Ionosphere-atmosphere interaction (during solar proton events)

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1. About middle atmosphere and ionosphere
   - Ozone
   - Catalysts NO_x and HO_x
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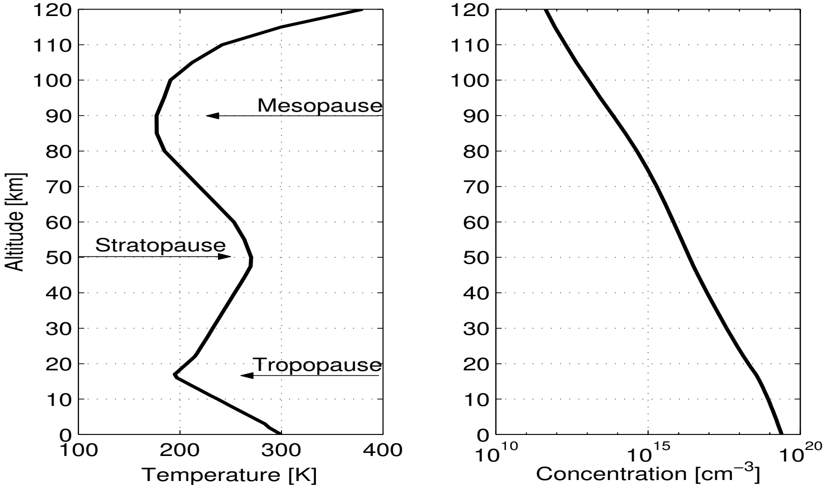
2. Solar proton events, forcing from the Sun
   - Increase in D-region ionization
   - Production of NO_x and HO_x, and subsequent loss of ozone
3. Open questions
   - Further reading

Middle atmosphere



Chemical composition

- Main middle atmospheric constituents are N_2 (78%) and O_2 (21%), the remaining 1% is mostly argon.
- Minor constituents, such as O_3 and CO_2, play important role in atmospheric chemistry, and heating and cooling processes.
- Constituents are either produced in the ground level and transported into the middle atmosphere, or produced in-situ by photochemical processes. Some have extra-terrestrial origin.

Chemical composition II

Continuity equation

Time-dependent concentration of an atmospheric species j can be solved from the continuity equation

$$\frac{\partial n_j}{\partial t} = P_j - L_j n_j - \nabla \cdot (n_j \bar{v}_j) \tag{1}$$

where n_j = concentration, t = time, P_j = local production rate, $L_j n_j$ = local loss rate, and $\bar{v}_j$ = velocity.

Transport

- Winds, air parcel transport
- Diffusion, mixing of gases

Dissociation/ionization at alt. z_o (see present. by K. Kauristie)

$$q_j(z_\mathrm{o},\chi) = \int_\lambda I(\lambda, z_\mathrm{o}, \chi)\, \eta_j(\lambda)\, \sigma_j(\lambda)\, n_j(z_\mathrm{o})\, d\lambda, \tag{2}$$

$I(\lambda, z_\mathrm{o}, \chi)$ = photon flux, $\sigma_j(\lambda)$ = cross section, $n_j(z_\mathrm{o})$ = gas concentration, η_j = efficiency, λ = wavelength, χ = zenith angle.

Chemical reactions

For a two-body reaction

$$\mathrm{A} + \mathrm{B} \rightarrow \mathrm{C} + \mathrm{D} \tag{3}$$

the reaction rate R is obtained from

$$R = k[\mathrm{A}][\mathrm{B}], \tag{4}$$

k is the T-dependent reaction rate coefficient (from lab. work), while $[\mathrm{A}]$ and $[\mathrm{B}]$ are the concentrations of constituents A and B.

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Ozone is a key constituent in the atmosphere

A minor gas

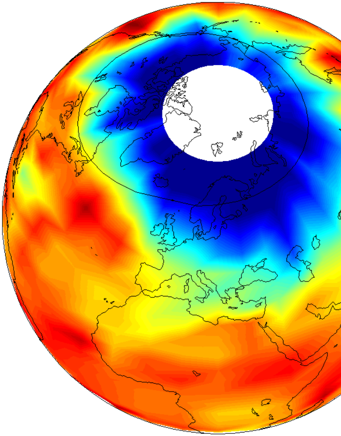
- Abundance $\leq$ 10 ppmv

Absorbs UV radiation

- Important to the thermal balance and dynamics
- Protects life on Earth

The ozone layer

- Located at 15–35 km
- Affected by CFC gases
- Ozone hole at Antarctica



Ozone chemistry and transport

Chapman, [1930]

$$\begin{aligned} O_2 + h\nu &\rightarrow O + O \\ O + O_2 + M &\rightarrow O_3 + M \\ O_3 + h\nu &\rightarrow O_2 + O \\ O + O_3 &\rightarrow 2O_2 \end{aligned}$$

Catalytic destruction

$$\begin{aligned} XO + O &\rightarrow X + O_2 \\ X + O_3 &\rightarrow XO + O_2 \\ \mathrm{Net:} & \\ O + O_3 &\rightarrow 2O_2 \end{aligned}$$

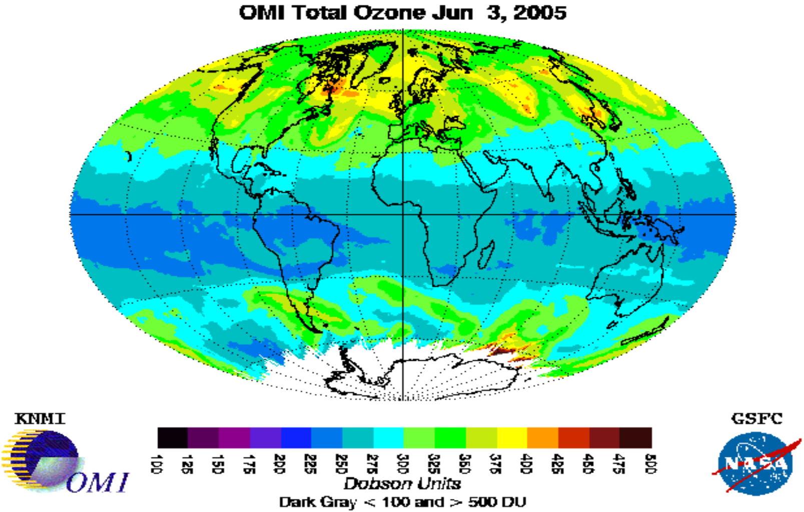
X can be Br, Cl, OH, or NO

Distribution by transport

- Production depends upon solar light, strongest in the equator
- Highest amount are found in the polar regions
- Chemical loss processes require solar radiation

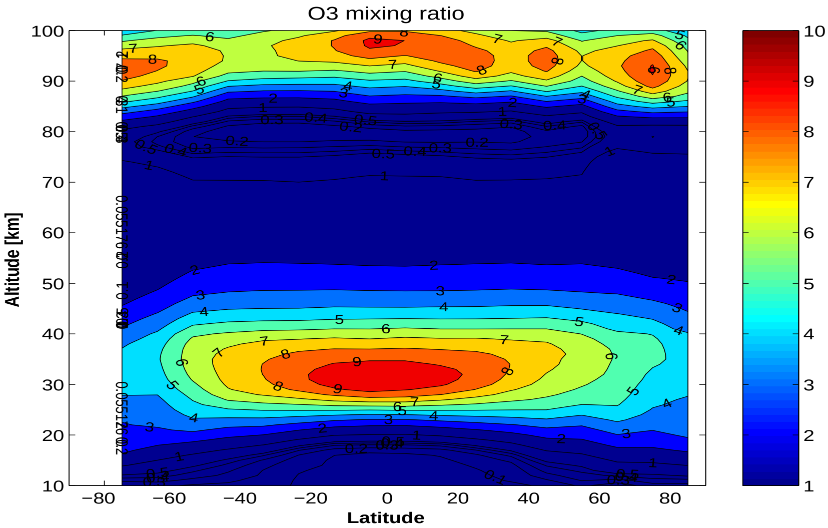
Total ozone column

EOS-Aura/OMI instrument



Ozone yearly mean for 2003

Envisat/GOMOS instrument



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Odd nitrogen and odd hydrogen

- Odd hydrogen HO_x = (H + OH + HO_2)
- Odd nitrogen NO_x = (N + NO + NO_2)
- Are chemically active, main catalysts of ozone loss in the upper stratosphere (NO_x) and mesosphere (HO_x).
- Particle precipitation in the polar regions contributes to their production $\longrightarrow$ Important role in Sun-Earth connection.

NO_x production

In the stratosphere, and lower thermosphere

$$N_2O + O(^1D) \rightarrow 2NO$$

$$\begin{aligned} N_2 + h\nu &\rightarrow N_2^+ + e^* \\ e^* + N_2 &\rightarrow 2N + e^* \\ N + O_2 &\rightarrow NO + O \end{aligned}$$

NO_x loss

Requires solar radiation

$$\begin{aligned} NO + h\nu &\rightarrow N + O \\ N + NO &\rightarrow N_2 + O \end{aligned}$$

OH_x production

From water vapour

$$H_2O + O(^1D) \rightarrow 2OH$$

$$H_2O + h\nu \rightarrow OH + H$$

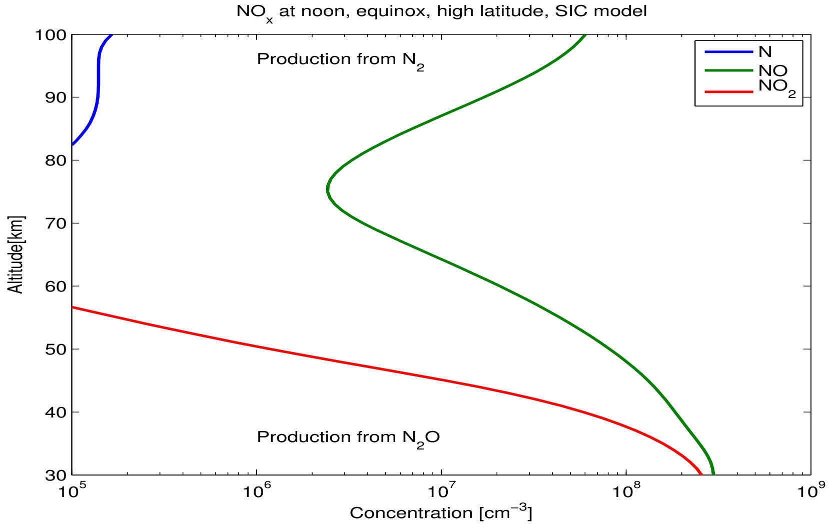
OH_x loss

“Cannibalistic” reactions, such as

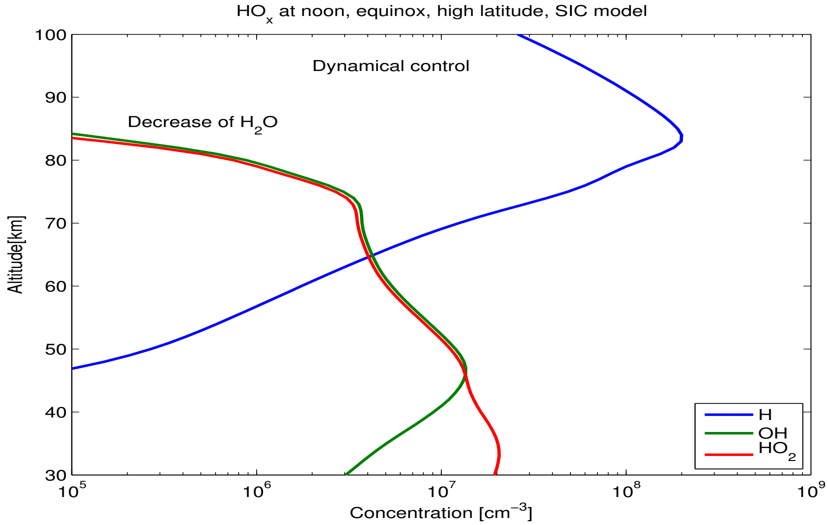
$$OH + HO_2 \rightarrow H_2O + O_2$$

Short chemical lifetime, transport can be neglected

Odd nitrogen profiles



Odd hydrogen profiles



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Ionospheric D-region

- Lowest region of the ionosphere, at 60–90 km, overlaps with the mesosphere, relatively low electron density: $10^2 - 10^4$ cm^{-3}
- Chemically much more complex than the regions above, because minor neutrals become important

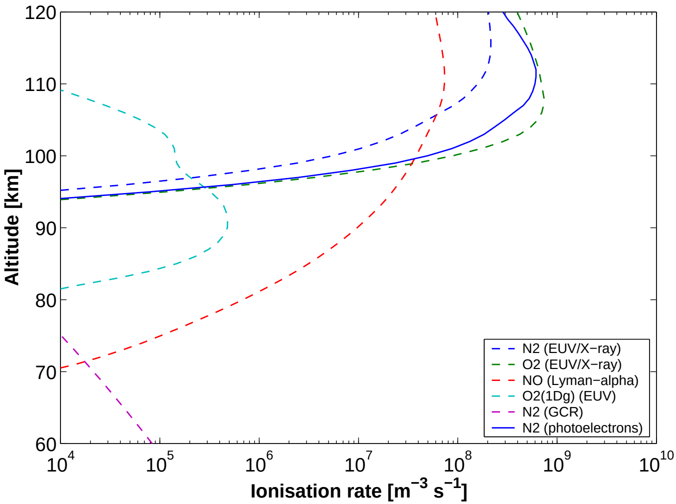
Ionization sources

- Lyman-α
- EUV
- hard X-rays
- particle precipitation

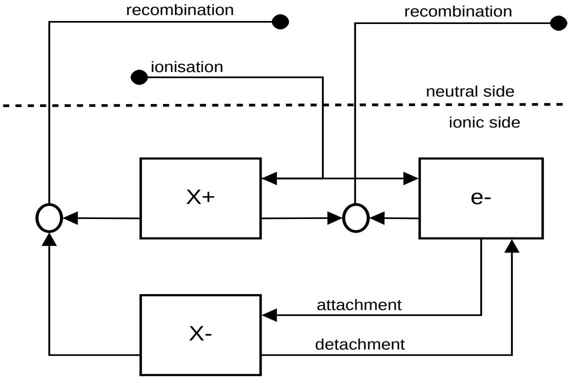
Specialities

- multitude of ions
- negative ions
- cluster ions
- complex chemistry

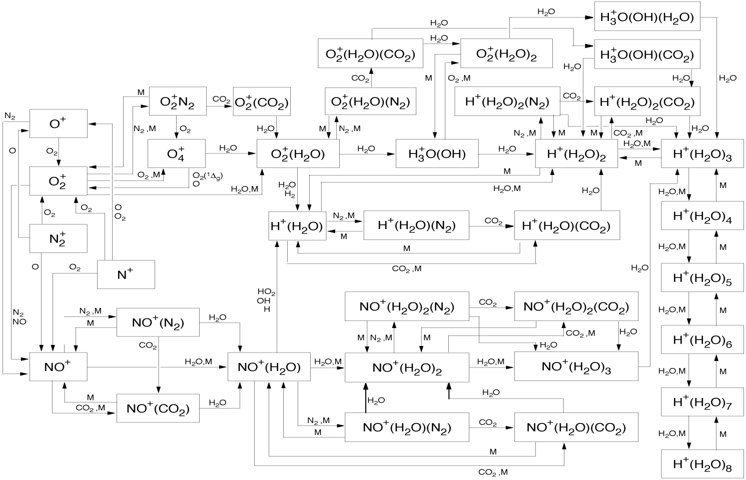
Quiet-time ionization rates



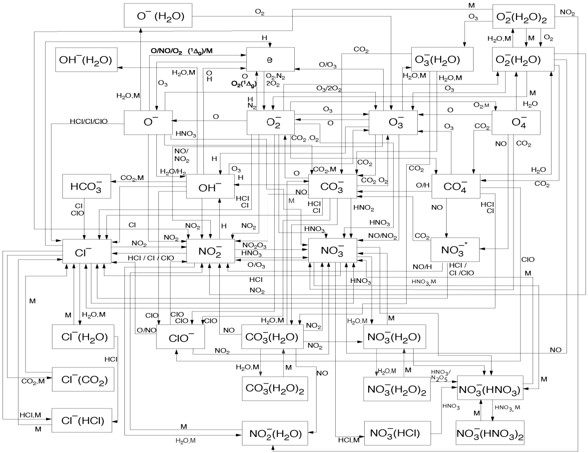
Charge balance



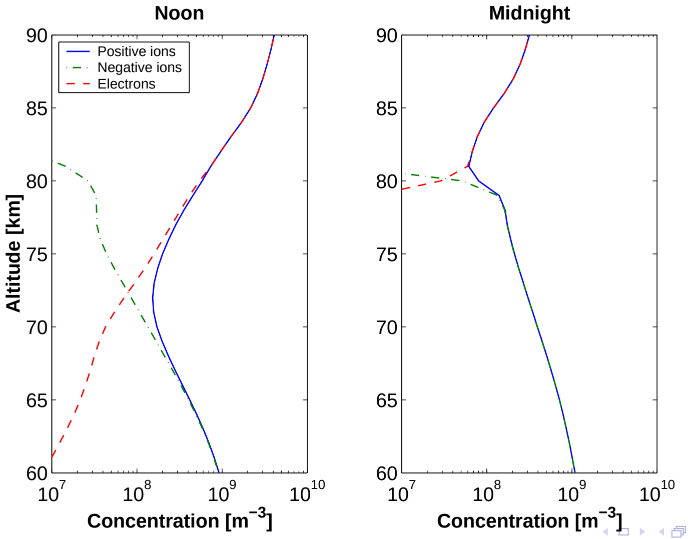
Positive ion reactions



Negative ion reactions



Profiles of electrons and ions



Ion composition

Positive ions

- Primary ion: NO^+, produced by Lyman-α
- Most abundant: $H^+(H_2O)_n$

Negative ions

- Primary ion: O_2^-, $e + O_2 + M \rightarrow O_2^- + M$
- Terminal ions: CO_3^-, NO_3^-, HCO_3^-

- Ion composition is affected by variation in ionization, and (changing) concentrations of minor neutral constituents
- Few rocket measurements of ion composition have been made, there are several issues still to be solved

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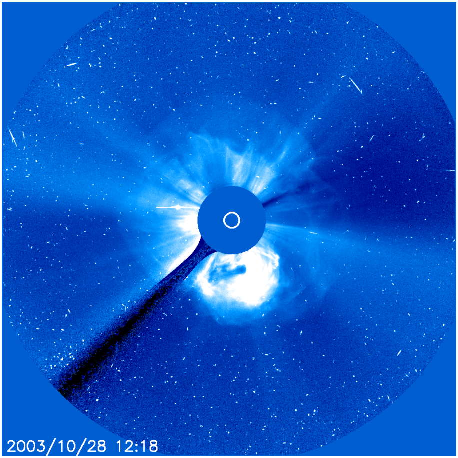
Coronal Mass Ejections

As seen by SOHO/LASCO

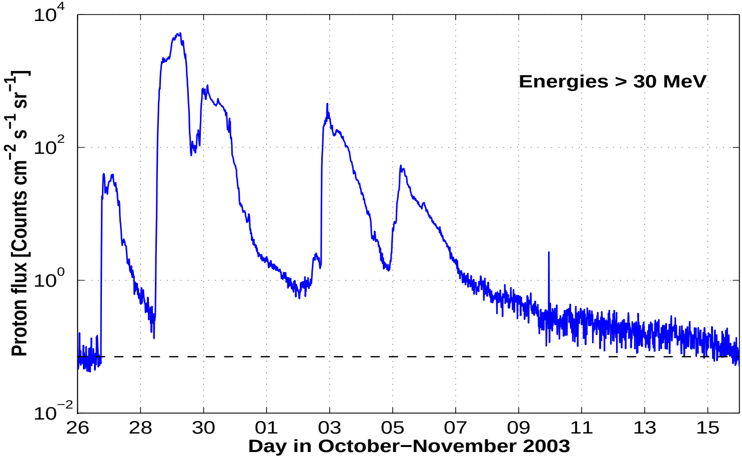


Originating from Sun

- High-energy protons are emitted, sometimes toward Earth
- Charged particles precipitate into atmosphere in polar regions
  ⇒ Solar Proton Event
- SPEs are sporadic
- Few per solar maximum

Proton flux at Geostationary orbit

GOES-11 measurements

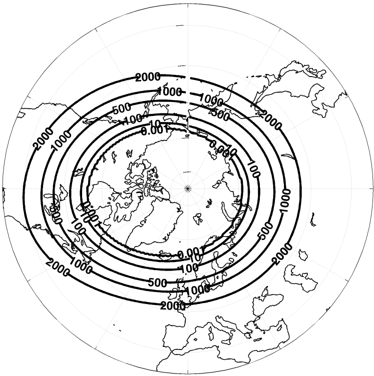


Geomagnetic rigidity cutoff

Charged particles are

- Are guided by Earth's magnetic field and penetrate the atmosphere in the polar regions
- Cutoff. Each location has a minimum rigidity, i.e. momentum per charge, which is required of a particle to reach it.
- Cutoff varies with time

Proton Cutoff Energies at 100km altitude: Kp=4



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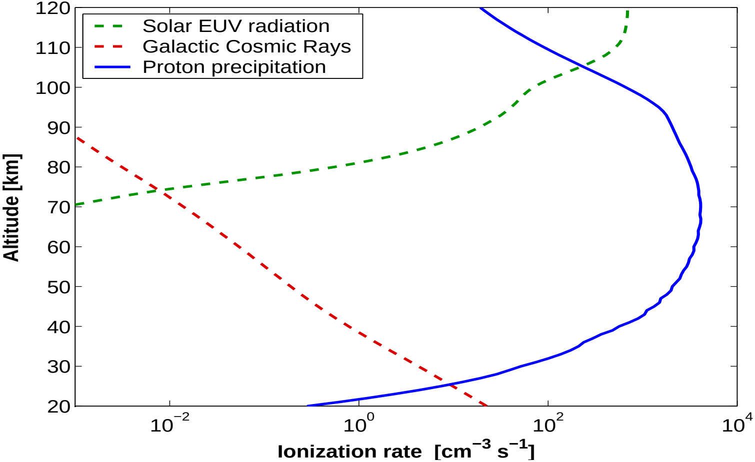
Ionization in the polar atmosphere

Model calculations using GOES data, proton energies $\geq$ 1 MeV



Total ionization rate due to proton precipitation

$$Q = \frac{1}{\Delta\epsilon} \int\int\int \left(\frac{dE}{dx}\right) F(E) \sin\theta \, d\theta d\phi dE \qquad (5)$$

Symbol explanation

- $\Delta\epsilon$ = average ionization energy $\approx$ 35 eV
- $F(E)$ = flux of protons above the atmosphere
- $\frac{dE}{dx} = \left(\frac{dR(E, z_o, \theta)}{dE}\right)^{-1}$ = energy loss per unit density travelled
- $R(E, z_o, \theta) = R(E) - \frac{1}{n(0)} \int_{z_o}^{\infty} \frac{n(z)}{\cos\theta} \, dz$ = remaining range at z_o
- $R(E)$ = range of a proton with energy E (from lab. measurements)

- Total ionization rate is divided between N_2, O_2, and O
- Primary products are N_2^+, N^+, O_2^+, O^+, as well as N and O

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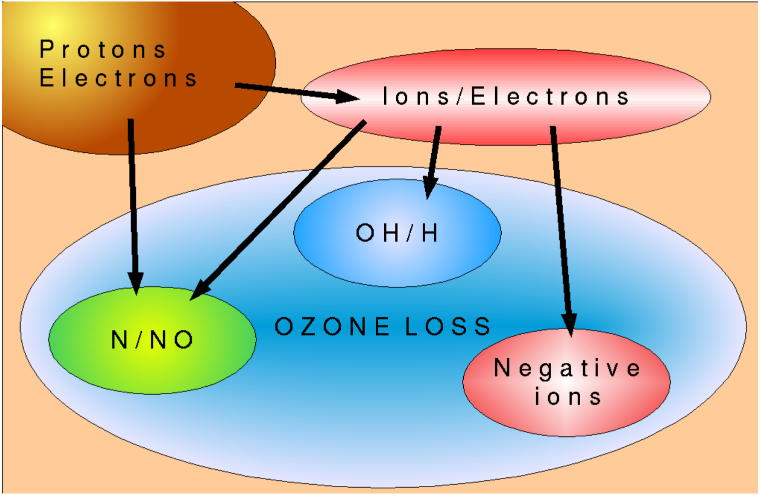
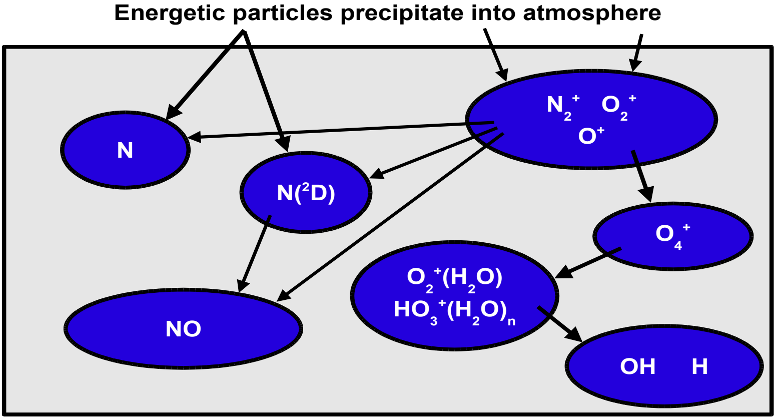
From particle precipitation to ozone loss



Production of OH and NO



Reactions producing NO_x and HO_x

NO_x production

By particle impact ionization, dissociation, ion chemistry

$$\begin{array}{rcl}
N_2 + p^* & \rightarrow & N_2^+ + e^* + p^* \\
e^* + N_2 & \rightarrow & 2N + e^* \\
N + O_2 & \rightarrow & NO + O \\
 & & \\
N_2^+ + O & \rightarrow & NO^+ + N \\
NO^+ + e & \rightarrow & NO
\end{array}$$

OH_x production

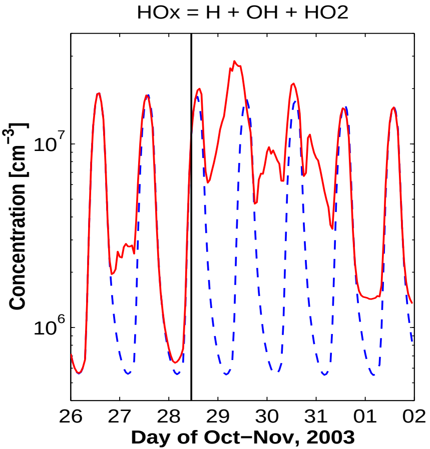
By ion chemistry, *e.g.*

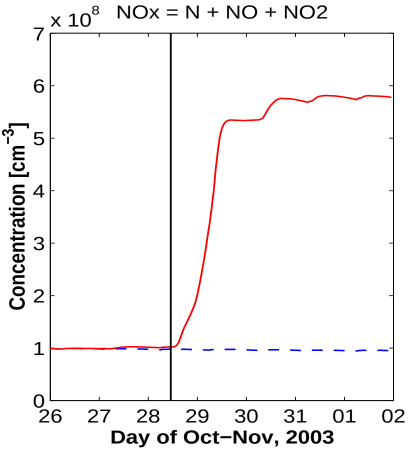
$$\begin{array}{rcl}
O_2^+(H_2O) + H_2O & \rightarrow & \\
H^+(H_2O) + & OH + & O_2 \\
H^+(H_2O) + nH_2O & \rightarrow & \\
H_3O^+(H_2O)_n & & \\
H_3O^+(H_2O)_n + e^- & \rightarrow & \\
(n+1)H_2O + & H & \\
\mathit{Net} : H_2O \rightarrow OH + H & &
\end{array}$$

- Ozone destruction follows by the catalytic reaction cycles!

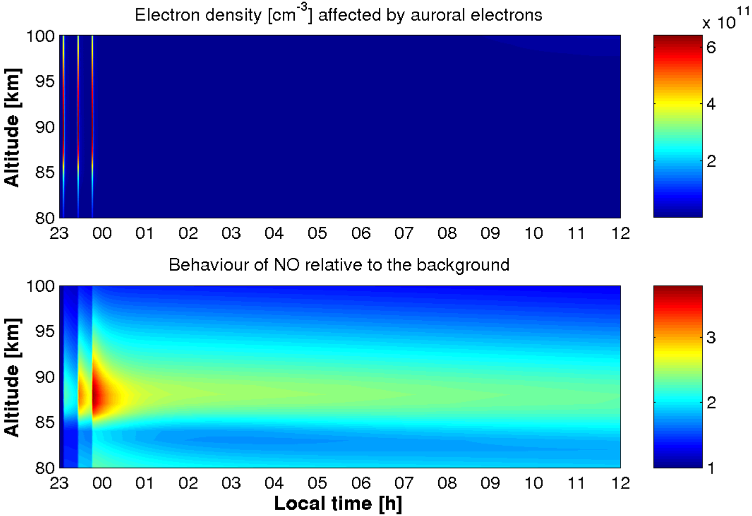
Response of HO_x and NO_x to the proton forcing

Modelling results, high latitude winter location





NO_x after hard auroral electron precipitation



Duration of ozone depletion

Depends on the level of solar illumination

Mesosphere/Summer pole

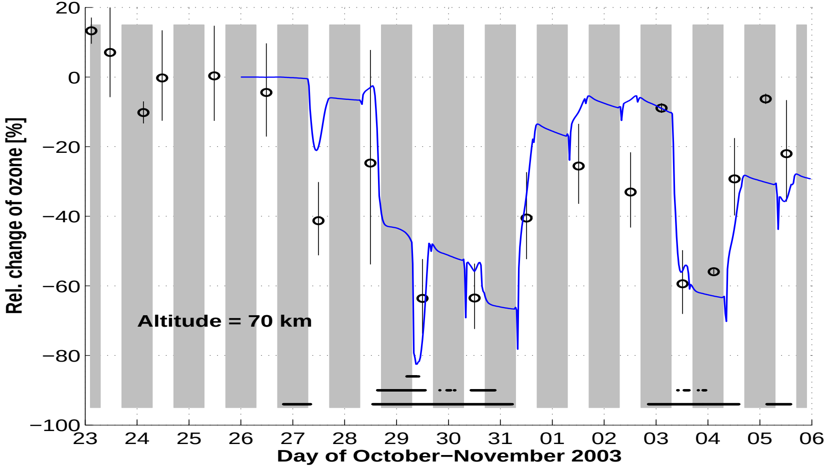
- Both HO_x and NO_x are short-lived
- Fast recovery due to photodissociation
- Ozone depletion lasts for days

Stratosphere/Winter pole

- NO_x is long-lived and can be transported
- Slow recovery
- depletion can last for months

Relative change of ozone during an SPE

SIC model vs. GOMOS at 70 km



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Questions about particle precipitation

1) Night-side effects

- Models predict long-lasting ozone depletion
- No satellite measurements existed...
- ...but now GOMOS has solved the question!

2) Production of HO_x

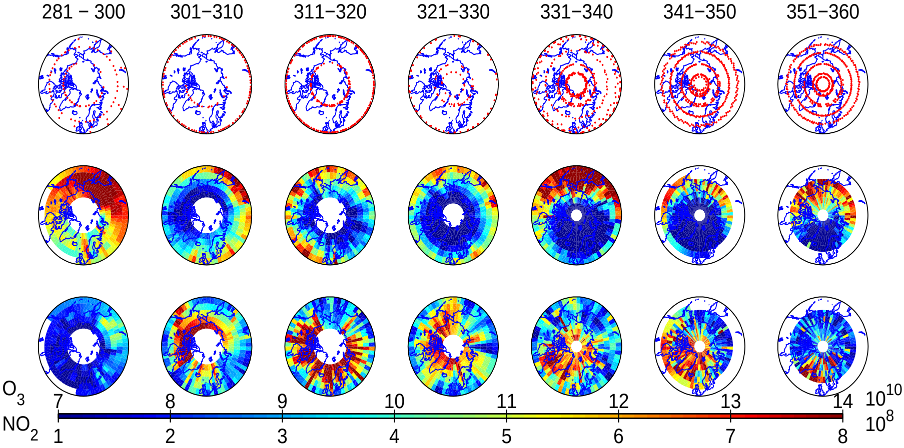
- Based on model predictions
- Satellite measurements required

3) Long-term effect on stratosphere and ozone layer?

- Models suggest: particle precipitation is important
- Confirmation requires measurements in polar night conditions

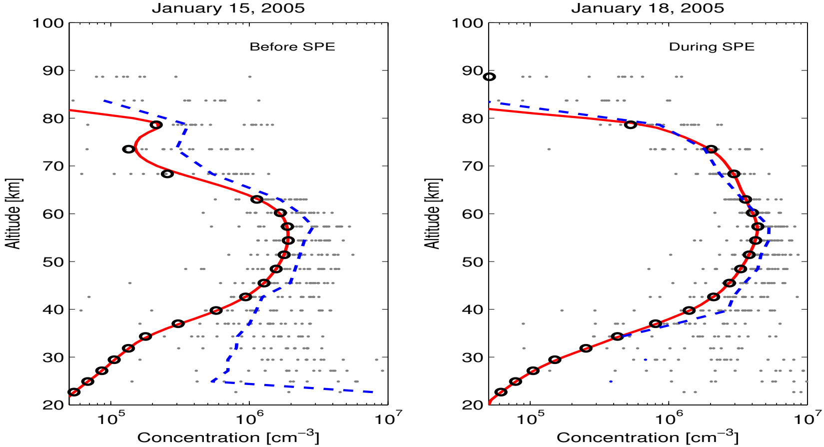
10-day average ozone and NO_2 concentrations

Latitudes $\geq 45^\circ$ shown at altitude 46 km, SPE is on from day 300 to 310



Measured HO_x during the January 2005 SPE

MLS/EOS-Aura vs. SIC model



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Recent papers by FMI/Earth Observation

- P. T. Verronen, A. Seppälä, M. A. Clilverd, C. J. Rodger, E. Kyrölä, C.-F. Enell, E. Turunen, and Th. Ulich, **Diurnal variation of ozone depletion during the October-November 2003 solar proton events**, *J. Geophys. Res.*, *110*, A09 S32, 2005.
- A. Seppälä, P. T. Verronen, E. Kyrölä, S. Hassinen, L. Backman, A. Hauchecorne, J.-L. Bertaux, and D. Fussen, **Solar proton events of October-November 2003: Ozone depletion in the Northern Hemisphere polar winter as seen by GOMOS/Envisat**, *Geophys. Res. Lett.*, *31*, L19 107, 2004.

Some good books

- Brasseur, G. P. and Solomon, S., *Aeronomy of the Middle Atmosphere*, Springer, Dordrecht, 3rd revised and enlarged edn., 2005.
- Hargreaves, J. K., *The solar-terrestrial environment*, Cambridge Atmospheric and Space Science Series, Cambridge University Press, Cambridge, UK, 1992.
- Rees, M. H., *Physics and chemistry of the upper atmosphere*, Cambridge atmospheric and space science series, Cambridge University Press, Cambridge, UK, 1989.