Atmospheric Physics
University of Toronto

The 2007 Noble Lecture Series

Atmospheric Chemistry and the Remote Sensing of the Global atmosphere March 26-30th 2007.

Lecture 3: SCIAMACHY Solar and Limb Retrievals

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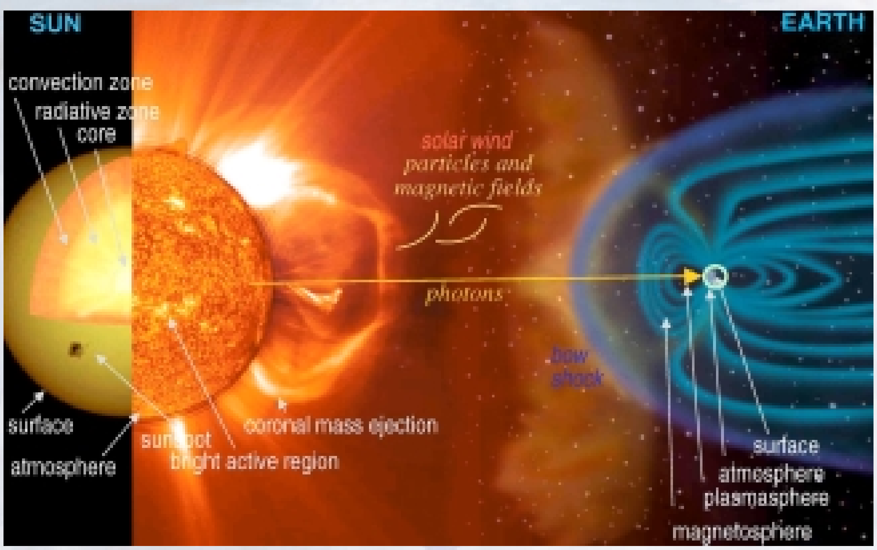
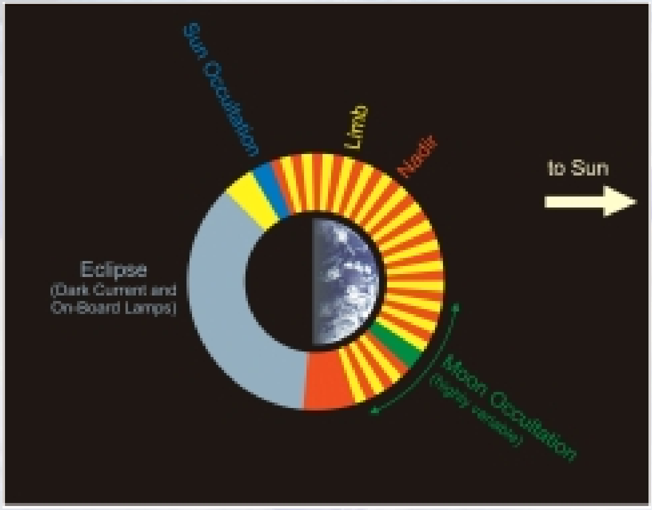
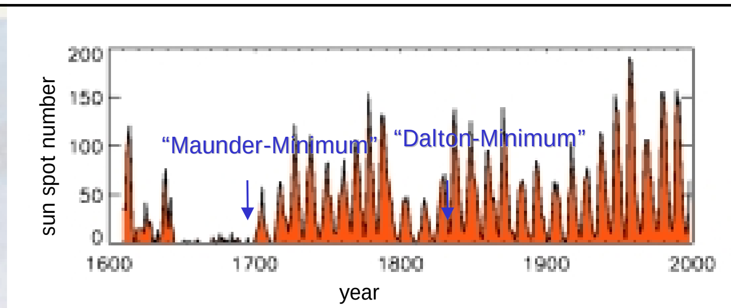
Solar-terrestrial: „Space weather“



SCIAMACHY orbit sequence

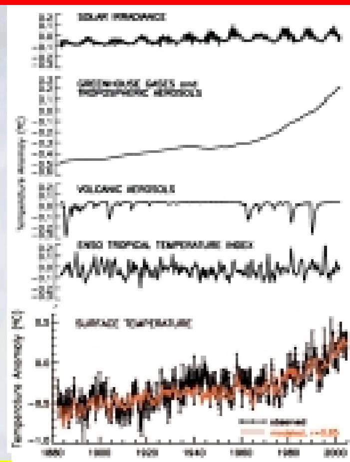


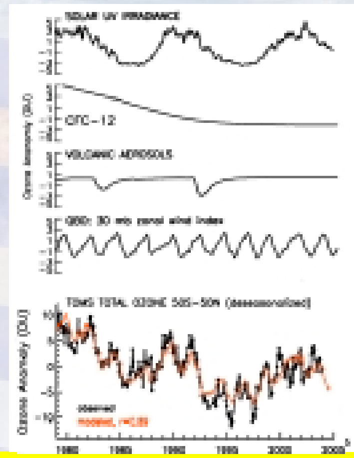


- 17th century („Maunder minimum“):
  - „little ice age“
  - famous Dutch winter paintings
- Other cyclic variation overlaying the 11y solar cycle (Schwabe) have periods of 87 years (Gleissberg) and 210 years (De Vries-Suess)

Solar variability, ozone, and climate

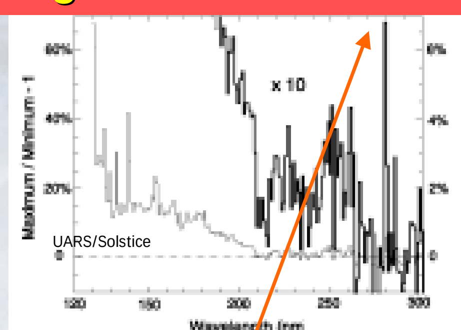
Lean et al., 2005





- 11-year solar cycle signature in sea surface temperature (SST) and ozone
- Note: recent increase in SST (+0.8°C) is not explained by the rather quiet sun (+0.1°K) but is related to increases in greenhouse gases (+0.7°K)

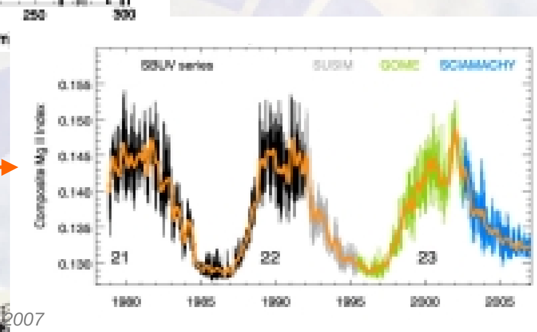
Change:UV solar irradiance over a solar cycle



Rottmann, 2000

- UV satellite irradiance observations cover solar cycles 21, 22, 23
- Largest variations observed in the UV spectral range

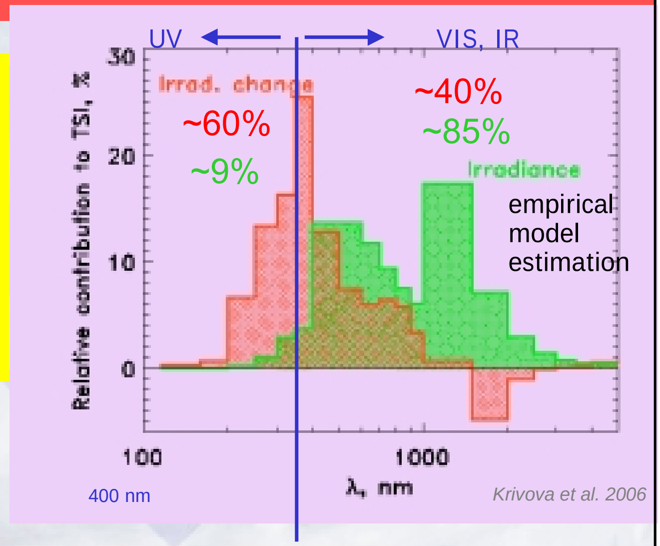
Mg II emission at 280nm



Weber et al., 2007

Spectral contribution to TSI (solar constant)

- UV contributes to about 9% to the total solar irradiance, but 30-60% to solar cycle variability of TSI (≈0.1%)
- Can we confirm this by satellite observations?



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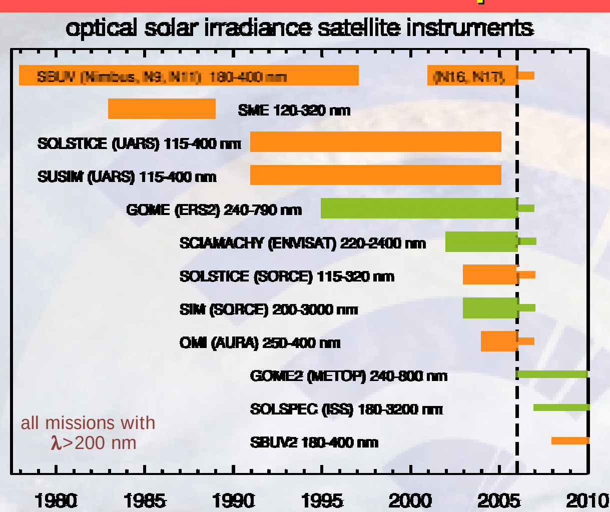
Past and future UV/Vis irradiance montoring from space



- UV irradiance monitoring from space since 1978
- only few missions cover visible/NIR wavelengths
  - GOME
  - SCIAMACHY
  - SIM
- disadvantage of „atmospheric sounders“ (GOME, SCIAMACHY, SBUV):
  - lack of rigorous inflight calibration

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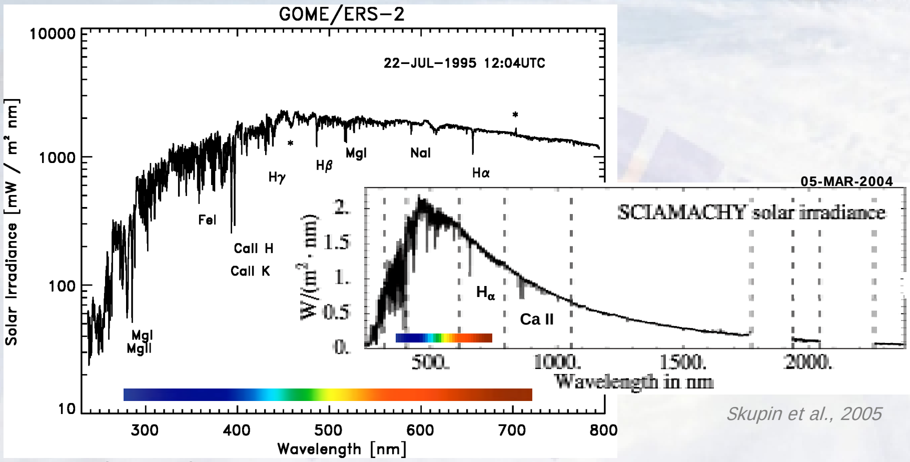
GOME and SCIAMACHY solar spectrum

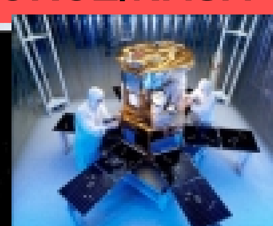


Skupin et al., 2005

- *Weber et al., 1998, Weber 1999*

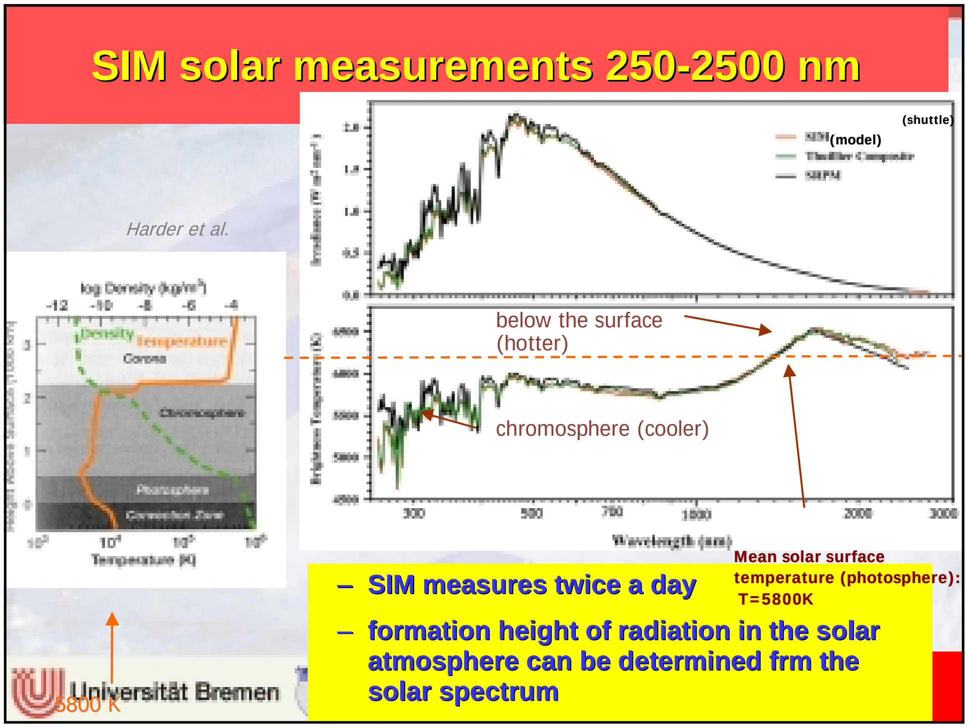
- **Direct full disc solar measurements with diffuser once a day (GOME & SCIAMACHY)**
- **Fraunhofer absorption lines (metals, H) are signatures of the solar atmosphere (photosphere and chromosphere)**

SIM aboard SORCE/NASA



Harder et al., 2005

- Solar Irradiance Monitor
- *Launched*: 2003
- *Orbit:* inclination: 40°, altitude 620 km
- *Measurements:* solar irradiance (twice a day)


SIM solar measurements 250-2500 nm
Harder et al.
(shuttle)
(model)
below the surface
(hotter)
chromosphere (cooler)
Mean solar surface
temperature (photosphere):
T=5800K
log Density (kg/m³)
Density
Temperature
Corona
Chromosphere
Photosphere
Convection Zone
Temperature (K)
Wavelength (nm)
– SIM measures twice a day
– formation height of radiation in the solar atmosphere can be determined frm the solar spectrum
5800 K
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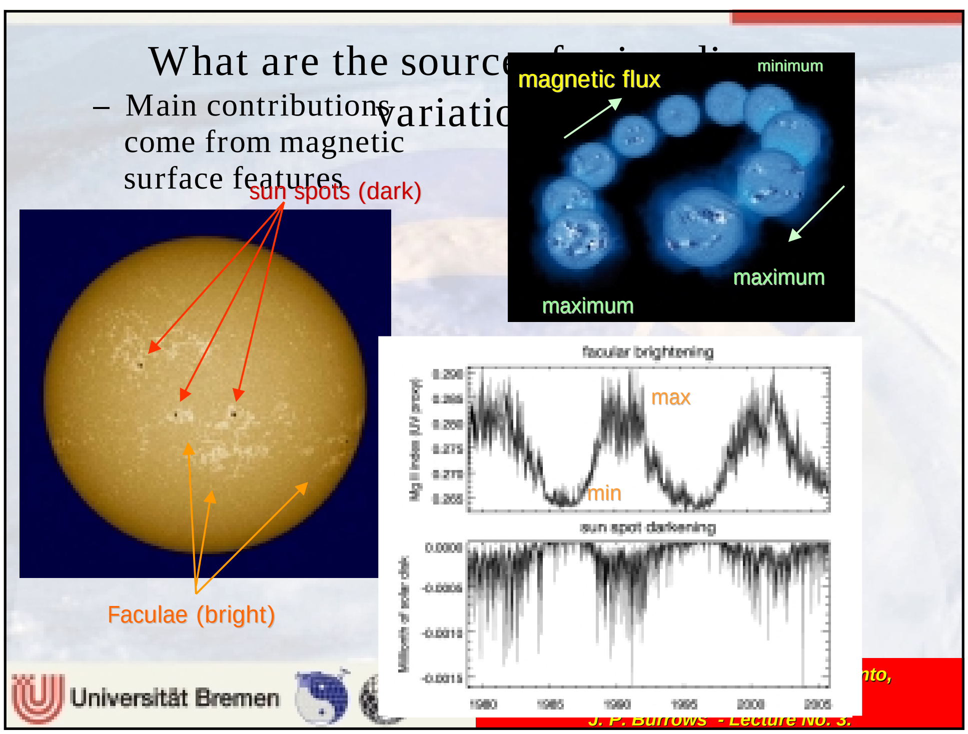
What are the sources of irradiance variation?
– Main contributions come from magnetic surface features
sun spots (dark)
Faculae (bright)
magnetic flux
minimum
maximum
maximum
facular brightening
max
min
sun spot darkening
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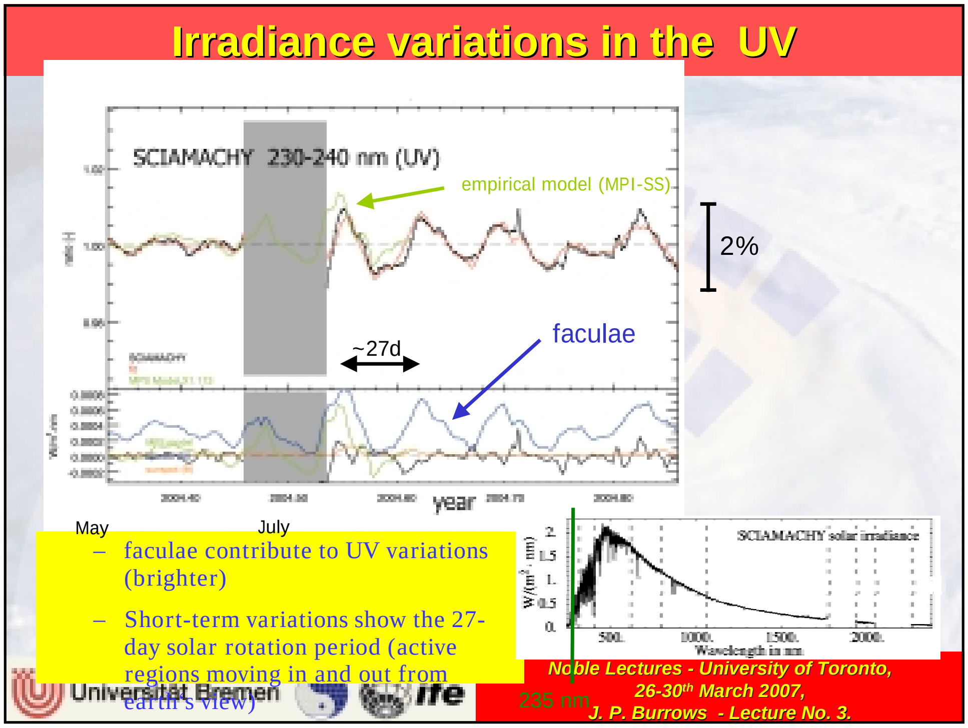
Irradiance variations in the UV
SCIAMACHY 230-240 nm (UV)
empirical model (MPI-SS)
2%
faculae
~27d
year
May
July
SCIAMACHY solar irradiance
W/(m², nm)
Wavelength in nm
235 nm
– faculae contribute to UV variations (brighter)
– Short-term variations show the 27-day solar rotation period (active regions moving in and out from earth's view)
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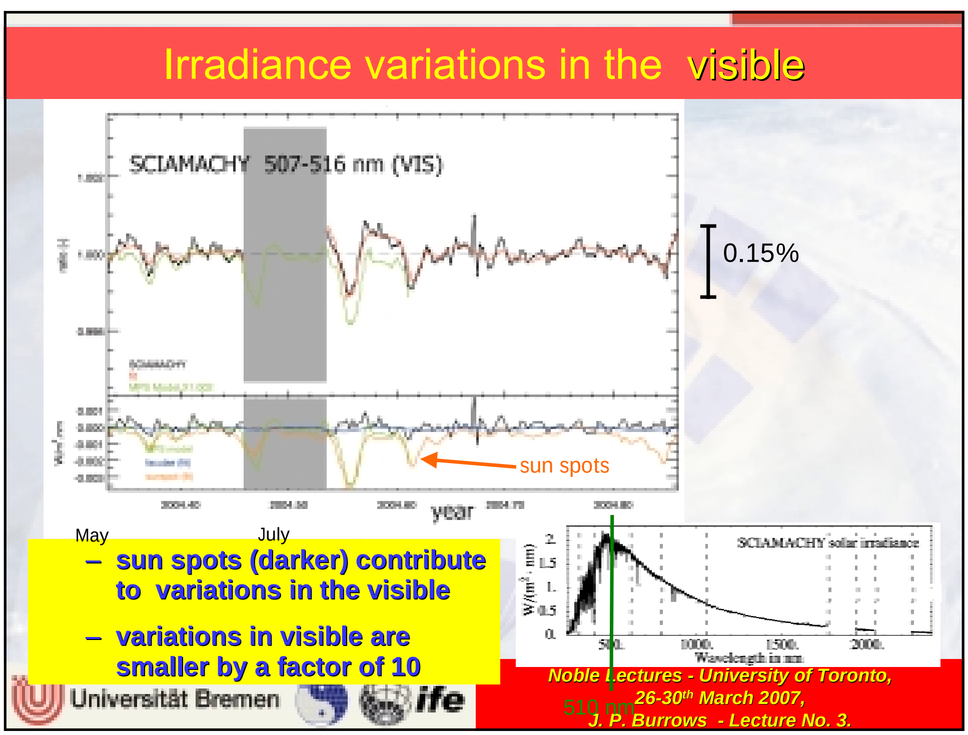
Irradiance variations in the visible
SCIAMACHY 507-516 nm (VIS)
0.15%
sun spots
year
May
July
SCIAMACHY solar irradiance
W/(m², nm)
Wavelength in nm
510 nm
– sun spots (darker) contribute to variations in the visible
– variations in visible are smaller by a factor of 10
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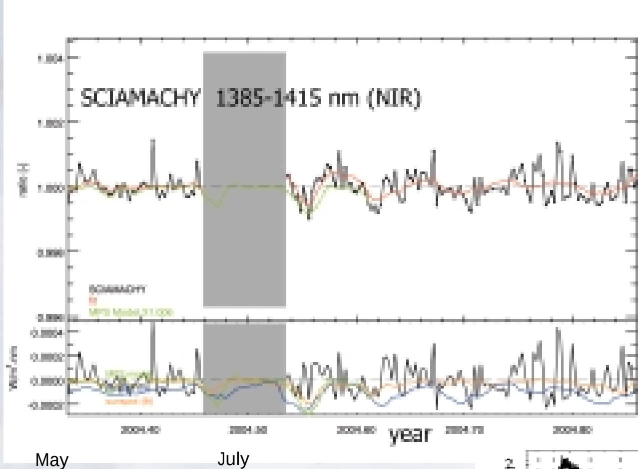
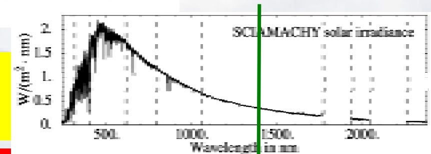
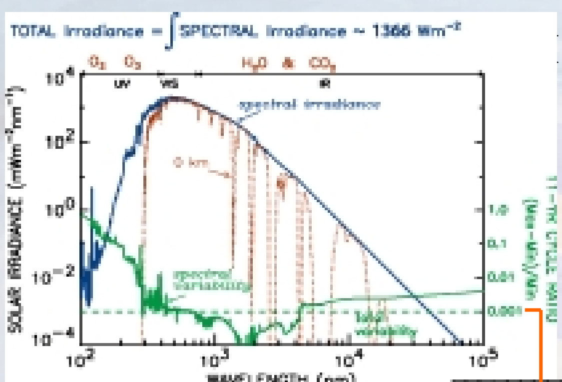
Irradiance variations in the near IR



0.1%

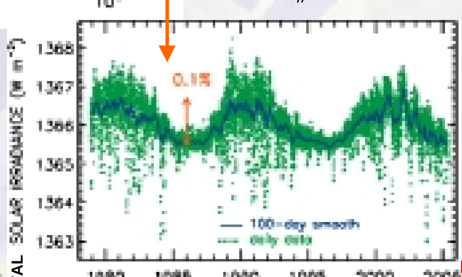


– **Very small variaton on the order of 0.1% in the near IR**



Lean et al.

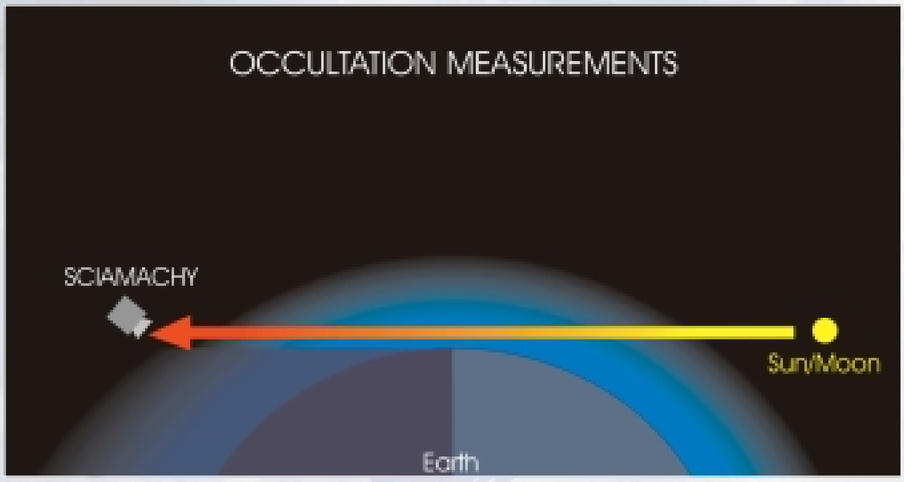
TSI=„solar constant“



Fröhlich et al.

– **The entire optical spectral range are measured daily since 2004 from space**

– **Variations due to solar activity on the order of 0.1% are detectable!**



Occultation Retrieval Precisions

	UT 5 –12 km	LS 12 –24 km	MS 24 –36 km	US 36 –45 km
O_3	1	1	1	1
NO_2	5 – 10	10 – 5	5 - 10	10 –50
BrO	Tbd	20	10	-
OClO	-	20	10	-
ClO	-	Tbd	-	-
H_2O	1	1	1-2	5
CH_4	1	1	1 - 5	5 - 20
CO_2	1	1	1 - 3	3 - 10
CO	1	1 – 10	10 – 20	—
N_2O	1	1 – 10	10 – 20	—

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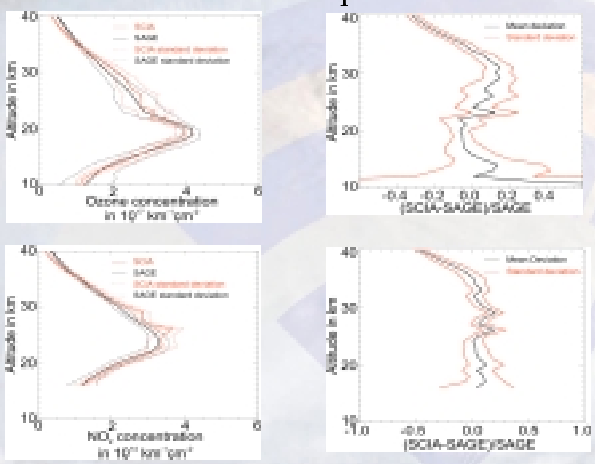
SOLAR OCCULTATION

Comparison with SAGE II (O_3 and NO_2)



- colocated distance: 40 –500 km
- Date : 17^{th} – 22^{nd} sept. 2002
- 25 colocated measurements
- quite good agreement b/n mean profiles
- Fitting window
  - O_3: 525-590 nm
  - NO_2 : 420-460 nm

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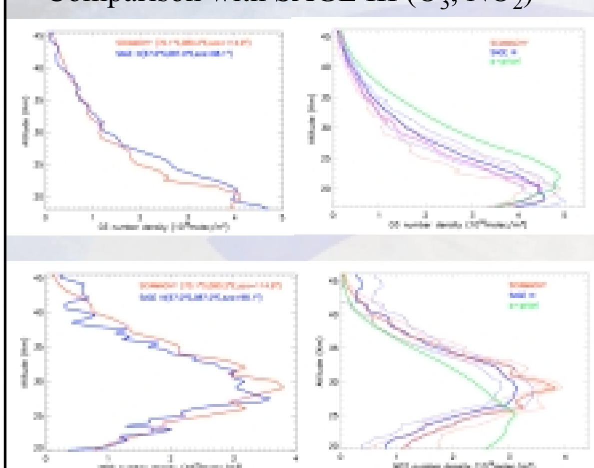
- Mean deviations and statistical variation are in the order of 10%.

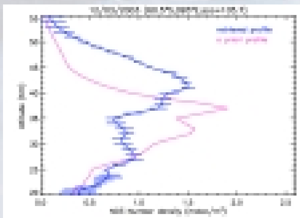
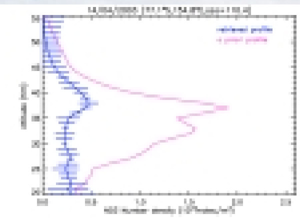
LUNAR OCCULTATION

Comparison with SAGE III (O_3, NO_2)

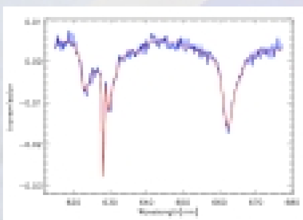
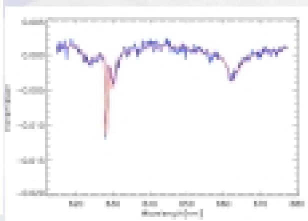


- Date: 12^{th} March, 2003
- Colocated distance: 500 -1000 km
- 9 colocated measurements
- Spectral window: 420-580 nm
- O_3 quite good in b/n 27 – 45 km
- SCIA NO2 results is slightly higher than SAGE III results due to difference in SZA.
- SZA for SCIAMACHY: 114–115°
- SZA for SAGE III: 96 - 100°

NO_3 from lunar occultation

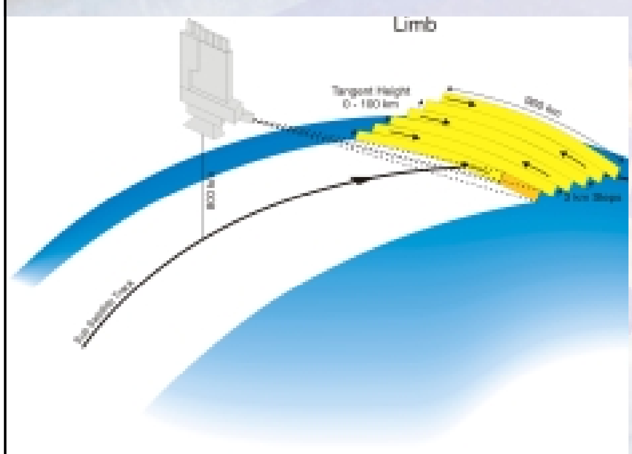



- Spetral window: 610-680 nm
- Altitude range : 22- 55 km
- March 12, 2003 quite high concentration was retrieved compared to April 14, 2003
- Results not validated

- Fit at 39 km is shown
- NO_3, O_3 and NO_3 are fitted
- Good fits are obtain

Limb Measurements



- vertical res.: 3 km
- horizontal resolution in azimuth:
  240 km (120 km min.)
- horizontal resolution in flight direction:
  approx. 400 km
- Observation optimised to match limb with nadir measurements
- Duration of Limb sequence: 60 sec.

Investigation of mesospheric / thermospheric metal species using SCIAMACHY data

Project team: M. Scharringhausen, J. P. Burrows, J. Notholt, C. v. Savigny, M. Sinnhuber

Investigation of mesospheric / thermospheric metal species using SCIAMACHY data

- What do we consider?
  - Na,Fe, Mg, Li, Si,... and ionized counterparts
- Where do mesospheric metals come from:
  - Cosmic dust/Meteors (ablation at 80 – 100km)
- Why is it interesting?
  - Amount of influx is very uncertain (40 - 400 tons/day)

    Metal abundance + composition of comic dust = estimate of total influx

  - Impact on stratospheric and mesopheric chemistry?

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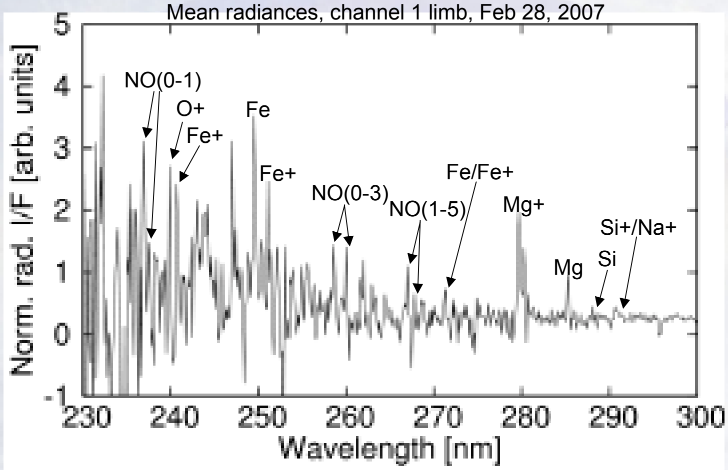
A large number of emission signals can be identified in the SCIAMACHY spectra



Impact on mesospheric/stratospheric chemistry

1) Formation of meteoric smoke (polymerization)

metal compounds + silicon oxides $\longrightarrow$ meteoric smoke (MS)

2) Catalytic water production (heterogeneous)

$$H_2 + O + MS \longrightarrow H_2O + MS$$

3) Catalytic chlorine production

$$(M) + HCl \longrightarrow (M)Cl + H \longrightarrow (M)Cl + h\nu \longrightarrow (M) + Cl$$

4) Meteoric smoke particles act as condensation nuclei for stratospheric clouds?

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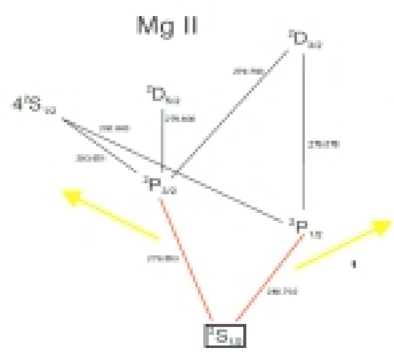
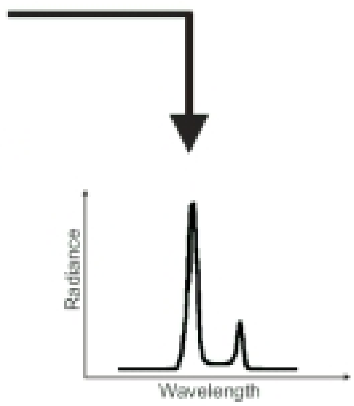
Retrieval principle for Mg+/Mg

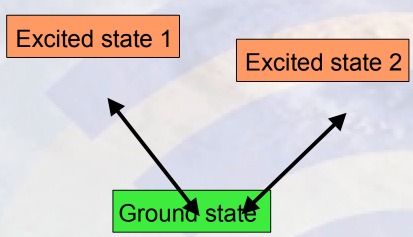


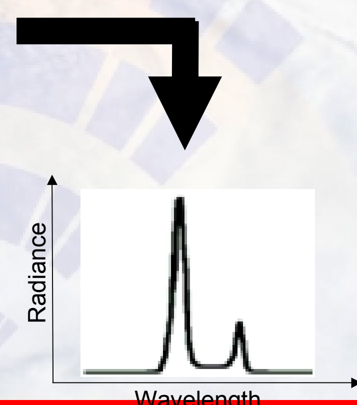


Resonance fluorescence:

- Excitation by sunlight
- Emission WL = excitation WL

Retrieval principle for Mg+/Mg





Resonance fluorescence:

- Excitation by sunlight
- Emission WL = excitation WL

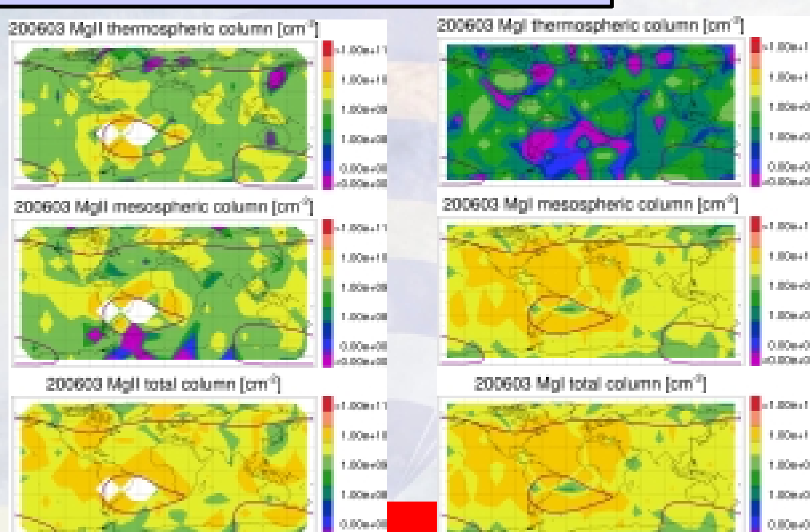
Radiative transfer equation to solve

$$I(\lambda) = F(\lambda) \cdot \gamma(\lambda) \cdot \int_{LOS} \tau_1(s) N(s) \tau_2(s) ds$$

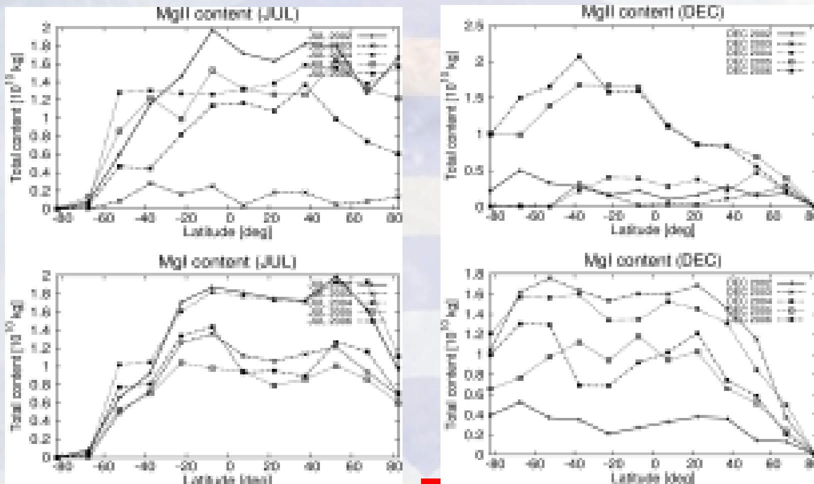
Measured radiance — Solar irradiance — Emissivity — Line-of-sight — Absorption — Number density

- Retrieval method: Optimal estimation using a radiative transfer model

First global maps of Mg and Mg+ number densities



Seasonal variation of total Mg and Mg+ content



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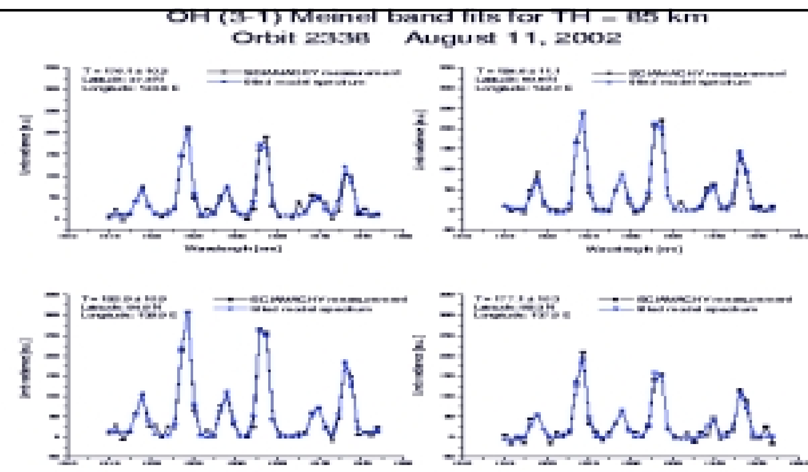

Accepted excitation mechanism

- $H + O_3 \rightarrow OH^* + O_2$
- Initial v' = 7, 8, 9
- Both radiative and quenching loss, latter may be sudden death or cascade

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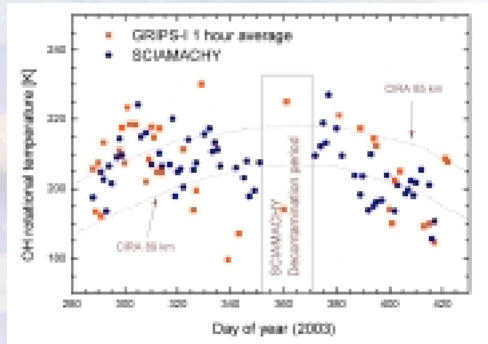
Validation of nighttime OH mesopause temperatures

- Comparison of SCIAMACHY OH* (3-1) rotational temperatures with collocated with collocated GRIPS-I 1-hour averages of ground-based OH* (3-1) rotational temperature measurements at Hohenpeißenberg (47° N/ 11° E) for the period October 15, 2003 through February 26, 2004.

- Note: Zenith and limb observations are weighted differently in terms of altitude and the temperatures are expected to differ slightly

- GRIPS data courtesy D. Offermann, M. Bittner, K. Höppner

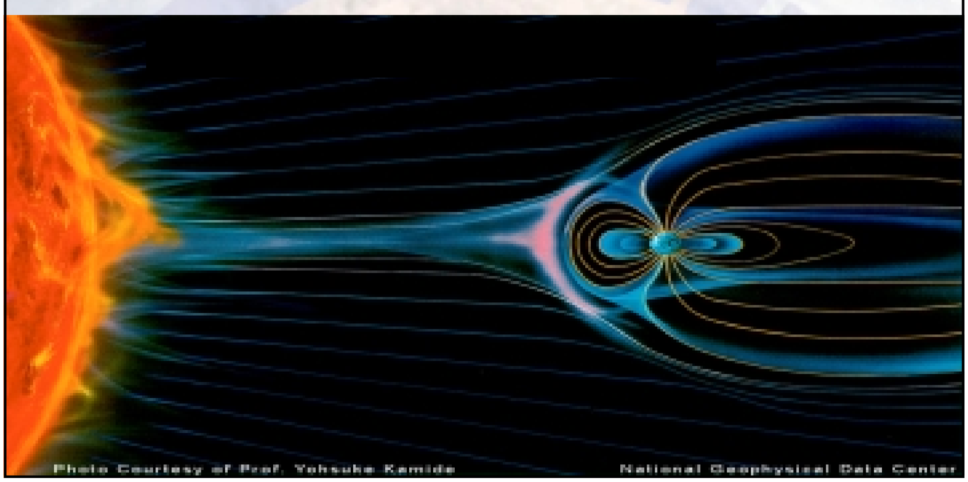


- Difference GRIPS I (MOHP) - SCIAMACHY: 2.6 K (11.1 K)

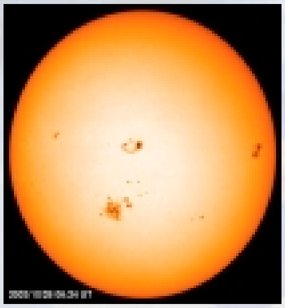
- Difference GRIPS II (Wuppertal) - SCIAMACHY: 2.3 K (9.7 K).

Solar Proton Events

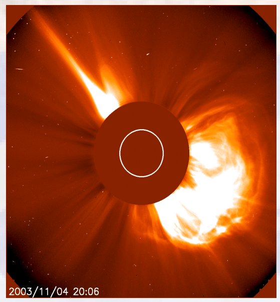
- SPE caused by coronal mass ejection (CME)
- Deposit >60° latitude
- Influence of SPE by complicated ion chemistry



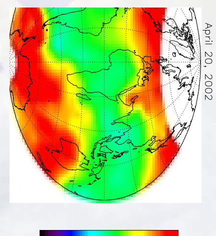
Solar Proton Events: Oct-Nov 2003



2. CMEs arrived at Earth in 1-2 days producing huge geomagnetic storms and important effects on atmospheric composition in the polar regions.

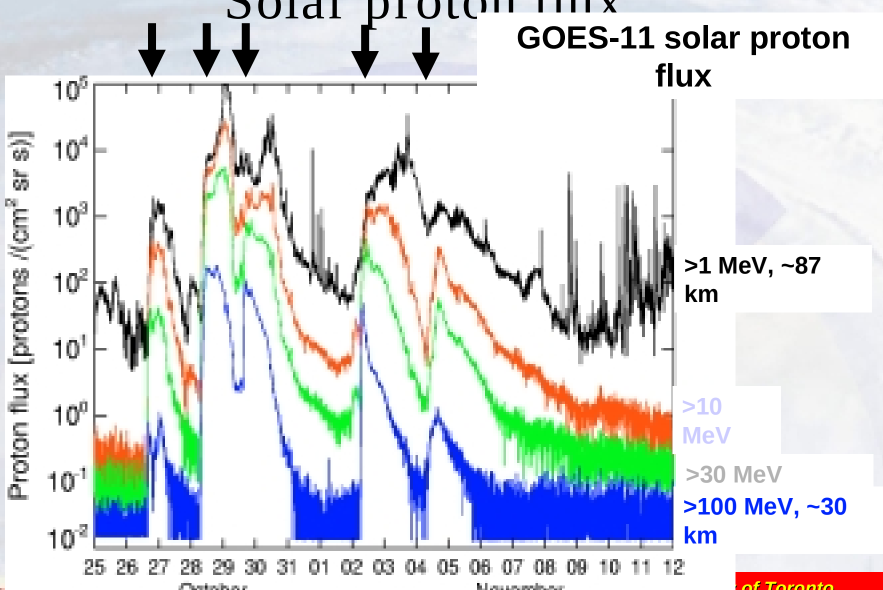


3. Earth was bombarded by very energetic protons (and electrons), driven to both polar regions (g. lat.>60°) where they penetrate down to the lower stratosphere.



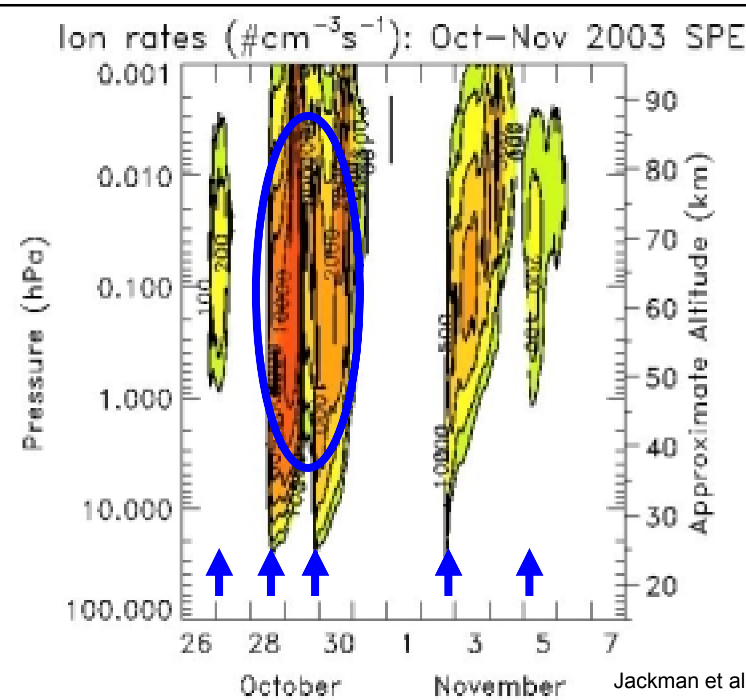
- Two solar active regions during 28-29 Oct and 3rd Nov 2003 produced solar flares, coronal mass ejections (CMEs) and solar energetic particles of unprecedented intensity.

Solar proton flux



Effects of solar proton events

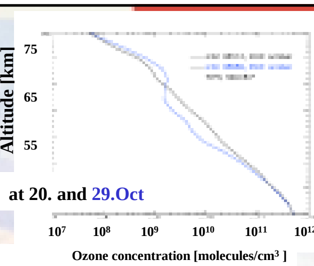
- Protons affect the mesosphere (~50-90 km) and the stratosphere (12-50 km)
- Energy deposition mainly in both polar caps (>60° geomagnetic latitude)
- Most of the energy deposited by protons creates ion pairs: free electrons and positive ions, hence affecting the atmospheric chemical composition.

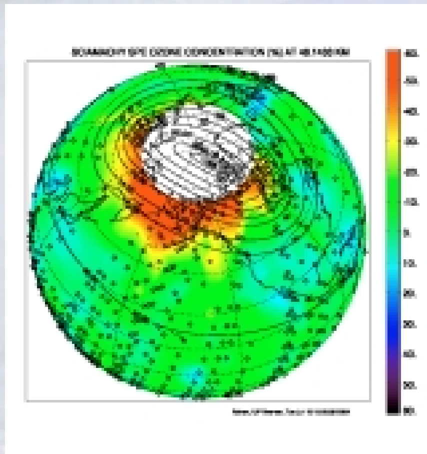


Jackman et al., AGU Sp. 2004

MESOZONE: OZONE DEPLETION DURING SPE

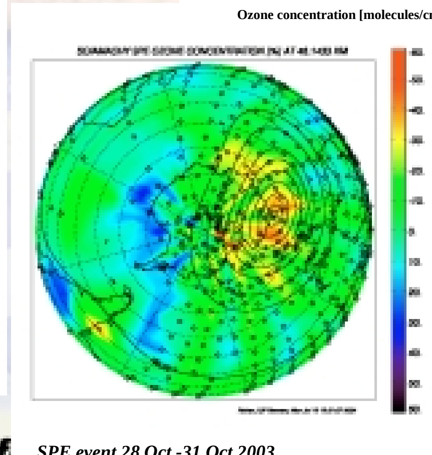
(G. Rohen, C. v. Savigny)





SPE event 28.Oct.-6.Nov..2003

Reference period: 20.-24.Oct. 2004



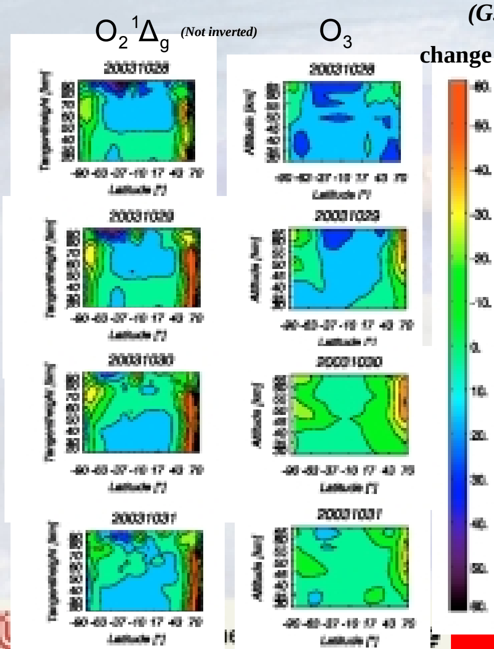
SPE event 28.Oct.-31.Oct.2003

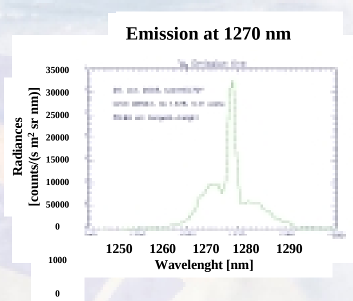
Simultanous measurements of $O_2(^1\Delta_g)$ and ozone

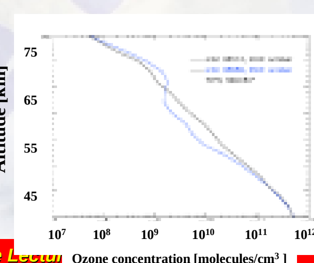
(G. Rohen, C. v. Savigny, J. P. Burrows)

$O_2\,^1\Delta_g$ *(Not inverted)* O_3

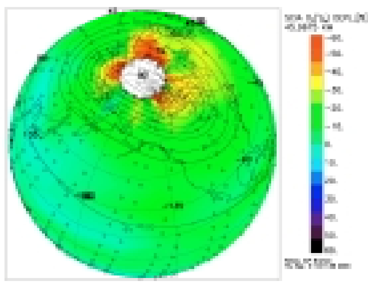
change [%]

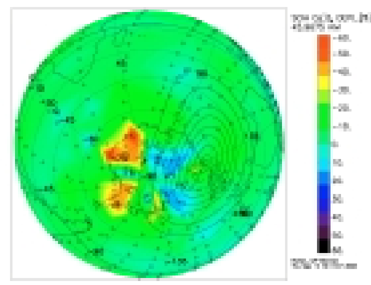




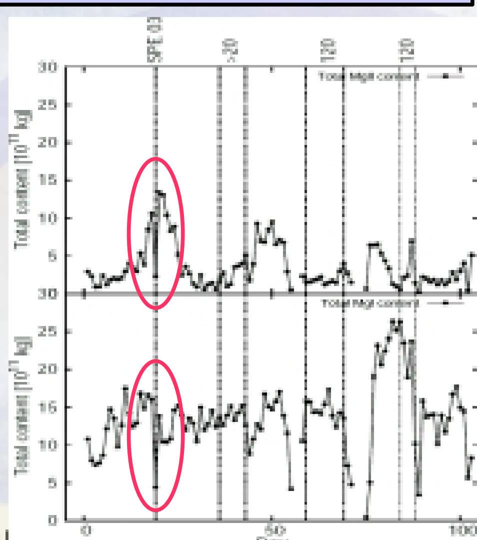


$O_2(1\Delta)$ from O_3 Photolysis
Difference between before and shortly after the Storm





Depletion of Mg+ and Mg during the 2003 SPE?



Day 0 = Oct 10, 2003

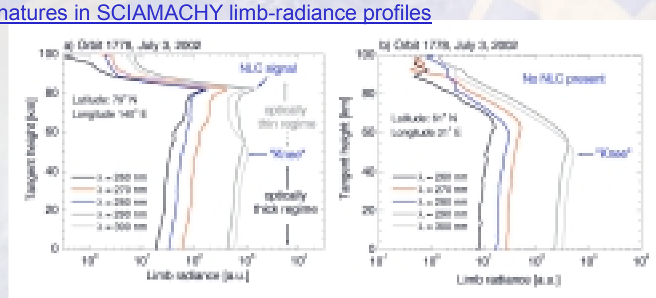
Noctilucent clouds

Courtesy of P. Parviainen

NLC signatures in SCIAMACHY limb radiance profiles

- Noctilucent clouds (NLCs) or polar mesospheric clouds (PMCs) occur at about 83 km altitude near the polar summer mesopause
- NLCs are potentially early indicators of global change, as their formation and existence depends very sensitively on temperature and ambient H_2O abundances
- SCIAMACHY is currently the only instrument allowing global and continuous observations and retrievals of NLC particle sizes

NLC signatures in SCIAMACHY limb-radiance profiles



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NLC particle size determination

I. In single scattering approximation the NLC backscatter is given by:

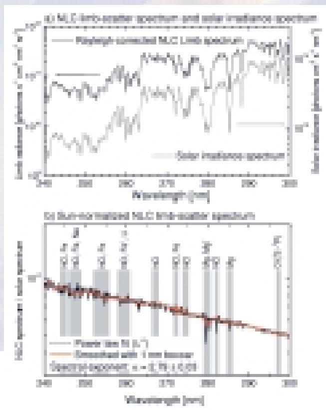
$$I_{NLC}(\lambda,\Theta) \propto q(\lambda,\Theta) \times S(\lambda)$$

$q(\lambda,\theta)$: Differential scattering cross section
$S(\lambda)$: Solar irradiance spectrum

II. The sun-normalized NLC-backscatter spectrum:

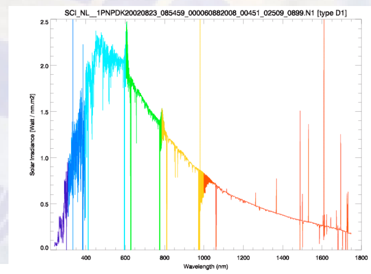
$$i(\lambda,\Theta) = \frac{I_{NLC}(\lambda,\Theta)}{S(\lambda)} \propto q(\lambda,\Theta) \propto \lambda^{-\alpha}$$

The spectral exponent α is related to the NLC particle size by Mie-calculations



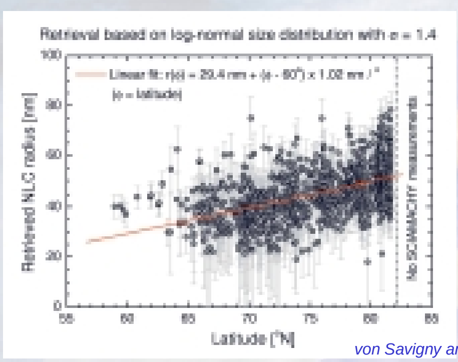
von Savigny et al. [2007]

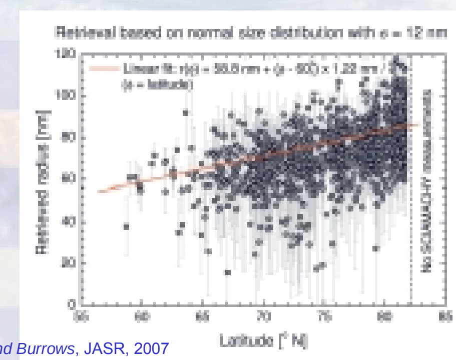
SCIAMACHY solar irradiance measurements



Skupin et al. [2005]

Latitudinal dependence of NLC radii for July 2005





von Savigny and Burrows, JASR, 2007

Shown are only measurements with:

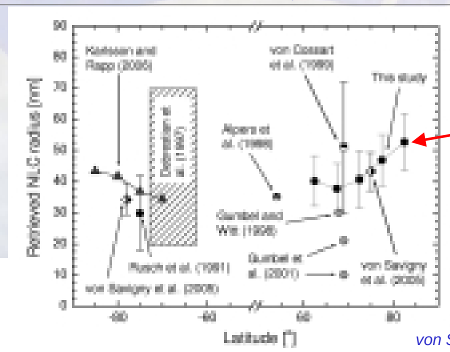
- Relative brightnesses exceeding 5
- Relative radius errors < 100 %

Comparison of existing NLC size retrievals

Previous NLC size retrievals:

Reference	Technique	Radii / width	Size distribution
Carbary et al. [1996]	limb-scatter	≈ 70 nm, σ ≈ 1.2	Log-normal
Debrestian et al. [1997]	solar occultation	< 70 nm, σ ≈ 1.4	Log-normal
Gumbel and Witt [1998]	rocket photometry	50 nm	δ-function
Rusch et al. [1991]	limb-scatter		Log-normal
von Cossart et al. [1999]	ground-based Lidar	50 nm, σ ≈ 1.4	Log-normal
Carbary et al. [2004]	limb-scatter	50 nm / 220 nm	Bi-modal
von Savigny et al. [2005]	limb-scatter	30–50 n, σ = 1.4	Log-normal
Karlsson and Rapp [2006]	limb-scatter	50–90 nm	(eff. Radius)
Rusch et al. [2006]	limb-scatter	15–20 nm, σ≈15 nm	Normal
Englert et al. [2006]	nadir-backscatter	80–220nm	Normal
Baumgarten et al. [2006]	ground-based Lidar	40–70 nm, σ≈15 nm	Normal
Model simulations:			
Berger and von Zahn [2002]		r_0 ≈ 40 – 50 nm	Normal
Rapp and Thomas [2006]		r_0 ≈ 40 nm	Normal

After conversion of radii to log-normal PSD with σ = 1.4



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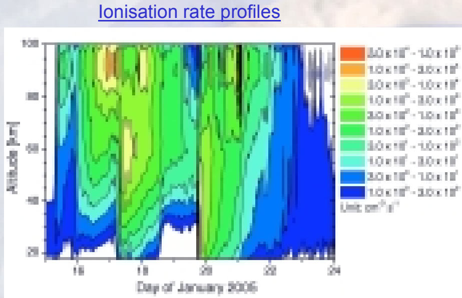
von Savigny and Burrows, JASR [2007]

NLCs during solar proton event in January 2005

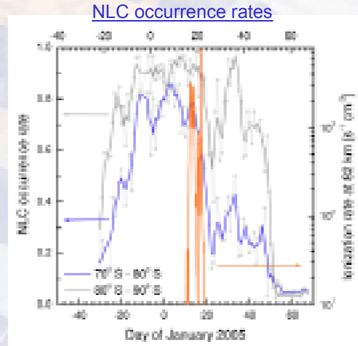
- In January 2005 a solar coronal mass ejection (CME) lead to precipitation of high energy solar protons into the polar atmosphere
- SCIAMACHY observed an unprecedented "depletion" of NLCs during the SPE

Ionisation rate profiles



Ionisation rates kindly provided by M.-B. Kallenrode (University of Osnabrück)

NLC occurrence rates



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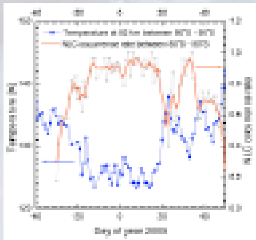
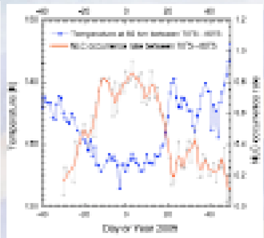
Anticorrelation of NLC occurrence rate and temperature

80° S - 90° S

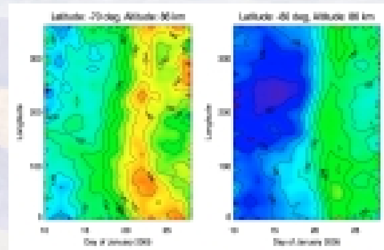


70° S - 80° S



Temperature increase of 10 – 14 K within 5 days for both latitude bands

Aura/MLS temperature measurements provided by M. Schwartz (JPL)



Longitudinal and temporal variation of the temperature at 70S / 80S latitude and 86 km altitude.

von Savigny et al., GRL, 2007

⟶ Temperature increase occurred first near the geomagnetic pole, indicating causal relationship with energetic particles

Possible causes for NLC reduction

- Ion-Chemistry mechanism:

  Chemistry following ionization by high-energy particles converts H_2O to HO_x

  ⟶ **Removal of H_2O required to maintain solid phase**

- Joule heating following ionization

- Adiabating cooling due to increased upward motion due to O_3 destruction

There are several indications that the NLC depletion was caused by the precipitating energetic particles, but the effect is not fully understood !

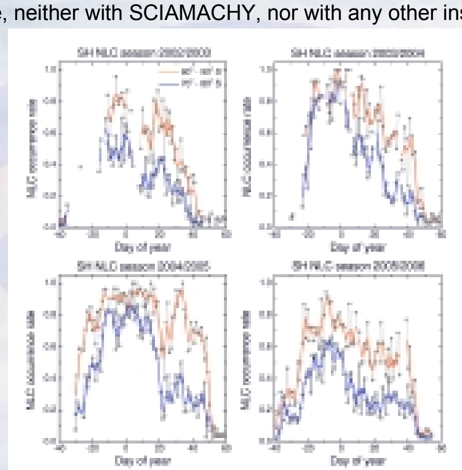
⟶ **Detailed model simulations required to understand this effect**

Potential implication:

Since SPEs occur more frequently during solar maximum, this mechanism may contribute to the observed solar cycle variation in NLCs

Interannual difference in NLC in SH occurrence rates

- A decrease in NLC occurrence rate as rapid as in January 2005 has never been observed before, neither with SCIAMACHY, nor with any other instrument



—— smoothed with 3-day boxcar

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Polar stratospheric clouds

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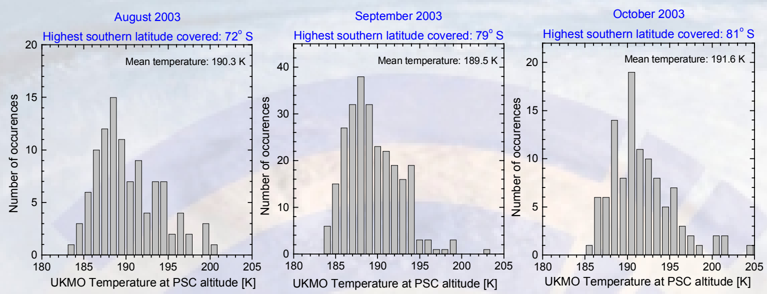
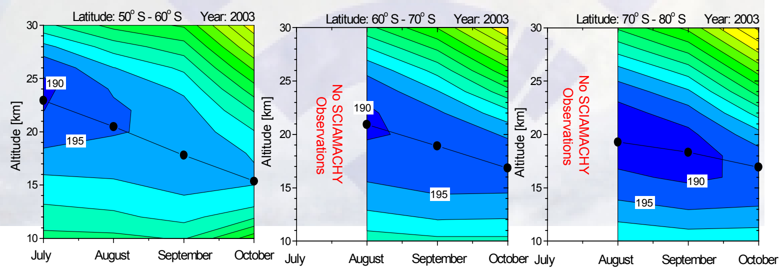
Histograms of temperature at PSC altitude

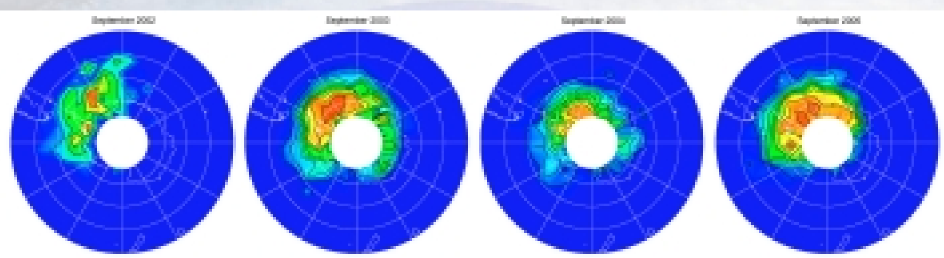


PSC descent during polar winter



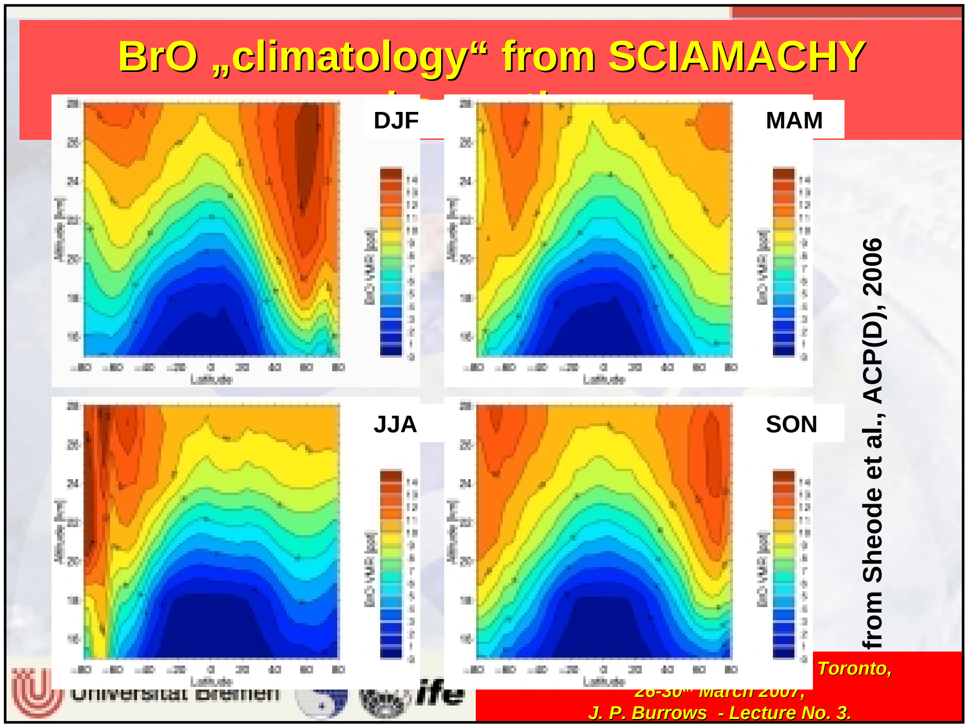
Polar stratospheric cloud climatology

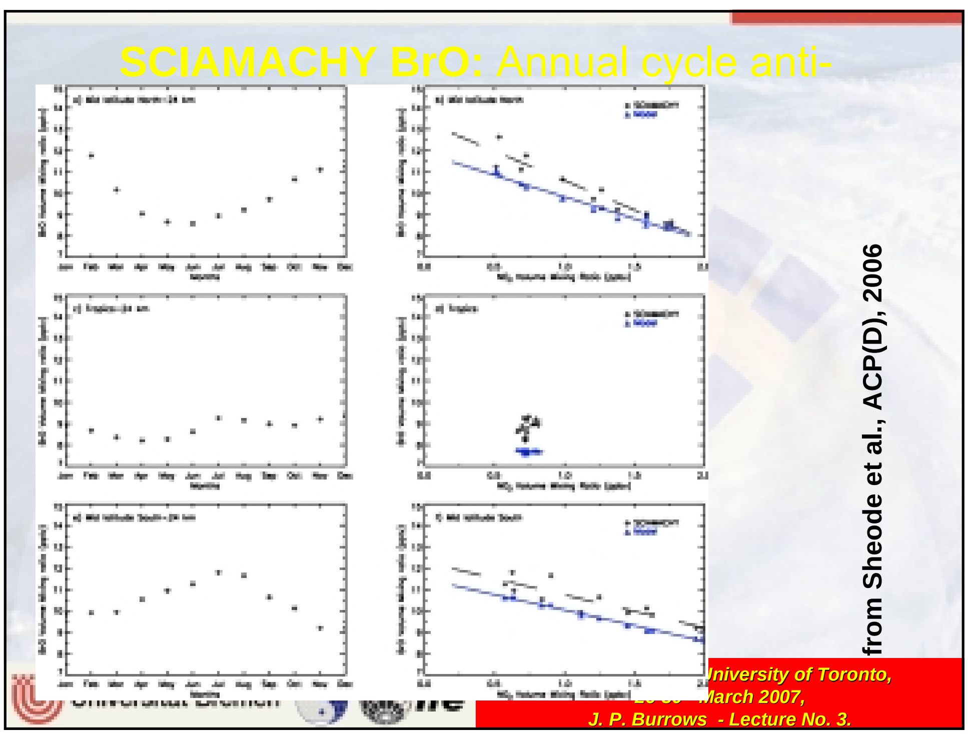
PSC occurrence rate for the month of September and 2002 – 2005



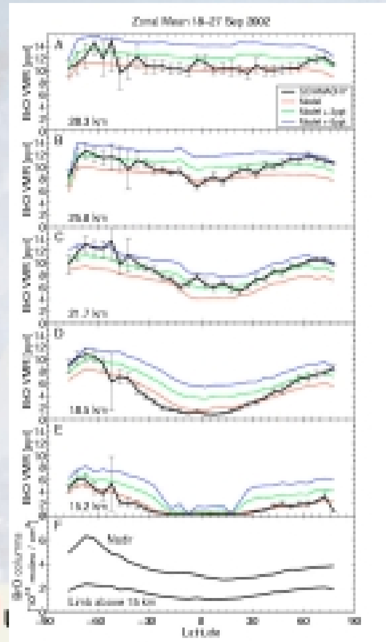
Reichl et al. [2007]

- A PSC climatology is available for all southern and northern hemisphere PSC seasons between July 2002 and March 2007 (Reichl et al., 2007)
- Distinction of PSC types under investigation


BrO „climatology“ from SCIAMACHY
DJF
MAM
JJA
SON
from Sheode et al., ACP(D), 2006
Toronto,
J. P. Burrows - Lecture No. 3.
Universität Bremen


SCIAMACHY BrO: Annual cycle anti-
from Sheode et al., ACP(D), 2006
University of Toronto,
March 2007,
J. P. Burrows - Lecture No. 3.

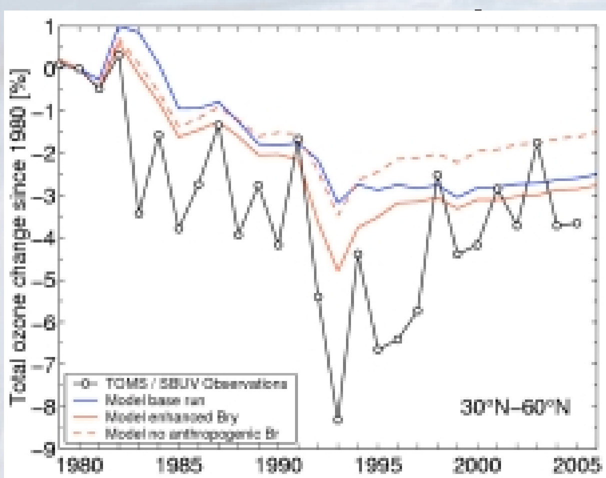
SCIAMACHY BrO: Stratospheric from VSLS



SCIAMACHY BrO observations suggest present contribution of ~3pptv bromine from very short-lived source gases.

from WMO (2007), based on Sinnhuber et al., GRL (2005)

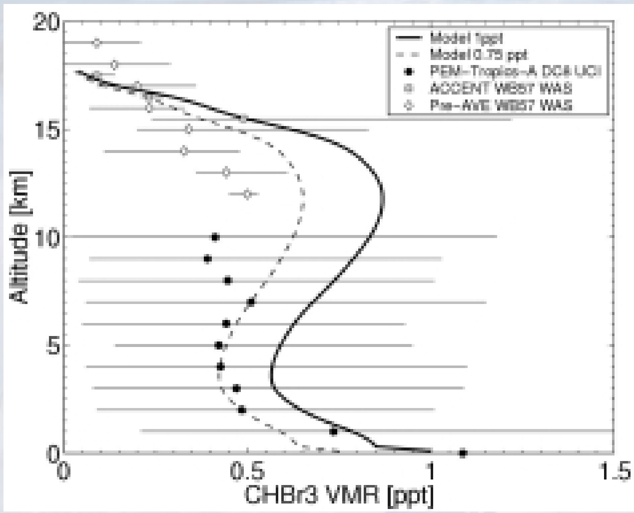
Impact of short-lived bromine on ozone



Additional bromine from very short-lived source gases has significant impact on calculated ozone trends (in particular for periods with enhanced aerosol loading).

from Sinnhuber et al., ACPD (2006)

Modelling transport of short-lived



Observations of ~3pptv of extra stratospheric bromine are broadly consistent with estimated contribution from very short-lived source gases.

from Sinnhuber and Folkins, ACP (2006)

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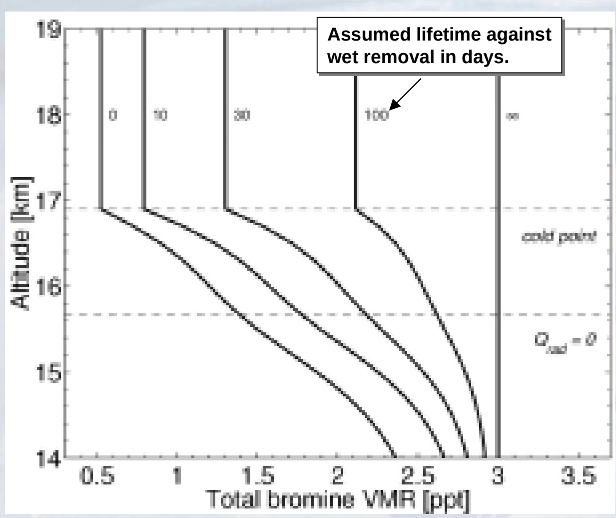
Critical factor: Wet removal in the



However, the modelled VSLS Product Gas Injection into the stratosphere depends critically on the processes of wet removal in the tropopause region – a key uncertainty in current models.

from WMO (2007), based on Sinnhuber and Folkins, ACP (2006)

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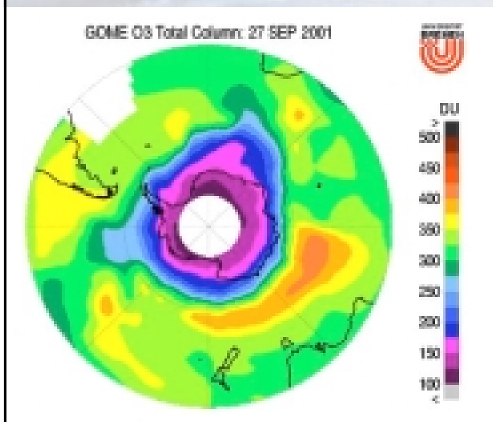
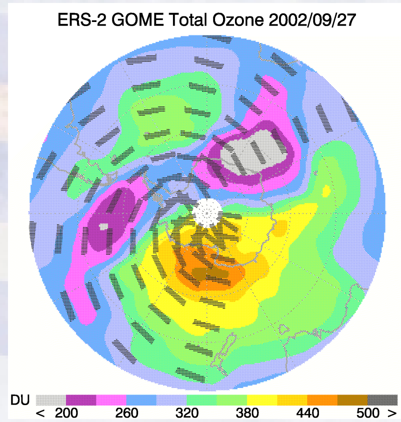
First Science: The SH O_3 Hole Anomaly 2002





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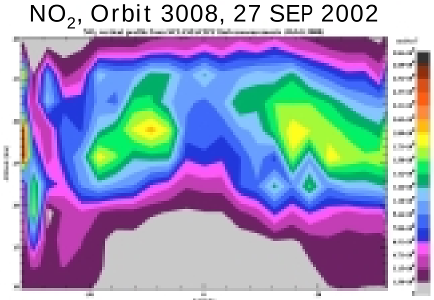
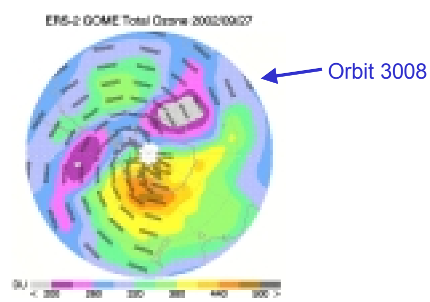
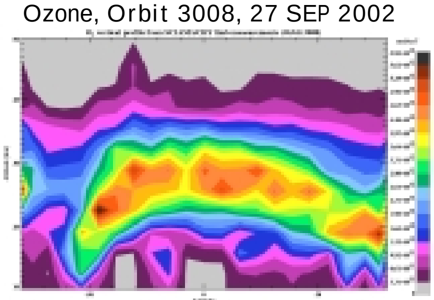
NO_2, Orbit 3008, 27 SEP 2002

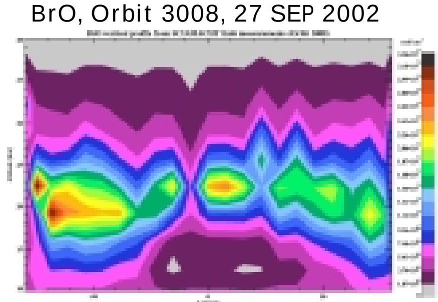




Ozone, Orbit 3008, 27 SEP 2002



BrO, Orbit 3008, 27 SEP 2002



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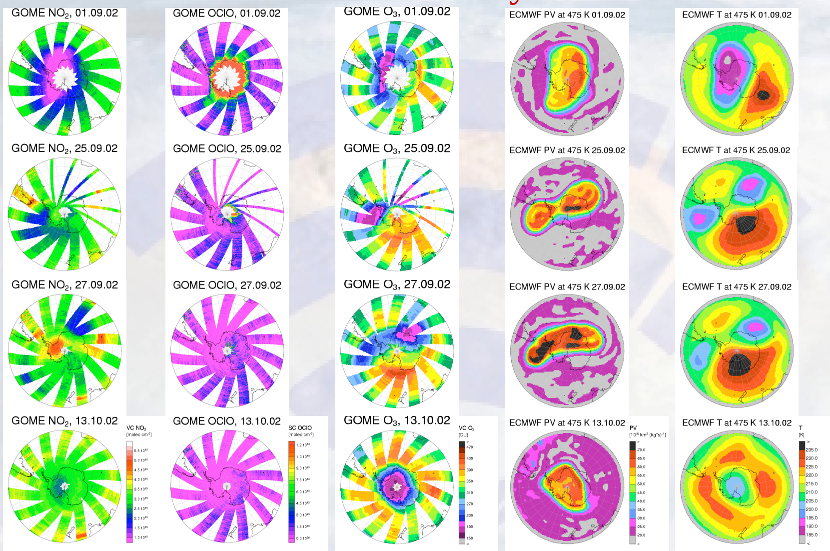
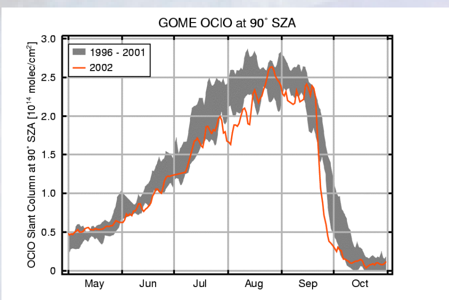
Overview of Retrieved Data from GOME during SH Anomaly



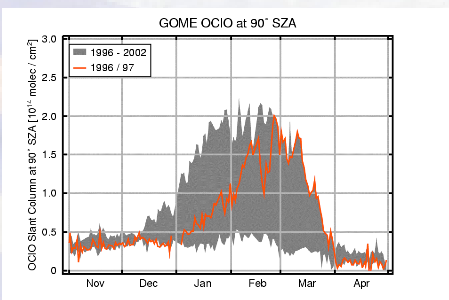
Chlorine Activation

Southern Hemisphere



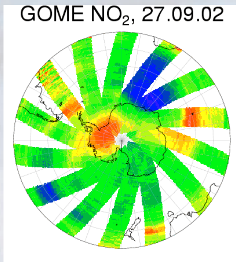
- small variability from year to year
- instability and early and rapid end of activation in 2002

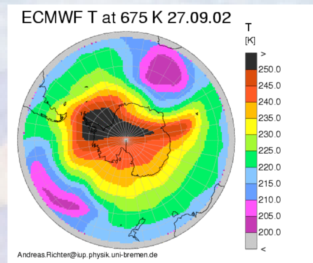
Northern Hemisphere

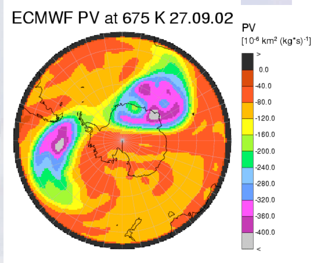


- large variability from year to year
- lower activation even in coldest years

NO2 Maximum Above South Pole in 2002







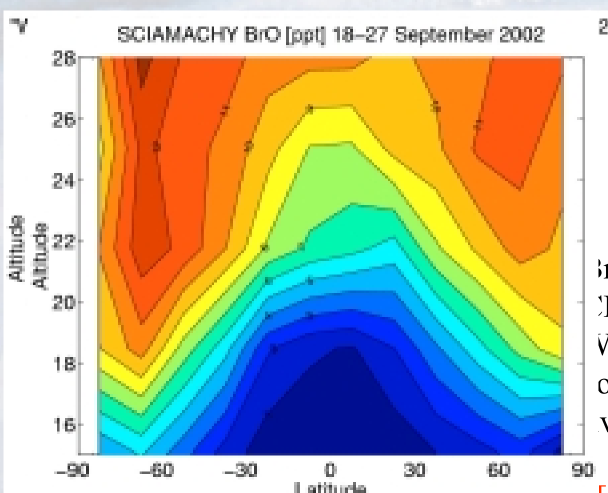
High NO2 forms

- in non-vortex air
- close to high temperatures
- at the vortex edge
- at several places

Possible Explanations:

- photolysis of reservoirs
- thermal decomposition of N2O5 or other reservoirs ClONO2, HNO3 etc.??
- descent of NOx rich air
- blocking effect at vortex edge

Bry estimated from MIPAS CFC-11



ıry estimated from
ːFC-11 according to
Vamsley et al (1998),
ontains only long-
ved source gases!

[preliminary analysis]

Summary and Conclusions

- All Solar and Limb Modes of SCIAMACHY are funtioning well
- The sceintific retrievals of data products are working well – some exciting results
- Much work to be done!!