A Scatter of Light from Polarized Worlds

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Class of 2011-2014

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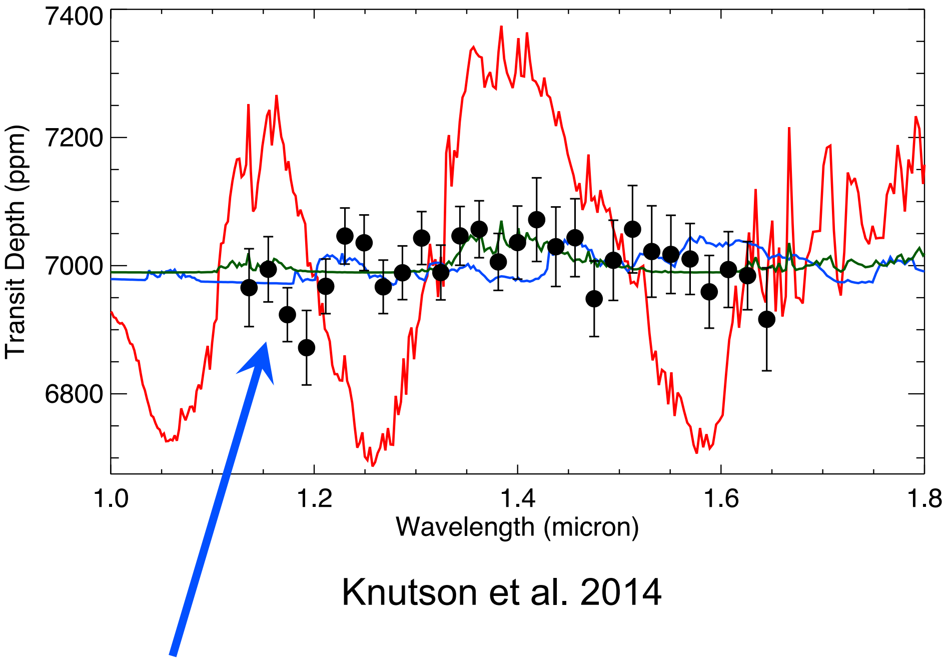
Exoplanet Science Must Diversify Techniques

Searching for keys under a lamppost

- Follow-up transmission spectroscopy and occultation photometry require transits due to calibration limitations (except for Birkby, imaging folks et al.)
- Only 9 / 65 close-in, RV-discovered planets transit (for a(1-e) < 0.075)
- CoRoT, HAT(S), Kepler, K2, KELT, MEarth, OGLE, PH, Qatar, (TESS), TRAPPIST, TrES, WASP, WTS, and XO planets increase the sample



Knutson et al. 2014

- But many exoplanets have flat transmission spectra from hazes or clouds
- Will have to vet these planets so JWST time is not wasted
- Difficult to identify specific absorber properties with existing techniques

➢ Main follow-up techniques can only study the select few planets with clear atmospheres in transiting geometries

After all this effort to find planets we can study, many will still be inaccessible to JWST

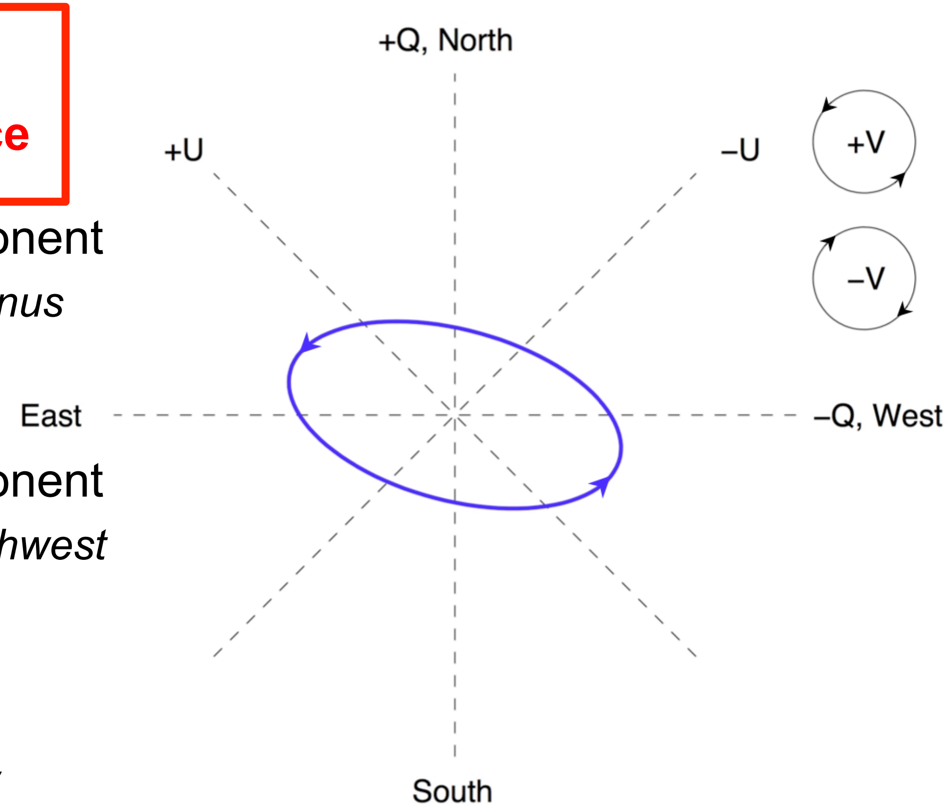
Polarization: Quadruple Your Information

Turn a scalar into a four-vector

1) Photometry
   - *Photon counting*
   - *“Stokes I”*

Nearly all exoplanet science

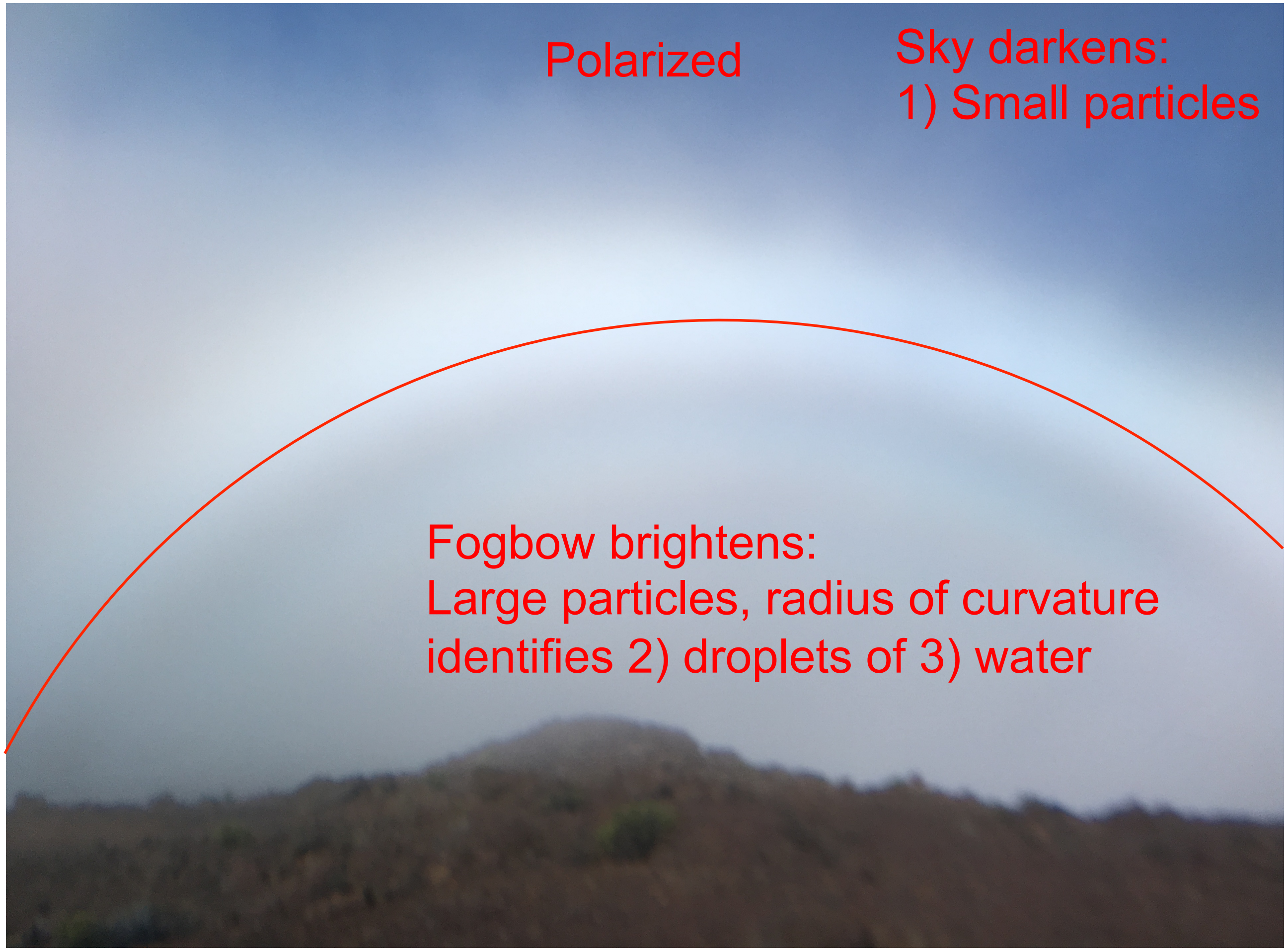
2) Linear Polarization “x” vector component
   - *Component of E field North / South minus East / West*
   - *“Stokes Q”*
3) Linear Polarization “y” vector component
   - *Component of E field Northeast / Southwest minus Northwest / Southeast*
   - *“Stokes U”*
4) Circular Polarization
   - *Component of E field CCW minus CW*
   - *“Stokes V”*
   - *Not relevant for exoplanets, but it identifies metallic regions on asteroids*



Polarimetry: measurement of the full electric field state of light

Polarization Ideal for Particulates

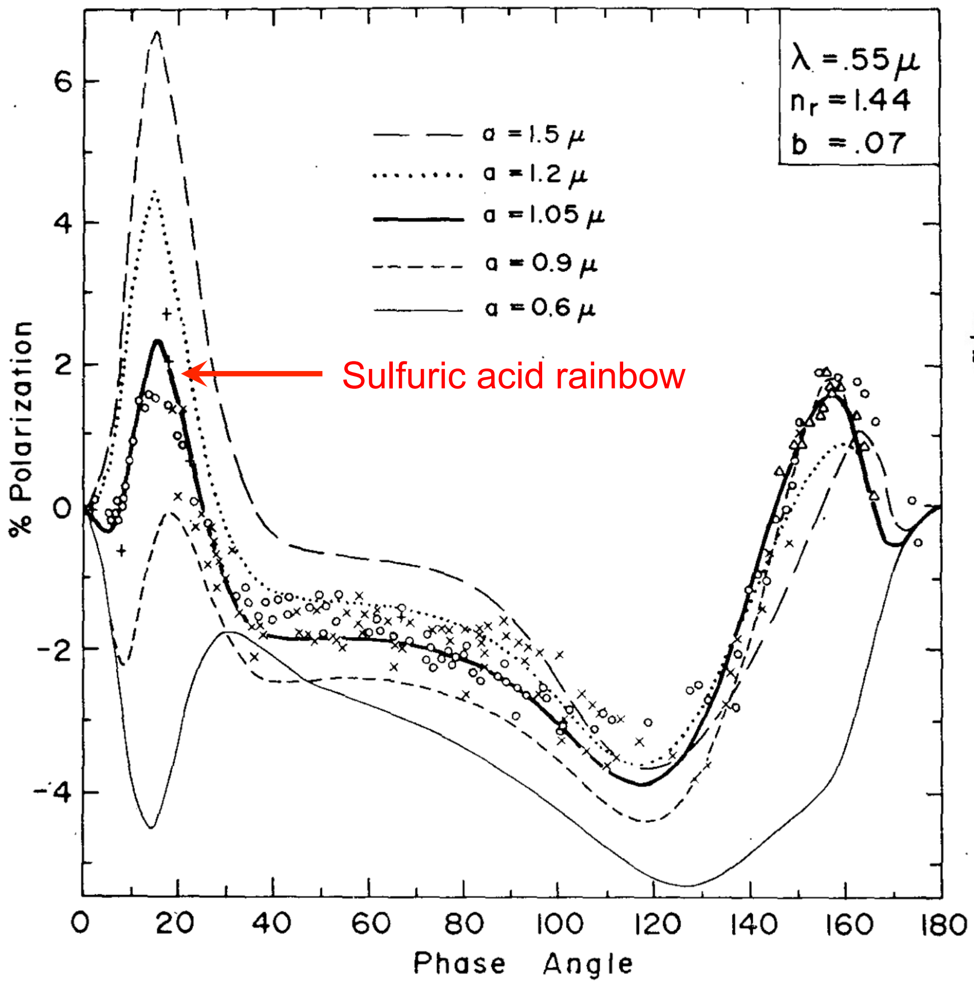
Polarized fogbow, Haleakala

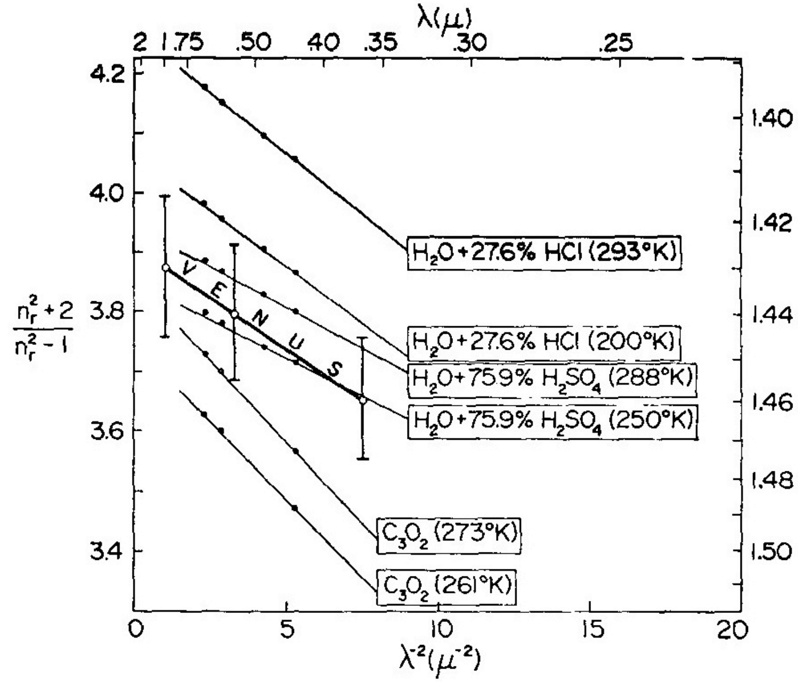


Polarimetry identifies gas molecules vs. fractal hazes vs. cloud particles

Discovery of Venus' Sulfuric Acid Clouds

Polarization encodes particle size, shape, index of refraction

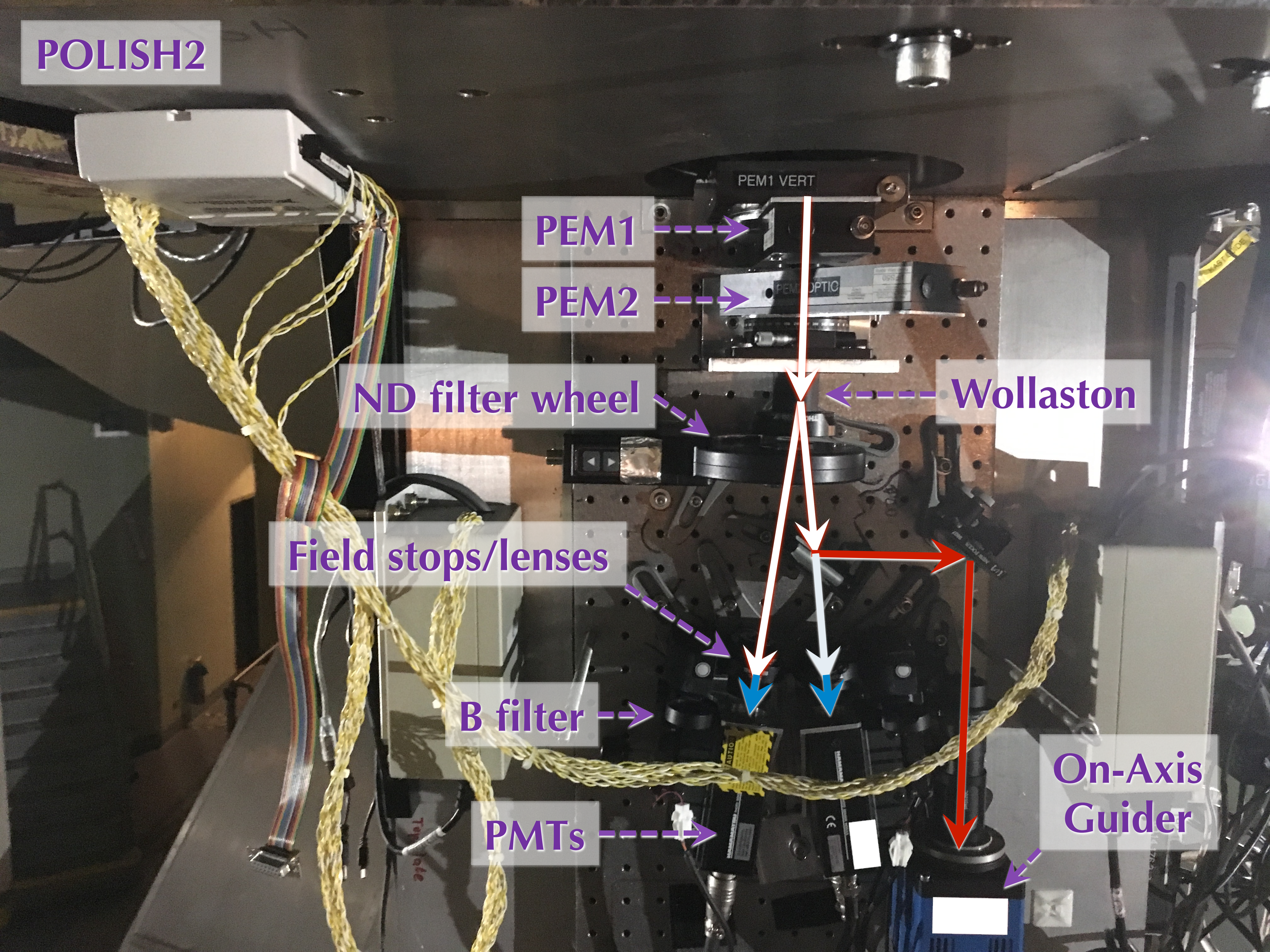




Data: Lyot 1929 (!)

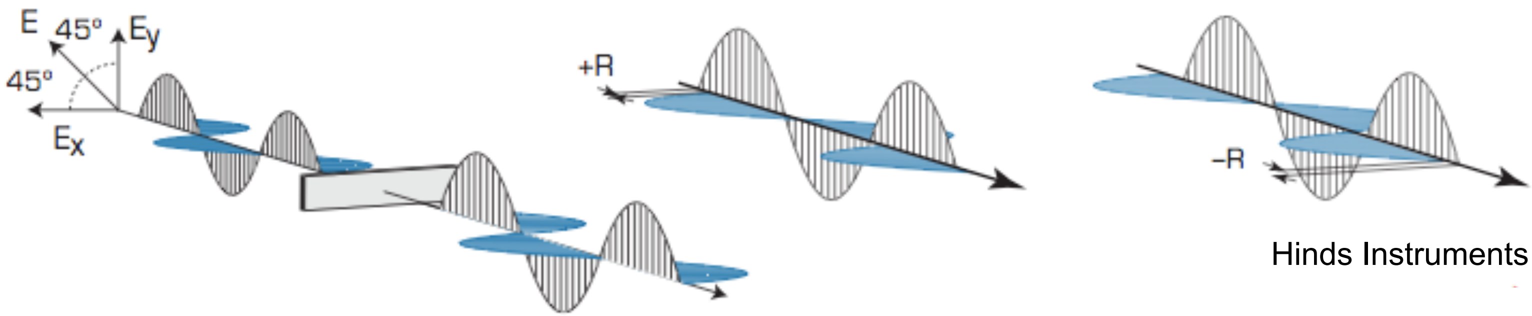
Models: Coffeen & Gehrels 1969;
Hansen & Hovenier 1974

Rainbows are polarized, and their geometry is caused by particle composition

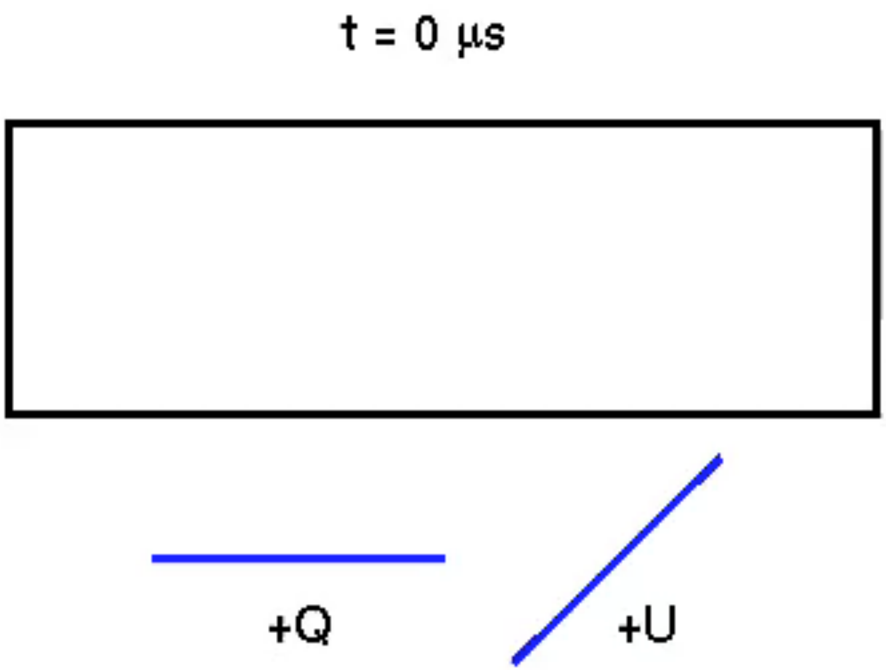

POLISH2
PEM1 VERT
PEM1
PEM2
ND filter wheel
Wollaston
Field stops/lenses
B filter
PMTs
On-Axis Guider

Photoelastic Modulators Enable 1 ppm Accuracy

Waveplates, FLCs limited to 10-100 ppm accuracy



Hinds Instruments

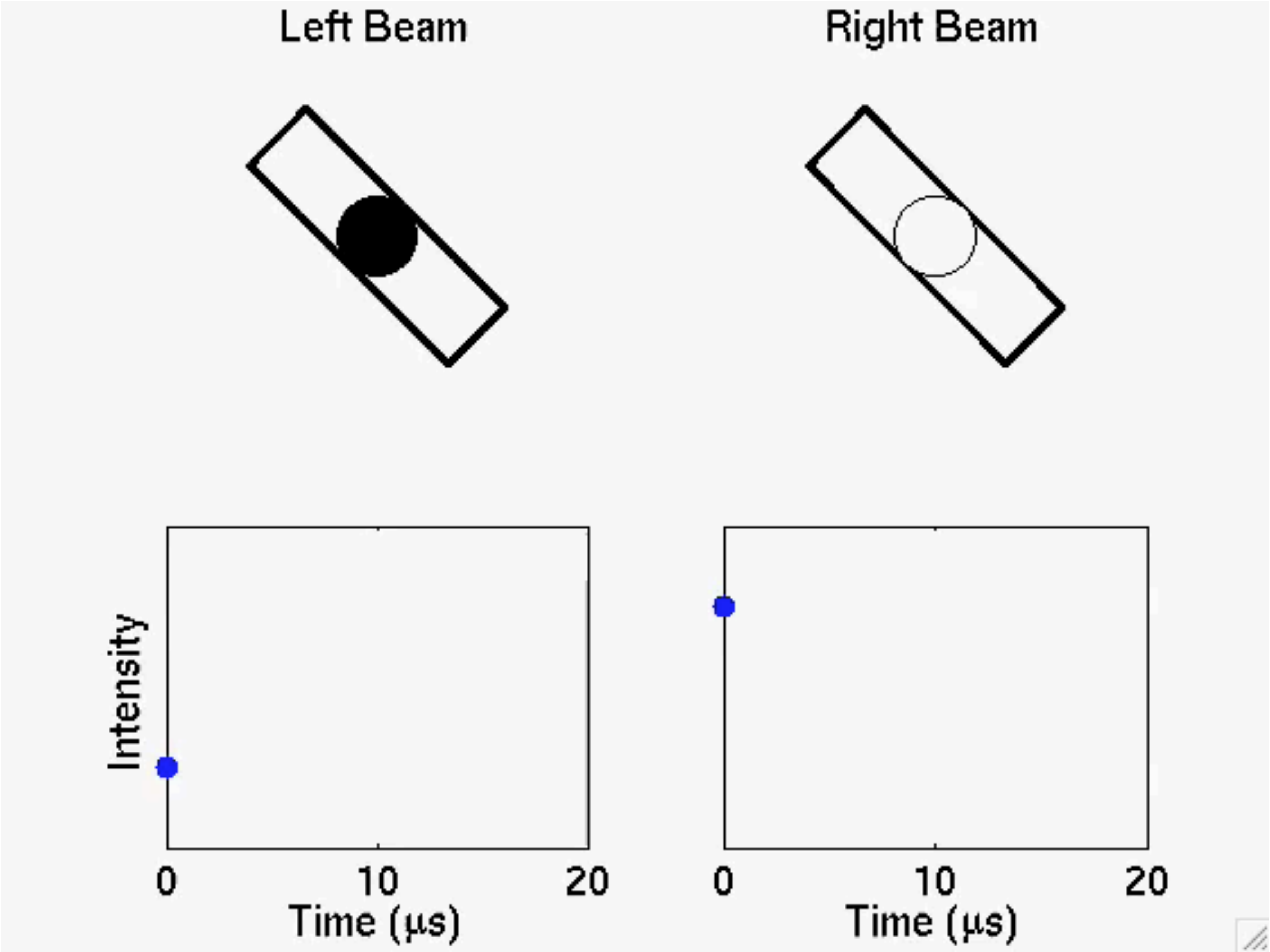


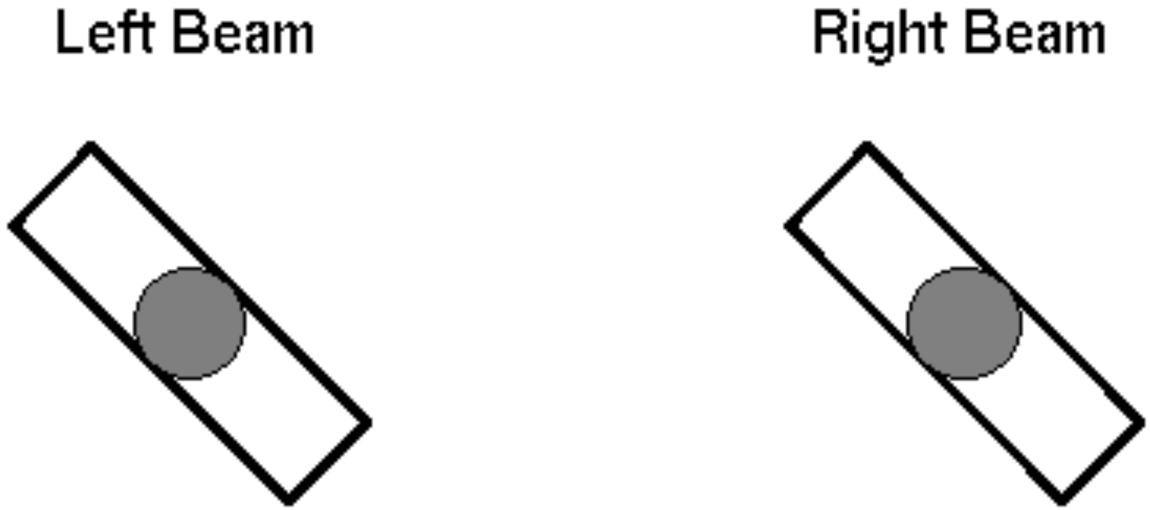
- <u>Birefringent material</u>

  Index of refraction is a function of E orientation

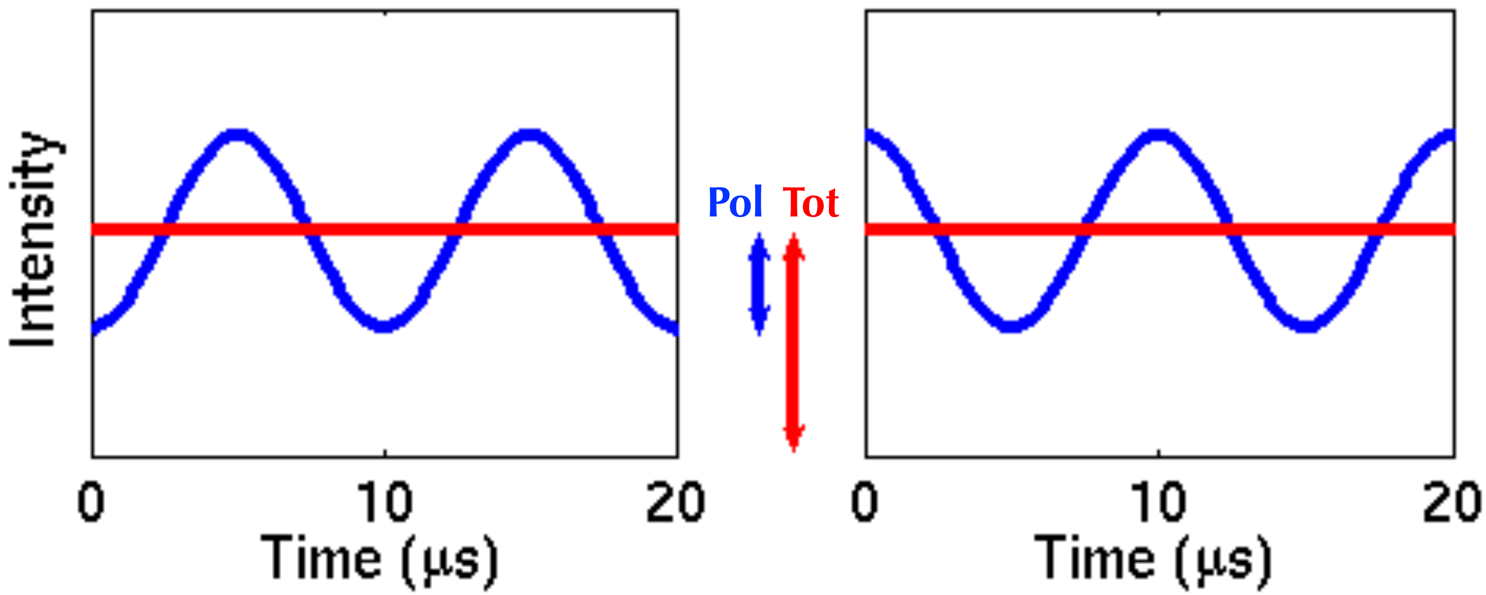
- <u>Non-birefringent material</u>

  Stress ⇒ birefringence


Left Beam
Right Beam
Intensity
0
10
20
Time (μs)
0
10
20
Time (μs)



$$P \propto \frac{AC}{DC}$$ from 1 to 1,000,000 ppm

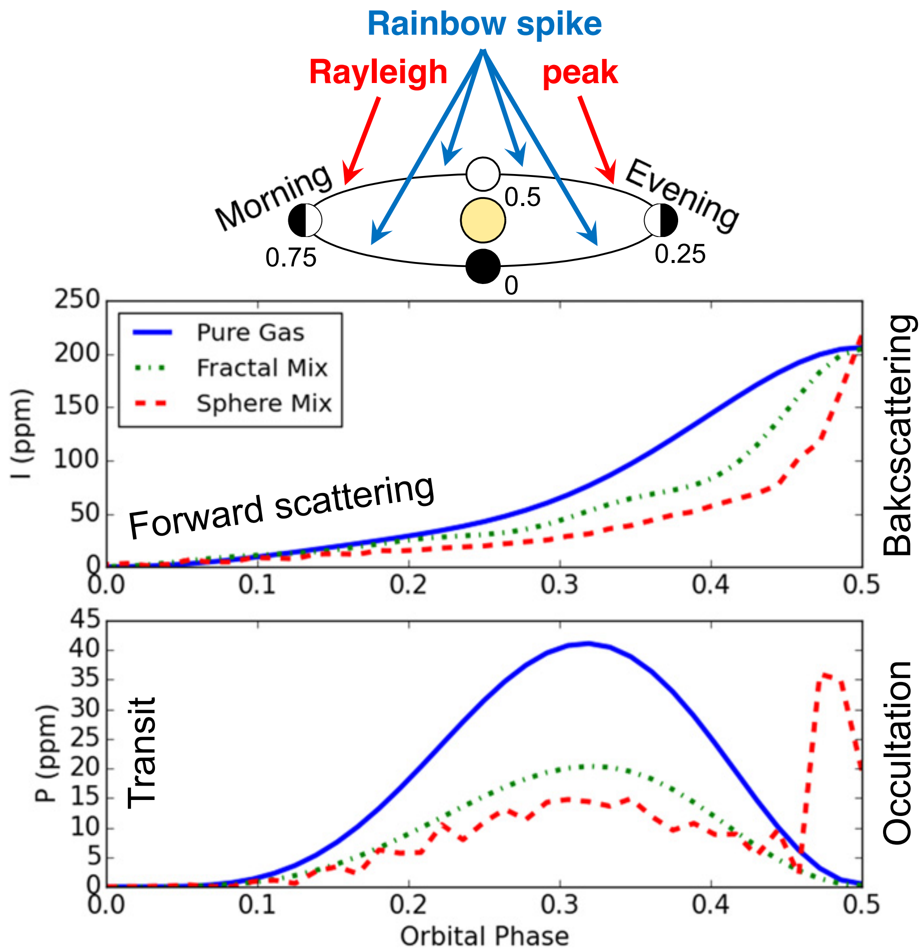


Polarization Signatures of Gases, Hazes, and Clouds

Amplitude and orbital phase location of polarization peak

- (Small) Gas molecules
  - *Strongly polarizing at orbital phases 0.3, 0.7; no rainbow*
- (Medium) Haze particles
  - *Weakly polarizing at orbital phases 0.3, 0.7; no rainbow*
- (Large) Cloud particles
  - *Weakly polarizing; has rainbow*

- Strong polarization at phases 0.3, 0.7 without rainbow: gas molecules
- Weak polarization at phases 0.3, 0.7 without rainbow: haze particles
- Weak polarization at phases 0.3, 0.7 with rainbow: cloud particles

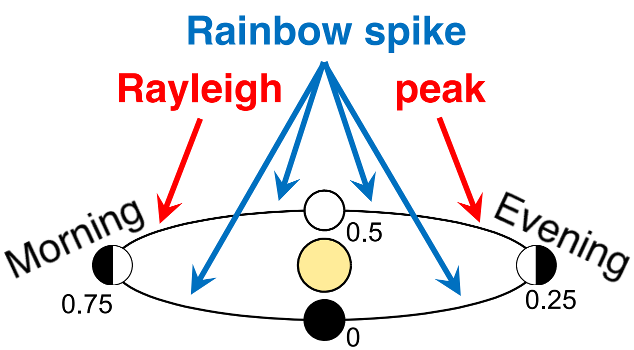


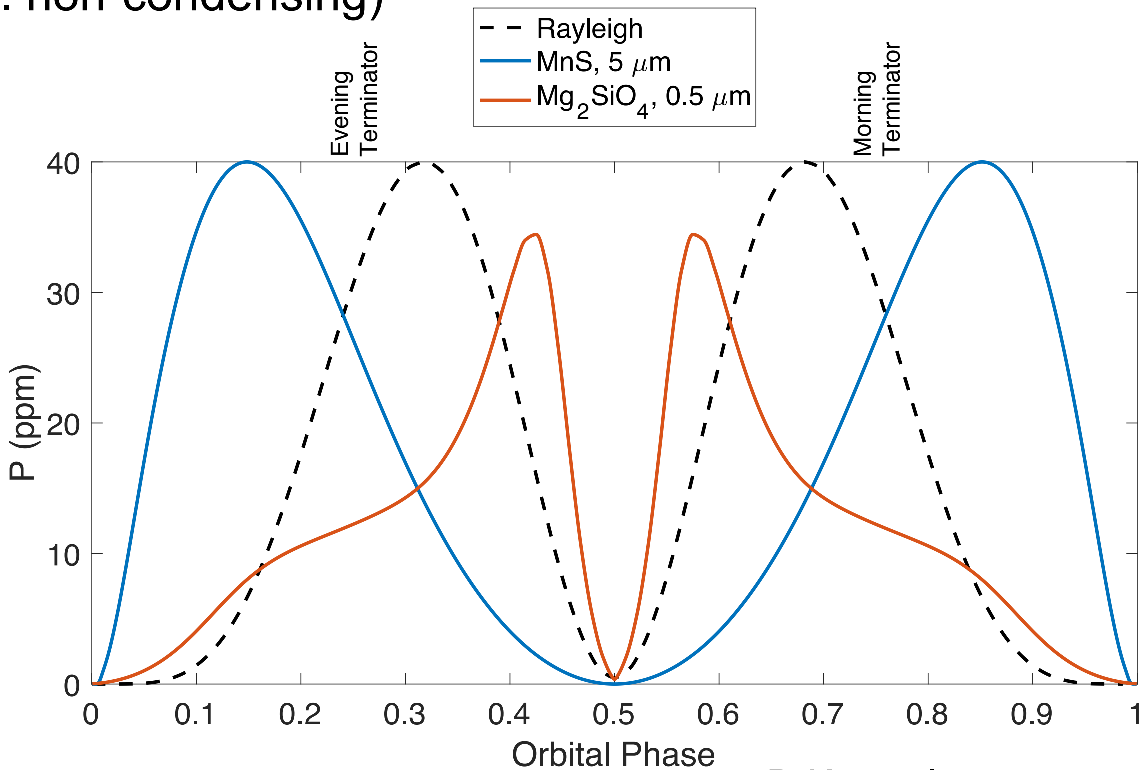
Kopparla et al. 2016

Hard to identify particles from intensity, easier in polarization

Full-Orbit Phase Curves are Crucial

- Identify particle composition: index of refraction vs. λ
- Identify particle size distribution: orbital phase location of peak polarization
- Distinguish differences in particle properties between morning and evening terminators (condensing vs. non-condensing)



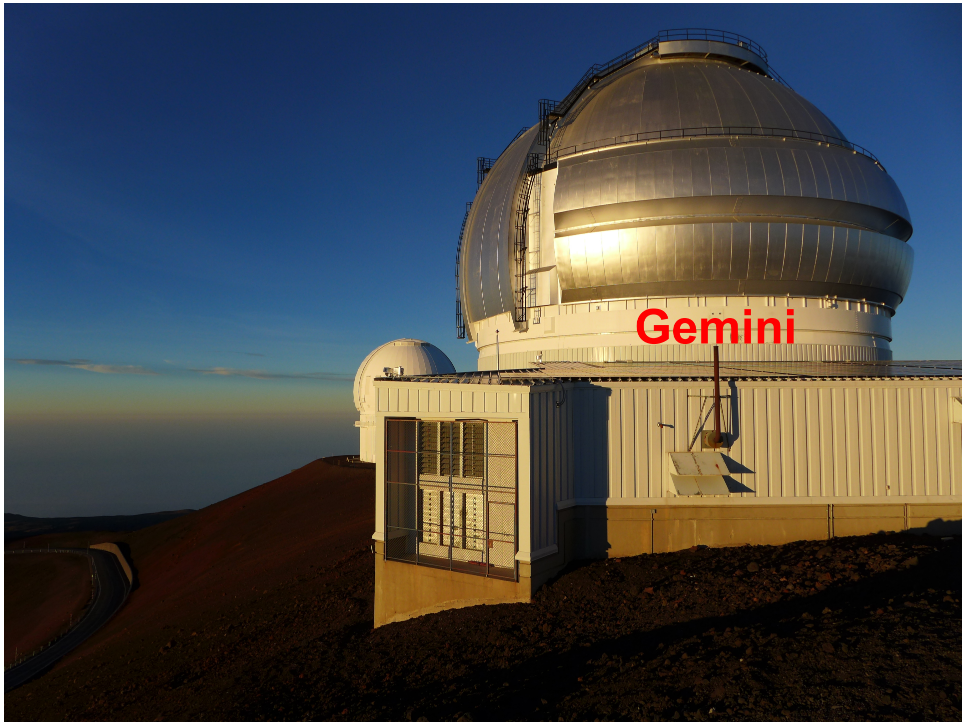


P. Kopparla

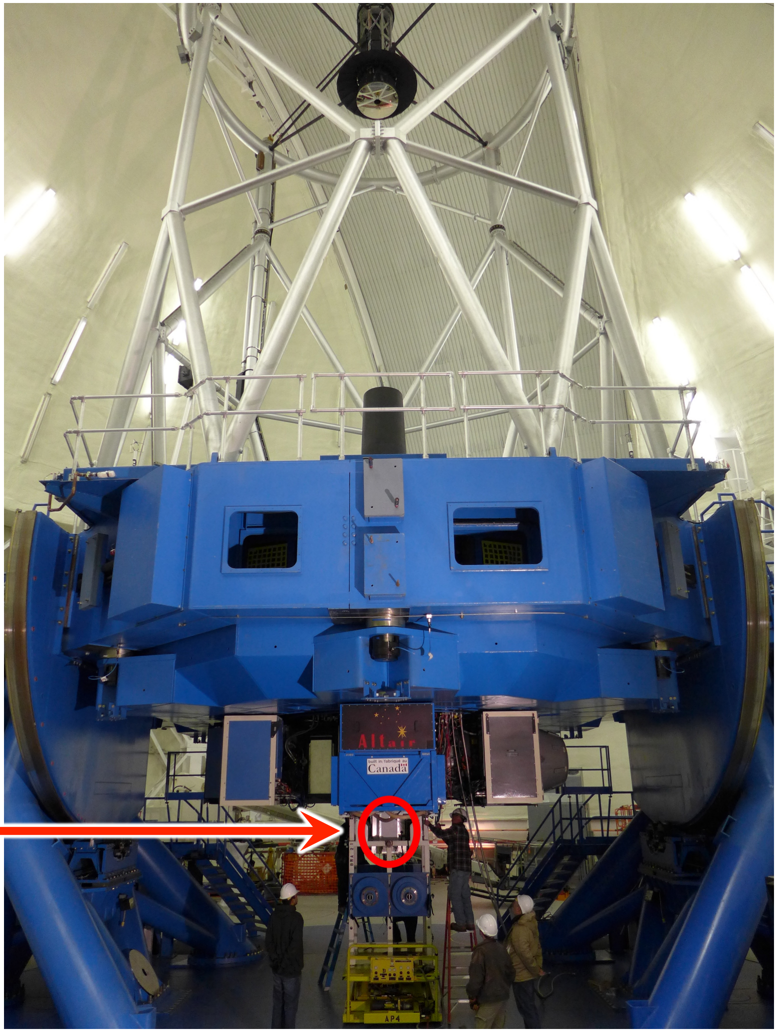
Polarimetry: Finding silver linings in clouds (and hazes, too)

Polarimetry Leverages Ground-Based Telescopes

Nov. 2016 commissioning, Gemini North 8-m

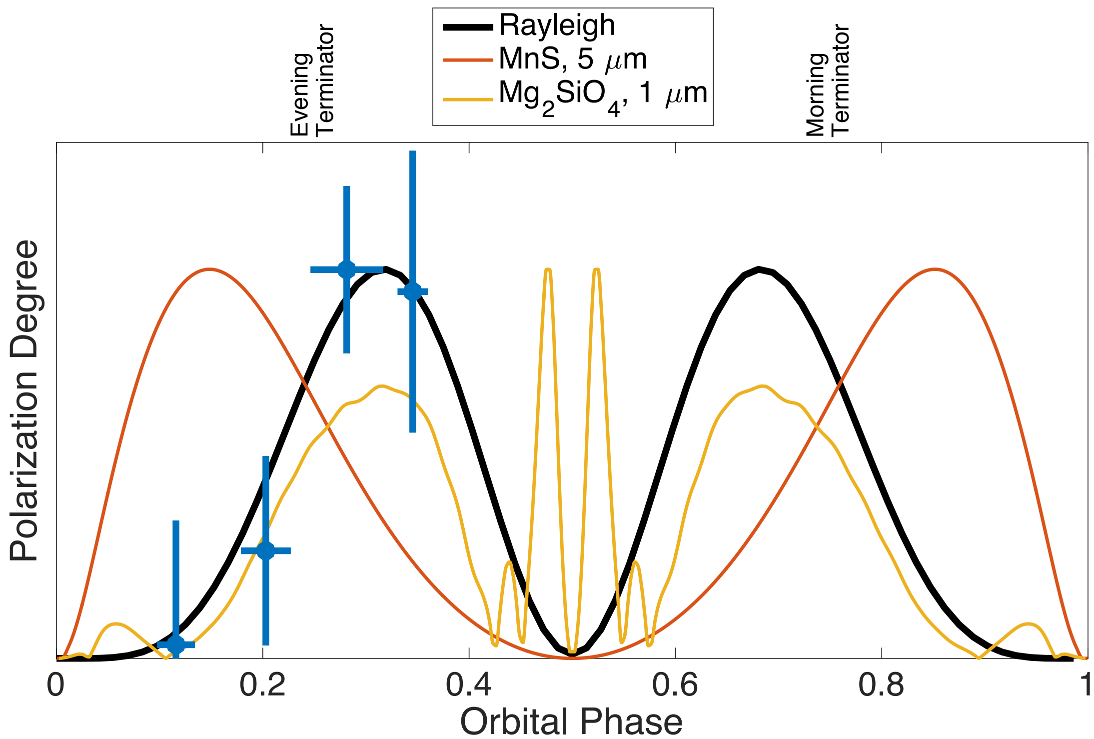


POLISH2



Discovery of Scattered Light from an Exoplanet

- B band geometric albedo of 0.335 ± 0.059: 4.7σ detection
- Null hypothesis (constant, zero polarization) rejected with 4.4σ confidence
- Albedo < 0.8 requires haze or cloud particles (17% of incident photons absorbed)
- Clear atmosphere rejected with 6.7σ confidence
- Next: distinguish hazes from clouds by searching for rainbow near phase 0.5



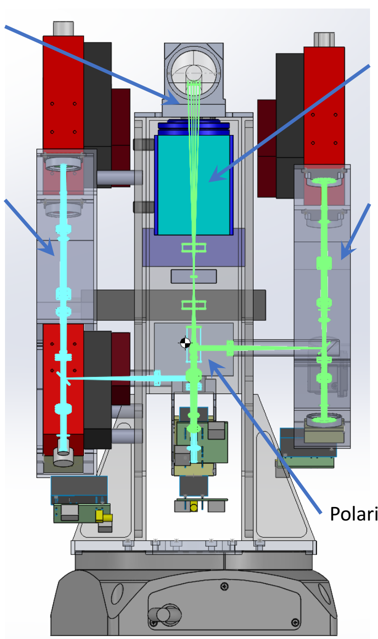
- Next: search for differences between morning and evening terminators

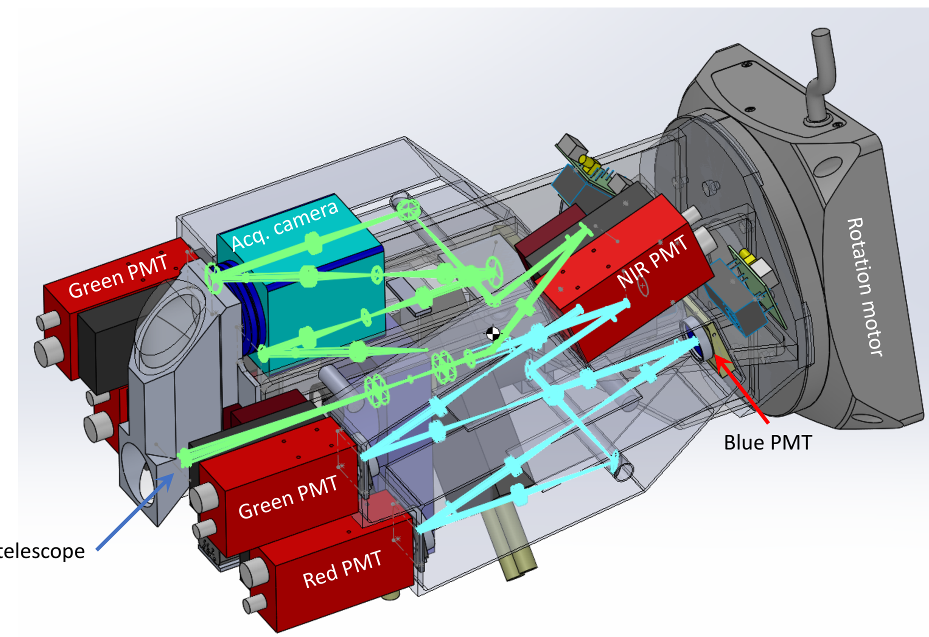
Exoplanet polarimetry has arrived

New Polarimeter PHALANX

Polarimeter for High Accuracy aLbedos of Asteroids aNd eXoplanets

- Gemini: Detailed exoplanet follow-up
- Lick: NASA-funded asteroid observations identifying surface metals
- Aerospace 1-m: asteroids and POLTERGEIST survey around bright stars
  - *POLarimetry of TERrestrial and Gaseous Exoplanets Inaccessible to Standard Techniques*





Simultaneous 5-band operation for isolation of exoplanet clouds and hazes

Conclusion

- Exoplanet clouds and hazes are common and do not play nicely with current follow-up techniques
- Full-orbit, multi-wavelength, ground-based polarimetry is ideally suited for such planets
  - *Particle size, shape, index of refraction, and composition affect phase curve*
- Short commissioning run in a single band was sufficient to discover scattered light from an exoplanet, requires absorber with 6.7σ confidence
- Polarimetry is naturally sensitive to scattered light surrounding elongation (90° scattering angle), conveniently when terminators are in view
  - *Differences in polarization signature between morning and evening terminators directly probe heat redistribution and cloud condensation*
- New polarimeter PHALANX to measure scattered light in 5 bands simultaneously
  - *Detailed studies at 6-10m, alt-az telescopes with Cassegrain foci*
  - *Survey of brightest stars with the Aerospace 1-m telescope*

Discovery of Scattered Light from an Exoplanet

- Telescope-induced polarization manifests as sinusoidal signature vs. parallactic angle on alt-az telescope
- Subtraction of this uncovers science signature