MEASURING TRACE GAS PROFILES FROM SPACE

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Profiling the Atmosphere

- Active
  - LIDAR
  - RADAR
- Passive
  - Occultation
  - Nadir backscatter
  - Nadir thermal emission (IASI, TES)
  - Limb scattering (OSIRIS, SCIAMACHY)
  - Limb thermal emission (MIPAS)

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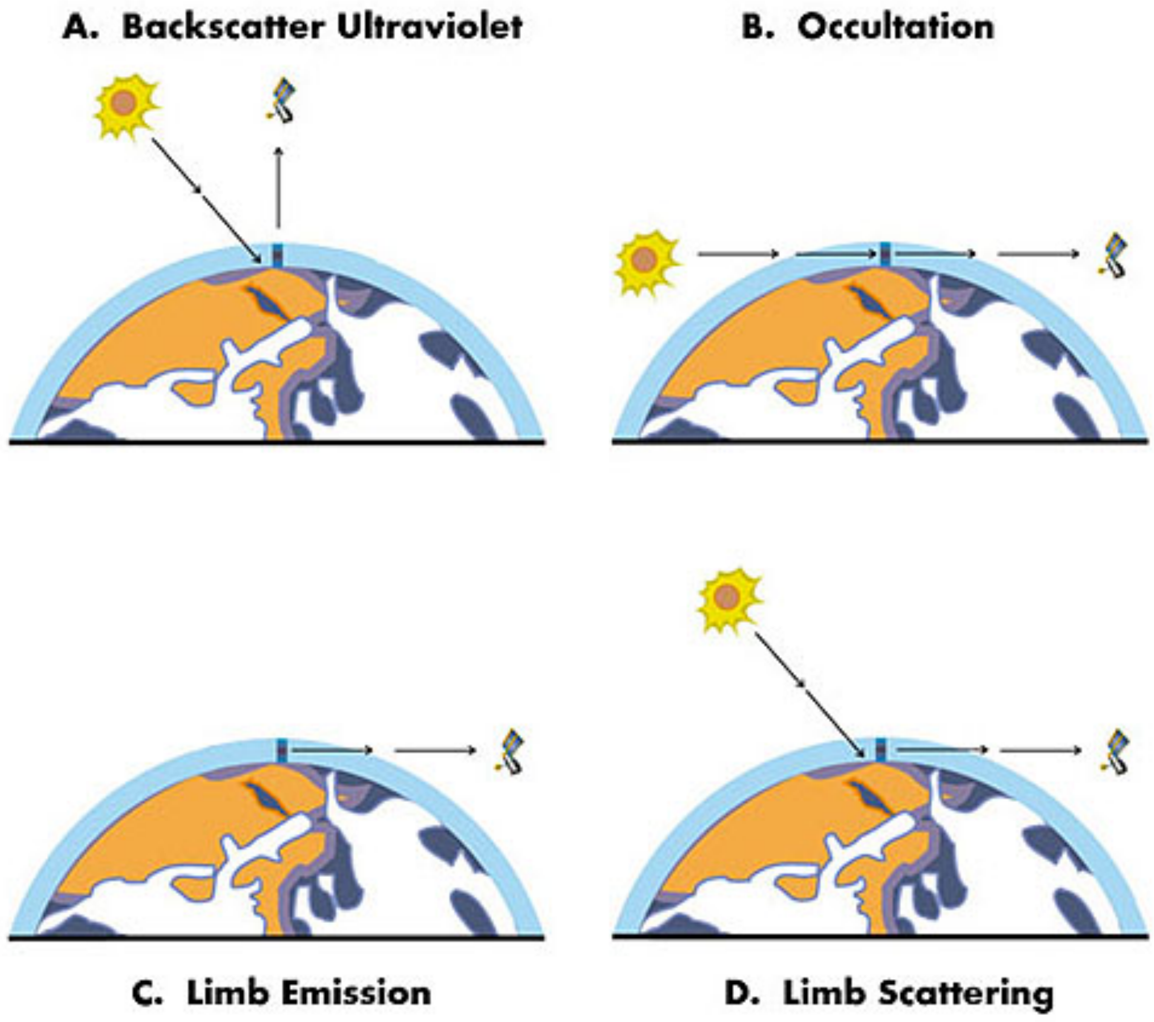
Passive Measurement Geometries



Nadir Backscatter Instruments

Instrument	Dates	Profiles retrieved from nadir?
TOMS	1978 – 2006	
GOME	1995 – 2011	O_3 (Liu et al., 2005)
SCIAMACHY	2002 – 2012	
OMI	2004 –	O_3 (Liu et al., 2010) SO_2 (Yang et al., 2010)
GOME-2A GOME-2B GOME-2C	2006 – 2012 – 2017 –	O_3 (Cai et al., 2012) SO_2 (Nowlan et al., 2011)
OMPS	2011 –	
TROPOMI	2015 –	
Sentinel-4	2017 –	
TEMPO	2018 –	
GEMS	2018 –	

Remote Sounding: Inverse Problem

$$\mathbf{y} = \mathbf{F}(\mathbf{x}) + \boldsymbol{\varepsilon}$$

- We have **y** (spectral data)
- We want **x** (profile & other fitted parameters)

- Requirements for inversion
  - Forward model (**F**)
  - Retrieval algorithm

Nadir Backscatter

- Global coverage
- Limited altitude information, and only for certain molecules (Ozone, volcanic SO_2)
- Almost always need *a priori* information on state of atmosphere (i.e., ozone profile climatology)
- Altitude information on ozone and SO_2 has so far been derived from OMI, GOME, and GOME-2 using the UV

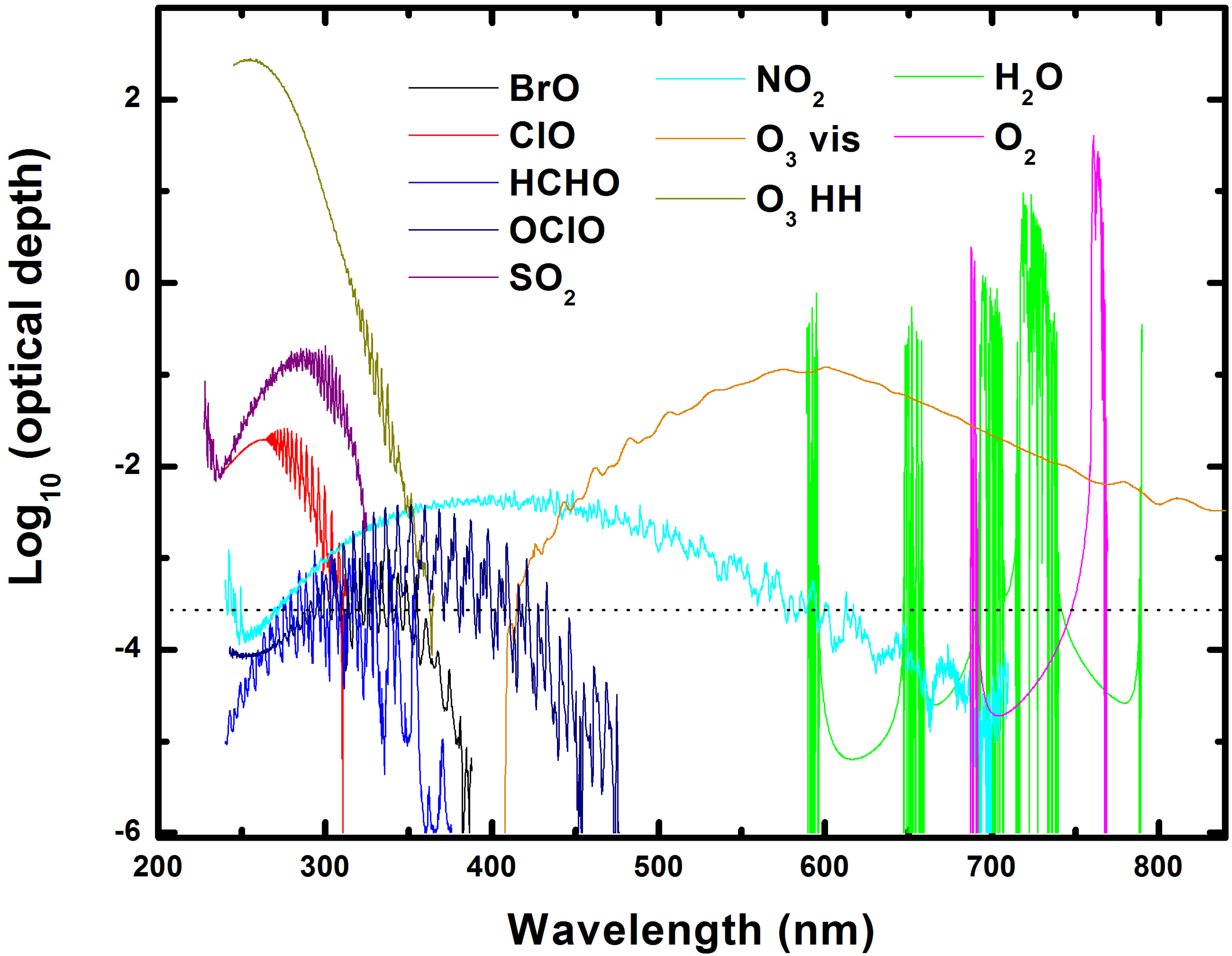
Optimal Estimation Approach

- Combine *a priori* knowledge with measurements
- Iterate until convergence

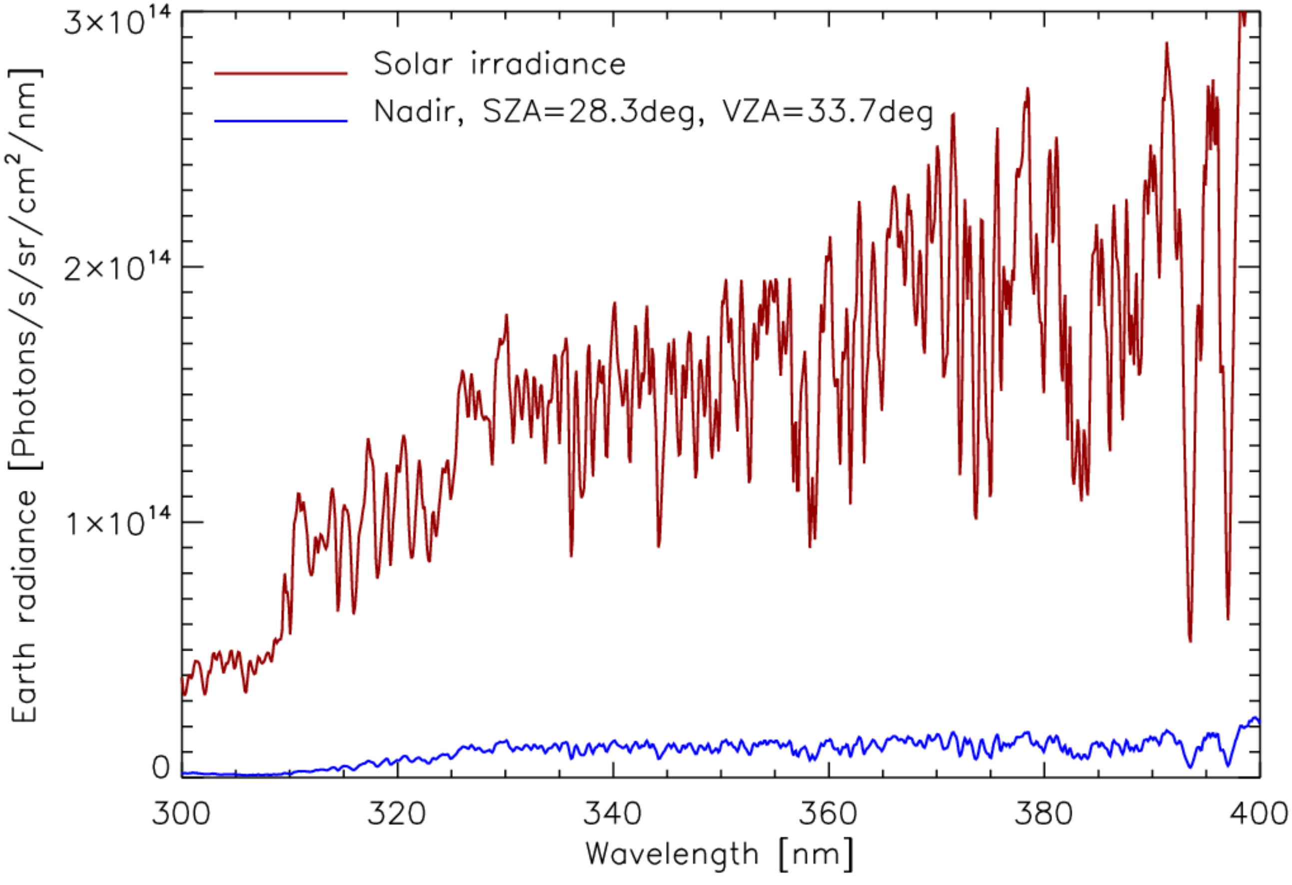
$$\Delta \mathbf{x} = (\mathbf{K}^T \mathbf{S}_\varepsilon^{-1} \mathbf{K} + \mathbf{S}_a^{-1})^{-1} [\mathbf{K}^T \mathbf{S}_\varepsilon^{-1} \Delta \mathbf{y} - \mathbf{S}_a^{-1} (\mathbf{x} - \mathbf{x}_a)]$$

$\mathbf{x}$ = current guess of retrieved parameter
$\mathbf{y}$ = measurements
$\mathbf{S}_\varepsilon$ = measurement error covariance matrix
$\mathbf{K} = \mathbf{dy/dx}$
$\mathbf{x}_a$ = a priori profile (climatology or from a model)
$\mathbf{S}_a$ = a priori error covariance matrix

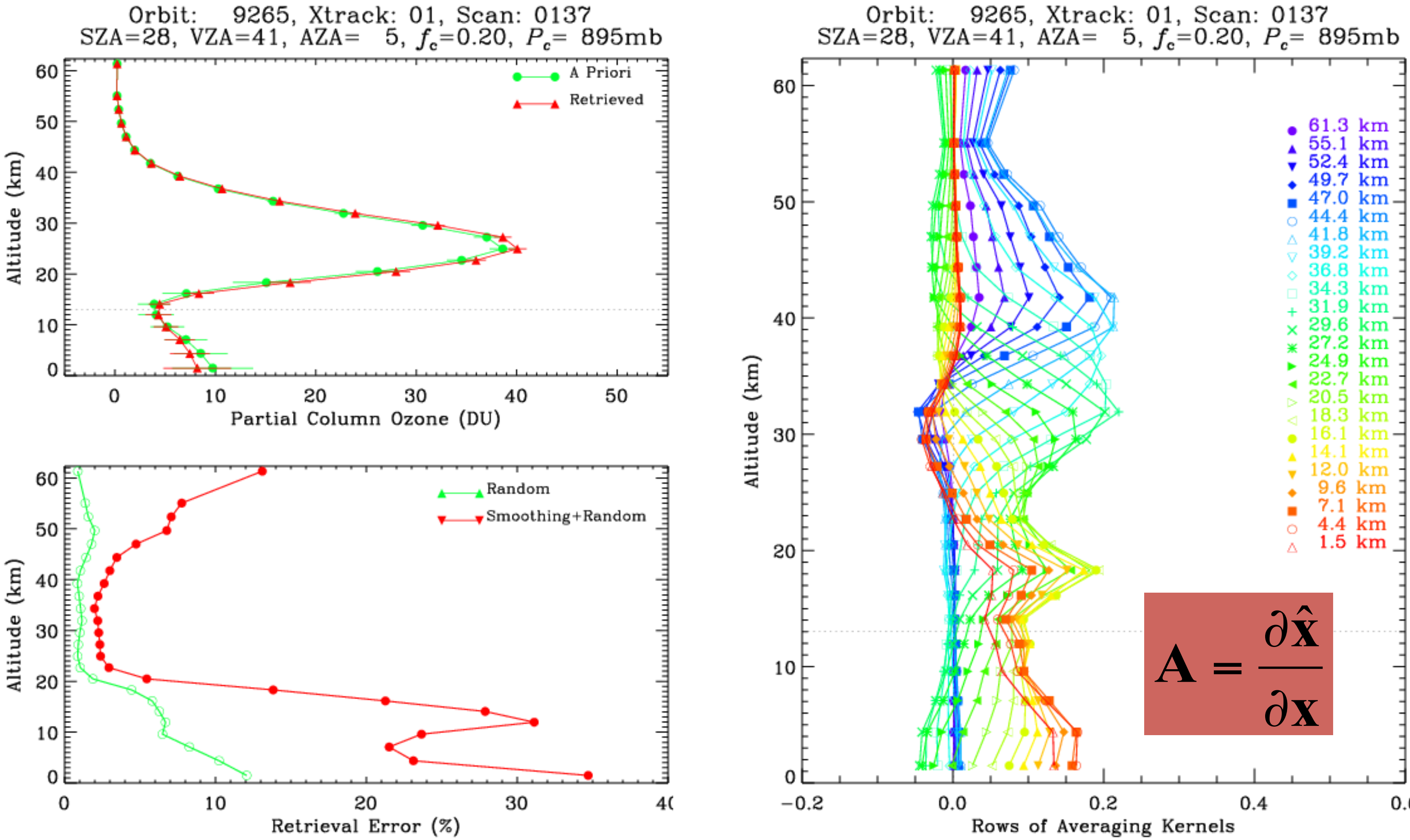
Optical Depths for Typical GOME Measurement Geometry



GOME-2 Spectra, Channel 2



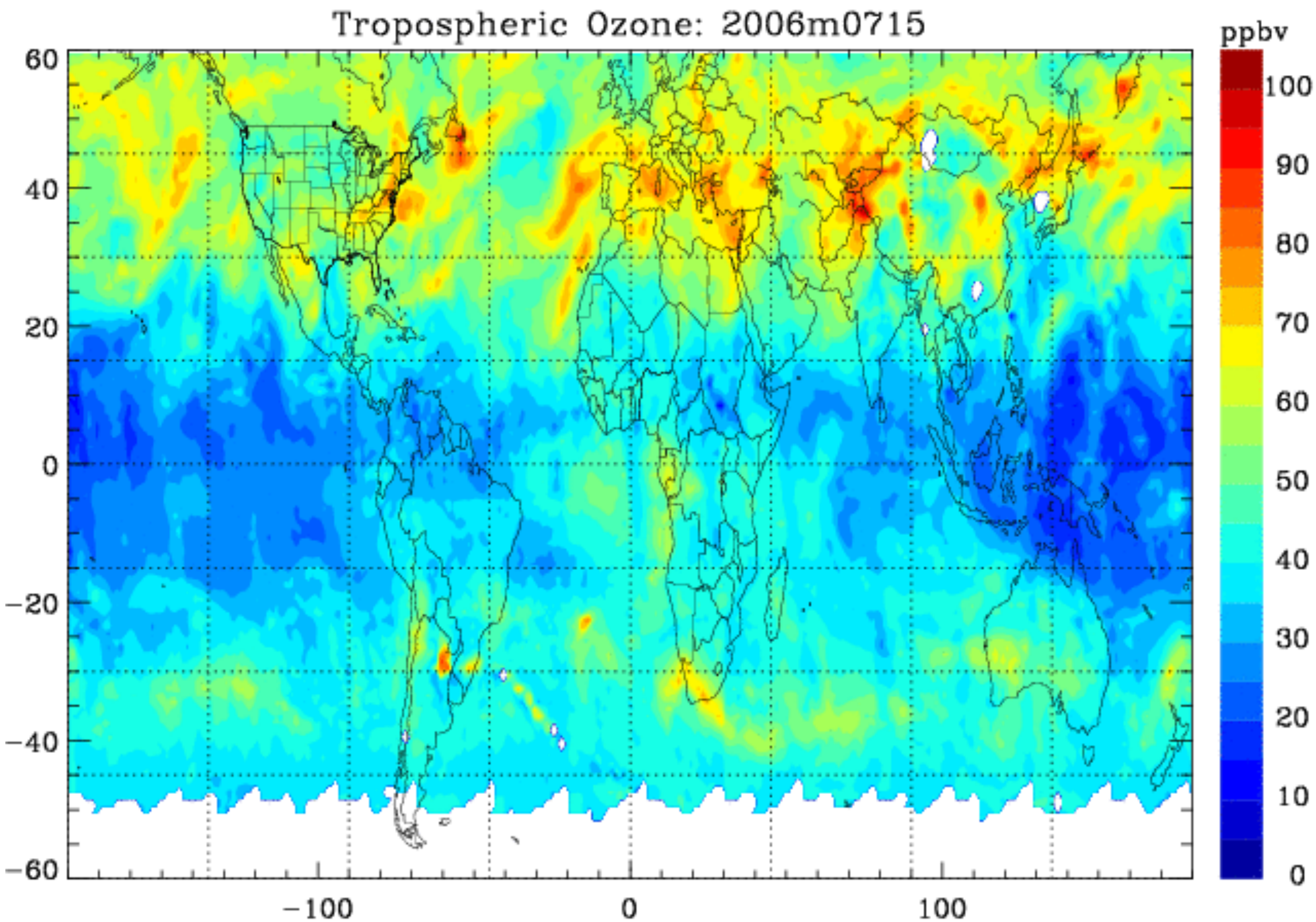
GOME-2 Ozone Profile (Backscatter)



$$\mathbf{A} = \frac{\partial \hat{\mathbf{x}}}{\partial \mathbf{x}}$$

(Z. Cai, Chinese Academy of Sciences)

OMI Tropospheric Ozone

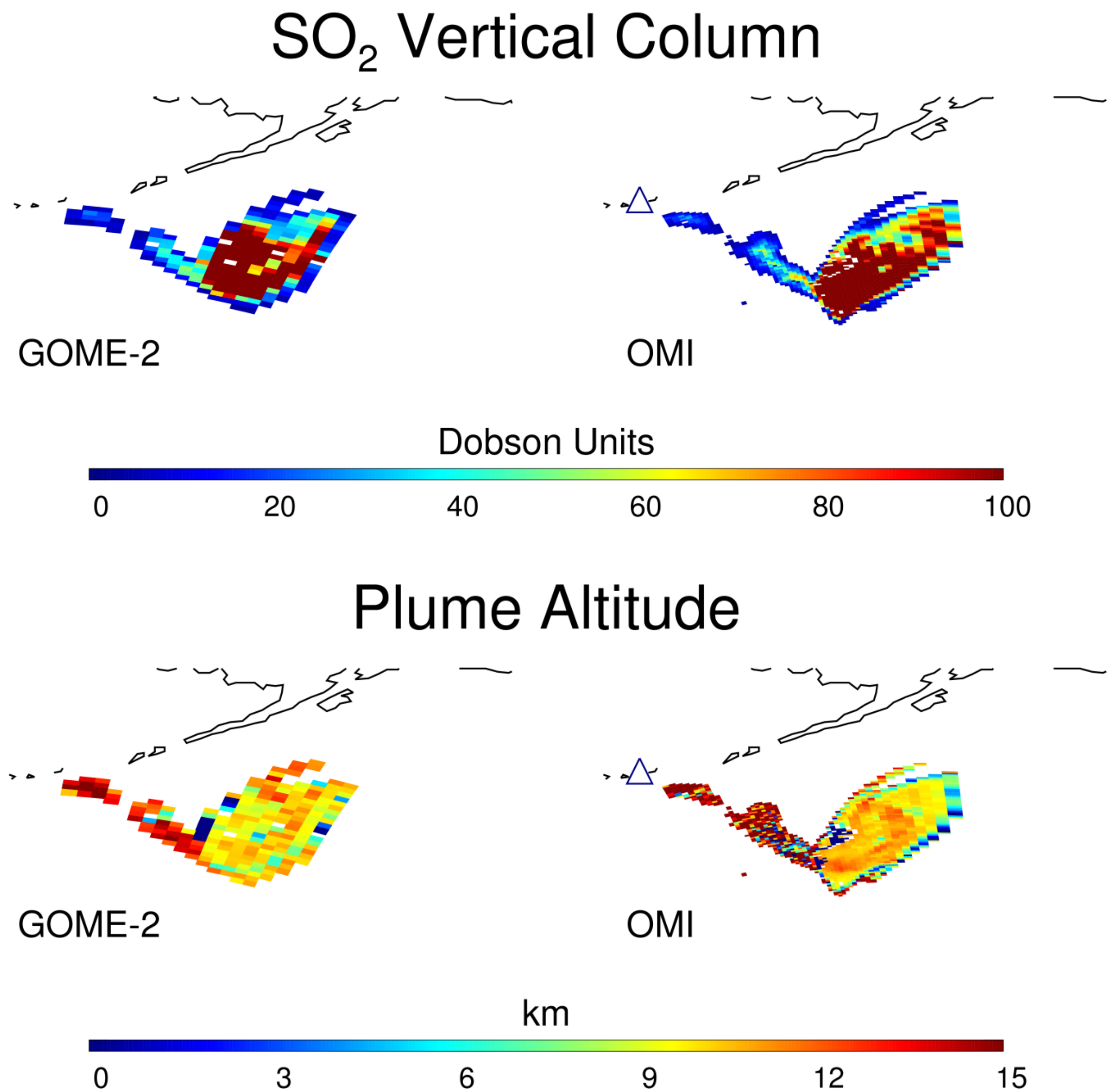


X. Liu (CfA)

GOME-2 and OMI SO_2

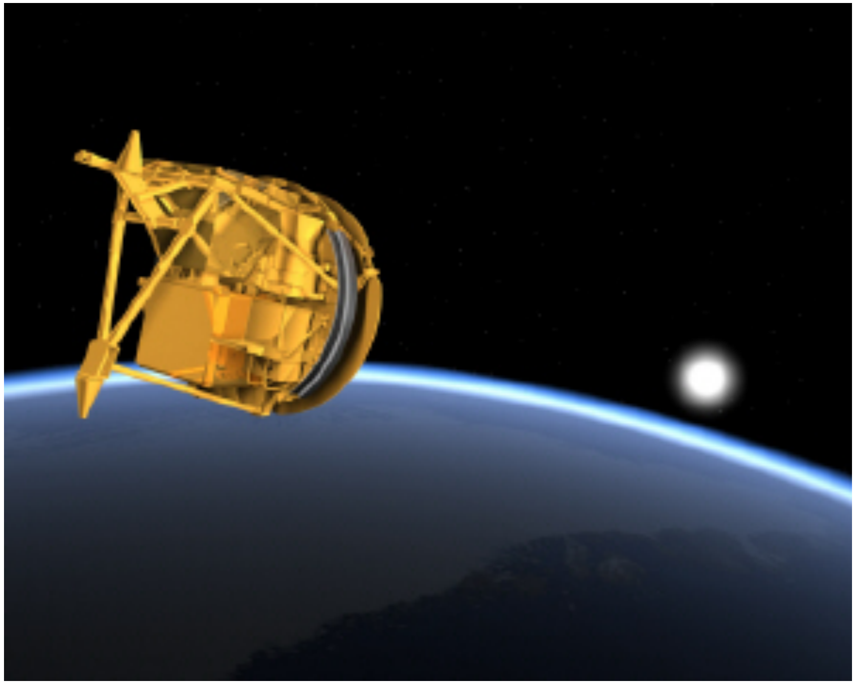
Mt. Kasatochi
Alaska
9 August 2008

A priori SO_2 altitude = 10 km
Uncertainty = 2 km



Occultation Measurements

- Self-calibrating
- High vertical resolution
- Sparse global coverage



Occultation Instruments

Instrument	Dates	Spectral Region	Source
ATMOS (shuttle)	1985 – 1994	infrared	Sun
HALOE	1991 – 2005	NIR, infrared	Sun
SAGE I SAGE II SAGE III SAGE III ISS	1979 – 1981 1984 – 2005 2001 – 2005 2015 –	UV, visible, NIR	Sun
GPS technique	1995 –	radio	GPS
ILAS ILAS II	1996 – 1997 2002 – 2003	NIR, infrared	Sun
SCIAMACHY	2002 – 2012	UV – infrared	Sun and moon
GOMOS	2002 – 2012	UV, visible, NIR	Stars
ACE-FTS	2003 –	infrared	Sun
ACE-MAESTRO	2003 –	visible, NIR	Sun

Atmospheric Chemistry Experiment

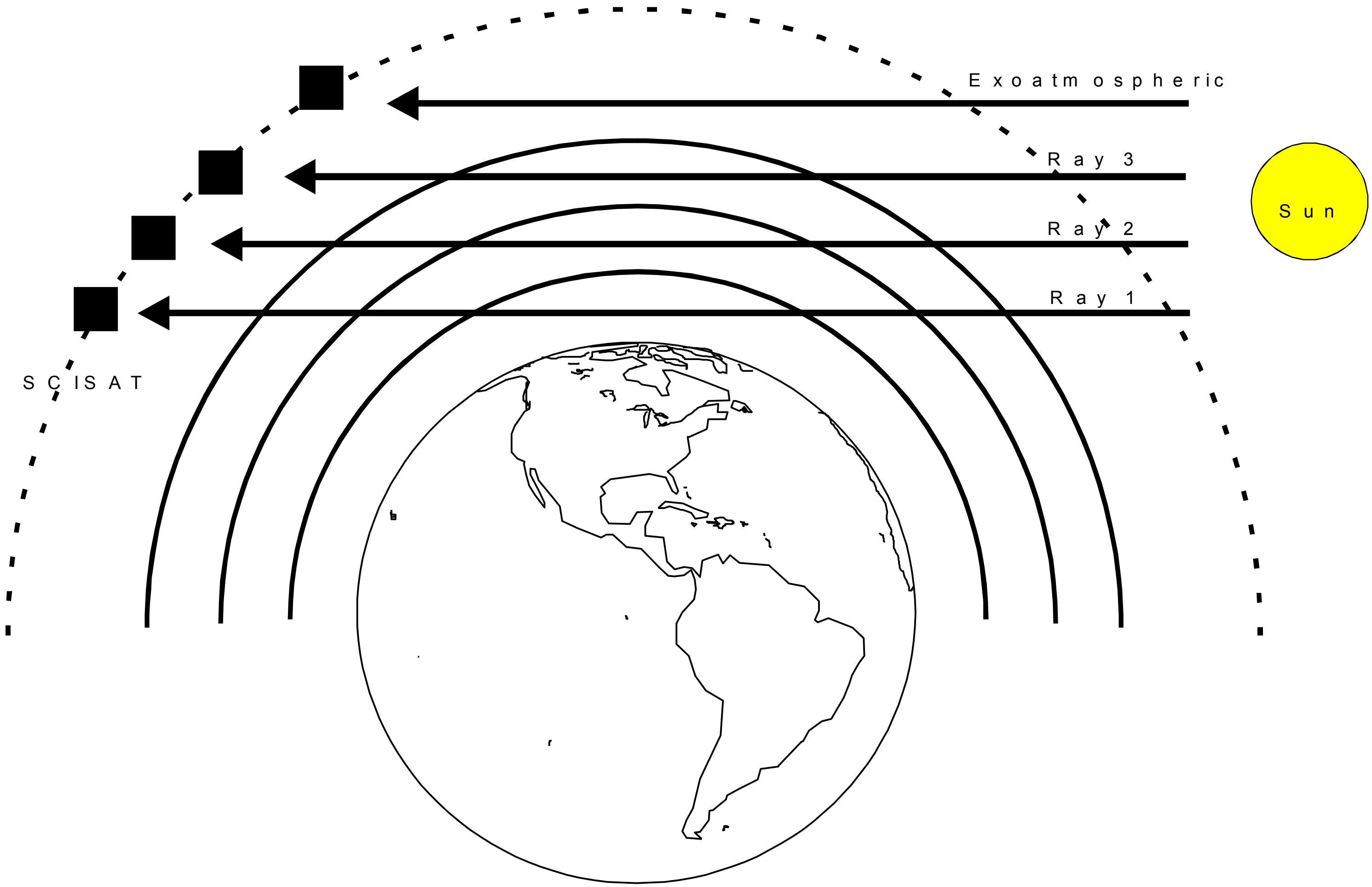
- ACE is on SCISAT satellite

- Launched August 12, 2003

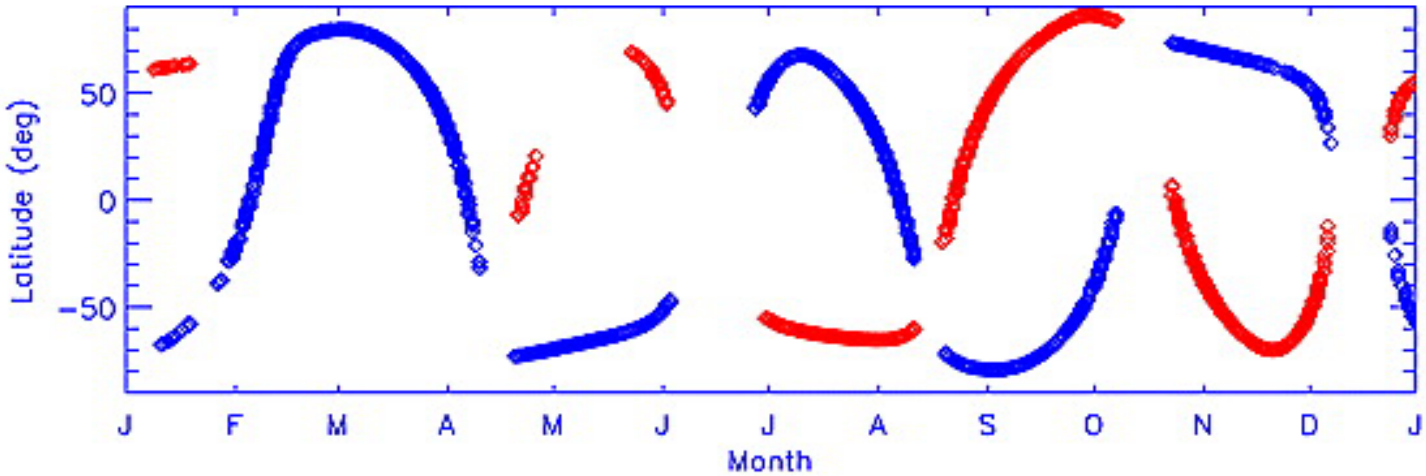
- Two primary instruments on-board
  - **ACE-FTS** (Fourier Transform Spectrometer)
    - **→ INFRARED**
  - **ACE-MAESTRO**
    - **→ VISIBLE-NIR**

- ACE-FTS measures:
  - H_2O, O_3, N_2O, NO, NO_2, HNO_3, N_2O_5, H_2O_2, HO_2NO_2, N_2, HCl, HF, $ClONO_2$, CFC-11, CFC-12, CFC-113, COF_2, $COCl_2$, COFCl, CF_4, SF_6, CH_3Cl, CCl_4, HCFC-22, HCFC-141b, HCFC-142b, CO, CH_4, CH_3OH, H_2CO, HCOOH, C_2H_2, C_2H_4, C_2H_6, OCS, HCN, ClO, acetone, PAN, aerosols

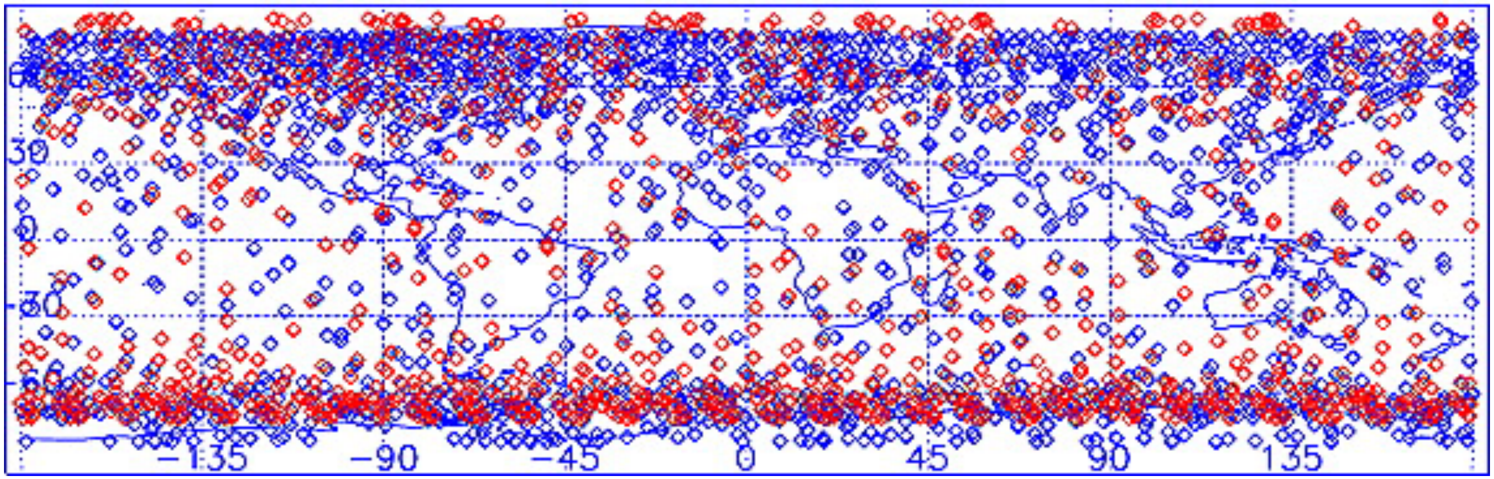
Solar Occultation Measurements



ACE Occultation Coverage: 2004

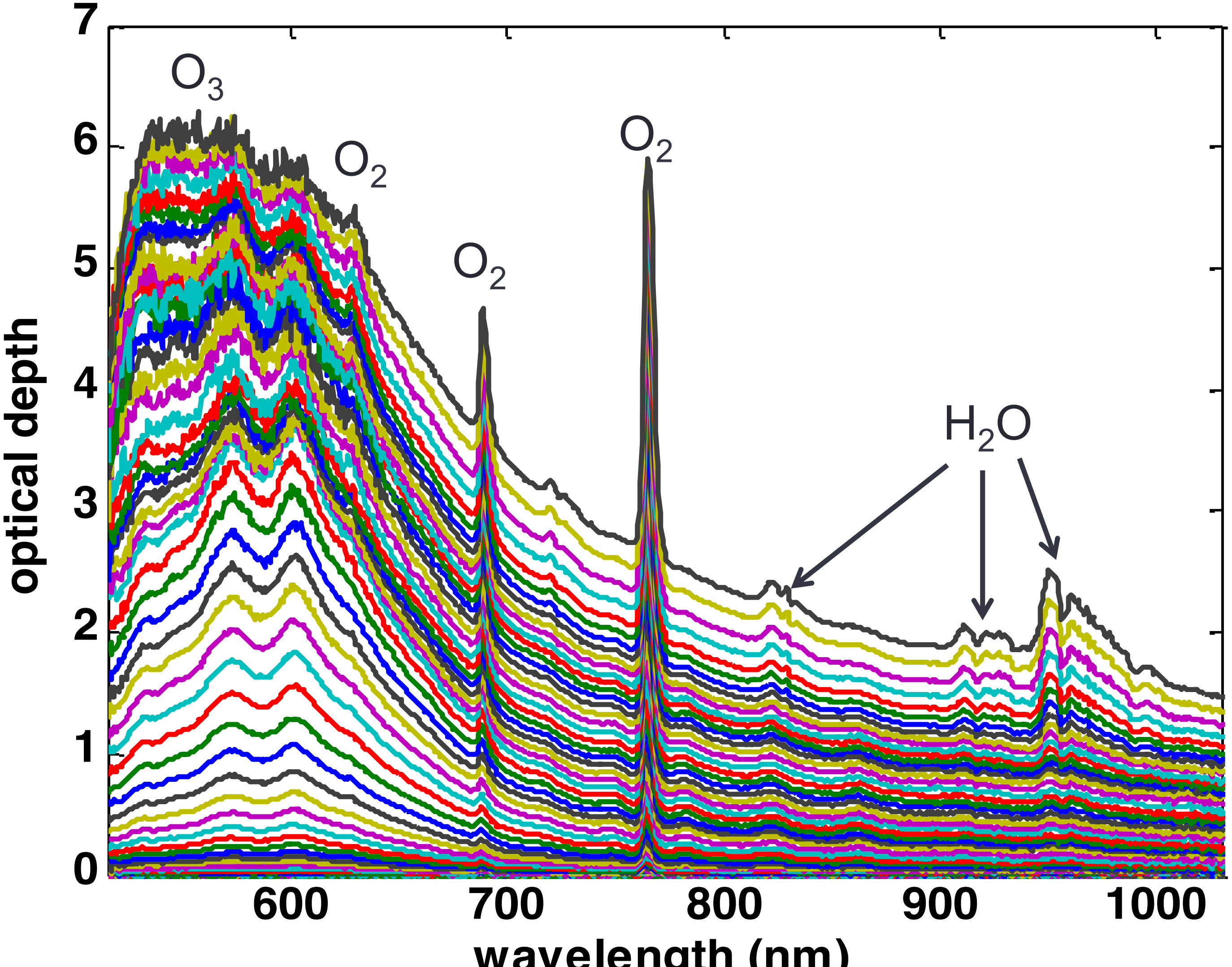


SUNRISE
SUNSET



Kar et al., 2007

MAESTRO Optical Depth Spectra



Occultation Retrievals

- Traditional method: “onion peeling”
- Newer approach: global fitting
  - Simultaneous fitting of every spectrum in an occultation
  - Arrange all spectra into one giant measurement vector

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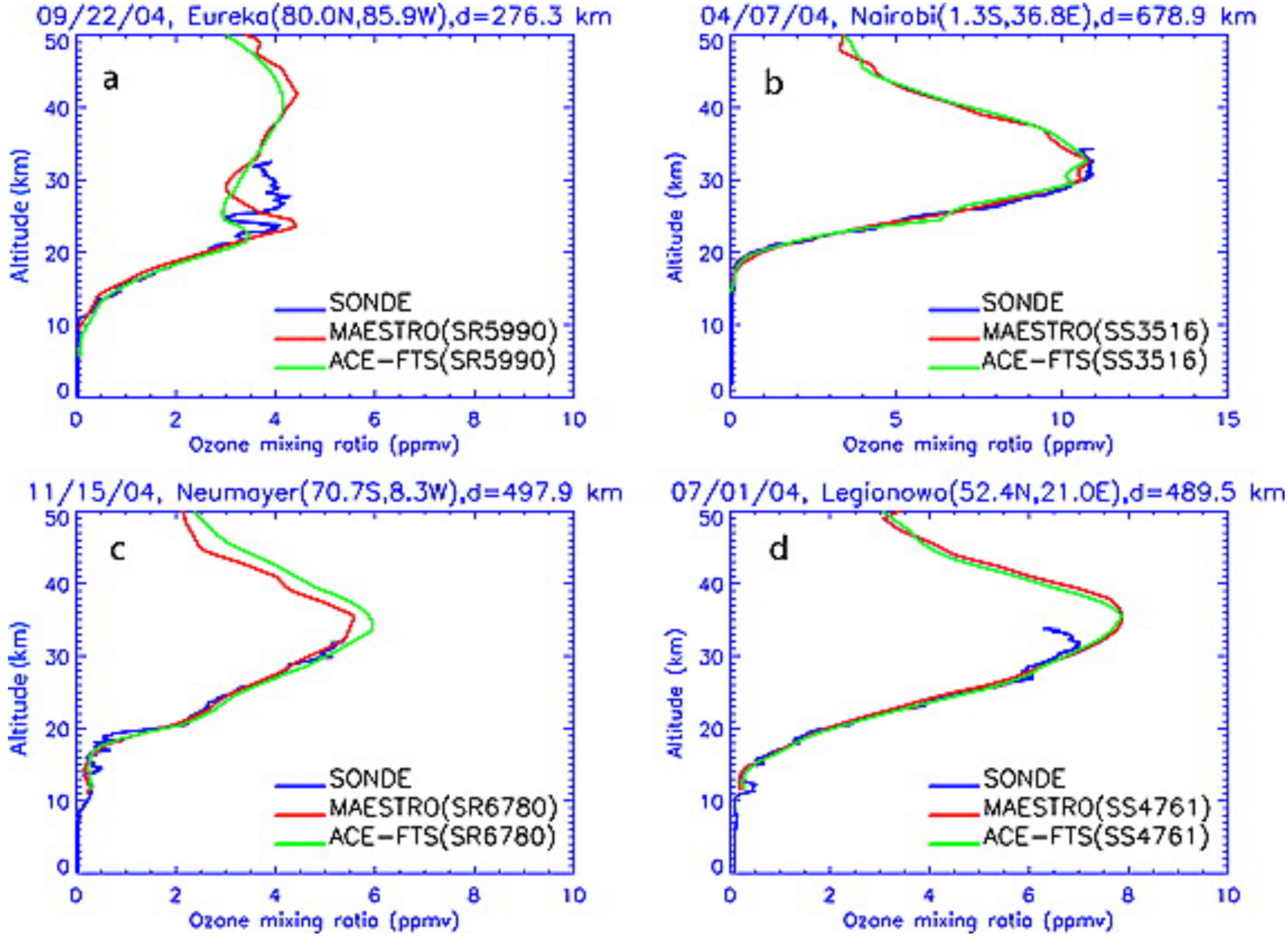
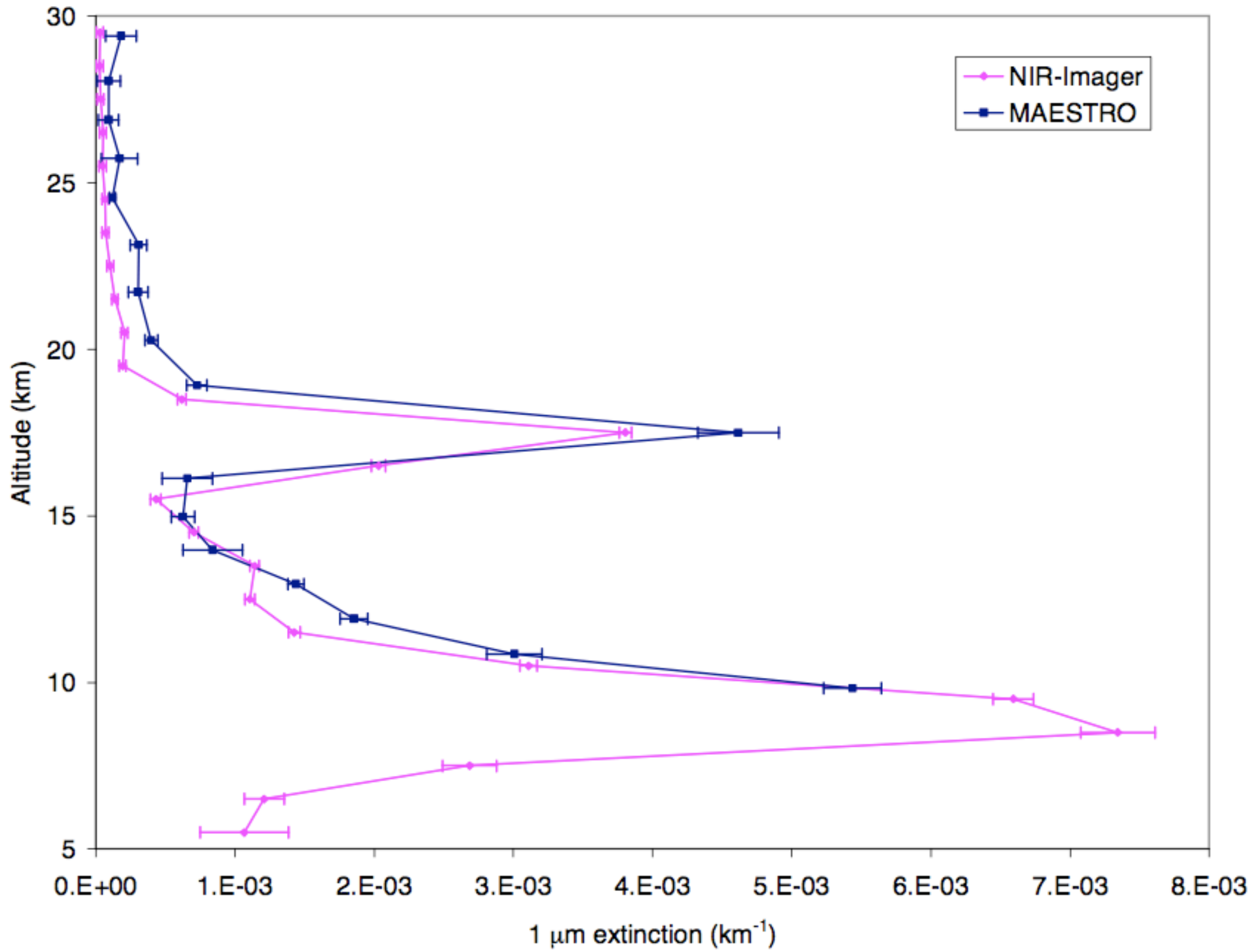
ACE-MAESTRO: Ozone Profiles



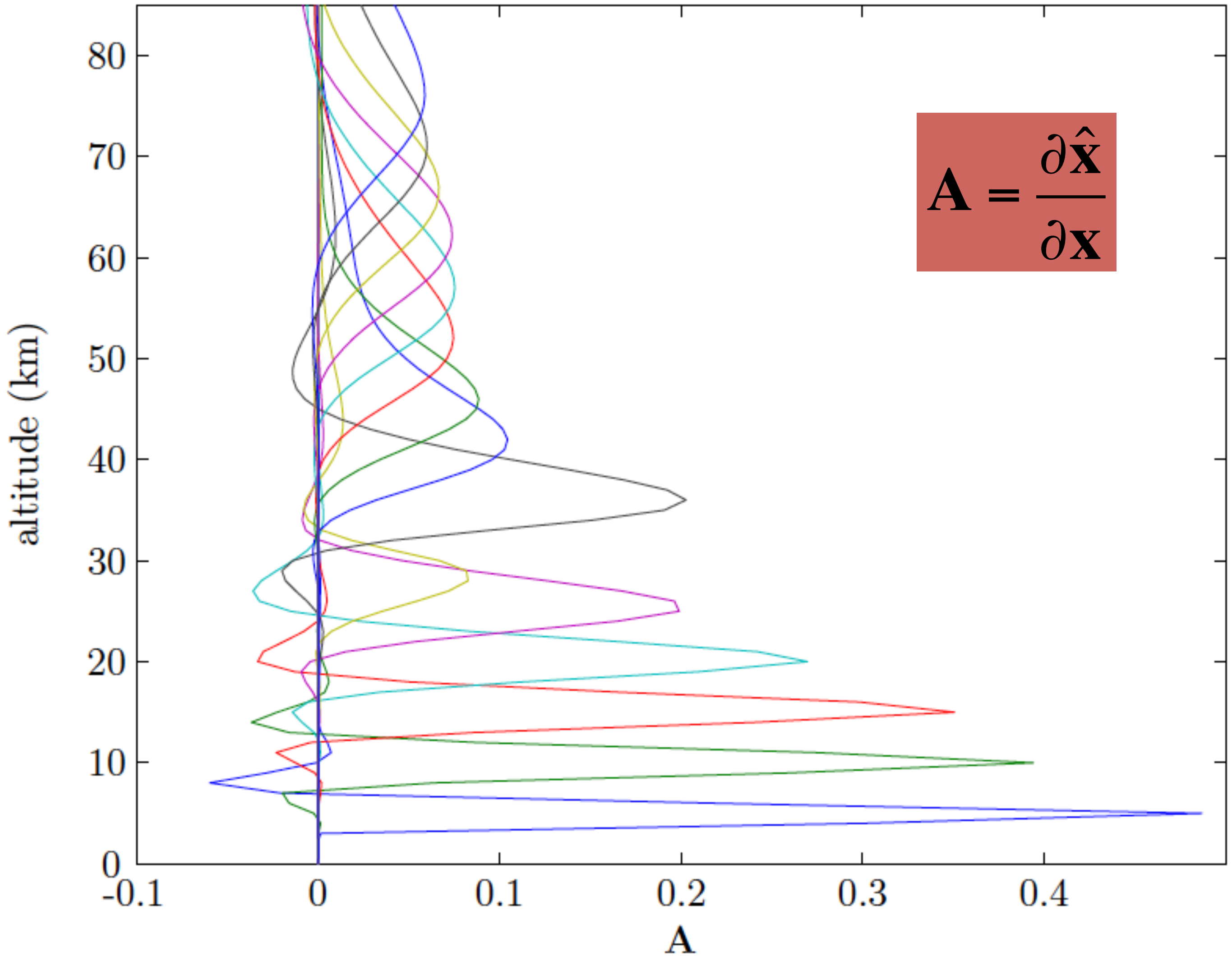
Kar et al., 2007

ACE-MAESTRO: Mt. Kasatochi Aerosols

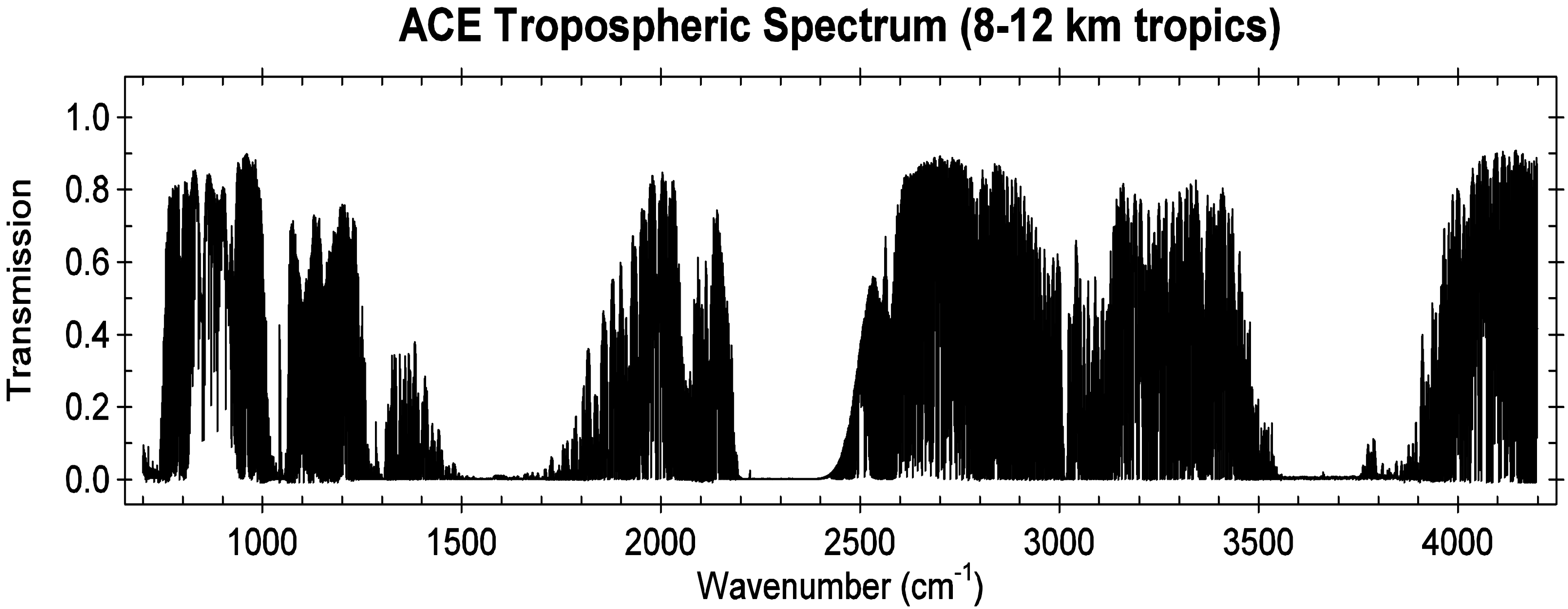


Sioris *et al.*, JGR, 2010

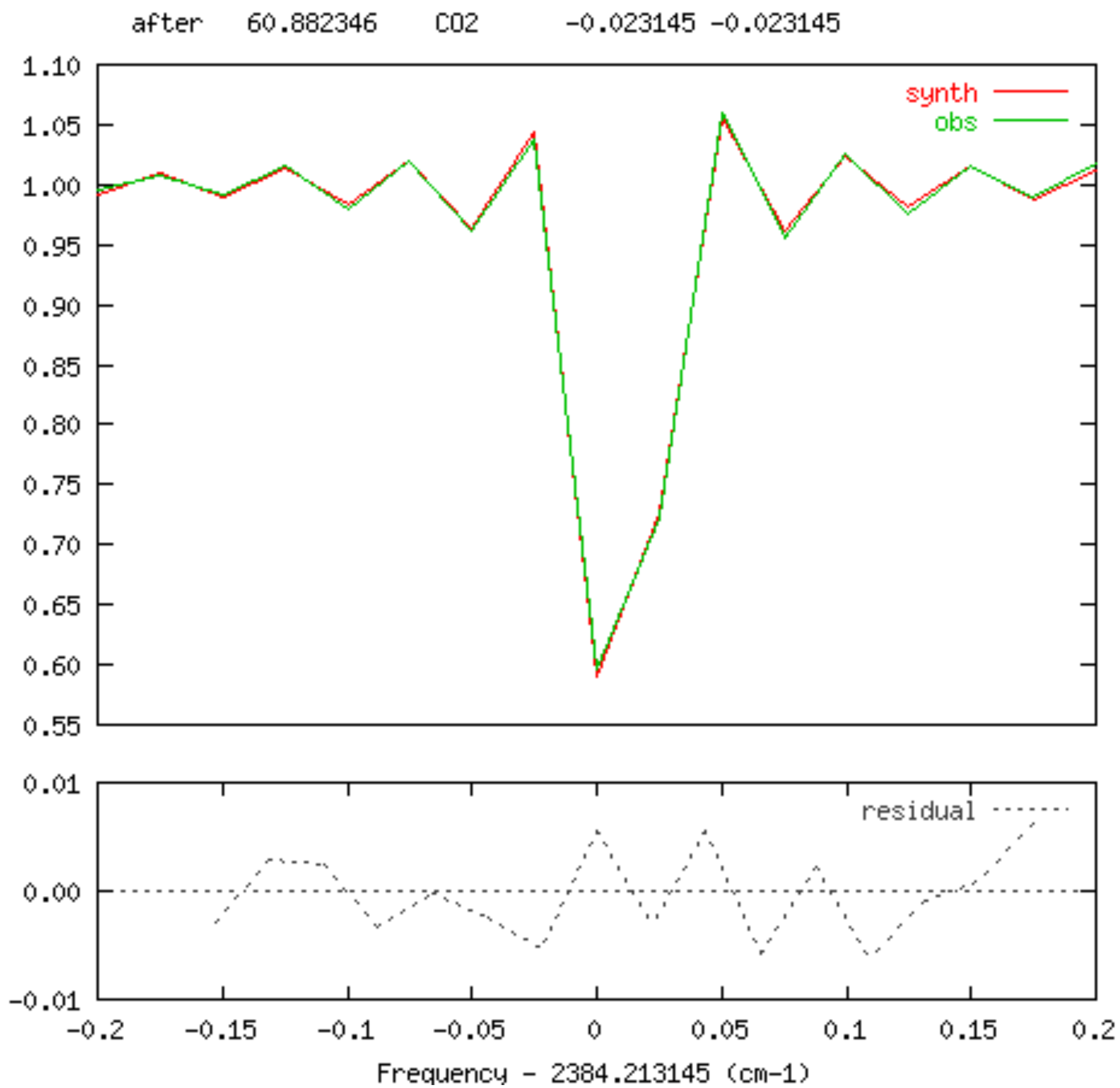
Density Averaging Kernels from O_2 Bands



ACE-FTS Spectra

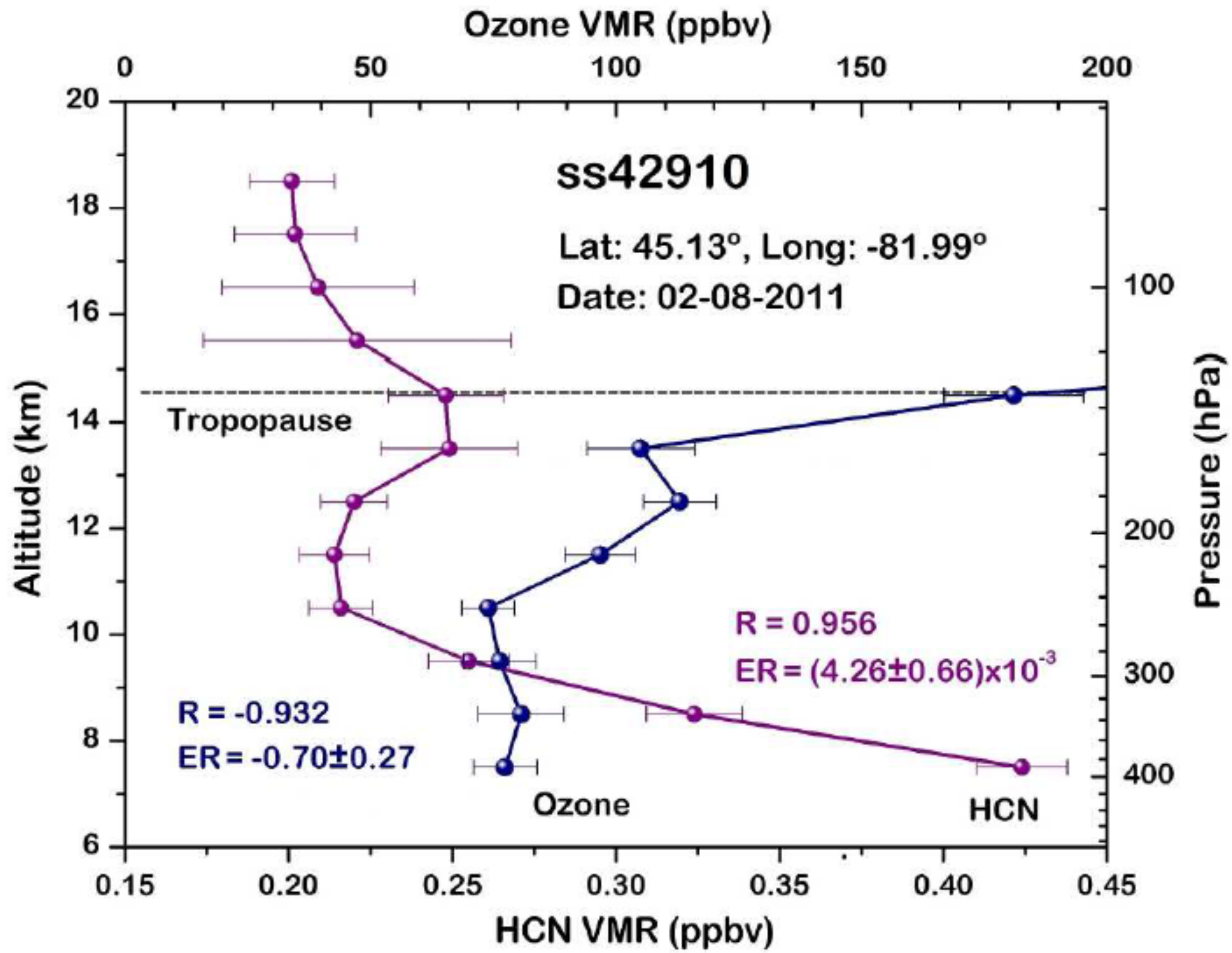


ACE-FTS CO_2 line (near 61 km)



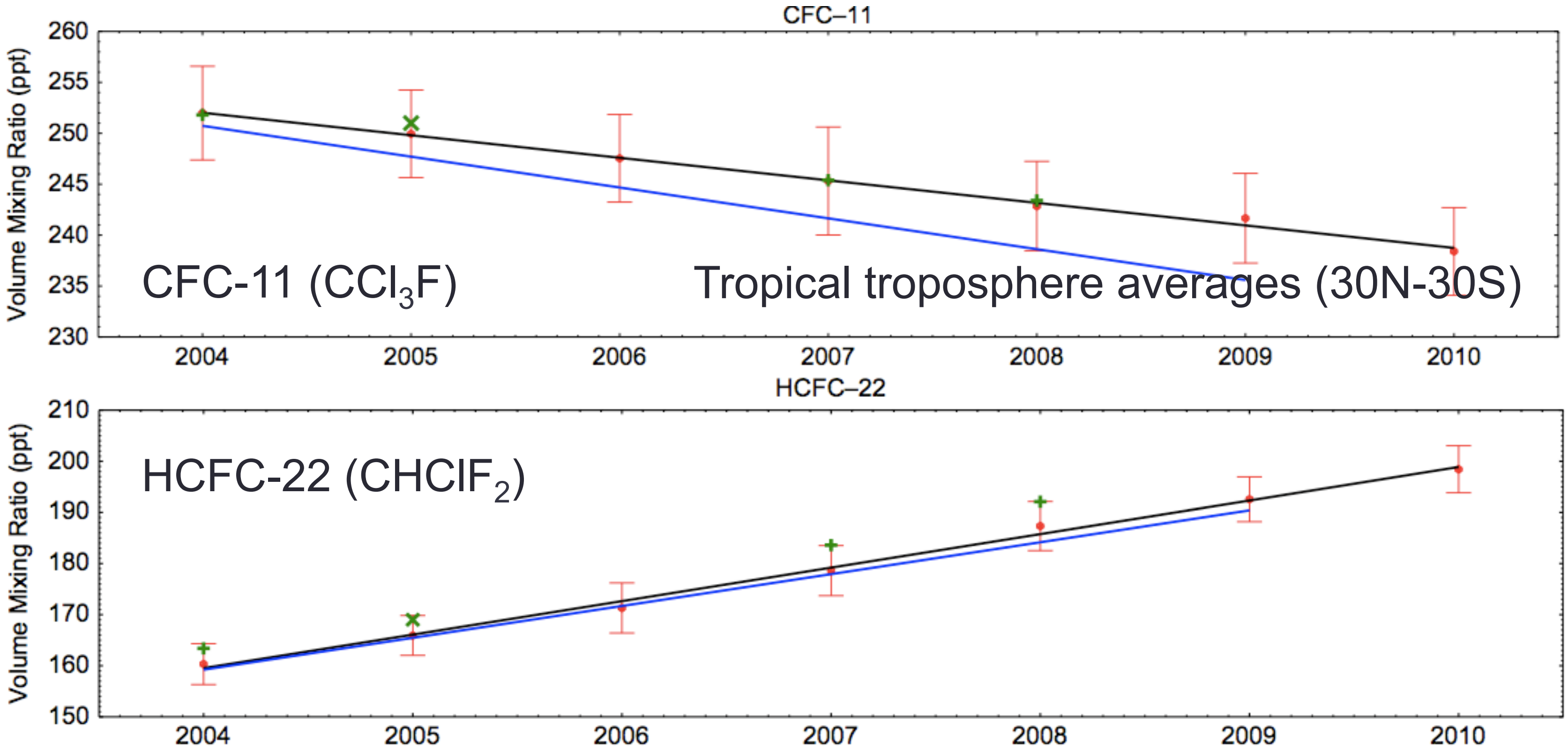
K. Walker, U of Toronto

ACE-FTS: Canadian Biomass Burning



Tereszchuk et al., ACP, 2013

Halogen-containing Species Trends

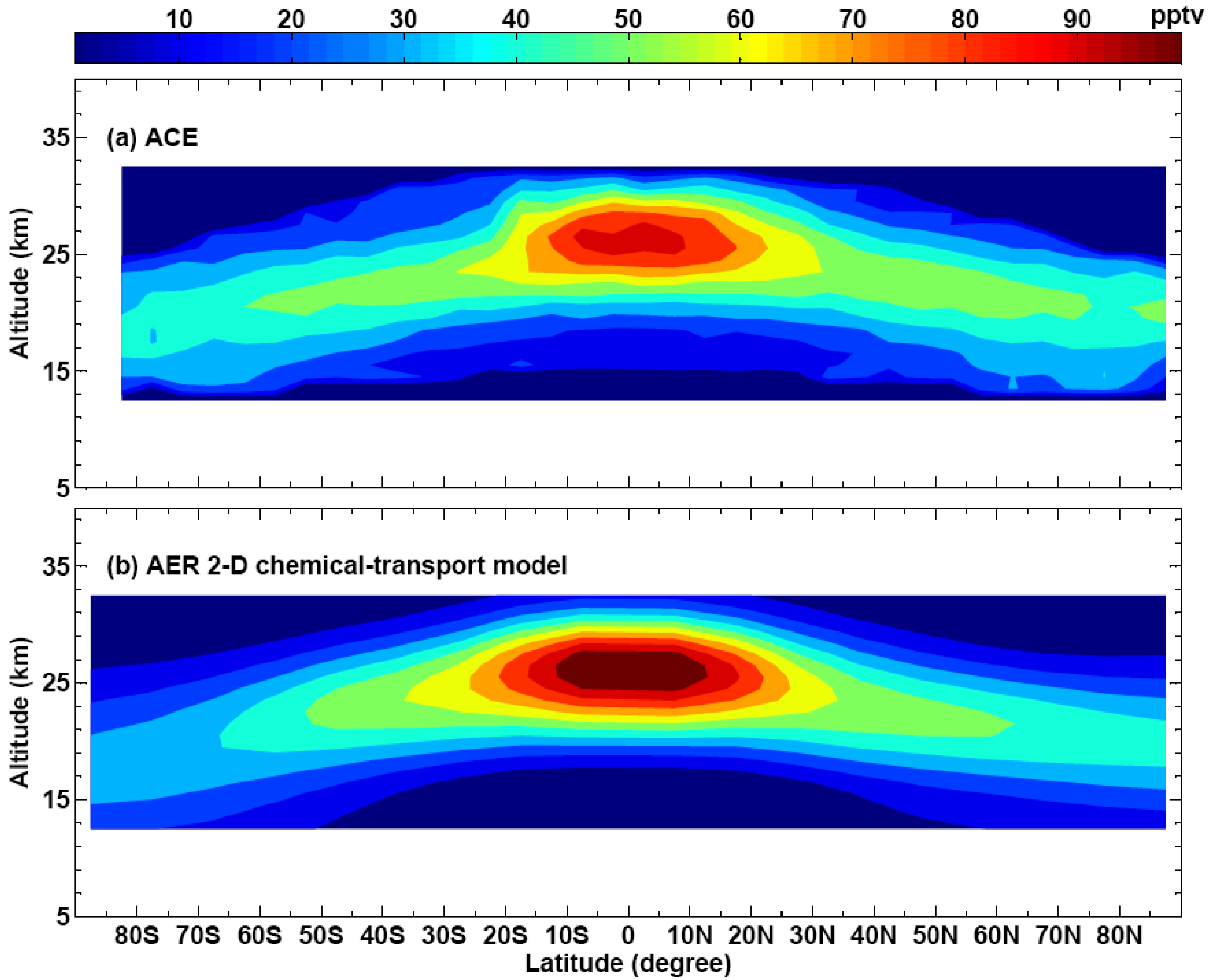


ACE-FTS meas. (~7-16 km)
SLIMCAT model (~7-16 km)
AGAGE meas. (surface)

A. Brown *et al.*, JQSRT, 112, 2552-2566 (2011)

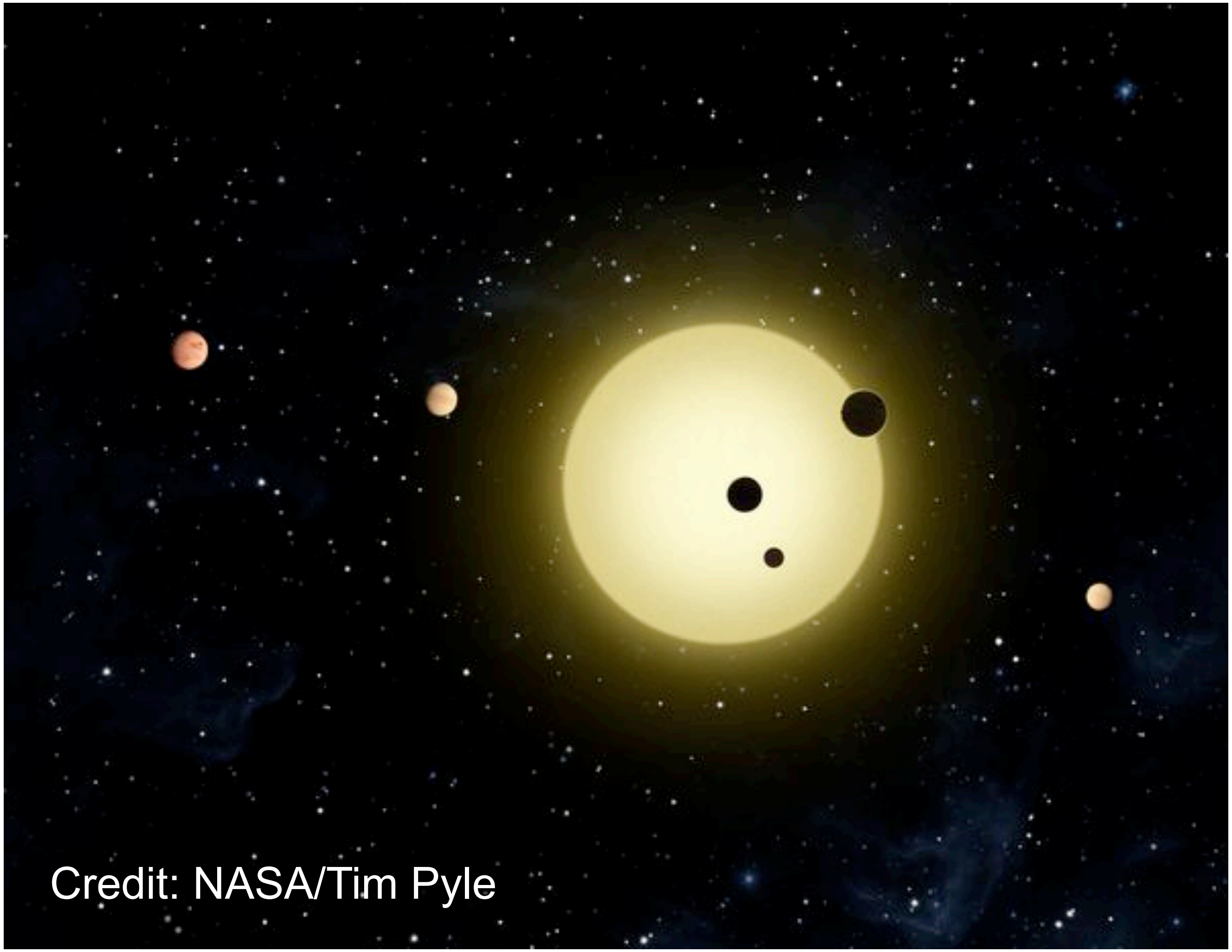
Distribution of COClF

- Carbonyl chlorofluoride is a product of chlorofluoro-carbon (CFC-11 mainly) decomposition
- Previously studied by aircraft instruments (5 - 12 km)
- First global picture obtained from ACE-FTS



D. Fu *et al.*, JQSRT, 110, 974-985 (2009)

Exoplanet atmospheres from occultation?



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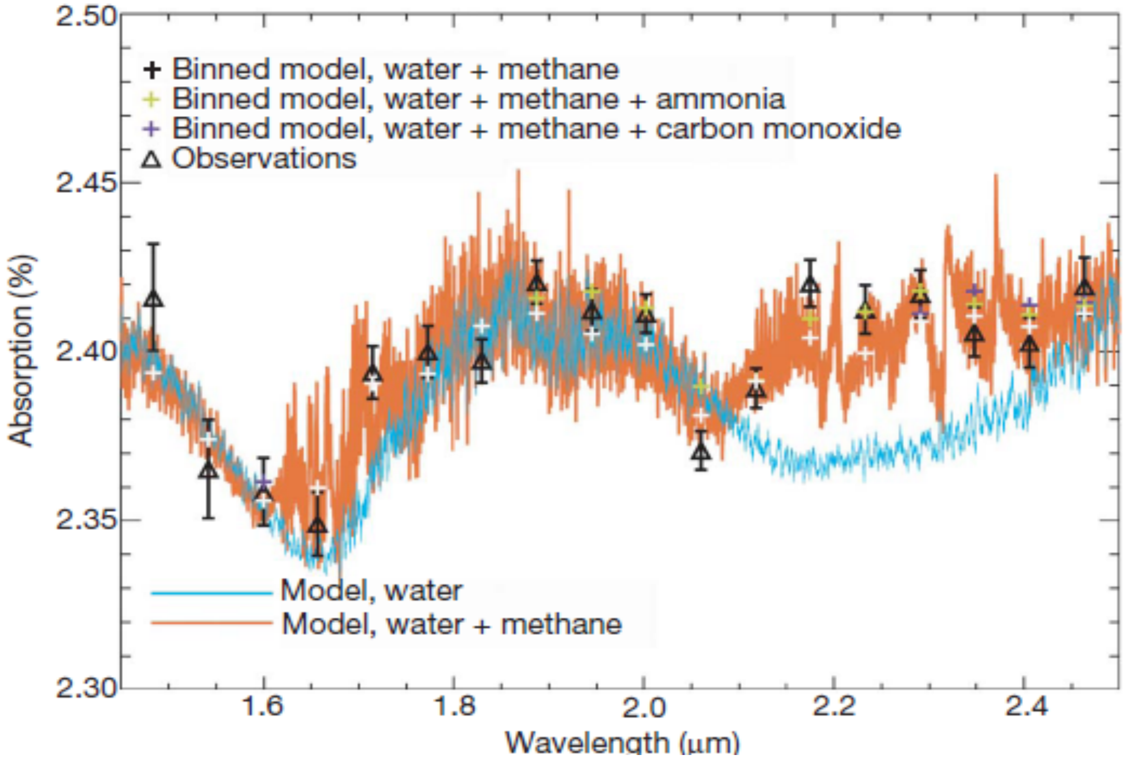
LETTERS

The presence of methane in the atmosphere of an extrasolar planet

Mark R. Swain[1]*, Gautam Vasisht[1]* & Giovanna Tinetti[2]*



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