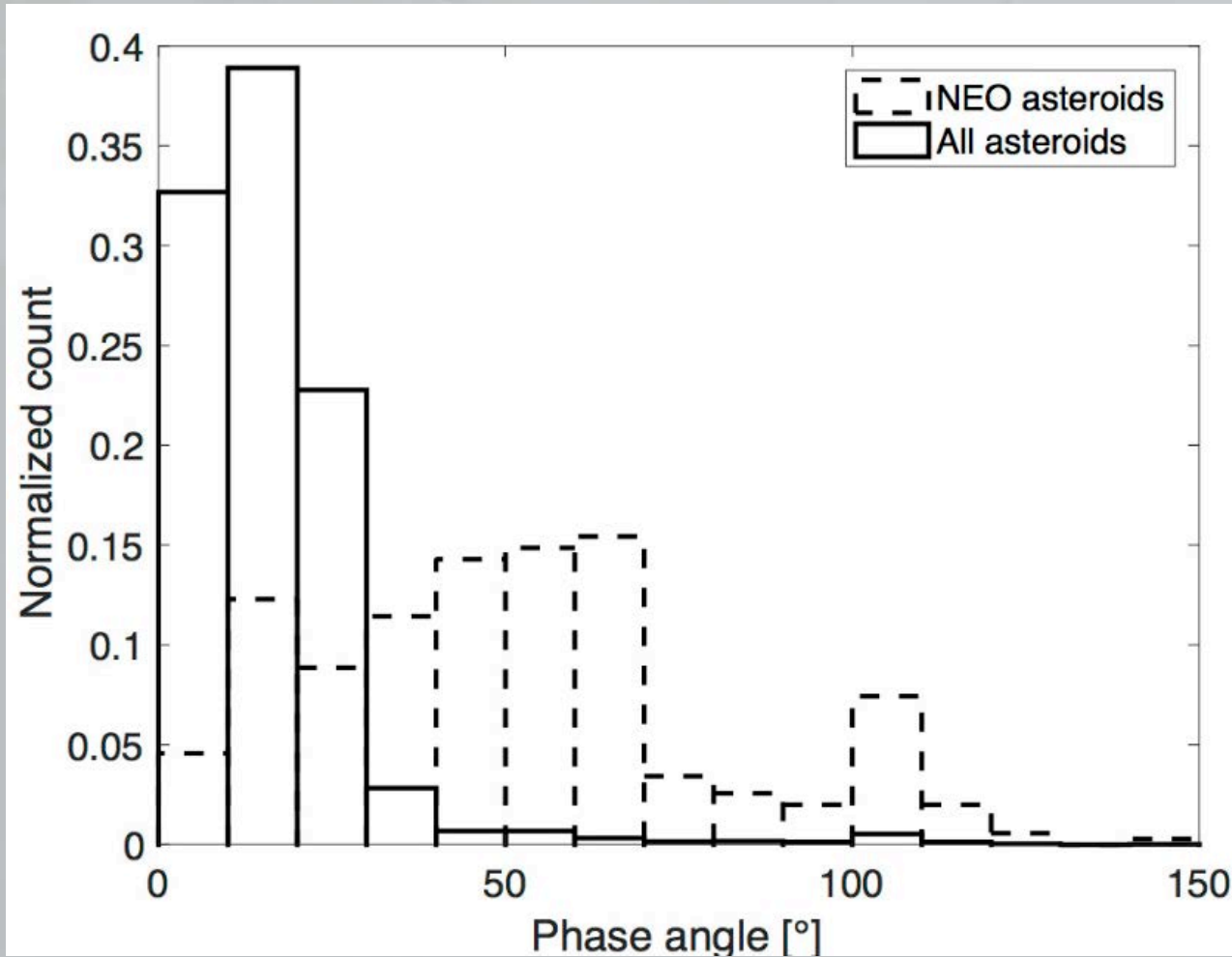


Why polarimetry is important?

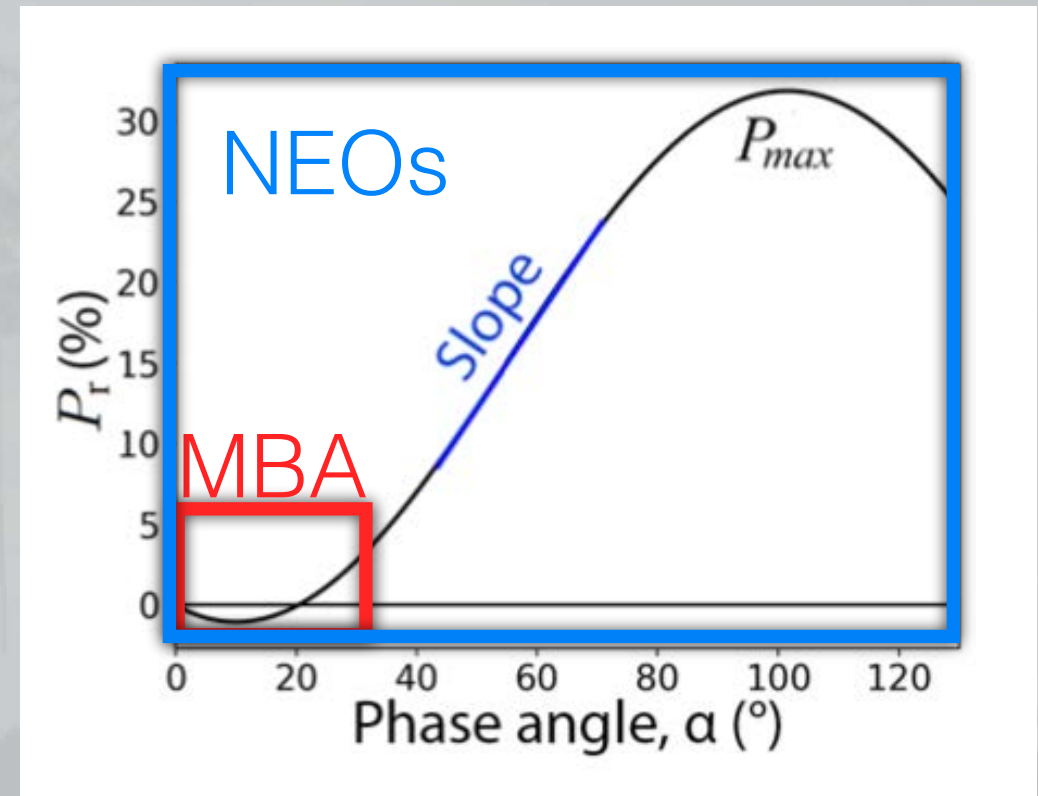


The phase-polarization curve is dependent on the albedo



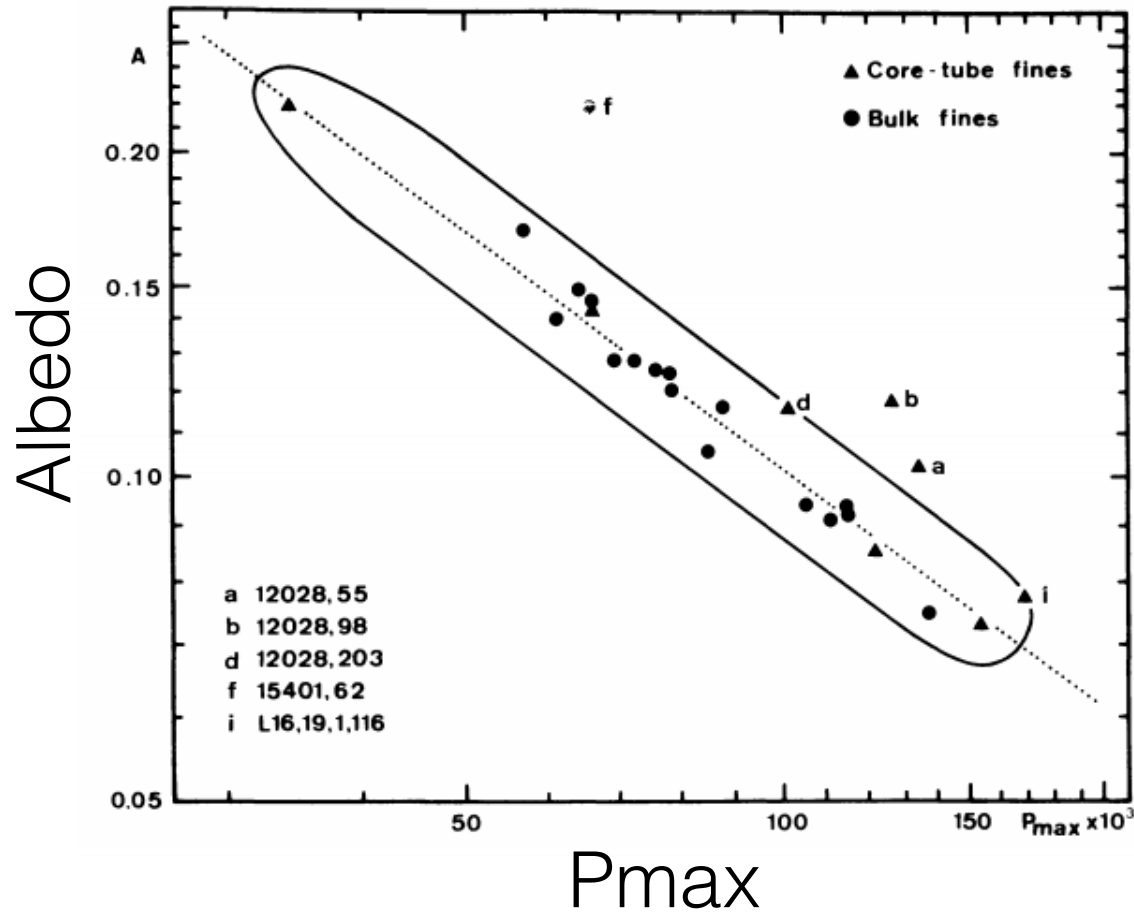


NEOs can be observed at higher phase angles



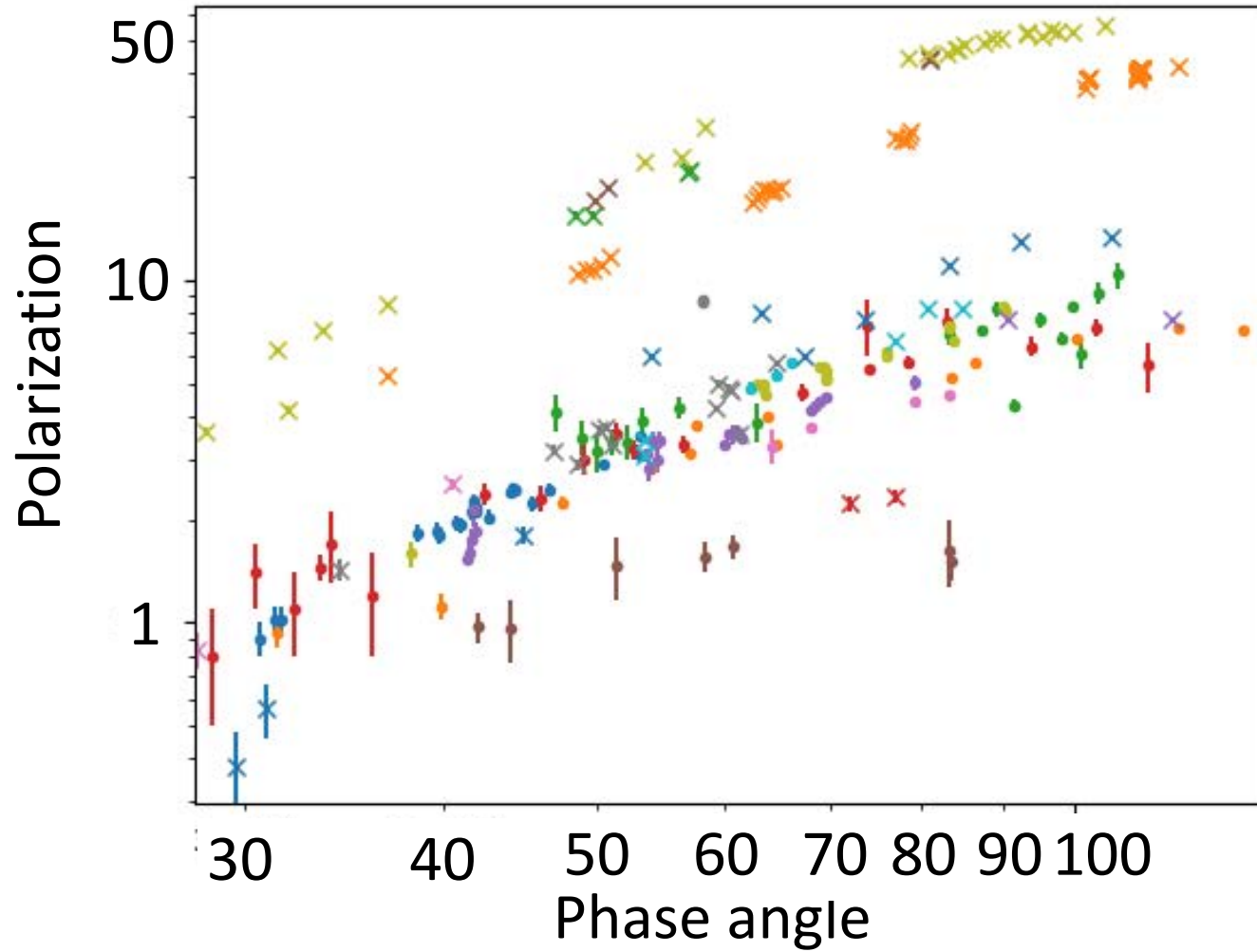
Polarimetry-Albedo relation

Bowell et al. 1973

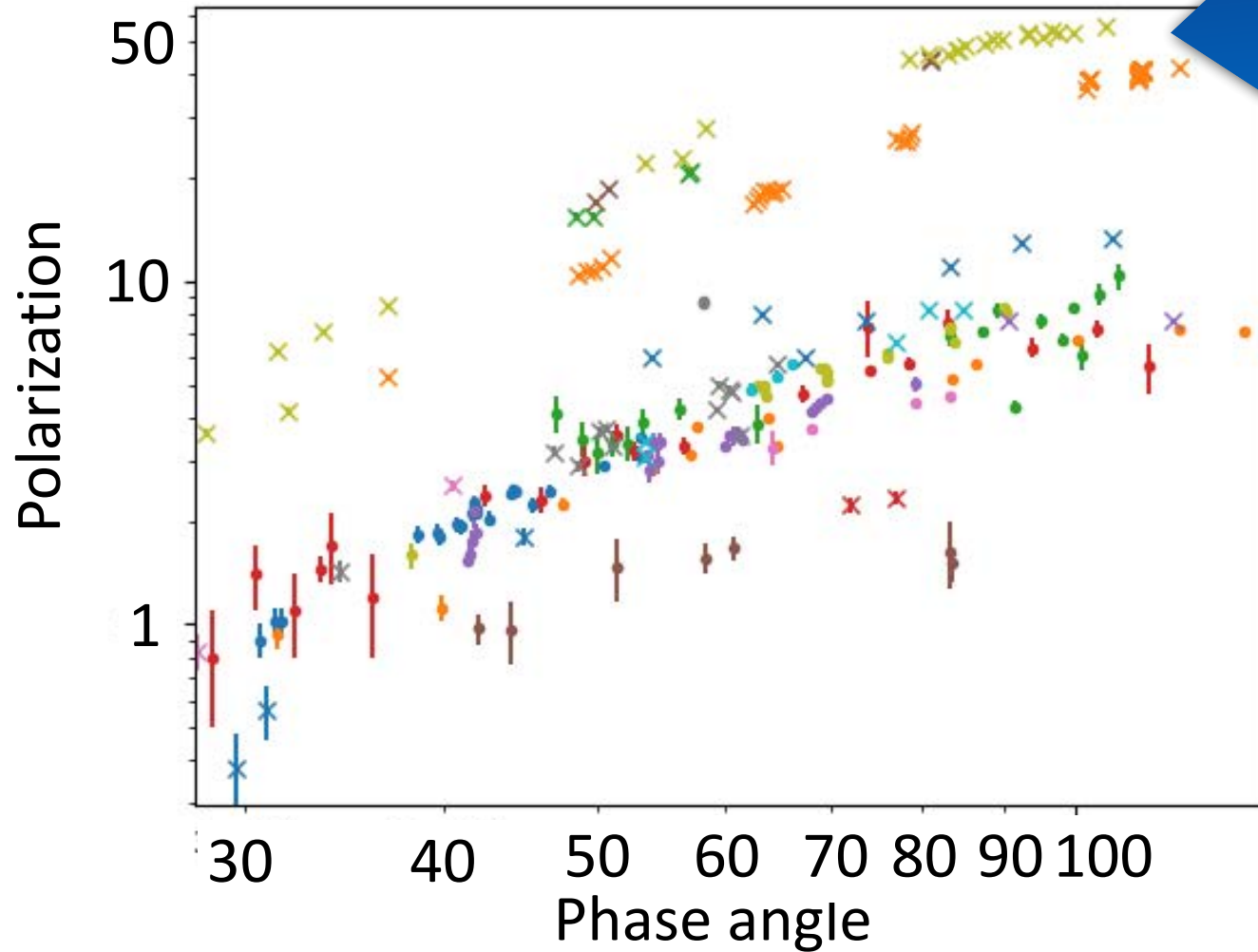


The Umov law is linking the albedo to the maximum of polarization

Polarimetry-Albedo relation

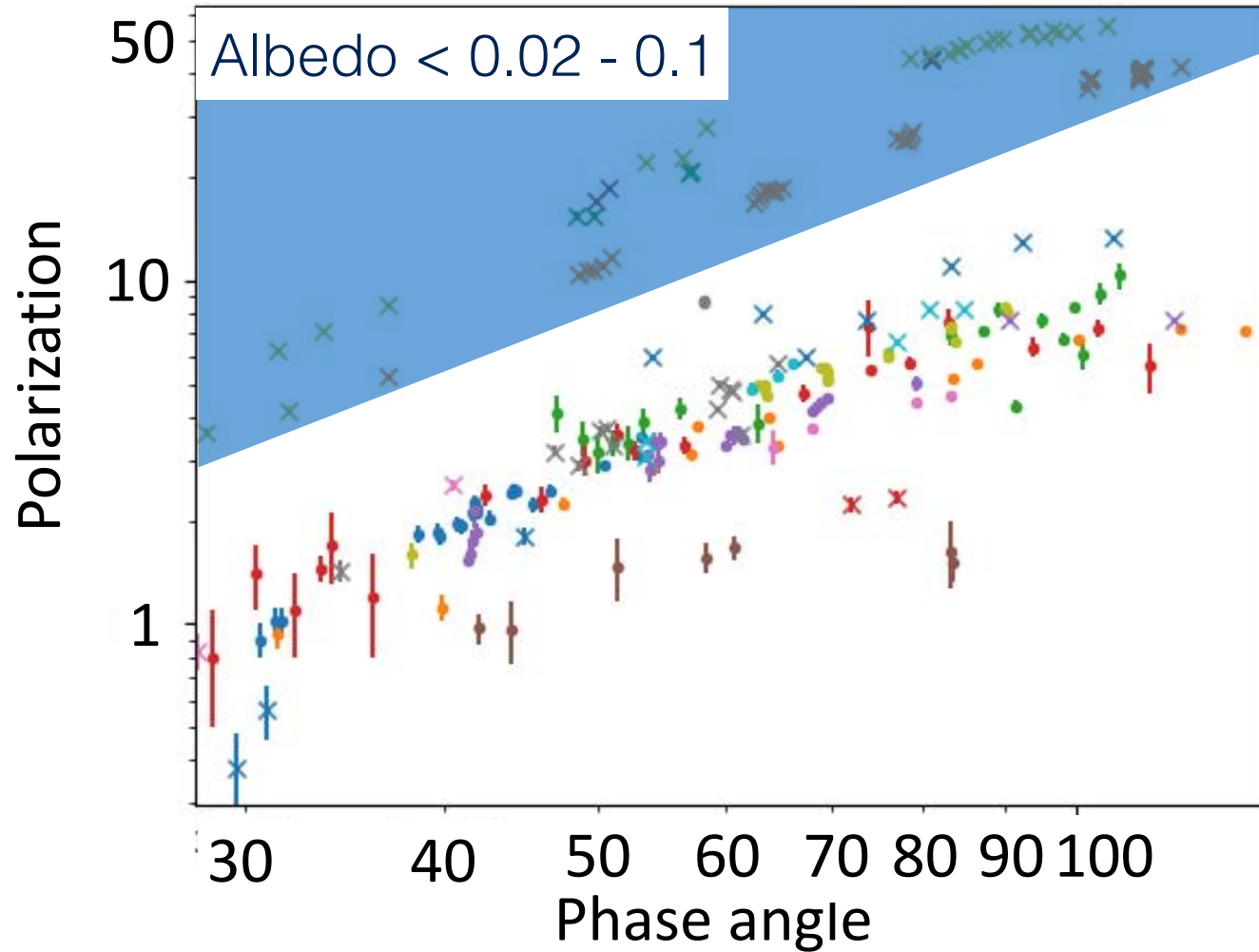


Polarimetry-Albedo relation



Ryugu
Bennu
1998 KU2
Phaethon
Albedo $\sim 0.02 - 0.1$

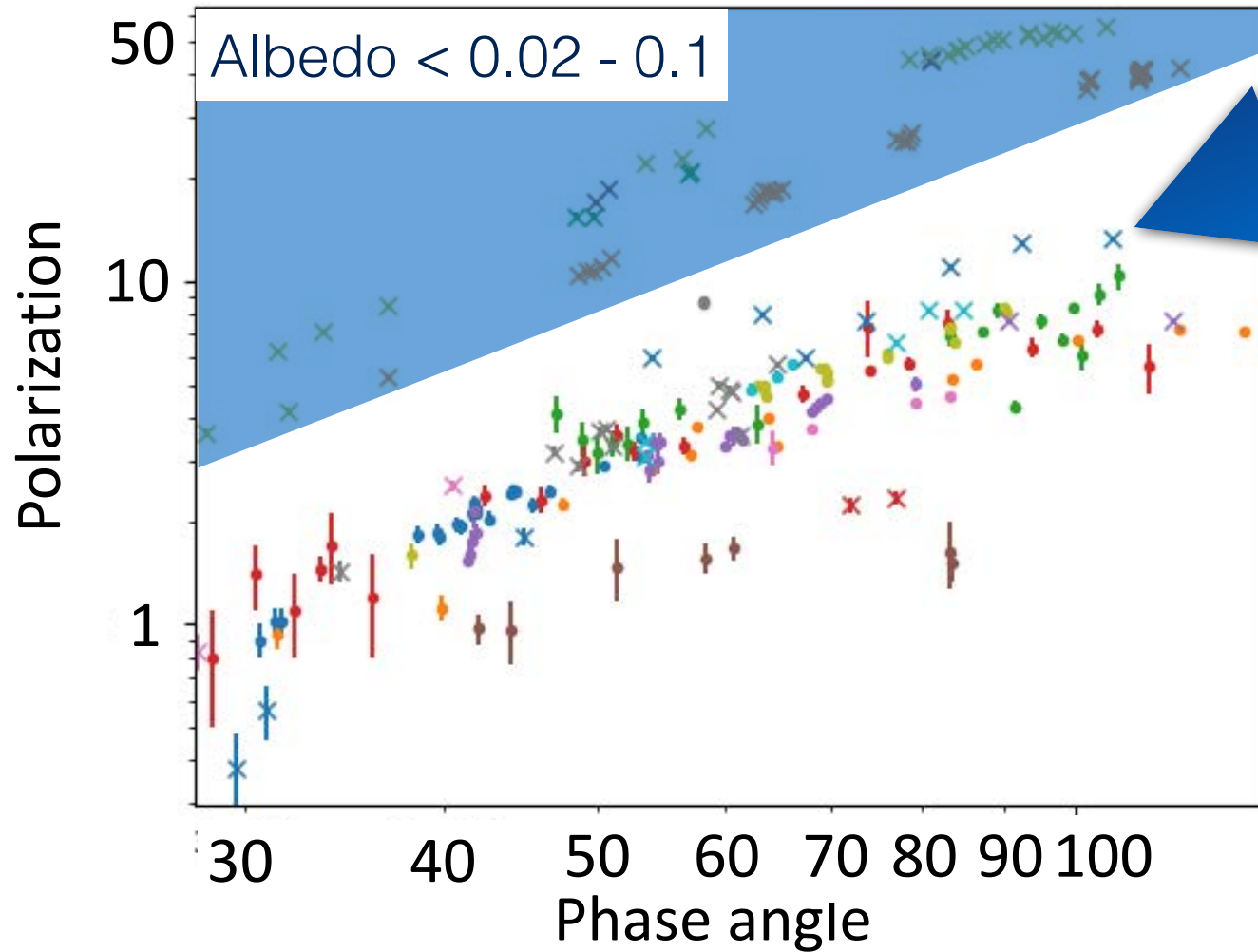
Polarimetry-Albedo relation



2021 PDC: 150m < D < 330m



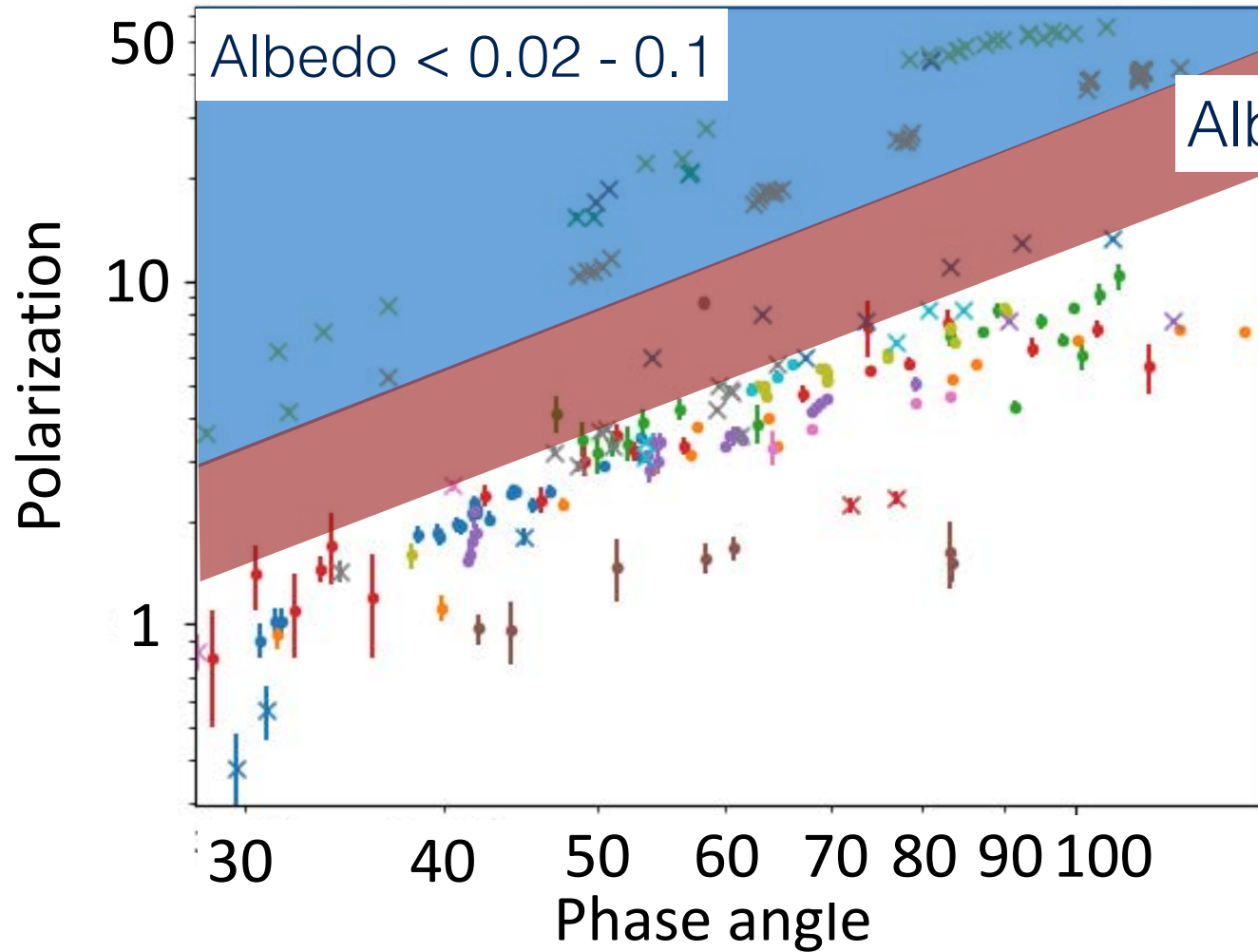
Polarimetry-Albedo relation



1999 JD6
Albedo ~ 0.14



Polarimetry-Albedo relation

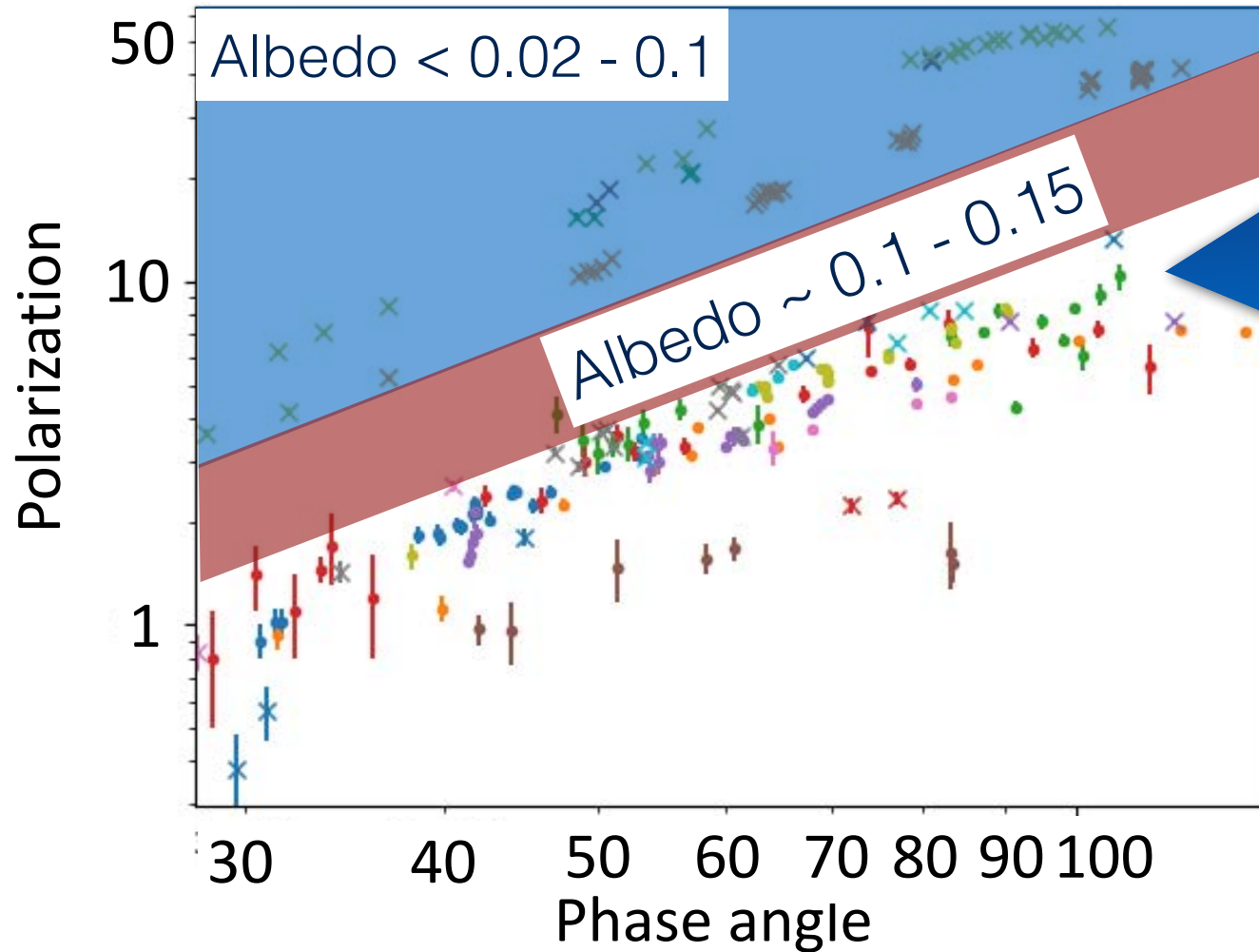


Albedo ~ 0.1 - 0.15

2021 PDC: 120m < D < 150m



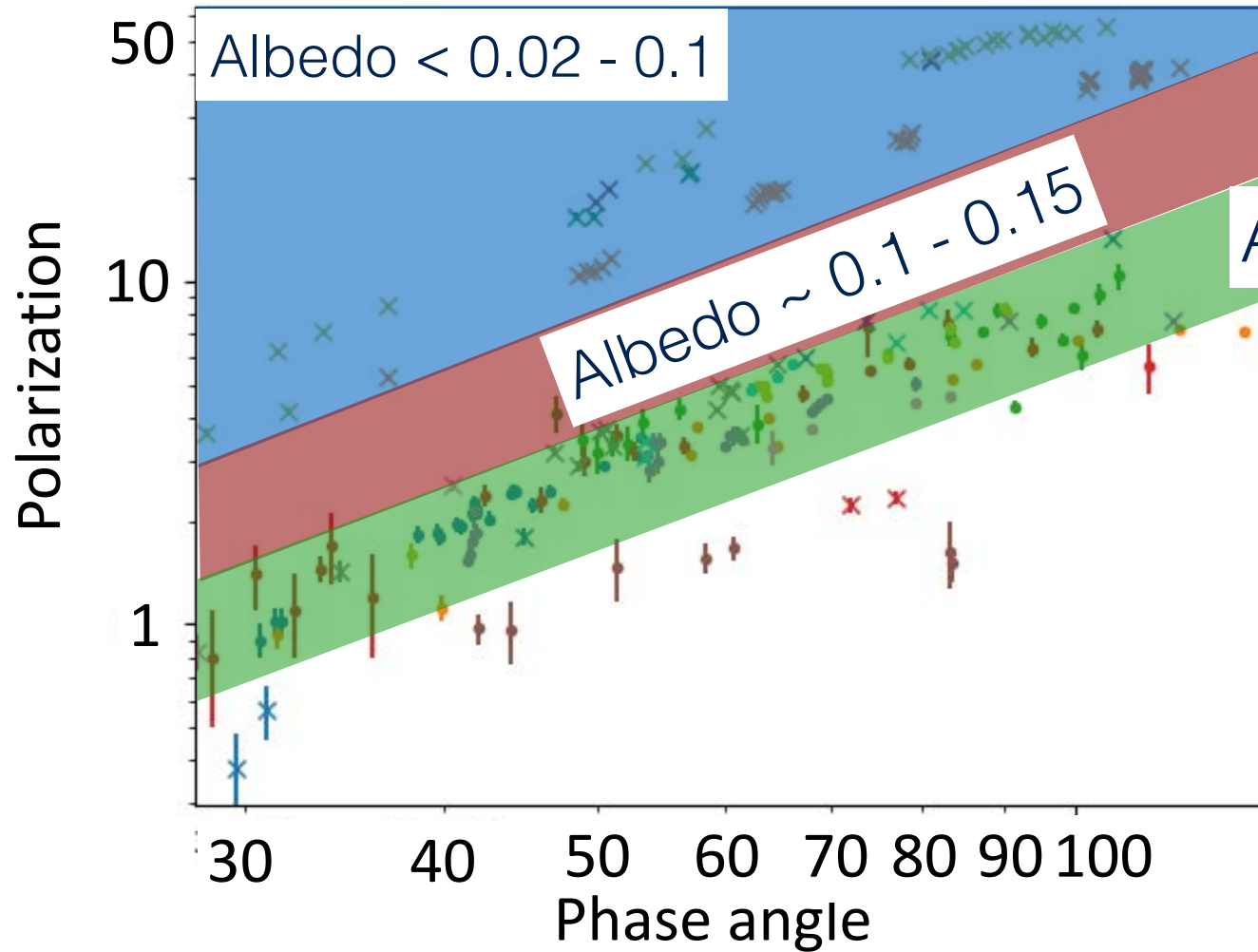
Polarimetry-Albedo relation



Mostly S-type
Apophis
Itokawa
Eros
Toro
Ivar
...

Albedo ~
0.15-0.35

Polarimetry-Albedo relation

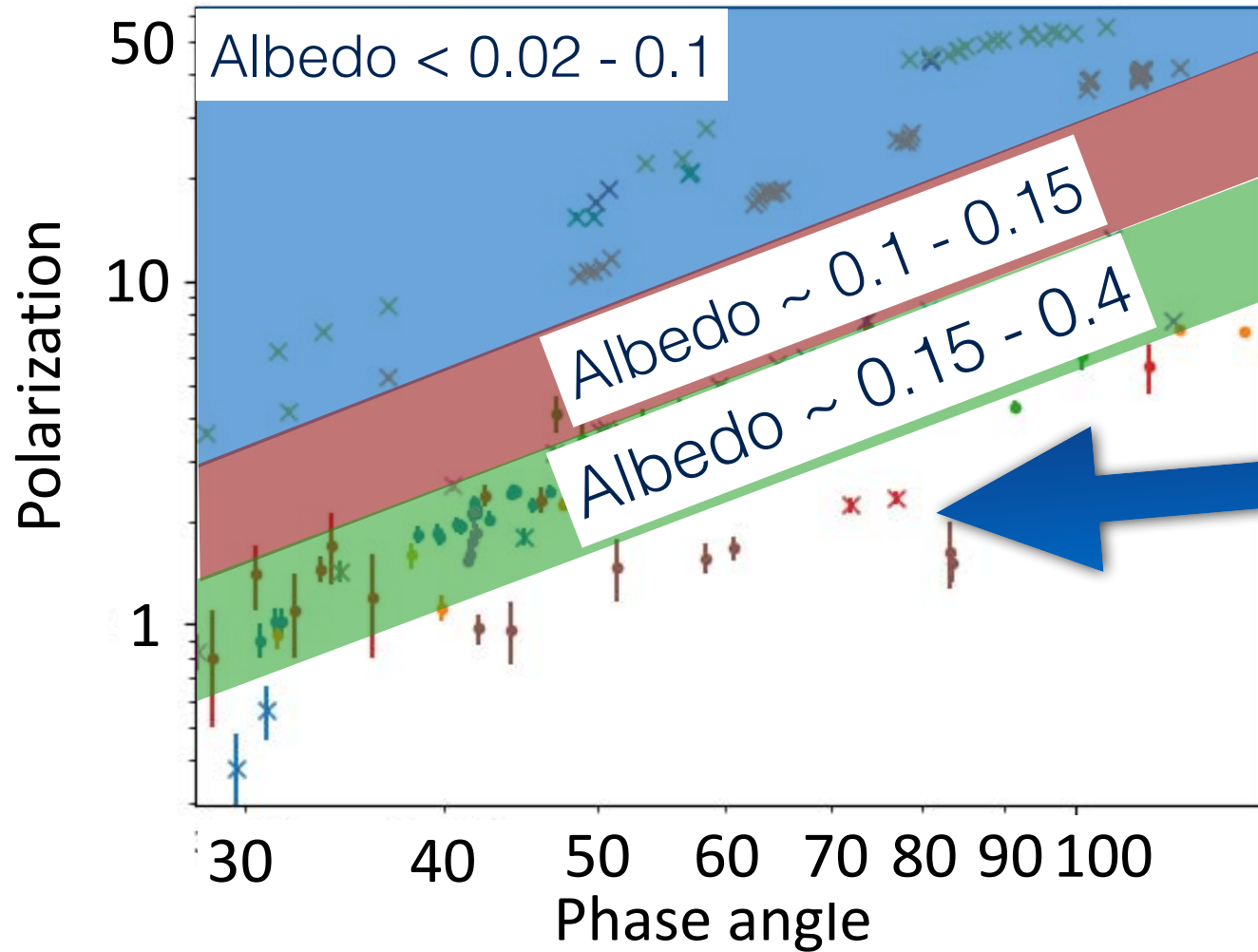


Albedo ~ 0.15 - 0.4

2021 PDC: 80m < D < 120m



Polarimetry-Albedo relation



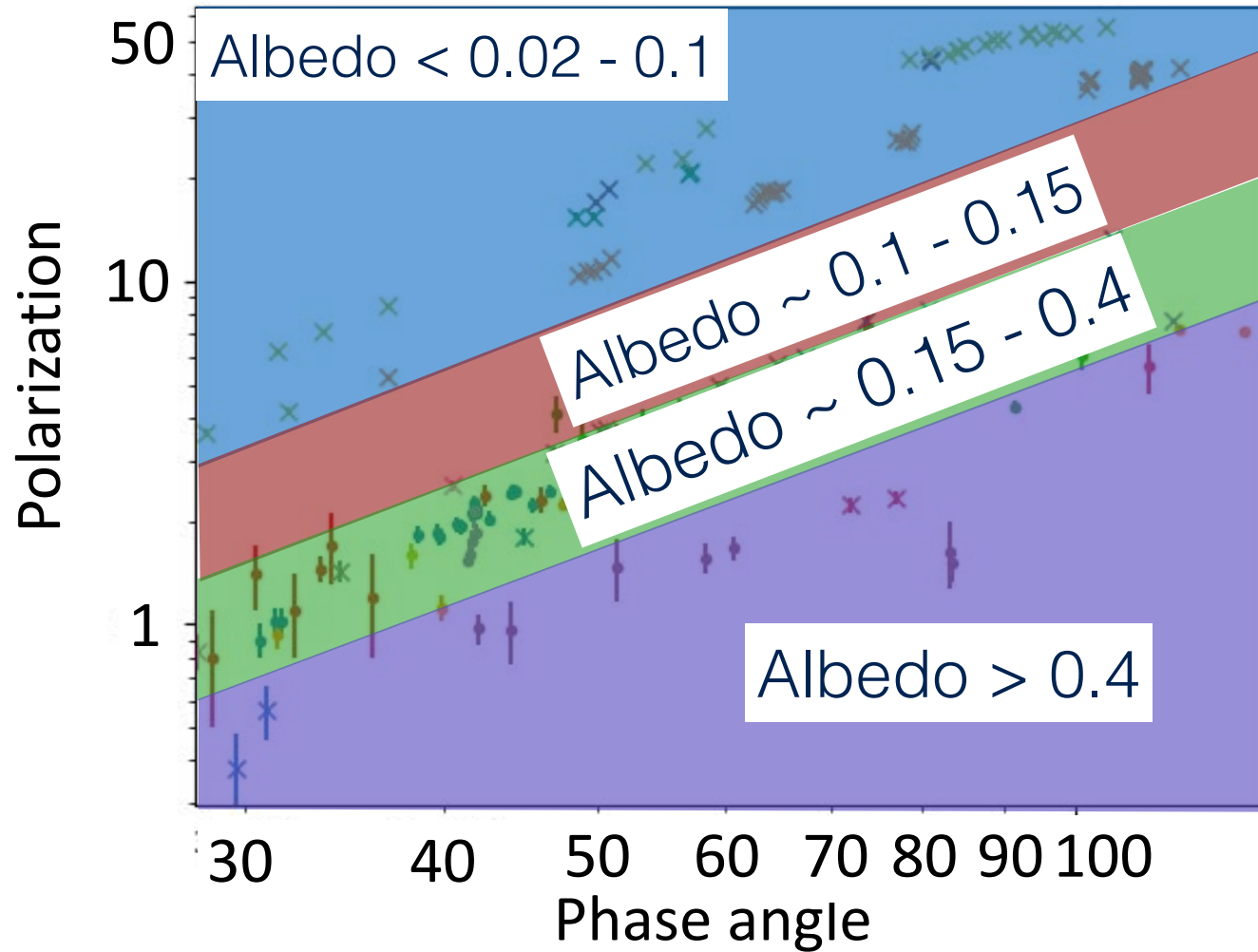
1999 WT24
2004 VD17

...

Albedo ~
0.45-0.75



Polarimetry-Albedo relation

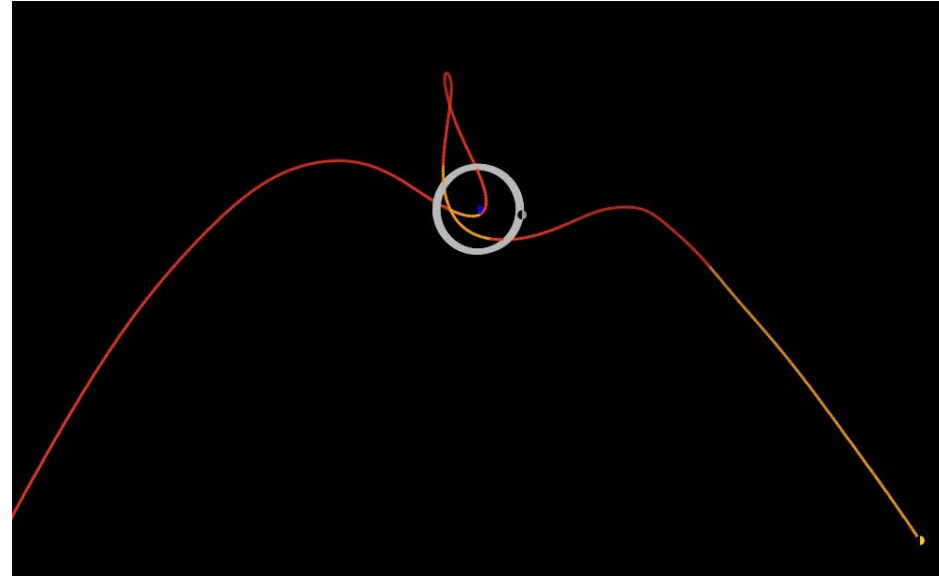


2021 PDC: 50m < D < 80m



- Polarimetry is very effective to obtain albedo information
- One measurement can reduce the size uncertainty by a factor of 2 to 10
- We need new observations to better calibrate the polarimetry-albedo relation
- We need more polarimeters on large aperture telescopes

Challenges in Differentiating NEOs and Rocket Bodies: 2020 SO Study



Presented by Prof. Vishnu Reddy, University of Arizona

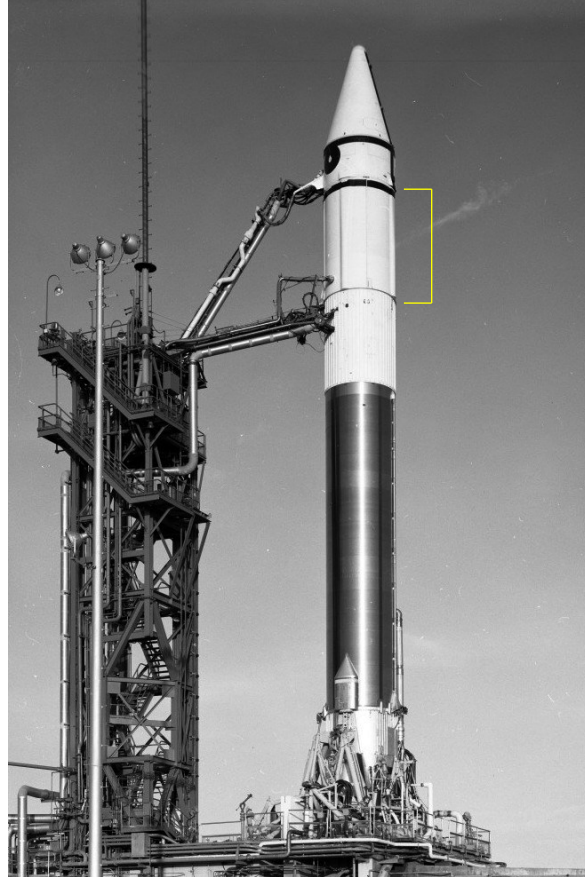
Team: Adam Battle, Peter Birtwhistle, Tanner Campbell, Paul Chodas, Al Conrad, Dan Engelhart, James Frith, Roberto Furfaro, Davide Farnocchia, Ryan Hoffmann, Olga Kuhn, David Monet, Neil Pearson, Jacqueline Reyes, Barry Rothberg, Benjamin Sharkey, Juan Sanchez, Christian Veillet, Richard Wainscoat

2020 SO: Background

- Discovered by PanSTARRS 1 telescope in Hawaii on September 17, 2020
- Temporarily captured on Nov. 8, 2020

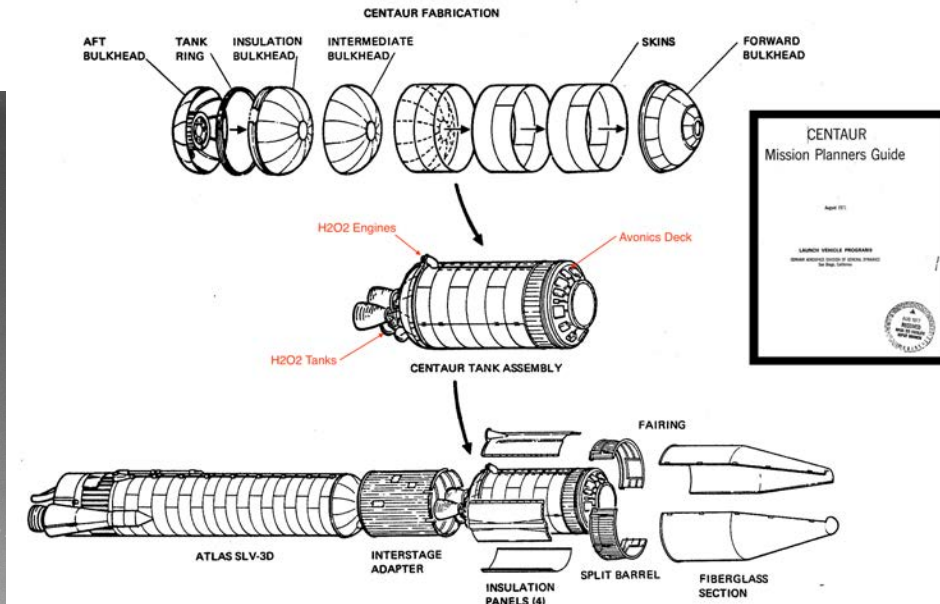
Two close approaches:

- Inbound approach on December 1, 2020 at a distance of 0.13 LD (50,414 km)
- Outbound approach on February 2, 2021 at a distance of 0.58 LD (225,144 km)
- Low orbital velocity and Earth like orbit
Paul Chodas suggested this could be artificial object (Surveyor 2 Centaur rocket booster)



Atlas-Centaur

FABRICATION SEQUENCE



- Launched September 20, 1966 from KSC, Florida
- Centaur upper stage went into heliocentric orbit similar to the Earth

Centaur D 2nd Stage Dimensions:

Length: 9.6 meters
Diameter: 3.05 meters
Unfueled Mass: 2631 kgs

Goals and Challenges

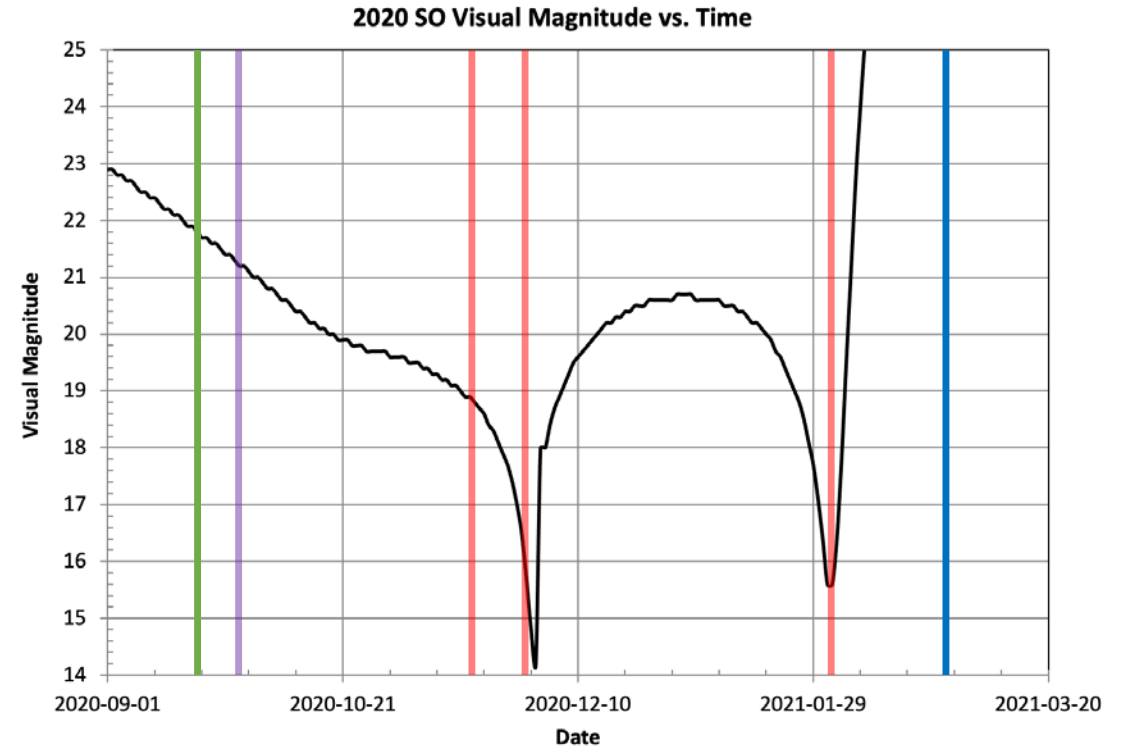
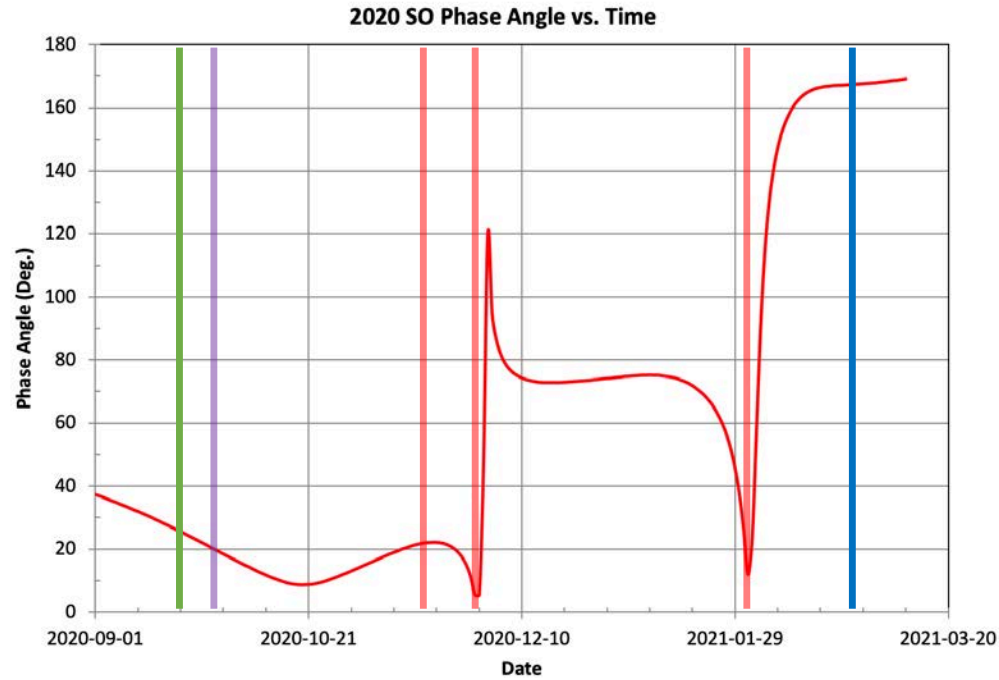
Study Goals:

- Is 2020 SO an asteroid or rocket body?
- If it is a rocket body, is it a Centaur upper stage from Surveyor 2?

Challenges:

- Observability: 2020 SO was too faint for traditional near-IR characterization till mid-Nov. Late Sept. 2020 it was at V. Mag. 21.5, which limited us to broadband colors.
- Can you tell the difference between an asteroid and rocket body with colors?
- Spectral Interpretation: Do we have relevant spectral libraries of analog materials to verify if 2020 SO is a Centaur R/B? Especially something that had been in space for 54 years?

Observability Plot and Table

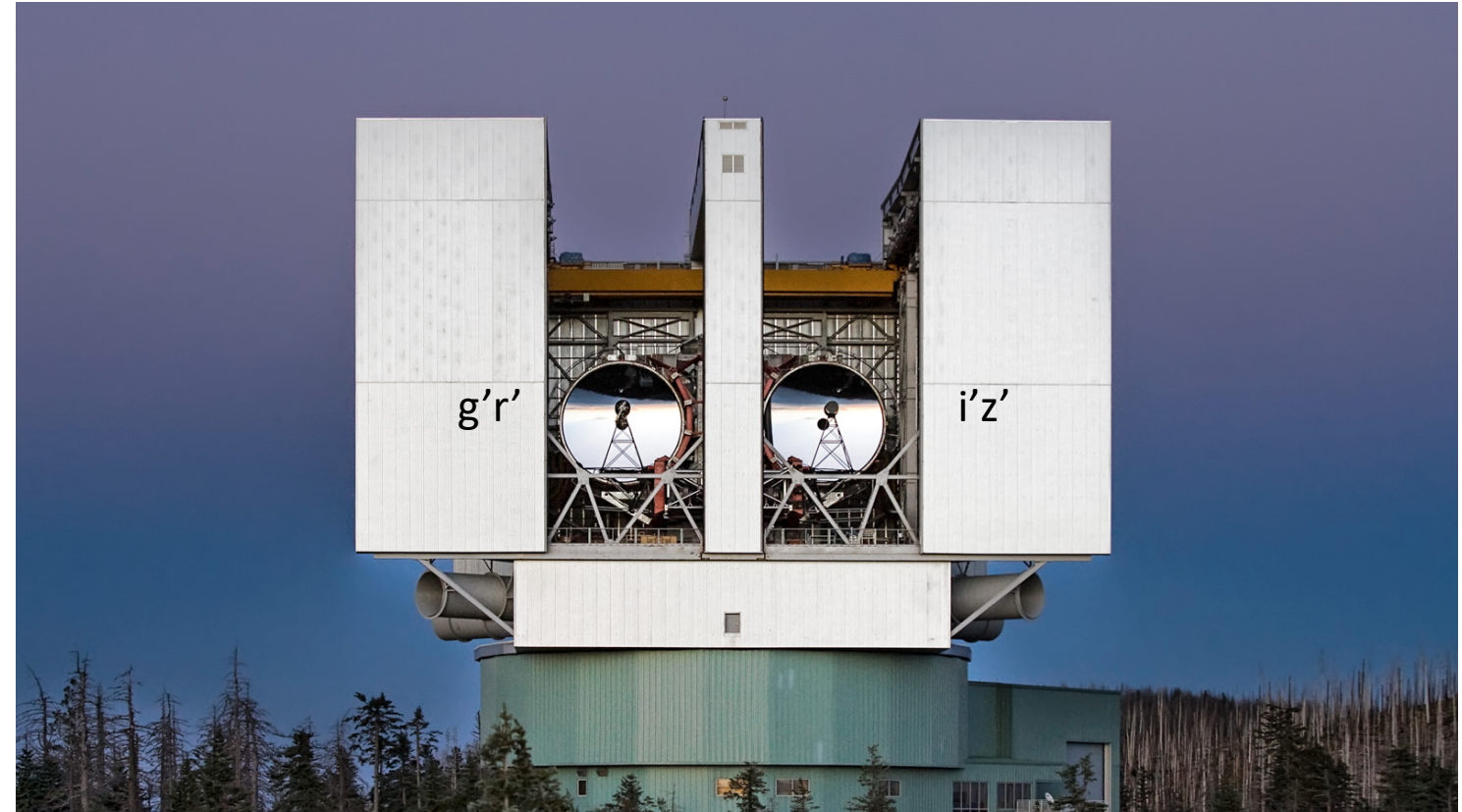


Date (UTC)	Target	V. Mag.	Phase Angle	Range (km)	Range (LD)	Telescope	Aperture	Instrument	Type of Observations	Wavelength Range	Spec. Res.
28-Sep-20	2020 SO	21.5	20.5	3420234	8.898	LBT	8.2-m	LBC	Sloan griz colors	0.464-0.90 μm	R=4
10-Oct-20	NORAD ID: 3598	~6-8	76.8	745	0.002	RAPTORS I	0.6-m	FLI 4220	Visible spectroscopy	0.438-0.950 μm	R~30
22-Oct-20	NORAD ID: 6155	~6-8	15.5	1300	0.003	RAPTORS I	0.6-m	FLI 4220	Visible spectroscopy	0.438-0.950 μm	R~30
17-Nov-20	NORAD ID: 4882	~6-8	80.6	4900	0.013	RAPTORS I	0.6-m	FLI 4220	Visible spectroscopy	0.438-0.950 μm	R~30
17-Nov-20	2020 SO	19.3	21.9	1160736	3.020	NASA IRTF	3.0-m	SpeX	Near-IR spectroscopy	0.69-2.54 μm	R~100
29-Nov-20	2020 SO	15.7	5.4	300896	0.783	NASA IRTF	3.0-m	SpeX	Near-IR spectroscopy	0.69-2.54 μm	R~100
30-Nov-20	2020 SO	14.9	5.5	152894	0.398	NASA IRTF	3.0-m	SpeX	Near-IR spectroscopy	0.69-2.54 μm	R~100
30-Nov-20	NORAD ID: 4882	~6-8	62.4	34000	0.088	NASA IRTF	3.0-m	SpeX	Near-IR spectroscopy	0.69-2.54 μm	R~100
2-Feb-21	2020 SO	15.8	23.8	221541	0.576	NASA IRTF	3.0-m	SpeX	Near-IR spectroscopy	0.69-2.54 μm	R~100

Color Observations

Study Lead: Ben Sharkey (grad student)

- Large Binocular Telescope: Two 8.2 meter optical/IR telescopes
- Instrument: Large Binocular Camera (red) and (blue) for color photometry (Sloan) and astrometry
- Exposure times: 60 seconds
- Visual Magnitude: 21.5
- Images: 10 per filter
- Filters: Sloan g'r'l'z'
- SNR: ~15 for g'r'i'; 10 for z'



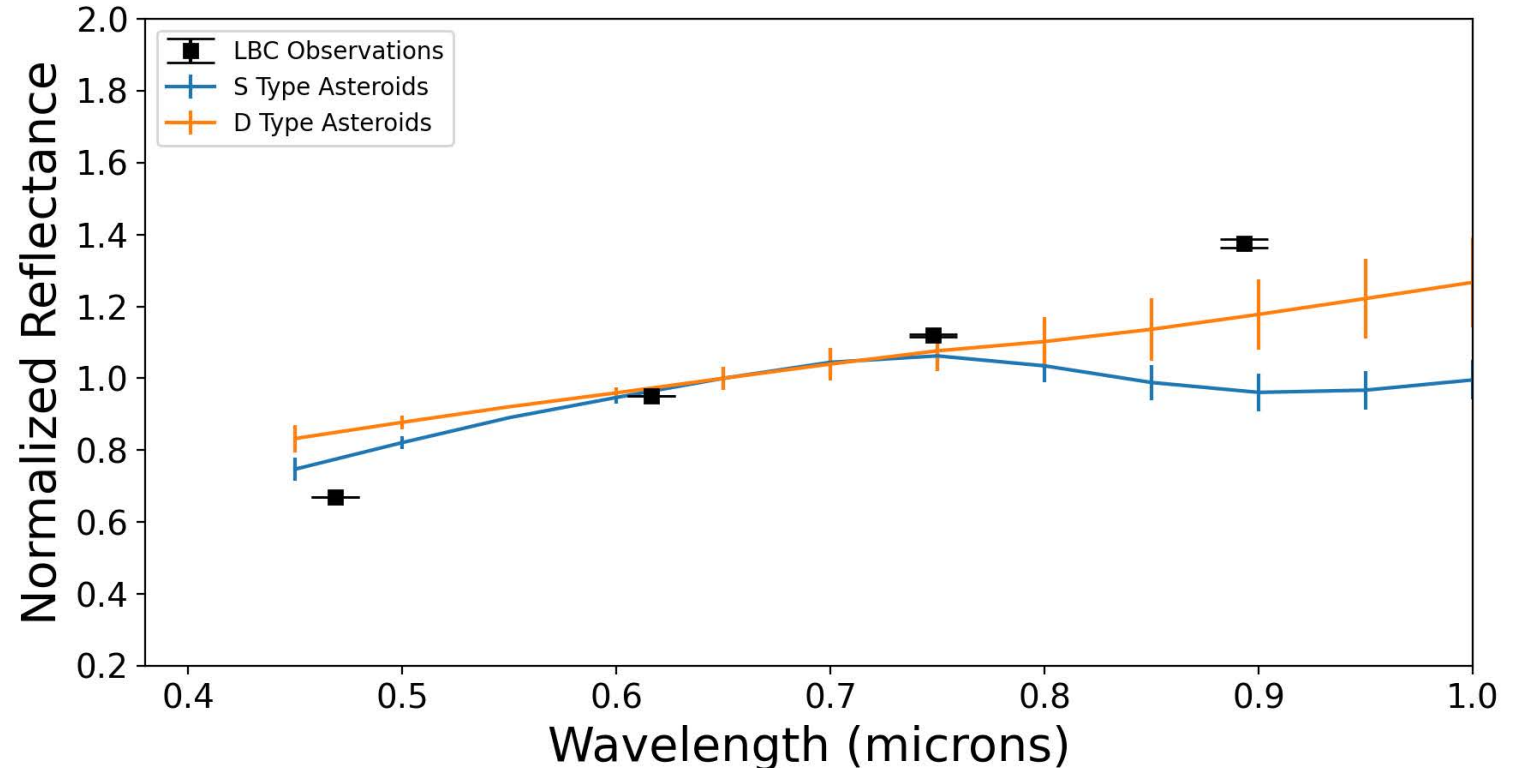
Mt. Graham, AZ

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Comparison with S-type and D-type asteroids



Visible Spectral Observations

- Goal: Observe another Centaur in Earth orbit from the same period and compare with LBT color spectrum of 2020 SO
- RAPTORS: Robotic Automated Pointing Telescope for Optical Reflectance Spectroscopy
- Telescope: 0.6-meter F/4.6 Newtonian optical/NIR telescopes (RAPTORS I and II)
- Instrument: FLI4210 CCD and Richardson Grating 30L transmission grating giving a spectral resolution $R \sim 30$
- Exposure times: 0.01-1.0 seconds (Object kept in the center to make sure there are no shutter effects)

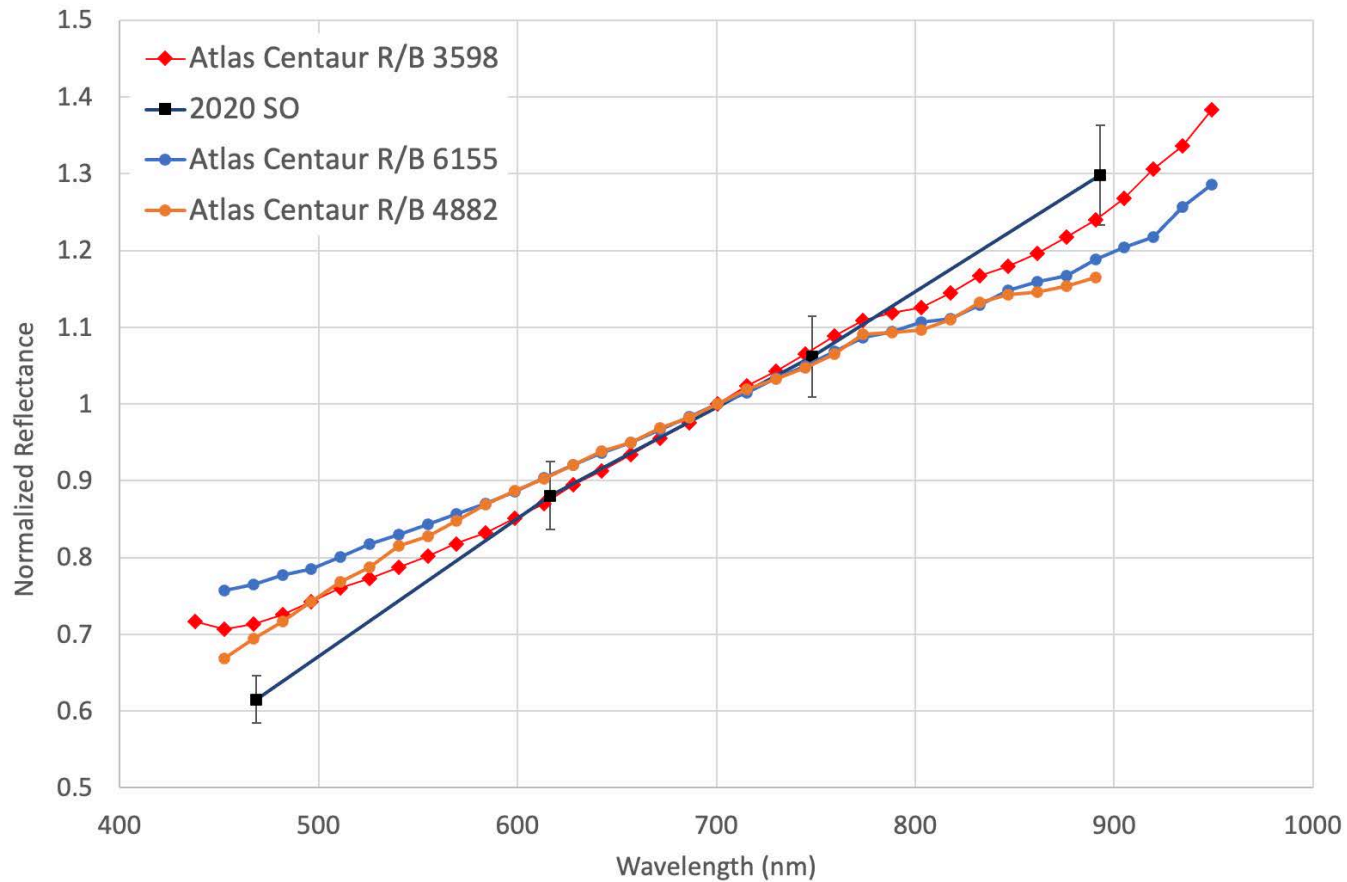
Study Lead: Adam Battle (grad student)



Tucson, AZ

Comparison with Centaur R/Bs

Here are the visible wavelength spectra of the three Centaur bodies NORAD ID 3598, 4882 and 6155. 3598 was launched in 1968, 4882 in 1971 and 6155 in 1972. All Centaur spectra are consistent with each other. Differences at the shortest and longest wavelengths could be due to phase angle.

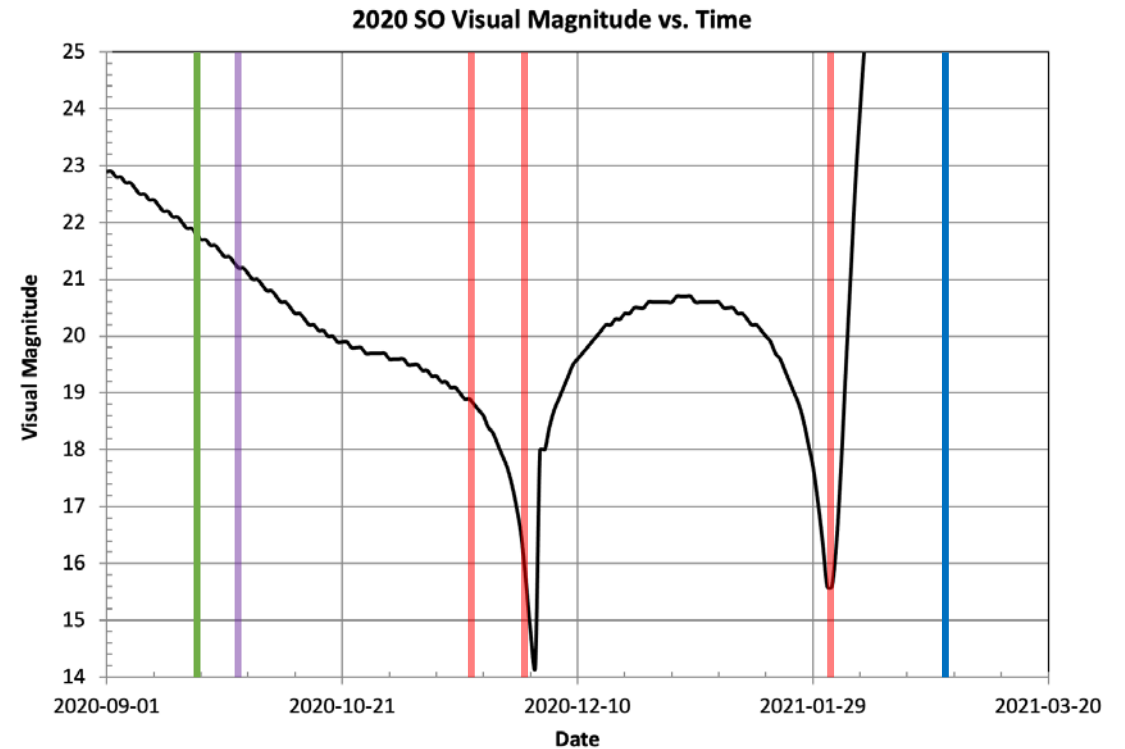


Near-IR Observations

- NASA IRTF: 3-meter IR telescope
- Instrument: SpeX spectrometer
- Exposure times: 200 seconds
- Visual Magnitude: 19.3, 15.7, 14.9 and 15.8



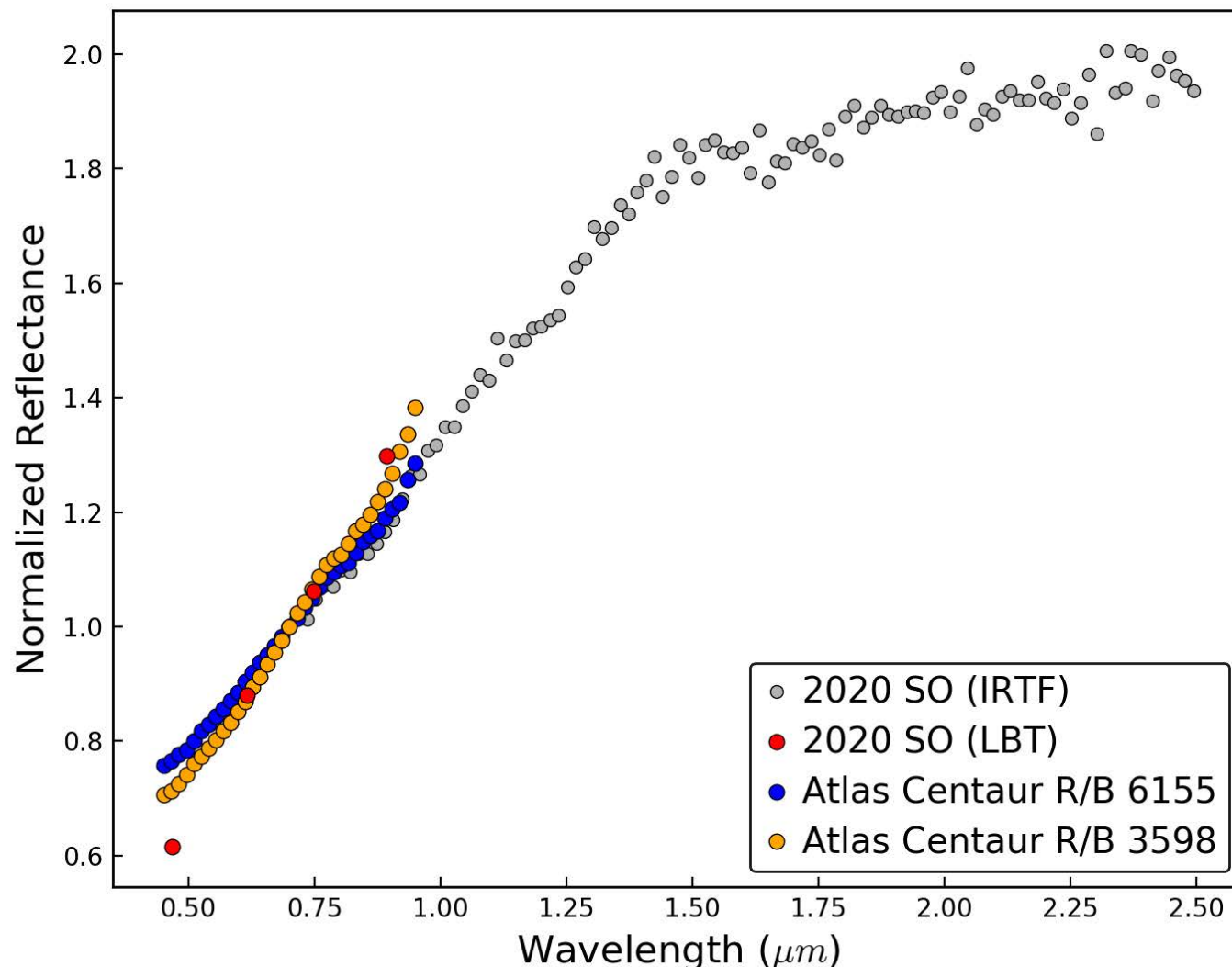
Mauna Kea, HI



Near-IR Observations

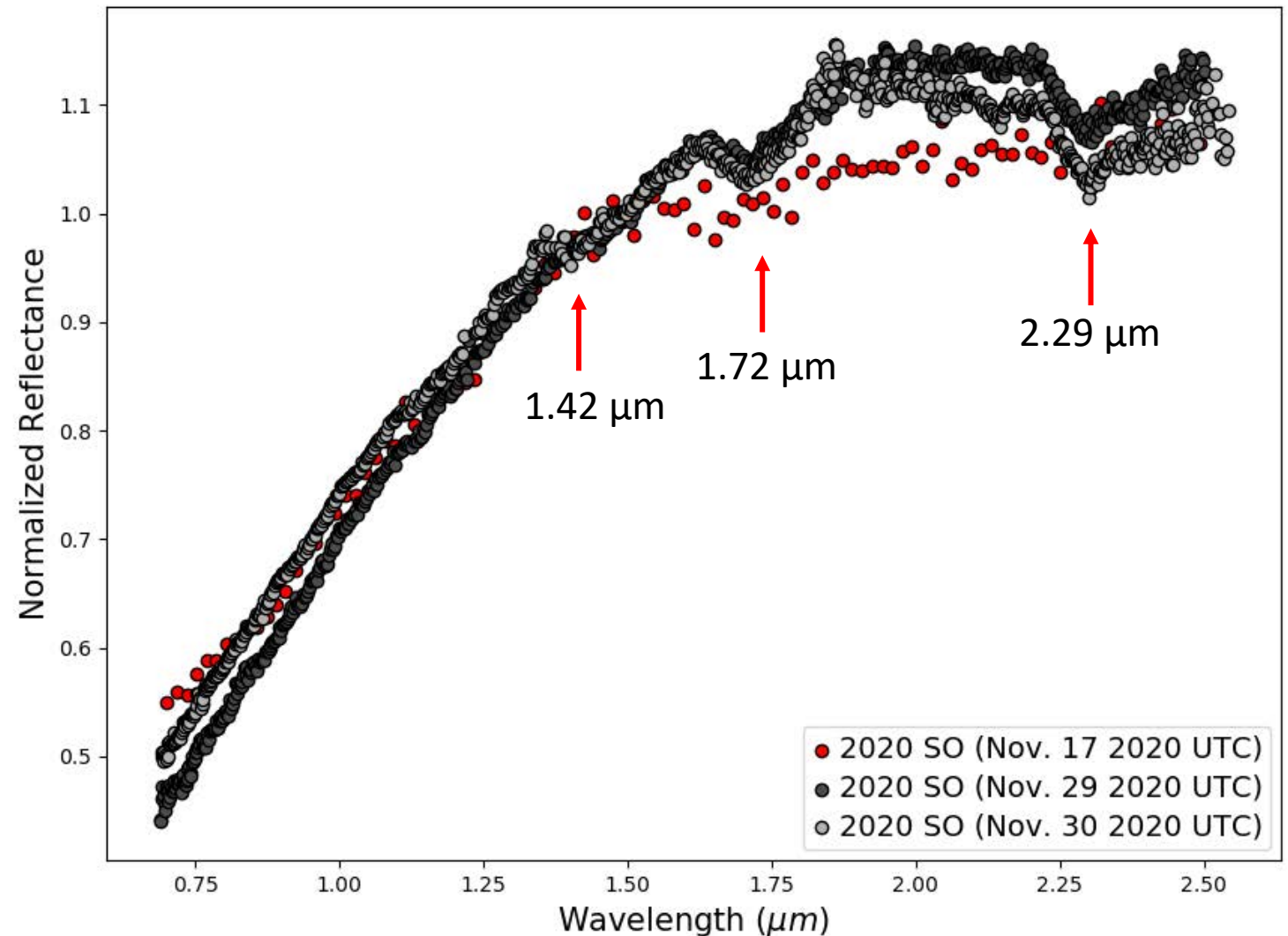
Study Lead: Juan Sanchez (post doc)

- First spectrum of 2020 SO (V. Mag. 19.3) obtained at the limit of IRTF's capabilities (V. Mag. 19.5)
- Steep red slope till 1.5 μm
- No major absorption features detected, possible weak ones
- Diagnostic absorption bands key to constraining composition
- Compared LBT 2020 SO data and RAPTORS spectra of Centaur R/Bs
- Consistent with NASA IRTF data



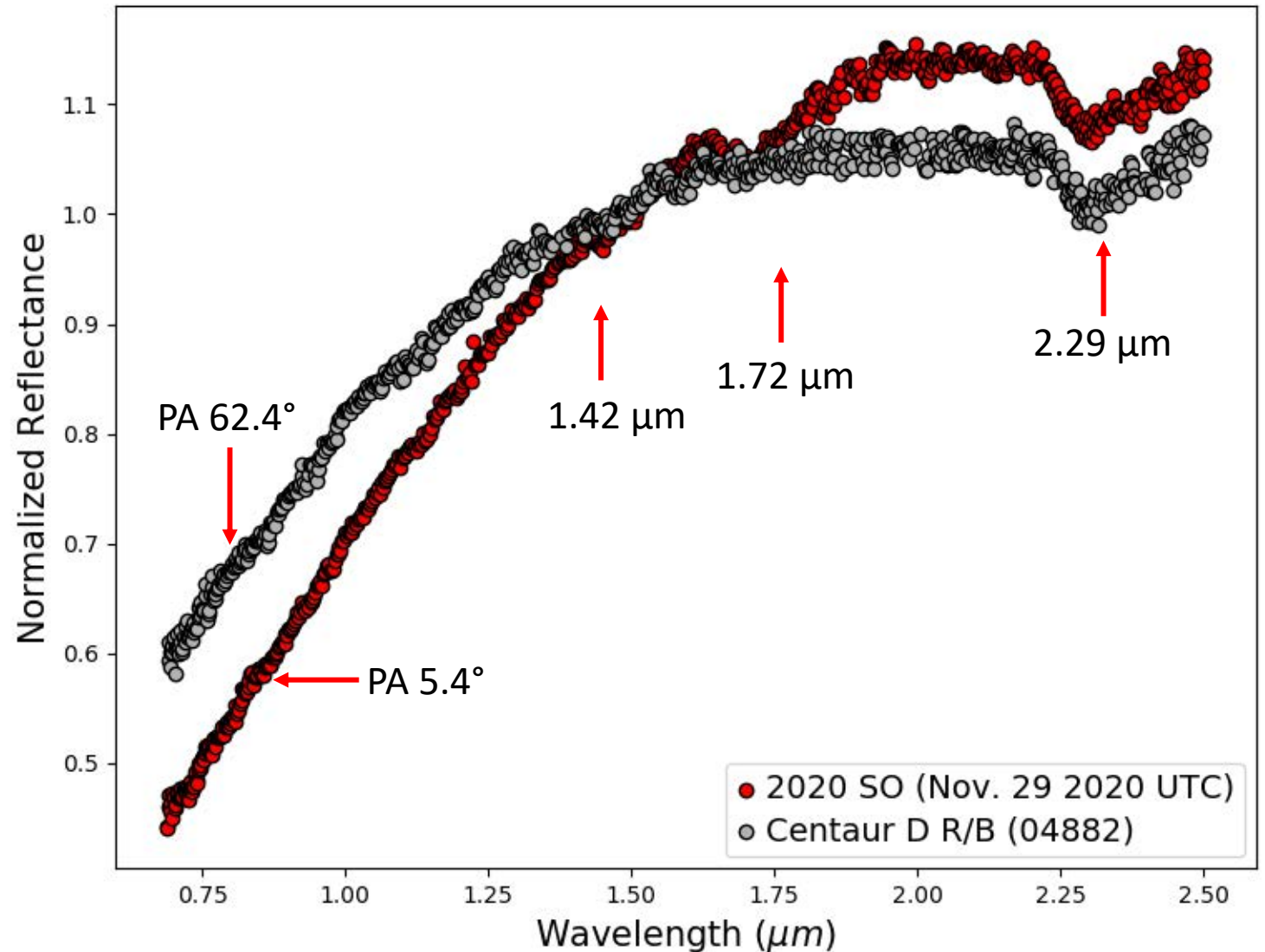
Near-IR Observations

- Next two spectra of 2020 SO were obtained days before close approach (Dec. 1, 2020)
- Spectral slope consistent with Nov. 17 data
- Major absorption bands are seen in spectra from Nov. 29, 30.
- Diagnostic absorption bands key to constraining composition
- Bands are located at 1.42 ± 0.02 , 1.72 ± 0.01 and $2.29 \pm 0.01 \mu\text{m}$
- But we did not have good lab spectral of analog materials



Near-IR Observations

- Spectrum of Centaur R/B (4882) consistent with 2020 SO
- Red spectral slope with absorption bands
- Absorption features at 1.42 ± 0.02 , 1.72 ± 0.01 are weaker in the Centaur than 2020 SO.
- Spectral slope and absorption band depth difference could be due to phase angle differences or space ageing
- What materials on 2020 SO is causing these absorption bands?

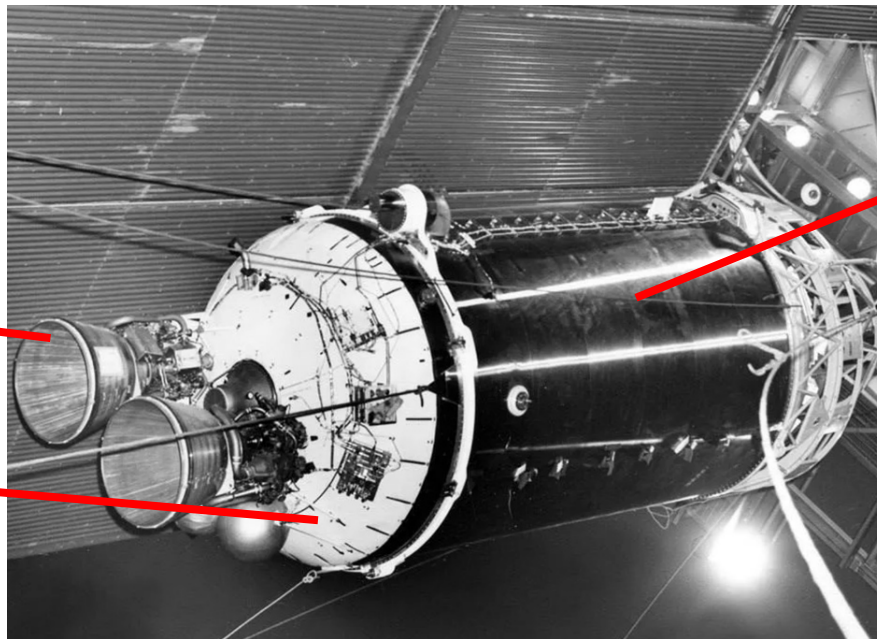


Interpretation

Spectrally-significant components

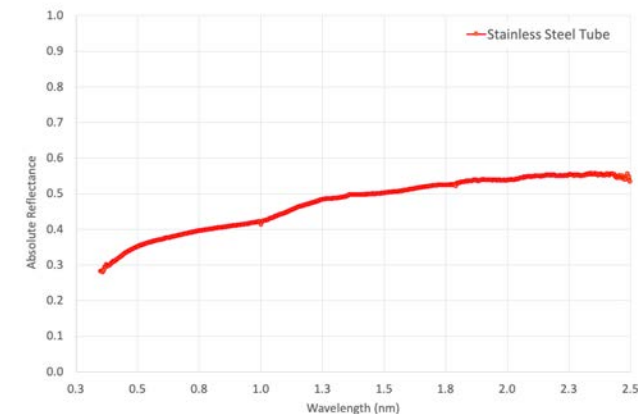
301 Stainless Steel

White polyvinyl fluoride

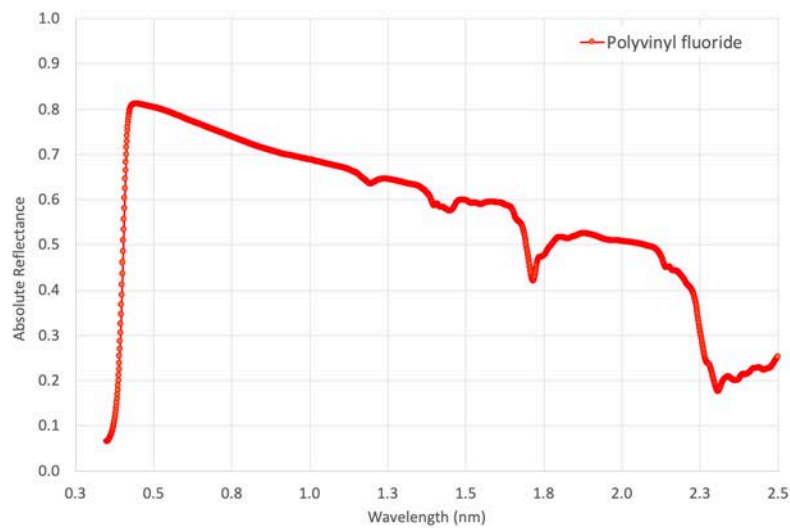


Study Lead: Neil Pearson (UA)

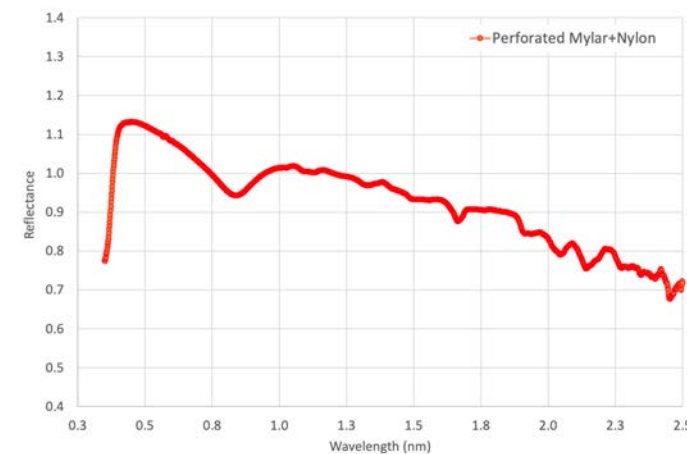
301 Stainless Steel



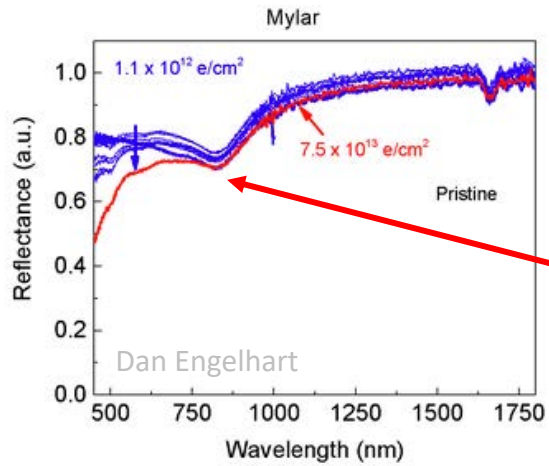
3.2.4 AFT BULKHEAD RADIATION SHIELD AND MEMBRANE. (Figures 3-19 and 3-20) The radiation shield is a rigid assembly made of laminated nylon fabric with aluminized Mylar on its inner surface and white polyvinyl fluoride on its outer surface. It is made up of 12 gores forming a complete ellipsoidal half covering the aft tank bulkhead. The shield is supported on brackets which hold it one inch from the tank bulkhead surface. Cutouts are provided for the LO₂ sump and the various equipment mounting brackets.



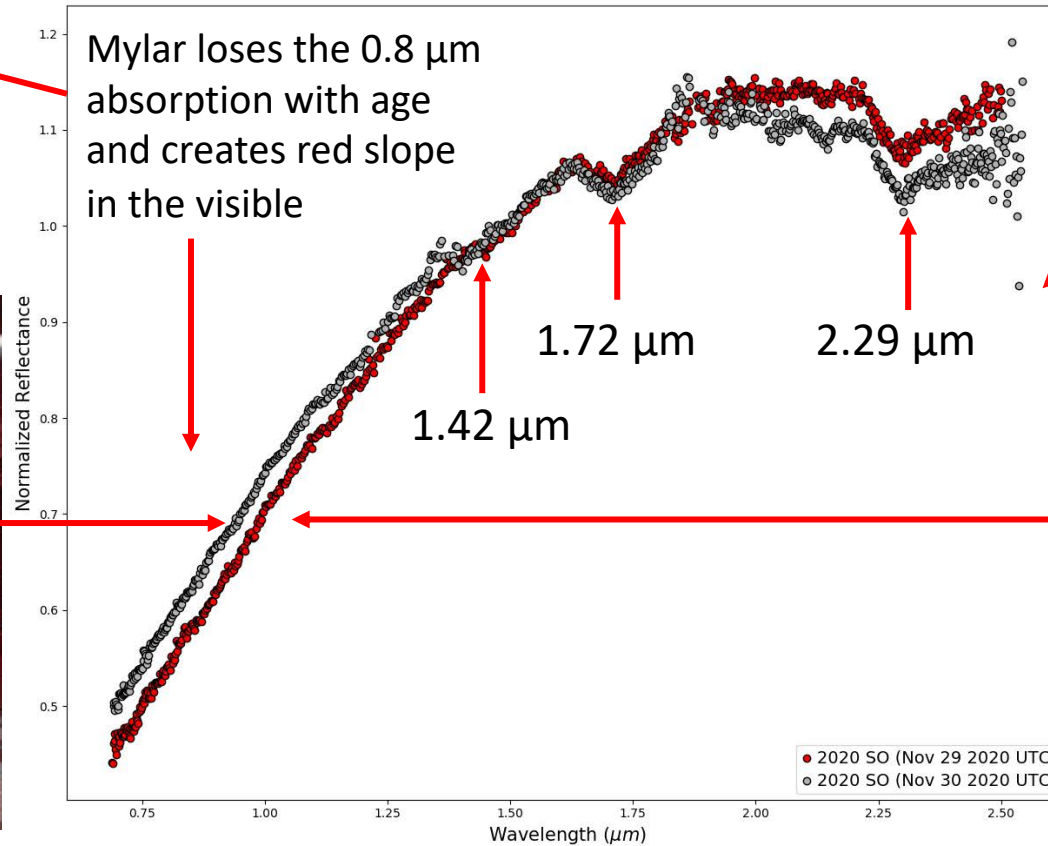
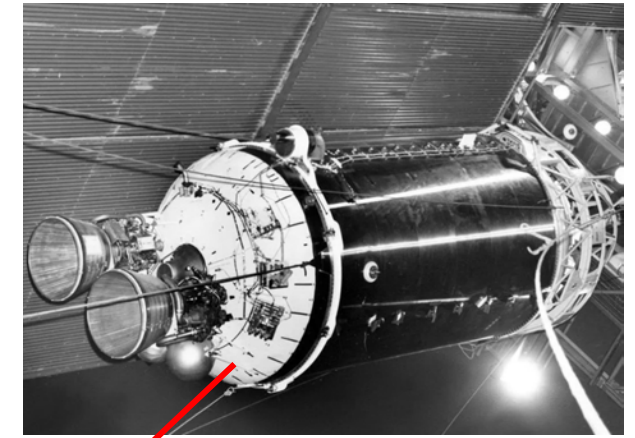
Aluminized Mylar



Interpretation



Object/ Material	Band I Center (μm)	Band II Center (μm)	Band III Center (μm)
PVF (Lab)	1.432 ± 0.001	1.716 ± 0.001	2.307 ± 0.001
2020 SO	1.430 ± 0.02	1.720 ± 0.01	2.290 ± 0.01



Stainless Steel also has red spectral slope similar to aged Mylar

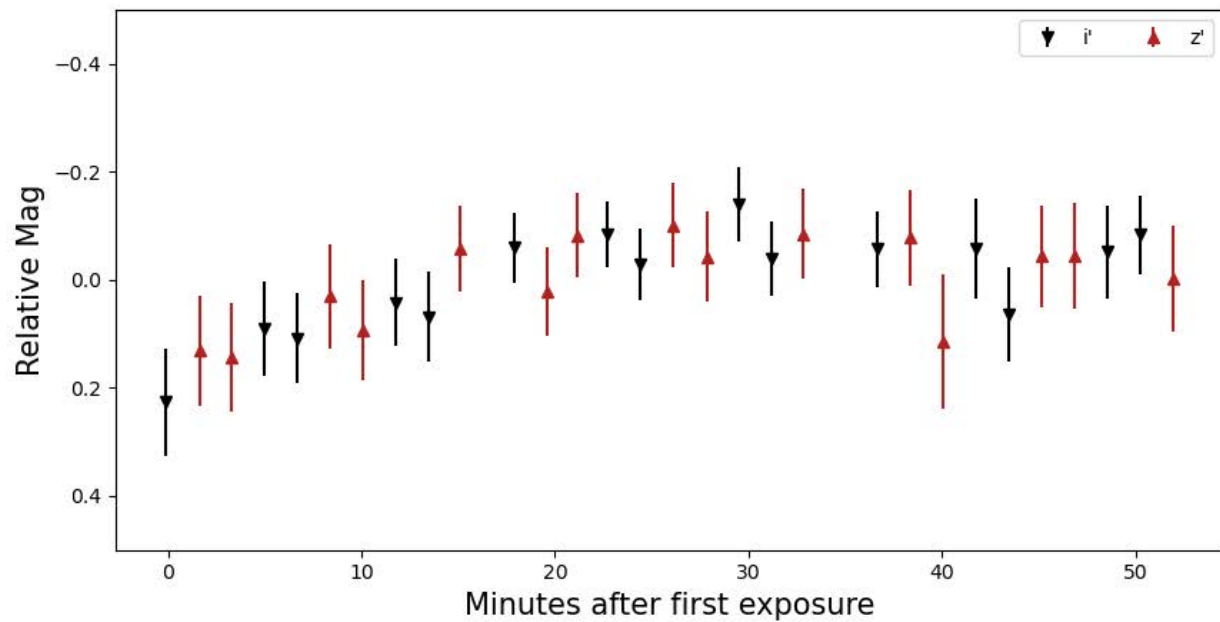
Summary

- We have demonstrated the power of spectroscopy in differentiating natural vs. artificial objects in near-Earth space.
- Fast turn around (2 weeks) for 2020 SO characterization (Asteroid Yes/No) after discovery (LBT color observations).
- Space ageing/weathering remains a major challenge in our ability to interpret 2020 SO spectra.
- We will attempt spectral mixing models once we have better end member lab spectra.

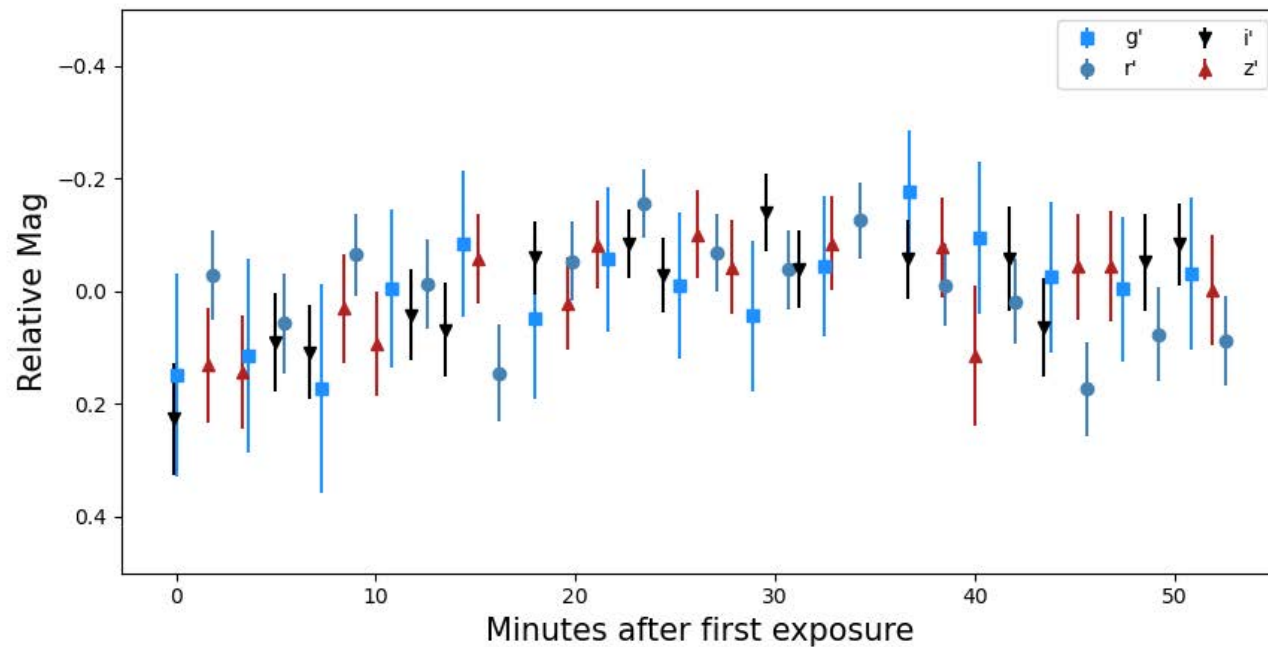
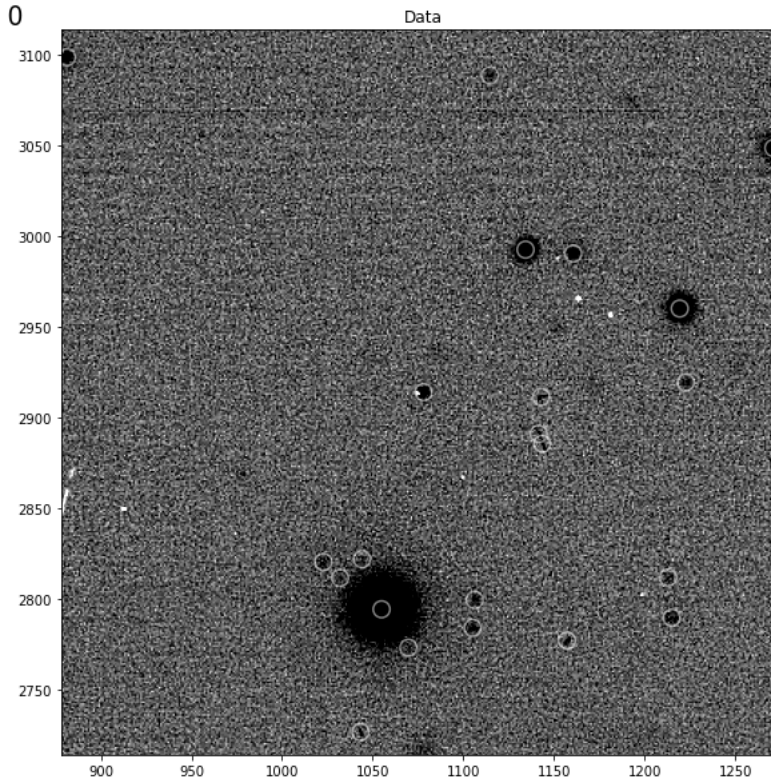
Acknowledgment: This work was funded by NASA Near-Earth Object Observations Grant NNX17AJ19G (PI: Reddy).

Backup Slides

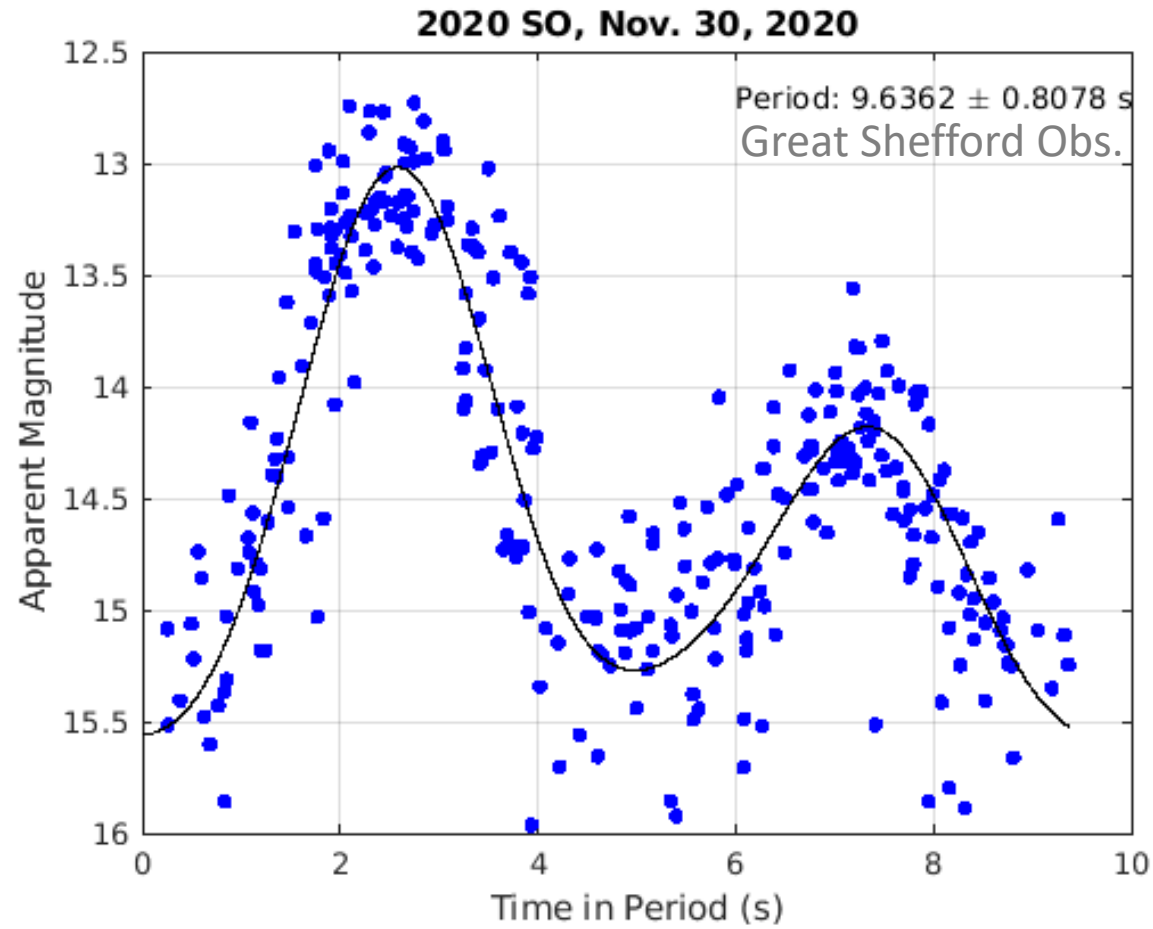
Lightcurve Observations



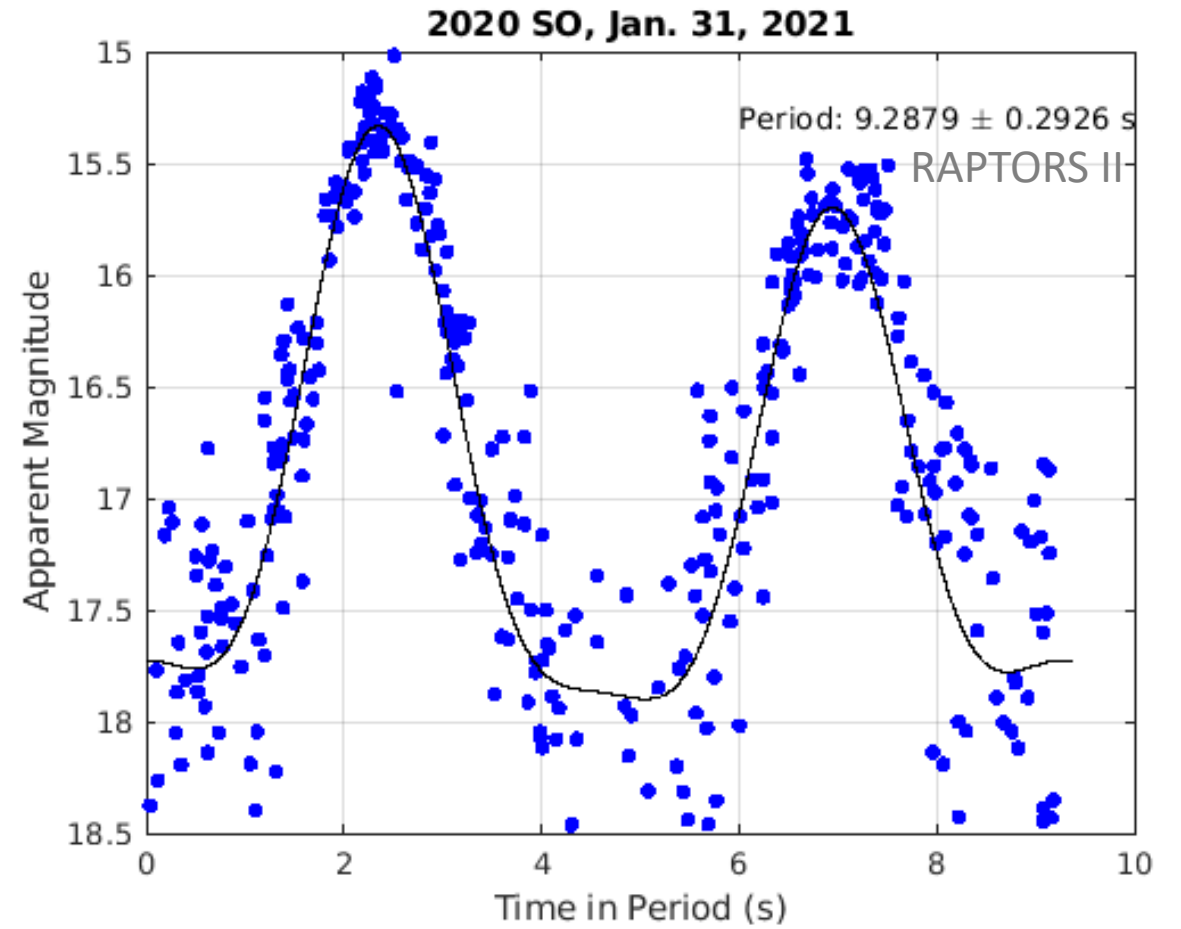
No clear evidence for a rotational period
Maybe a fast rotator or tumbling?



Lightcurve Observations



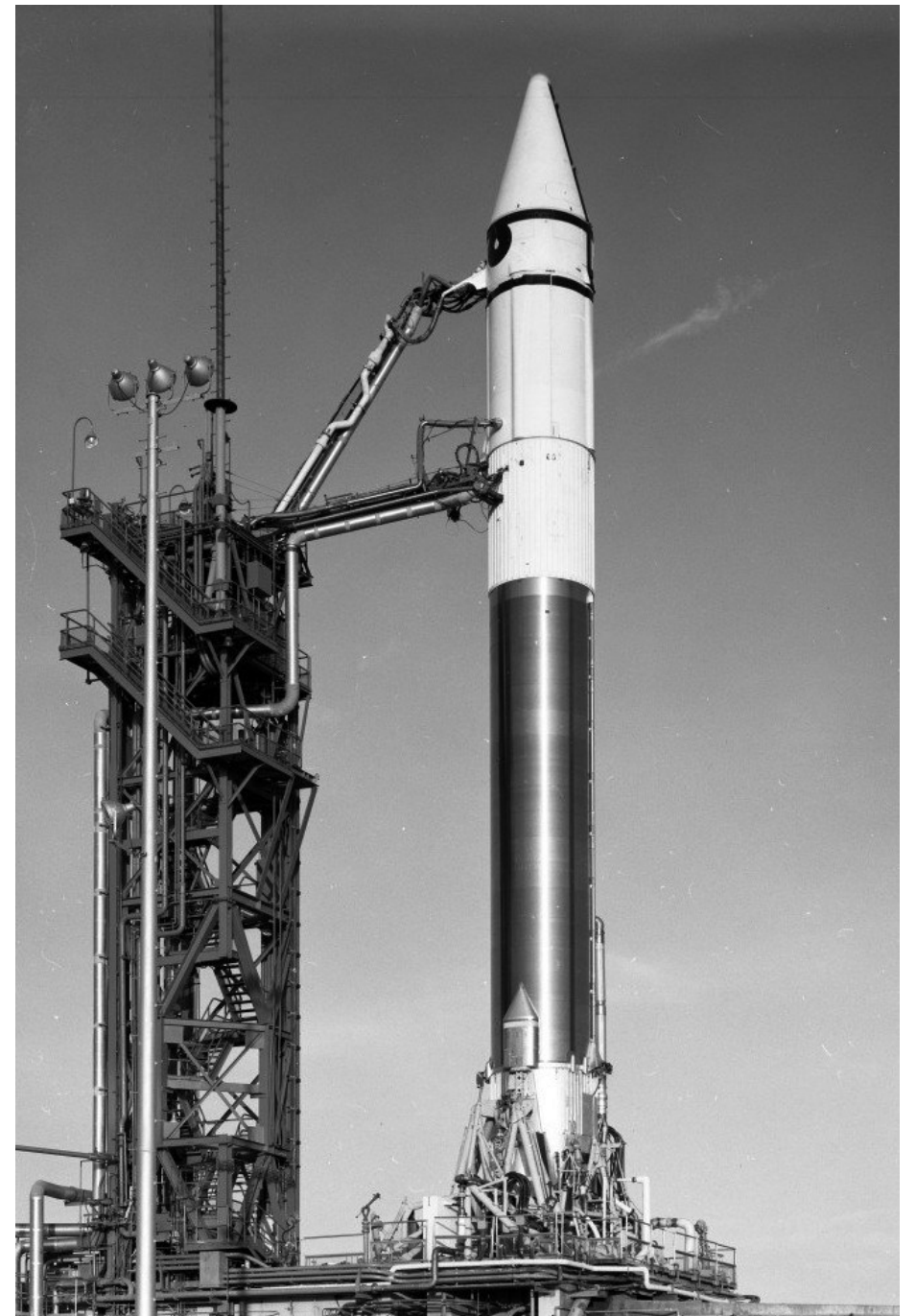
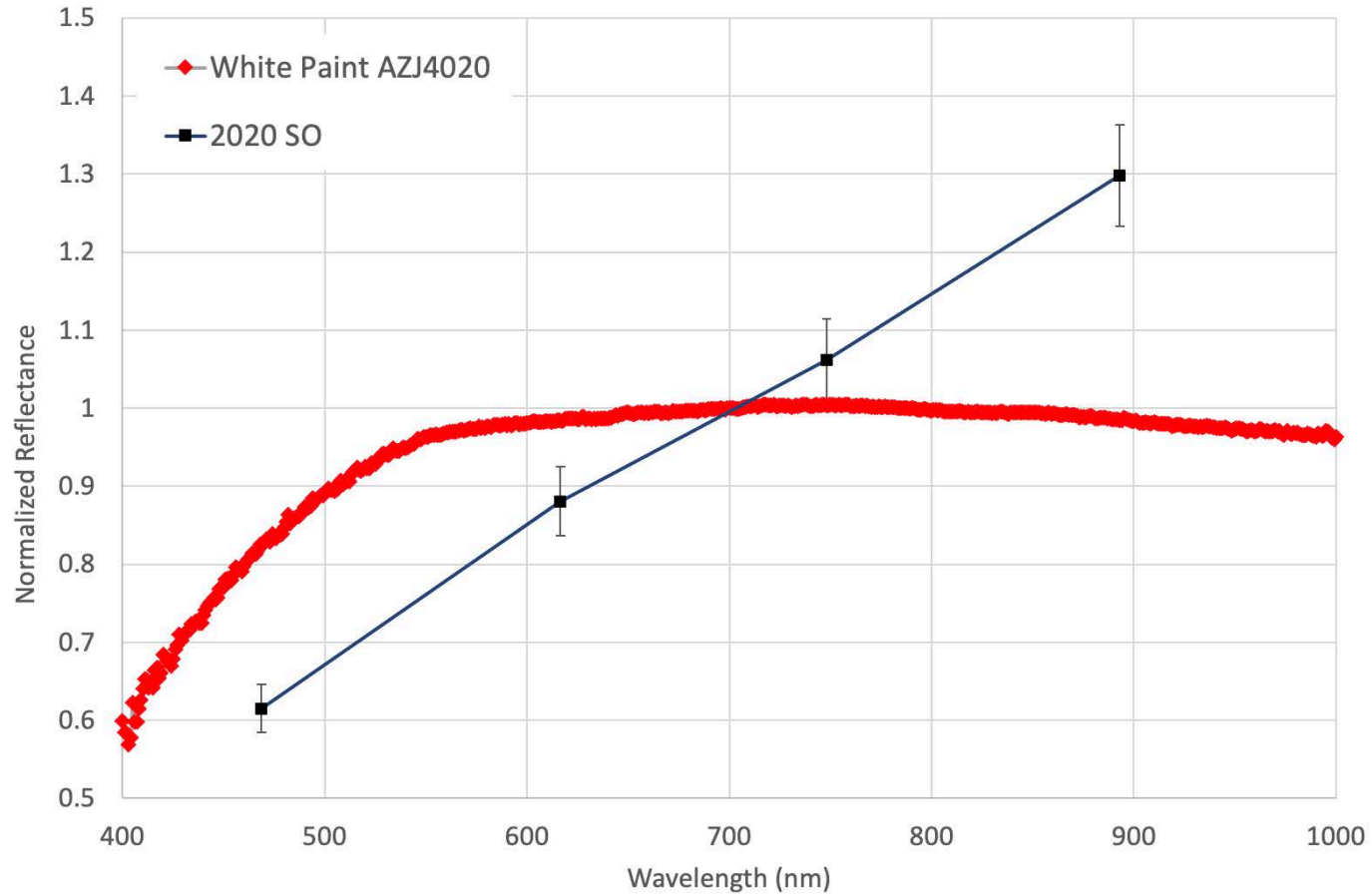
Close Approach 1, Range 94,000 km



Close Approach 2, Range 360,000 km

Color Observations

- Is the Centaur D Stage really painted white?



Color Observations

- If it is not white paint what is it?
- Phillip Anz-Meador (Jacobs, at NASA JSC)
- “Centaur D (operational) models jettisoned the foam insulation panels revealing the SS underneath”
- 2020 SO should be made of Stainless Steel 301.

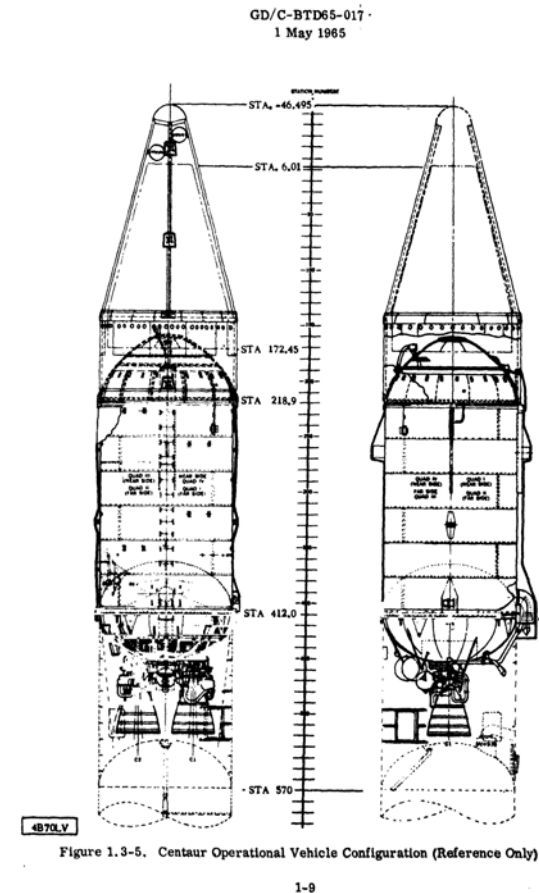
FABRICATION SEQUENCE



Visible Spectral Observations

Centaur D History: 24 Centaur D upper stages were launched between Aug. 1965 and Aug. 1972. Eight of which remain in Earth orbit. The three we picked were based on their visibility from Tucson. Two in LEO orbits were extremely challenging for spectroscopy, third was in GTO and easier to track at apogee.

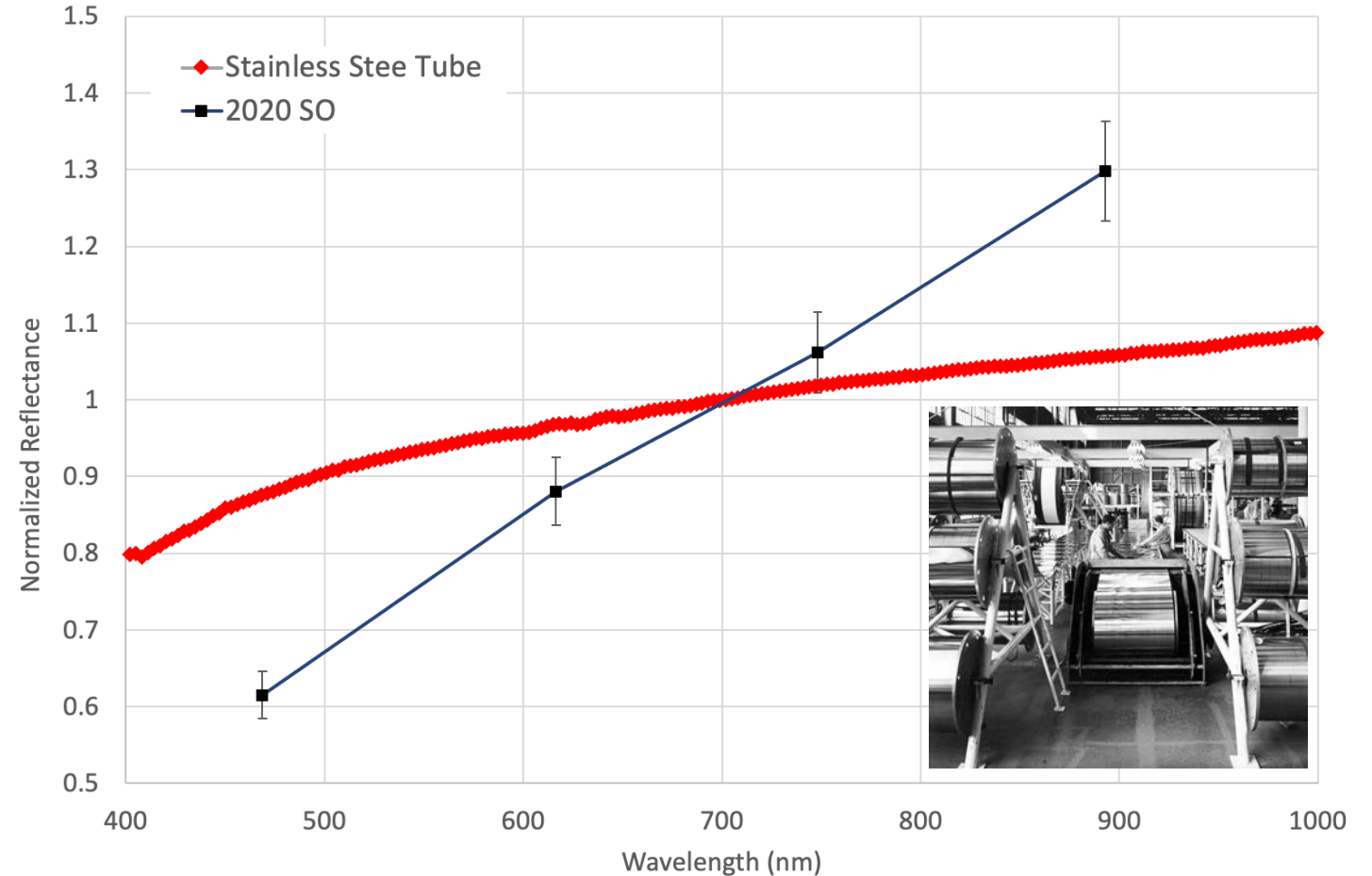
Launch Vehicle	Seq. Name	Launch Date			Primary Payload	NORAD ID	Period (Min)	Inclination (Deg)	Apogee Altitude (km)	Perigee Altitude (km)
Atlas-LV3C	AC-11	14	JUL	1967	Surveyor 4	2883	113.38	64.66	2499	265
Atlas-SLV3C	AC-16	07	DEC	1968	OA0 2	3598	99.00	34.99	746	676
Atlas-SLV3C	AC-18	12	AUG	1969	ATS 5	4069	703.13	17.88	37299	2331
Atlas-SLV3C	AC-25	26	JAN	1971	Intelsat-4 2	4882	652.52	27.33	36499	585
Atlas-SLV3C	AC-26	20	DEC	1971	Intelsat-4 3	6779	655.72	28.31	36599	648
Atlas-SLV3C	AC-28	23	JAN	1972	Intelsat-4 4	5816	651.92	27.78	36449	605
Atlas-SLV3C	AC-29	13	JUN	1972	Intelsat-4 5	6058	647.68	26.27	36294	543
Atlas-SLV3C	AC-22	21	AUG	1972	OA0 3	6155	97.85	35.01	682	630



Date (UTC)	Target	V. Mag.	Phase Angle	Range (km)	Range (LD)	Telescope	Aperture	Instrument	Type of Observations	Wavelength Range	Spec. Res.
28-Sep-20	2020 SO	21.5	20.5	3420234	8.898	LBT	8.2-m	LBC	Sloan griz colors	0.464-0.90 μm	R=4
10-Oct-20	NORAD ID: 3598	~6-8	76.8	745	0.002	RAPTORS I	0.6-m	FLI 4220	Visible spectroscopy	0.438-0.950 μm	R~30
22-Oct-20	NORAD ID: 6155	~6-8	15.5	1300	0.003	RAPTORS I	0.6-m	FLI 4220	Visible spectroscopy	0.438-0.950 μm	R~30
17-Nov-20	NORAD ID: 4882	~6-8	80.6	4900	0.013	RAPTORS I	0.6-m	FLI 4220	Visible spectroscopy	0.438-0.950 μm	R~30
17-Nov-20	2020 SO	19.3	21.9	1160736	3.020	NASA IRTF	3.0-m	SpeX	Near-IR spectroscopy	0.69-2.54 μm	R~100
29-Nov-20	2020 SO	15.7	5.4	300896	0.783	NASA IRTF	3.0-m	SpeX	Near-IR spectroscopy	0.69-2.54 μm	R~100
30-Nov-20	2020 SO	14.9	5.5	152894	0.398	NASA IRTF	3.0-m	SpeX	Near-IR spectroscopy	0.69-2.54 μm	R~100
30-Nov-20	NORAD ID: 4882	~6-8	62.4	34000	0.088	NASA IRTF	3.0-m	SpeX	Near-IR spectroscopy	0.69-2.54 μm	R~100
2-Feb-21	2020 SO	15.8	23.8	221541	0.576	NASA IRTF	3.0-m	SpeX	Near-IR spectroscopy	0.69-2.54 μm	R~100

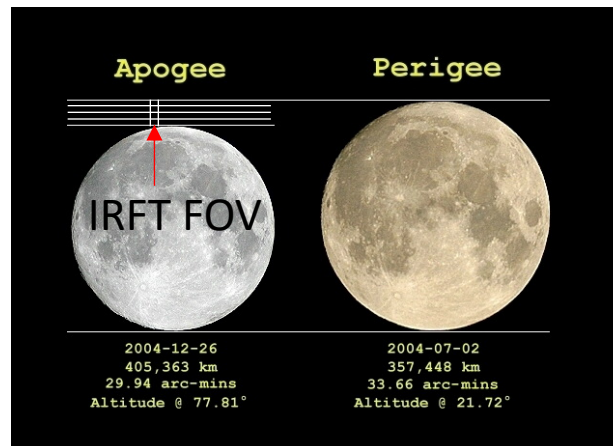
Color Observations

- Spectra of SS 301 obtained from AFRL (Dan Engelhart)
- These spectra were not aged under the assumption that Stainless Steel won't oxidize like Aluminum would.
- Plot on the right compares 2020 SO griz colors with Stainless Steel Tube.
- Both have red spectral slopes, but 2020 SO is redder than lab spectrum of Stainless Steel.



Chasing Centaur

- Identifying specific materials requires extensive lab spectroscopy if we can get the material samples
- How do spectra of materials change with space ageing?
- Logical solution was to observe another Centaur with the IRTF, preferably one of three we observed with RAPTORS I (visible spectra)



IRTF Tracking Limit: 40"/sec
Centaur Rates: RA Rate: 13 "/sec

Launch Vehicle	Seq. Name	Launch Date			Primary Payload	NORAD ID	Period (Min)	Inclination (Deg)	Apogee Altitude (km)	Perigee Altitude (km)
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Challenges

TLE for 4882 was 2.5 days old

Centaur position off by 8.15' (8X IRTF FOV)

We tried to observe 4882 from my backyard a few hours before IRTF observations but was too low in the sky.



Tucson, AZ

ACCURATE NEO ORBITS FROM OCCULTATION OBSERVATIONS

Paper IAA-PDC-21-6-09 (Session 6b, #4)

7th Planetary Defense Conference – PDC 2021
26-30 April 2021, Vienna, Austria and via Webex

David W. Dunham^{1&2}, J. B. Dunham¹, M. Buie³, S. Preston¹, D. Herald^{1,4}, D. Farnocchia⁵, J. Giorgini⁵, T. Arai⁶, I. Sato⁶, R. Nolthenius^{1,7}, J. Irwin¹, S. Degenhardt¹, S. Marshall⁸, J. Moore¹, S. Whitehurst¹, R. Venable¹, M. Skrutskie⁹, F. Marchis¹⁰, Q. Ye¹¹, P. Tanga¹², J. Ferreira¹², D. Vernet¹², J.P. Rivet¹², E. Bondoux¹², J. Desmars¹³, D. Baba Aissa¹⁴, Z. Grigahcene¹⁴,
and H. Watanabe¹⁵

¹International Occultation Timing Assoc. (IOTA, P. O. Box 423, Greenbelt, MD 20768, USA, iotatreas@yahoo.com), ²KinetX Aerospace (david.dunham@kinetx.com), ³Southwest Research Inst., Boulder, CO, ⁴Trans Tasman Occultation Alliance, ⁵Jet Propulsion Lab., ⁶Planetary Exploration Res. Ctr. (PERC), Chiba Inst. of Tech., Japan, ⁷Cabrillo College, Santa Cruz, CA, ⁸Arecibo Obs., ⁹Univ. of Virginia, ¹⁰SETI Inst. and Unistellar, ¹¹Univ. of Maryland, ¹²Obs. de la Côte d'Azur, ¹³Paris Obs., ¹⁴Algiers Obs. – CRAAG, ¹⁵Japanese Occultation Information Network



Version of 2021 April 26, 7pm EDT



Outline

- IOTA & Asteroidal Occultations Introduction & History
- The 1975 Jan. 24 Occ'n of κ Gem by Eros
- The 2019 July Occ'n by Phaethon, 1st small NEO occ'n
- Other Phaethon occultations, 2019 Sep. to 2020 Oct.
- Improvement of Phaethon's orbit – A2 acceleration
- More Opportunities in 2021 & 2022
- First Observed Occultation by Apophis, 2021 Mar. 7
- Almost lost it – 2nd Positive Occ'n, 2021 Mar. 22
- 2021 April Occultations – Apophis Orbit Nailed
- Conclusions
- Additional Resources

IOTA and Asteroidal Occultations Introduction

- The observer network that became IOTA formed in 1960's
- to observe lunar grazing occultations with mobile efforts
- The mobile techniques to observe lunar grazes, were used effectively to observe asteroidal occultations in the late 1970's
- Starting in the 1980's, IOTA began recording occultations with video equipment, improving the observations
- Using stars and the Earth's rotation to pre-point stationary telescopes at multiple locations
- Working with the NASA PDS Small Bodies Node and the Minor Planet Center, IOTA archives all asteroidal occultation observations
- ESA's Hipparcos and Gaia missions have greatly improved prediction accuracy, resulting in a large increase in observed occultations
- The sizes, shapes, and accurate positions of hundreds of asteroids have been determined
- Dozens of close double stars have been discovered, the diameters of several stars have been measured, and some asteroidal satellites have been discovered, and several characterized.

Lunar Occultation Geometry

← TO STAR IOTA started in the early 1960's by observing lunar occultations, especially grazing ones

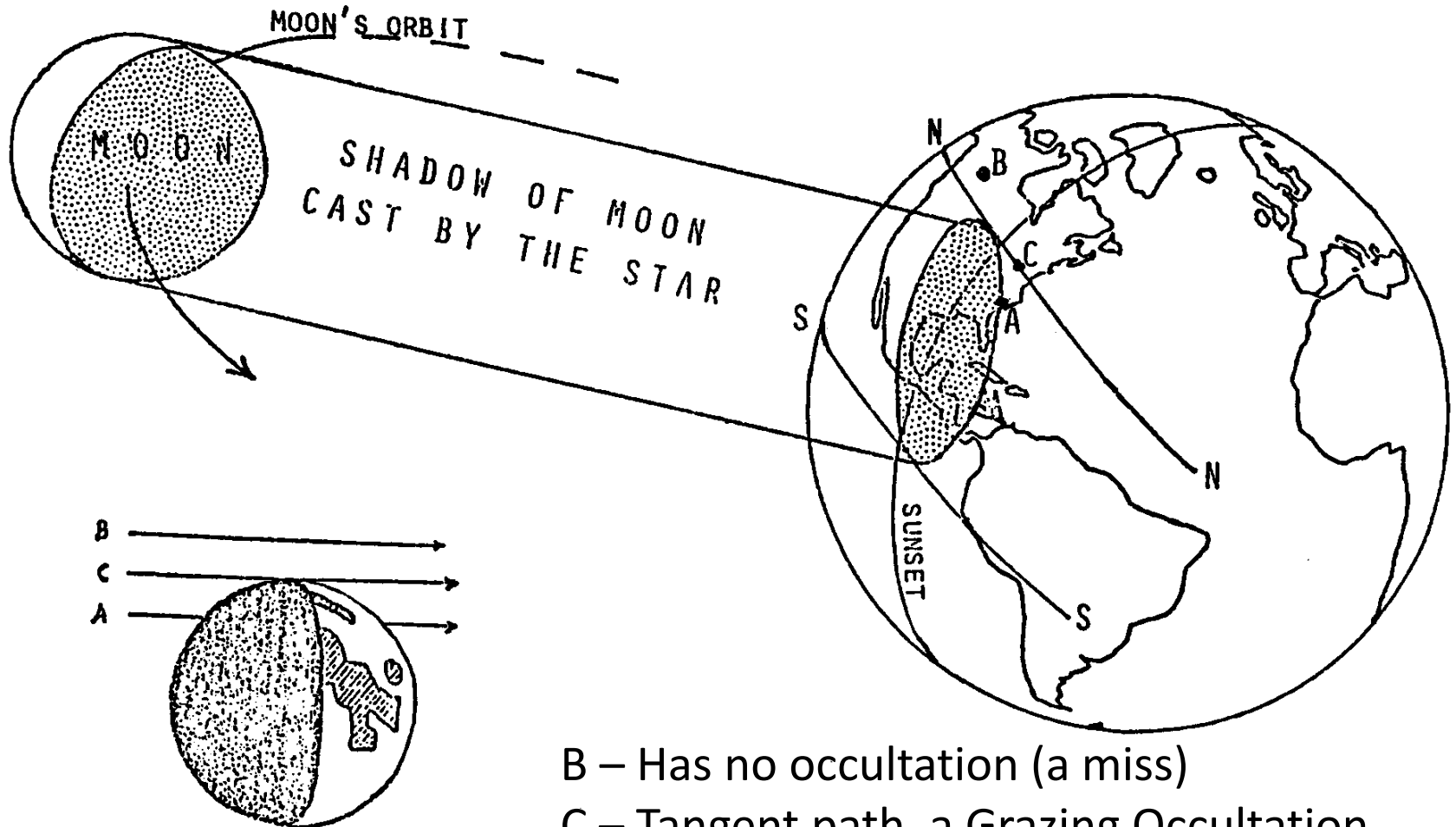


Figure 2-1b

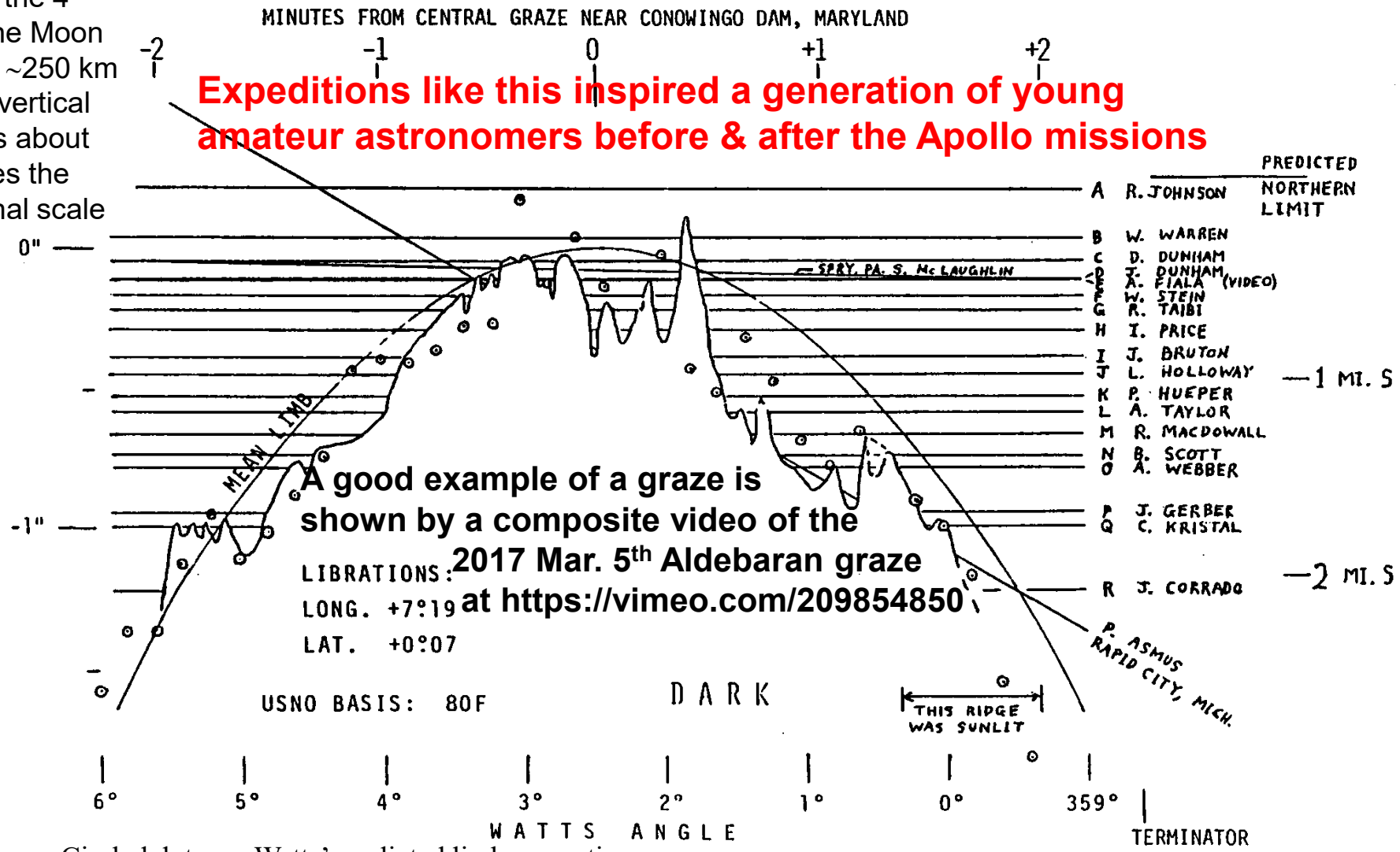
- B – Has no occultation (a miss)
- C – Tangent path, a Grazing Occultation
- A – Total Occultation

Lunar Profile from Graze of delta Cancri – 1981 May 9-10

Alan Fiala, USNO, obtained the first video recording of multiple events during this graze, with 7 D's and 7 R's

During the 4 min., the Moon moved ~250 km so the vertical scale is about 40 times the horizontal scale

Expeditions like this inspired a generation of young amateur astronomers before & after the Apollo missions



Circled dots are Watts' predicted limb corrections

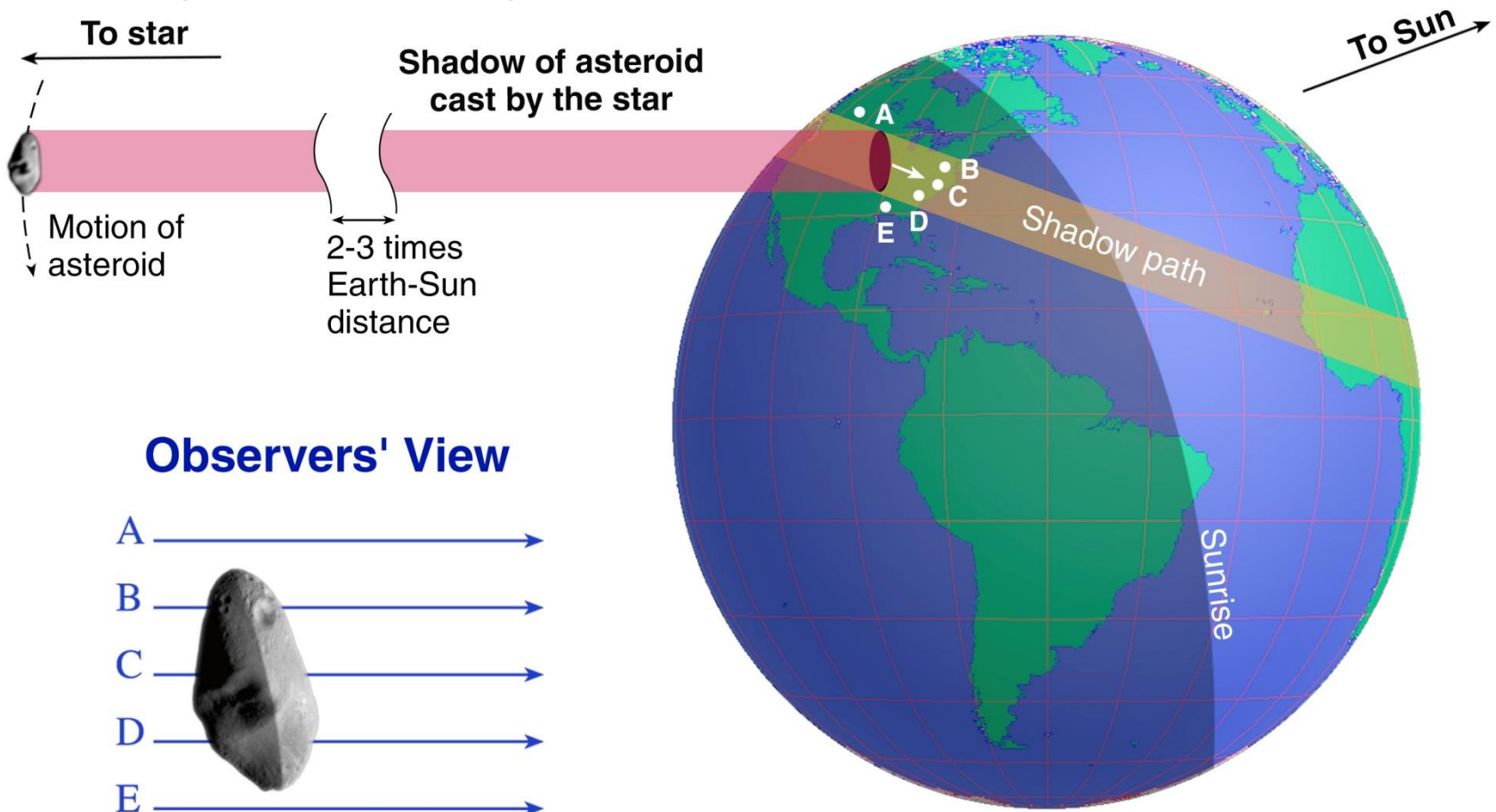
Starting in 1965, cable systems were developed for observing grazing occultations, first at USNO, then by 3 clubs in California (Riverside, Santa Barbara, and Mount Diablo Astronomical Society), and Milwaukee, Wisconsin



This is a Riverside A.S. expedition near Adelanto in 1966. Mobile observation was needed since graze paths were narrow. The observations were visual, with audio tones recorded at the central station for this cable system.

Geometry of an Asteroid Occultation

IOTA began observing asteroidal occultations in the late 1970's



Observers' View

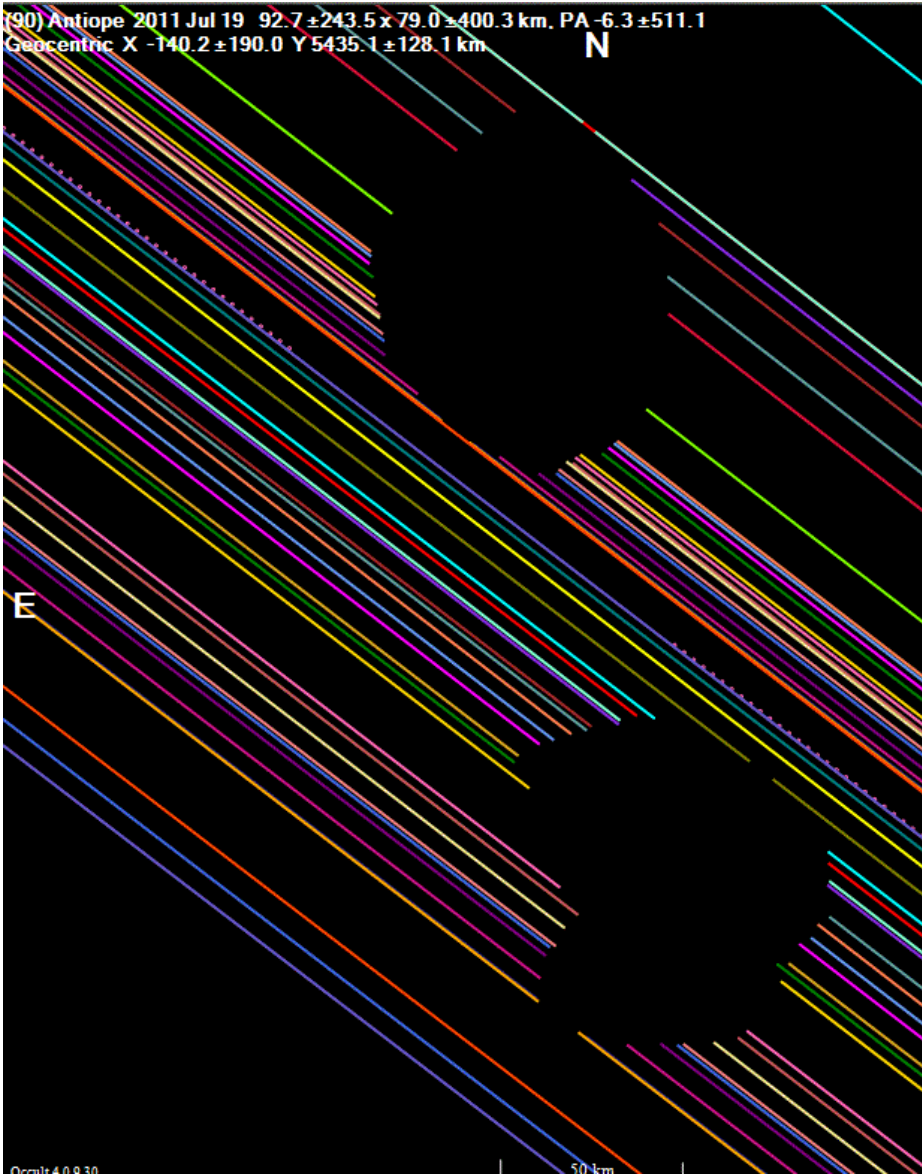


A, E: Negative observations
B, C, D: Positive observations

The more stations that can be deployed, the better the resolution of the asteroid's shape

Many Occultations of Interesting Main Belt Objects

2011 July 19 occ'n of LQ Aquarii by
the Binary Asteroid (90) Antiope



Technology now allows observers to record transient astronomical phenomena more precisely and to fainter magnitudes than ever before. A small, inexpensive, yet very sensitive camera (RunCam Night Eagle Astro) will allow you to participate in IOTA's programs to accurately record occultations and eclipses, to measure the sizes and shapes of hundreds of asteroids, discover duplicity of both close double stars and asteroids with satellites, and measure the angular diameters of many stars. Occultations provide excuses for travel, or you can just observe them from home, to further astronomical knowledge. Some use specially-made easily-transported telescopes; there is room for innovative design & construction of equipment & software to record asteroidal occultations.



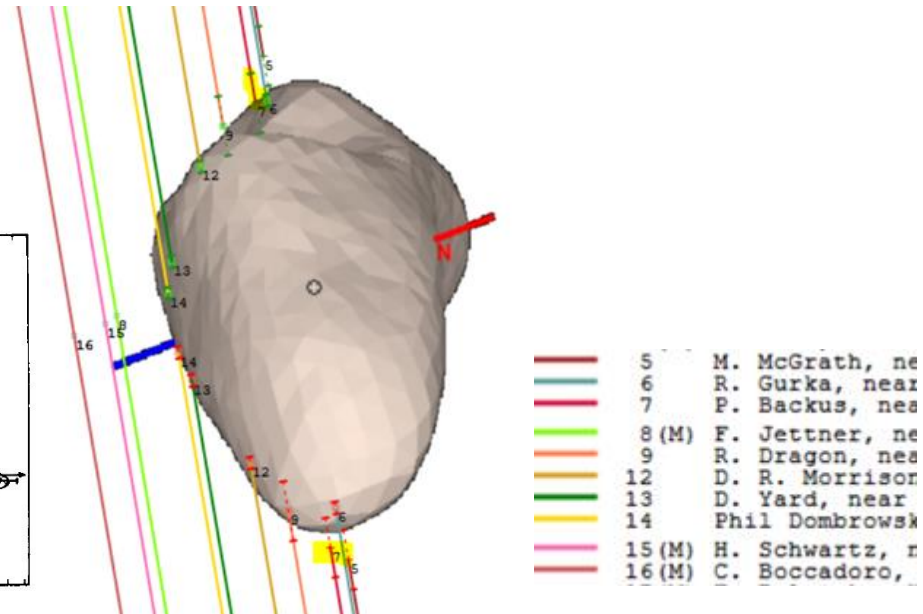
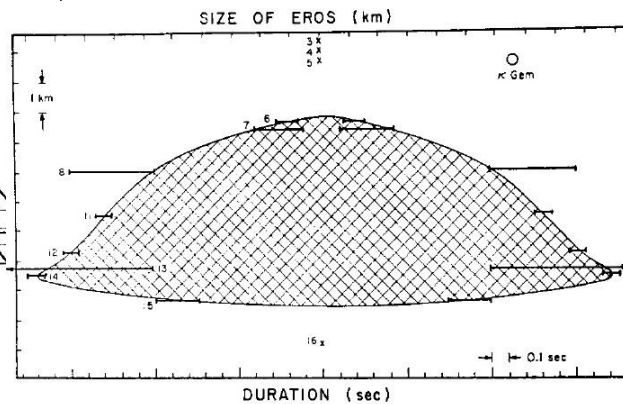
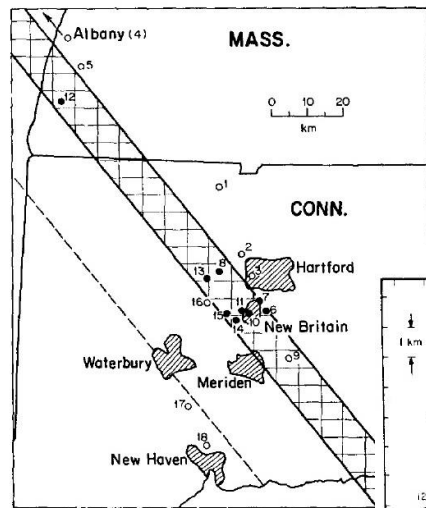
Near left: 10-in suitcase telescope deployed for an asteroidal occultation in the Australian Outback. ⁸

Remote Stations for Asteroidal Occultations

- Separation should be many km, much larger than for grazes, so tracking times & errors are too large
- Unguided is possible since the prediction times are accurate enough, to less than 1 min. = $\frac{1}{4}^\circ$ (now the prediction time errors are only a few seconds)
- Point telescope beforehand to same altitude and azimuth that the target star will have at event time and keep it fixed in that direction
- Plot line of target star's declination on a detailed star atlas; Guide 8 or 9, or C2A can be used to produce the charts
- From the RA difference and event time for the area of observation, calculate times along the declination line
- Adjust the above for sidereal rate that is faster than solar rate, add 10 seconds for each hour before the event; done automatically by Guide & C2A
- Can usually find "guide stars" that are easier to find than the target
- Find a safe but accessible place for both the attended & remote scopes
- Separation distance limited by travel, set-up, & pre-pointing time, but we have had success with software to control small Win10 computer recordings; then the main limit is battery life, which can be several hours
- Sometimes it is better to have remote sites attended for starting equipment later (allows larger separations) and security, if enough people can help

First observed occultation by a NEO, 1975 Jan. 24, κ Gem occulted by Eros

from O'Leary et al.,
Icarus, Vol. 28, pp.
133-146 (1976)



Left, map of observers & sky plane plot from the 1976 Icarus paper. Right, modern sky plane plot of the chords fitted to Eros' shape model derived from NEAR-Shoemaker data. This was the first occultation by ANY asteroid that was observed from multiple stations. Especially, the stations deployed by the Pioneer Valley Colleges led by Brian O'Leary was the first successful coordinated effort to observe such an event by mobile observers. A crucial observation, now known to be a false negative, resulted in the wrong squashed shape shown by O'Leary et al. It would be 44 years before an occultation by another NEO would be observed.

(3200) Phaethon

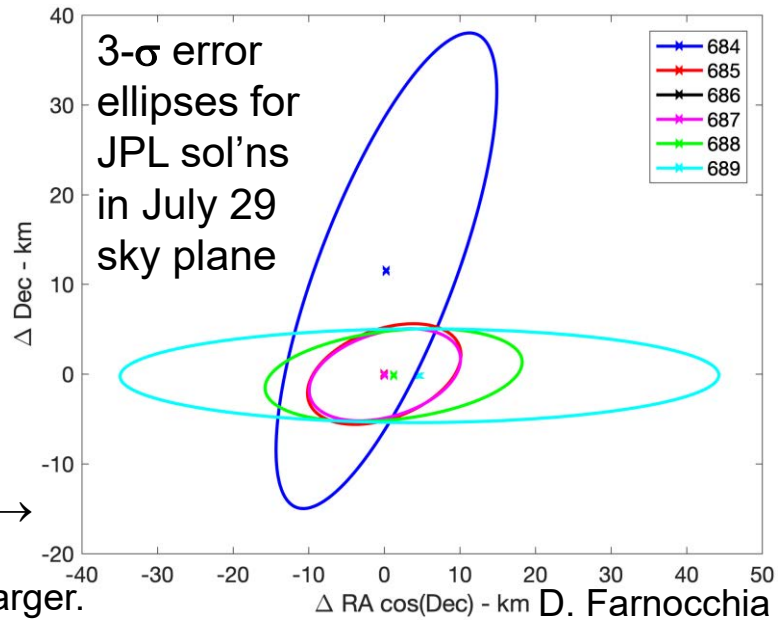
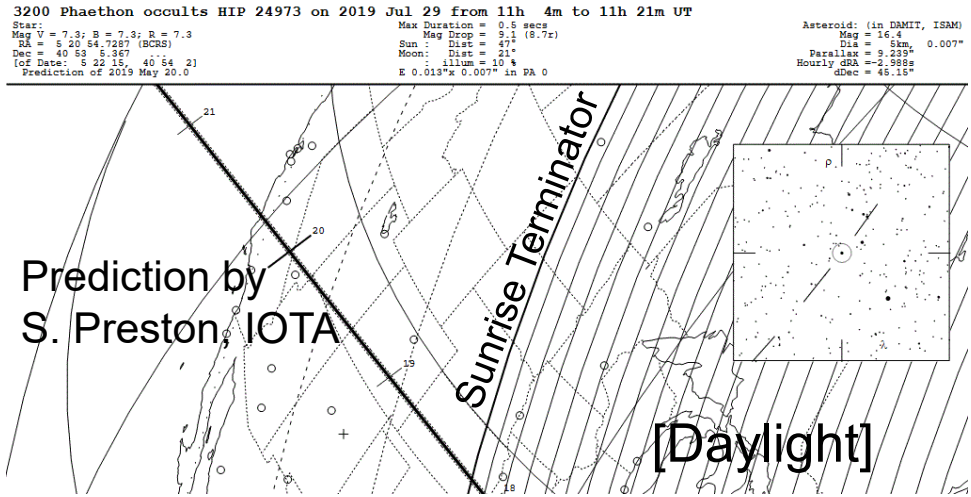
- (3200) Phaethon was the first asteroid to be discovered by a spacecraft (IRAS).
- Phaethon is the parent body of the Geminids meteor stream that puts on one of the largest annual meteor displays
- This mysterious object may be a (nearly) dead comet nucleus, or a very active asteroid, throwing off boulders like has been observed on Bennu by OSIRIS-REx
- Phaethon is an Apollo asteroid with a perihelion of only 0.14 AU, <half Mercury's, with aphelion 2.4 AU in the Main Belt. The extreme thermal changes near perihelion likely drive its shedding of pebbles and dust, creating the trail imaged by the Parker Solar Probe. Small non-gravitational forces on its orbit have been detected.
- JAXA's DESTINY+ spacecraft plans to launch in 2024 and fly by Phaethon in 2025 -see <https://en.wikipedia.org/wiki/DESTINY+>
- Radar observations show Phaethon to be nearly spherical with a diameter of nearly 6 km
- Thermal IR data give a diameter of ~4.5km



Radar image of 3200 Phaethon taken by Arecibo,
December 17, 2017

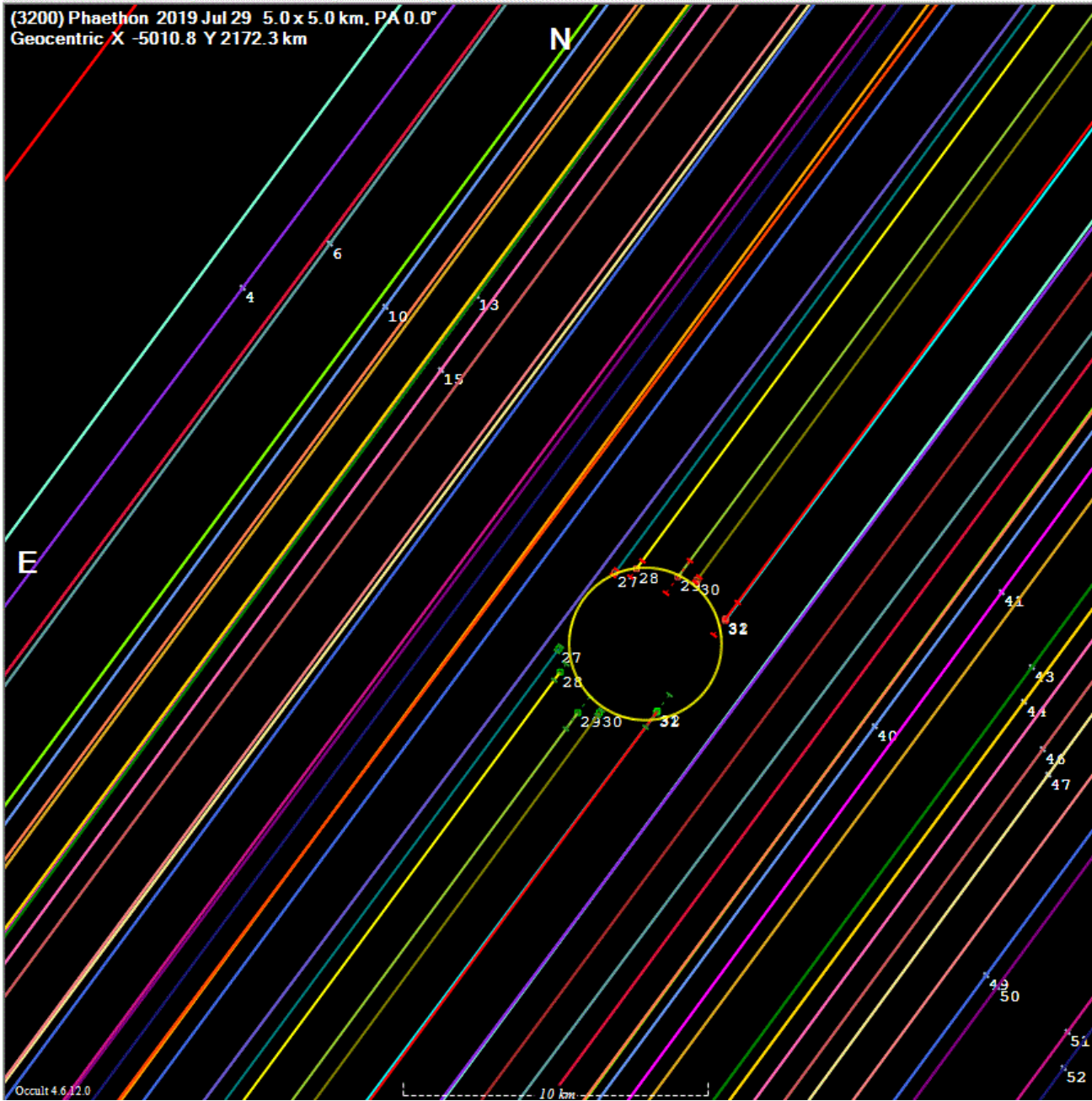
THE 2019 JULY 29 OCC'N OF 7.3-MAG. SAO 40261 BY PHAETHON

- This event was first identified by Isao Sato in Japan. In January 2019, he alerted US observers via a message that he sent to the IOTAoccultations list server.
- To obtain an accurate astrometric point for orbit improvement, and to resolve the diameter discrepancy, Tomoko Arai, PI of DESTINY+, requested that NASA & IOTA try to observe this rare bright occultation by the small NEO in the sw USA.
- This was by far the smallest object that IOTA had tried to predict and observe; we needed help.
- Those who predicted this occultation, and analyzed the observations of it, all had to modify their software, to take into account previously-neglected effects that weren't significant for occultations by all of the larger objects studied in the past. Even the difference in the gravitational bending of light by the Sun, for the star and Phaethon, was noticeable.
- Jon Giorgini computed JPL solution 684 after including radar measurements made in 2017. Then Davide Farnocchia computed JPL 685, manually adding Gaia astrometry; this was key.
- Adding new astrometric observations just confirmed JPL 685, so it was used for the final prediction.



Phaethon's motion was from lower left to upper right, \rightarrow so the 3σ limits (JPL 685) were 8 km + Phaethon's radius from center; the ground projection was a little larger.

2019 July 29 Phaethon occ'n, all successful chords



Find best fit

Center X 0.1 0.0 Centered on Shape model
 Center Y -0.1 0.0

Major axis (km) 5.0 0.0 a/b=1.00
 Minor axis (km) 5.0 0.0 dMag=0.00
 Orientation 0.0 0.0 Motion 8.90km/s, Y

Circular Use assumed diameter Include Miss events

Double star
 Sepn (masec) 0.0 0.0 0 solutions
 PA of 2nd 0.0 0.0 #1 #3
 #2 #4

Show: Both Primary Secondary

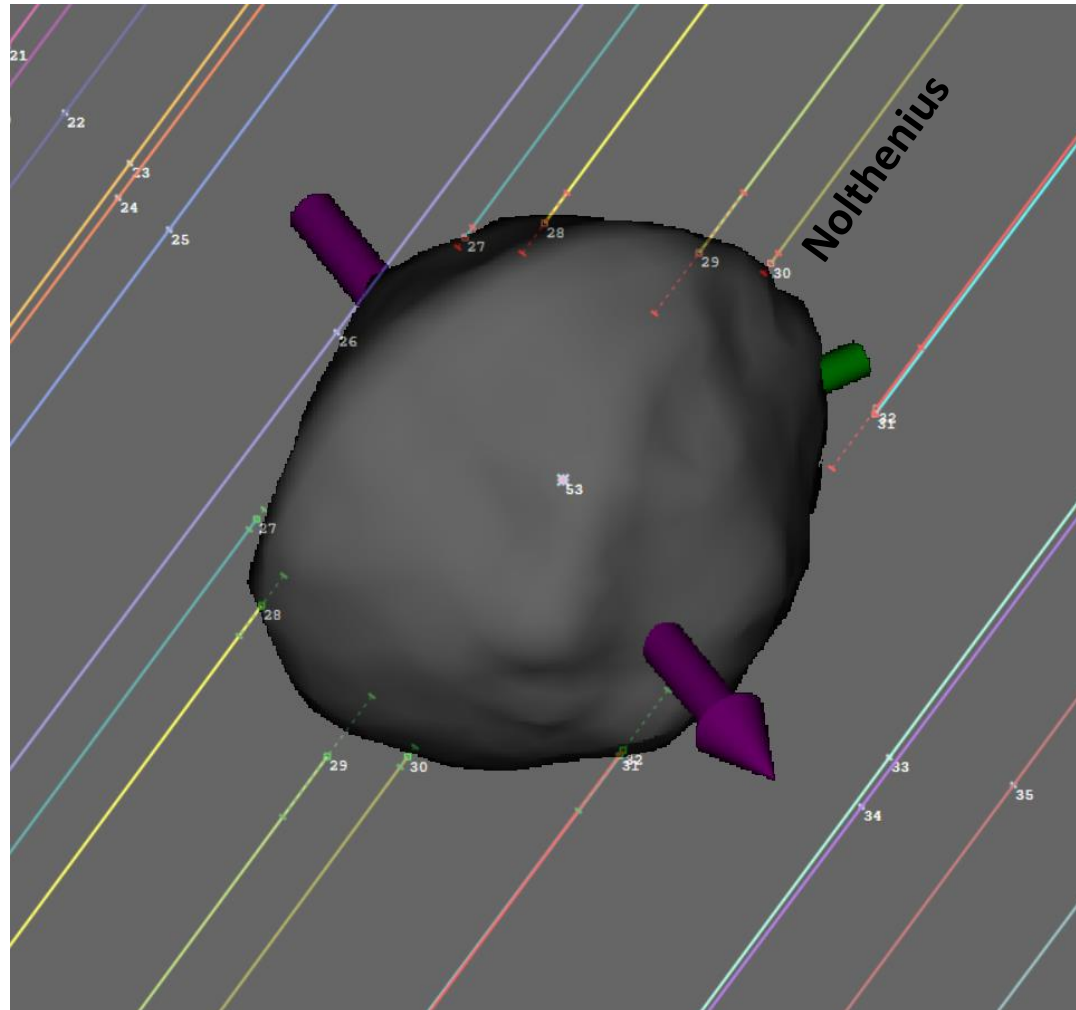
Plot scale Quality of the fit
 No reliable position or size

RMS fit 0.2 ± 0.3 km Opacity

1 (M)	R Royer
2 (M)	W Merline
3 (M)	K Caceres
4 (M)	J Kok
5 (M)	S Degenhardt
6 (M)	R Howard
7 (M)	S Degenhardt
8 (M)	S Degenhardt
9 (M)	S Degenhardt
10 (M)	R Howard
11 (M)	S Degenhardt
12 (M)	J Briggs
13 (M)	E Wilson
14 (M)	B Whitehurst & J M
15 (M)	R Howard
16 (M)	B Whitehurst & J M
17 (M)	M Buie
18 (M)	B Whitehurst & J M
19 (M)	W Thomas
20 (M)	J Keller
21 (M)	B Whitehurst & J M
22 (M)	B Whitehurst & J M
23 (M)	J Bardecker
24 (M)	B Keeney
25 (M)	B Whitehurst & J M
26 (M)	R Leiva
27	B Whitehurst & J M
28	S Degenhardt
29	Q Ye, Q Zhang et a
30	R Nolthenius
31	A Parker & I Shera
32	S Degenhardt
33 (M)	K Getrost
34 (M)	A Vebiscer & J Jew
35 (M)	B Whitehurst & J M
36 (M)	D Terrell & J Salm
37 (M)	K Bender
38 (M)	F Marchis

2019 July 29 Phaethon occultation, positive chords

fitted to a shape model determined from 2017 December Arecibo radar observations



by
Dave Herald and
Sean Marshall

The event provided accurate information about Phaethon's size (verifying the radar value), shape, and orbit that will be valuable for DESTINY+'s planning, and will help obtain more data from future occultations that can be better predicted.

All Observed Occultations by (3200) Phaethon

Date	Star mag.	# stations positive/all	Locations(s)	Remarks
2019 July 29	7.3	6/52	s.w. USA	8 SwRI 16in., 44 IOTA stations
2019 Sept. 29	12.0	3/4	s. California	2 pre-pointed 10in. scopes, 2 8in. SCTs
2019 Oct. 12	11.3	2/2	Virginia	UVA expedition with 14in. SCTs
2019 Oct. 15, 17h	11.5	2/2	Japan	Clouds at more stations that tried
2019 Oct. 15, 19h	11.1	3/3	DE, FR, Algeria	In FR, a 1m portable scope was used
2019 Oct. 25	11.3	3/3	Italy, Algeria	2 nd Phaethon occ'n for D. Baba Aissa
2020 Oct. 5	11.2	1/4	s. Mississippi	R. Venable, pre-pointed 11 & 14in SCTs

To ensure success, the first event needed a deployment across 4 States by scores of professional and amateur observers, forming a network of stations with an unprecedentedly small spacing between them. After the 2019 July 29th success, it was possible to predict the Sept. 29th event, and then each of the others, with better improvement each time as more observations were added to the orbit solutions.

“Star mag.” measures the star’s magnitude, with lower numbers for brighter stars, like rankings. The first event was visible with binoculars; all the others needed telescopes.

Positive chords recorded the occultation, while all includes negative observations; SCT= Schmidt-Cassegrain Telescope.

More about these observations is in the longer presentation I gave at the 2020 meeting of the International Occultation Timing Association. It is the 4th from the bottom, on the 2020 IOTA presentations page at:

<http://occultations.org/community/meetingsconferences/na/2020-iota-annual-meeting/presentations-at-the-2020-annual-meeting/> .

Phaethon Orbit A2 Determinations

(units $\text{au/d}^2 \times 10^{-15}$)

JPL sol. #	Value	Sigma	Value in sigma's	Basis
684	-4.84	± 1.39	3.48	MPC obs. & 2017 radar
685	-3.76	± 1.74	2.16	Adds Gaia obs.
707	-5.60	± 0.67	8.41	Adds 2019 7/29 occ'n point
712	-5.44	± 0.59	9.22	Adds 2019 7/29 & 9/29 occ'ns
718	-6.27	± 0.61	10.28	Adds the 4 2019 Oct. occ'ns
742	-5.71	± 0.87	6.56	Adds more Gaia obs. and 2020 Oct. 5 occ'n point

The A2 term for most NEO's is caused by the Yarkovsky effect, but for Phaethon, mass loss due to strong thermal heating near perihelion is likely the main driver, as evidenced by the Geminids & the Phaethon dust trail imaged by the Parker Solar Probe.

Future Phaethon Occultations

3200 Phaethon occults HIP 16761 on 2021 Nov 13 from 6h 38m to 6h 46m UT

Star:
Mag V = 8.9; B = 9.0; R = 8.8
RA = 3 35 42.0373 (astrometric)
Dec = 39 18 34.995
[of Date: 3 37 9, 39 22 56]
Prediction of 2020 Oct 17.0

Max Duration = 0.2 secs
Mag Drop = 8.4 (8.0x)
Sun : Dist = 158°
Moon: Dist = 81°
: illum = 68 %
E 0.001"x 0.001" in PA 90

Asteroid: (in DAMIT, ISAM)
Mag = 17.3
Dia = 5 ±1km, 0.005"
Parallax = 6.716"
Hourly dRA = -7.248s
dDec = -20.64"



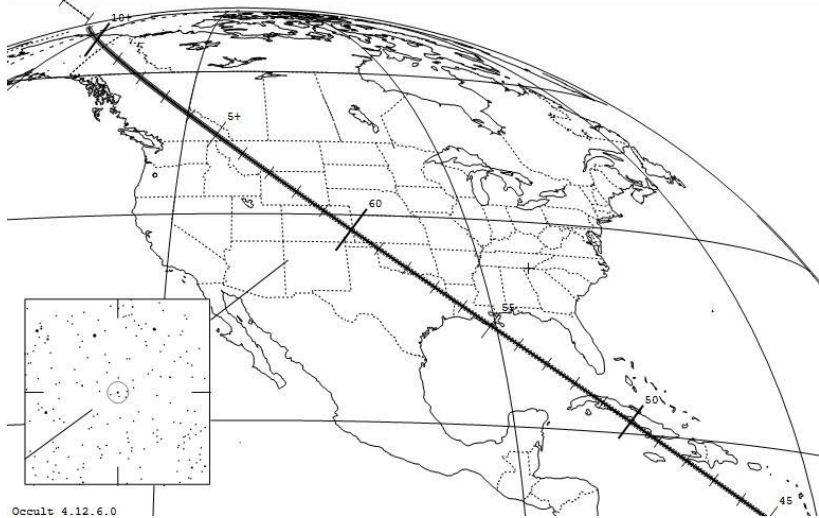
Predictions for 10 more Phaethon occultations in late 2021 are at <http://iota.jhuapl.edu/2020-2022Phaethon.htm>, including the one above.

Occultations by (99942) Apophis

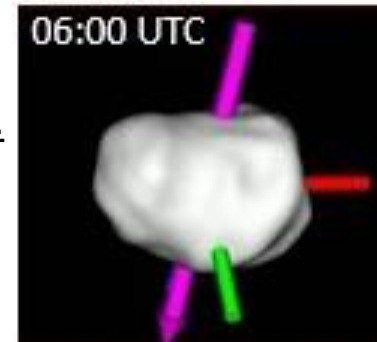
- Discovered in 2004; very close approach in 2029 identified
- Elongated object, about 350m x 170m, from 2011 radar obs.
- 2029 flyby near ring of geosats; no threat, but great sci. opp.
- But could pass through “keyhole” into a resonant orbit
- With the best orbit before 2021, small chance of 2068 impact
- If impact, total destruction to 25km; severe damage to 300 km

99942 Apophis occults HIP 45887 on 2021 Mar 7 from 5h 36m to 6h 11m UT
Star: (Dia = 0.1 mas) Max Duration = 0.07 secs Asteroid: (Dia = 0.23 ± 0.00km, 3.7 mas)
Mv 8.4; Mb 8.8; Mr 8.2 Mag Drop = 7.8 (7.6r) Mag = 16.2
RA = 9 21 22.7270 (astrometric) Sun : Dist = 150° Dia = 0.23 ± 0.00km, 3.7 mas
Dec = - 6 40 15.497 Moon: Dist = 123° Parallax = 18.031"
[of Date: 9 22 26, - 6 45 48] Hourly dRA = -10.759s
Prediction of 2021 Mar 14.0 Error 200.0R200.0 mas in PA 90° dDec = -120.07"
Reliable 1.5 (beware) JPL3/14/2021, Star+PeakEphemUncert

Paris Obs.'s Lucky Star Project found a 7th-mag. occ'n across N. America on 2021 Feb. 22, but without radar, it could not be predicted well. They found another event, star mag.8.4, with map at left, and radar data were expected a few days before. The shape model with new spin state, aspect for the event from Marina Borzovic, is at right.

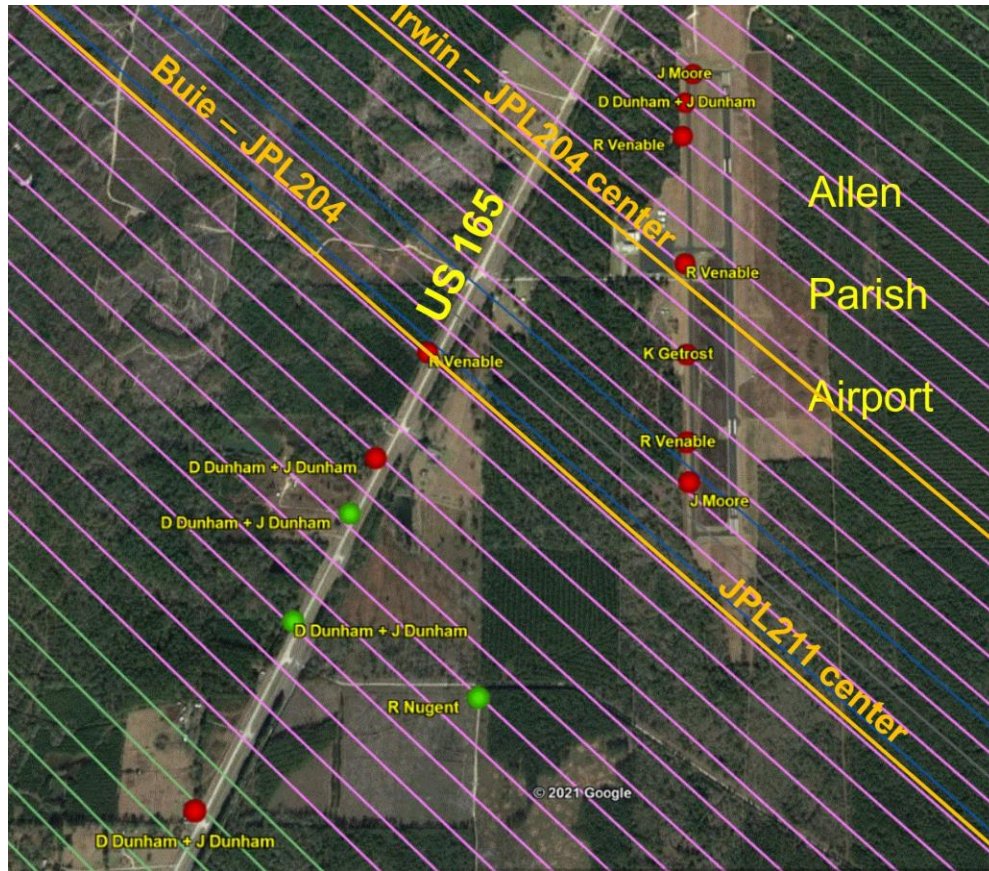


Occult 4.12.6.0



Much information about past observed Apophis occultations, and predictions for future ones, are at <http://iota.jhuapl.edu/Apophis2021.htm>.

2021 March 7 Stations near Oakdale, Louisiana



6 IOTA observers deployed telescopes at a small airport and along US 165 south of Oakdale, Louisiana. Red dots mark stations that had a miss, while 3 green dots mark 3 that recorded the occultation. The station locations were selected to be close to the diagonal tracks shown on the map, 107 meters apart as projected on the ground. They were 80 meters apart on the plane of the sky. J. Moore pre-pointed 2 systems that recorded the star, R. Venable 4, and D & J Dunham, 5, 2 of which (green dots) recorded the occultation, as did R. Nugent between them. K. Getrost recorded a miss.

Orange lines show 3 predictions, two based on JPL orbit 204 computed on March 5 refined with the radar obs. made the previous 3 nights. JPL orbit 211 shows a later prediction that should be close to where the path would have been, if the Gaia position for NY Hydrae had been correct, as noted below. Some of the lines were covered by observers in Oklahoma, Colorado, and British Columbia; their observations were all negative.

Dunham “Mighty Midi” Systems at A30 & A28



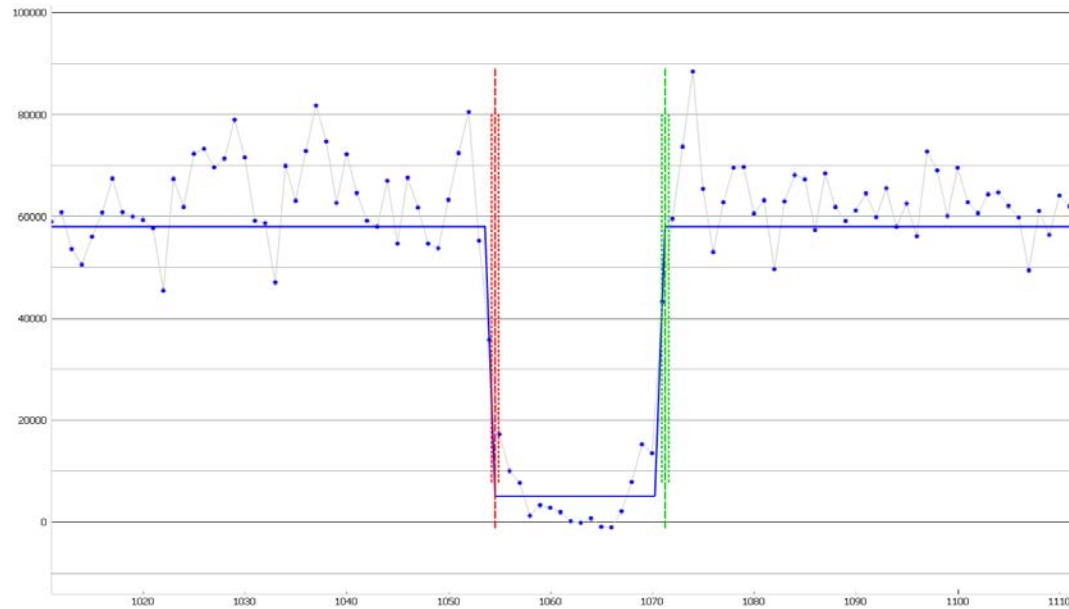
David and Joan Dunham's equipment used on line A30 (northern, left) and line A28 (southern, right). Both stations used 80mm f/5 refractors with f/0.5 focal reducers, small video cameras, an IOTA video time inserter (VTI) for accurate time-stamping of the videos with GPS 1PPS (the VTI is under the towel at A28), and iView "stick" Win10 computers to record the video. Except for the cameras, the equipment was the same at the two stations. These pictures were taken during a practice run at their home 3 nights before the occultation.

Venable's 2021 Mar. 22 stations, Yeehaw Jct., Florida



The March 7th observations were quickly analyzed to update the orbit, as 4 nights later, there was an Apophis occultation in Europe. Two observers from Thessaloniki, Greece traveled to the path predicted by the new orbit JPL207, but both had a miss. On March 22nd, an occultation of a 10.0-mag. star was predicted for the eastern USA. Some tried the event in n.e. Alabama and Illinois, where they had a miss. **R. Venable deployed 5 telescopes near Yeehaw Junction, Florida, as shown above. Only his easternmost telescope recorded the occultation.** The path between the blue lines was computed from JPL orbit 207 (updated using the March 7th observations) and used for planning. The better path between the yellow lines was computed later from JPL orbit 214a that used later occultation observations. **By spreading his scopes out enough, Venable saved Apophis' accurate orbit;** the JPL 207 error apparently was due to error in Gaia's position of NY Hya caused by its duplicity (eclipsing binary) that was occulted on Mar. 7.

2021 April 11 Apophis occultation in New Mexico



With Apophis' orbit nailed by the April 4th observations, we were able to accurately locate the three observers, each with one telescope, for the April 11th occultation of a 10.1-mag. star, so that each had occultations. Above is Kai Getrost's light curve of the occultation that was recorded with 100 frames per second from Farmington, New Mexico with a QHY 174M GPS camera attached to a 20-inch Dobsonian telescope. Effects of Fresnel diffraction are evident.

Summary of all observed positive Apophis occultations with O-C's from JPL 214a

2021 Date	mag. [1]	Loc. [2]	Total #	# pos.	$\Delta\alpha$ [3]	$\Delta\delta$ [3]	Δt [3]	RUWE [4]
March 7	8.4	LA,OK,CO,BC	29	3	-11.0	+1.2	+0.17	1.45 [5]
March 22	10.0	FL,AL,IL	9	1	+0.4	-0.5	-0.02	1.15
April 4	11.0	NM	8	3	+0.3	-0.1	-0.01	0.90
April 10	12.6	Japan	2	1?				
April 11	10.1	NM	3	3	+0.5	-0.5	-0.03	0.85

[1] This is the Gaia g magnitude of the occulted star.

[2] For location, the country is given, or 2-letter US State/Canadian Province codes.

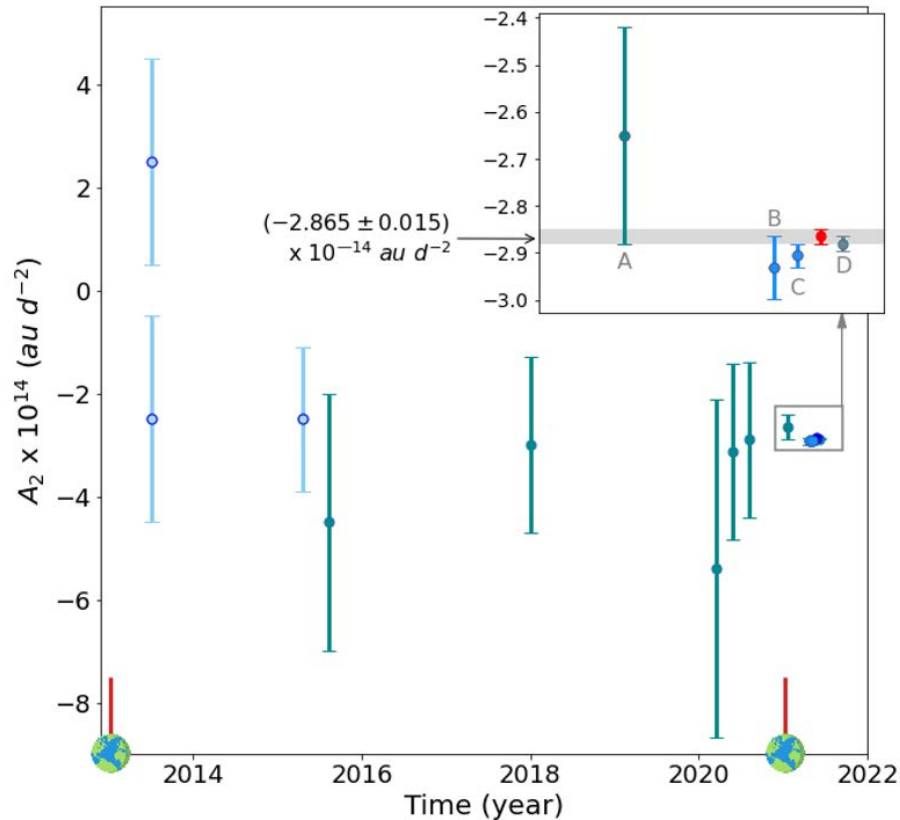
[3] The O-C residuals are relative to JPL orbit 214a, in mas, but in seconds for Δt .

[4] The RUWE is for the Gaia 3rd Early Data Release (EDR3); values >1.40 indicate stars that are likely to have positional errors larger than the formal errors from the Gaia astrometric solution.

[5] The star is NY Hydrae, an eclipsing variable with a 4.8-day period.

We believe NY Hydrae's duplicity, more than the RUWE value, is the main explanation of the large residuals on Mar. 7. Slide 17 shows the path (JPL 211, which was almost the Same as JPL 214a) that would have occurred on March 7th, if the Gaia position of NY Hydrae had NOT been in error. That threw us off after that event, causing the observers in Greece for the Mar. 11 occultation, to be in the wrong place and have a miss. Fortunately, Venable was able to spread his stations out far enough on Mar. 22 to catch that occultation (slide 19). The table shows that the residuals for March 7th stick out like a sore thumb, demonstrating the astrometric power of observations of occultations by small NEOs.

Occultations helped retire the risk of Apophis



Gaia Image of the week, 2021 Mar. 29. “Apophis’ Yarkovsky acceleration improved through stellar occultation”

Also, please see Tanga et al’s poster, “Stellar occultations by NEAs, challenges and opportunities” that notes, DART/Hera target Didymos should be next for occ’ns

Evolution in time of our knowledge of the average Yarkovsky acceleration for 99942 Apophis. The light blue data represent the early theoretical estimates from approximate models of the physical properties of Apophis¹. The other data are measurements enabled by the collection of more optical and radar astrometry. On the horizontal axis, close encounters with the Earth (enabling collection of accurate astrometry) are marked. The inset shows the last estimates compared to our value, in red, obtained from all the observations available on March 15, including the occultation observed on March 7, 2021. For more, see https://www.cosmos.esa.int/web/gaia/iow_20210329.

Predictions of future Apophis occultations

2021 Date	U.T.	mag. [1]	Location	duration, sec.	Event Notes
May 4	3.1h	8.7	cen. Chile, Baja, s. CA	0.17	[3]
May 6	3.1h	11.6	n. Chile, Sonora, s.AZ	0.16	[4]
May 20	18.0h	10.6	Oman, e. TR, e. UA	0.10	[5]
Sep. 5	1.6h	6.4	S. Sudan, Ethiopia	0.02	[6]
Sep. 27	7.7h	8.5	n. Florida, s.e. GA	0.02	[7]

[1] This is the Gaia g magnitude of the occulted star.

[2] For location, the country or its 2-letter code is given, or 2-letter US State code.

[3] The star is SAO 79801 = XZ 11903, spectral type F0. Near Borrego Springs, CA, the Sun alt. is -8° . In Chile, the path is over Santiago and Vina del Mar, star alt. 9° .

[4] On the coast south of Antofagasta, Chile, the star alt. is 9° . In southern Arizona, the Sun alt. is -11° ; the path passes over the town of Sells, & Goodyear.

[5] In eastern Turkey, the Sun alt. is -16° ; west of Kharkiv, Ukraine, it is -7° . The path is also over w. U.A.E., n. Qatar, and e. Iraq.

[6] The star is ZC 1125 = SAO 79386, spectral type F6V. The Gaia EDR3 RUWE is high, 2.5, so the path may be a few km off.

[7] The star is SAO 98045. The star altitude is 9° at the Atlantic coast.

During June, July, and August, Apophis is too close to the Sun so no observable occultations occur then. In September, the event durations become much shorter so only brighter stars have a reasonable chance to be observed with video.

Maps and path details are on the IOTA Apophis page at

<http://iota.jhuapl.edu/Apophis2021.htm>

Conclusions

- The rare bright 2019 July 29th occultation was the first successful campaign for a small NEO; it's the smallest asteroid with multiple timed chords during an occultation. One of the largest collaborations of amateur and professional astronomers for an occultation enabled this success.
- The radar size and shape were verified, and the improved orbit allowed a good prediction for the Sept. 29th occultation, then subsequent events, and an improvement of Phaethon's A2 non-gravitational parameter by a factor of 3.
- Recently, the occultation technique was successfully applied to Apophis, which is more than 10 times smaller than Phaethon, further demonstrating the astrometric power of observations of NEO occultations for planetary defense.
- Information about the sizes, shapes, rings, satellites, and even atmospheres of Kuiper Belt objects, Centaurs, Trojans, and other asteroids is proportional to the number of stations that can be deployed for occultations by them
- So we encourage as many others as possible to time occultations by TNO's and by other asteroids from their observatories
- We want students to learn to make the necessary mobile observations, including the multi-station techniques pioneered by IOTA, to observe NEO occultations; someday, one or more of them might observe an occultation that will save the world, or part of it.
- We hope that the pursuit of NEO occultations will inspire a new generation of astronomers to learn, apply, & improve the techniques for mobile occultation observation, like lunar grazing occultations did for us in the 1960's and 1970's.
- A longer more detailed version of this presentation (Power Point) is at <http://iota.jhuapl.edu/PDC2021NEOccultationsDunhamPresentationLong.pdf>

Additional Resources

- A longer and more detailed version of the Phaethon presentation is available, 4th from the bottom, on the presentations page of the 2020 IOTA meeting at: <http://occultations.org/community/meetingsconferences/na/2020-iota-annual-meeting/presentations-at-the-2020-annual-meeting/> Another interesting talk there describes a fully automatic portable system, by A. Knox, the 4th from the top.
- IOTA Apophis occultations Web page: <http://iota.jhuapl.edu/Apophis2021.htm>
- MNRAS paper about IOTA's/NASA's asteroidal occultation archive and results: <https://arxiv.org/abs/2010.06086>
- IOTA main Web site, especially the observing pages: <http://occultations.org/>
- Occult Watcher for finding asteroidal occultations for your observatory and area, and for coordinating observations: <http://www.occultwatcher.net/>
- Link to George Viscome's occultation primer: <http://occultations.org/documents/OccultationObservingPrimer.pdf>
- IOTA YouTube videos (Tutorials and notable occultations): <http://www.asteroidoccultation.com/observations/YouTubeVideos.htm>
- SwRI Lucy Mission Trojan occultations Web site (SwRI expeditions planned for many of them): <http://lucy.swri.edu/occultations.html>
- RECON TNO/Centaur occultations Web site (Mainly, w. USA events): <https://www.boulder.swri.edu/~buie/recon/reconlist.html>
- Lucky Star TNO/Centaur/Trojan occultations Web site: <https://lesia.obspm.fr/lucky-star/predictions.php>



Jet Propulsion Laboratory
California Institute of Technology

A New Method for Asteroid Impact Monitoring and Hazard Assessment

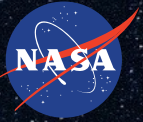
Javier Roa Vicens, Davide Farnocchia, and Steven R. Chesley

javier.roa@jpl.nasa.gov

7th IAA Planetary Defense Conference
(Virtual) April 26-30, 2021

Introduction

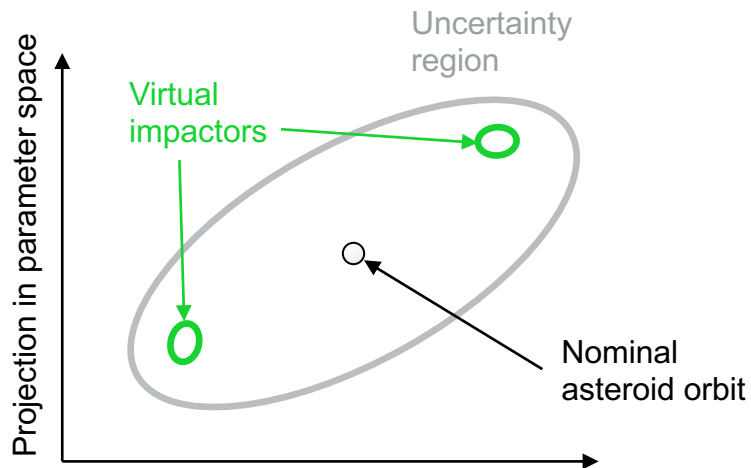
Motivation for a new impact monitoring algorithm



Goal of Impact Monitoring

Identify and characterize all virtual impactors (VIs) compatible with the orbital uncertainty distribution.

VI: region in parameter space leading to impacts along the same dynamical path.*



Challenges

1. Many VIs that must be separated.
2. Impact probabilities (IP) are usually small ($\sim 10^{-7}$).
3. Nongravitational parameters must be handled automatically.
4. Pathological cases (Earth-like orbits, nonlinearities).

• Monte Carlo:

- | | | | |
|------|------|------|------|
| 1. ✗ | 2. ✗ | 3. ✓ | 4. ✓ |
|------|------|------|------|

• Line of Variations (LOV):*

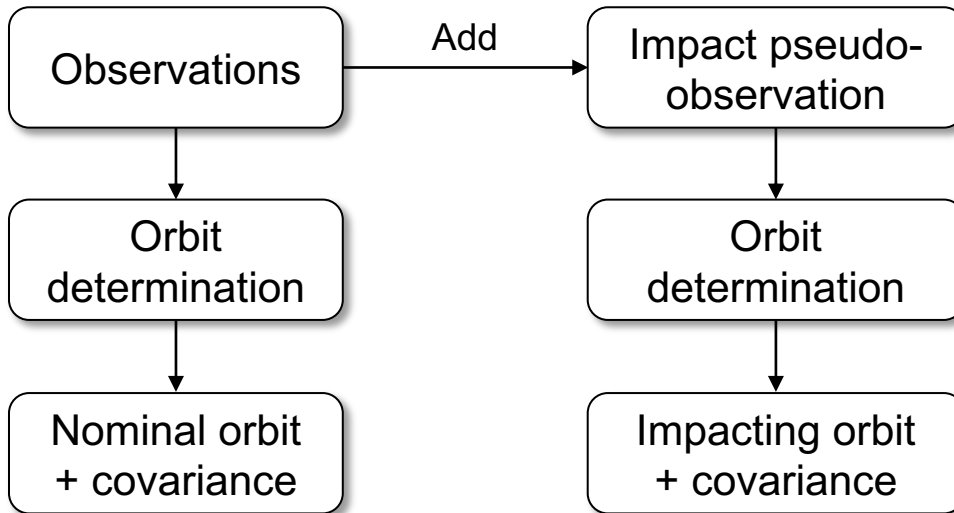
- | | | | |
|------|------|------|------|
| 1. ✓ | 2. ✓ | 3. ✗ | 4. ✗ |
|------|------|------|------|

Increased rate of NEA discoveries calls for a more robust method

*Milani, A. et al. (2005): "Nonlinear impact monitoring: line of variation searches for impactors," Icarus, 173, 362-384

Impact Pseudo-Observation I

Finding VIs using an orbit-determination program



Impact pseudo-observation

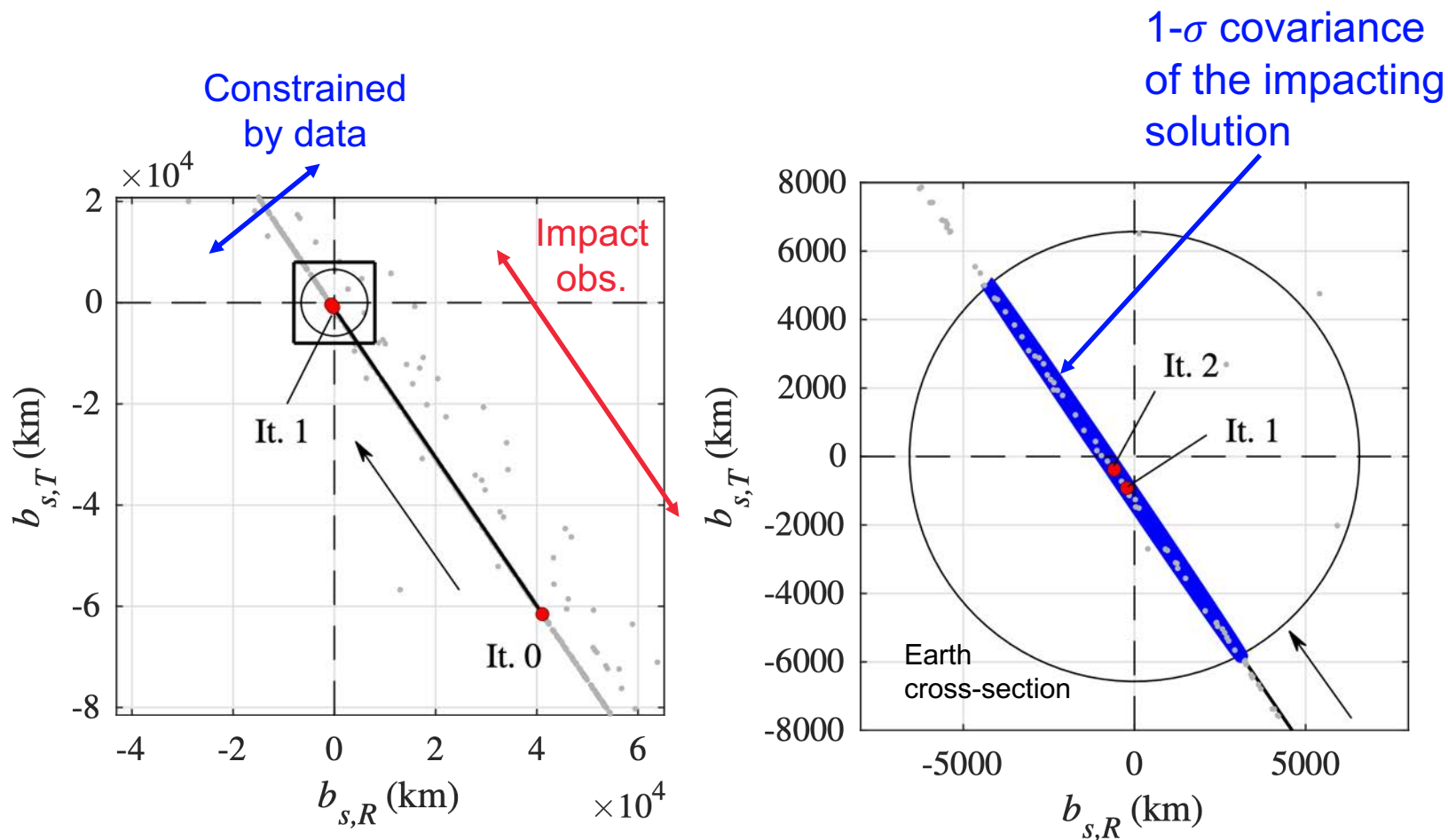
Add the impact condition as an observation:

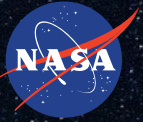
- The residuals are the B-plane coordinates at the time of close approach.
- The uncertainty is a fraction of the Earth radius.

- No simplifying assumptions about the dynamics or the uncertainty distribution in parameter space.
- The covariance of the fit approximately models the VI in parameter space.
- Use the same operational OD program used to produce the nominal orbit.

Impact Pseudo-Observation II

Finding VIs using an orbit-determination program





Operation of Sentinel

1. **Initial MC exploration:** detect close approaches for further investigation.
2. **Find VIs:** run OD filter extended with the impact pseudo-observation.
3. **Characterize the VIs:** use importance sampling to estimate the IP.

Features and Comparison with Sentry (LOV based)

- Sentinel has been running and mirroring Sentry for a few months.
- Sentinel handles nongravitational parameters systematically.
- More robust in pathological cases.
- Median runtimes for 100-year exploration and IP down to 10^{-7} :
 - Monte Carlo: 14 days (20,000 min)
 - Sentry: 20 min
 - Sentinel: 40 min
- Sentinel provides the nominal orbit and the uncertainty of each VI
⇒ useful for negative observation campaigns.



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Hosted by UNOOSA in collaboration with ESA



Q&A

Session 6b: NEO Characterization



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End of Day 2

Thank you

