Auroral aeronomy

Tima Sergienko

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Optical methods in auroral physics research,
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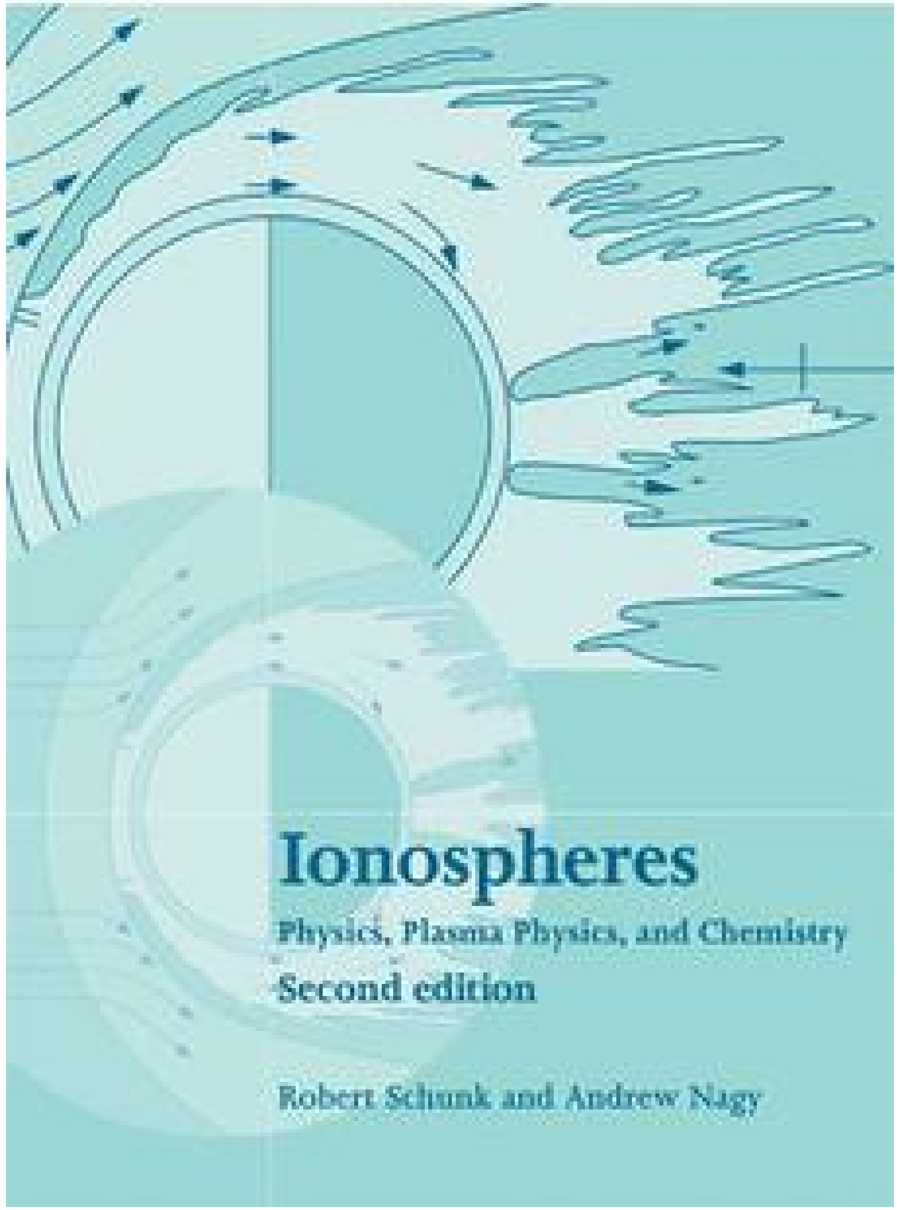
Cambridge Atmospheric and Space Science Series



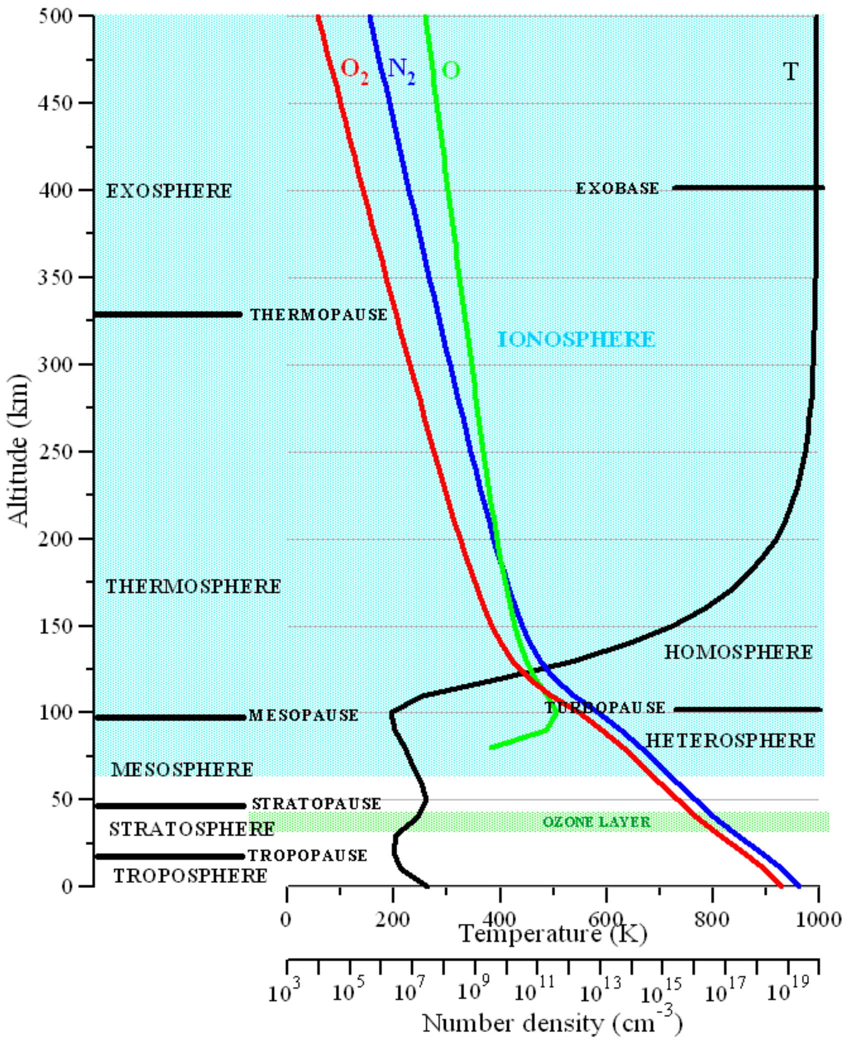
Ionospheres

Physics, Plasma Physics, and Chemistry

Second edition

Robert Schunk and Andrew Nagy

The Earth's atmosphere



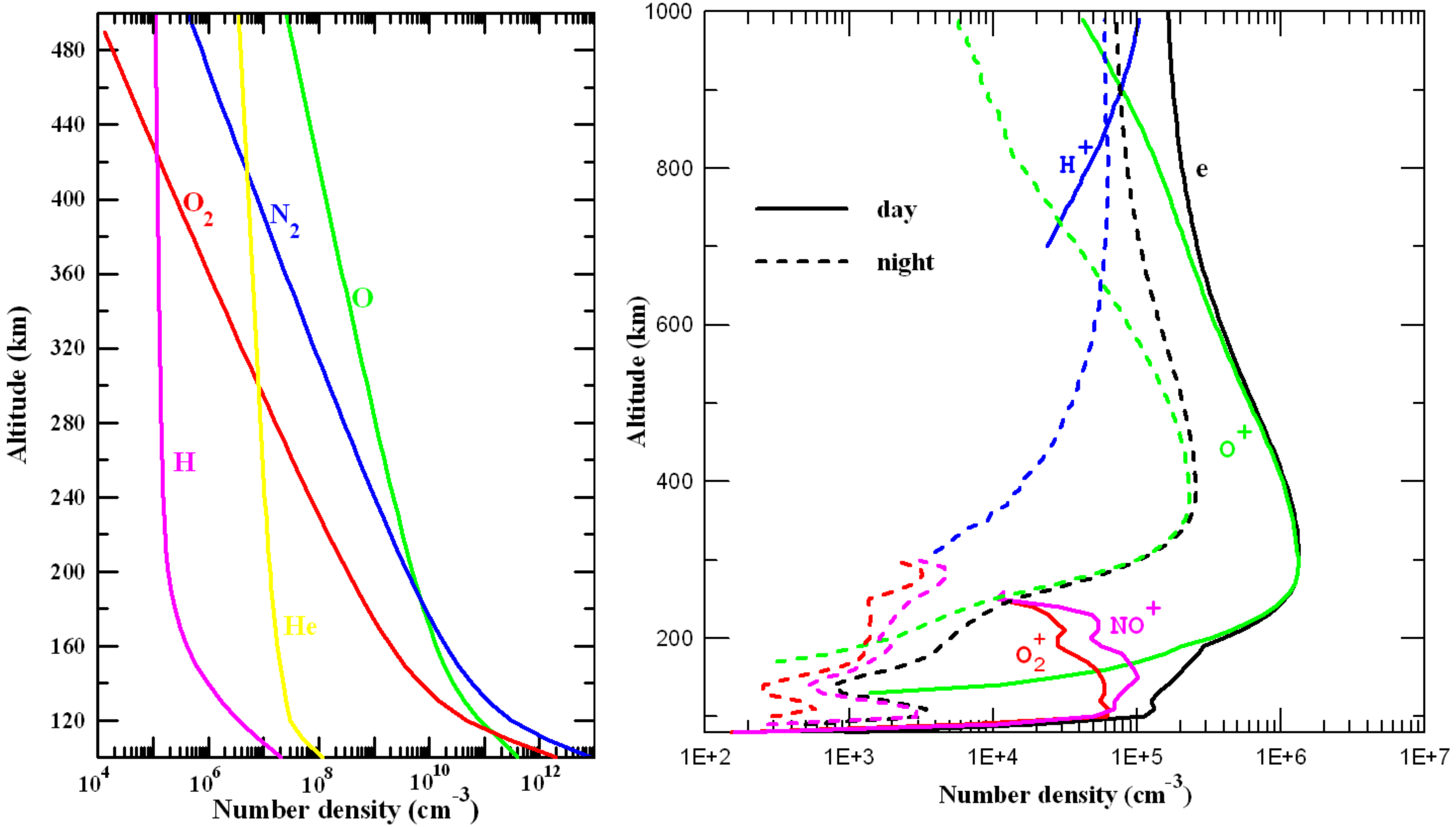
Temperature stratified layers

Troposphere: ~**0-10 km**
Stratosphere: **~10-45 km**
Mesosphere: **~40-95 km**
Thermosphere: **~95-400 km**

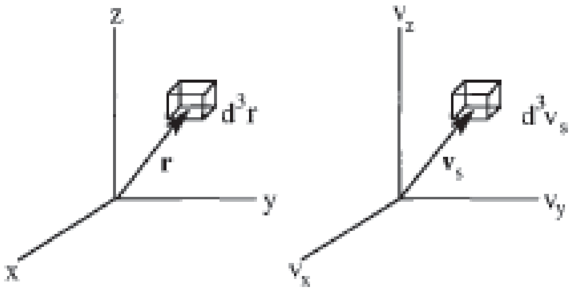
Moving stratified layers

Heterosphere: ~**0-100 km** turbulent moving, the atmospheric species are mixed.
Homosphere: ~**100-400 km** molecular diffusion, diffusion separation of the various species
Exosphere: **>400 km** the neutral particles follows balistic trajectories.

Earth’s thermosphere and ionosphere



Distribution function and Boltzmann equation



Distribution function $f_s(\boldsymbol{r},\boldsymbol{v_s},t)$ corresponds to the number of particles of species s that, at time t, are located in a volume element d^3r about $\boldsymbol{r}$ have velocities in a velocity-space volume element d^3v_s about $\boldsymbol{v}_s$. Alternatively, f_s can be viewed as a probability density in the $(\boldsymbol{r}, \boldsymbol{v}_s)$ phase space.

$$\frac{df_s(x,v_s,t)}{dt} = \frac{\partial f_s}{\partial t} + \frac{dr}{dt}\nabla f_s + \frac{dv_s}{dt}\nabla_v f_s$$

$$\frac{\partial f_s}{\partial t} + \boldsymbol{v}_s \nabla f_s + \boldsymbol{a}_s \nabla_v f_s = 0$$ Vlasov equation

$$\frac{\partial f_s}{\partial t} + \boldsymbol{v}_s \nabla f_s + \boldsymbol{a}_s \nabla_v f_s = \frac{\delta f_s}{\delta t}$$ Boltzmann equation

$$\frac{\delta f_s}{\delta t} = \iint d^3 v_t d\Omega \left| v_s - v_t \right| \sigma_{st}(v_{st},\theta)\left(f_s' f_t' - f_s f_t \right)$$ Boltzmann collision integral

$$\boldsymbol{a}_s = \boldsymbol{G} + \frac{e_s}{m_s}\left(\boldsymbol{E} + \boldsymbol{v}_s \times \boldsymbol{B}\right)$$ Gravitational and Lorentz accelerations

Moments of the distribution function

$$\langle \xi(v_s) \rangle = \int d^3 v_s\, f_s(r, v_s, t)\, \xi(v_s)$$

Zero moment $\quad n_s = \int d^3 v_s\, f_s \quad$ Number density

First moment $\quad \boldsymbol{u}_s = \frac{1}{n_s} \int d^3 v_s \boldsymbol{v}_s\, f_s \quad$ Drift velocity

Second moment $\quad T_s = \frac{3m_s}{k} \int d^3 v_s \left(\boldsymbol{v}_s - \boldsymbol{u}_s \right)^2 f_s \quad$ Temperature

Third moment $\quad \boldsymbol{q}_s = \frac{m_s}{2} \int d^3 \boldsymbol{v}_s \left(\boldsymbol{v}_s - \boldsymbol{u}_s \right)^2 \left(\boldsymbol{v}_s - \boldsymbol{u}_s \right) f_s \quad$ Heat flow

General transport equations

$$\frac{\partial f_s}{\partial t} + \boldsymbol{v}_s \nabla f_s + \boldsymbol{a}_s \nabla_v f_s = \frac{\delta f_s}{\delta t}$$

$$\nabla \cdot \left(f_s \boldsymbol{a}_s \right) = \boldsymbol{a}_s \cdot \nabla f_s + \cancel{f_s \left(\nabla \cdot \boldsymbol{a}_s \right)} = \boldsymbol{a}_s \cdot \nabla f_s$$

$$\nabla \cdot \left(f_s \boldsymbol{v}_s \right) = \boldsymbol{v}_s \cdot \nabla f_s + \cancel{f_s \left(\nabla \cdot \boldsymbol{v}_s \right)} = \boldsymbol{v}_s \cdot \nabla f_s$$

$$\frac{\partial f_s}{\partial t} + \nabla \cdot \left(f_s \boldsymbol{v}_s \right) + \nabla \cdot \left(f_s \boldsymbol{a}_s \right) = \frac{\delta f_s}{\delta t}$$

$$\int d^3 v_s \frac{\partial f_s}{\partial t} = \frac{\partial}{\partial t} \int d^3 v_s f_s = \frac{\partial n_s}{\partial t} \qquad \int d^3 v_s \nabla \cdot \left(f_s \boldsymbol{v}_s \right) = \nabla \cdot \int d^3 v_s f_s \boldsymbol{v}_s = \nabla \cdot \left(n_s \boldsymbol{u}_s \right)$$

$$\int d^3 v_s \nabla \cdot \left(f_s \boldsymbol{a}_s \right) = \int_S dA_v \left(f_s a_s \right) \cdot \hat{\boldsymbol{n}}_v = 0 \qquad \int d^3 v_s \frac{\delta f_s}{\delta t} = \frac{\delta n_s}{\delta t}$$

$$\frac{\partial n_s}{\partial t} + \nabla \cdot \left(n_s u_s \right) = \frac{\delta n_s}{\delta t}$$

Continuity equation

13-moment transport equations

Continuity equation

$$\frac{\partial n_s}{\partial t} + \nabla \cdot (n_s \boldsymbol{u}_s) = \frac{\delta n_s}{\delta t}$$

Momentum equation

$$n_s m_s (\frac{\partial \mathbf{u}_s}{\partial t} + \mathbf{u}_s \cdot \nabla \cdot \mathbf{u}_s) + \nabla p_s + \nabla \cdot \boldsymbol{\tau}_s - n_s m_s \mathbf{g} - n_s e_s (\mathbf{E} + \mathbf{u}_s \times \mathbf{B}) = \frac{\delta \mathbf{M}}{\delta t}$$

Energy equation

$$\frac{3}{2}\left(\frac{\partial p_s}{\partial t} + \mathbf{u}_s \cdot \nabla p_s\right) + \frac{3}{2} p_s (\nabla \cdot \mathbf{u}_s) + \nabla \cdot \mathbf{q}_s + \boldsymbol{\tau}_s : \nabla \mathbf{u}_s = \frac{\delta E_s}{\delta t}$$

Pressure tensor equation

$$\frac{\partial \boldsymbol{\tau}_s}{\partial t} + \mathbf{u}_s \cdot \nabla \boldsymbol{\tau}_s + \boldsymbol{\tau}_s (\nabla \cdot \mathbf{u}_s) + \frac{e_s}{m_s}\left[\mathbf{B} \times \boldsymbol{\tau}_s - \boldsymbol{\tau}_s \times \mathbf{B}\right] + p_s \left[\nabla \mathbf{u}_s + (\nabla \mathbf{u}_s)^T - \frac{2}{3}(\nabla \cdot \mathbf{u}_s)\mathbf{I}\right] +$$
$$+ \frac{2}{5}\left[\nabla \mathbf{q}_s + (\nabla \mathbf{q}_s)^T - \frac{2}{3}(\nabla \cdot \mathbf{q}_s)\mathbf{I}\right] + \left[\boldsymbol{\tau}_s \cdot \nabla \mathbf{u}_s + (\boldsymbol{\tau}_s \cdot \nabla \mathbf{u}_s)^T - \frac{2}{3}(\boldsymbol{\tau}_s : \nabla \mathbf{u}_s)\mathbf{I}\right] = \frac{\delta \boldsymbol{\tau}_s}{\delta t}$$

Heat flow equation

$$\frac{\partial \mathbf{q}_s}{\partial t} + \mathbf{u}_s \cdot \nabla \mathbf{q}_s + \frac{7}{5}\mathbf{q}_s \cdot \nabla \mathbf{u}_s + \frac{7}{5}\mathbf{q}_s (\nabla \cdot \mathbf{u}_s) + \frac{5}{2}(\nabla \mathbf{u}_s) \cdot q_s + \frac{5}{2}\frac{k p_s}{m_s}\nabla T_s + \frac{1}{n_s m_s}(\nabla \cdot \boldsymbol{\tau}_s) \cdot (p_s \mathbf{I} - \boldsymbol{\tau}_s) +$$
$$+ \left(\frac{7}{2}\frac{k}{m_s}\nabla T_s - \frac{1}{n_s m_s}\nabla p_s\right) \cdot \boldsymbol{\tau}_s - \frac{e_s}{m_s}\mathbf{q}_s \times \mathbf{B} = \frac{\delta \mathbf{q}_s}{\delta t}$$

Photoionization

$$N_2 + h\nu \rightarrow N_2^+ + e$$
$$O_2 + h\nu \rightarrow O_2^+ + e$$
$$O + h\nu \rightarrow O^+ + e$$

Photoionization rate $Q_s(z)$ (i-e pair·cm^{-3}·s^{-1})

$$Q_s(z) = n_s(z) \sum_{\lambda \le \lambda_m} I_\lambda(z) \sigma_{s\lambda}^{ion}$$

$n_s(z)$ is the number density of neutral specie, s; (cm^{-3})

$I_\lambda(z)$ is the photon flux at the wavelength λ; (ph·cm^{-2}·s^{-1})

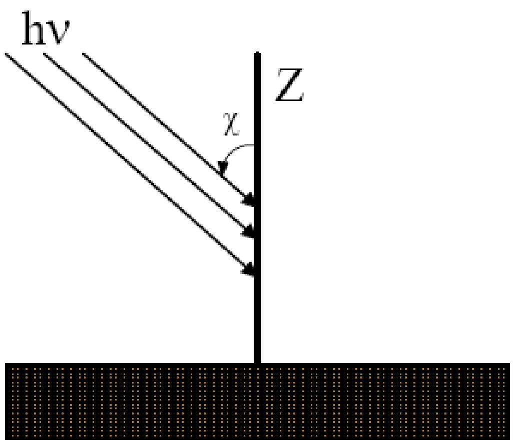
$\sigma_{s\lambda}^{ion}$ is the ionization cross section of the photons with wavelength λ for the neutral specie s; (cm^2)

λ_m is the ionization threshold wavelength

Ionization threshold wavelength

Neutral	N_2	O_2	O
eV	15.58	12.06	13.62
nm	79.58	102.8	91.03

Absorption of solar radiation into the Earth's atmosphere



$$dI_\lambda(z) = -\sum_s I_\lambda(z) n_s(z) \sigma^a_{s\lambda} dl$$

$$dl = \sec\chi dz \text{ for } \chi < 80^\circ$$

$$dl = Ch(\chi) dz \text{ for } \chi \geq 80^\circ$$

$Ch(\chi)$ is the Chapman function

$$I_\lambda(z,\chi) = I_{\lambda\infty} \exp(-\tau(z,\lambda,\chi))$$

$I_{\lambda\infty}$ is the unattenuated photon flux at the top of atmosphere

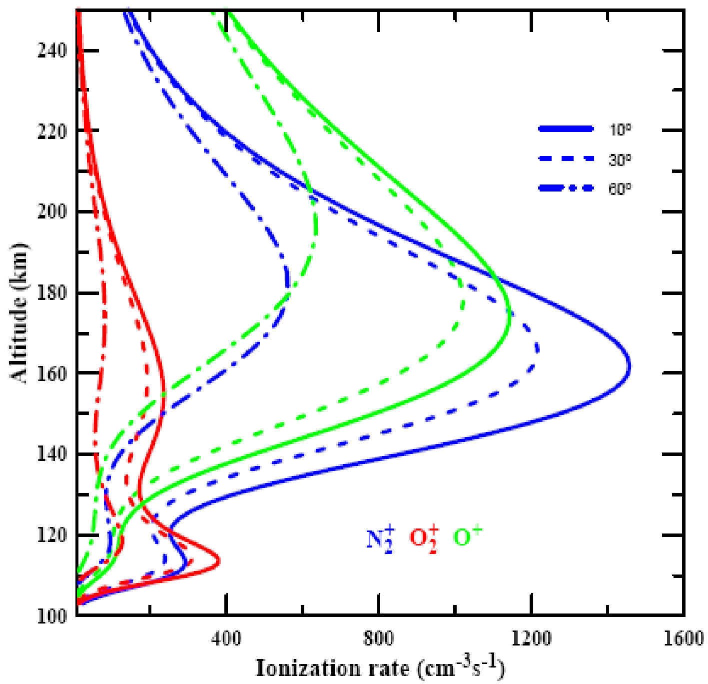
$$\tau(z,\lambda,\chi) \equiv \sec\chi \sum_s \sigma^a_{sl} \int_\infty^z n_s(z) dz$$

the optical depth

$$Q_s(z) = n_s(z) \sum_{\lambda \leq \lambda_m} I_{\lambda\infty} \sigma^{ion}_{s\lambda} \exp(-\tau(z,\lambda,\chi))$$

the photoionization rate

Chapman production function.



$$n_s(z) = n_s(z_0)\exp\left[-\frac{(z-z_0)}{H_s}\right]$$

$H_s = \dfrac{kT_s}{m_s g}$ - the neutral gas scale height

$$\int_z^\infty n_s(z')dz' = n_s(z)H_s$$

$$\tau(z,\lambda,\chi) = \sec\chi \sum_s n_s(z_0)\exp\left[-\frac{(z-z_0)}{H_s}\right]\sigma_{s\lambda}^a H_s$$

For the one-component atmosphere

$$Q(z) = I_\infty \sigma^{ion} n(z_0)\exp\left[-\frac{(z-z_0)}{H} - n(z_0)\sigma^a H \sec\chi \exp\left(-\frac{(z-z_0)}{H}\right)\right]$$

Chapman production function

The altitude of the peak production rate

$$z_m = z_0 + H\ln\left[n(z_0)H\sigma^a \sec\chi\right]$$

The maximum production rate

$$Q(z_m,\chi) = \frac{I\infty\sigma^{ion}\cos\chi}{H\exp(1)}$$

Excitation and ionization by auroral electrons

Kinetic (classical) approach

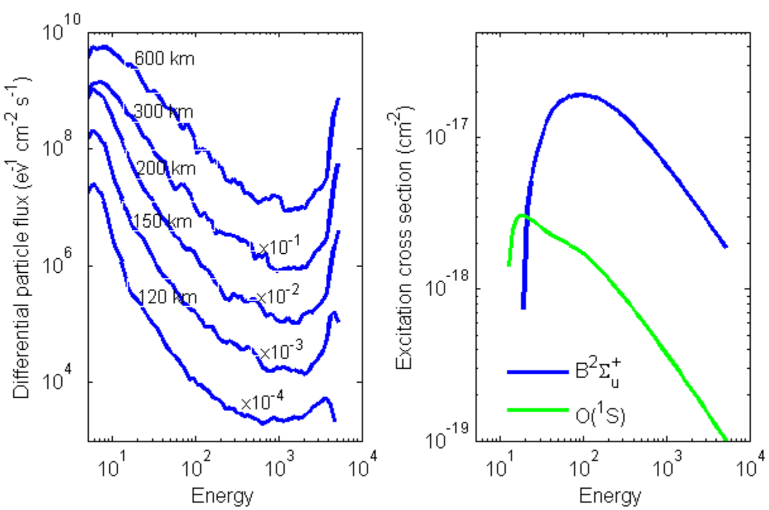
$$Q_i^j(h) = [N_i(h)] \int_E \sigma_i^j(E) f(E,h) dE$$

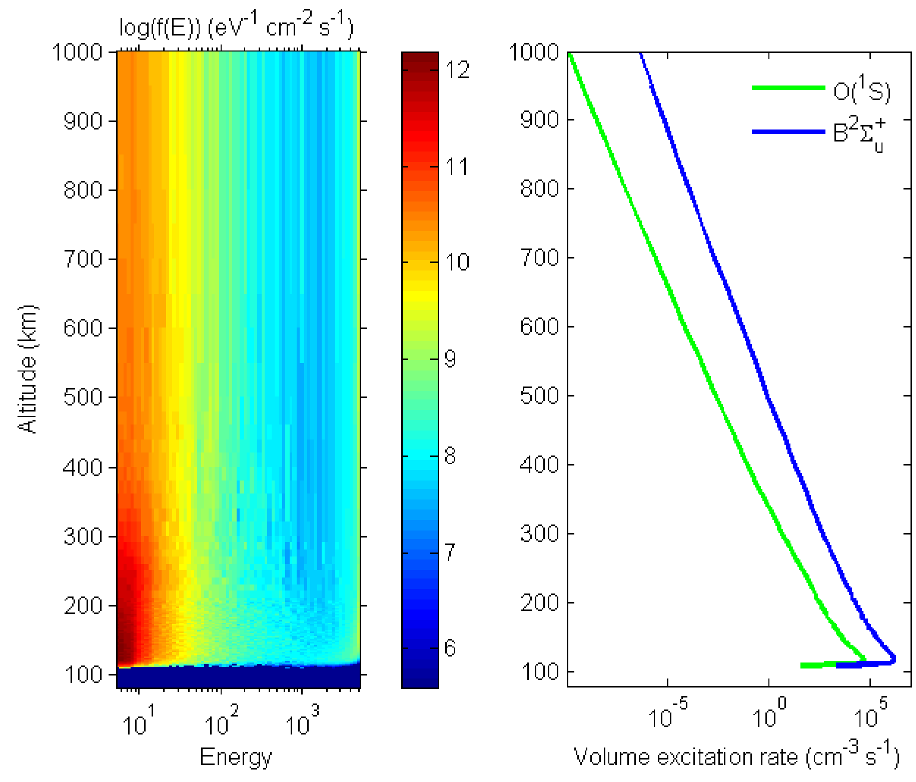
Q_i^j – excitation rate at altitude h(cm^{-3} s^{-1})

$[N_i]$ – concentration of the atmosperic gase (cm^{-3})

$\sigma_i^j(E)$ – exitation cross section of stae j (cm^2)

f(E,h) – differential electron particle flux at altitude h (eV^{-1} cm^{-2} s^{-1})





Auroral electron transport equation

$$\frac{\partial f}{\partial t}+\mu v\frac{\partial f}{\partial s}+\frac{e}{m}\varepsilon_{\|}\mu\frac{\partial f}{\partial v}+\left(\frac{e}{m}\varepsilon_{\|}-\frac{v^2}{2B}\frac{dB}{ds}\right)\frac{1-\mu^2}{v}\frac{\partial f}{\partial \mu}=\frac{\delta f}{\delta t}$$

$\mu = \cos\alpha, \alpha$ - pitch angle, s - distanse along the magnetic field line

$\varepsilon_{\|}$ – externally parallel electric field

$\Phi \equiv \frac{2E}{m^2} f, E$ – electron energy

$$\sqrt{\frac{\mathrm{m}}{2\mathrm{E}}}\frac{\partial \Phi}{\partial t}+\mu\frac{\partial \Phi}{\partial s}+e\varepsilon_{\|}E\mu\frac{\partial}{\partial E}\left(\frac{\Phi}{E}\right)+\left(\frac{e\varepsilon_{\|}}{E}-\frac{1}{B}\frac{dB}{ds}\right)\frac{1-\mu^2}{2}\frac{\partial \Phi}{\partial \mu}=\sqrt{\frac{m}{2E}}\frac{\delta \Phi}{\delta t}$$

Auroral electron transport equation

Steady state, no electric field, constant magnetic field

$$\mu \frac{\partial \Phi(E,s,\mu)}{\partial s} = -a - b + c + d + f + Q$$

$$a = \Phi(E,s,\mu)\sum_k n_k(s)\sigma_k^{tot}(E)$$

Losses of electron with energy E and pitch angle μ due to elastic and inelastic collisions

$$b = n_e(s)\frac{\partial\left(L(E)\Phi\right)}{\partial E}$$

Energy losses due to collisions with thermal electrons

$$c = \sum_k n_k(s)\sigma_k^{el}(E)\int_{-1}^{1} p(E,\mu' \to \mu)\Phi(E,s,\mu')d\mu'$$

Production of electrons with pitch angle μ due to elastic scattering of electrons with pitch angle μ'

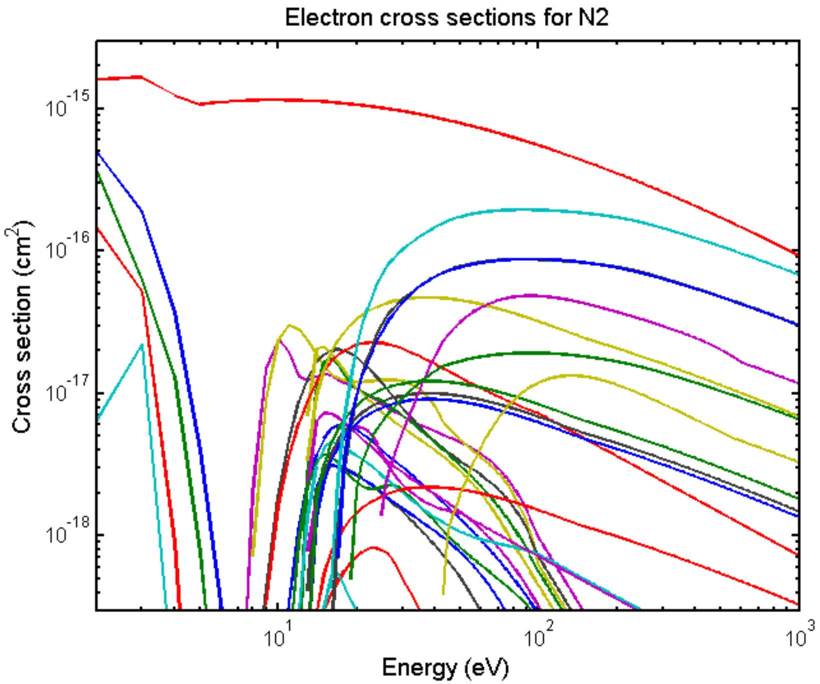
$$d = \sum_k n_k(s)\sum_j \sigma_j^k(E+\Delta E \to E)\int_{-1}^{1} p_j^k(E+\Delta E,\mu' \to \mu)\Phi(E+\Delta E,s,\mu')d\mu'$$

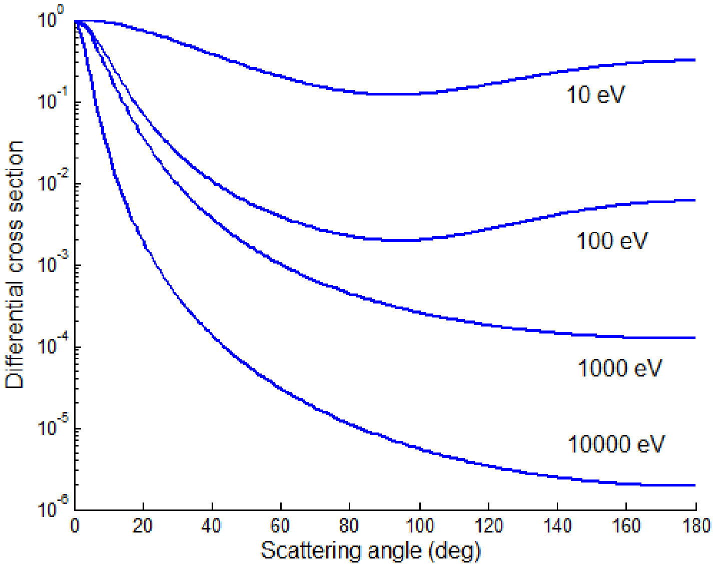
Production of electrons with energy E and pitch angle μ due to inelastic collisions

$$f = \sum_k n_k(s)\int_{E+\Delta E_{ion}}^{\infty}\sigma_{ion}^k(E' \to E)\int_{-1}^{1} p_{ion}^k(E',\mu' \to \mu)\Phi(E',s,\mu')dE'd\mu'$$

Production of secondary electrons with energy E and pitch angle μ in ionization

Electron collision cross sections





Excitation and ionization by auroral electrons

Energy approch

$$Q_i^j(h) = \frac{p_i[N_i]}{\varepsilon_i^j} W(h)$$

$$W(h) = \rho(h) \int_E \frac{\lambda(E, l/R(E))}{R(E)} f_0(E) dE$$ - electron energy deposition rate at altitude h (eV cm^{-3} s^{-1})

$[N_i(h)]$ – gas concentration, (cm^{-3})
$i = N_2, O_2, O$

$$p_i = \frac{a_i}{a_{N_2}[N_2] + a_{O_2}[O_2] + a_O[O]}$$

$$a_{N_2} = 1, a_{O_2} = 0.7, a_O = 0.4$$

ε_i^j - energy cost of excited state j, (eV)

$\rho(h)$ – atmosphere mass density at altitude h (gm sm^{-3})

$\lambda(E, l/R(E))$ – normalized energy dissipation function

$R(E)$ – particle range (gm cm^{-2})

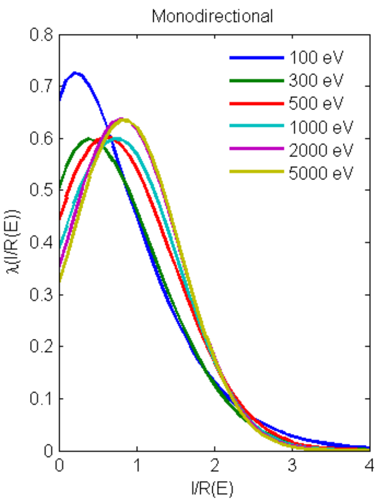
$$l = \int_h^{h_0} \rho(h) d(h)$$ - distance from the top of ionosphere (h_0) til altitude h in mass units (gm cm^{-2})

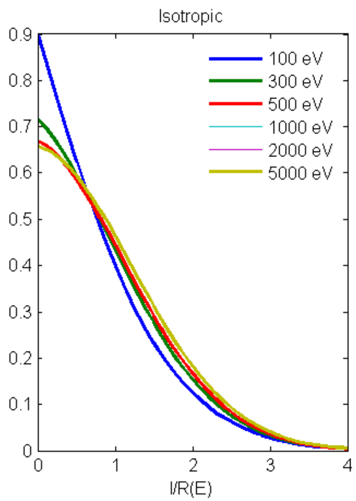
$f_0(E)$ – initial differential electron particle flux at the top of ionosphere (h_0) (eV^{-1} cm^{-2} s^{-1})

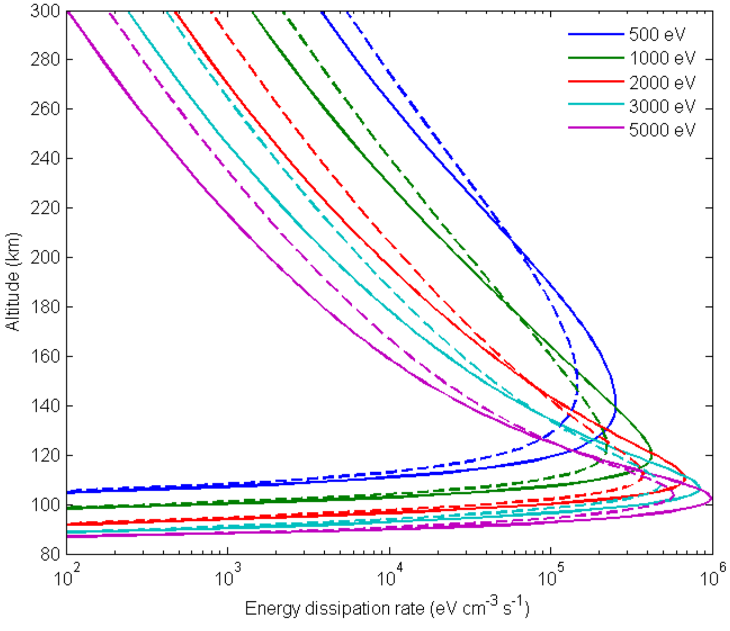
Excitation and ionization by auroral electrons

Energy dissipation rate

$$W(h) = \rho(h)\int_E \frac{\lambda\left(E, \, {}^{l}\!/\!{}_{R(E)}\right)}{R(E)} f_0(E)dE$$







Excitation and ionization by auroral electrons

Excitation energy cost

Electron energy lost on excitation of gas i

$$W_i(h) = [N_i(h)]\int_E f(E)\sum_k I_k \sigma^k(E)dE$$

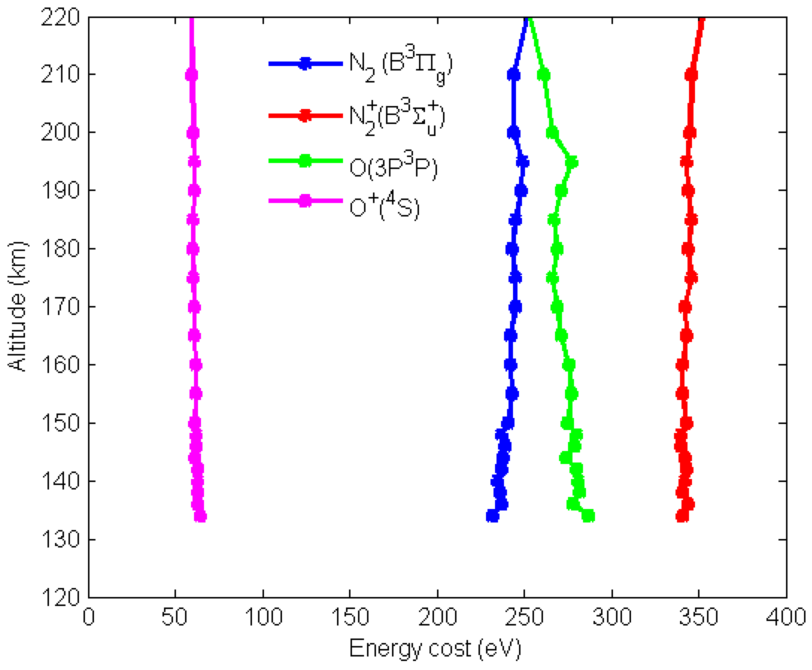
I_k - excitation threshold of k^{th} state of gas i

Excitation rate of k^{th} state of gas i

$$Q_i^k(h) = [N_i(h)]\int_E f(E)\sigma_i^k(E)dE$$

Excitation energy cost of k^{th} state of gas i

$$\varepsilon_i^k(h) = \frac{W_k(h)}{Q_i^k(h)} = const$$



Chemical reactions

	Reaction	Rate constant $cm^3\ s^{-1}$
	Photoionization	
Q1	$O + h\nu \rightarrow O^+ + e$	
Q2	$O_2 + h\nu \rightarrow O_2^+ + e$	
Q3	$N_2 + h\nu \rightarrow N_2^+ + e$	
	Dissociative recombination	
R1	$NO^+ + e \rightarrow N + O$	$4.0\times10^{-7}(300/T_e)^{0.5}$
R2	$O_2^+ + e \rightarrow O + O$	$1.95\times10^{-7}(300/T_e)^{0.7}$
R3	$N_2^+ + e \rightarrow N + N$	$2.2\times10^{-7}(300/T_e)^{0.39}$
	Ion-molecule reactions	
R4	$O^+ + O_2 \rightarrow O_2^+ + O$	2.1×10^{-11}
R5	$O^+ + N_2 \rightarrow NO^+ + N$	1.2×10^{-12}
R6	$N_2^+ + O_2 \rightarrow O_2^+ + N_2$	5.0×10^{-11}
R7	$N_2^+ + O \rightarrow O^+ + N_2$	9.8×10^{-12}
R8	$N_2^+ + O \rightarrow NO^+ + N$	1.3×10^{-10}

When photochemestry is more important than transport processes, the continuity equation for ions and electron is

$$\frac{dn_s}{dt} = P_s - L_s$$

where P_s is the production rate and L_s is the loss rate.

$$\frac{dn(N_2^+)}{dt} = Q_1 - \left[k_3 n_e + k_6 n(O_2) + (k_7 + k_8) n(O)\right] n(N_2^+)$$

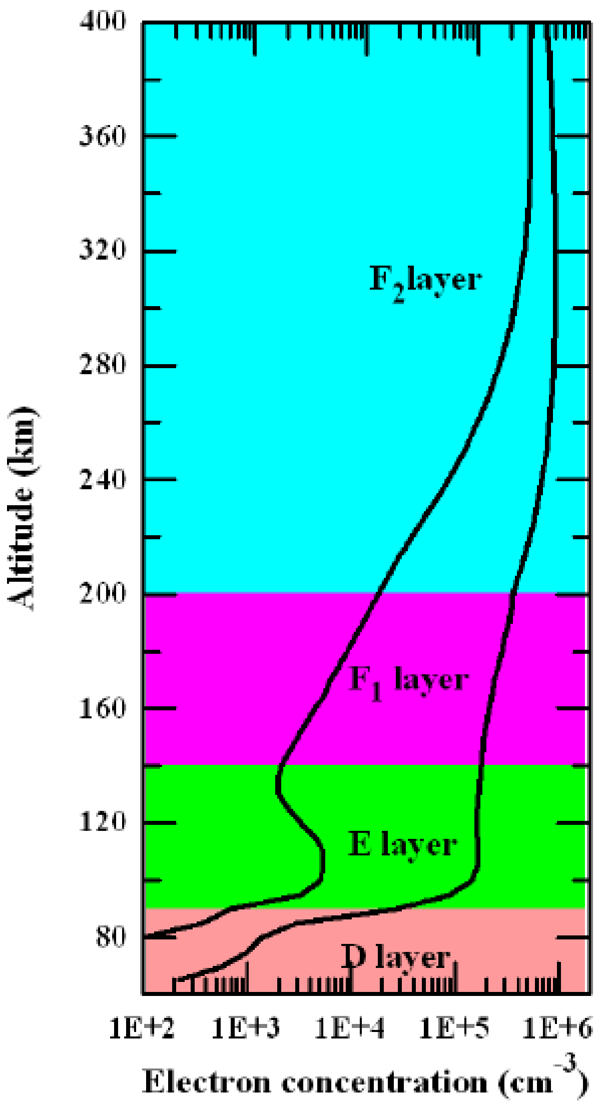
$$\frac{dn(O_2^+)}{dt} = Q_2 + k_4 n(O^+) n(O_2) + k_6 n(N_2^+) n(O_2) - k_2 n_e n(O_2^+)$$

$$\frac{dn(O^+)}{dt} = Q_3 + k_7 n(N_2^+) n(O) - \left[k_4 n(O_2) + k_5 n(N_2)\right] n(O^+)$$

$$\frac{dn(NO^+)}{dt} = k_5 n(O^+) n(N_2) + k_8 n(N_2^+) n(O) - k_1 n_e n(NO^+)$$

$$\frac{dn_e}{dt} = Q_1 + Q_2 + Q_3 - \left[k_1 n(NO^+) + k_2 (O_2^+) + k_3 (N_2^+)\right] n_e$$

Earth ionosphere layers



D-layer:

$$NO + h\nu(\lambda = 121.6nm) \rightarrow NO^+ + e$$
$$O_2 + h\nu(\lambda < 10nm) \rightarrow O_2^+ + e$$
$$N_2 + h\nu(\lambda < 10nm) \rightarrow N_2^+ + e$$

Very complicated ion composition (positive and negative ions, water cluster ions)

Chemical processes dominate.

$T_e \approx T_i \approx T_n$

E-layer:

$$O_2 + h\nu(80nm < \lambda < 102.8nm) \rightarrow O_2^+ + e$$
$$O_2 + h\nu(1nm < \lambda < 10nm) \rightarrow O_2^+ + e$$
$$N_2 + h\nu(1nm < \lambda < 10nm) \rightarrow N_2^+ + e$$

Dominant ions are NO^+, O_2^+, N_2^+

Chemical processes dominate

$T_e \approx T_i \approx T_n$

F_1-layer:

$$N_2 + h\nu(10nm < \lambda < 90nm) \rightarrow N_2^+ + e$$
$$N_2 + h\nu(10nm < \lambda < 90nm) \rightarrow N_2^+ + e$$

Dominant ions are NO^+, O_2^+, N_2^+

Chemical processes dominate

$T_e > T_i \approx T_n$

F_2-layer:

$$O + h\nu(10nm < \lambda < 90nm) \rightarrow O^+ + e$$

Dominant ion O^+

Transition from chemical to diffusion dominance.

$T_e > T_i > T_n$

Quadratic and linear lows of electron loss

E,F_1 regions (90-180 km)

Electron production rate

$$P_e = Q_1 + Q_2 + Q_3 = Q^e$$

Electron loss rate

$$L_e = \left[k_1 n(NO^+) + k(N_2^+)\right] n_e$$

For ionospheric plasma $\sum n(ion) = n_e$

Effective recombination coefficient

$$\alpha_{eff} = \left[k_1 \frac{n(NO^+)}{n_e} + k_2 \frac{n(O_2^+)}{n_e}\right] n_e$$

Quadratic low of the electron losses

$$\frac{dn_e}{dt} = Q^e - \alpha_{eff} n_e^2$$

F_2 region (>200 km)

Dominant ion is O^+

$$\frac{dn_e}{dt} = \frac{dn(O^+)}{dt} = Q_1 - L(O^+)$$

O^+ loss rate

$$L(O^+) = \left[k_4 n(O_2) + k_5 n(N_2)\right] n(O^+)$$

Effective loss coeffisient

$$\beta_{eff} = k_4 n(O_2) + k_5 n(N_2)$$

Liner low of the electron losses

$$\frac{dn_e}{dt} = Q_1 - \beta_{eff} n_e$$

$$Q_1 \sim n(O) \sim \exp(-z/H_0)$$

$$\beta_{eff} \sim n(N_2) \sim \exp(-z/H_{N_2})$$

For steady-state conditions

$$n_e = \frac{Q_1}{\beta_{eff}} \sim \frac{\exp(-z/H_O)}{\exp(-z/H_{N_2})} = \exp\left[\frac{m_{N_2} - m_O}{kt} gz\right]$$

Electron density increases exponentially with altitude?

Involving the plasma transport is needed.

Ambipolar diffusion

F_2 region (>200 km)

Major ion is O^+ $\quad n_i = n(O^+)$

Charge neutrality $\quad n_e = n_i$

Zero current $\quad n_e\mathbf{u}_e = n_i\mathbf{u}_i$

Steady state condition $\quad \frac{\partial \mathbf{u}}{\partial t} \to 0$

Flow is subsonic $\quad (\mathbf{u}\cdot\nabla)\mathbf{u} \to 0$

The ion and electron momentum equations along magnetic field

$$\nabla_{||}p_i - n_i e E_{||} - n_i m_i g_{||} = n_i m_i \nu_{ie}(u_{e||} - u_{i||}) + n_i m_i \nu_{in}(u_{n||} - u_{i||})$$

$$\nabla_{||}p_e - n_e e E_{||} - n_e m_e g_{||} = n_e m_e \nu_{ei}(u_{i||} - u_{e||}) + n_e m_e \nu_{en}(u_{n||} - u_{e||})$$

Using $n_i m_i \nu_{ie} = n_e m_e \nu_{ei}$, the edition of the equations yields

$$\nabla_{||}(p_e + p_i) - n_i(m_i + m_e)g_{||} = n_i(m_i\nu_{in} + m_e\nu_{en})(u_{n||} - u_{i||})$$

Taking into account that $m_e << m_i$ equation reduces to

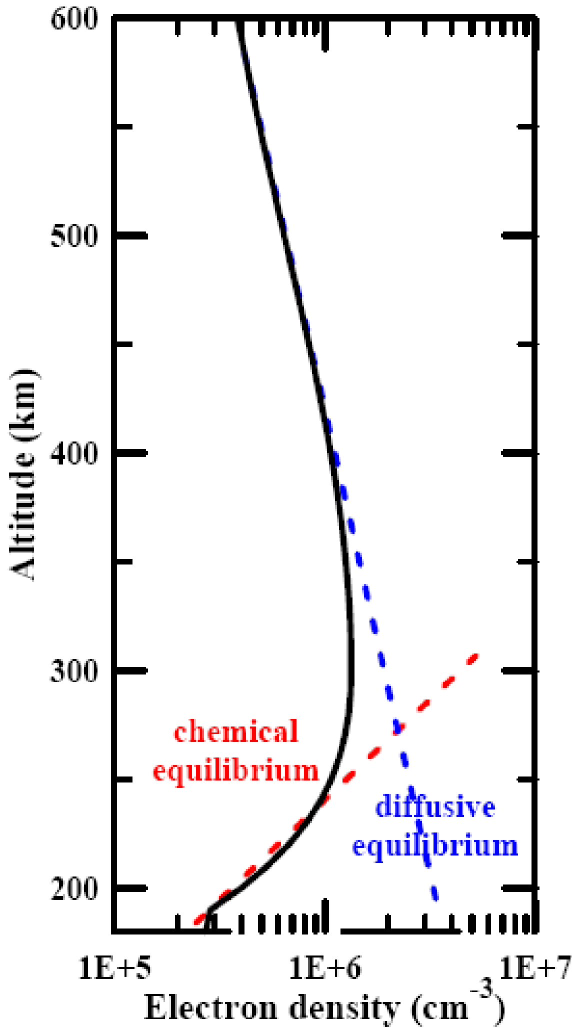
the ambipolar diffusion equation

$$u_{i||} = u_{n||} - D_a\left[\frac{1}{n_i}\nabla_{||}n_i + \frac{1}{T_p}\nabla T_p - \frac{m_i g_{||}}{2kT_p}\right]$$

$D_a = \frac{2kT_p}{m_i\nu_{in}}$ is the ambipolar diffusion coefficient

$T_p = \frac{T_e + T_i}{2}$ is the plasma temperature.

Ionospheric maximum formation



Diffusion equilibrium equation

$$\frac{1}{n}\frac{\partial n}{\partial z} = -\frac{1}{H_p} - \frac{1}{T_p}\frac{\partial T_p}{\partial z}$$

For $T_p = const$

$$n(z) = n_0 \exp\left(-\frac{(z-z_0)}{H_p}\right)$$

Photochemical equilibrium equation

$$n_e(z) = \frac{Q_1}{\beta_{eff}} \sim \exp\left[\frac{m_{N_2} - m_O}{kt} gz\right]$$

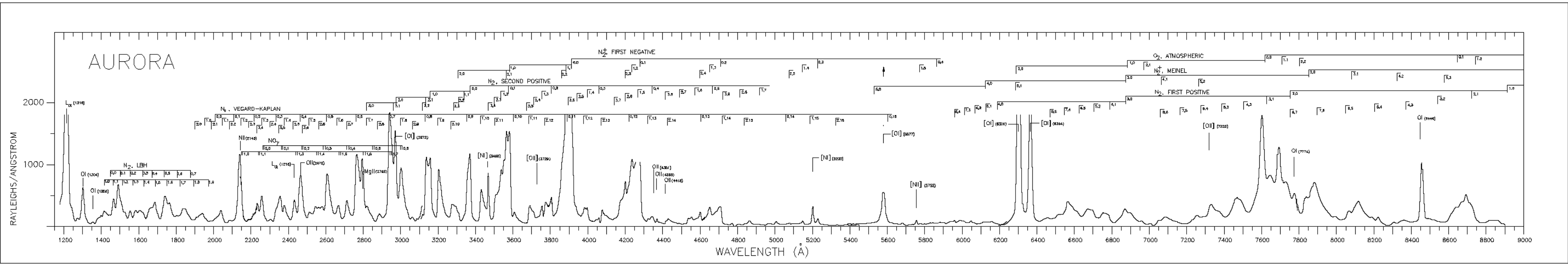
The F region peak density occurs at the altitude where the diffusion and chemical processes are of equal importance.

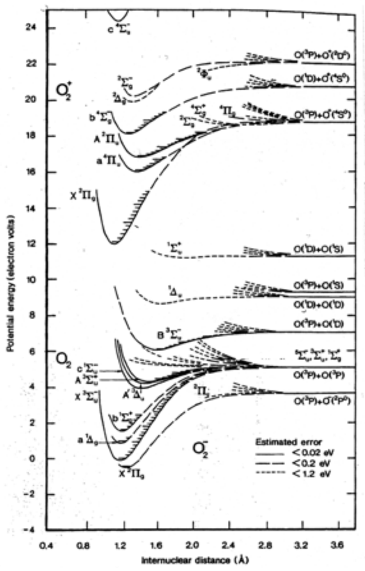
Auroral aeronomy II

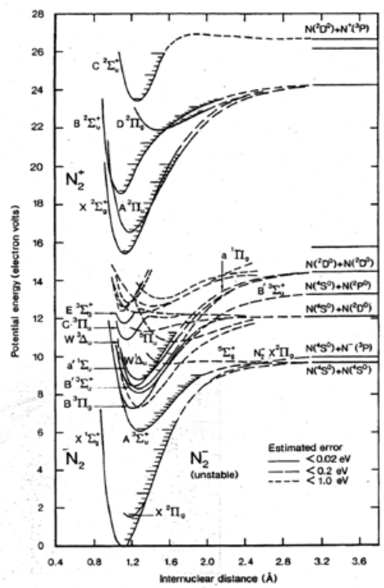
Tima Sergienko

AGF-351
Optical methods in auroral physics research,
UNIS, Longyearbyen

Auroral spectrum







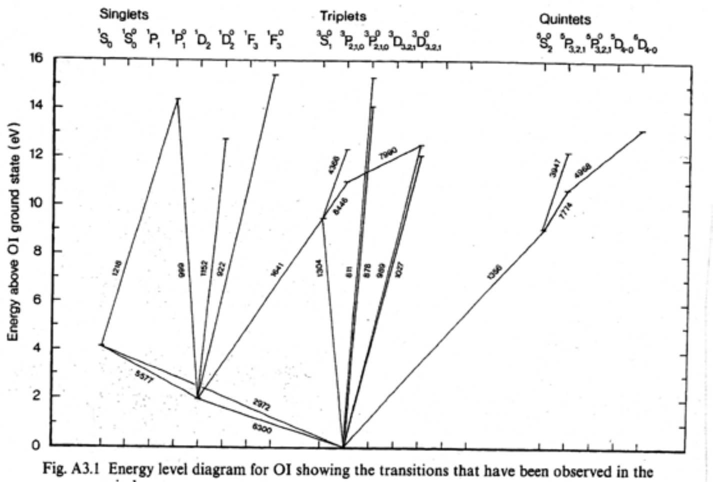
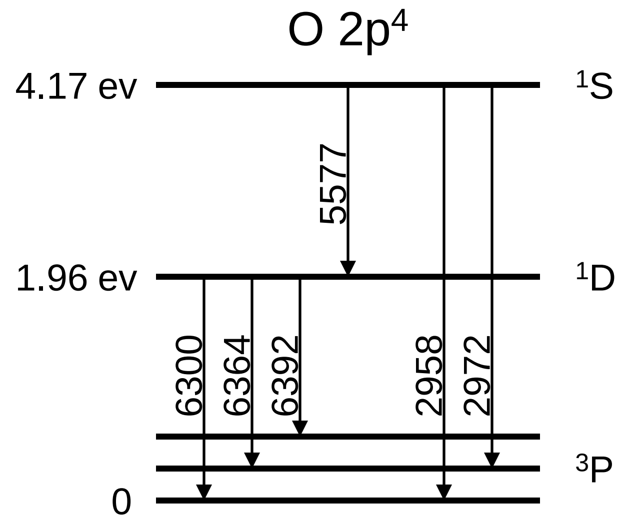


Fig. A3.1 Energy level diagram for OI showing the transitions that have been observed in the airglow or aurora.

Volume emission rate and intensity

Atomic line:



$V_{kk'} = A_{kk'} N_k$ (cm^{-3} s^{-1})

$A_{kk'}$ – Einstein coefficient for transition between states k and k' (s^{-1})

N_k – concentration of atoms excited at state k (cm^{-3})

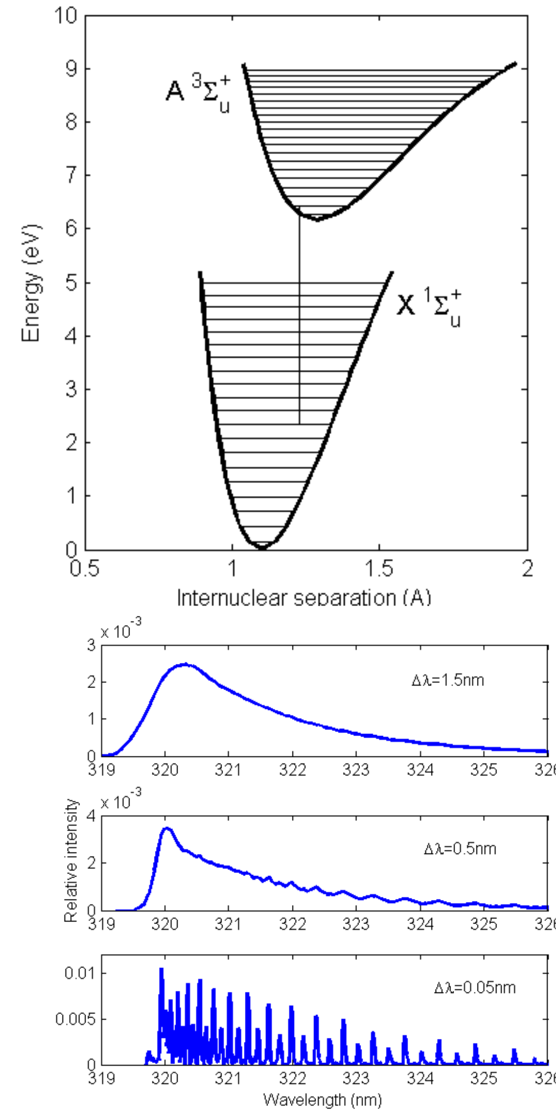
Volume emission rate and intensity

Molecular band:

$$V_{kk'}^{vv'}(J,J') = \sum_{\substack{J,J' \\ \Delta J=0,\pm 1}} A_{kk'}^{vv'}(J,J')\cdot N_k^{v}(J)$$

$A_{kk'}^{vv'}(J,J')$ - Einstein coefficient for transition between electronic states *k* with vibrational level *v* and rotational level *J* and electronic states *k'* with vibrational level *v'* and rotational level *J'* (s-1)

$N_k^{v}(J)$ - concentration of molecular excited at electronic states *k* with vibrational level *v* and rotational level *J* (cm-3)



Volume emission rate and intensity

Total emission from a column of unit cross section along the line of sight

$$4\pi I = \int_h V(h)\,dh$$ photon cm-2 str-1 s-1

$$I(\text{Rayleigh}) = \frac{4\pi}{10^6} I(\text{photon cm}^{-2}\ \text{str}^{-1}\ \text{s}^{-1})$$

Volume emission rate and intensity

Continuity equation:

$$\frac{dN^*}{dt} = Q - L$$

Productions, Q

Electron impact

$$N + e^- \rightarrow N^* + e^-$$

Energy transfer

$$N + M^* \rightarrow N^* + M$$

Radiative cascading

$$N^{**} \rightarrow N^* + h\nu$$

Losses, L

Radiative transfer

$$N^* \rightarrow N^{**} + h\nu$$

Quenching

$$N^* + M \rightarrow N \quad + M$$

Excitation of atmospheric gases by auroral electrons

Kinetic (classical) approch

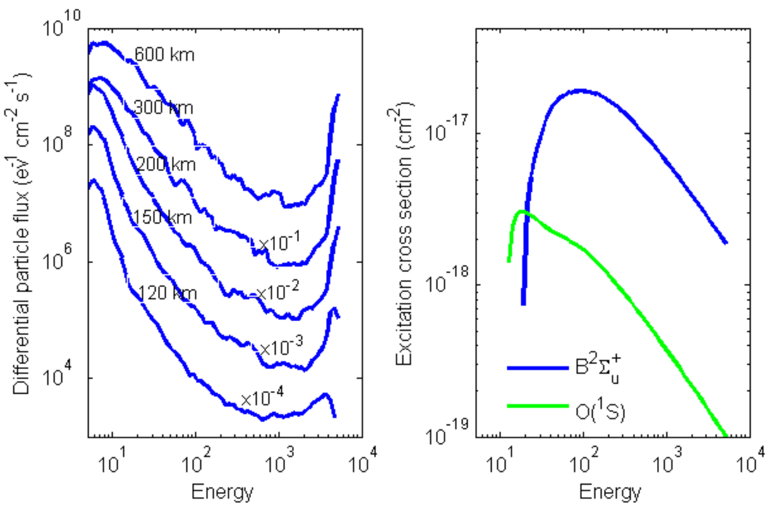
$$Q_i^j(h) = [N_i(h)] \int_E \sigma_i^j(E) f(E,h) dE$$

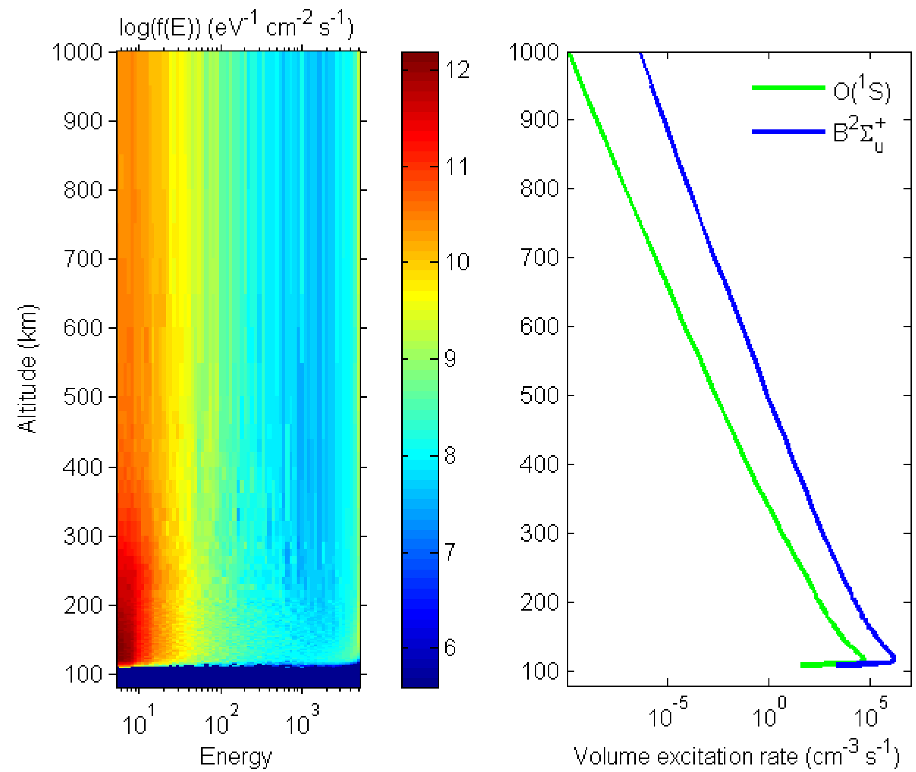
Q_i^j – excitation rate at altitude h(cm^{-3} s^{-1})

$[N_i]$ – concentration of the atmosperic gase (cm^{-3})

$\sigma_i^j(E)$ – exitation cross section of stae j (cm^2)

f(E,h) – differential electron particle flux at altitude h (eV^{-1} cm^{-2} s^{-1})





Auroral emissions

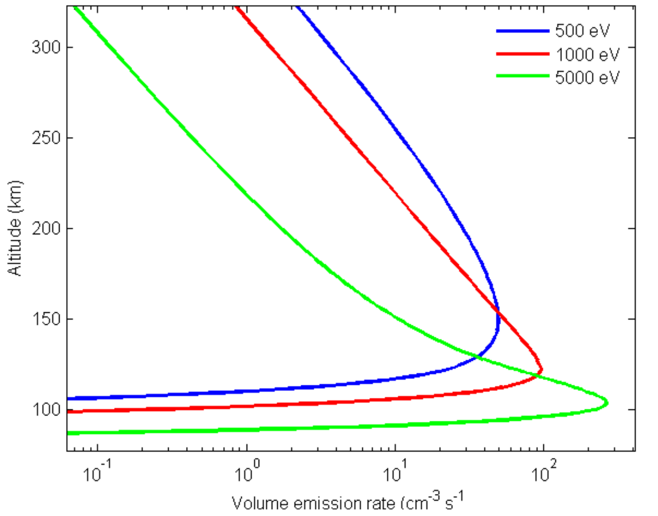
Fist negative bands of molecular nitrogen ion

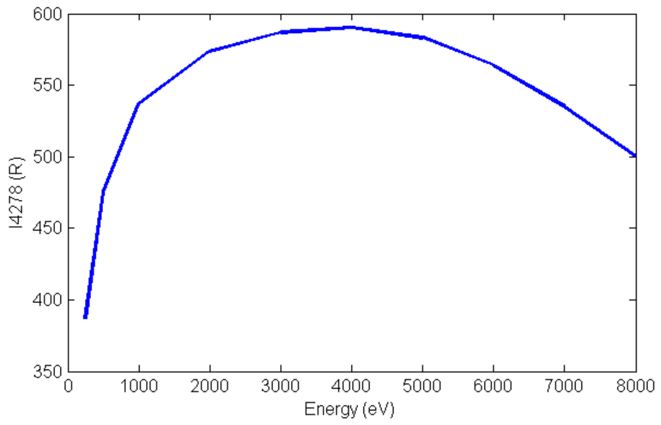
$$\frac{dN_v^{B^2\Sigma_u^+}}{dt} = Q - L = 0, \tau < 10^{-5} s$$

$$Q_v^{B^2\Sigma_u^+} = Q^{B^2\Sigma_u^+} q_{v''v}^{X^1\Sigma_g^- \to B^2\Sigma_u^+} = \frac{p_{N_2}[N_2]W}{\varepsilon_{B^2\Sigma_u^+}} q_{v''v}^{X^1\Sigma_g^- \to B^2\Sigma_u^+}$$

$$L = N_v^{B^2\Sigma_u^+} \sum_{v'} A_{vv'}^{B^2\Sigma_u^+ \to X^2\Sigma_g^+}$$

$$V_{vv'} = \frac{q_{v''v}^{X^1\Sigma_g^- \to B^2\Sigma_u^+} p_{N_2}[N_2]W}{\varepsilon_{B^2\Sigma_u^+}} \frac{A_{vv'}^{B^2\Sigma_u^+}}{\sum_{v''} A_{vv''}^{B^2\Sigma_u^+ \to X^2\Sigma_g^+}}$$





Auroral emissions

Auroral green line

Productions

$$O + e^- \rightarrow O(^1S) + e^-$$

$$O_2 + e^- \rightarrow O(^1S) + O + e^-$$

$$O_2^+ + e_{th}^- \rightarrow O(^1S) + O$$

$$O_2^+ + N(^4S) \rightarrow O(^1S) + NO^+$$

$$O_2 + N(^2P) \rightarrow O(^1S) + NO$$

$$O_2 + N^+ \rightarrow O(^1S) + NO^+$$

$$N_2(A^3\Sigma_u^+) + O \rightarrow O(^1S) + N_2$$

Losses

$$O(^1S) \rightarrow O(^1D) + h\nu_{5577}$$

$$O(^1S) \rightarrow O(^1D) + h\nu_{2958}$$

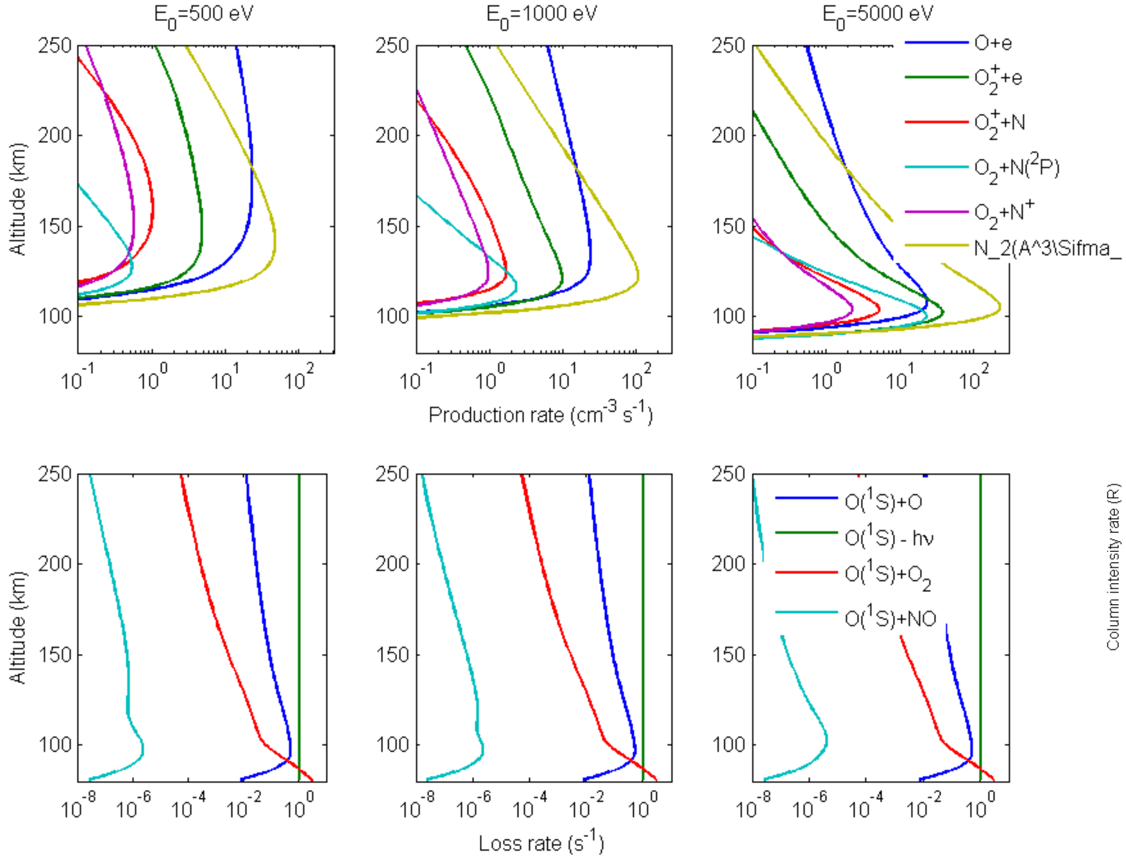
$$O(^1S) + NO \rightarrow O + NO$$

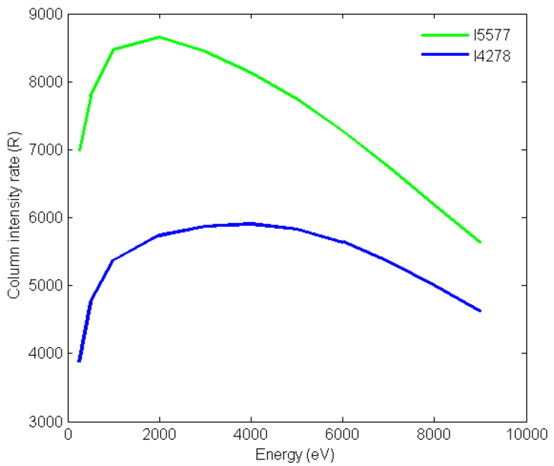
$$O(^1S) + O_2 \rightarrow O + O_2$$

$$O(^1S) + O \rightarrow O + O$$

Auroral emissions

Auroral green line





Auroral emissions

Auroral red line

Productions

$$O + e^- \rightarrow O(^1D) + e^-$$

$$O_2 + e^- \rightarrow O(^1D) + O + e^-$$

$$O_2^+ + e_{th}^- \rightarrow O(^1D) + O$$

$$O(^1S) \rightarrow O(^1D) + h\nu_{5577}$$

$$O_2 + N(^2D) \rightarrow O(^1D) + NO$$

$$O + N(^2D) \rightarrow O(^1D) + N$$

$$O_2 + N(^2P) \rightarrow O(^1D) + NO$$

$$O_2 + N^+ \rightarrow O(^1D) + NO^+$$

Losses

$$O(^1D) \rightarrow O(^1D) + h\nu_{6300,6364,6392}$$

$$O(^1D) + N_2 \rightarrow O + N_2$$

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

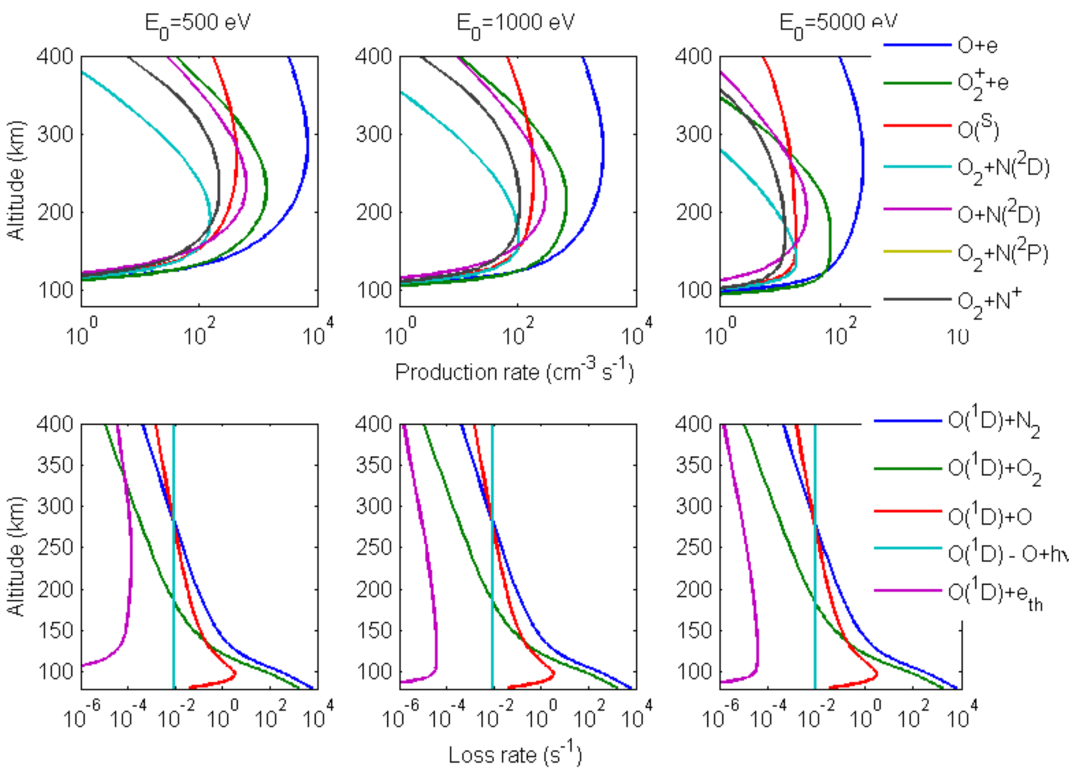
$$O(^1D) + O_2 \rightarrow O + O_2$$

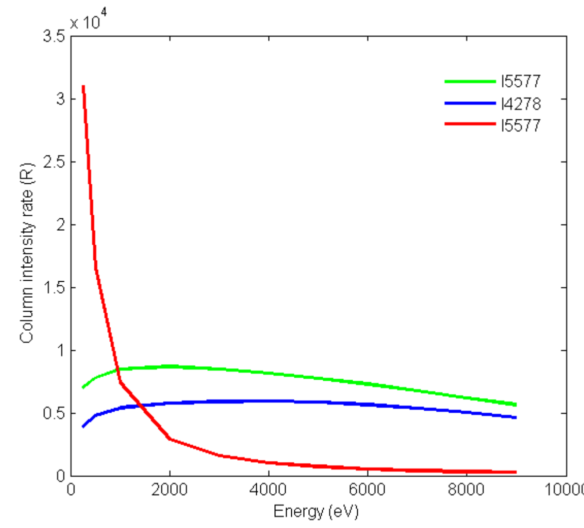
$$O(^1D) + O \rightarrow O + O$$

$$O(^1D) + e_{th} \rightarrow O + e_{th}$$

Auroral emissions

Auroral red line





Auroral emissions

N2 triple band system

Production

Electron impact

$$N_2 + e \rightarrow N_{2v}^{i} + e$$

Radiative transfer

$$N_{2v'}^{j} \rightarrow N_{2v}^{i} + h\nu$$

Collisional transfer

$$N_{2v'}^{j} + N_2 \rightarrow N_{2v}^{i} + N_2$$

Loss

Quenching

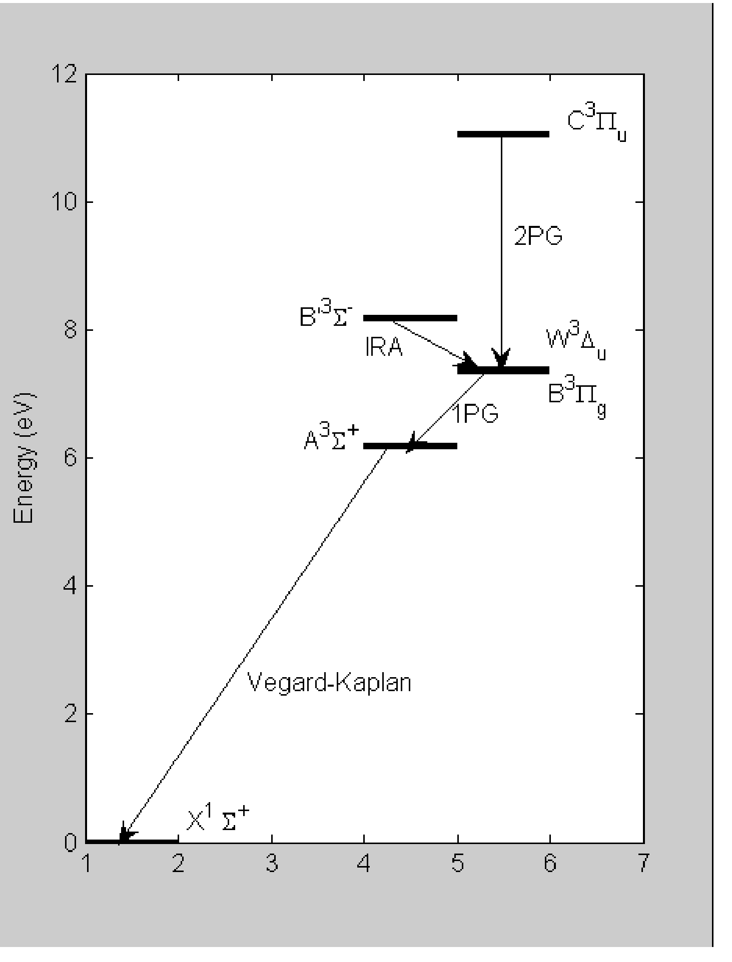
$$N_2 + [M] \rightarrow N_2 + [M]$$

Radiative transfer

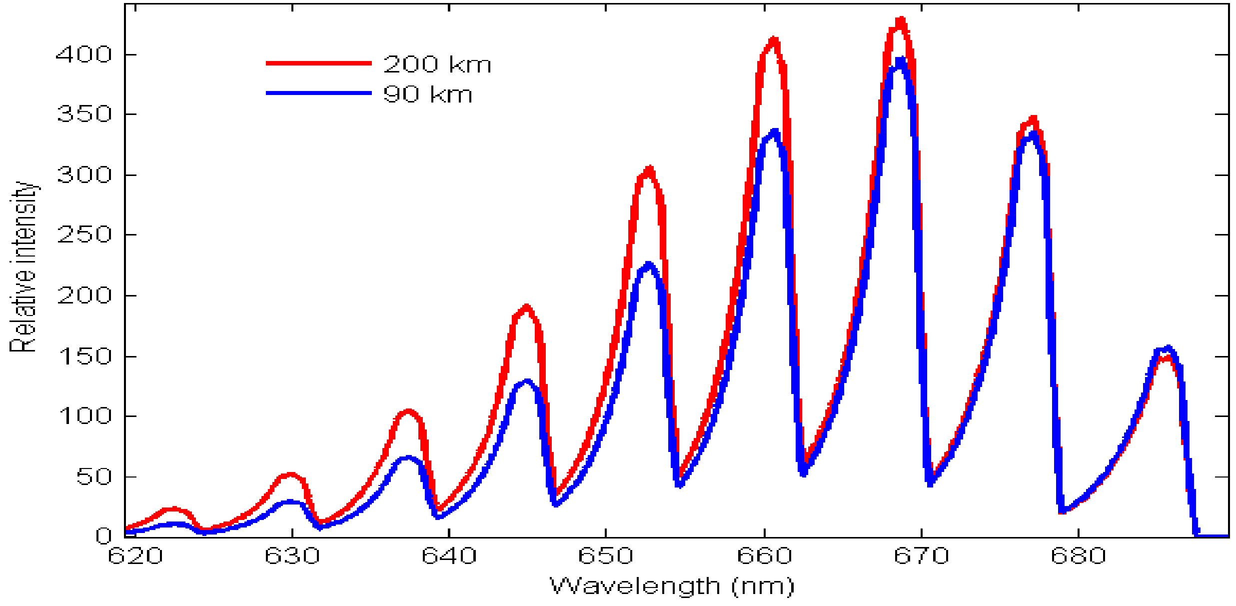
$$N_{2v}^{i} \rightarrow N_{2v'}^{j} + h\nu$$

Collisional transfer

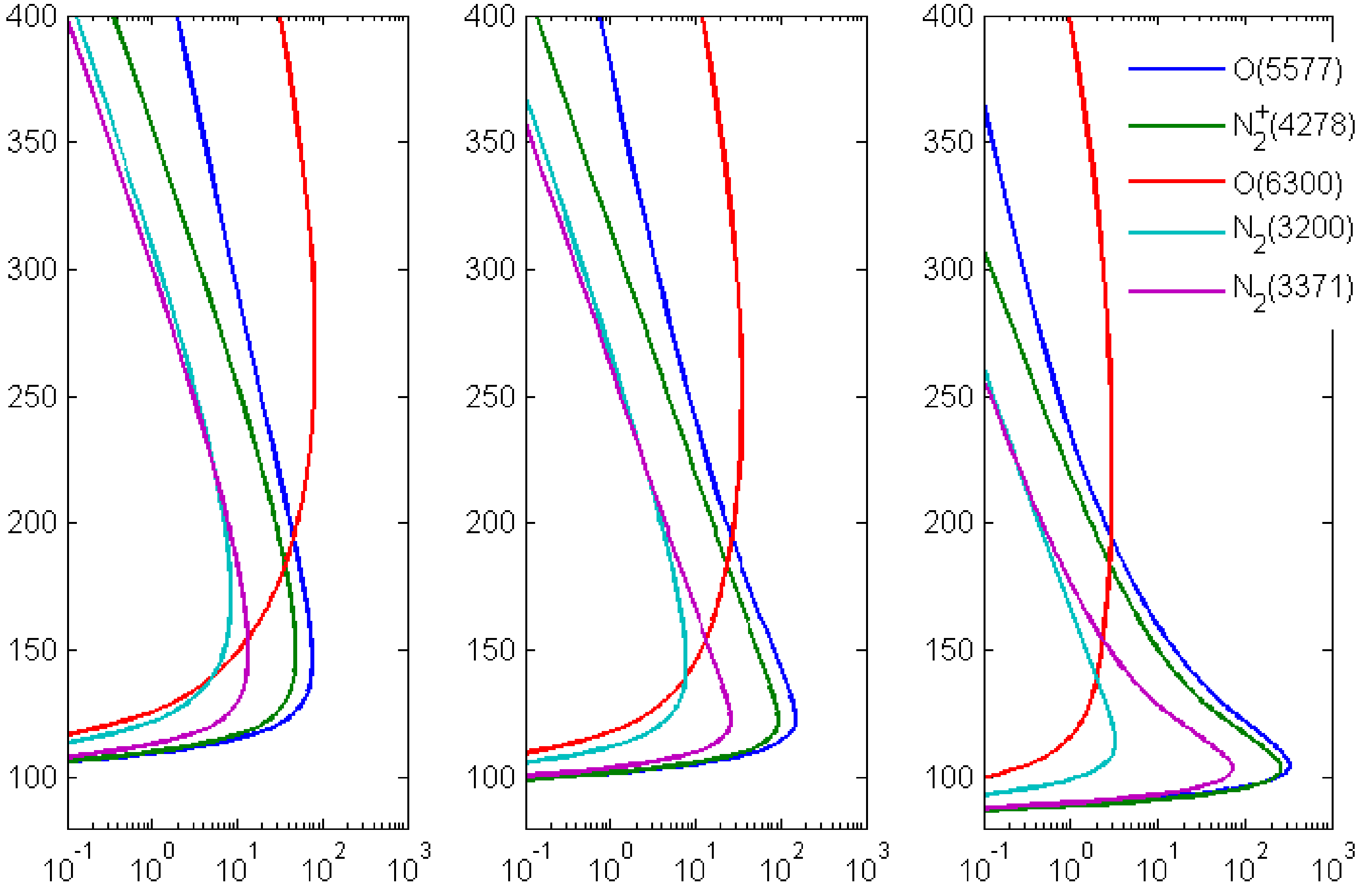
$$N_{2v}^{i} + N_2 \rightarrow N_{2v'}^{k} + N_2$$



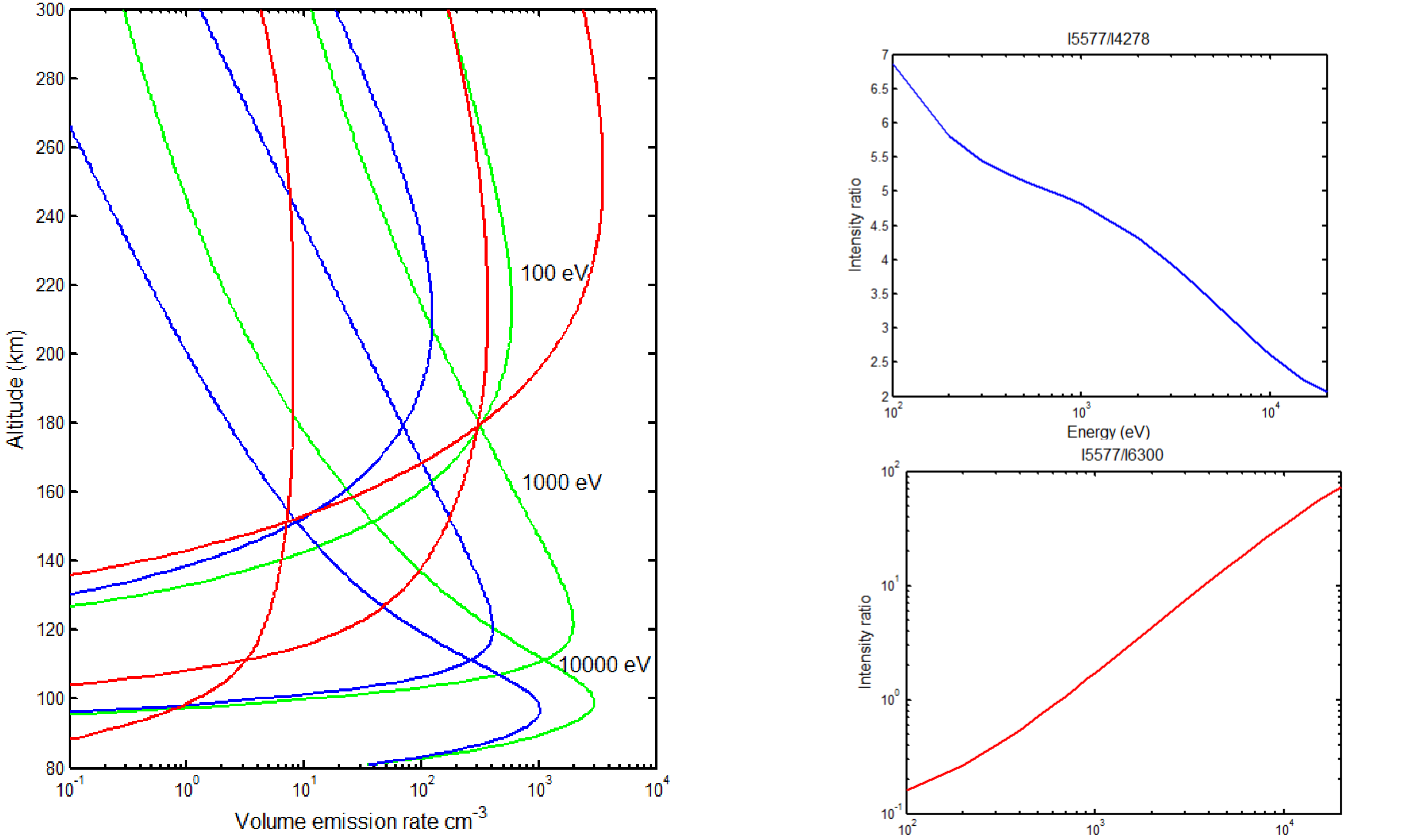
Auroral emissions



Auroral emissions

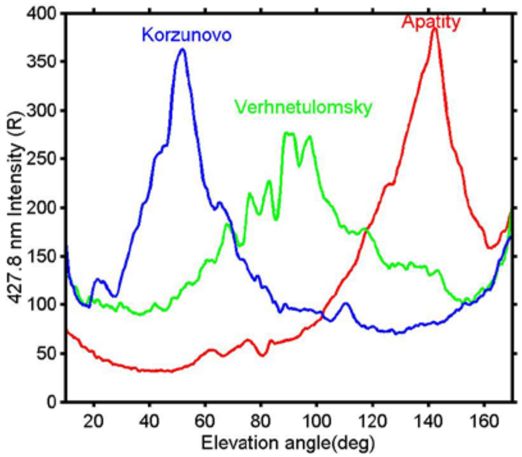


Diagnostic of the auroral particle parameters

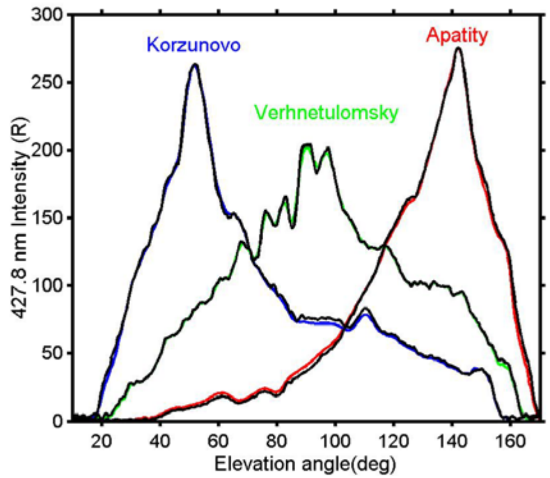


Reconstruction of electron spectra from auroral emission altitude profile

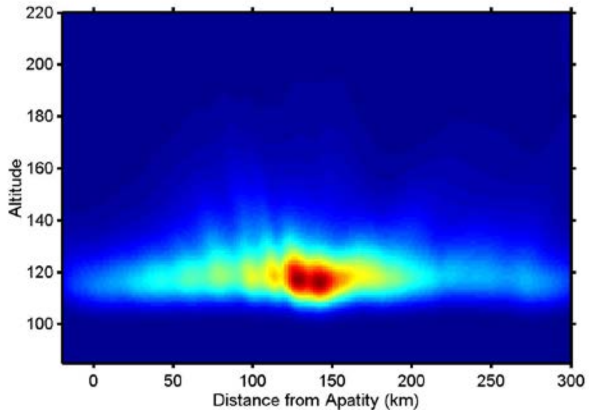
Scanning photometer records at 23.24:00 UT



Scanning photometer records at 23.24:00 UT after background subtraction.
Black lines show the photometer records calculated from the reconstructed emissions

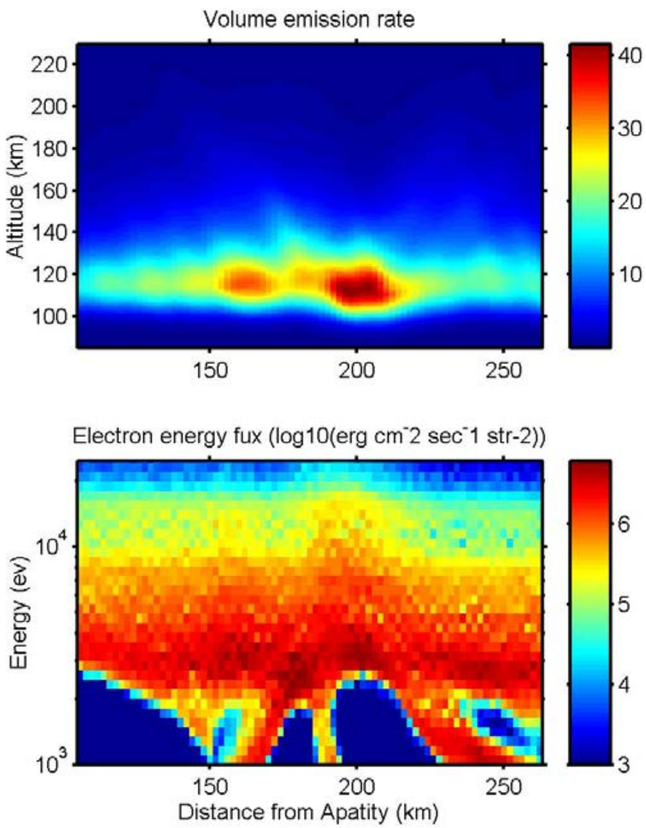


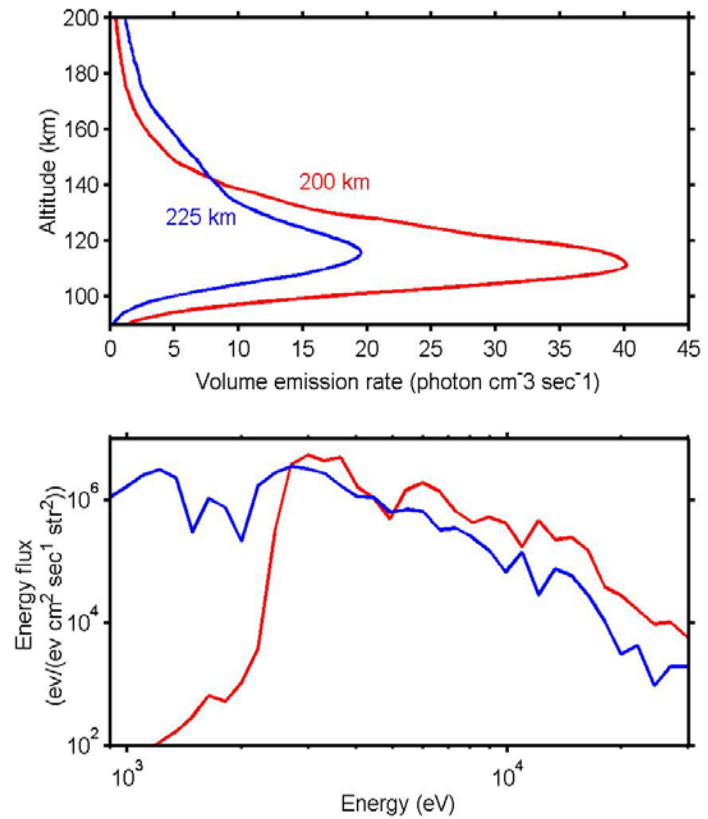
Reconstructed volume emission rate of the 427.8 nm emission



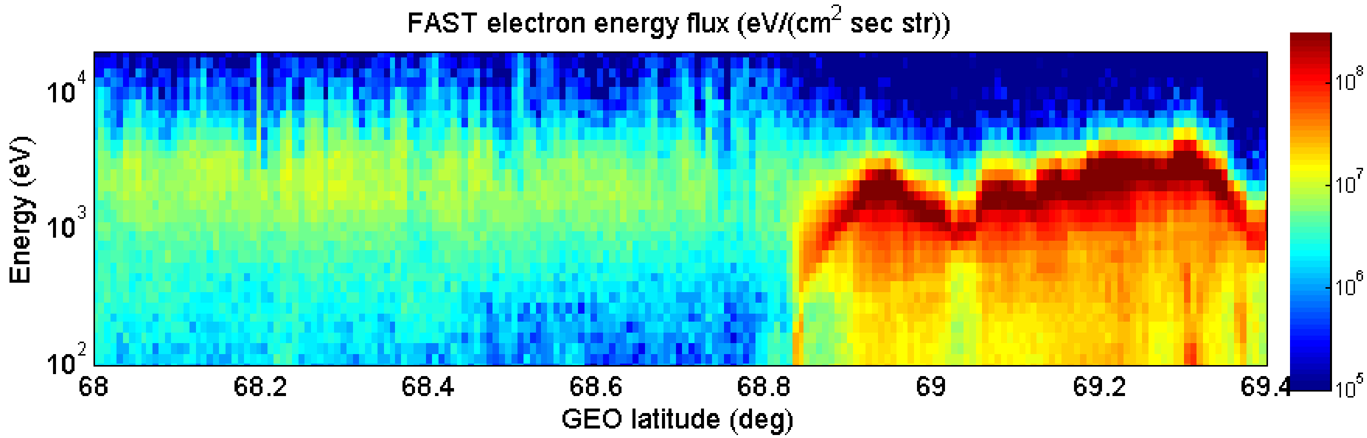
Reconstruction of electron spectra from auroral emission altitude profile

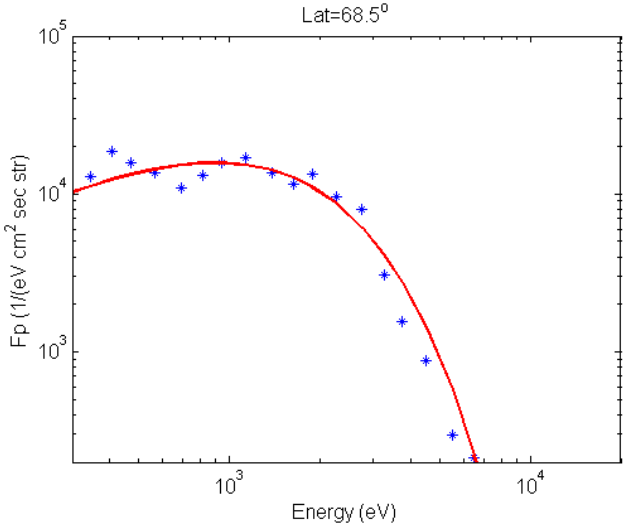
$$V_{4278} = A_{4278} \frac{\rho(h) p_{N_2}[N_2]}{\varepsilon_{v=0}^{B^2\Sigma_u^+}} \int_E \frac{\lambda(E, l/R(E))}{R(E)} f_0(E) dE$$

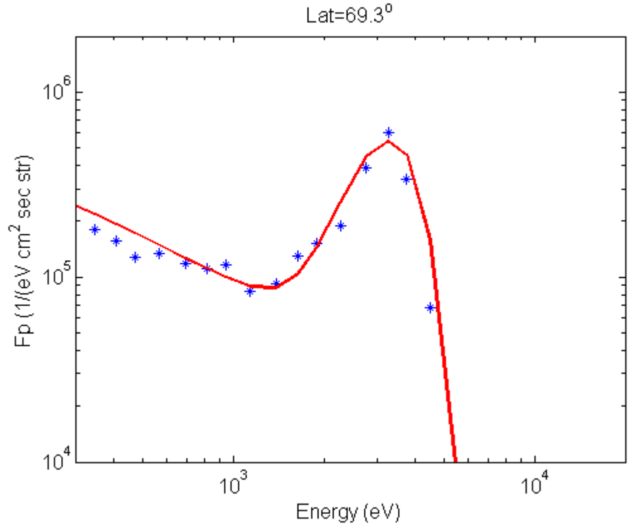




Auroral electron spectra







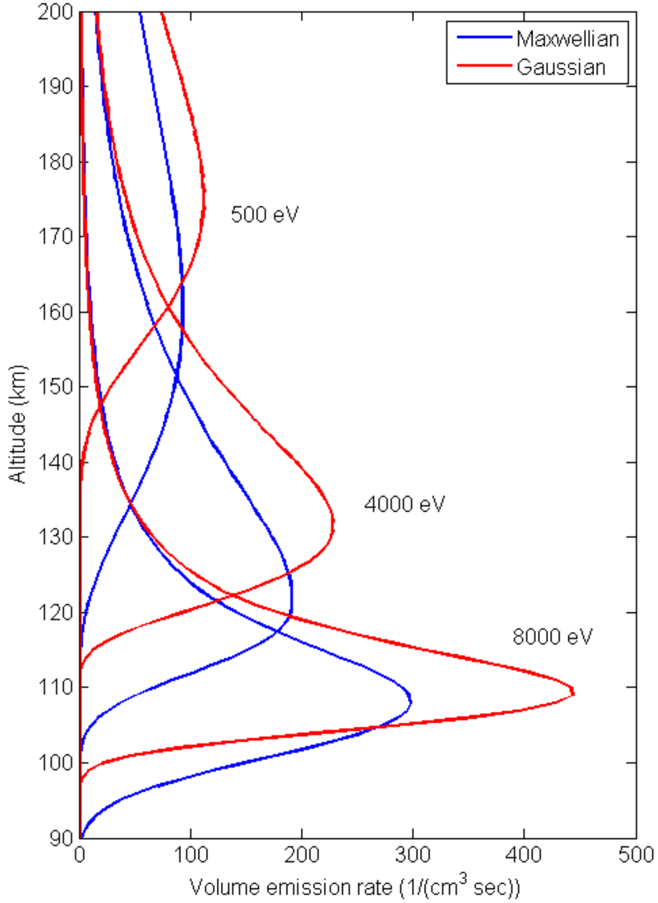
Maxwellian

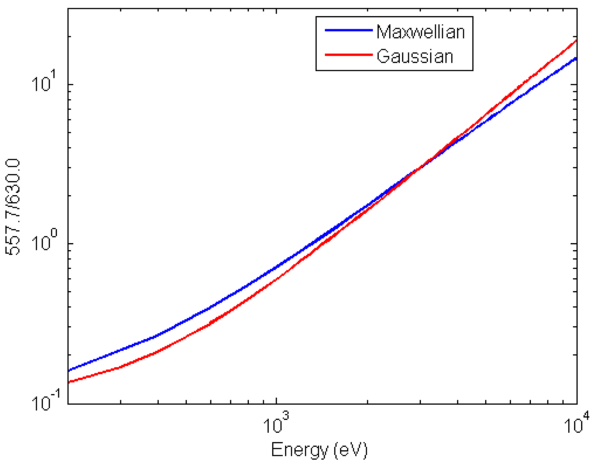
Gaussian

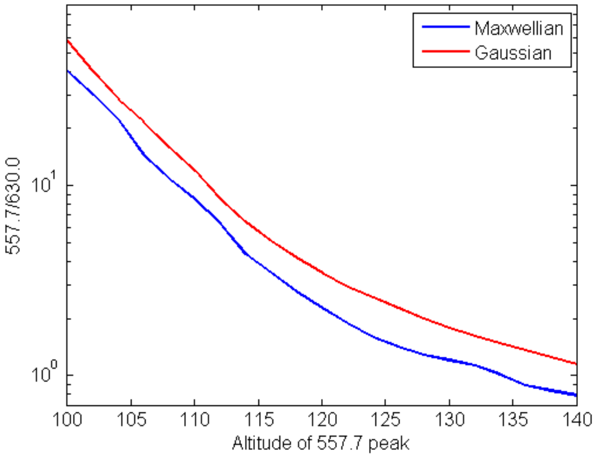
$F(E)=Q*E*exp(-E/E0)$

$F(E)=Q*exp(-(E-E0)^2/E0^2)+Q*A/E^b$

Maxwellian vs. Gaussian







Deducing atomic oxygen concentration from Vegard-Kaplan and 1NG emissions

$$0 = Q_{v'} + \sum_{v''} N_{v''}^{B^3} A_{v'',v'}^{1PG} - N_{v'}^{A^3} \left(\sum_{v''} A_{v',v''}^{VK} + \sum_{v''} A_{v',v''}^{1PG} + [N_2] k_{N_2} + [O_2] k_{O_2} + [O] k_O + +[NO] k_{NO} \right)$$

$$[O(h)] = \frac{\dfrac{I_{v'}^{1NG}(h)}{I_{v'}^{VK}(h)} \dfrac{\varepsilon_v^{A^3 eff} A_{v',v''}^{VK} \sum_v A_{v',v}^{1NG}}{\varepsilon_{v'}^{B^2} A_{v',v''}^{1NG}} - \sum_v A_{v',v}^{VK} - [O_2] k_{O_2}}{k_O}$$