Implementation of Improved Magnitude Parameters for Solar System Planetary Ephemerides

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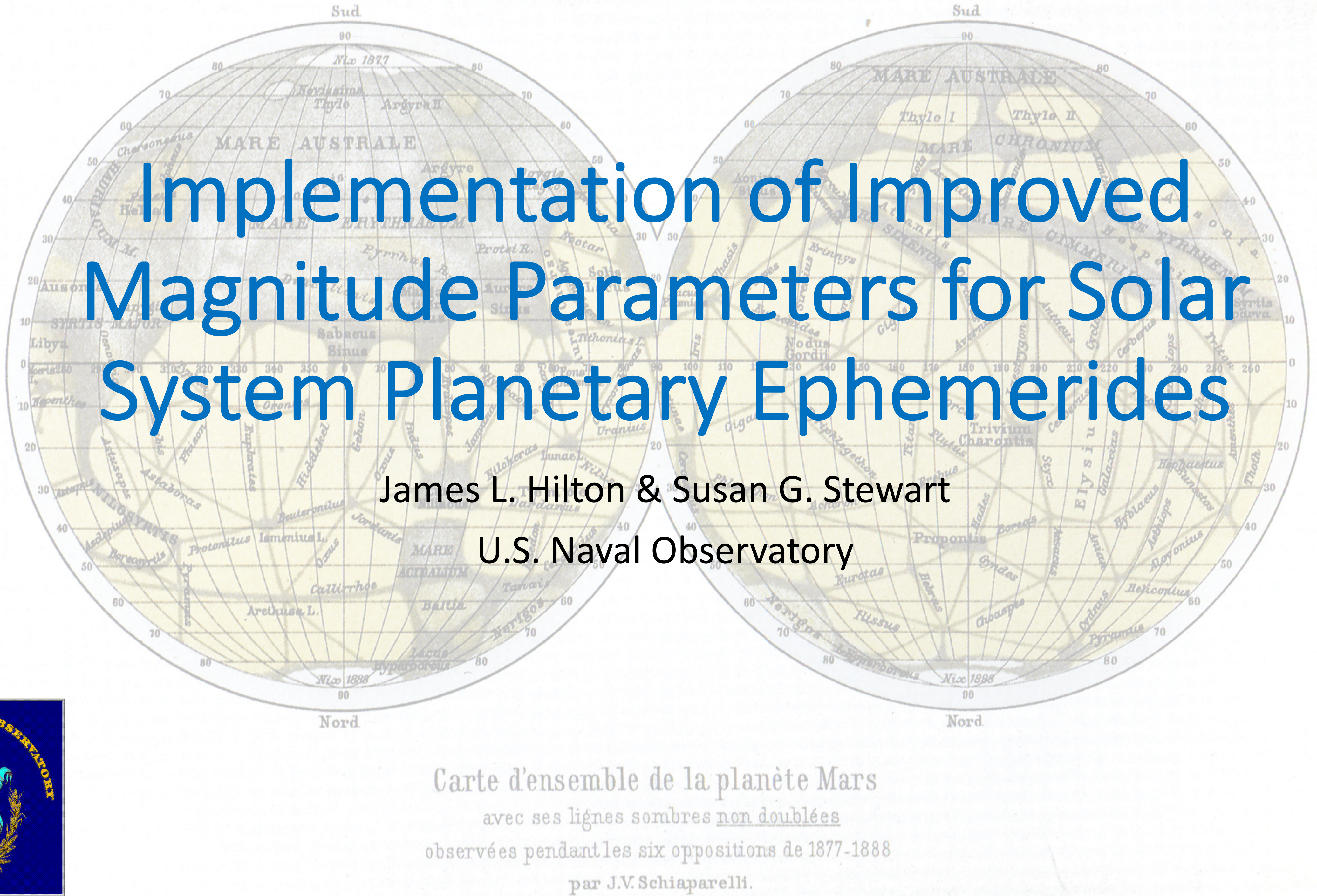
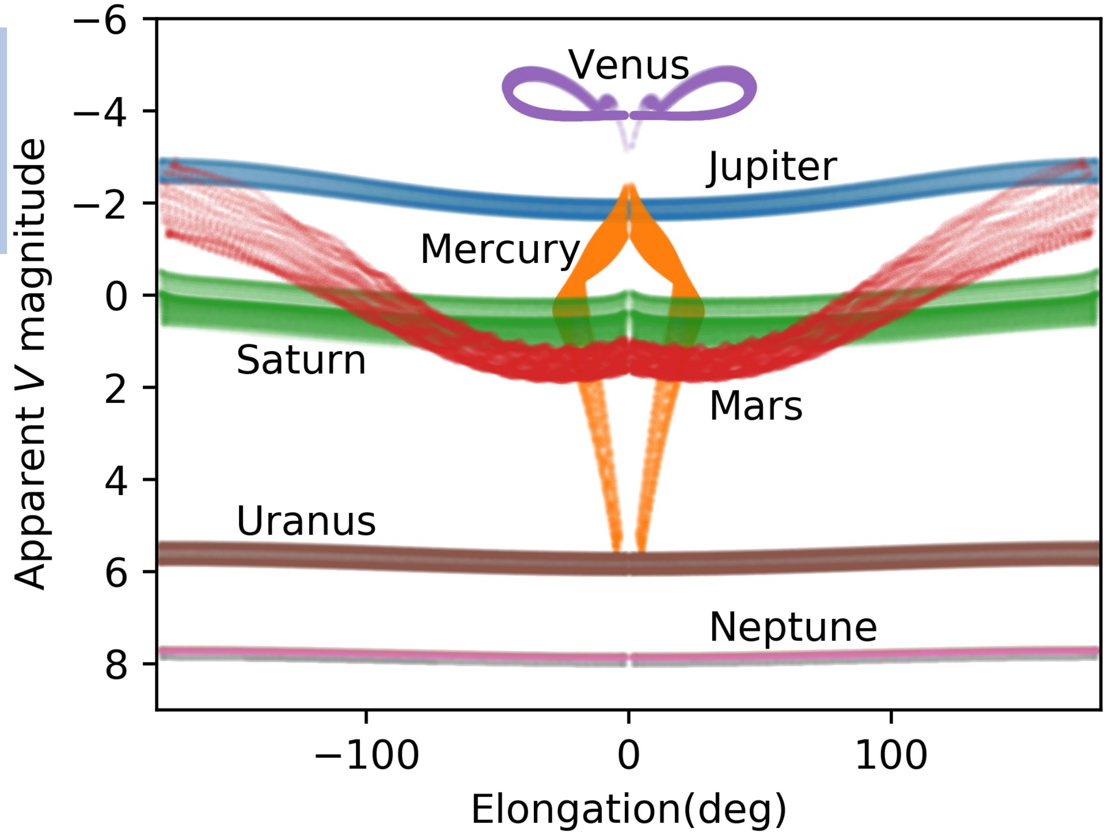


The apparent magnitudes for each of the planets constitutes a special case:

- Mercury and Venus have phase angles as great as 180°
- Mercury and Mars have surface markings
- Venus' atmosphere produces a glory



- Mars has observable dust storms and seasons
- Saturn has rings that can be brighter than the planet itself
- The sub-Earth and sub-solar latitudes on Uranus vary almost from pole to pole

Beginning with the 2021 edition *The Astronomical Almanac* will feature new algorithms for the ephemerides of the apparent magnitudes of the planets

Except for Mercury and Venus (Hilton 2005), previous algorithms for computing planetary magnitude taken from Harris (1961)

- Improved accuracy required for identification and planning.
    - Previous algorithms might be accurate to 10% (25% for Mars) in flux
    - New algorithms accurate to about 4% for outer planets, 6-8% for Mercury and Venus and 20% for Mars
- Reignites dormant branch of ephemeris research at an opportune time
    - Required for interpretation of data from direct imaging studies of exoplanets – such as HabEX

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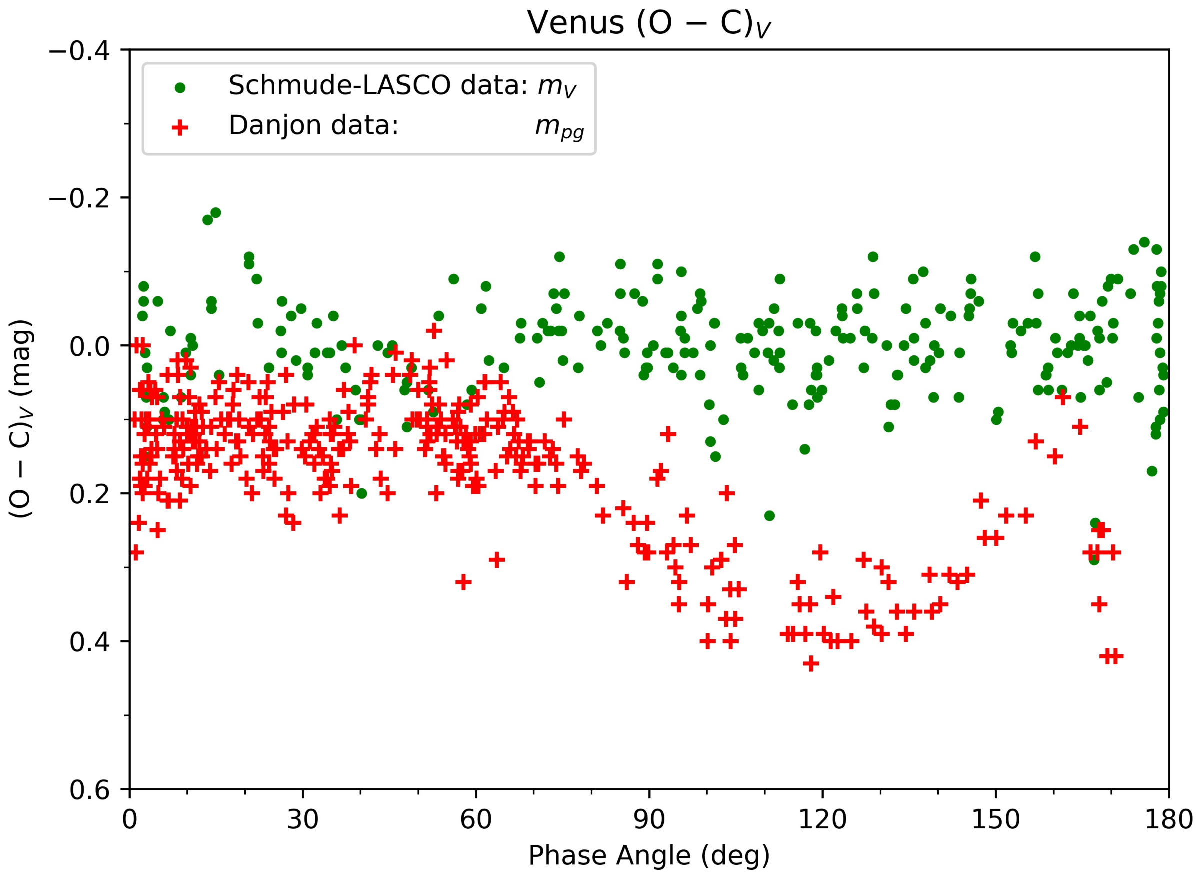
- Harris (1961) based on Danjon's photographic observations
- Observations were linearly corrected from m_{pg} to m_V but there is an obvious offset and non-linearities at large phase angles between the two data sets.

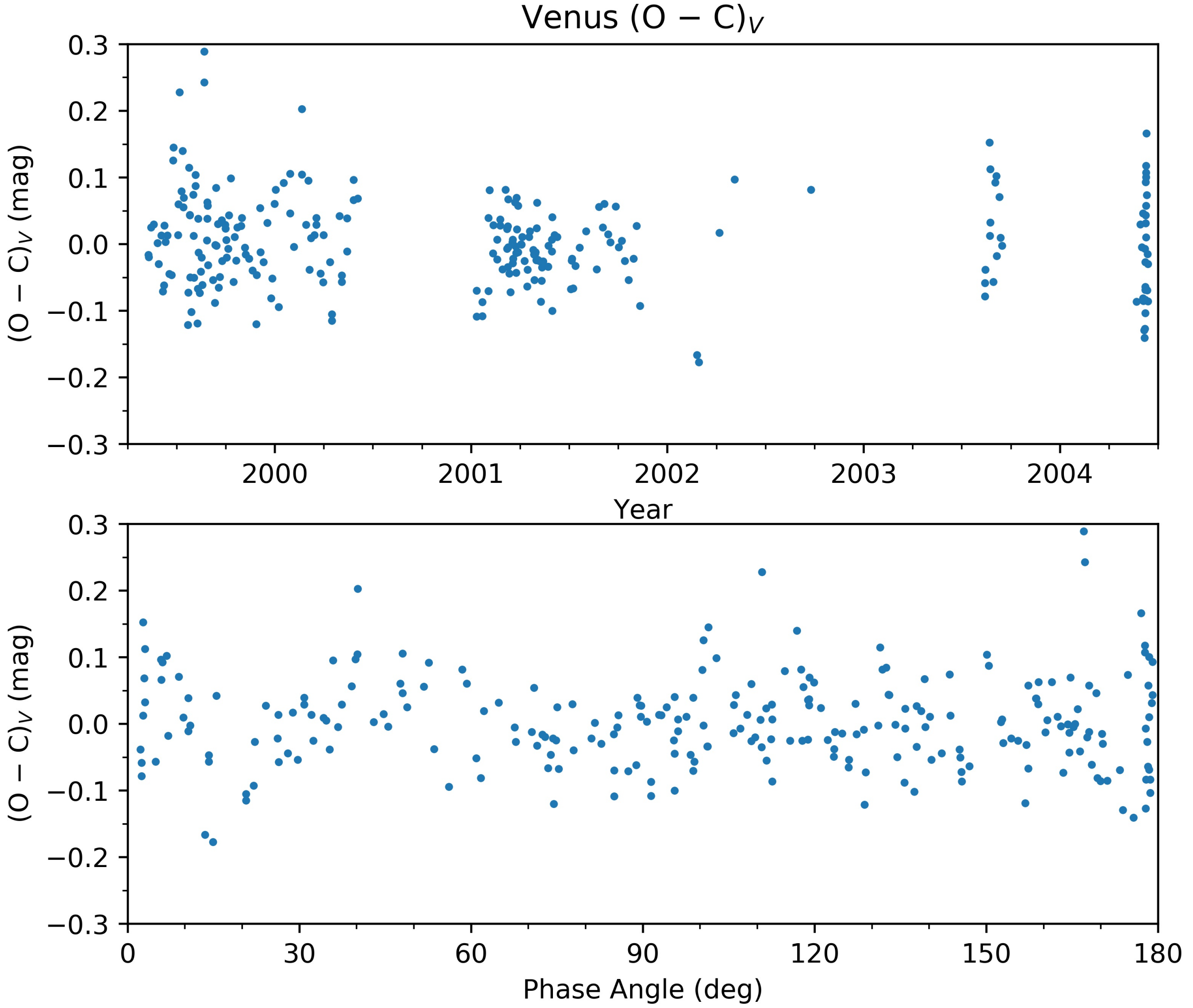


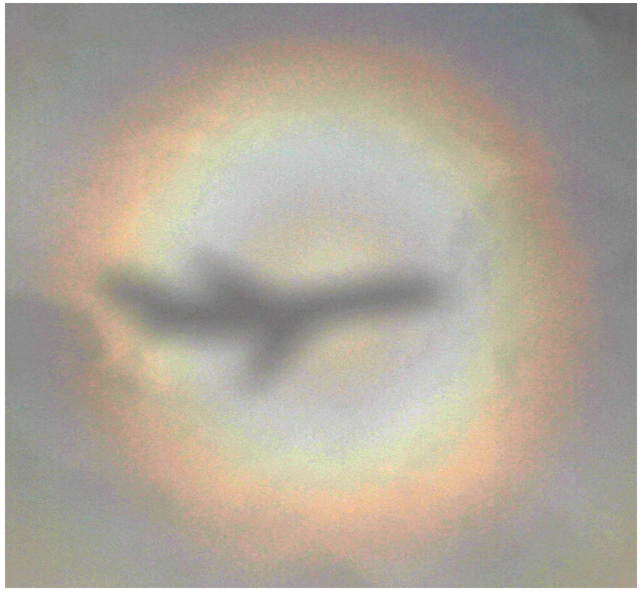
The only parameters used in the old algorithm were planet-Earth and planet-Sun distances, phase angle, and ring tilt for Saturn

- Mars and Mercury have significant surface albedo features
- Mars has seasonal changes
- Disentangling Saturn from its rings is non-trivial
- Phase angles are insignificant for Uranus and Neptune
- Uranus' has significant change in albedo with latitude and has a maximum sub-Earth latitude near 90°.
- Neptune may have a time-varying albedo but it may also change with latitude.

Future Work: Venus

Zone	Phase Angle Range	RMS uncertainty
	(deg)	(mag)
Glory	0 – 5	0.08
Mid-range	5 – 165	0.06
Forward Scatter	165 – 180	0.07





The current algorithm fit the glory and mid-range sections with a single polynomial possibly degrading the quality of the fit.

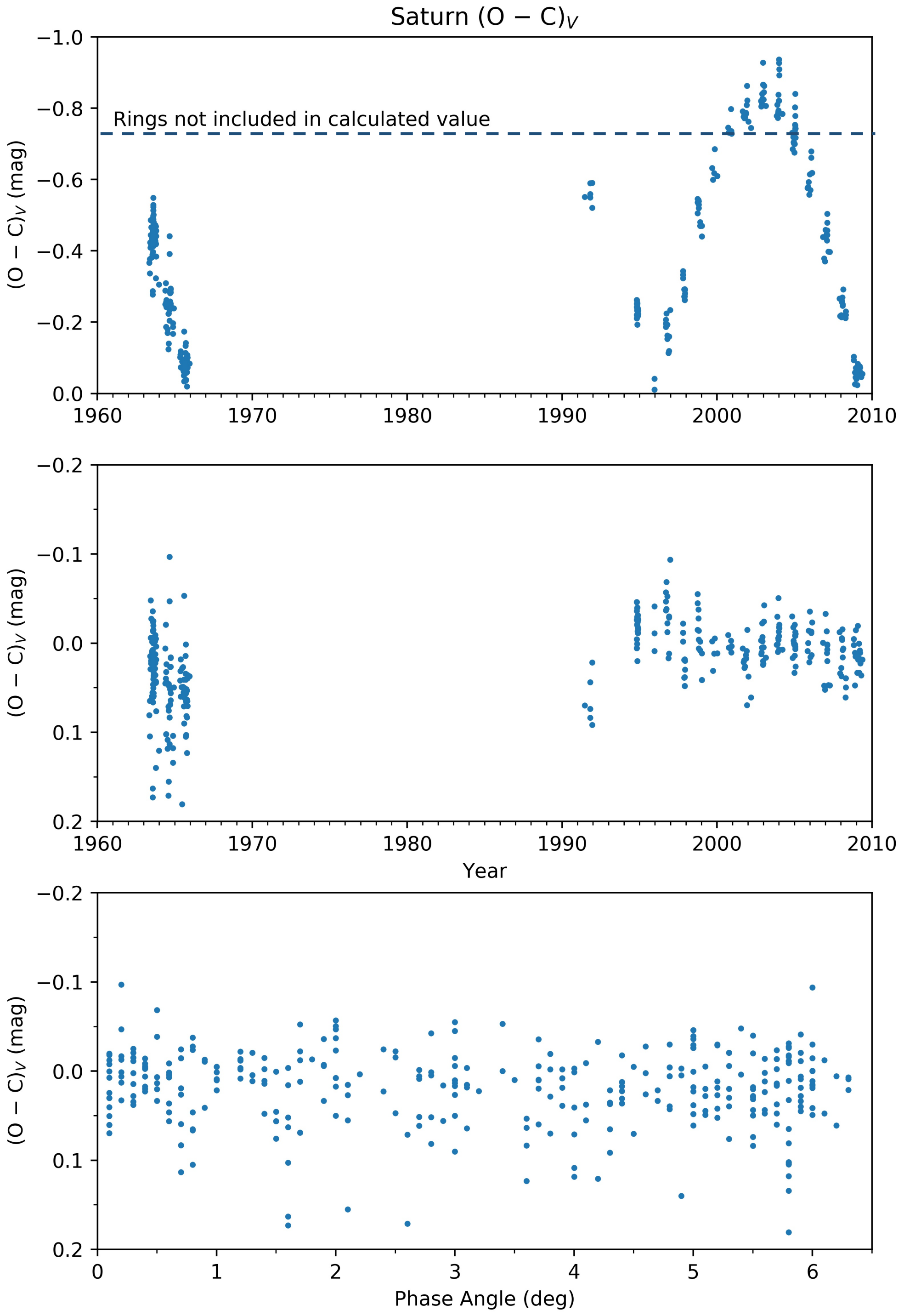
Future Work: Saturn

Selection	RMS uncertainty
	(mag)
Planet and rings	0.04
Planet alone	0.24

The rings alone can be brighter than the planet alone.

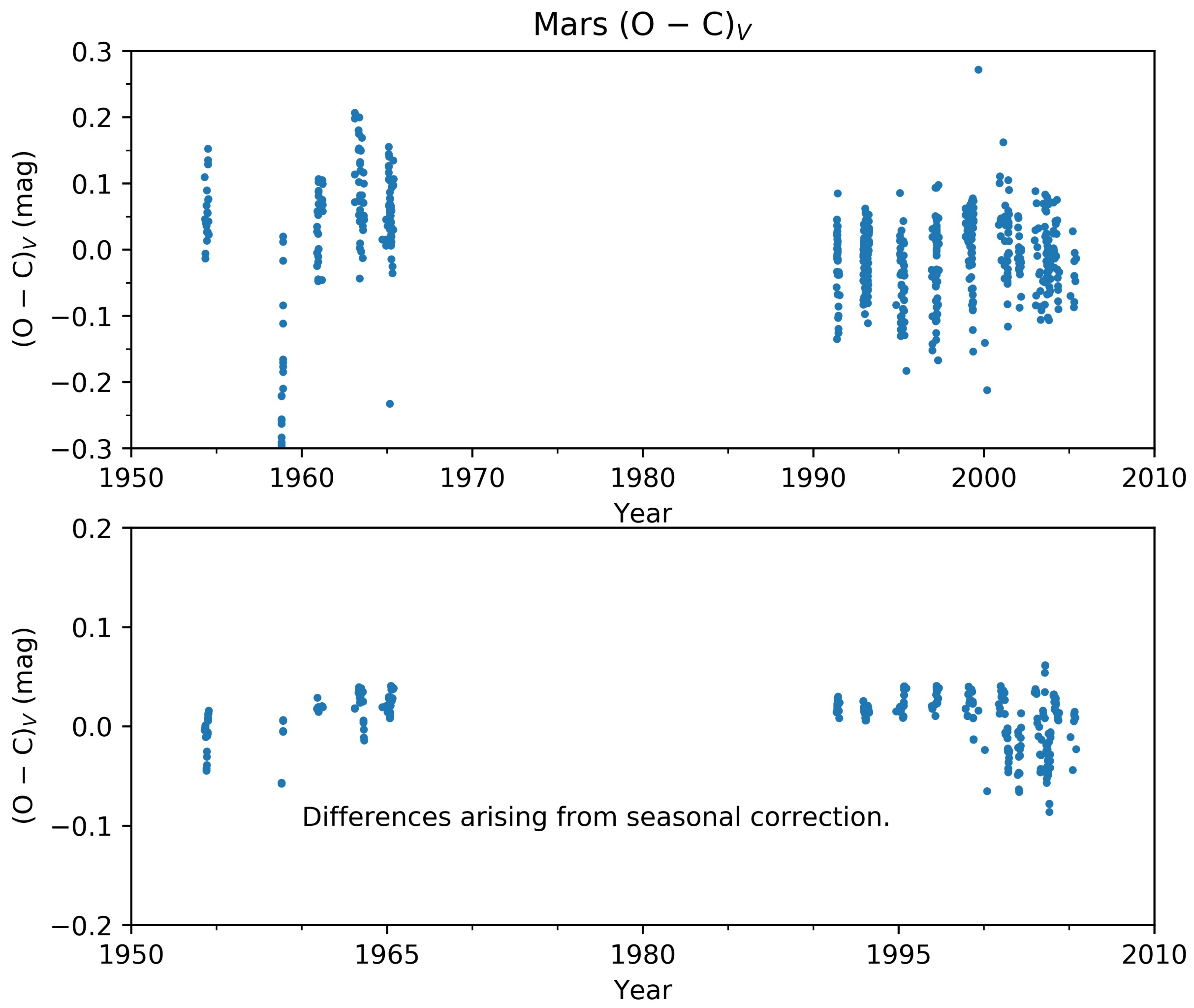
The uncertainty in the planet itself is much greater than for the planet-ring system

- This increases the uncertainty in the average surface brightness.



Future Work: Mars

Parameter	Variation in V
	(mag)
Mars – Earth distance	4.28
Mars – Sun distance	0.41
Phase Angle	0.78
Season	0.15
Rotation	0.11



The surface markings on Mars are a major problem.
The current seasonal correction primarily provides an offset in the mean V that varies from year to year.

Future Work: General

- The RMS uncertainty in the apparent magnitudes of Jupiter, Uranus, Neptune, and Saturn including its rings is 0.04 mag
  - This may be the limit to predicting the apparent magnitudes of planets with opaque atmospheres
- Goal is to reach an RMS uncertainty of 0.04 mag for all the planets including Saturn without its rings.
- It is unclear at this time how to resolve the issue of Mercury and Mars’ surface markings. May not be achievable for Mars, but reducing the RMS uncertainty to 0.1 mag is

Future Work: General (Continued)

- All of the planets suffer from spotty observation histories and older (pre-photoelectric photometer) observations are unreliable
- There may be a systematic problem with the reduction of observations.

Additional Slides

References

- Harris, D.L. 1961 “Photometry and Colorimetry of the Planets and Satellites,” in *Planets and Satellites*, G.P. Kuiper & B.A. Middlehurst, eds. (Chicago: U of Chicago Press), 272–342
- Hilton, J.L. 2005, “Improving the Visual Magnitudes of the Planets in *The Astronomical Almanac*. I. Mercury and Venus,” *Astron. J.*, **129**, 2902–2906
- Mallama, A. 2007, “The Magnitude and Albedo of Mars,” *Icarus,* **192**, 404–416
- Mallama, A. & Hilton, J.L. 2018, “Computing Apparent Planetary Magnitudes for *The Astronomical Almanac*,” *Astron. Comput*., **25**, 10–24

Algorithms (Mallama & Hilton 2018)

- All Planets

$$V = 5 \log_{10} (r\, d) + \Delta V$$

V = the apparent magnitude

r = the planet-Sun distance

d = the planet-Earth distance

ΔV = the planet specific algorithm

- Mercury

$$\Delta V = -0.613 + 0.063280\,\alpha - 0.0016336\,\alpha^2 + 3.3644 \times 10^{-5}\,\alpha^3 - 3.4265 \times 10^{-7}\,\alpha^4 + 1.6893 \times 10^{-9}\,\alpha^5 - 3.0334 \times 10^{-12}\,\alpha^6$$

α = the phase angle in deg, $2\overset{\circ}{.}1 < \alpha < 169\overset{\circ}{.}5$

Algorithms (Continued)

- Venus

$$\Delta V = \begin{cases} -4.834 - 0.001044\,\alpha + 3.687 \times 10^{-4}\,\alpha^2 \\ \quad - 2.814 \times 10^{-6}\,\alpha^3 + 8.938 \times 10^{-9}\,\alpha^4 & 0.^\circ9 \le \alpha < 163.^\circ7 \\ +236.05828 - 2.81914\,\alpha + 8.39034 \times 10^{-3}\,\alpha^2 & 163.^\circ7 \le \alpha < 179^\circ \end{cases}$$

α = the phase angle in deg

- Mars

$$\Delta V = -1.601 + 0.02267\,\alpha - 0.001302\,\alpha^2 + L(\lambda_e) + L(L_S)$$

α = the phase angle in deg

$L(\lambda_e)$ is a function of the sub-Earth longitude

$L(L_S)$ is a function of the planetocentric orbital longitude of the Sun

Algorithms (Continued)

- Jupiter

$\Delta V = -9.395 - 3.7 \times 10^{-4}\, \alpha + 6.16 \times 10^{-4}\, \alpha^2$

α = the phase angle in deg

- Saturn

$\Delta V = -8.914 - 1.825 \sin \beta + 0.026\, \alpha - 0.378\, e^{-2.25\, \alpha} \sin \beta$

α = the phase angle in deg

β = mean tilt of the ring plane to the Earth and Sun

(If the Earth and Sun are on opposite sides of the ring plane $\beta = 0$)

Algorithms (Continued)

- Uranus

$\Delta V = -7.110 - 8.6 \times 10^{-4}\,\phi + 6.16 \times 10^{-4}\,\alpha^2$

ϕ = the sub-Earth latitude in deg

- Neptune

$$\Delta V = \begin{cases} -6.89 & t < 1980.0 \\ -6.89 - 0.0054\,(t - 1980.0) & 1980.0 \le t \le 2000.0 \\ -7.00 & 2000.0 < t \end{cases}$$

t = the decimal year