THERMOPHYSICAL MODELING OF (1566) ICARUS FROM GROUND-BASED INFRARED OBSERVATIONS

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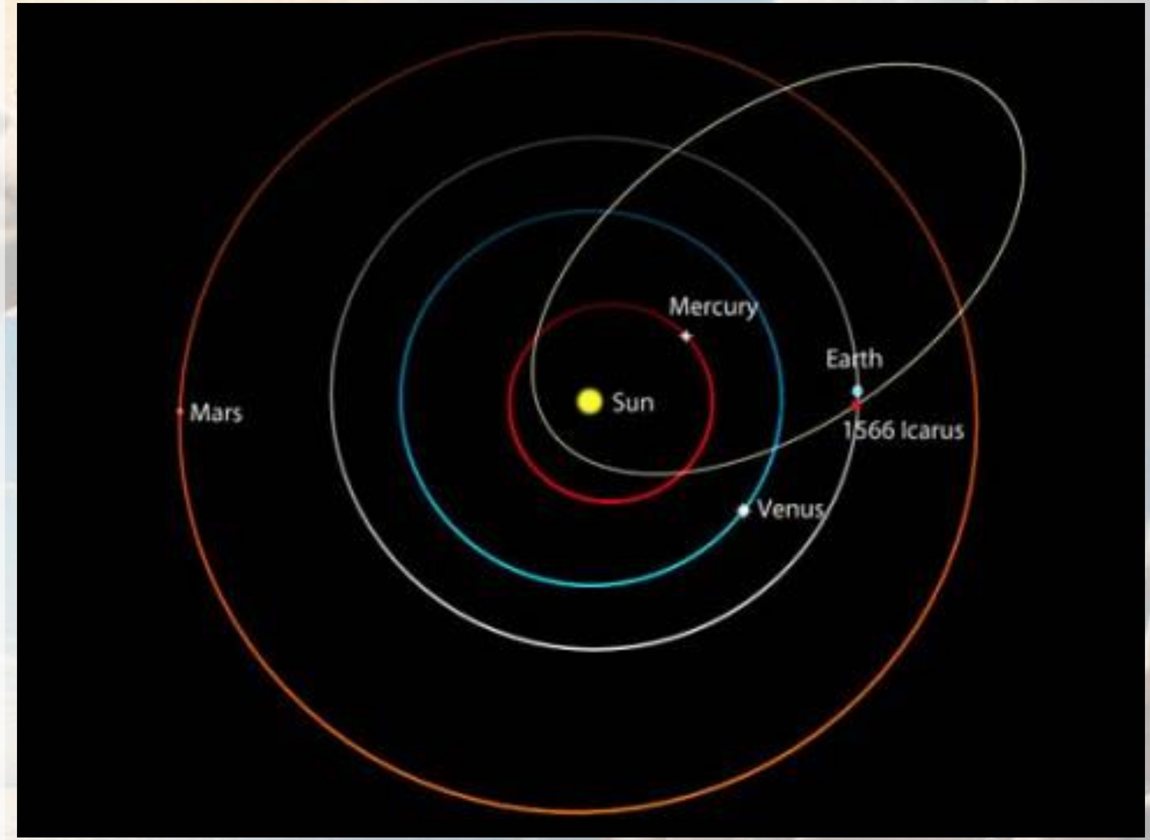
EU-ESA Workshop on Size Determination of Potentially Hazardous near-Earth Asteroids

WHY STUDY (1566) ICARUS?

- potentially hazardous NEA
  - Earth MOID = 0.0352 AU/13.7 LD
  - rare close passes to Earth (every 9, 17 yr)

- possibly linked to Taurid-Perseid meteors (Kasuga & Jewitt 2019)
  - rotational disruption? (P_{rot} = 2.27 hr)
  - near-Sun disruption? (Granvik+ 2016)
  - debris hazard to Earth?

- very low radar albedo (Greenburg+ 2017)
  - first asteroid to be observed using radar
  - low signal → no shape model
  - $D_{eff} = 1.44 \pm 0.26$ km
  - uncertain spin orientation, ***H*** mag, albedo



credit: Sky & Telescope

TALK OUTLINE:

1. shape modeling & TPM from space-based observations
    - results overview
2. ground-based IRTF/MIRSI observations
    - 2024 observations (close flyby with Earth)
    - reduction steps
3. size determination
    - surface temperature modeling
    - observational effects
4. albedo estimation (future work & theoretical)
    - visible photometry & absolute magnitude
    - polarimetry
    - multi-epoch near-infrared photometry

Shape Modeling & TPM

<u>Photometric Dataset:</u>

- 42 lightcurves from 1968, 2015 (LCDB)
- 5 *Gaia* DR3 datapoints

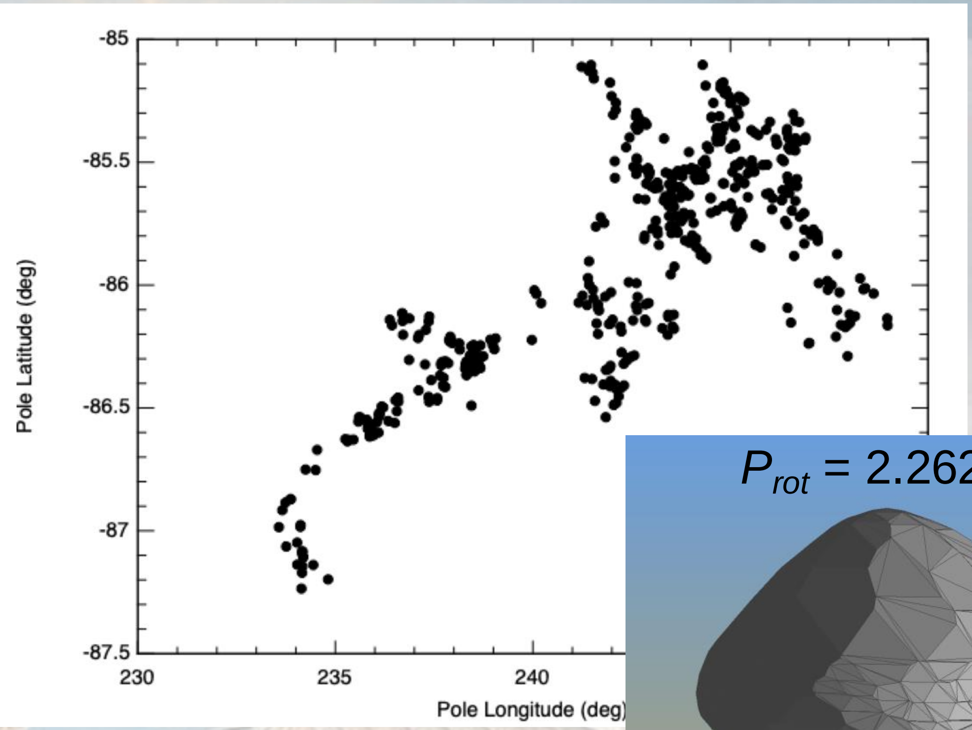
lightcurve inversion w. MCMC →
(Muinonen+ 2020)

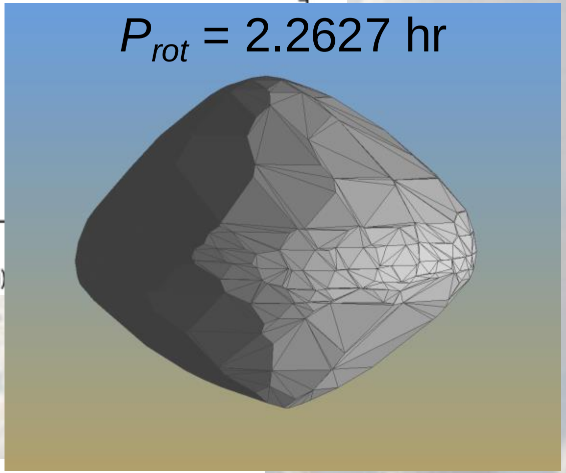
<u>IR Dataset:</u>

- NEOWISE W1 & W2: 3.35 μm, 4.60 μm
  2010, 2014, 2020
- Spitzer CH1 & CH2: 3.55 μm, 4.49 μm →
  (IRAC) 2014, 2017

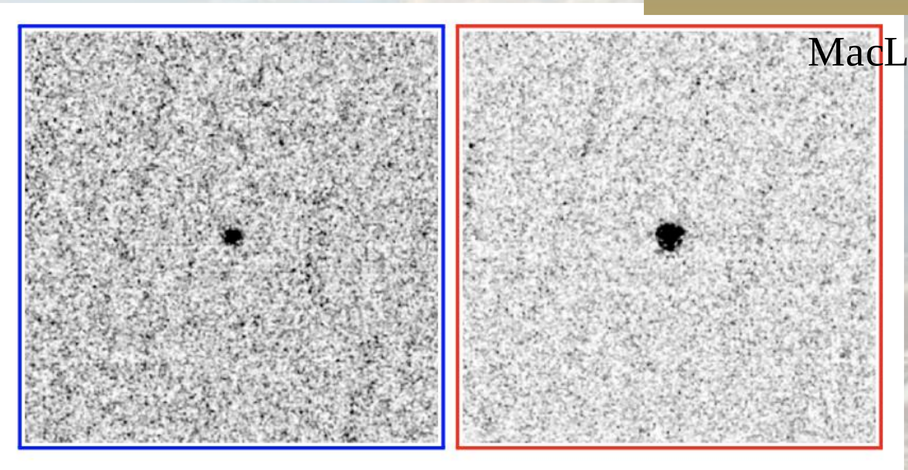
<u>Thermophysical Model (TPM):</u>

- MacLennan & Emery (2019, 2021)
- use the set of spins and shapes with TPM



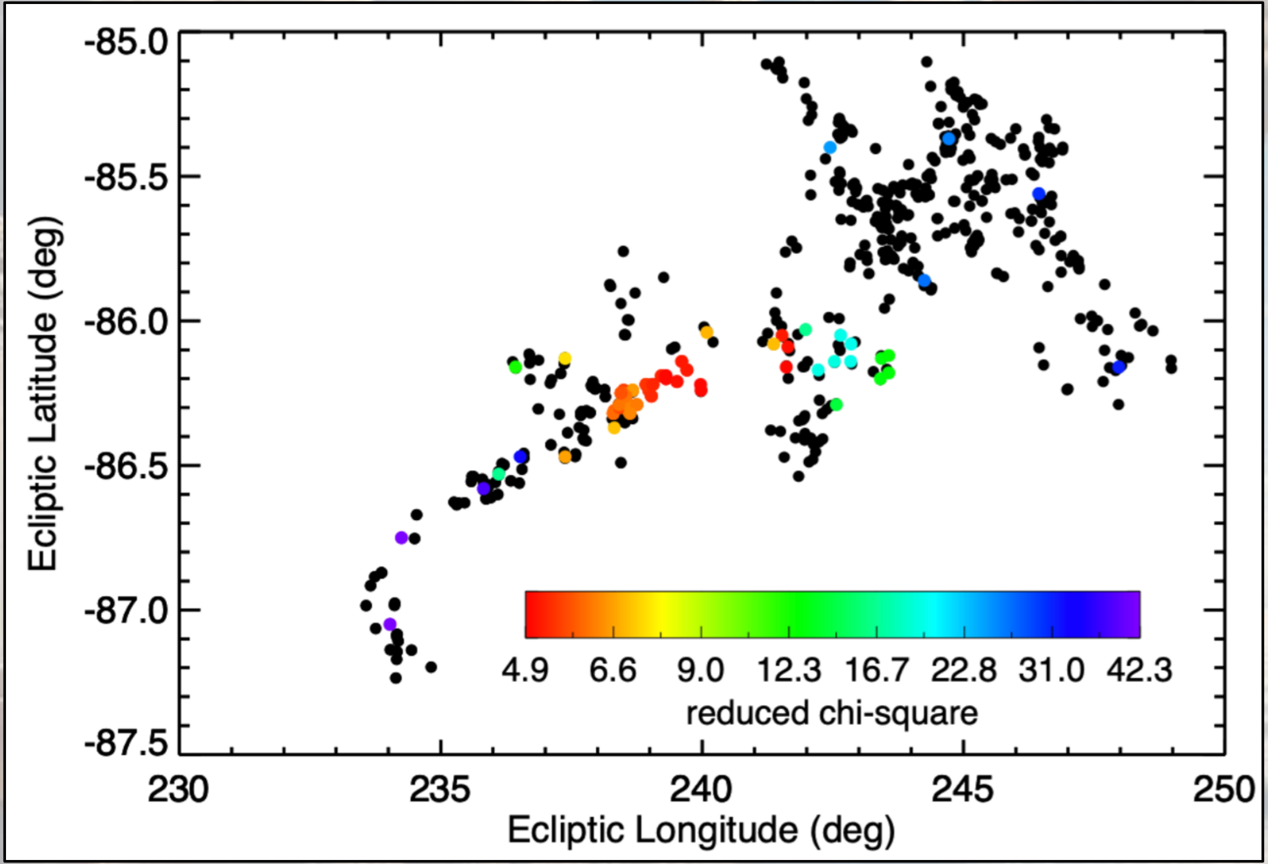


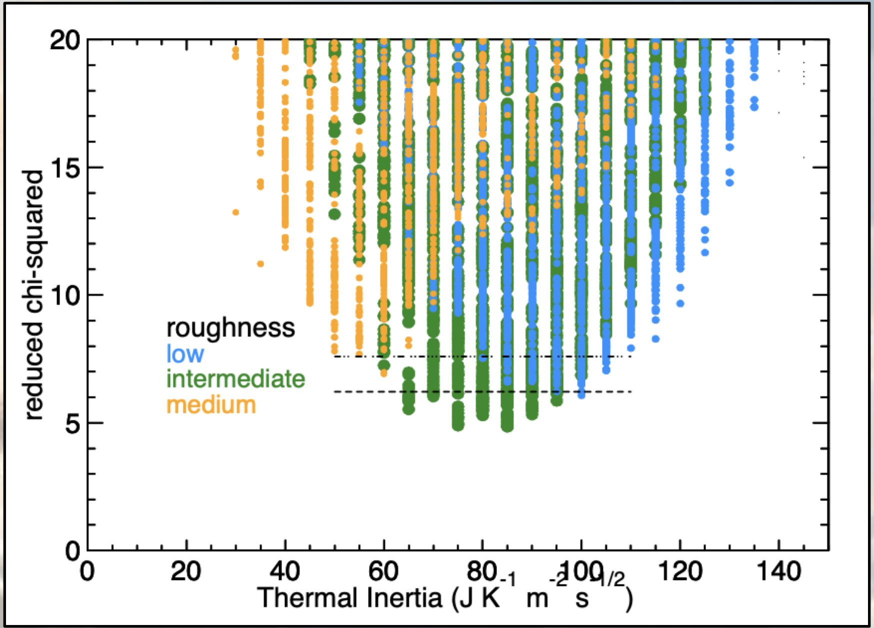
MacLennan+ in prep

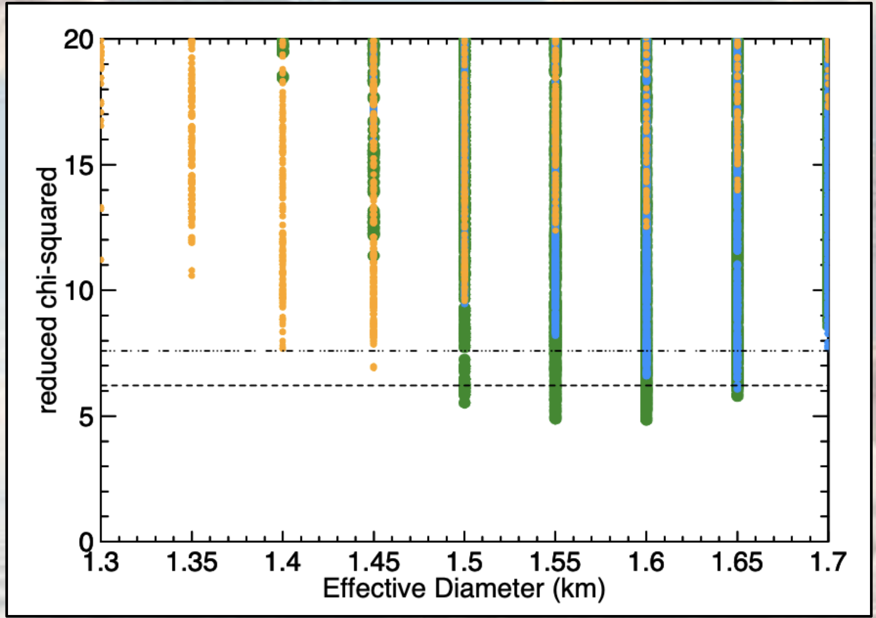


SHAPE MODELING & TPM

$D_{eff} = 1.57 \pm 0.1$ km
low thermal inertia (lunar-like)
moderate roughness
improved spin constraint







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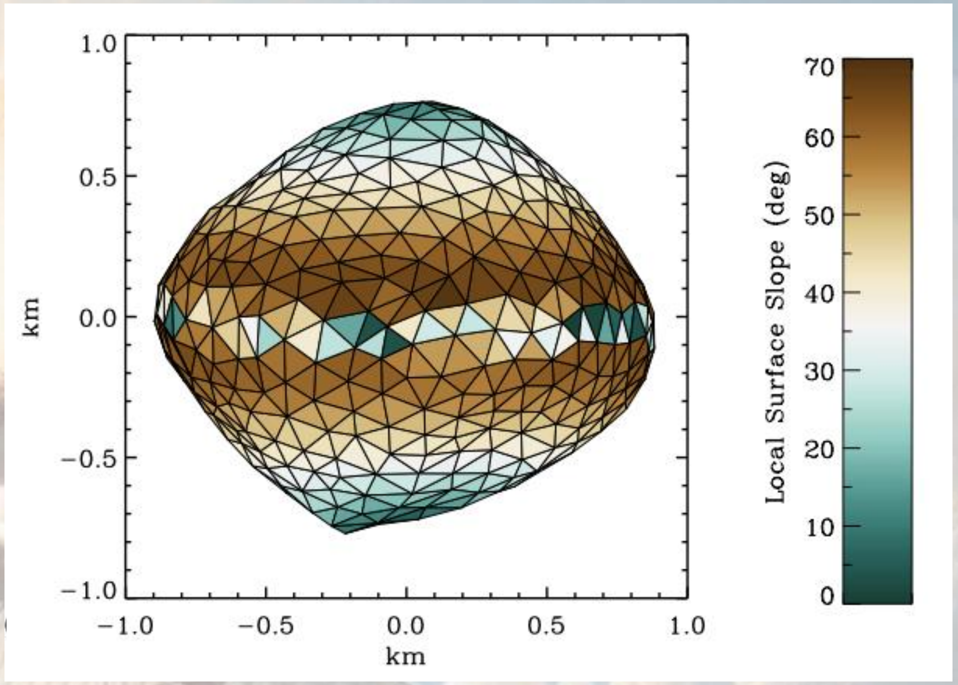
SHAPE MODELING & TPM

- bulk density from Yarkovsky drift modeling
  - Greenberg+ (2017)

- surface slopes approach 70º
  - 0º = net force is downwards
  - 90º = perpendicular to local surface

- risk of landslides & centrifugal ejection?
  - possible explanation for meteor shower link

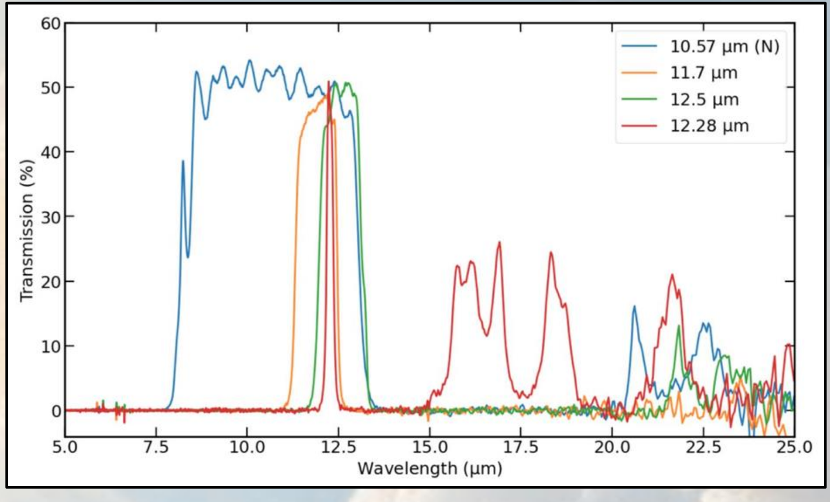


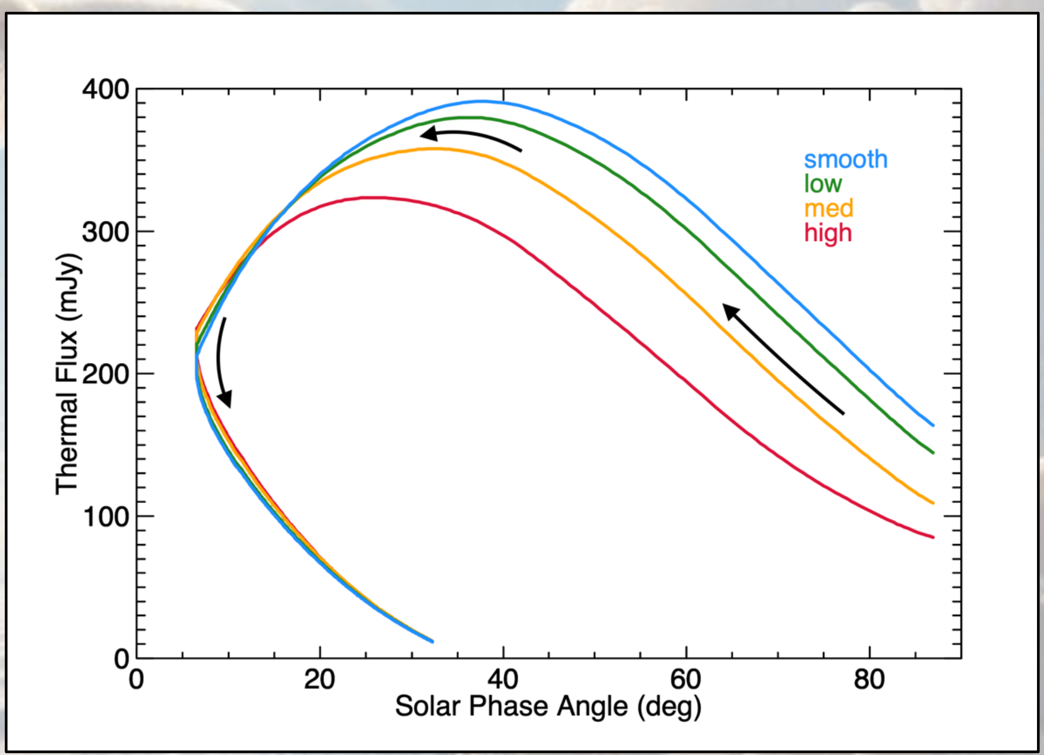
MacLennan+ in prep

- June 2024: Icarus makes a rare ”close” 0.21 AU flyby with Earth
- opportunity to conduct a multi-instrument observing campaign
  - ground-based infrared, near-infrared spectra, visible polarimetry, and photometry were acquired

NASA IRTF Observation Planning

- MIRSI: Mid-Infrared Spectrometer and Imager
  - NEA thermal emission peaks around 10 micron (N-band)
- objects brighter than ~1-2 Jy are most easily detected in sky subtracted pairs
  - multi-wavelength observations possible with narrow filters
- fainter than 1 Jy should be visually bright enough to guide using the MIRSI Optical Camera (MOC)
  - Icarus' N-band fluxes: 200 – 400 mJy
  - V-band: 15th to 16th mag





MIRSI/MOC OBSERVATIONS

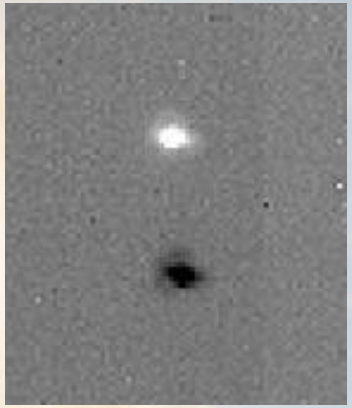
- the sky has STRONG thermal emission
  - take short (0.01 sec) exposures
  - co-add hundreds of images

- nod telescope to acquire A-B pairs
  - top left shows a sky-subtracted pair
  - top right shows the stacked pair

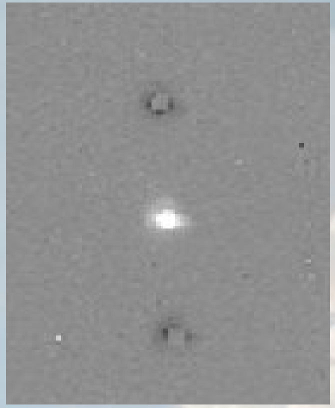
- dither the target across the detector
  - Icarus’ sky motion was 7-9”/minute
  - guide with MOC (bottom) to ensure the target is positioned correctly on the detector

- Hora+ 2024 describes the basic operation and data reduction steps

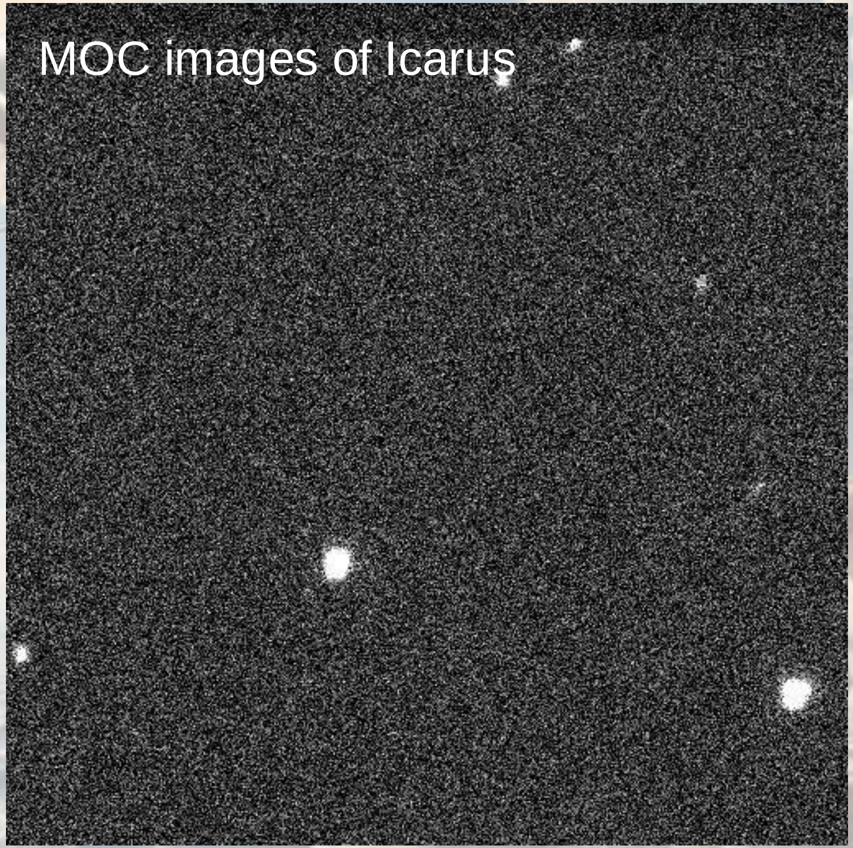
Vega



subtracted pair



stacked pair



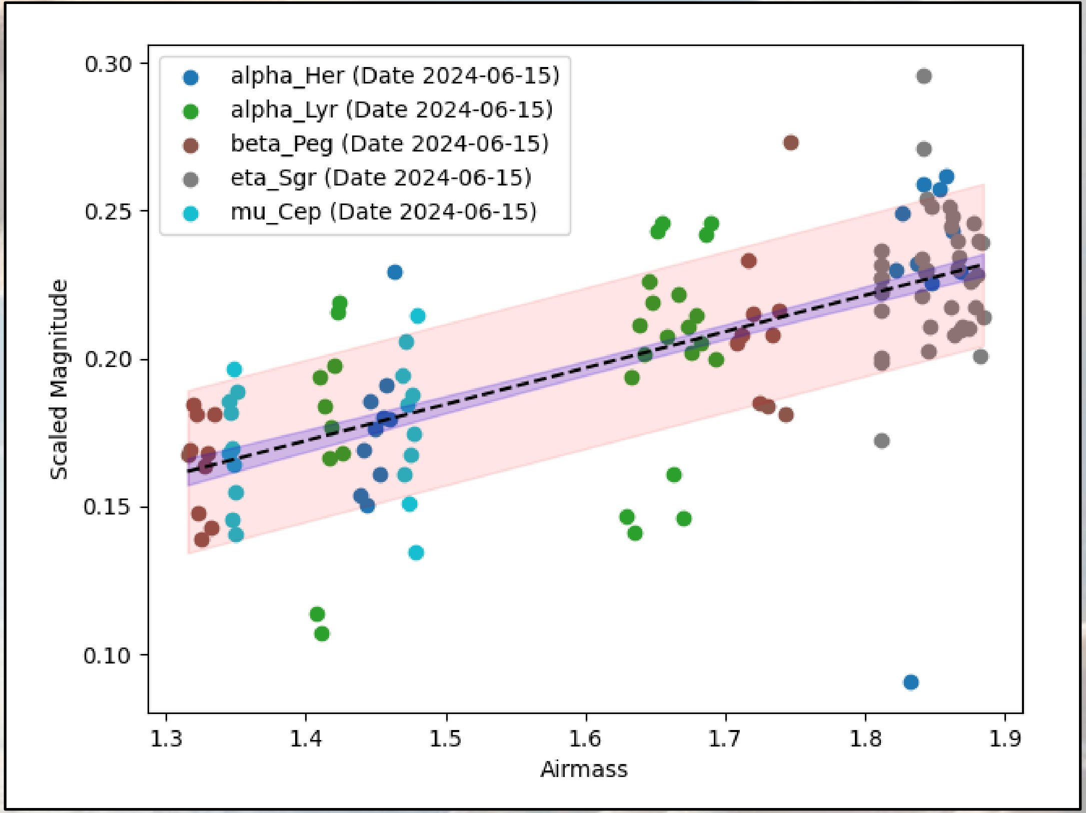
MIRSI Star Reduction & Calibration

- stars are bright enough to be detected in sky subtracted A-B pairs

1. create image mosaics from A-B pairs and extract counts in circular aperture

2. derive magnitude extinction factors for absolute flux calibration
   - fit a constant slope (e.g. 0.1 mag/airmass) for all stars (2 per night is enough)
   - critical for *high airmass* observations
   - can vary up to a factor of 2 across different nights!

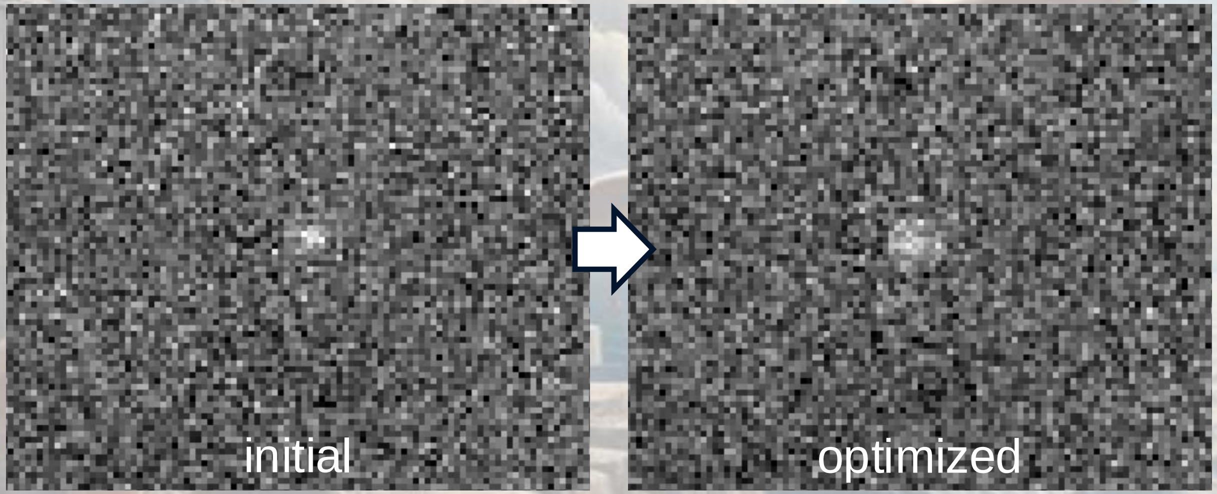
1. typical 1σ uncertainties are 0.02 to 0.04 mag

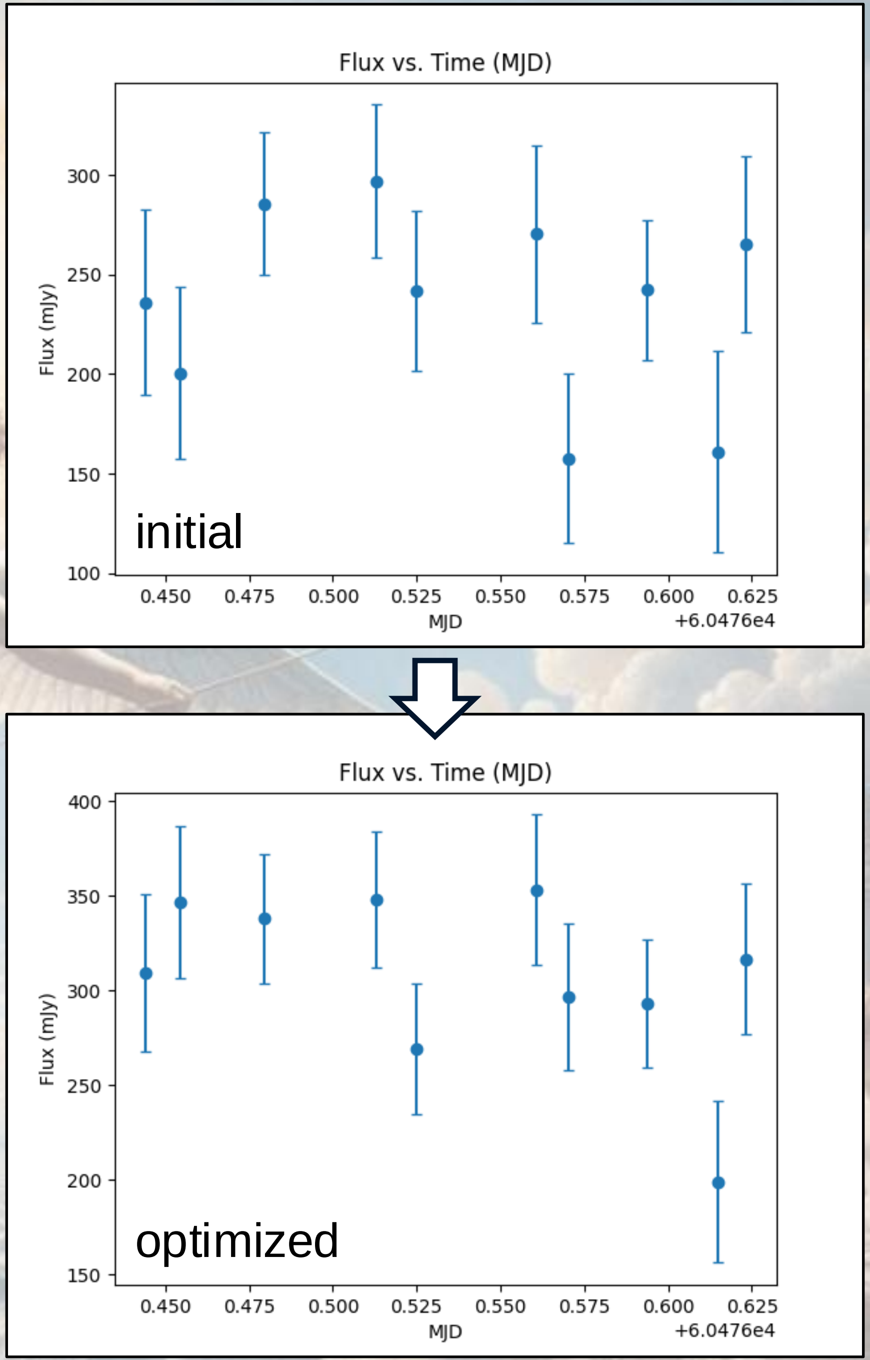


MIRSI Asteroid Reduction

- use telescope offsets for initial alignment and blind stacking

- search for optimal image shifts to maximize signal in a small aperture
  - requires lots of computation
    significant increase in ADU counts!!
    50 mJy difference



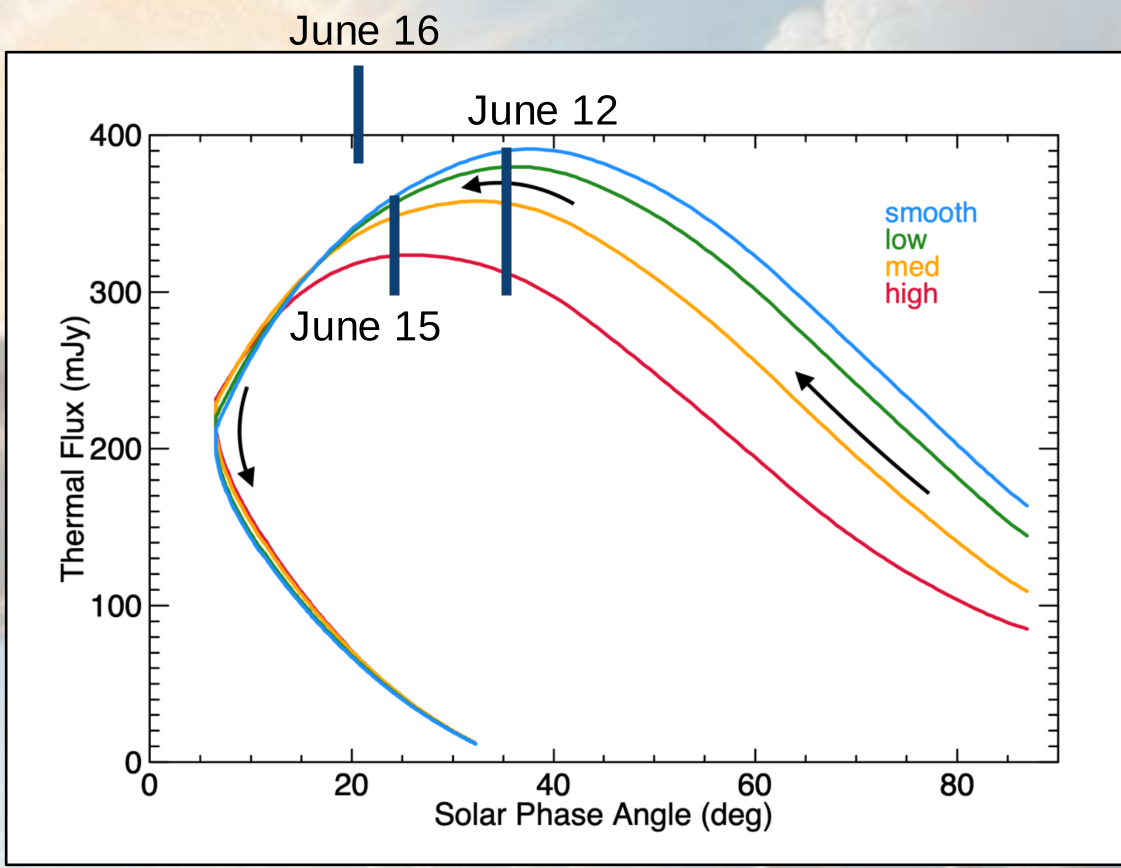


Size Estimation

- MIRSI fluxes are consistent with predicted fluxes from space-based results
  - except! for June 16 (highest airmass)

- 30 mJy for 300 mJy source uncertainty corresponds to ~10% size uncertainty
  - without proper stacking, the size estimate would be ~25% smaller

- Icarus' ***H*** and ***p*** estimates are uncertain
  - *rarely* observed near opposition
  - similar situation to other PHAs!!!



Albedo Determination

- Bond albedo, ***A***
  - used in thermal modeling to compute the total amount of absorbed solar radiation

- geometric albedo, ***p***
  - calculated using modeled brightness at zero phase angle
  - defined for a spherical object

- single-scattering albedo, ***w***
  - proportion of incident light scattered
  - more flexible: can use any phase angle

Albedos from Optical Photometry & Size

- simultaneous *r'*-band photometry using the \`Opihi 17" telescope on the IRTF
  - large f.o.v. (0.54 deg^2)
  - opihi exp. time < mirsi exp. time

1. compute phase function parameters
   - use absolute magnitude (*H*) with size estimation from thermal IR → ***p***

2. given the size, model the brightness at some phase angle → ***w***
   - can use shape model or sphere
   - better for sparse, high phase angle observations (uncertain *H* magnitude)

- ***A*** can be calculated from ***w*** and ***p***


Credit: NASA IRTF

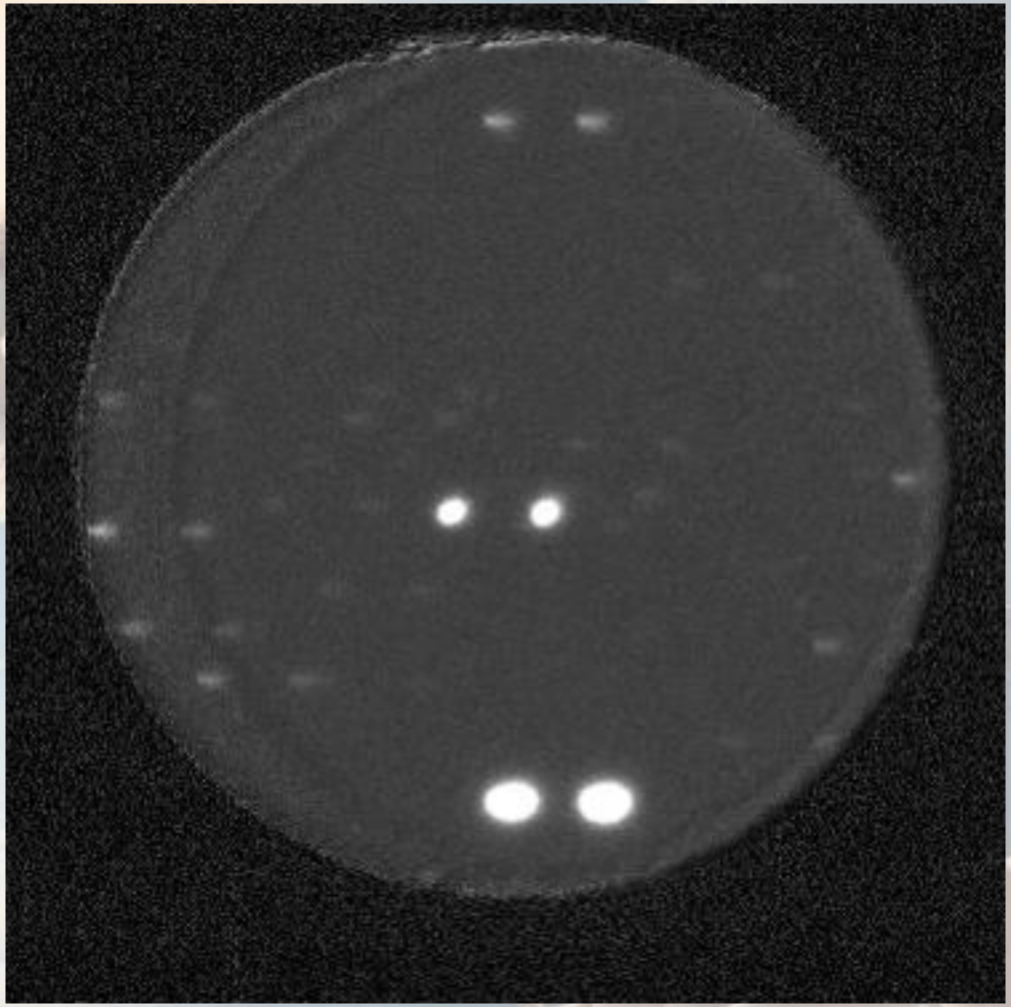
ALBEDOS FROM POLARIMETRY

- empirical relationship between polarimetric parameter(s) and asteroid geometric albedos
  - P_{max}, P_{min}, h (slope)
    vs.
  - Bond albedo, ***A***
  - geometric albedo, ***p***
  - single-scattering albedo, ***w***

- typical ***p*** uncertaintaies are 20% or larger from size & absolute magnitude relationship

- upcoming work will esimate and compare the albedo of Icarus to its polarization properties

Icarus: June, 15 2024 (NOT-ALFOSC)

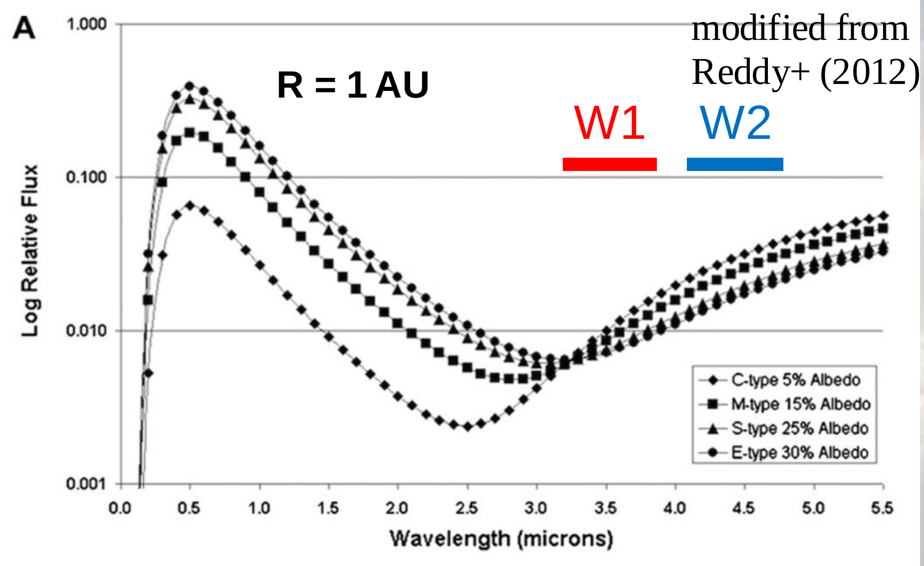


ALBEDOS FROM NEAR-INFRARED PHOTOMETRY?

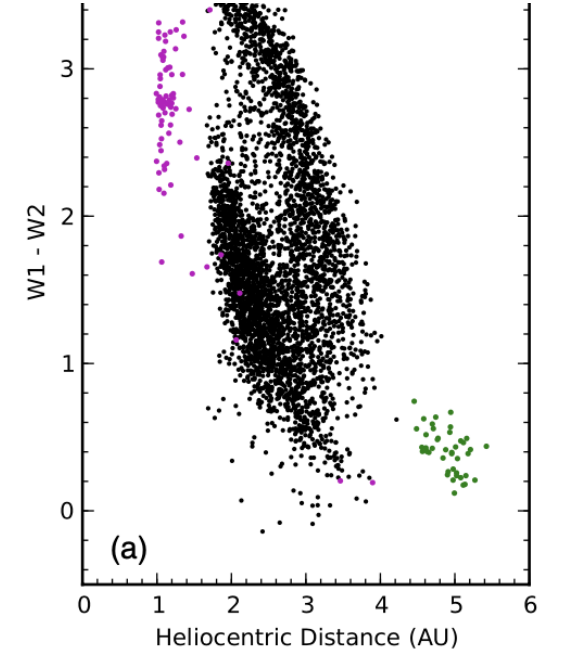
- *thermal excess* at longer spectral wavelengths (Reddy et al. 2012) gives ***A*** to high precision
    - compare to that of ***p*** from the size & ***H***

- near IR multi-photometric thermal contribution is sensitive to albedo
    - thermal / (thermal + reflected) changes with heliocentric distance (R_{au})
    - size independent
    - WISE W1-W2 shows albedo clusters →
    - roughness, thermal inertia, shape may have notable effects in some cases

- size can be calculated from albedo and ***H***



modified from Reddy+ (2012)



Masiero+ (2011)

SUMMARY & DISCUSSION

- ground-based thermal IR observations with MIRSI camera are possible for small PHAs
  - detection of Icarus (~1.4 km) from 0.21 – 0.23 AU from Earth
  - proper calibration and analysis is critical to accurate flux estimation
  - comparable size accuracy to space-based observations

- Icarus and other PHAs will rarely be observed near opposition
  - albedo could be calculated using the size and the brightness at any phase angle
  - consider other brightness conventions, e.g. $V(\alpha = 30^{o})$ for size estimation?

- how can albedo estimates be improved?
  - improvement in albedo precision and relationship(s) to polarization parameters
  - possible to use near-infrared fluxes to estimate Bond albedos?
  - 10+ years of NEOWISE W1 & W2 data

THANK YOU!