High Phase Angle Observations of Uranus from New Horizons: Implications for Future Direct Imaging Observations

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1. Introduction

- Ice giant-sized exoplanets are among the most abundant planets to exist around other stars [1]

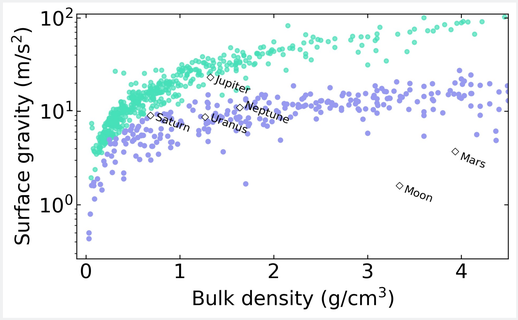

Fig. 1. Bulk density vs. surface gravity for a subset of exoplanets with mass and radius constraints from the Exoplanet Archive [2]. Uranus and Neptune lie in a distinct group of exoplanets (green) that differ from the gas giant planets (purple).

- Future direct imaging missions will enable the detection and characterization of cool and warm ice giant-sized planets, alongside terrestrial planets [3]
- Directly-imaged planets will have high phase angles due to observational and instrumental constraints
- "Ground-truth" observations of Solar System planets will provide a baseline for interpreting exoplanet data and testing atmospheric models
- New Horizons observed the ice giants in September 2023 at high phase in four color filters (Blue, Red, NIR, CH_4)

2. Observations

- 6 scans over 1 rotation of Uranus
- Phase angle (α): 43.9°
- Target-spacecraft distance: 69.5 AU
- Complementary low-phase observations from HST and ground-based community observers

MVIC Filter	Bandpass (nm)
Blue	400-550
Red	540-700
Near-IR	780-975
CH_4	860-910

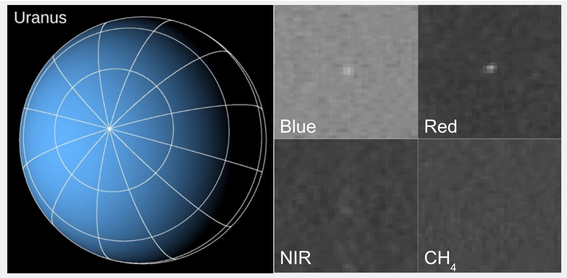

Fig. 2. Left: Orientation of Uranus as seen from NH in 2023. Right: 2023 MVIC frames centered on detections or non-detections of Uranus in the Blue, Red, NIR, and CH_4 filters.

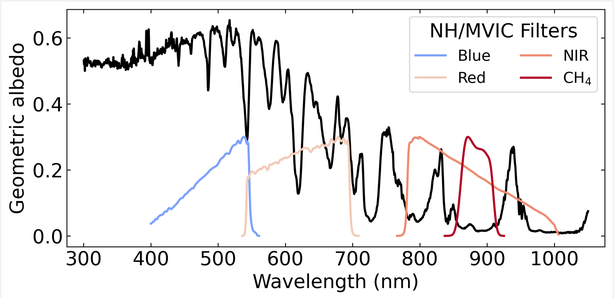

Fig. 3. Geometric albedo spectrum of Uranus from [4] against the NH/MVIC color filters. Filters are normalized to a max of 0.3 for display purposes.

3. Data Reduction & Analysis

- We performed aperture photometry using the `photutils.aperture_photometry` routine
- We assume dominant noise sources to be Poisson noise and read noise
- We calculated Uranus's expected and observed contrast by calculating the reflectance (I/F) as observed by NH and then the planet-star contrast ratio

$$F = \frac{c}{P_{\mathrm{Uranus}}} \longrightarrow \mathrm{I} = \frac{F}{A_{pix}} \longrightarrow \frac{\mathrm{I}}{F} = \frac{\pi I r^2}{F_\odot}$$

$$\frac{F_p}{F_s} = \frac{I}{F}\left(\frac{R_p}{r}\right)^2 \Phi(\alpha)$$

where c is the count rate, P_{Uranus} is an MVIC calibration-dependent keyword, and A_{pix} is the area of Uranus in pixels

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4. Preliminary Results

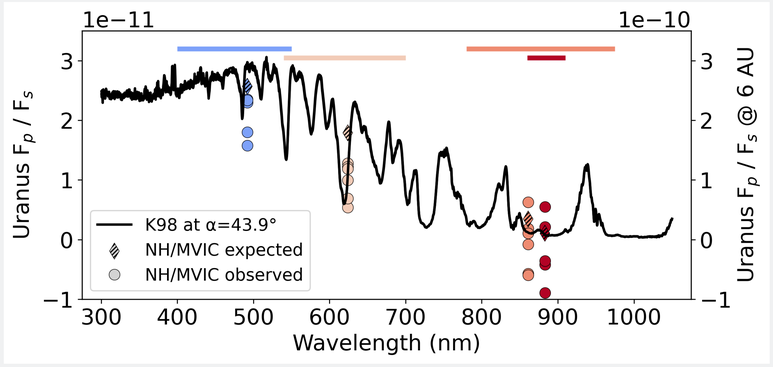

Fig. 4. Flux ratio of Uranus at α=43.9° (black) converted from the geometric albedo spectrum in [4] using a Lambertian phase function. NH/MVIC observations are shown with colored circles. Expected NH/MVIC points are shown with diamonds, calculated by convolving the spectrum with the MVIC filters. The contrast ratio for a Uranus-like planet at a closer-in planet-star separation of 6 AU is shown on the right axis. NH/MVIC bandwidths are indicated with horizontal bars.

5. Implications and Future Work

- Observations of Uranus at α=43.9° suggest deviation from a flux ratio calculated assuming a Lambertian phase function
- Uranus-like exoplanets may be dimmer than predicted at moderate phase angles
- Previous work indicates the Solar System planets deviate from a simple Lambertian phase function assumption [e.g., 7,8], and will likely be true for directly imaged exoplanets
- Future work:
  - Compare phase curves of Uranus across all phase angle observations to model albedo spectra; assess variation as a function of phase angle
  - Repeat with Neptune data
  - Provide constraints on detectability for direct imaging missions

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