The importance of the phase function for both limb scattering aerosol extinction retrievals and estimations of the energy balance effects

Robert Loughman, P.K. Bhartia, Zhong Chen, Philippe Xu, Ernest Nyaku, Ghassan Taha, Surendra Bhatta and Peter Colarco

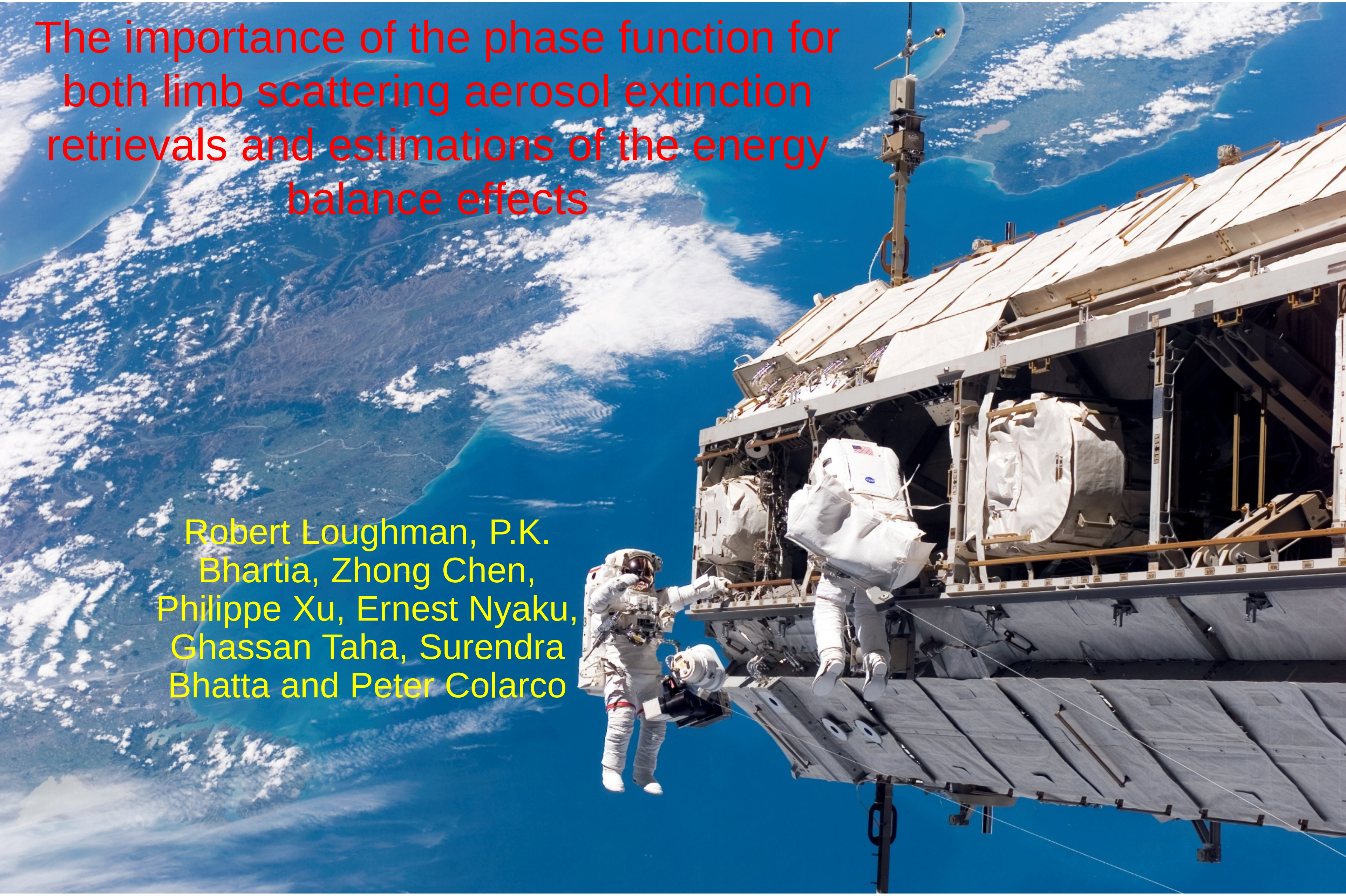

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Photo credit: NASA, STS-116 crew

September 7, 2017 – Workshop on the Measurement of Stratospheric Aerosol 2017

Outline

- How has limb scattering data traditionally been used to characterize stratospheric aerosols?
- What value can we add by combining:
  - Solar occultation (SO) data for extinction properties &
  - Limb scattering (LS) + LIDAR data for scattering properties?
- How can the sensitivity of LS and LIDAR measurements to the aerosol size distribution (ASD) be put to good use?
- What is the scientific value of the aerosol phase function?
- Conclusions and acknowledgements

What stratospheric aerosol properties must we monitor?

- Example: How much solar radiation does the stratospheric aerosol layer reflect back to space?

- *To answer this question, we primarily need to know:*

1. How much aerosol scattering occurs per unit of path length?

   (quantified by its *extinction coefficient, β*)?

2. How is the light scattered by aerosols distributed into various directions?

   (quantified by its *phase function, **P***)?

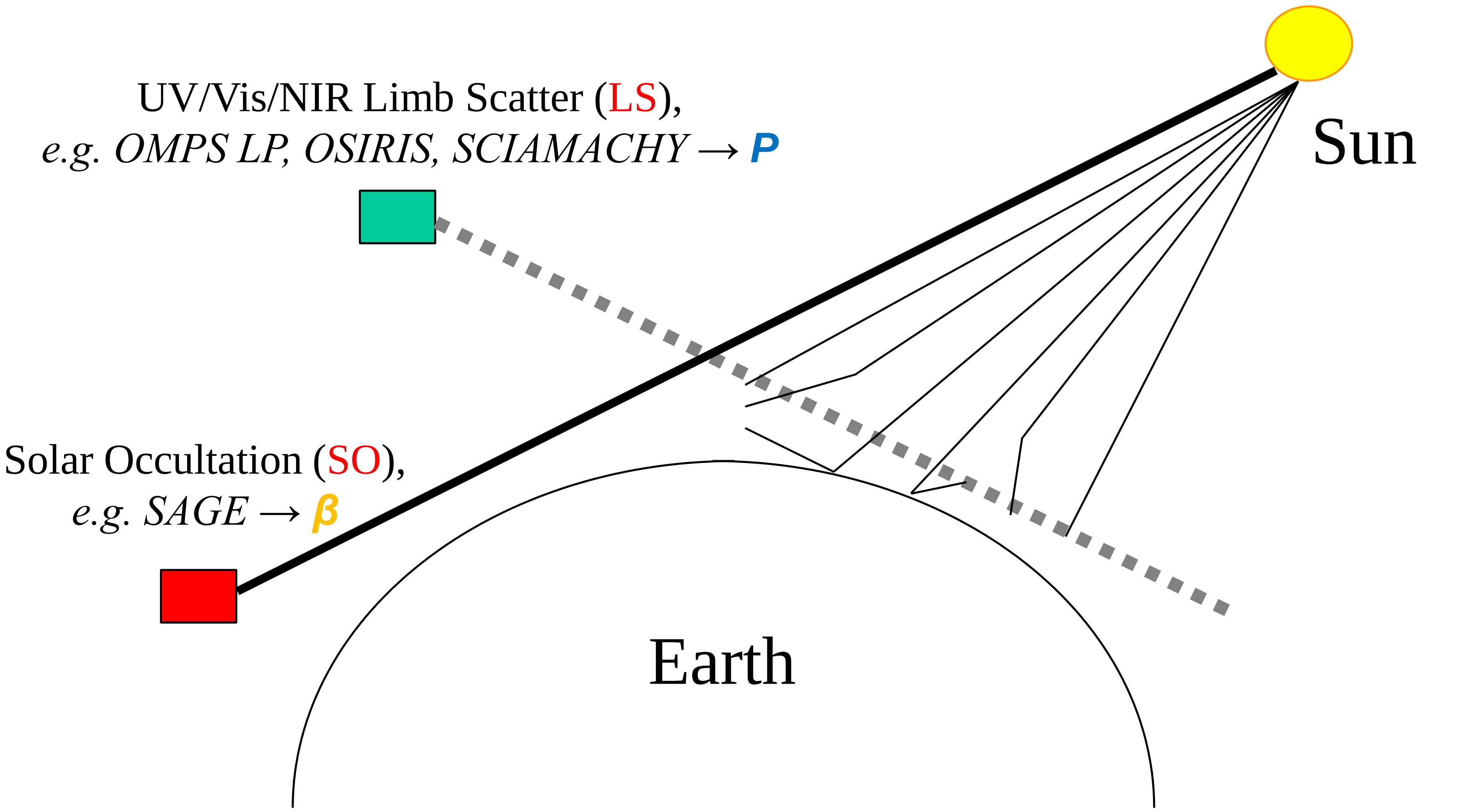
Simplifying assumptions

- Tackle the easiest problem first, and characterize stratospheric aerosols under the simplest possible conditions:
  - An *optically thin* aerosol layer…
  - That is *horizontally homogeneous*…
  - & is composed of *spherical, sulfuric acid droplets*.
- So we're focused primarily on "background" aerosol conditions (perhaps including "aged volcanic" aerosol)
- *Fresh* volcanic plumes often violate all of the criteria above, and represent a much more difficult problem

A simplified history of satellite stratospheric aerosol measurements

- *1980 – early 2000s*: We had SAGE (SO) observations, but no consistent LS measurements
  - SO measures transmission directly (providing ***β***), but tells us nothing at all about ***P***.
- *Early 2000s – 2016*: We had several missions providing LS observations … but no SO measurements
  - LS observations provide much better global coverage… but also are more difficult to interpret
- *February 2017*: SAGE III returns (with both SO and LS measurement modes), + OMPS LP and OSIRIS are still active!
  - So… what can we do with this new combination?

Complementary SO and LS measurements



Ambiguous LS stratospheric aerosol information

- LS observations are influenced by both the extinction and scattering properties of the particles
- The aerosol contribution to the LS radiance scales roughly with the product (*β* **x** ***P***)
- Often, LS observations have been *interpreted* by **assuming *P*** in order to **infer *β***
- We've tried to learn more from LS observations of ***β(λ)****…* but (as learned from SAGE SO studies, and reiterated by Larry yesterday), the wavelength variation of ***β(λ)*** in the 0.5 – 1 µm region contains limited ASD information.

Caveats for LS ASD assumptions

- Of course, a single ASD cannot be correct at all geographic locations, times & altitudes
- Many of the ASDs assumed in LS missions are based on the U. of Wyoming OPC fits, from various places and times
  - But all were defined prior to the corrections proposed by Kovilakam and Deshler (2015)
  - And all were defined without the recently-added size bin near r ~ 0.075 µm
  - We are particularly sensitive to the **coarse mode fraction (CMF) & the number of particles near** r **~ 0.1 µm**

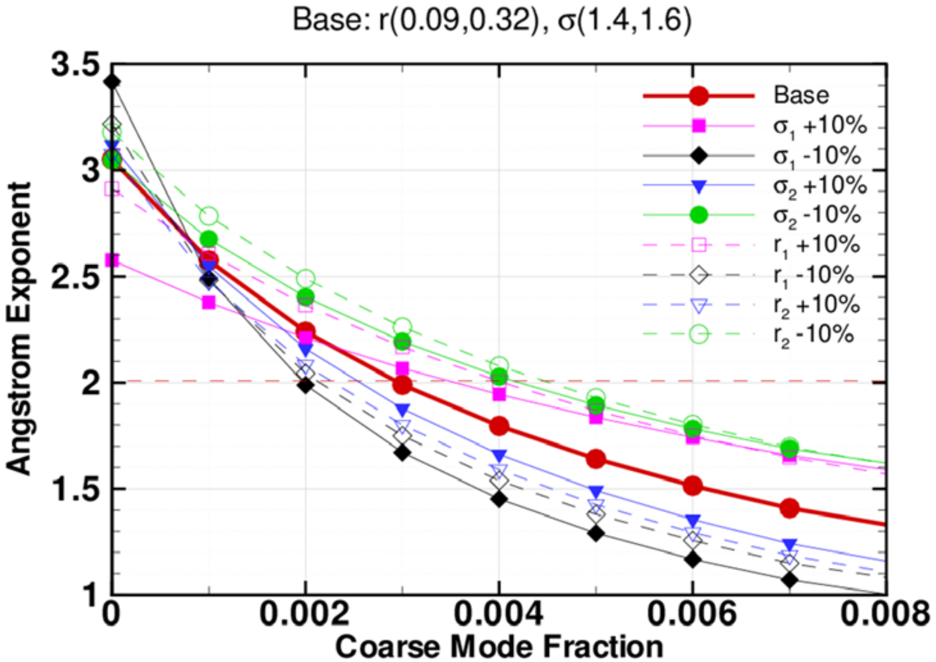
Origin of the V1 OMPS LP ASD

- Guided by the SPARC ASAP report (2006), we sought a bi-modal log-normal ASD, consisting of:

  A *dominant fine mode* (background aerosols), +

  a *small coarse mode* (relatively fresh volcanic aerosols)

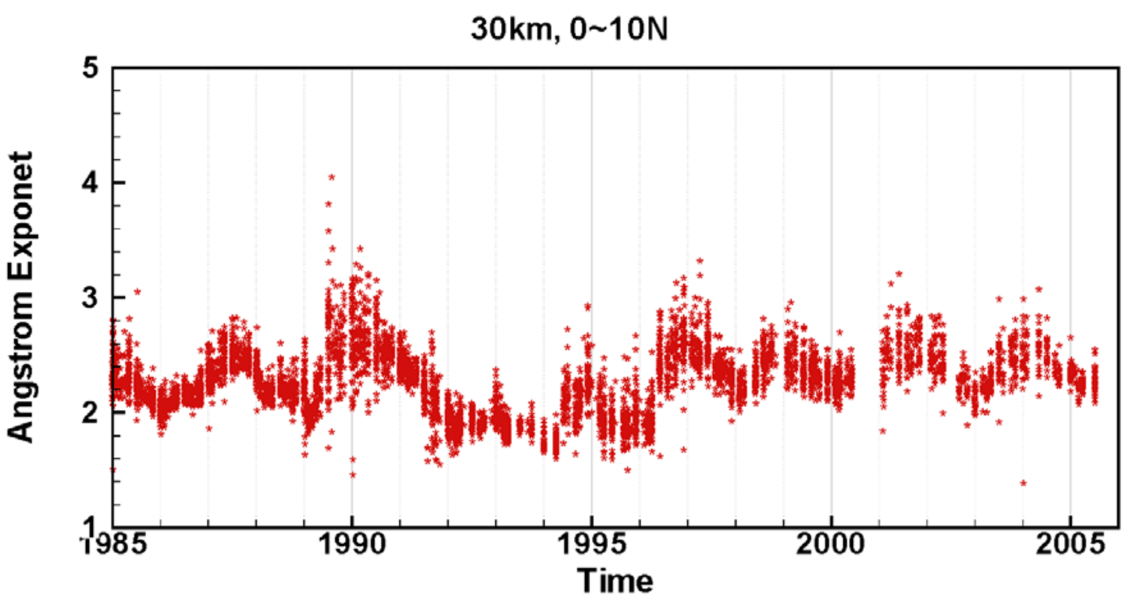
- The coarse mode fraction (**CMF**) indicates the relative concentrations of the 2 modes, and greatly influences the Angstrom exponent α:



Loughman et al. (2017), AMTD

Scale CMF using SAGE II α

- SAGE II V7 aerosol data frequently show Angstrom exponent α(525/1020) ≈ 2 for "background" aerosol
  - Drop cases with β(1020 nm) < 4 × 10^{-6} km^{-1}
    - Quality control (L. Thomason, private communication)
    - Correlation between β(525 nm) & β(1020 nm) declines when β(1020 nm) is too small



Loughman et al. (2017), AMTD

ASD issues for LS missions

1. If the assumed ***P*** is incorrect by +X%, this will produce a compensating error ≈ –X% in the retrieved ***β***. (True for V1.4 SCIAMACHY and V1 OMPS LP; less true for OSIRIS V5.07, which uses a 750/470 wavelength pair.)
2. As Ghassan showed yesterday, OMPS LP ***β*** retrievals show poor self-consistency (in ascending vs. descending node comparisons, for example).

So it appears that we need to improve our assumed ***P*** (by changing our assumed ASD), but how?

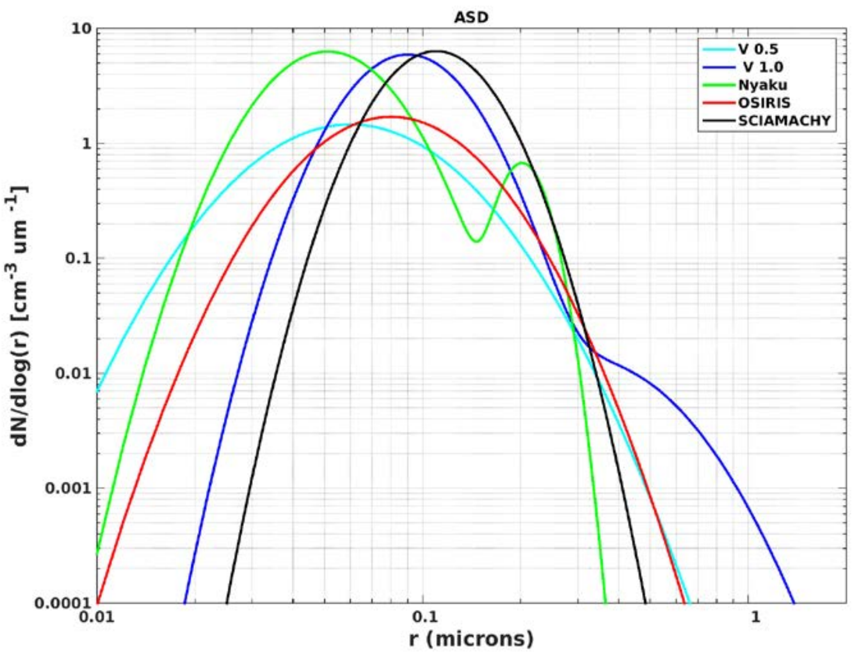
Observe the behavior of ***P*** for the LS ASDs assumed now…

Assumed log-normal aerosol size distributions (ASD) for LS missions

	Source	r_0 (μm)	*σ*	*α*
OMPS (V0.5)	Loughman et al. (2015)	0.06	1.73	2.34
OSIRIS (V5)	Bourassa (2007)*	0.08	1.6	2.44
SCIA (V1.1)	Von Savigny et al. (2015)*	0.11	1.37	2.82
Nyaku	Nyaku (2016)*	0.05	1.44	2.56
	CMF= 0.04	0.20	1.15	
OMPS (V1.0)	Pueschel et al. (1994)†	0.09	1.4	2.00
	CMF = 0.003	0.32	1.6	

* = derived from U. of Wyoming (OPC) data provided by T. Deshler's group

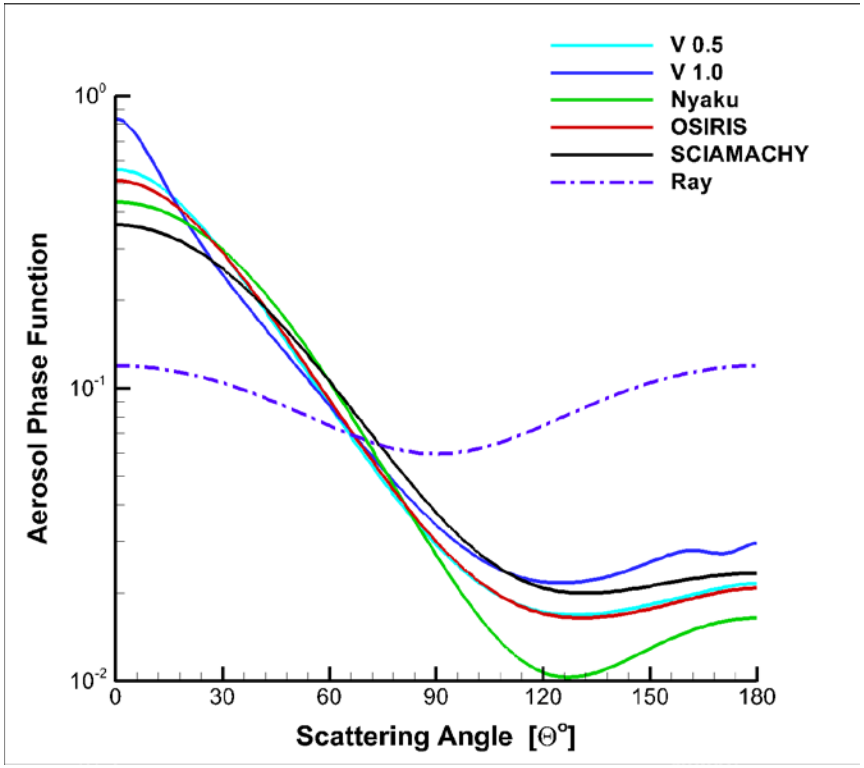
Loughman et al. (2017), AMTD



How do these ASD differences affect *P*(λ=675 nm), for spherical sulfate aerosols?

$$\alpha(525/1020) = \frac{-\ln[\beta(525)/\beta(1020)]}{\ln[525/1020]}$$

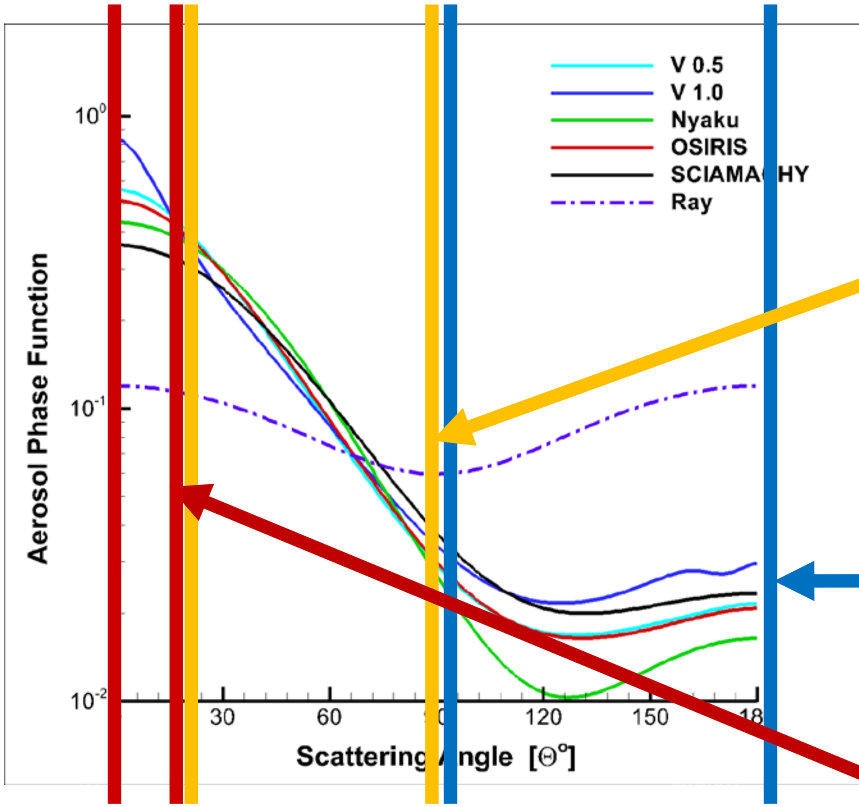
Variation of *P* for these ASDs



- Consensus for scattering angle $\Theta \approx$ 30-90^0
- Disagreement → 50% or more elsewhere, especially back-scattering ***P***
- Note LIDAR's problem (Θ = 180^0)!

Loughman et al. (2017), AMTD

Using LS radiances to derive *β*, *P*, or neither



For LS retrievals of *β* despite uncertainty about the true ASD, use *these* *Θ*. (*N. Hemisphere* for OMPS LP – SAGE III LS opportunity!).

To learn about the ASD from LS observations (through ***P***) instead, *these* *Θ* values are best. (*S. Hemisphere* for OMPS LP – SAGE III LS opportunity!).

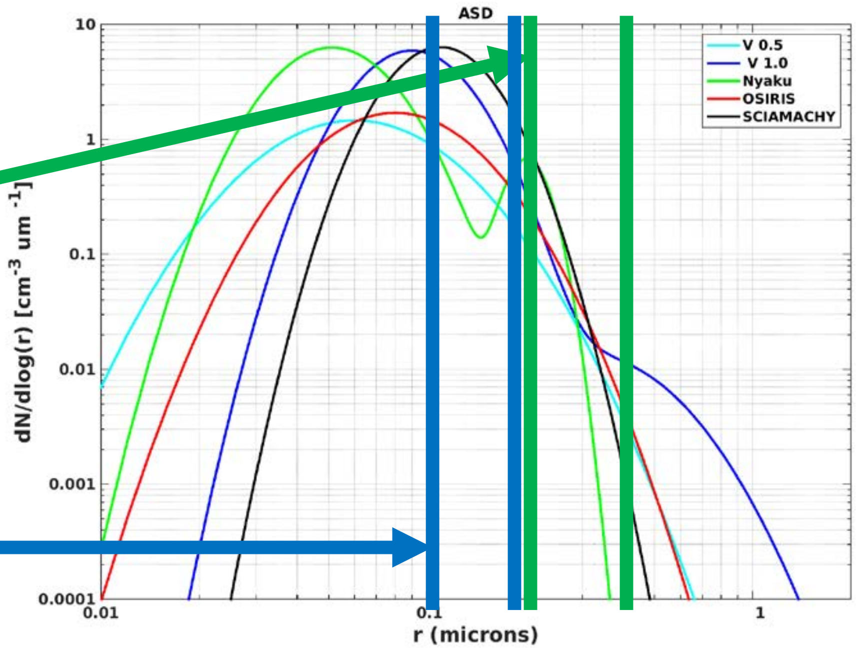
- Consensus for scattering angle *Θ* ≈ 30-90°
- Disagreement → 50% or more elsewhere, especially back-scattering ***P***
- Note LIDAR's problem (*Θ* = 180°)!

(*These* *Θ* values are inaccessible for current LS instruments.)

ASD influence on *α* and ***P***

Based on our studies of *λ* = 675 nm, we postulate that ***α(525/1020)*** depends primarily on particles sizes in the *r* ≈ 0.2 – 0.4 µm range.

While ***P*** depends primarily on smaller particles, with *r* ≈ 0.1 – 0.2 µm.

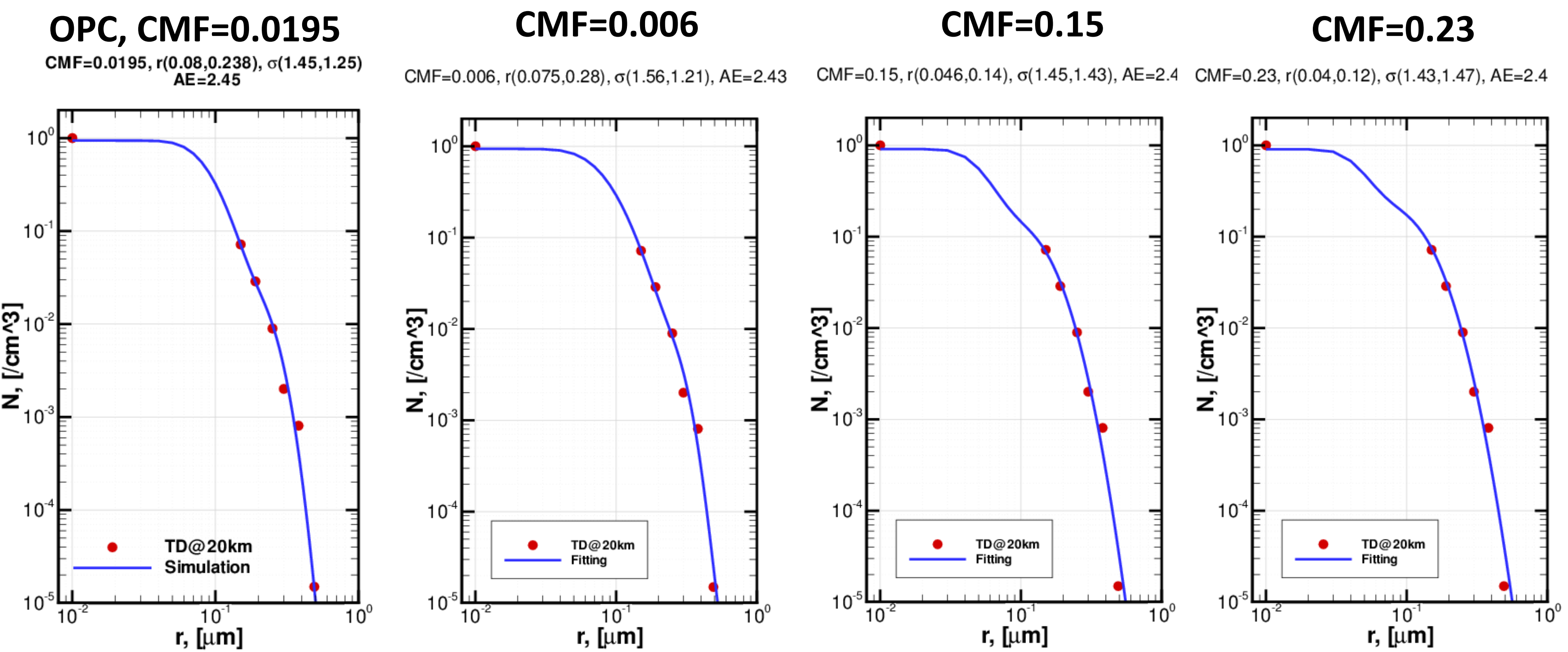


So we dug into the information provided by OPC data in the *r* ≈ 0.1 – 0.2 µm particle size range.

Early conclusions from analysis of OPC data

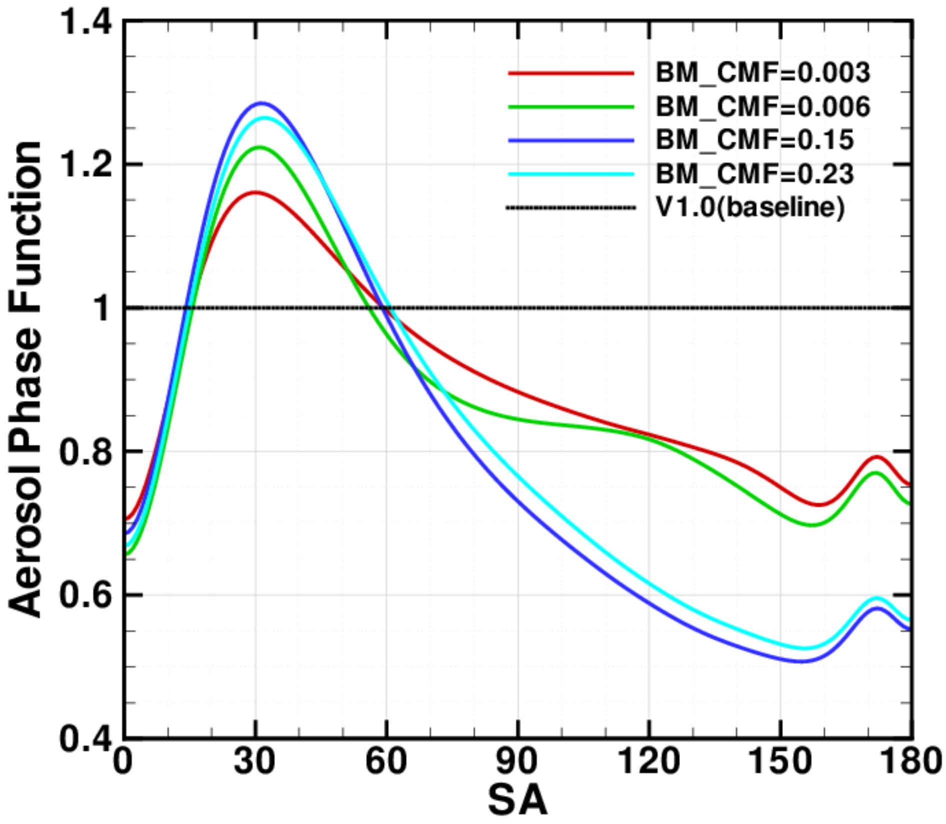
- For background stratospheric conditions, OPC data often does not provide sufficient information for a robust bi-modal log-normal (5 parameter) fit.
- Therefore the ***P*** derived from OPC data is very sensitive to the details of the model used to fit the data, rather than information that the data provides unambiguously.
- These fits can be particularly variable for those key particles with $r \approx 0.1$ µm
- Model simulations (from CARMA) produce ASDs that resemble gamma distributions more closely than bi-modal log-normal distributions in this key $r \approx 0.1$ µm area

4 bi-modal log-normal fits to OPC data



- The 4 fits above (OPC reported + 3 others) all fit the OPC data (•) well, and all give similar $\alpha(525/1020) \approx 2.4$.
- But they differ significantly in the r ≈ 0.1 µm OPC data gap region…

Resulting variation of *P* at 675 nm

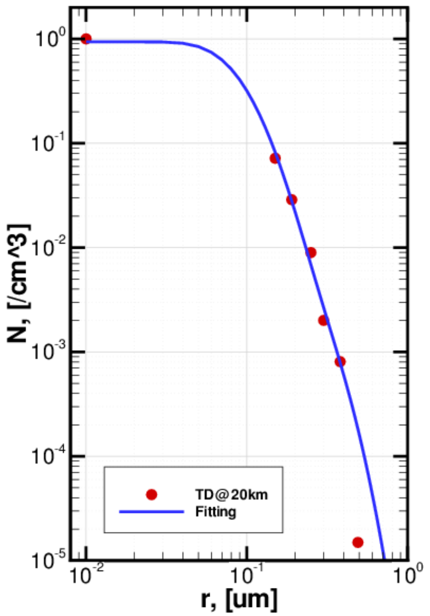


- …And therefore the ***P*** derived from OPC data is very sensitive to the details of the model used to fit the data, especially for $\Theta \approx 30^o$ and $\Theta > 90^o$.
- And so far, we've only included bi-modal log-normal fits.

Various fits to OPC data (12/4/00)

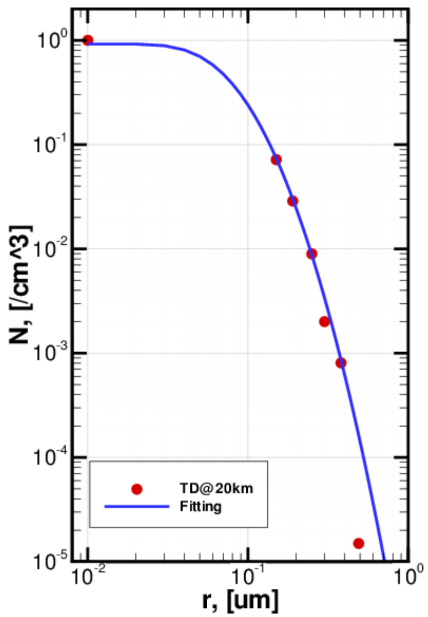
BM

CMF=0.003, r(0.078,0.28), σ(1.56,1.40), AE=2.36



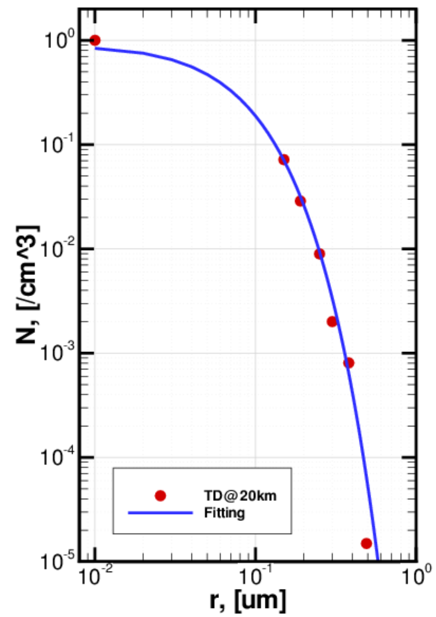
UM

r=0.065, σ=1.75, AE=2.2

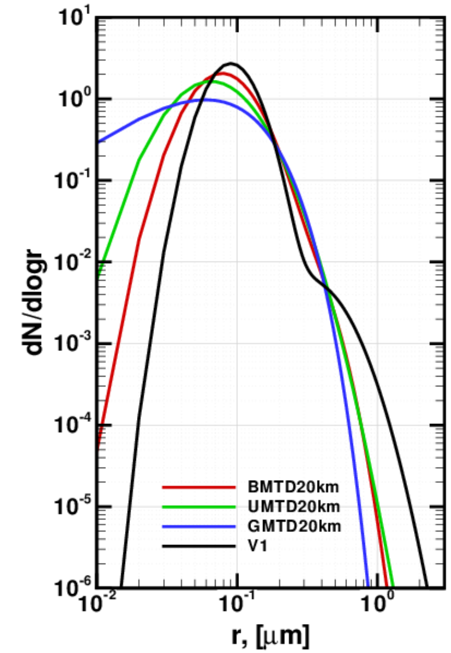


GM

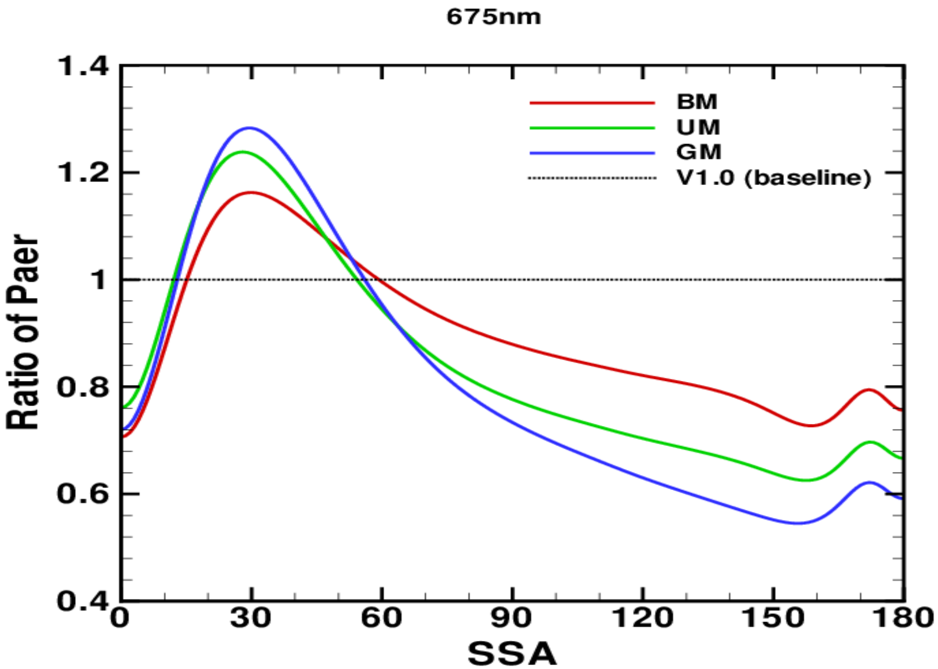
α=1.28, β=21.5, AE=2.3

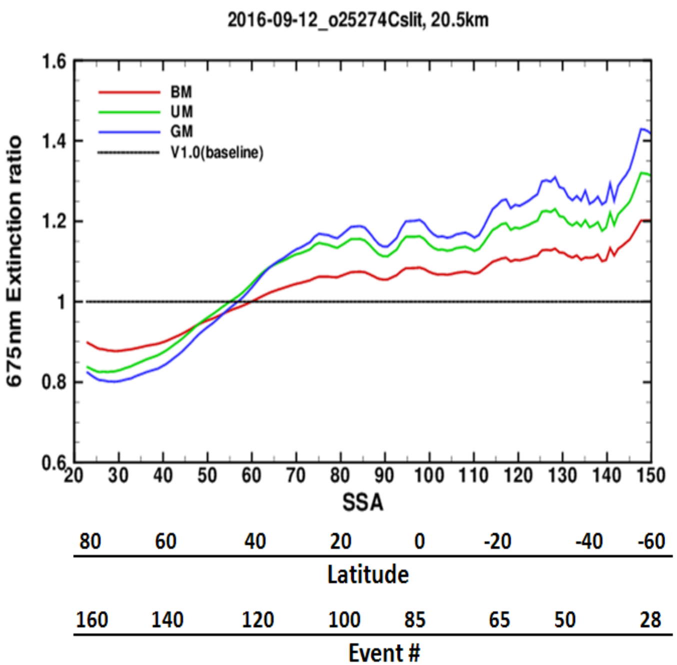


ASDs



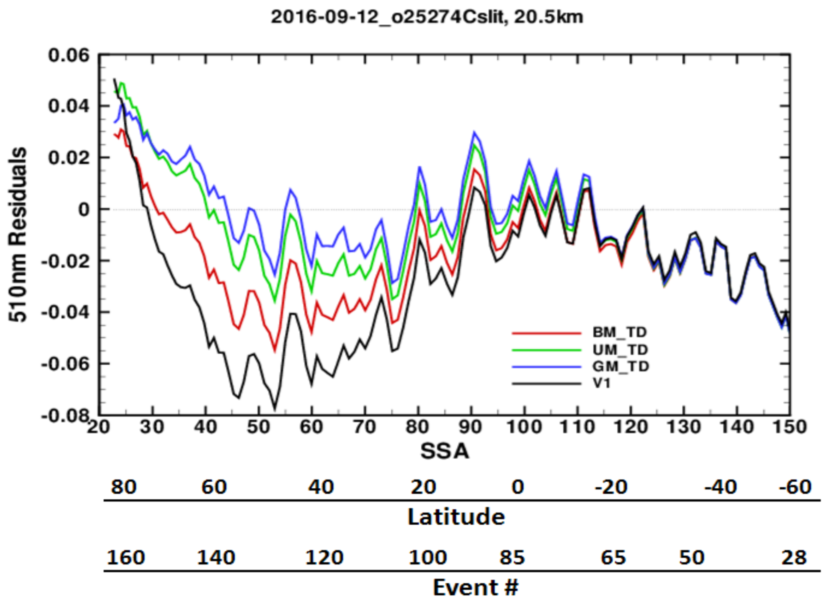
- For a different example, try bi-modal (BM), uni-modal (UM, 2 parameter) and gamma distribution (GM, 2 parameter) fits.
- Examine how the OMPS LP *β* retrievals respond to this change…



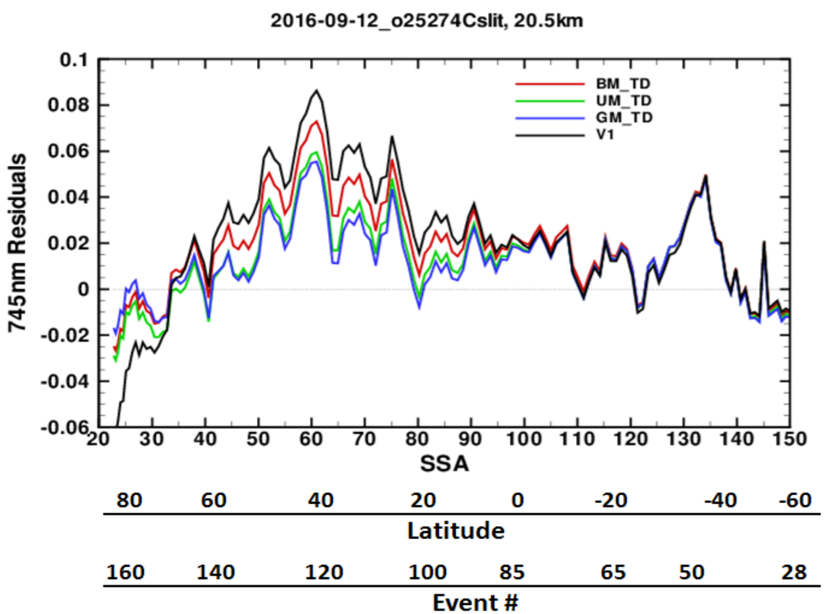


- As expected, there's an inverse relationship between assumed ***P*** and retrieved ***β***
- But can we use the OMPS LP data at other wavelengths to help us choose a fit?
- Consider the radiance residuals at non-675 nm wavelengths, assuming various ASDs + Mie theory to characterize ***β(λ)*** and ***P(λ)***

510 nm residuals



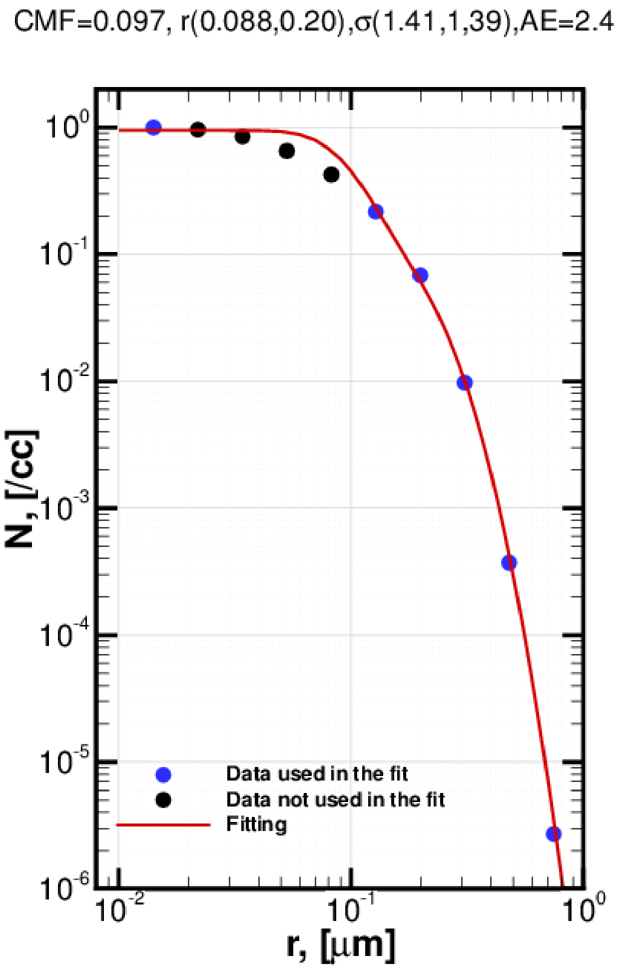
745 nm residuals



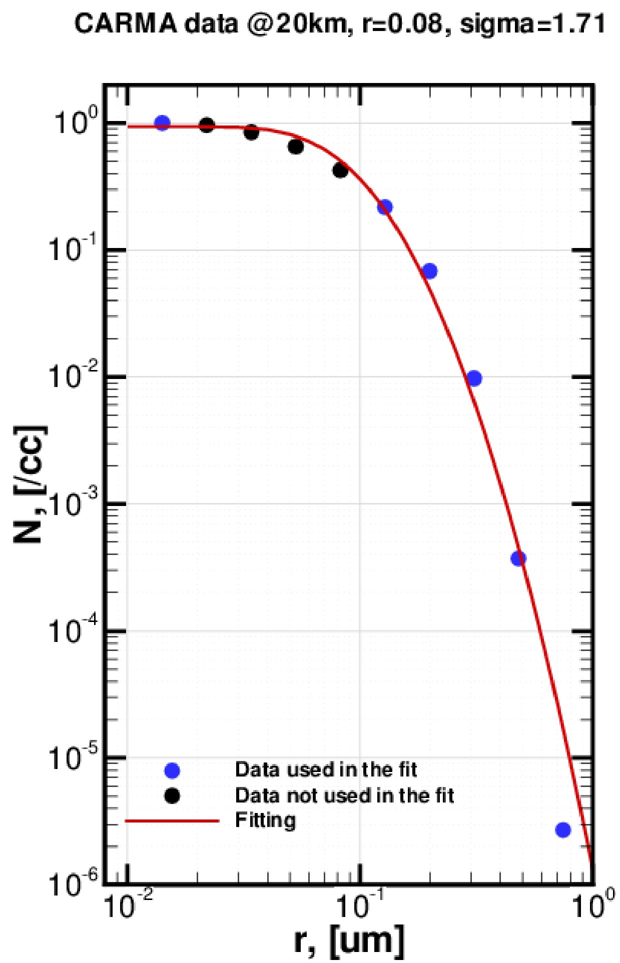
- In this comparison, the GM fit best minimizes the 510 and 754 nm residuals (& the V1 and BM models are worst).
- Note the competing effects of ***P(λ)*** and ***β(λ)***: Relatively little residual reduction for large *Θ*, more significant reduction for *Θ* < 90°.

- Begin with the ASD produced by the CARMA model at 20 km
- Use various models to fit *only* the size bins available in OPC data… and again, the **GM** fit tracks the “missing” CARMA data best.

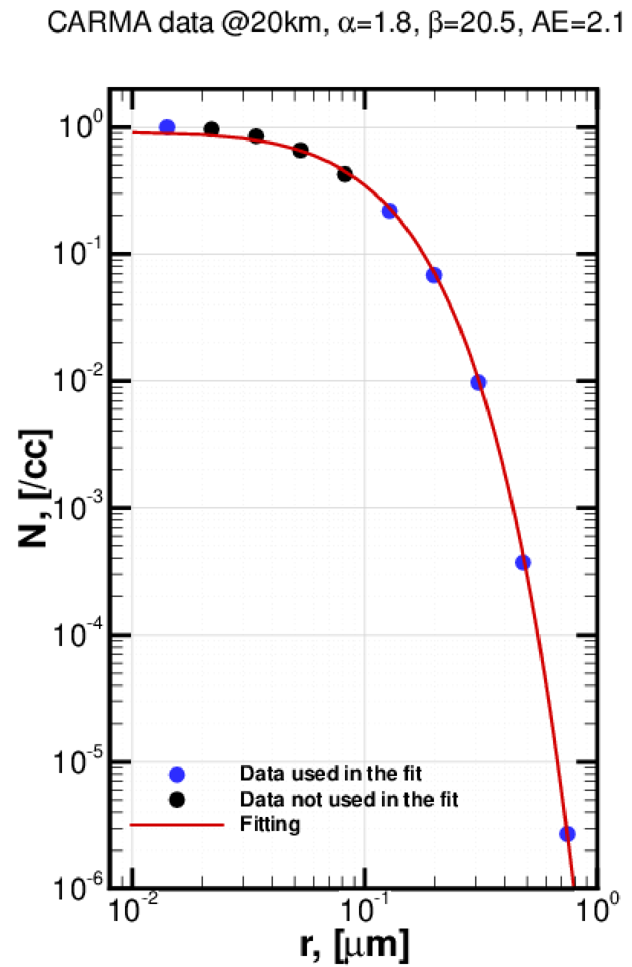
BM



UM



GM



Bottom Line

- But focusing on ASD properties is somewhat of a diversion from the questions that most interest me:
- Having actual observations of ***P(Θ)*** as it varies (with height, latitude, longitude and time) would provide clear and direct benefits for several problems, in addition to the inherent value of improved ASD knowledge:
  - Improved retrieval of ***β*** from LS or LIDAR data
  - Improved estimate of stratospheric aerosol reflection (relative to studies that estimate ***P***, e.g. with constant LIDAR ratio), to guide (or deter) those who might want to "geoengineer."

Conclusions and Future Plans

- LS and LIDAR retrievals of β show significant sensitivity to the assumed ASD properties, through P (unless $\Theta \approx 60^o$)… but those ASD properties clearly vary with space and time.
- OPC data does not always provide sufficient independent information to specify P.
- In-situ measurements, satellite measurements and model calculations of ASD are not easy to reconcile.
- But these “problems” also present an opportunity:
- With the return of SAGE occultation data, we propose to use its retrievals of β as “truth”, then use scattering-based observations (LIDAR, LS, etc.) to estimate P on that basis.

Questions and Acknowledgements

- The resulting ***P*** retrievals will contain significant ASD information, and also be valuable in their own right:
- If our knowledge of ***P*** (especially for $\Theta > 90^o$) is so uncertain, then how can we estimate the cooling effect of stratospheric aerosols well, even if we know β?

- Thank you to LS colleagues on the OMPS, OSIRIS and SCIAMACHY missions for sharing data and expertise.
- Thank you to Terry Deshler and all of his colleagues for maintaining and sharing their OPC data record.
- Thank you to NASA's OMPS LP Science Team for supporting this work (through SSAI sub-contract 21702-17-010 and its many predecessors).

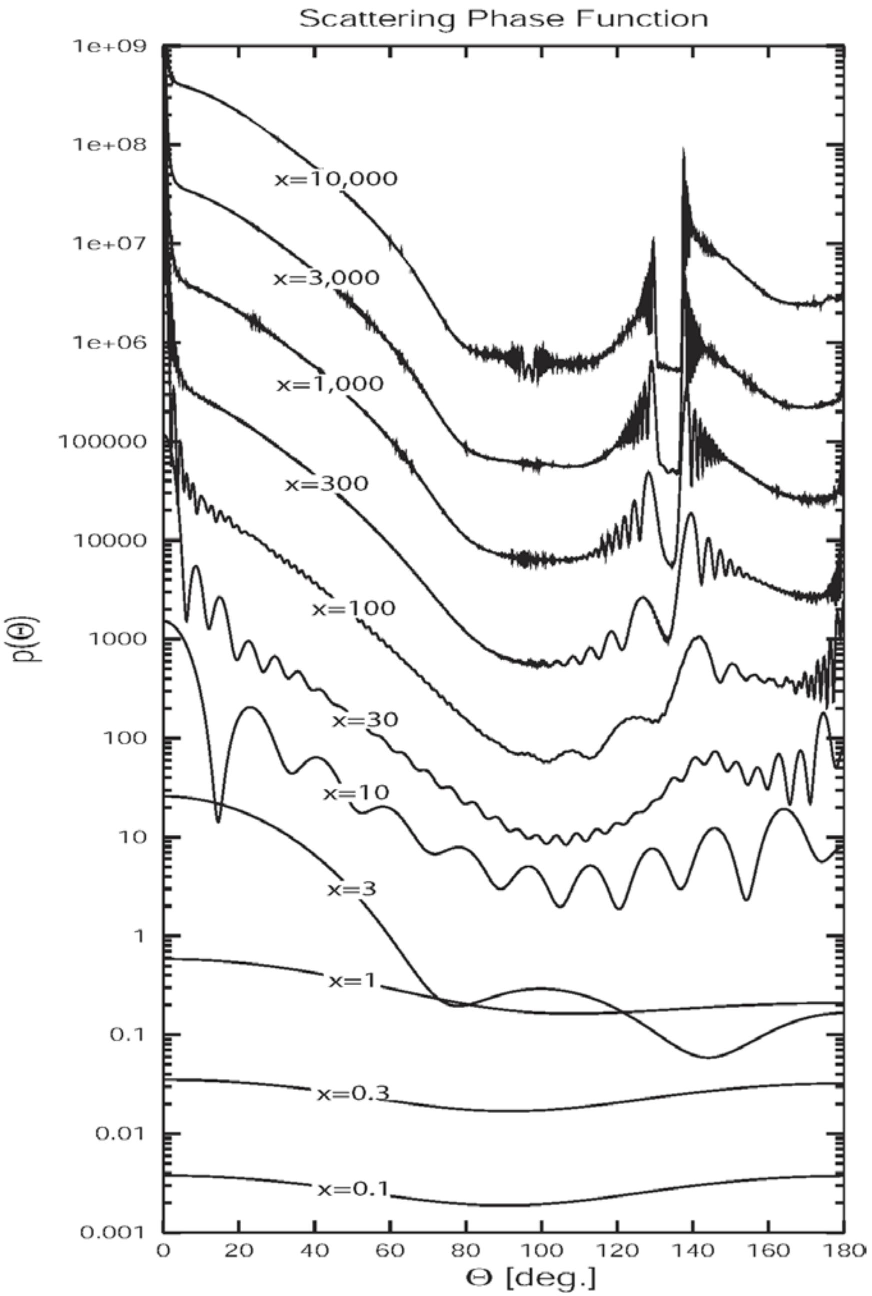
THE END

BACKUP SLIDES

Finally, the best of both worlds

- *February 2017*: SAGE III instrument placed on ISS
- What if we combine SO (SAGE) and LS (OSIRIS, OMPS LP + SAGE) data to retrieve **both *β* and *P***, expanding our knowledge of aerosol picture?
    - Instead of assuming *P* to infer *β* from LS measurements, use SO data to provide *β*, then infer *P* from LS measurements.
- This mimics (somewhat) the AERONET system for tropospheric aerosols: Solar extinction measure-ments (for *β*) combine with almucantar data (for *P*).

P plots



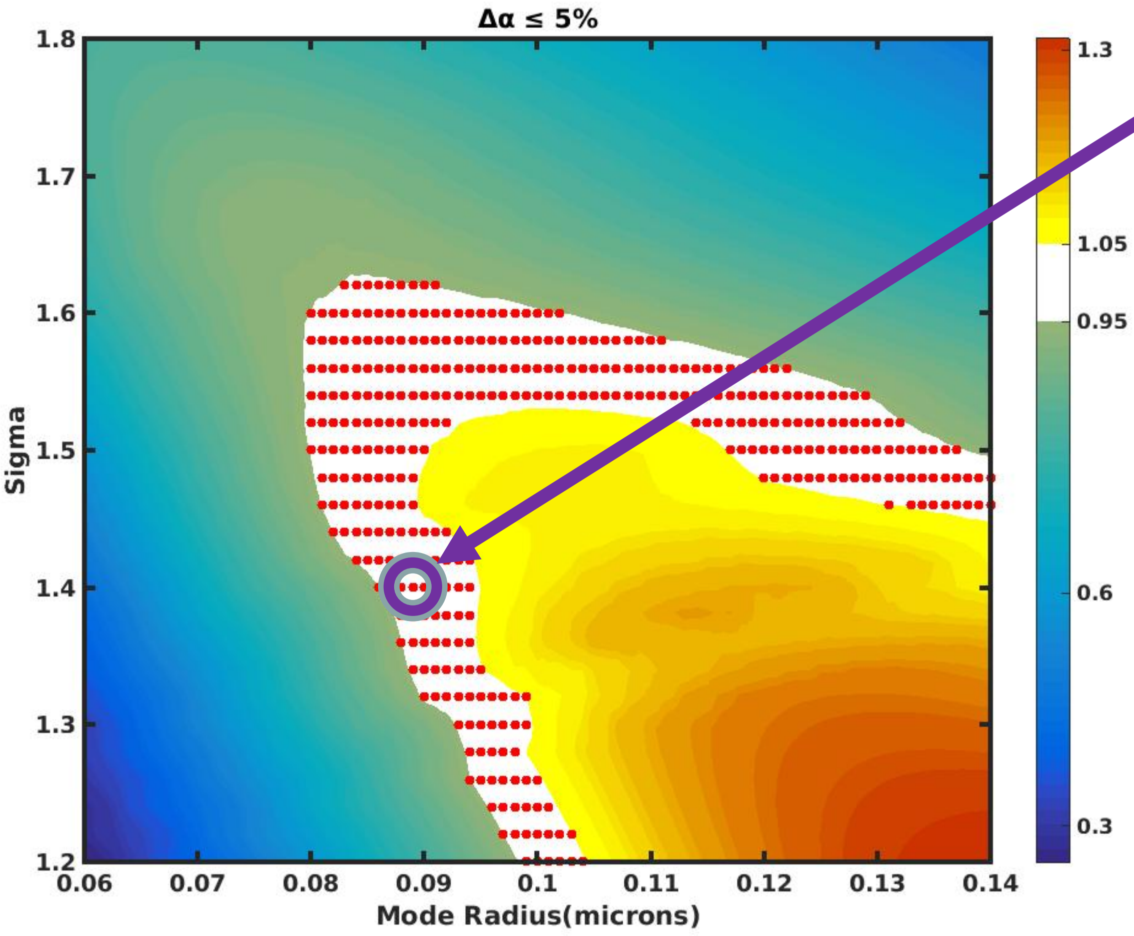
- x = "size parameter"
- $x = \frac{particle\ circumference}{radiation\ wavelength}$
- Small particles (x <~ 1) scatter ~ isotropically ("Rayleigh scattering", and have $\alpha \approx 4$)
- Stratospheric aerosols have $0.1 < x < 5$ – large changes occur in both α (0 – 2.5) and scattering phase function P (especially in back-scattering directions)

Petty, 2006

Combining *β* with *P*

- What can we learn about the ASD by combining *β* information with *P* information?
- In the next plots, we **fix C_f + the coarse mode** properties, and **vary the fine mode** properties
- Red dots on the next page indicate combinations of (*r*, *σ*) for which:
  - Angstrom coefficient α(525/1020) ≈ 2 (the V1 algorithm value) to within ±5%

Δα(521/1020) < 5%



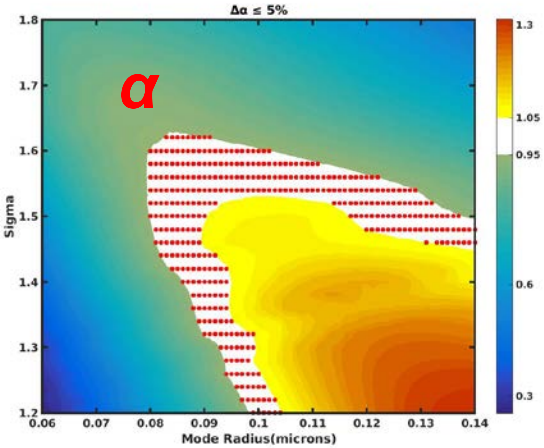
Here is the true V1 OMPS fine mode (r_0, σ) combination:

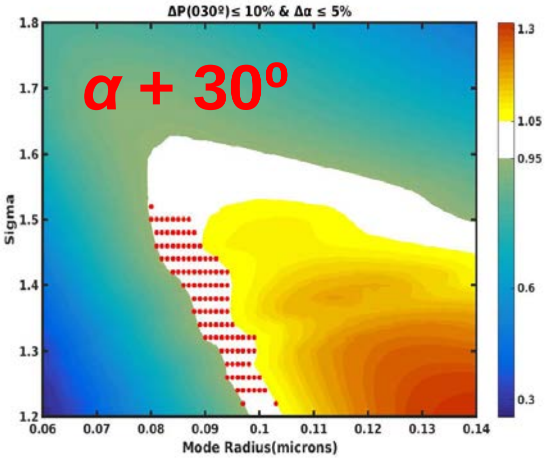
(0.09 µm, 1.4)

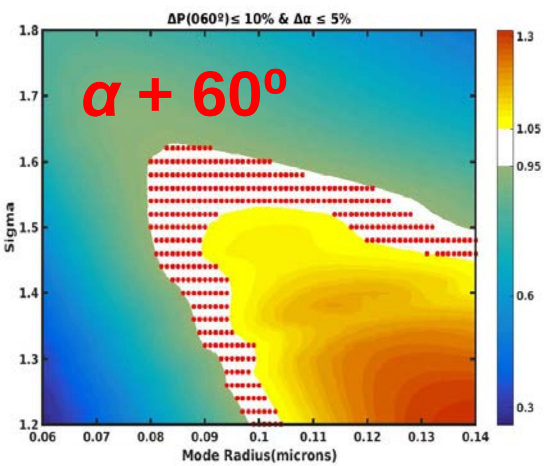
… but many other combinations *also* fit to within 5%!

Combining *β* with *P*

- What can we learn about the ASD by combining *β* information with *P* information?
- In the next plots, we **fix C_f + the coarse mode** properties, and **vary the fine mode** properties
- The upper left corner = a copy of the previous page, indicating combinations of (*r, σ*) for which:
  - α(525/1020) ≈ 2 to within ±5%
  - For the other plots, we add a second criterion:
  - *P*(*Θ, λ*= 675 nm) matches the V1 value to within ±10%

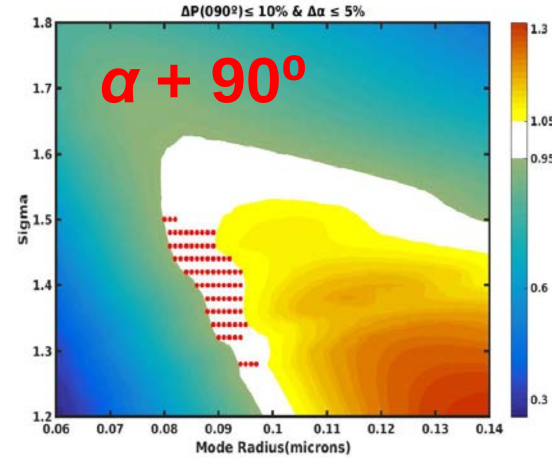


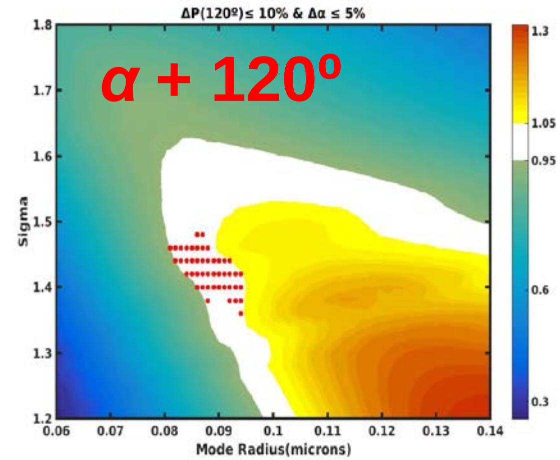


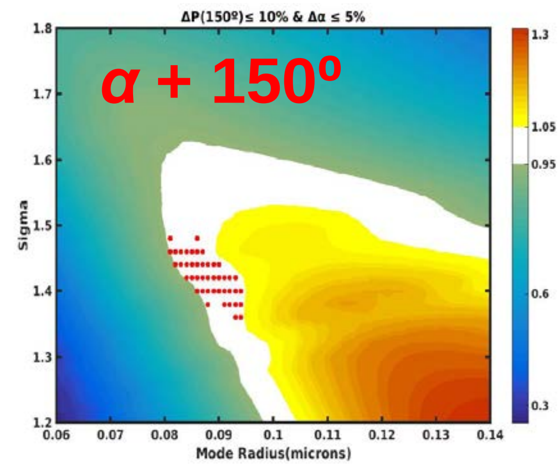


Adding the phase function criterion offers significant additional information, especially for *Θ* > 90º:

Adding the *ΔP(Θ=120º) < 10%* criterion eliminates 88% of the fine mode (r_0, σ) combinations that satisfied the *Δα* criterion alone



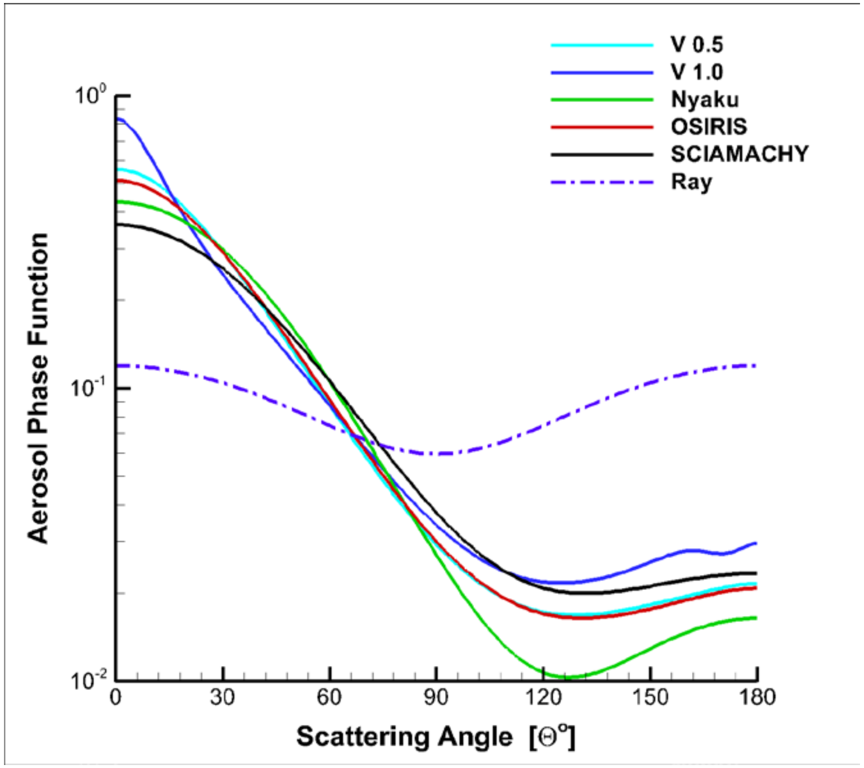


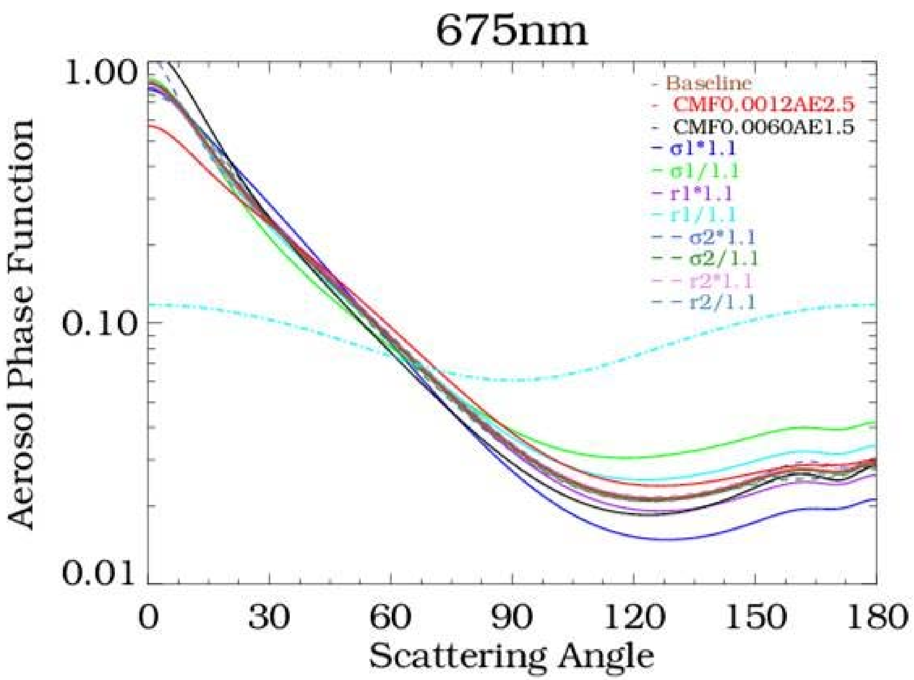


But let me quickly demolish that tidy conclusion…

- Remember that we fixed (i.e., assumed perfect knowledge of) the coarse mode and C_f values
- *P* observations are less useful for determining the properties of the coarse mode… in the OMPS V1 case
- But the Nyaku dissertation provides a counter-example (greater sensitivity to the coarse mode)…
- So the answer to the question “Which properties are we most sensitive to?” depends on the state of the aerosols at a particular time and place…

Which ASD properties are we sensitive to? That depends…



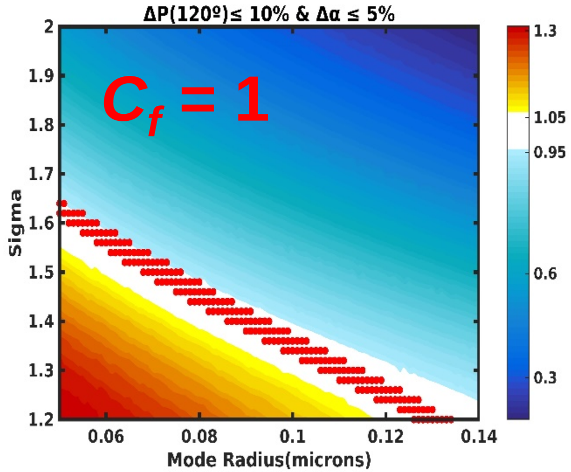


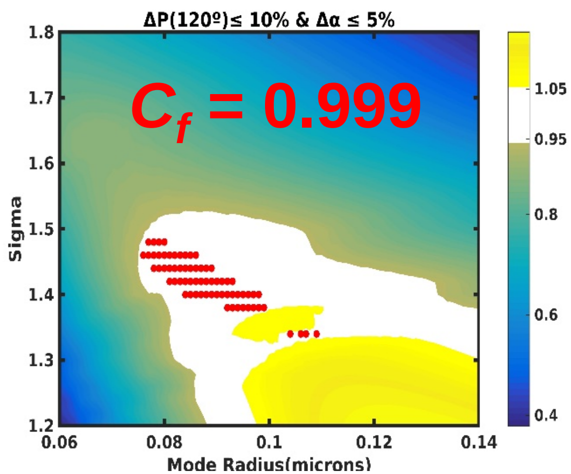
- Perturbation analysis of OMPS V1 *P* shows greatest sensitivity to σ (*fine mode*)
- Nyaku perturbation analysis shows *P* is most sensitive to σ (*coarse mode*)

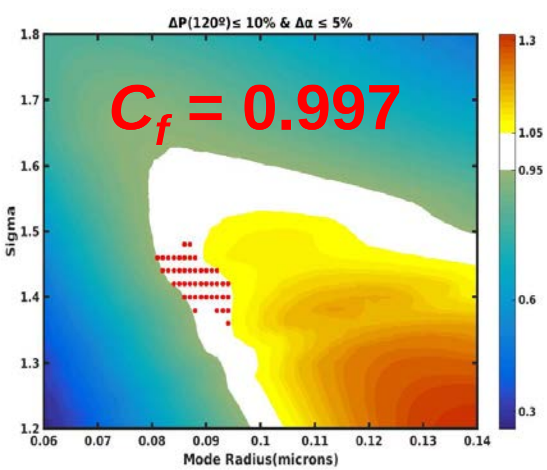
- Consensus for Θ ≈ 30-90°
- Disagreement → 50% or more elsewhere, especially back-scattering *P*

What about C_f?

- Implications when *P* is more sensitive to fine mode
  - U of Wyoming OPC data offer just 1 piece of information about aerosols with $r < 0.1$ microns
  - A recent update adds a 2nd piece of information … but OPC data is still much less sensitive to the fine mode than the coarse mode.
  - α (from SO data) is also more affected by coarse particles
  - But is it realistic to think that we know C_f perfectly? Try varying that …

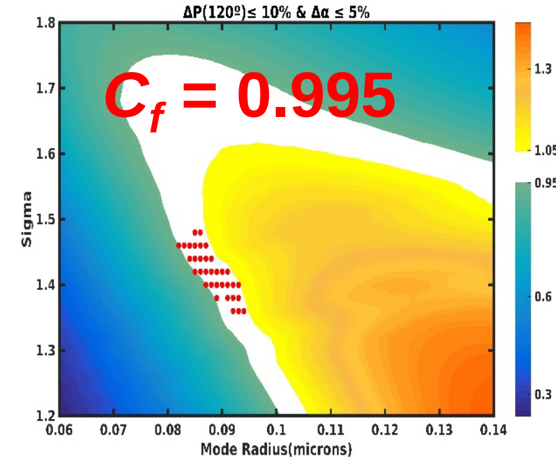


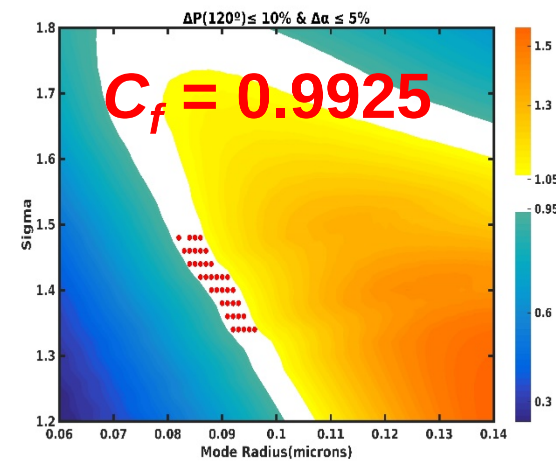


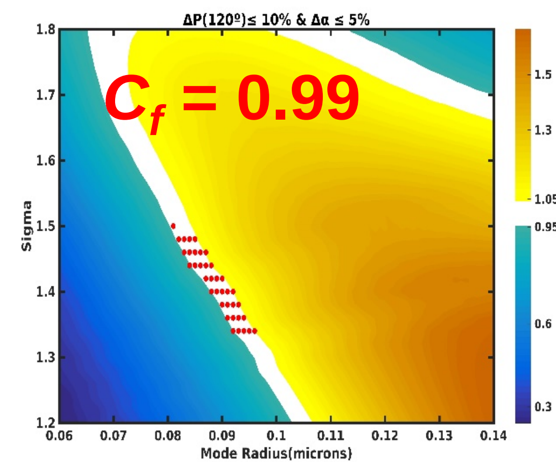


The shape of the set of points that satisfies the *Δα < 5%* criterion changes greatly when the coarse mode is eliminated.

ΔP(Θ=120º) < 10% offers ≈ the same high-quality additional information, regardless of the value of C_f







Quick summary of other observations

- Measuring *P* at additional wavelengths (500-1000 nm) adds little additional information about ASD
- But if we measure *P* directly, even at just one wavelength, we can better assess whether the ASD is:
  - single-mode,
  - or multi-mode,
  - or maybe not log-normal at all (as some models predict)!

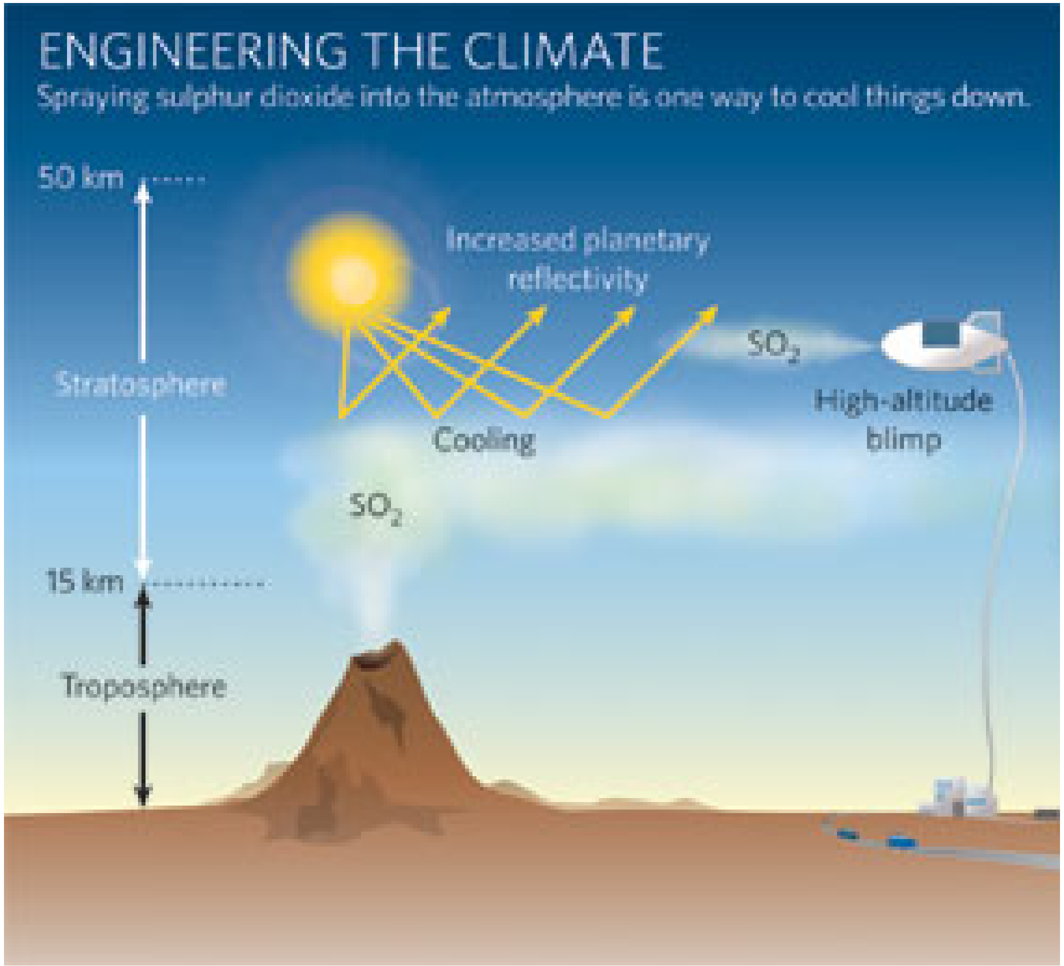
Conclusions and Acknowledgements

- The most useful application of ISS SAGE III LS data is to sample $P(\Theta > 90^0)$, especially in the S. Hemisphere.
- OMPS LP, OSIRIS, CALIPSO, etc. *all* provide β estimates that suffer due to significant uncertainty about this quantity.
- Direct observations of $P(\Theta)$ at just one back-scattering angle provides better ASD information than the λ variation of β (at least in the λ = 300-1000 nm range).
- Improving $P(\Theta)$ may also improve estimates of the stratospheric aerosol cooling effect.
- Thank you to LS colleagues for sharing data and expertise, + P. Colarco, D. Flittner, NASA's OMPS LP Science Team, and SSAI for support of this work (through sub-contract 21702-17-010 and its many predecessors).

Caveats

- This can only work with zonal means, etc. (since we aren't measuring β & P simultaneously or coincidently)
- Need to have homogeneity, etc.
- Note that P is smallest where it's most sensitive to fine mode properties, so assuming 10% accuracy for those angles (150 deg) may be optimistic…
- Suggest looking back at other occultation data from early 2000 – 2016 period (GOMOS, SCIA, others?)

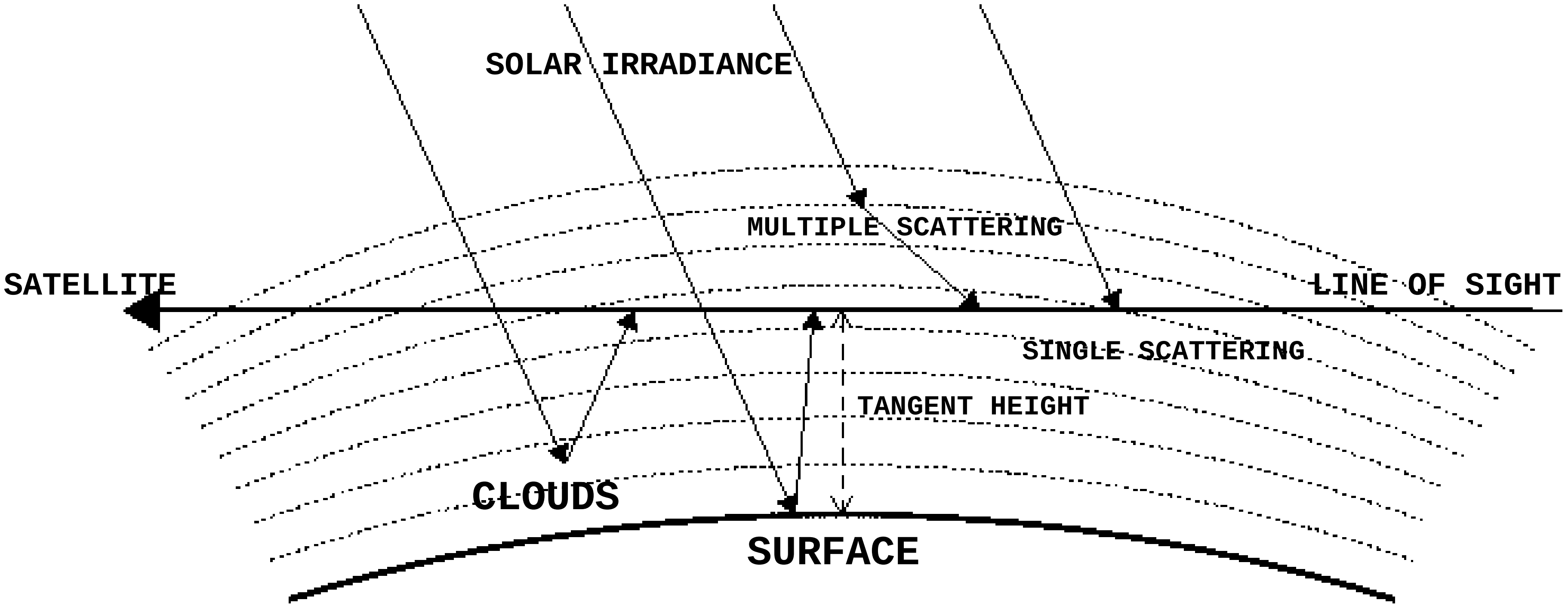
Shading the Earth with aerosols…



- Paul Crutzen recently brought new attention to an old idea:
- "Geoengineering" – in this case, injecting SO_2 to stimulate additional stratospheric aerosols
- This should increase surface cooling, offset global warming
- *Feasible?* Probably.
- *Unintended consequences?* Likely.
- More on this later…

Morton (2007)

Limb Scattering (LS) Schematic



LS measurements will play a major role in monitoring the stratosphere.

Space Shuttle View of Limb Scatter Observations