Disk-integrated measurements of the Moon in the ultraviolet

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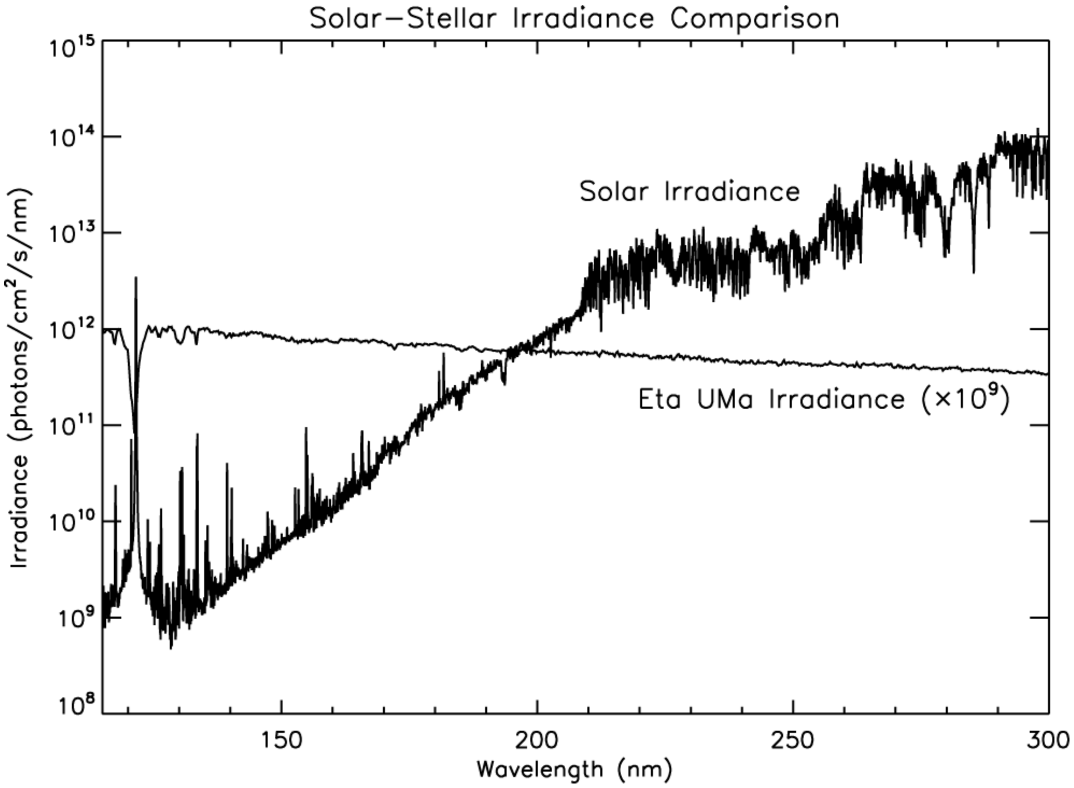
Outline

- The SOLSTICE instrument
- Observations
- Data Processing
- Results
  - Reflectance
  - Photometric fits
  - Polarization
- Conclusions

SOLar STellar Irradiance Comparison Experiment (SOLSTICE)

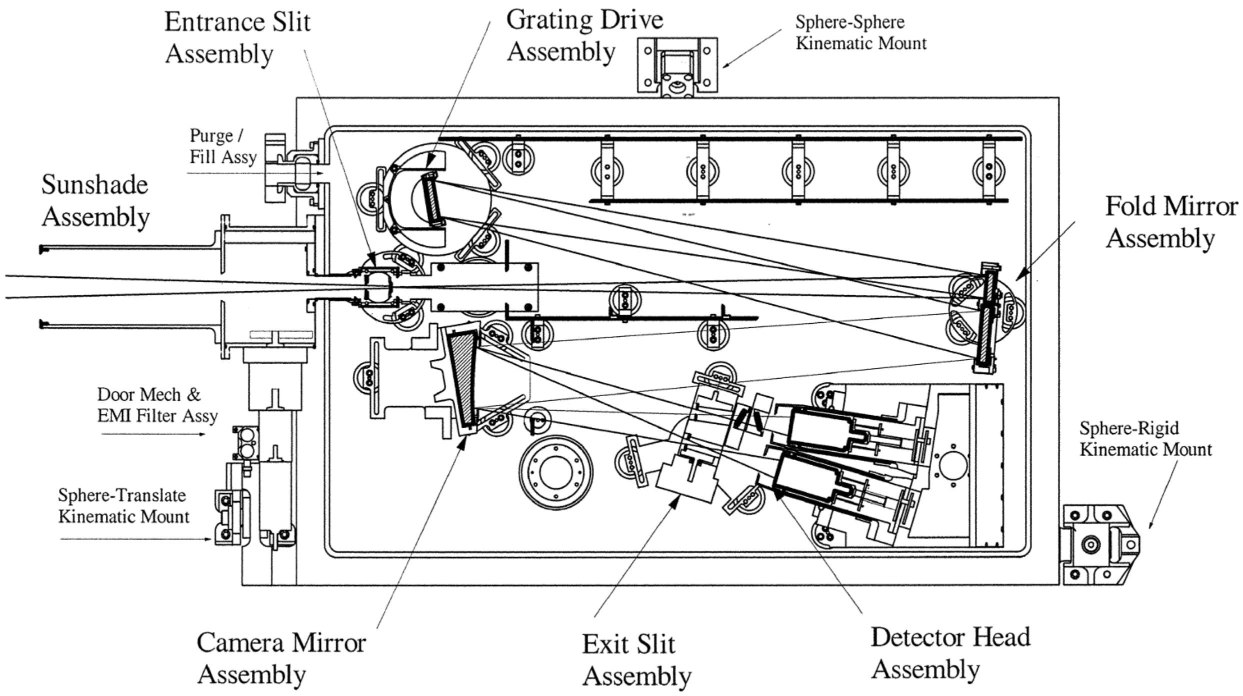
- Measures solar irradiance in ultraviolet
  - 115-180 nm Far Ultraviolet (FUV)
  - 180-300 nm Middle Ultraviolet (MUV)
- Measures stellar irradiance for tracking long term degradation
- On board SORCE:
  - Low Earth Orbit

Solar-Stellar Ratio



Need a large dynamic range ($\sim10^9$) to measure both Sun and stars with same optics and detectors

SOLSTICE Layout



- Scanning grating monochromator
- Operates as an objective grating spectrometer in stellar mode

- Change entrance aperture $2\text{x}10^4$
- Widen exit slit 10 or 20
- Lengthen integration 10^3

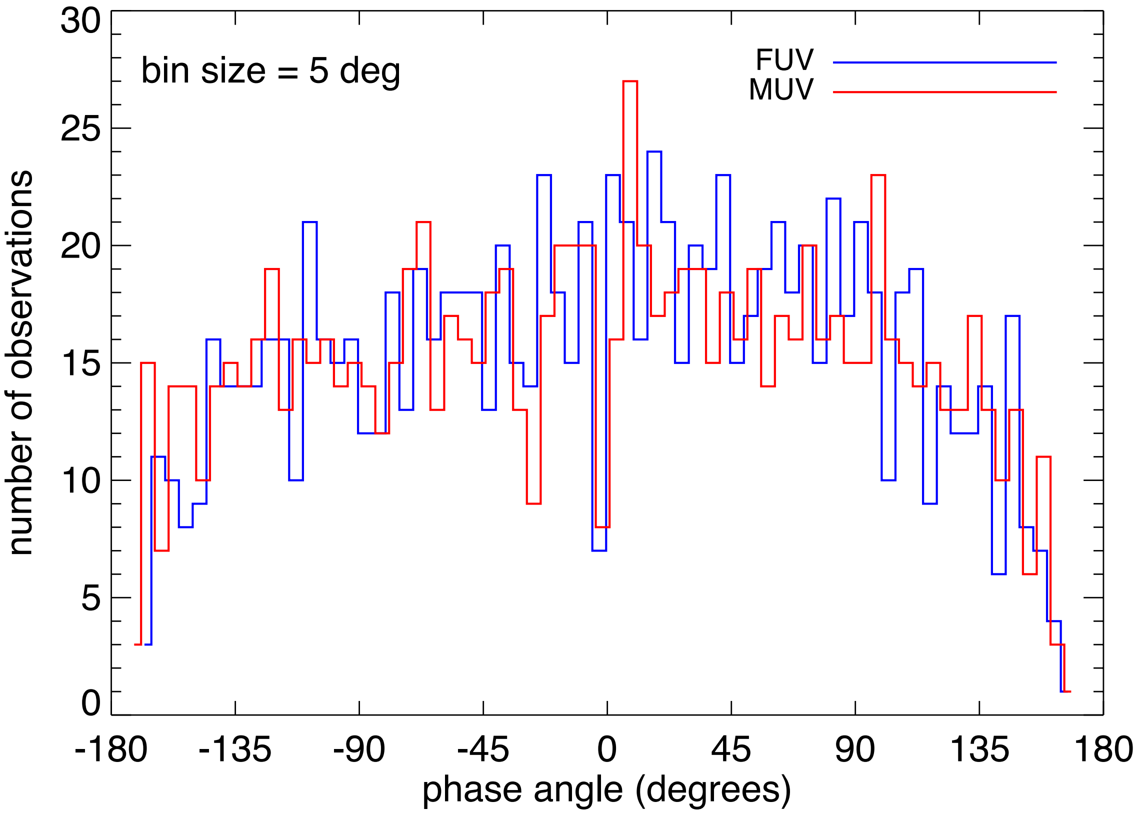
UV presents unique challenges

- Solar variability
  - Visible wavelengths (>400nm): ~0.1%
  - Middle-ultraviolet (200-300nm): ~2-3%
  - Far-ultraviolet (115-200nm): 10-40%
- Poorly characterized calibration targets
  - Ground calibration of UV instruments has a high uncertainty
  - Hot, bright stars are frequently used in-flight but previous measurements also have a high uncertainty

Lunar Observing Campaign

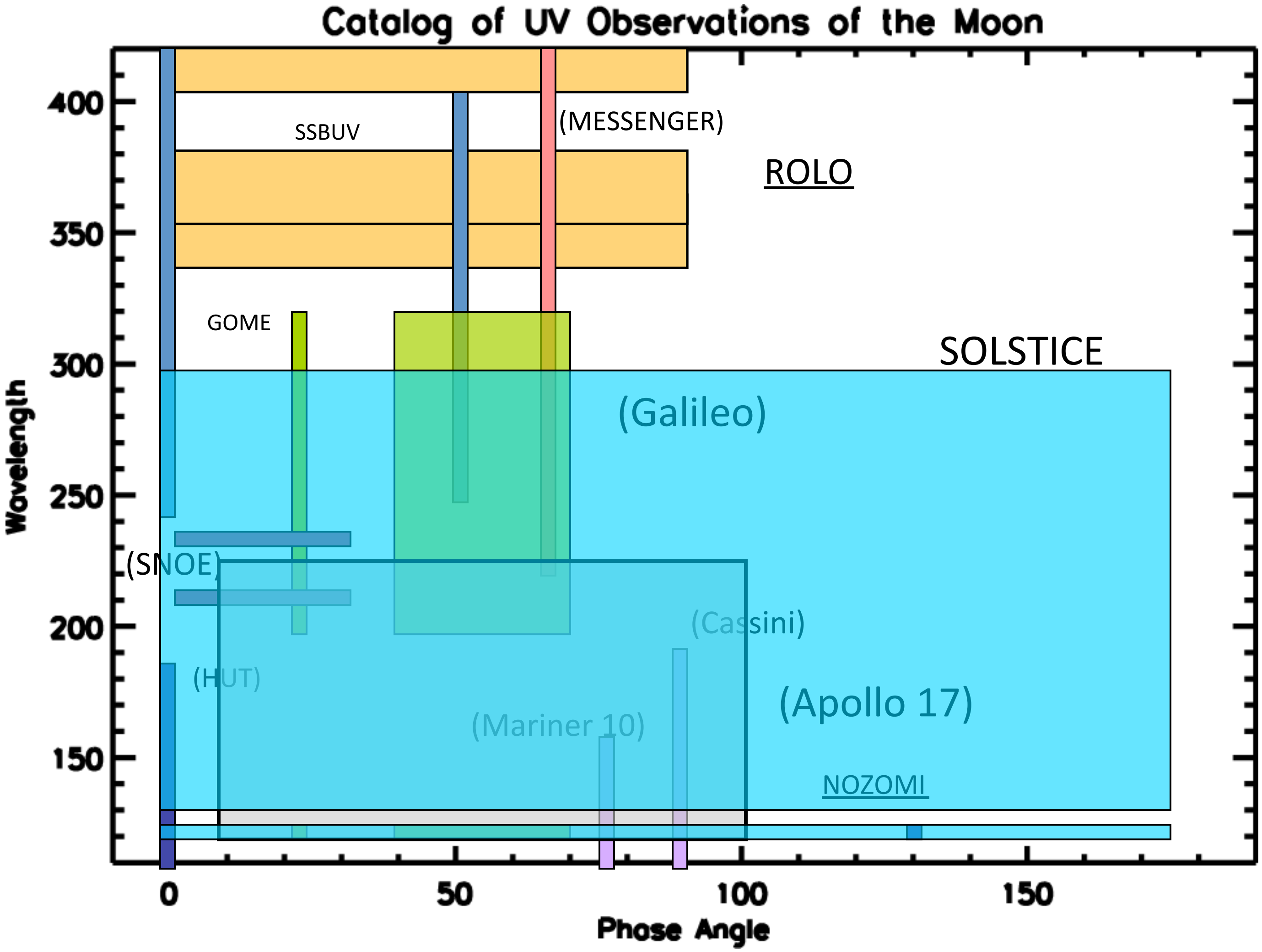
- June 2006 to December 2010
- Added the Moon to the schedule of eclipse calibration activities
- On average, we observed one disk-integrated spectrum per day in each channel
  - Over 1000 complete spectra in each channel
- NASA Grant: LASP Lunar Albedo Measurement and Analysis from SOLSTICE (LLAMAS)

Phase angle coverage



Min Abs(phase)	0.1°
Min phase	-171.7°
Max phase	168.6°

Wavelength and phase coverage in context



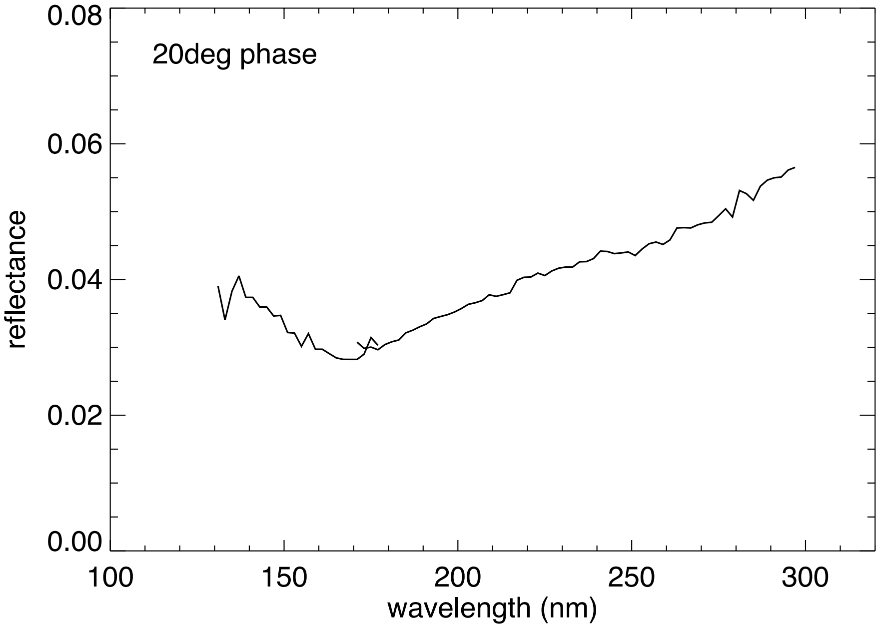
Derivation of reflectance

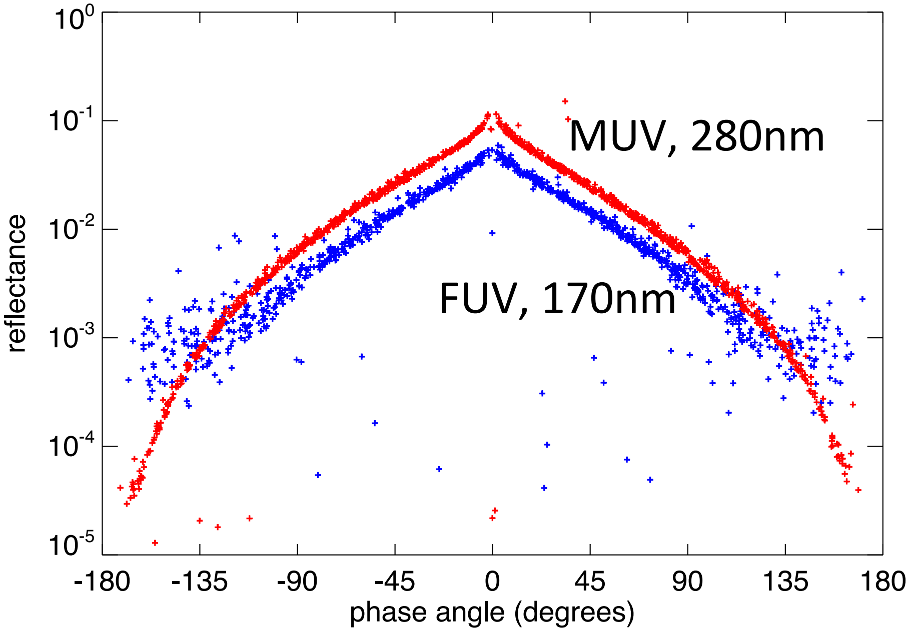
$$\frac{E_M}{E_S} = \frac{C_M}{C_S} \frac{A_S \Delta\lambda_S}{A_M \Delta\lambda_M} \Gamma$$

$$r = \frac{E_M / \Omega_M}{E_S / \pi}$$

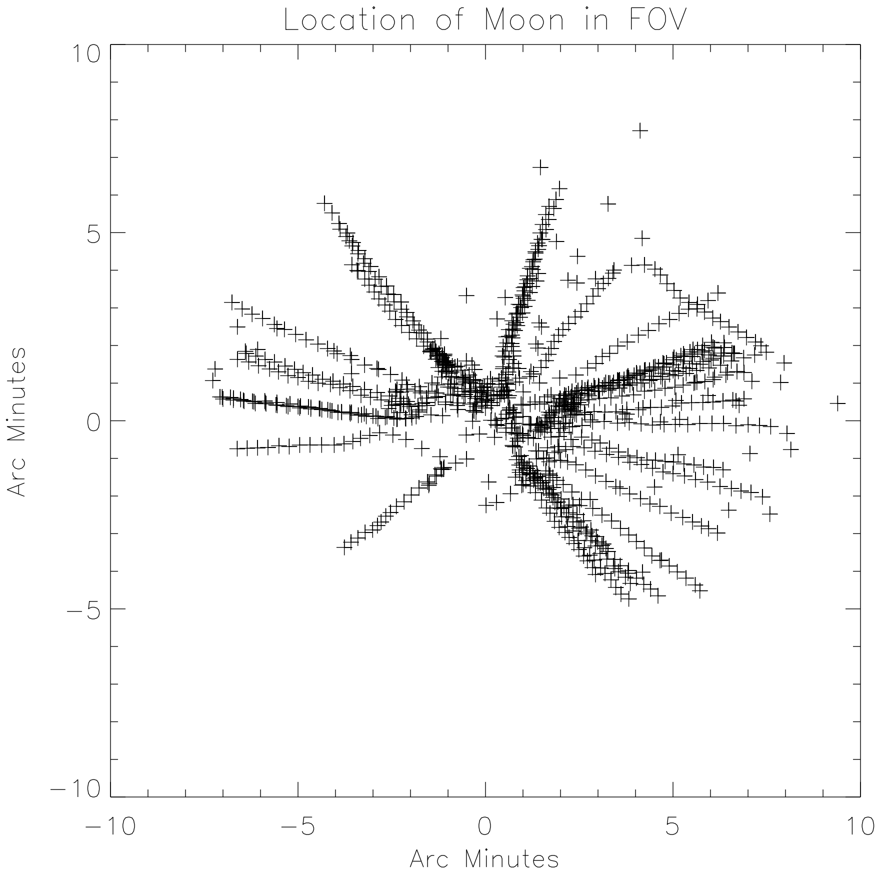
Note that by making both Solar and Lunar irradiance measurements with SOLSTICE, all calibration terms cancel out except for knowledge of the aperture areas and a single correction factor (Gamma).

Example reflectance and phase curves



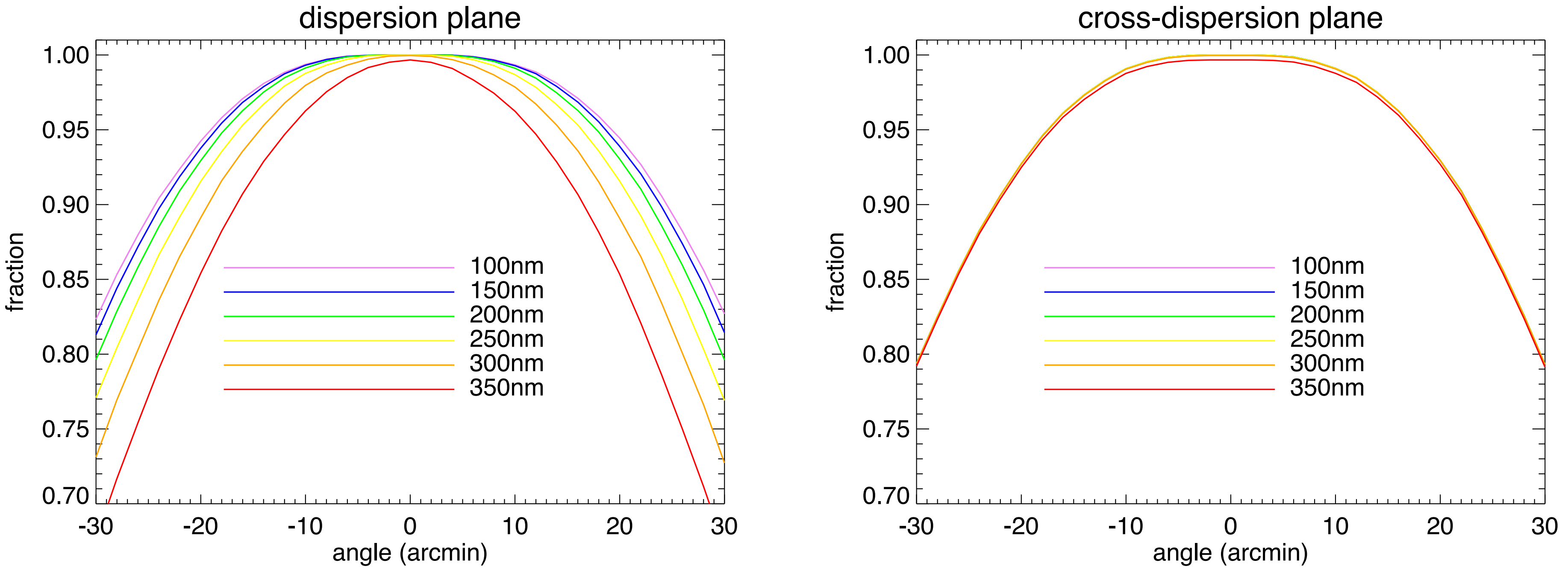


Systematic corrections



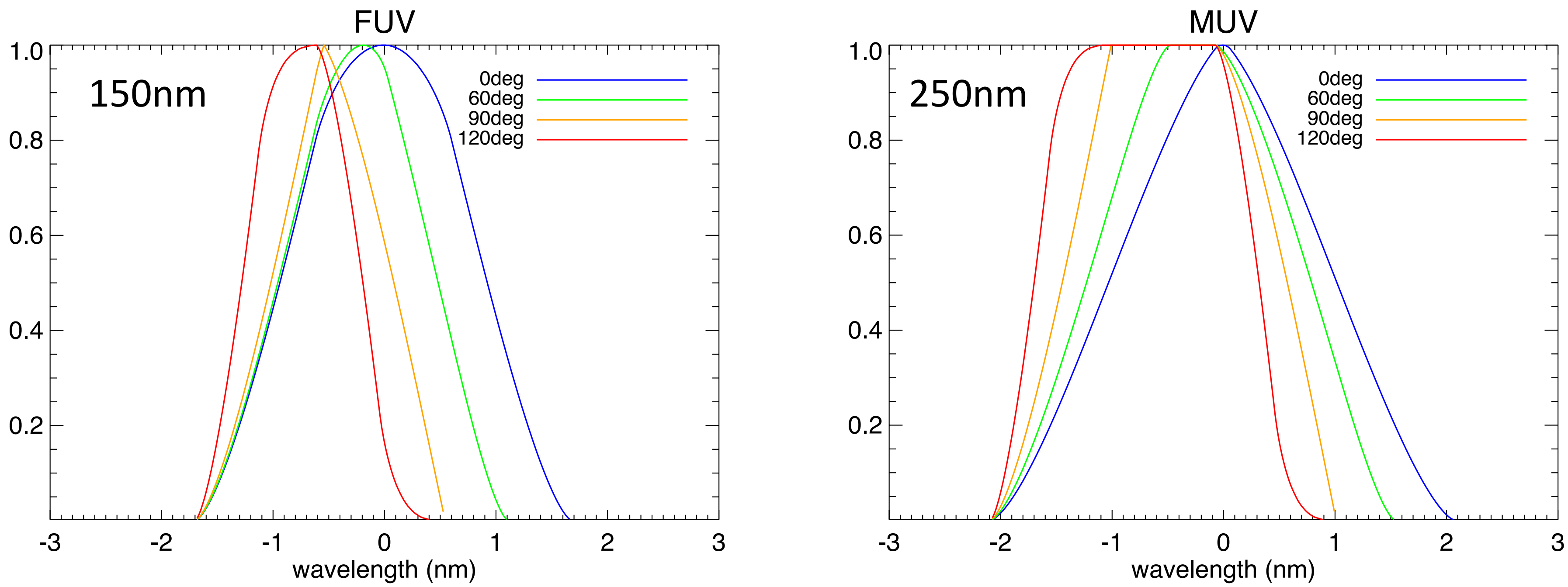
- Vignetting (1-3 % for MUV, 5-10% for FUV)
- Wavelength shifts (~1-2 nm)
- Changes in resolution with phase and roll angle
- Polarization (not yet applied, discussed later)

Vignetting



Fraction of light that reaches the detector as a function of target position (from Zemax raytrace)

Variation in resolution

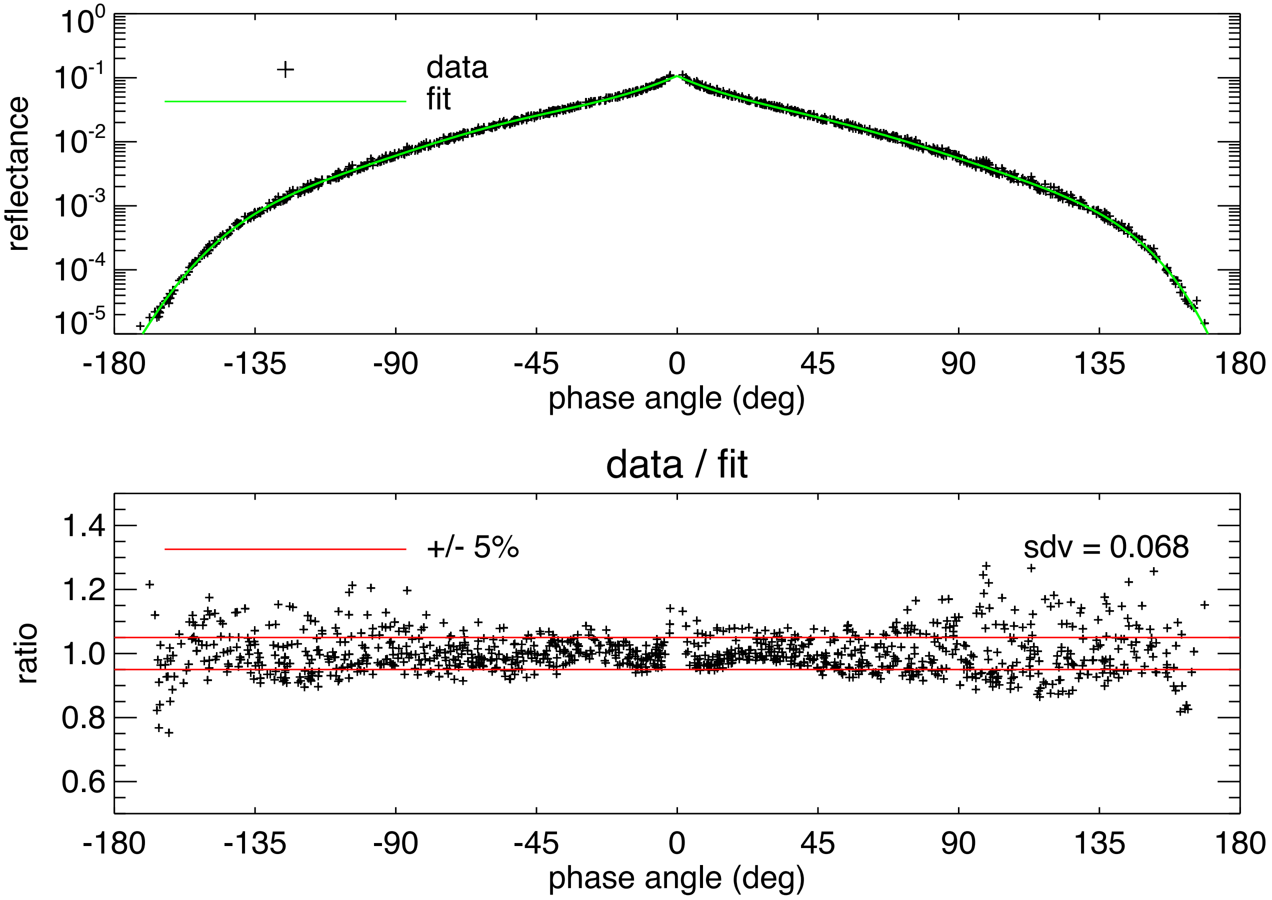


Point-spread function in each channel at four different phase angles (0deg s/c rotation)

Photometric modeling

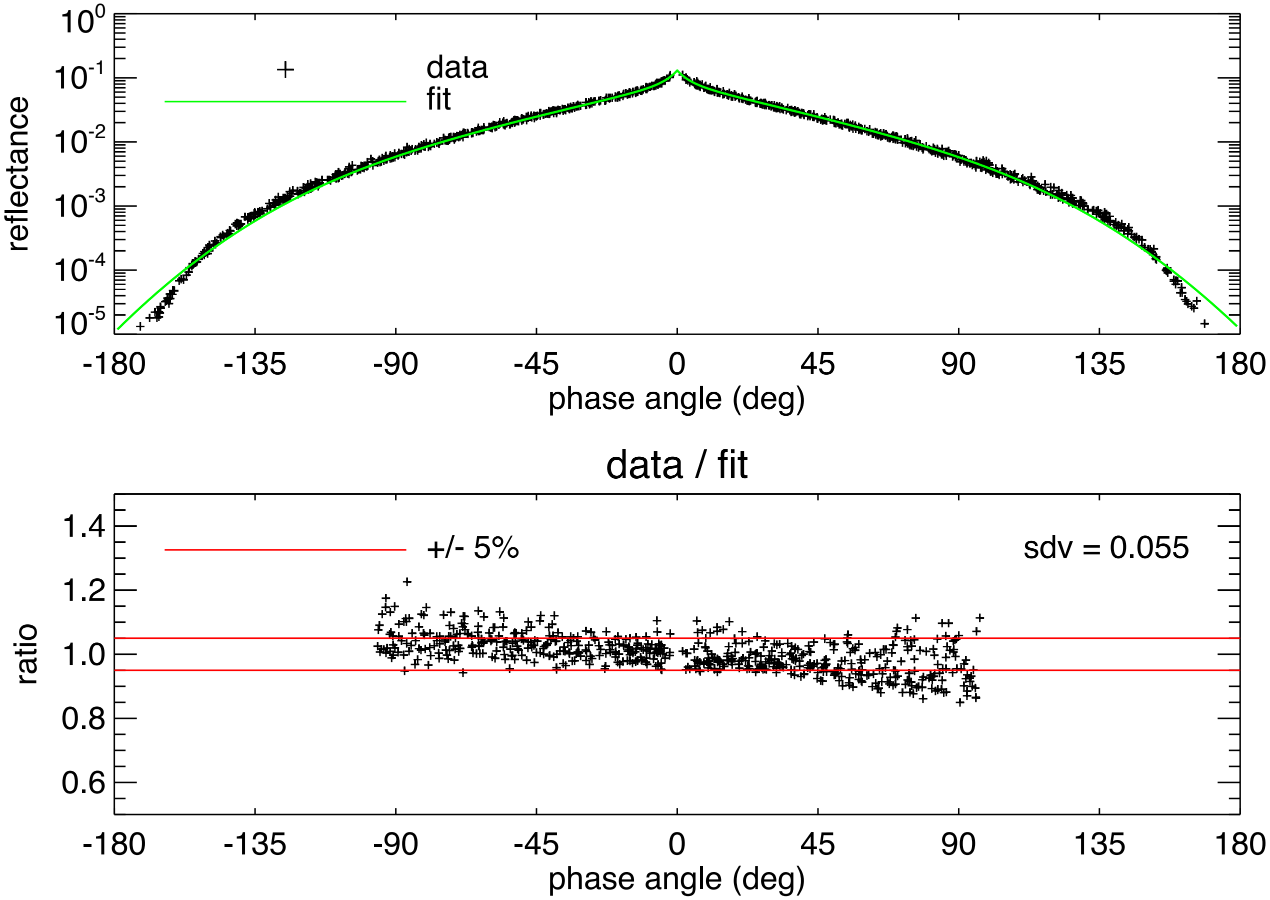
- Polynomial
  - 7th order polynomial used to fit wide phase range Mercury observations from SOHO [Mallama et al, 2002, Icarus 155]
  - Simple, but nonphysical
- ROLO
  - Empirical model, but tailored to the shape of the lunar phase curve
  - Achieves good fits (~1% rms) of visible, IR measurements [Kieffer and Stone, 2005, Astron J 129]
  - Only valid for phase range 1.6° to 97°
- Hapke
  - Semi-physical coefficients related to surface properties
  - Widely used, long history
  - Non-unique without resolved data [Domingue and Hapke 1989, Icarus 78]

7^{th} order polynomial fit



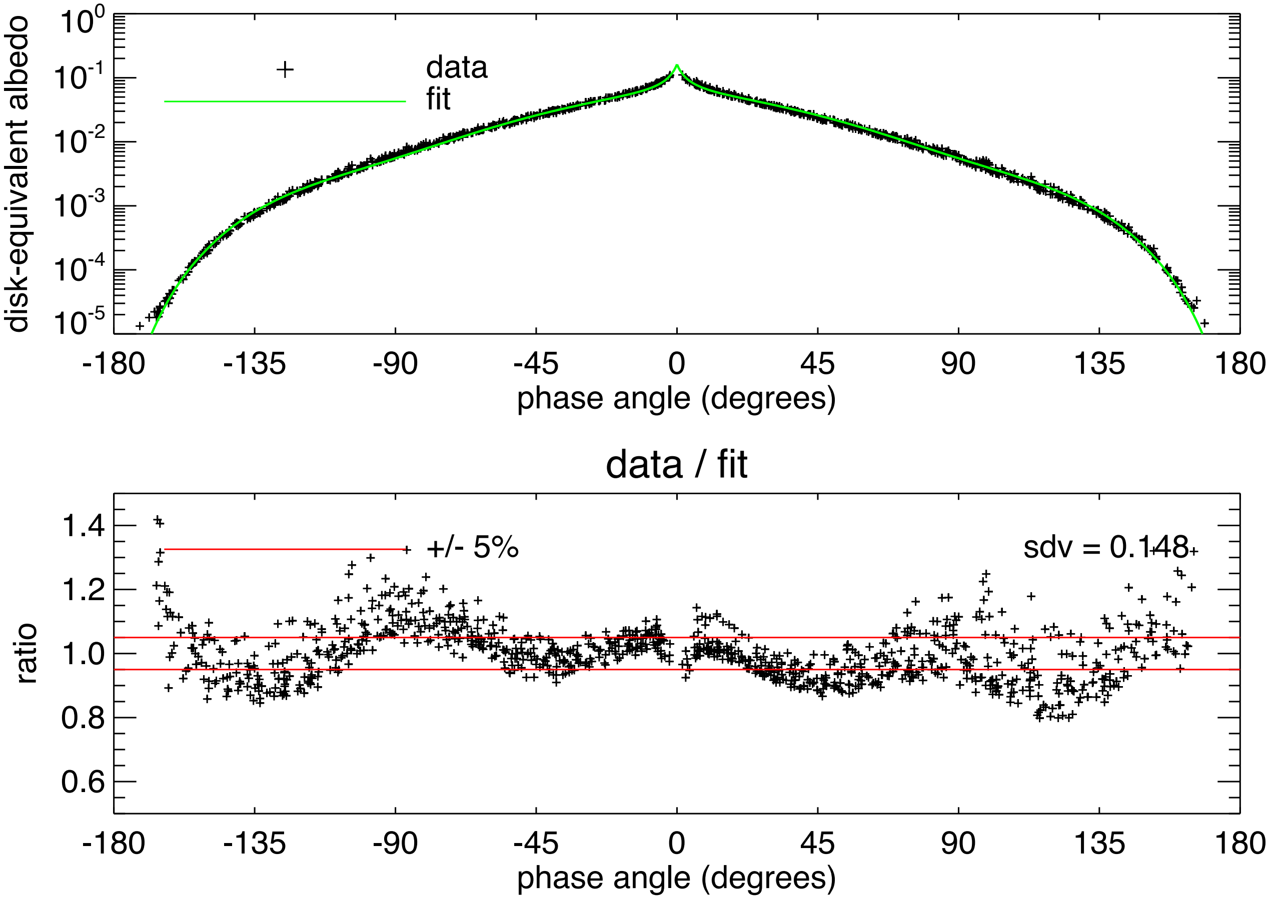
- 280nm
- Residual systematic structure evident at small and possibly large phase angles
- Positive and negative phases fit independently

ROLO photometric function fit



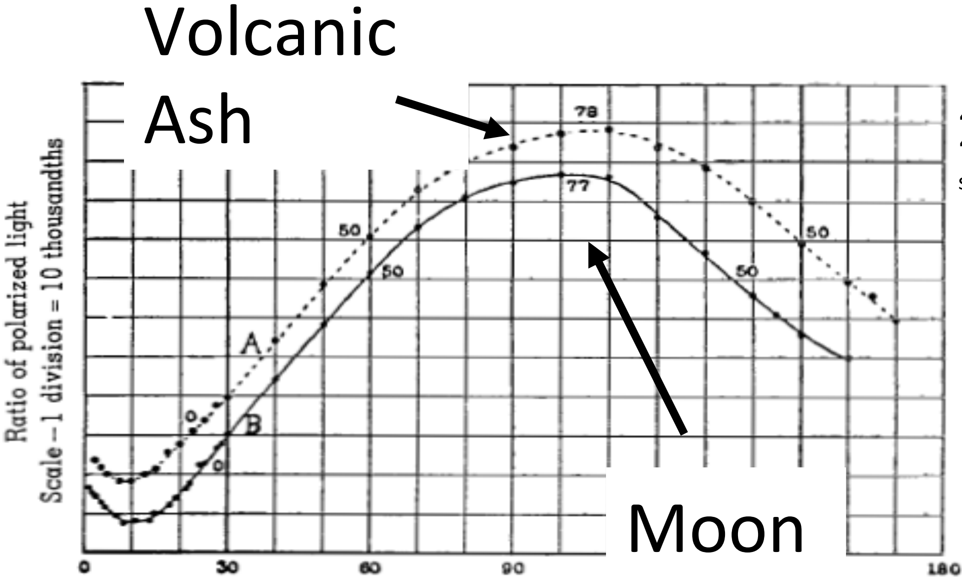
- Only fit to phase range 1.6° to 97°
- Missing linear term?
- No other obvious systematic variation
- Need to add functional terms to represent turn down at large phase

Hapke fit



- No separation of positive and negative phases
- Significant systematic structure

Lunar Polarization



Volcanic Ash

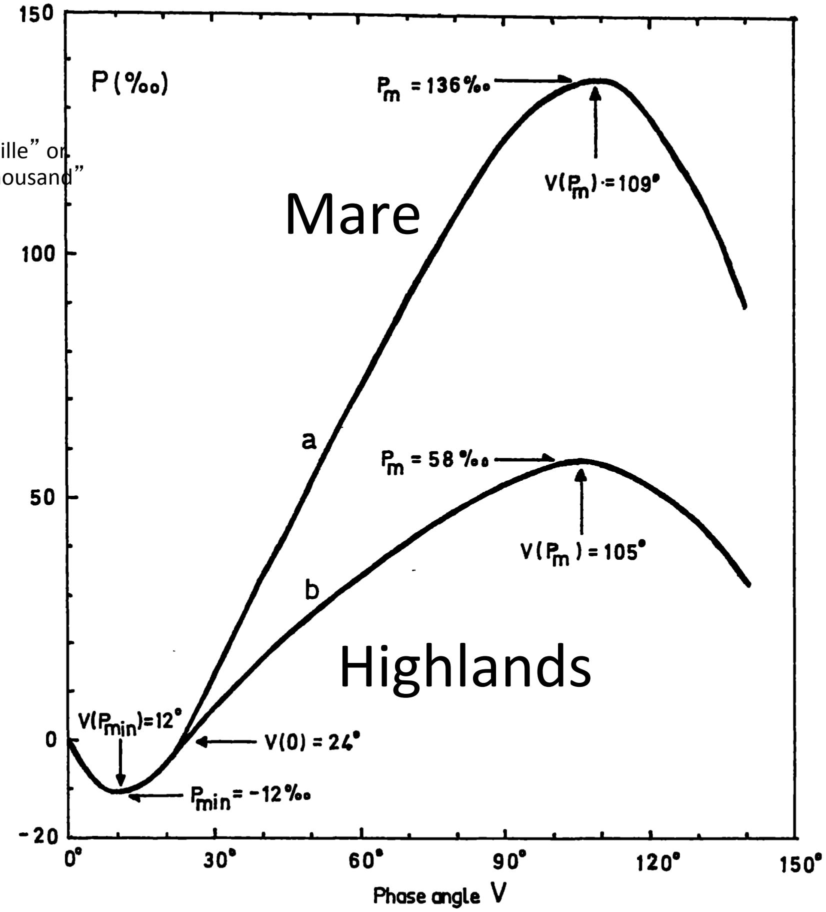
Moon

A – Mixture of ashes, of 0.13 albedo
B – Average curve for the Moon

Figure 51. Lunar Ground and Volcanic Ashes

Lyot, 1929

“per mille” or “per thousand” symbol

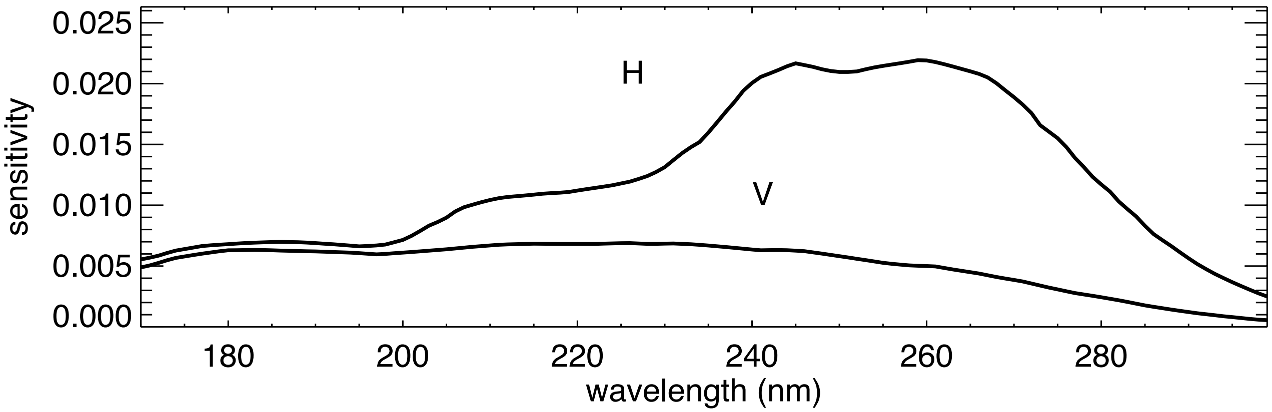


Mare

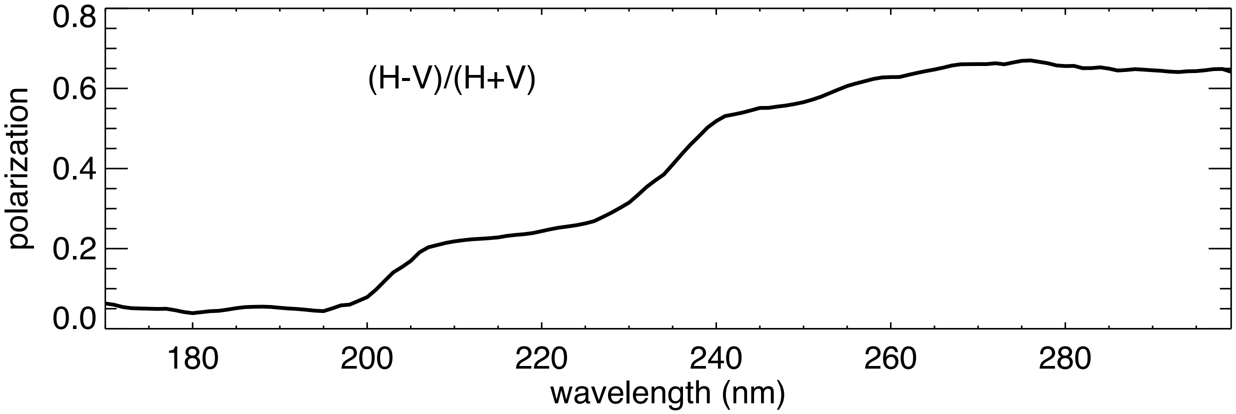
Highlands

1971, Dollfus & Bowell

Instrument polarization response

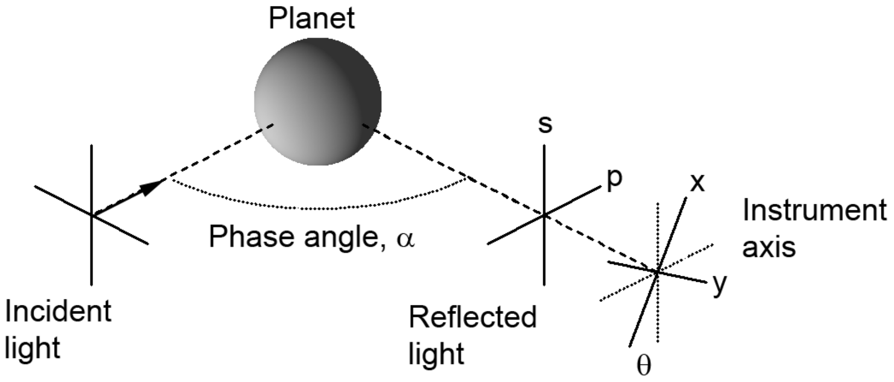


Instrument sensitivity due to polarized light at two orientations

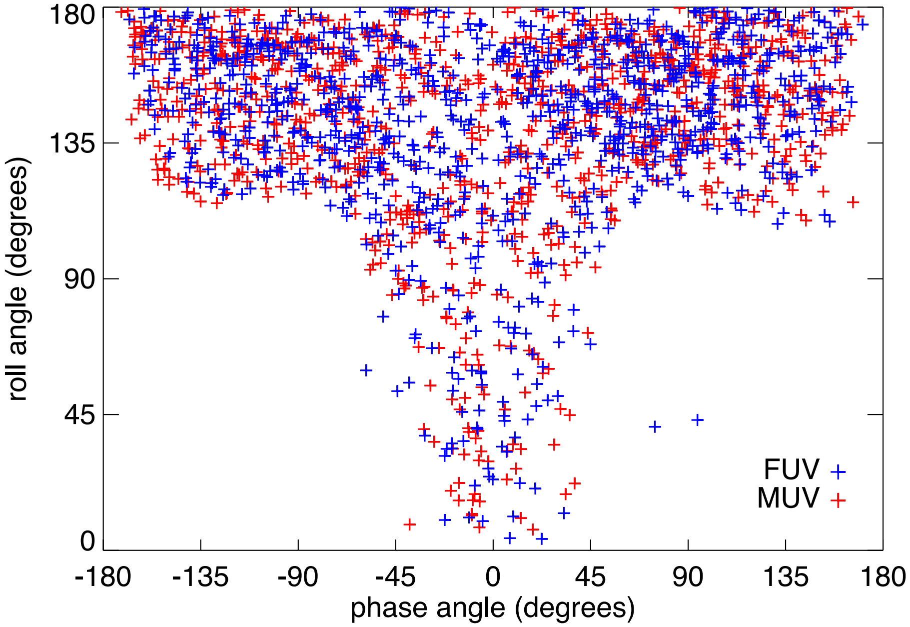


Derived linear polarization sensitivity

Variation in roll angle enables polarization measurement



Geometry of an observation. The scattering plane is defined by the Sun, Moon, and observer (spacecraft). The spacecraft roll angle, θ, is defined between one spacecraft axis and the normal to the scattering plane.



Distribution of sampled roll angles at each phase angle.

Calculating Polarization Fraction

We can express the measured signal in terms of the spacecraft roll angle, θ

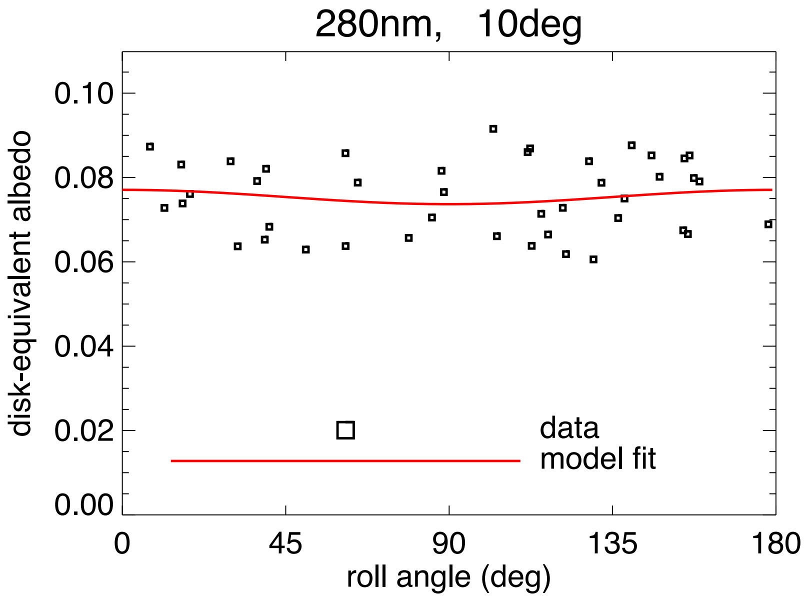
$$C(\lambda,\theta) = A + B\cos 2\theta$$

The polarization of the lunar irradiance is then given by:

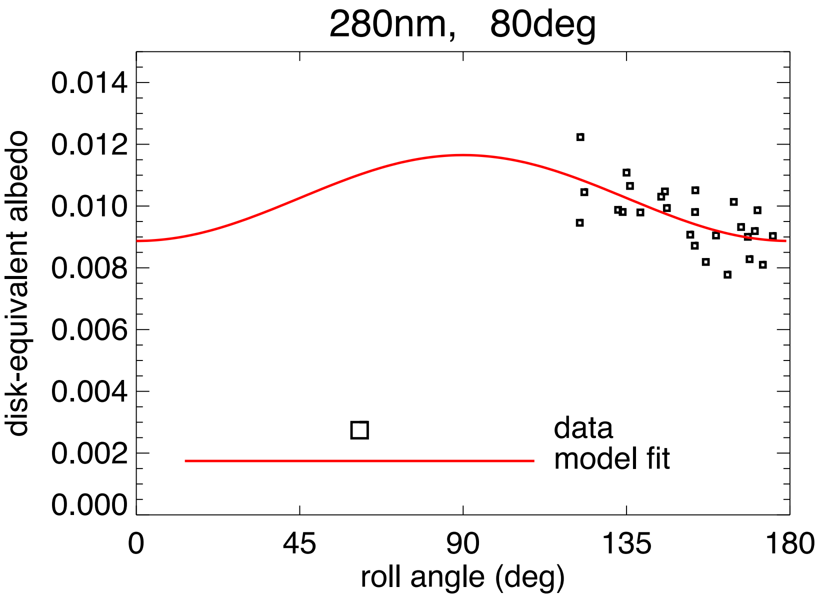
$$P_M = \frac{B}{A}\cdot\frac{1}{P_I}$$

Extracting P_m

For each wavelength and phase angle, we can find A and B using least-squares fitting algorithm.

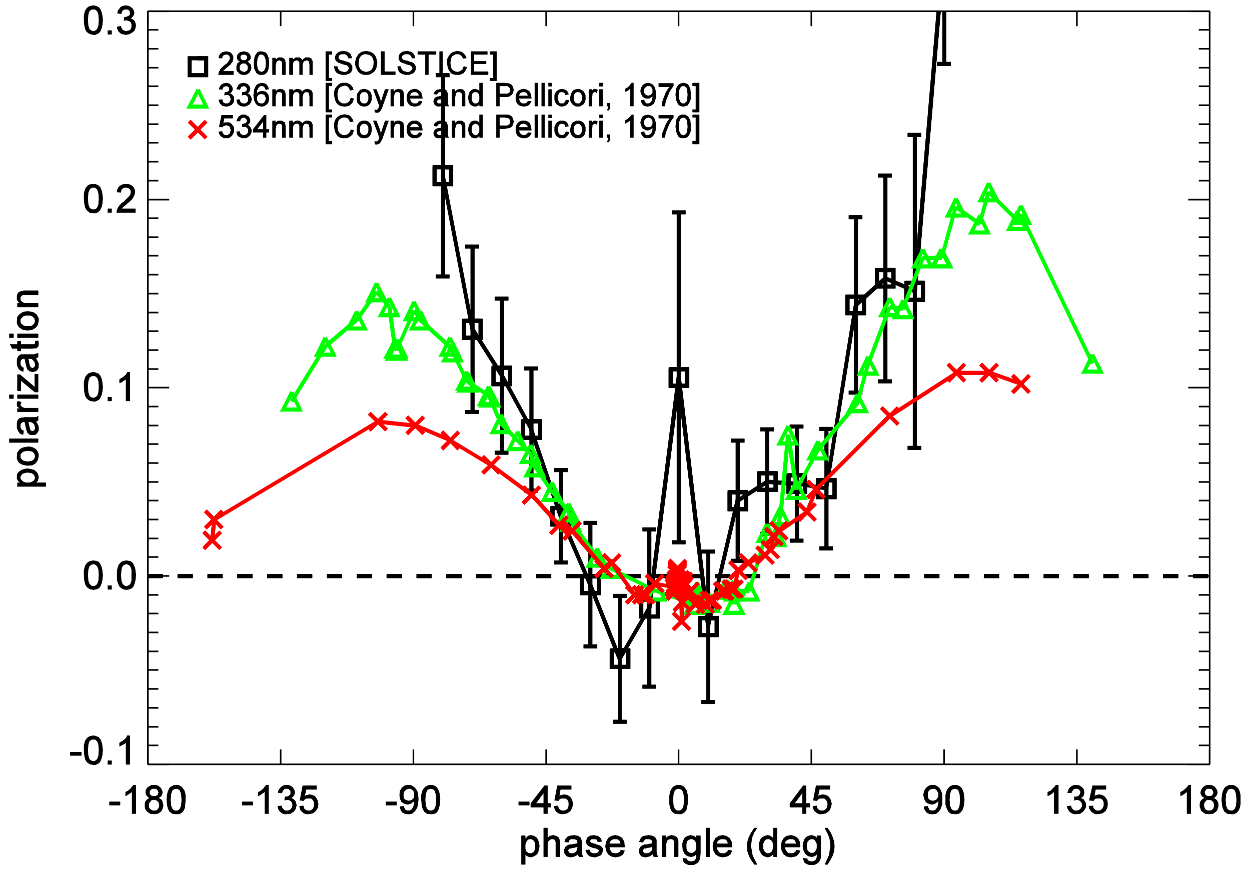


280nm, 10deg

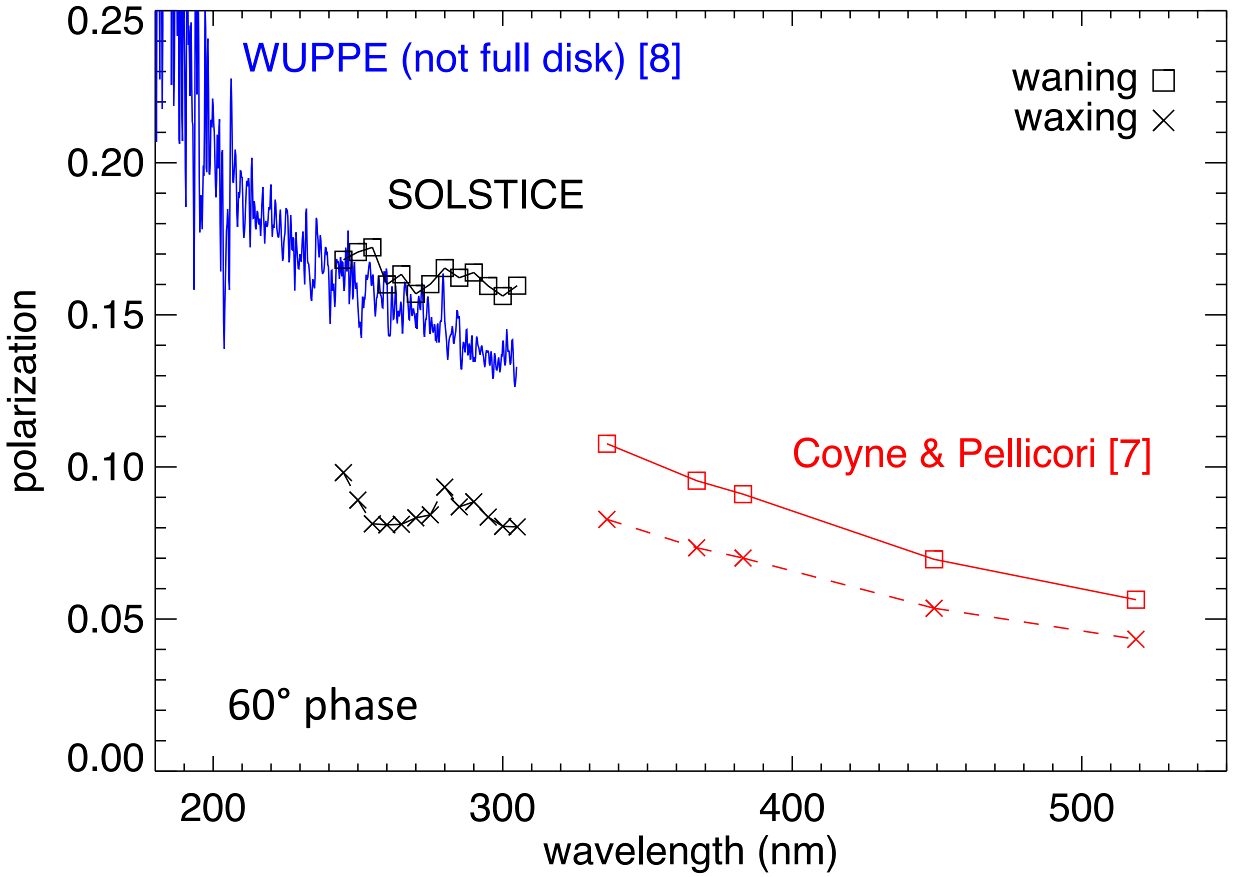


280nm, 80deg

Polarization vs Phase



Polarization



Fox et al, 1998, WUPPE, MNRAS 298

Coyne & Pellicori, 1970, Astron. J. 75

Conclusions

- SOLSTICE observes both the Sun and Moon directly, leading to a uniquely accurate measure of reflectance
- Wide phase coverage: -170 to +170°
- Wide UV wavelength coverage: 121, 130 - 300 nm
- Photometric modeling will enable the use of the integrated Moon as a UV calibration target
  - FUV requires nearly simultaneous solar spectrum
- Need to improve corrections for systematic effects (resolution, wavelength, vignetting, polarization) such that residuals are on the order of random uncertainty
- Ultimately, reduced data and model will be available to the public

Acknowledgements & References

Coyne GV, Pellicori SF (1970) Wavelength dependence of polarization. xx. the integrated disk of the moon. Astron J. 75:54-60. doi:10.1086/110940

Domingue, D. and Hapke, B. (1989) Fitting Theoretical Photometric Functions to Asteroid Phase Curves, Icarus 78, 330-336.

Fox GK, Code AD, Anderson CM, Babler BL, Bjorkman KS, Johnson JJ, Meade MR, Nordsieck KH, Weitenbeck AJ, Zellner NEB (1998) Solar system observations by the wisconsin utraviolet photopolarimeter experiment — iii. the first ultraviolet linear spectropolarimetry of the moon. MNRAS 298:303-309. doi:10.1046/j.1365-8711.1998.01633.x

Kieffer, H. and Stone, T. (2005) The spectral irradiance of the Moon, Astron. J. 129, 2887-2901

Snow, M., Holsclaw, G., McClintock, W. E., and Woods T. N. (2012) Absolute ultraviolet irradiance of the Moon from the LASP Lunar Albedo Measurement and Analysis from SOLSTICE (LLAMAS) project. In: Cross-calibration of Past and Present Far UV Spectra of Solar System Objects and the Heliosphere, E. Quemerais, M. Snow, and R. M. Bonnet (eds), ISSI Scientific Report No. 12 (in press)

Snow, M., Holsclaw, G., McClintock W. E., and Woods, T. N. (2007) Absolute ultraviolet irradiance of the Moon from SORCE SOLSTICE. Proc. SPIE 6677:66770D

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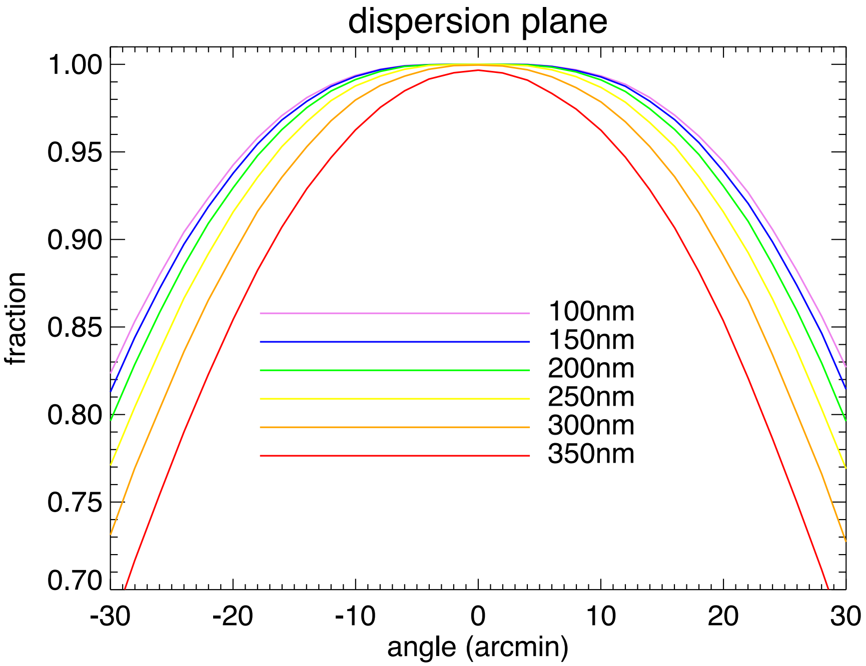
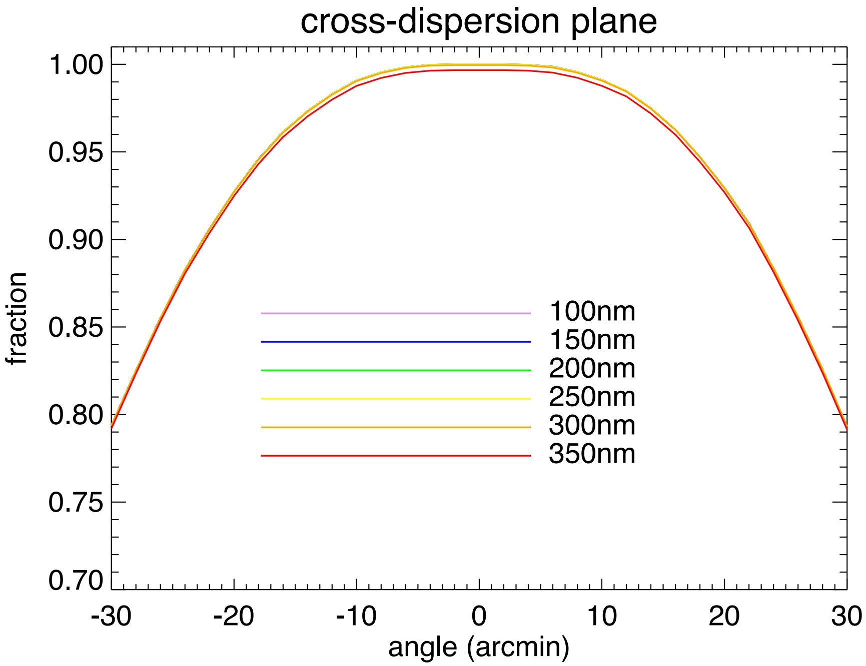
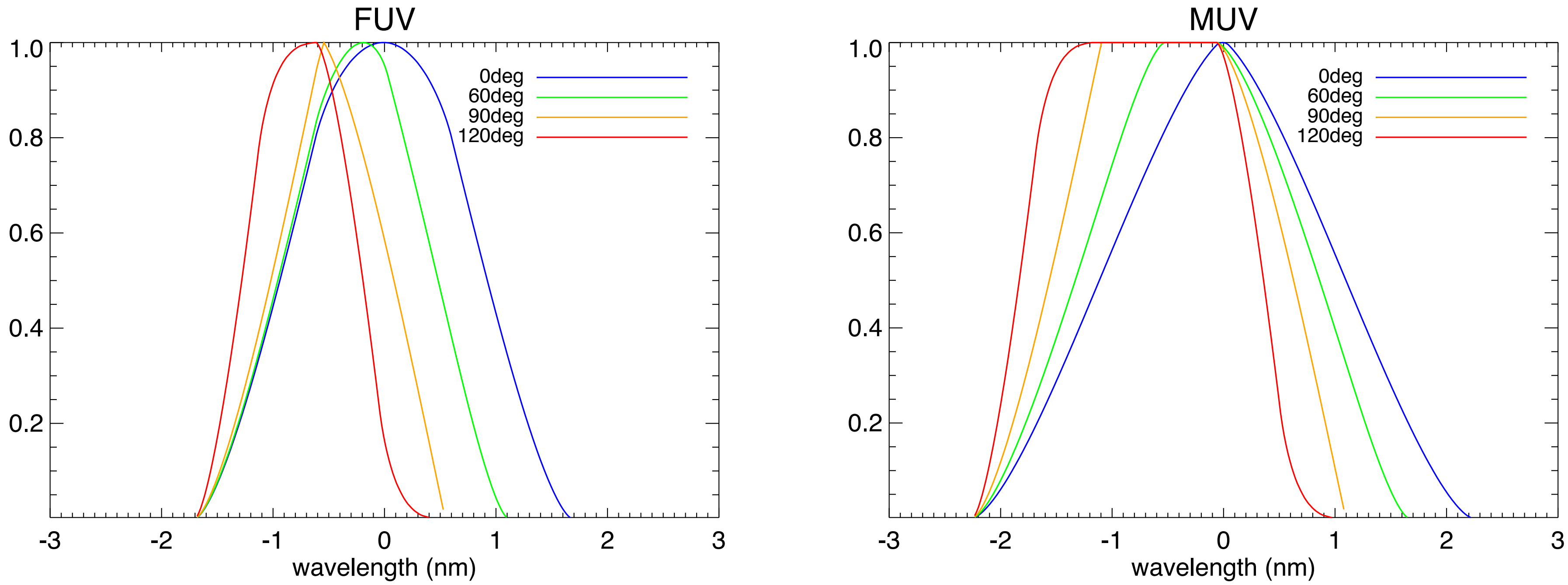
Backup

Vignetting


dispersion plane
fraction
1.00
0.95
0.90
0.85
0.80
0.75
0.70
-30
-20
-10
0
10
20
30
angle (arcmin)
100nm
150nm
200nm
250nm
300nm
350nm

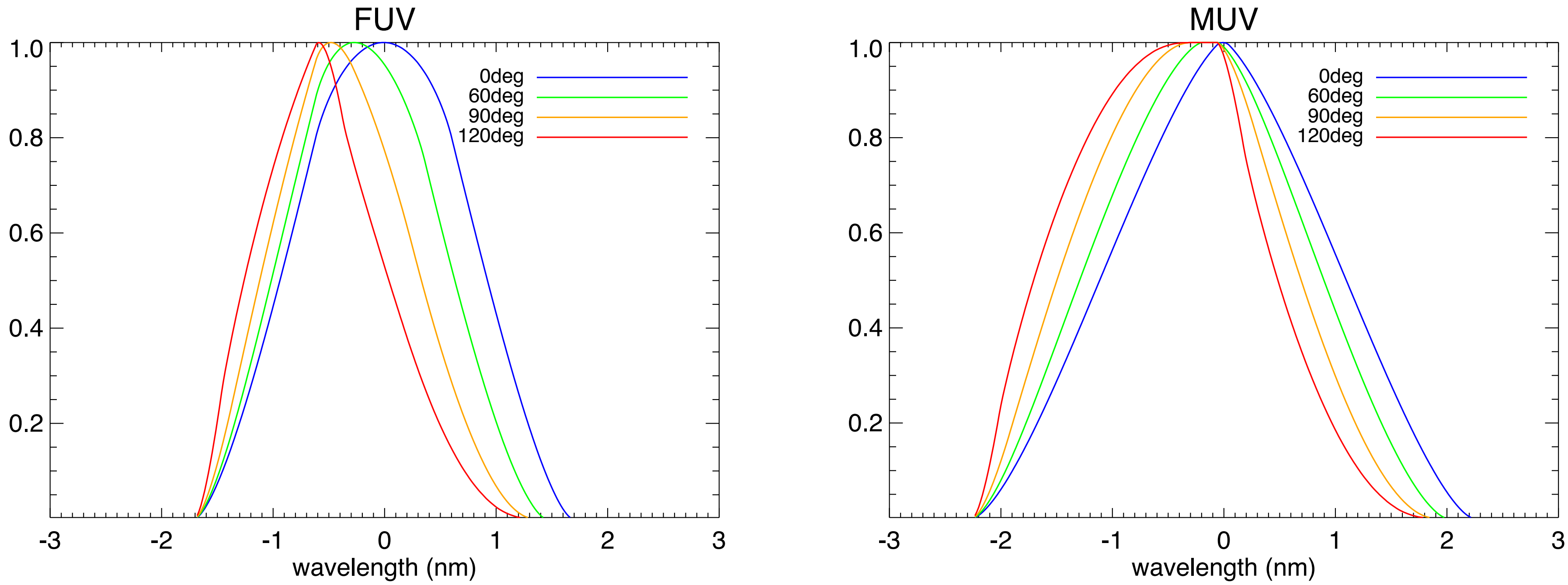

cross-dispersion plane
fraction
1.00
0.95
0.90
0.85
0.80
0.75
0.70
-30
-20
-10
0
10
20
30
angle (arcmin)
100nm
150nm
200nm
250nm
300nm
350nm

Variation in resolution



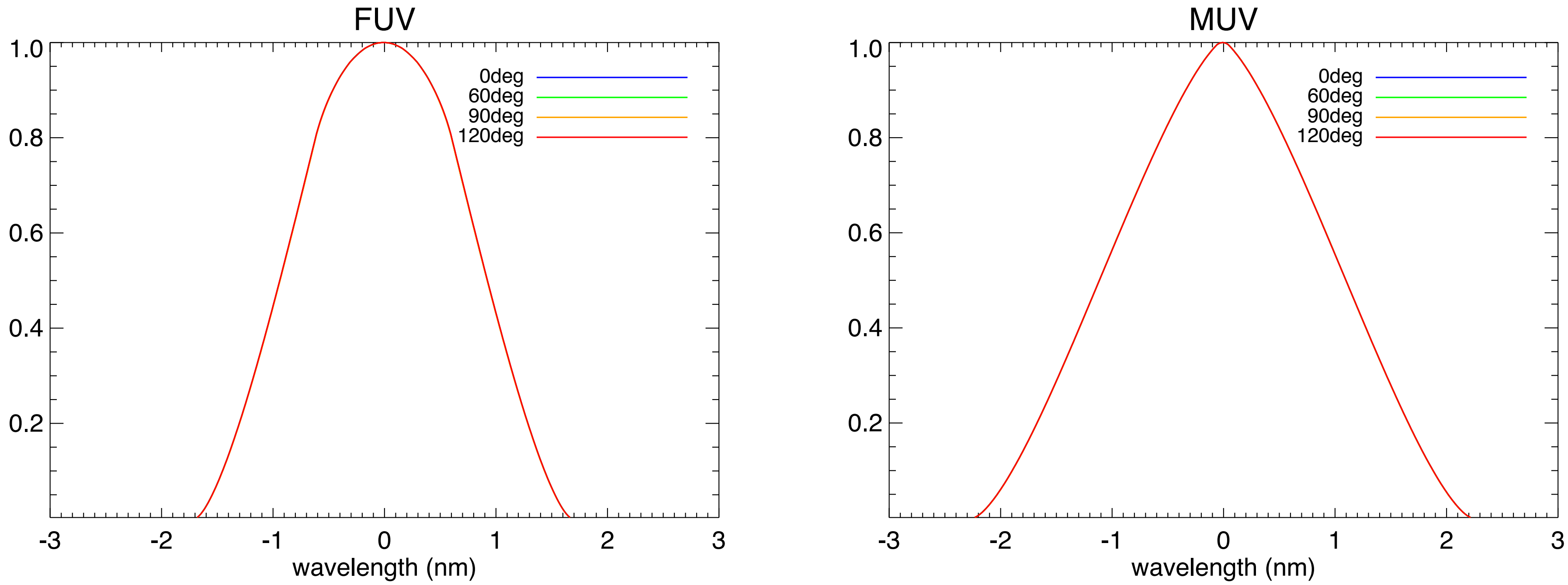
0 degree rotation (terminator perpendicular to dispersion plane)

Variation in resolution



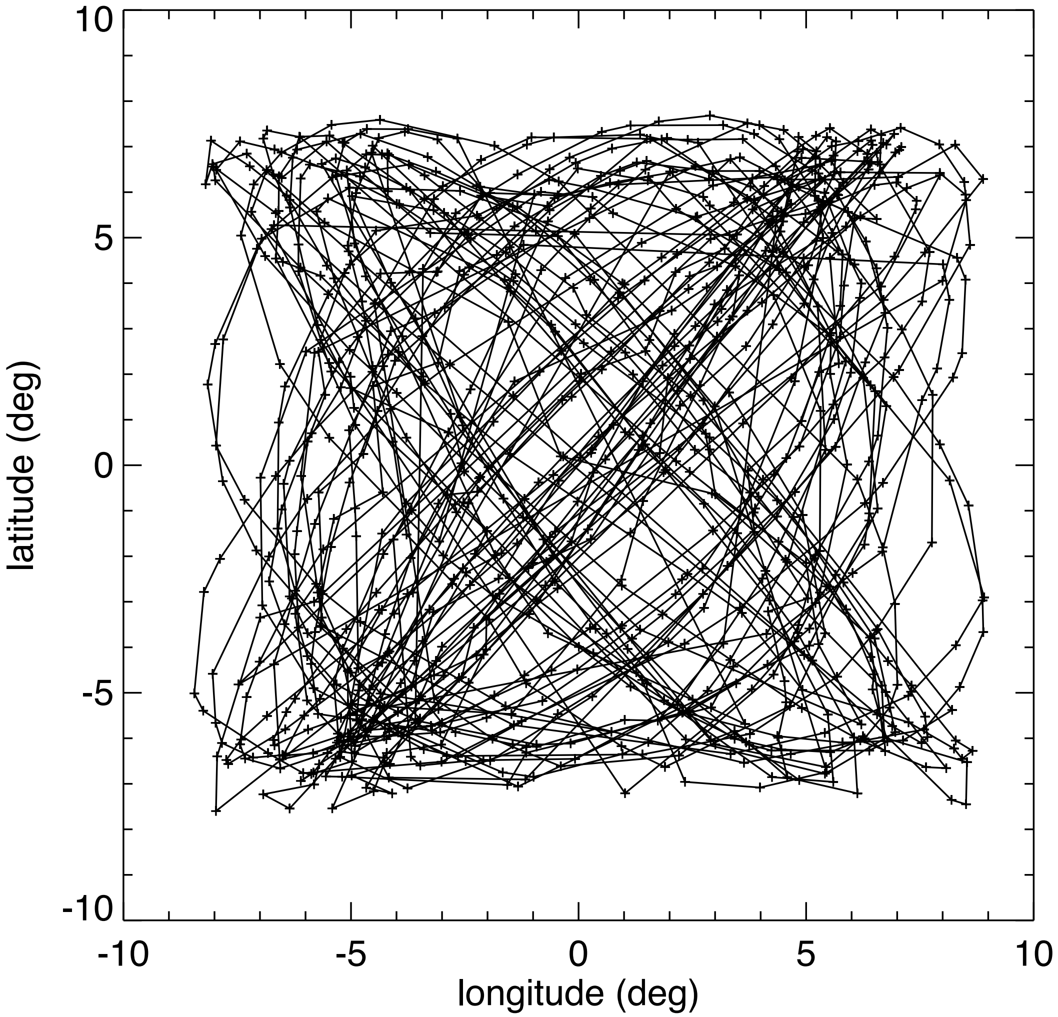
45 degree rotation

Variation in resolution



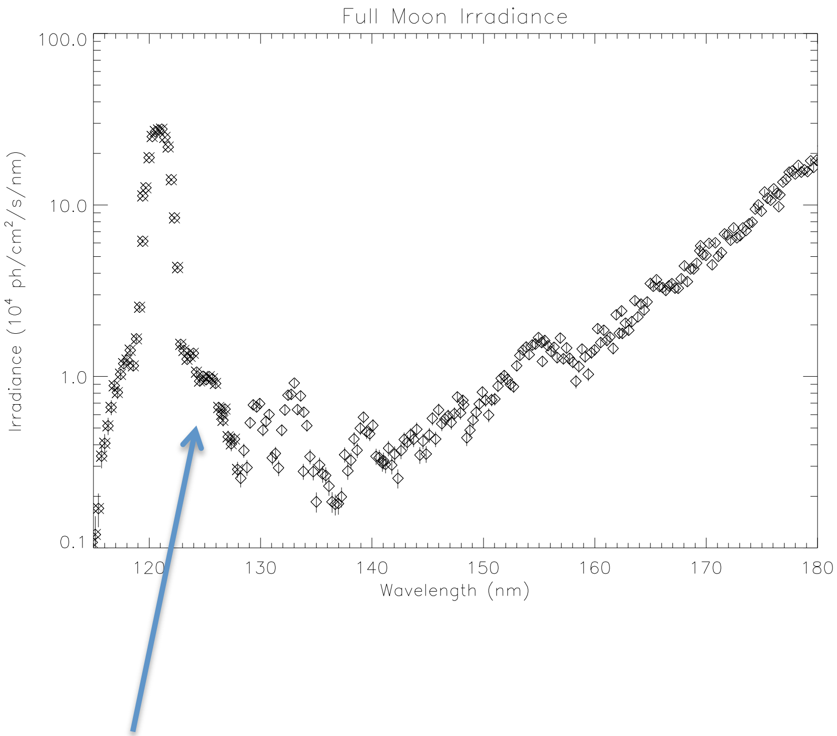
90 degree rotation (terminator parallel to dispersion plane)

Libration coverage

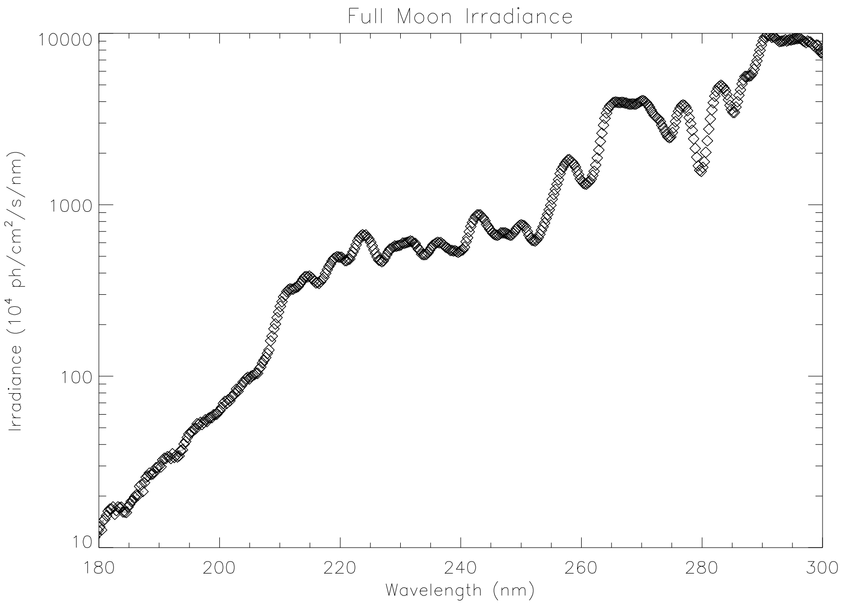


- Selenographic coordinates of the sub-spacecraft point for all observations

Lunar Irradiance Spectra



Geocoronal hydrogen contamination



Phase angle 2 degrees

Variability of solar irradiance with wavelength

- Visible wavelengths (>400nm): ~0.1%
- Middle-ultraviolet (200-300nm): ~2-3%
- Far-ultraviolet (100-200nm): 10-40%

Solar variability

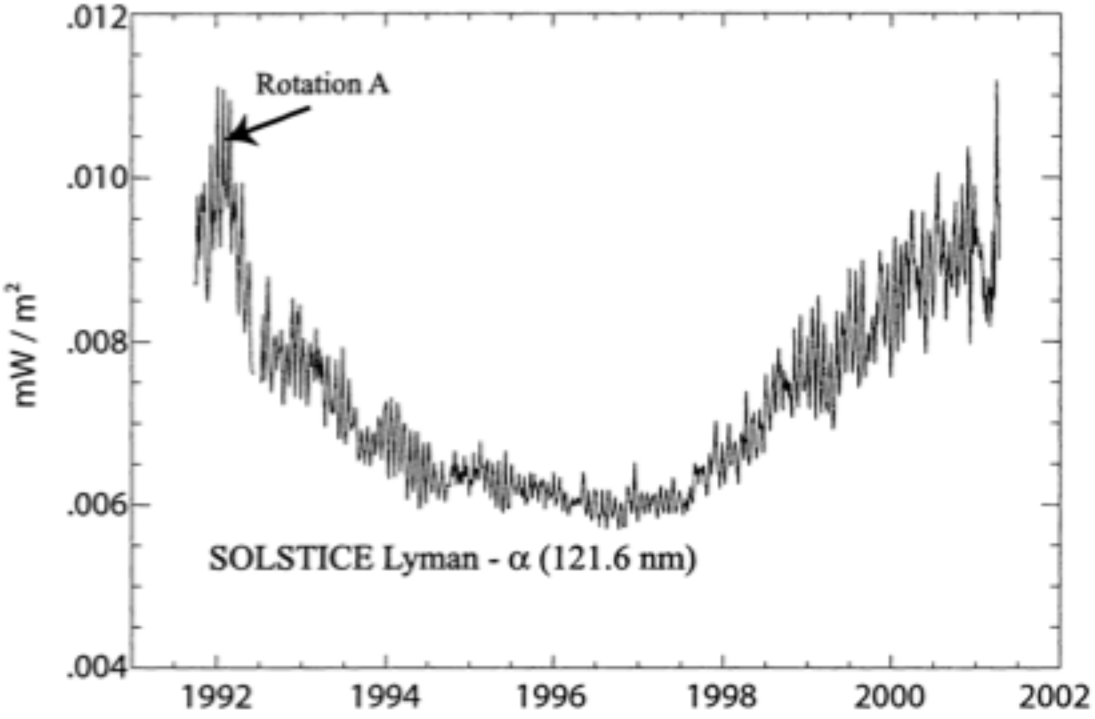


Figure 2. Time series from 1991 to 2001 of *UARS* SOLSTICE data for the single wavelength 121.6 nm. This is the strong Lyman-α emission line of atomic hydrogen.

- Plot of the solar irradiance at 121.6nm vs time
- This illustrates the two different time-scales of solar variability:
  - 27 day rotation
  - 11 year solar cycle

Reference: G. Rottman, The solar irradiance and its variations, The Evolving Sun and its Influence on Planetary Environments. ASP Conference Proceedings, Vol. 269., 2002., p.25

27-day variation

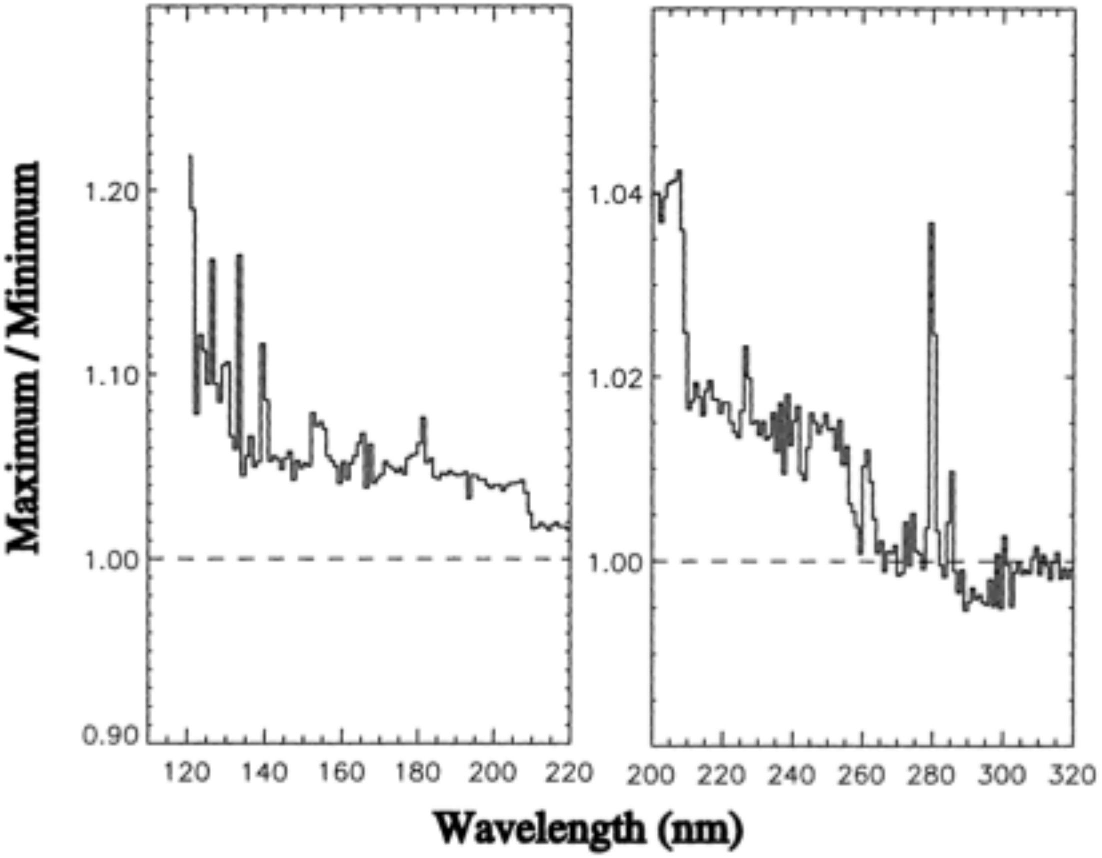


Figure 4. Solar 27-day variation as a function of wavelength for the specific rotation identified "A" in Figures 2 and 3. Similar time series similar are examined for each wavelength from 120 to 300 nm and the ratio of maximum to minimum is calculated for each. The wavelength axis is split at 220 nm in order to expand the scale for the weak variations at the longer wavelengths.

Solar cycle variation (~5.5 year)

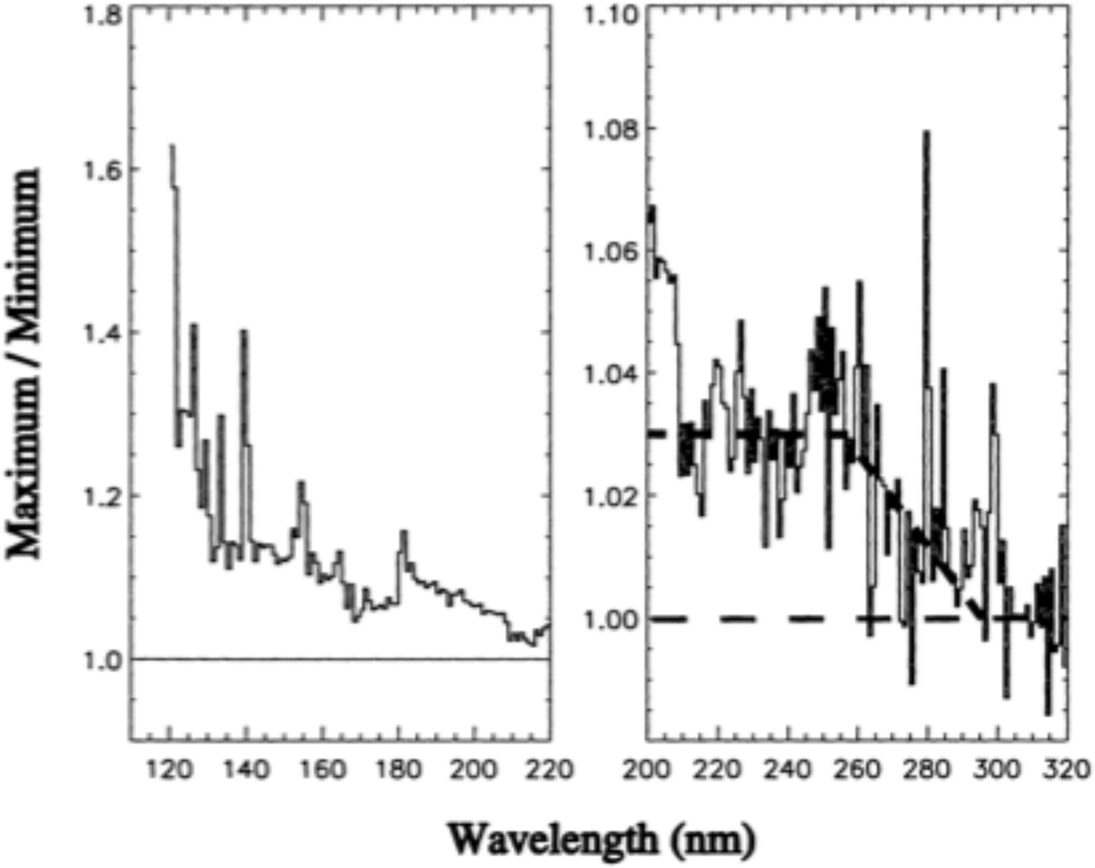
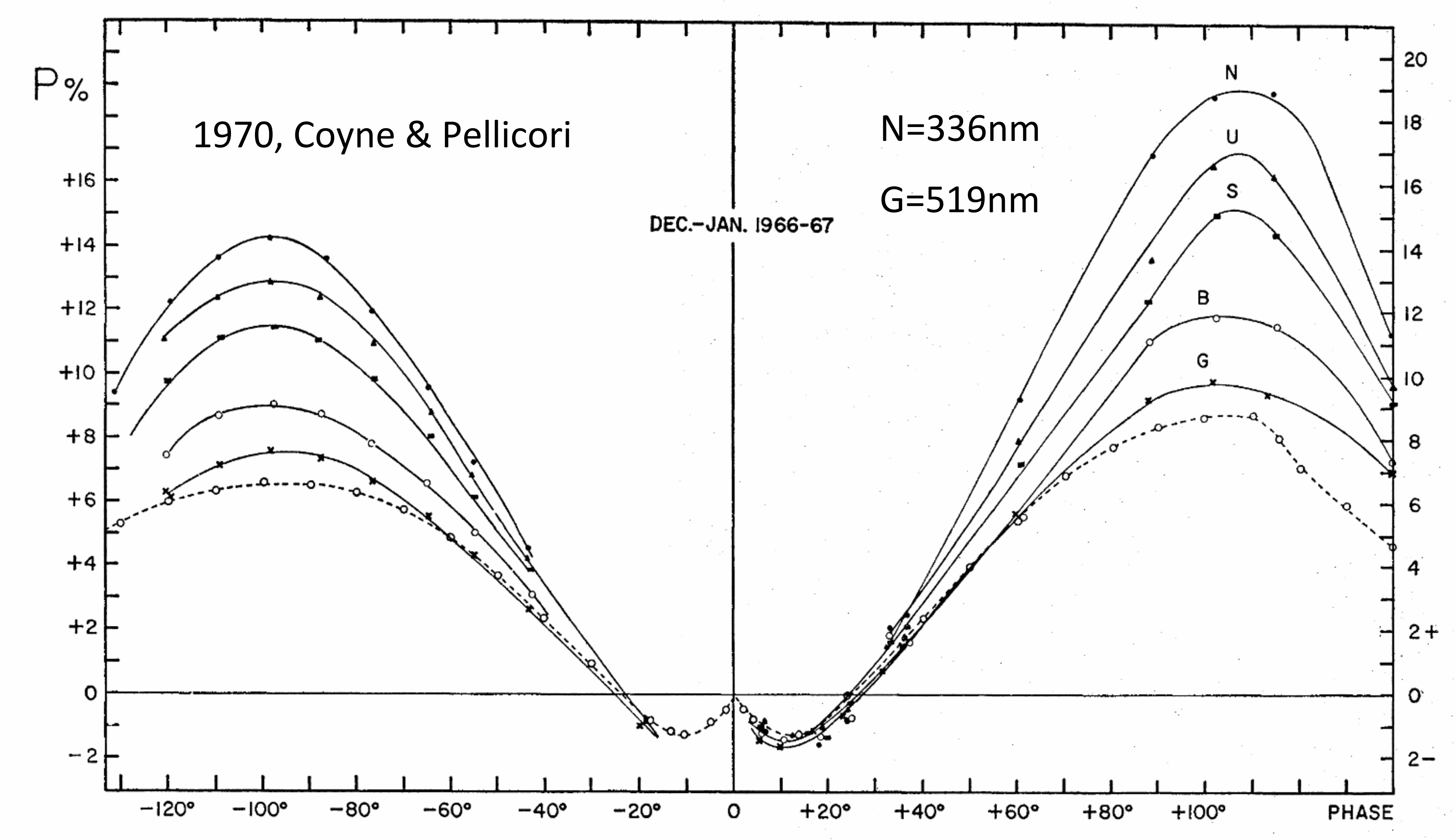


Figure 5. Solar cycle variation as a function of wavelength measured from early in 1992 to a minimum in mid 1996. An 81-day running mean of time series of the type shown in Figure 2 is made to remove the influence of the 27-day variability. This analysis is repeated for all wavelengths from 120 to 320 nm.

Lunar Polarization



1970, Coyne & Pellicori

N=336nm

G=519nm

Fig. 2. Percentage polarization of moon as a function of wavelength and phase angle. Dashed curve is taken from Lyot (1929).