Modeling exoplanet phase curves

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Motivation

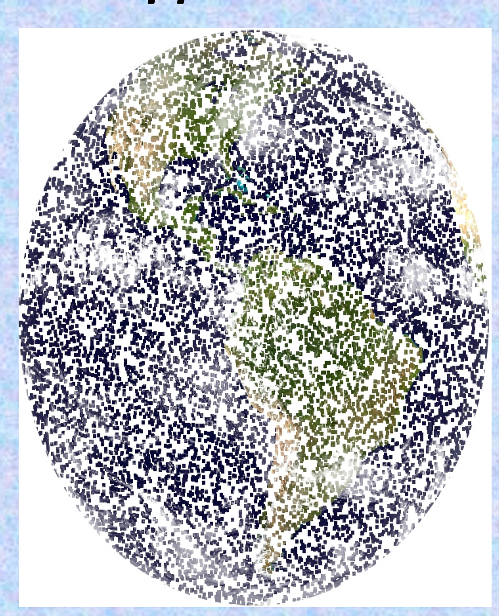
Starlight reflected from a spatially-unresolved planet yields unique insight into the planet's envelope [HH74, MA09]. Exoplanet phase curves have been inferred from Kepler data [DE14,ES14]. Soon, CHEOPS, JWST, PLATO and TESS will also contribute to the available phase curves. We explore a PBMC algorithm [GM14b] to efficiently evaluate the starlight reflected by a planet. The examples explored include Venus and the Earth diurnal light curve as determined from Messenger data. Although the PBMC algorithm produces the full Stokes vector, we here focus on the planets' brightness.

Disk integration with the PBMC algorithm

Backward Monte Carlo algorithms simulate the photon paths from the observer towards the planet; thus each photon contributes to the estimated Stokes vector at the observer's location. In the Pre-Conditioned BMC [GM14b] the accuracy of a solution is proportional to $O(1/N^{1/2})$, where N is the number of simulated photons, and independent of the dimension of the integral to evaluate. Thus, **integration over the disk involves a computational cost similar to the solutions over a spatially-resolved parcel.**

Non-MC approach

MC approach



In the PBMC framework, 10^5-10^6 photon realizations over the disk suffice to provide disk-integrated solutions to within 3% accuracy or better.

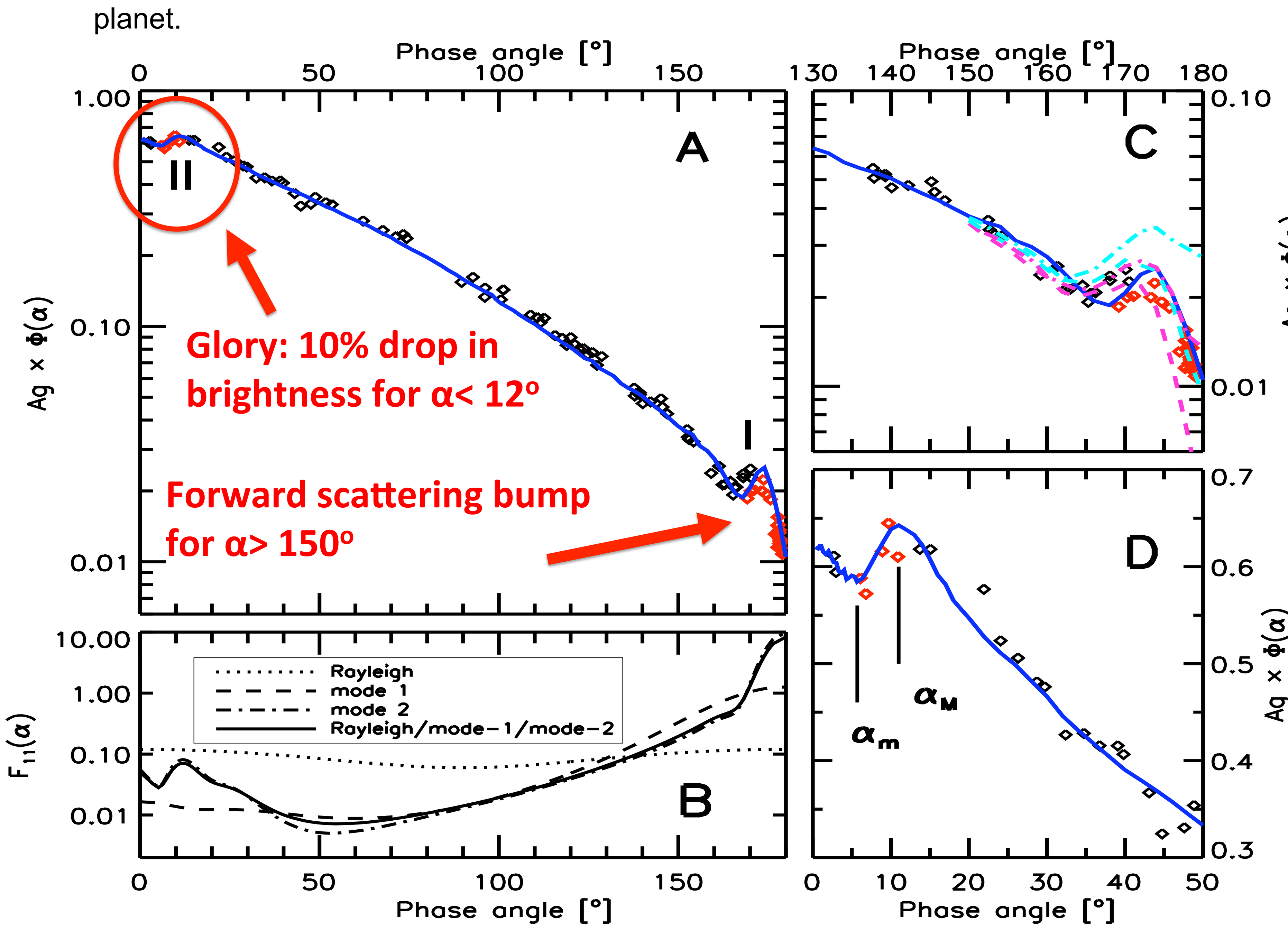
Even for non-uniform atmosphere/cloud / surface configurations, this takes from seconds to one minute to calculate: much less than traditional methods that evaluate the solutions over disjoint parcels and add them later.

This efficiency allows us to quickly explore the space of parameters.

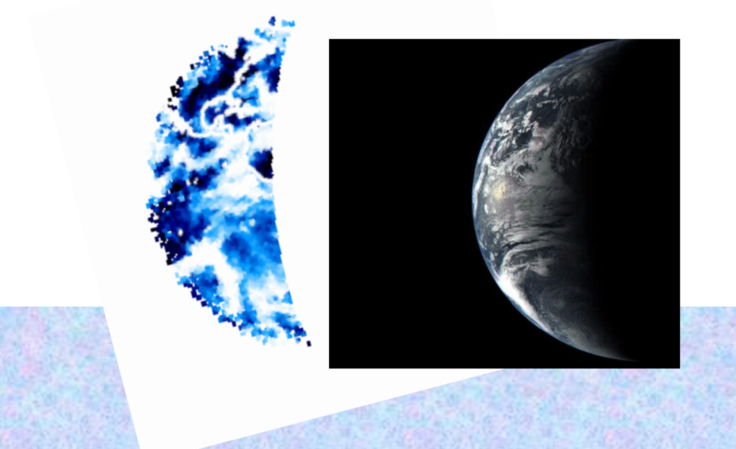
Glory revealed in Venus' disk-integrated photometry

The Venus phase curves have been studied over decades [HH74,MA09]. Venus thus represents a clear example of what we might someday achieve in the investigation of exoplanets [GM14a].

Below: Published brightness phase curve [symbols; MA09] and model predictions [GM14a] (solid). **Feature II** is a ***glory***. It occurs in the backscattering by spherical (liquid) droplets of H_2SO_4/H_2O following a narrow size distribution. This is the first identification of a **glory** in the photometric phase curve of a planet.



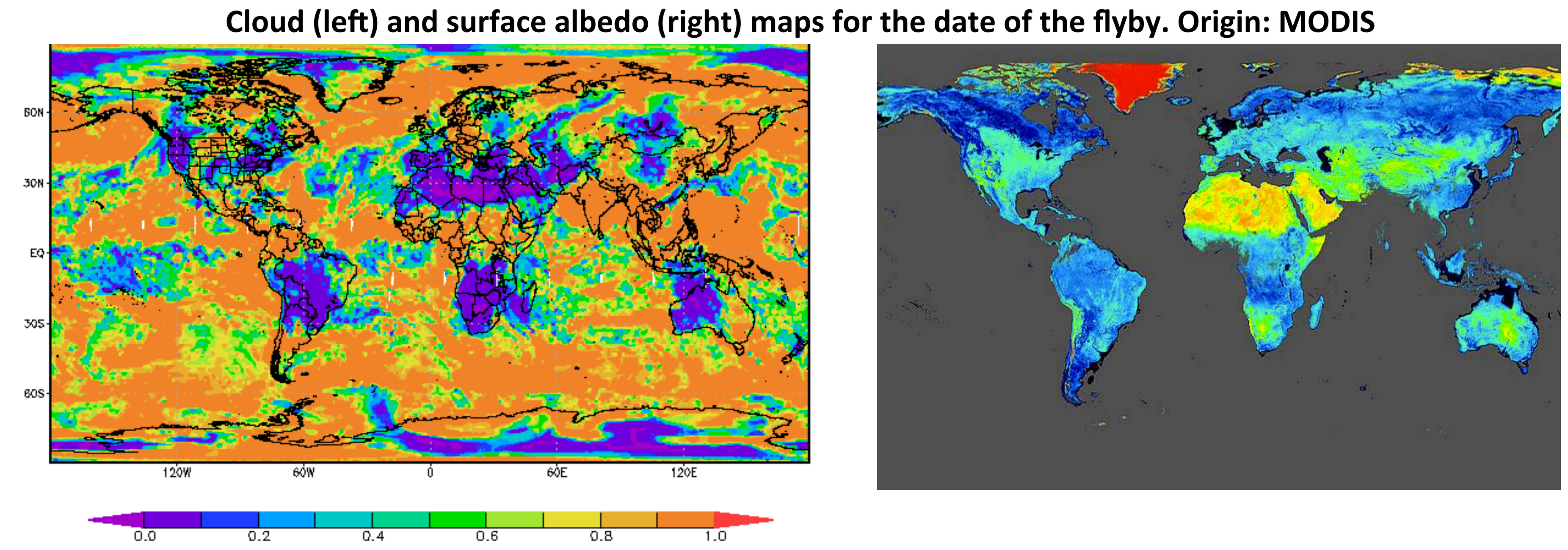
The 2005 Messenger flyby



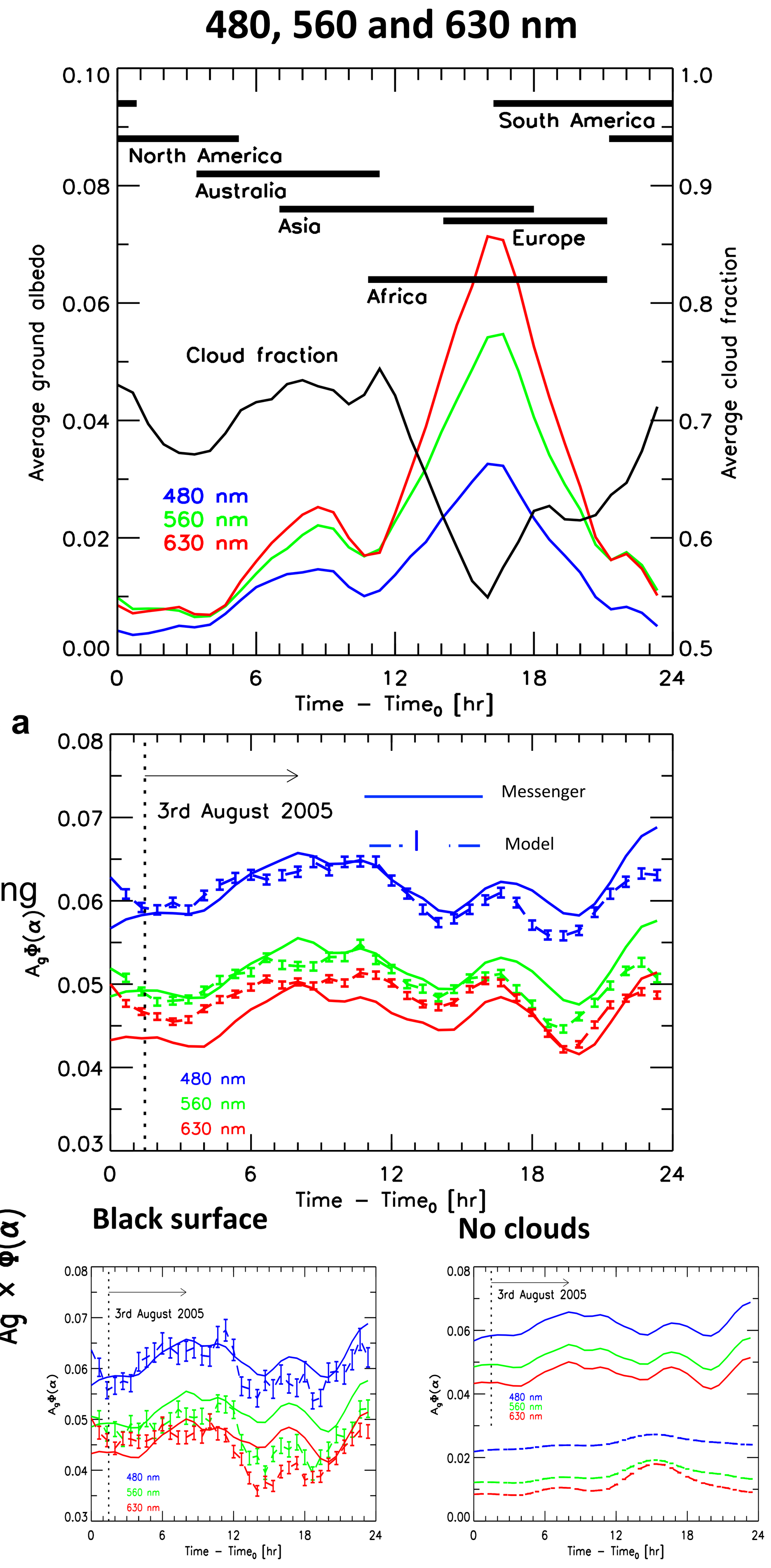
Left: Model-simulated and Messenger image of Earth

In August 2005, Messenger did an Earth flyby. On the departure leg, the Wide Angle Camera captured images of the planet for 24 hours at 3 separate wavelengths. The corresponding diurnal light curves show changes in the planet's brightness that correlate with the cloud fraction and/or the surface albedo. The simulations utilize cloud fractions for the flyby date (3rd August 2005) from MODIS. The wavelength-dependent surface albedos are also from MODIS.

Cloud (left) and surface albedo (right) maps for the date of the flyby. Origin: MODIS

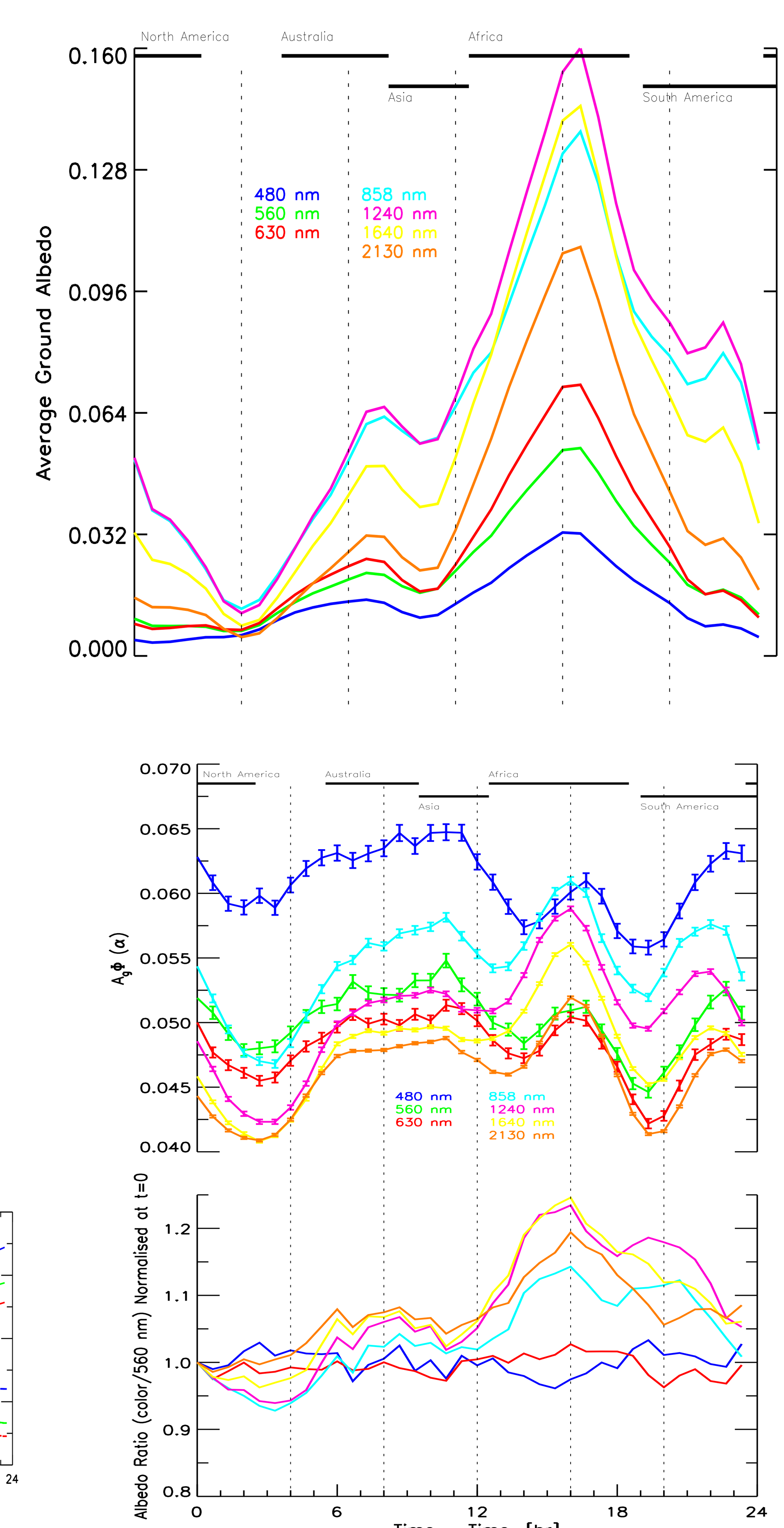


Observed and modeled light curves at 480, 560 and 630 nm



Left: Messenger diurnal light curves and Model simulations. The view of Africa's Sahara desert (low cloud fraction and high albedo) clearly shows up in the Messenger and model light curves.

Modeled light curves from 480 to 2130 nm



Right: Model-simulated light curves from 470 to 2130 nm. Contrasts are highest between 858 and 1640 nm, especially when the Sahara desert is in the field of view.

Summary and outlook

→ The PBMC algorithm can efficiently produce phase curves in brightness/polarization.
→ The PBMC algorithm has been tested against data from Venus and Earth.
→ The Venus phase curves show clear evidence of a glory at small phase angles.
→ Earth modeling suggests the advantages of the NIR to sound surface features.
→ The PBMC algorithm can be used to produce phase curves based on GCM simulations and to investigate earthshine data in both brightness and polarization.

References

[DE13] Demory et al., 2013, Inference of inhomogeneous clouds in an exoplanet atmosphere, ApJL, 776, id.L25.
[ES14] Esteves et al., 2014, Changing Phases of Alien Worlds: Probing Atmospheres of Kepler Planets with High-Precision Photometry, arXiv: 1407.2245.
[GM14a] García Muñoz, Pérez-Hoyos & Sánchez-Lavega, 2014, *Glory revealed in disk-integrated photometry of Venus*, Astron. & Astrophys Leters, 566, id.L1..
[GM14b] García Muñoz, A. & Mills, 2014, F.P., *Pre-Conditioned Backward Monte Carlo solutions to polarization in irradiated planetary atmospheres*, Astron. & Astrophys, arXiv:1408.4019.
[HH74] Hansen, J.E. & Hovenier, J.W. *Interpretation of the polarization of Venus*, Journal of Atmospheric Science, 31, 1137, 1974
[MA09] Mallama, A., *Characterization of terrestrial exoplanets based on the phase curves and albedos of Mercury, Venus and Mars*, Icarus, 204, 11, 2009