Problem Sheet: Planetary outer atmospheres
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1.

1. The more energetic an auroral electron, the deeper in the atmosphere it is likely to be thermalized.
2. The more energetic a solar photon, the deeper in the atmosphere it is likely to be absorbed.
3. The use of recombination coefficients is enough to derive the electron density from the electron production rate in a region where transport is dominant.
4. Let's consider two wavelengths, λ_1 and λ_2, with $\lambda_1 > \lambda_2$ and a photo-absorption cross section $\sigma(\lambda)$ associated with the dominant neutral species present in the atmosphere. If $\sigma(\lambda_1) < \sigma(\lambda_2)$, then solar photons of wavelength λ_1 are going to deposit their energy deeper in the atmosphere than the more energetic solar photons of wavelength λ_2.
5. At Jupiter, the main aurora is primarily induced by the interaction of the planet with the space environment.
6. Aurora is observed throughout the Solar System and can be used as a fingerprint of atmospheric species and a tracer of plasma processes and magnetic field line configuration.
7. The solar flux at Neptune is 9 times less than at Saturn.
8. Solar photons of 180 nm are effective ionizers.
9. For a thermal electron population, it is possible to define a temperature.
10. Photochemical equilibrium applied to ionospheric plasma means thermal electron production rate equals thermal electron loss rate.
11. The profile in altitude of the electron density always peaks at the same altitude as the profile in altitude of the electron production rate. .
12. In the ionospheric region, the ion densities are several orders of magnitude lower than the neutral densities.
13. Both ionospheric electrons and photoelectrons are thermal.

2. Short Problems.

(i) At which distance from the Sun should Uranus be located to experience a solar power input equal to the auroral power input, which it undergoes at its current location? Express the solution in AU.

(ii) The spectroscopic analysis of H_2 Lyman and Werner emissions can be used to derive the energy of incident auroral electrons over the 10-200 keV energy range. Why is softer electron precipitation not detected by this technique?

3. Let's focus on the ionosphere of Saturn. Assume in this problem that H_2 and H_3^+ are the dominant neutral and ion species, respectively, and that all H_2^+ ions are converted to H_3^+ ions. The electron temperature is assumed to be 600 K.

(i) The nightside ionosphere at high latitudes is under auroral electron precipitation with the electron number density having reached 2×10^4 cm^{-3} at an altitude z of 1300 km above the 1 bar level. There is a sudden increase in the electron precipitation level yielding an additional 100 cm^{-3}s^{-1} in electron production rate.

(a) Calculate the electron number density at 1300 km after the increase in electron precipitation. By which factor has the electron number density increased? How would a significant increase in electron temperature, as a result of the precipitation intensification, affect the electron density?

(b) If the electron bombardment stops totally, how long will it take to have the electron density reduced by a factor of 2? of 10?

(ii) At low latitudes, under sunlit conditions the peak H_3^+ number density has reached a value of 5×10^3 cm^{-3}.

What is the effect of an influx of water from the rings? Quantify your response. The water number density at this ionospheric region is about 10^5 cm^{-3}.

Ionization sources

- **Ionisation potential**:
  - H_2: 15.43 eV ←→ 80 nm
  - H: 13.60 eV ←→ 91 nm
  - CH_4:12.55eV ←→ 99 nm

13 eV ←→ ~100 nm

- **Solar EUV radiation**:
  - Solar flux / (Sun-planet distance)^2
- **Energetic particles** from the space environment
  - A few keV to a few 100s keV

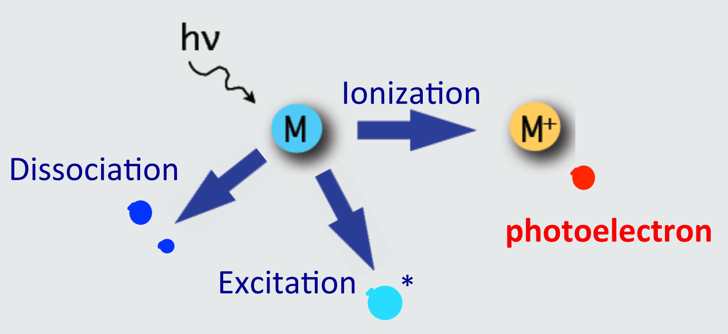
Energy sources

	Solar EUV input*	Auroral input*	Auroral particle input**
Earth (1 AU)	500 GW ($1 \text{x} 10^{-3}$ W/m^2)	80 GW	1-10 keV
Jupiter (5.2 AU)	800 GW ($1.3 \text{x} 10^{-5}$ W/m^2)	10^5 GW	30-200 keV 2-30 mW m^{-2}
Saturn (9.5 AU)	200 GW ($4.4 \text{x} 10^{6}$ W/m^2)	(5-10)x10^3 GW	10-20 keV ~ 1 mW m^{-2}
Uranus (19 AU)	8 GW	100 GW	-
Neptune (30 AU)	3 GW	1 GW	-

* *Auroral input refers to "particle + Joule heating" (Strobel 2002)*

** *Values valid for the main auroral oval, inferred from the analysis of auroral emissions (e.g., Fox et al. 2008, Gustin et al. 2004, 2009)*

Absorption of solar radiation in an atmosphere



✓ In the EUV, primarily extinction in the beam

→ apply Beer-Lambert Law: $$\frac{dI_\lambda(s)}{I_\lambda} = -\sum_i \sigma_i^{abs}(\lambda) n_i(s)$$

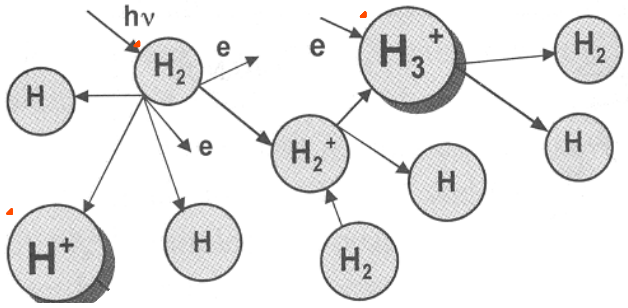
✓ **Attenuated solar flux** at wavelength λ and at altitude z:

$$I_\lambda(z) = I_\lambda^\infty \, exp\left(-\sum_i \sigma_i^{abs}(\lambda) \int_z^\infty n_i(z') sec(\chi) \cdot dz'\right)$$

✓ **Photoelectron production rate** at λ:

$$P_{e,\lambda}(z) = \sum_i \sigma_i^{ion}(\lambda)\, n_i(z)\, I_\lambda(z) \propto I_\lambda^{TOA}$$

Photo-chemistry in an H_2 atmosphere



$H_2^+ + H_2 \rightarrow H_3^+ + H$

$k_0 = 2.0 \times 10^{-9}$ cm^3 s^{-1}

$H_3^+ + e^- \rightarrow$ neutral products

$\alpha_0 = 1.73 \times 10^{-6} \times Te^{-0.5}$ cm^3 s^{-1}

with Te in K.

- Charge exchange reaction **$H^+ + H_2(v \geq 4) \rightarrow H_2^+ + H$** **(1)**

  controls the abundance of H_3^+ as it is quickly followed by:

  $H_2^+ + H_2 \rightarrow H_3^+ + H$

- Reaction rate **$k_1^* = k_1\,[H_2(v \geq 4)]/[H_2]$**
  - Low k_1^* means less charge exchange reaction and increase in ionospheric densities

  ➢ $k_1 = 10^{-9}$ cm^3 s^{-1} [*Huestis*, 2008]

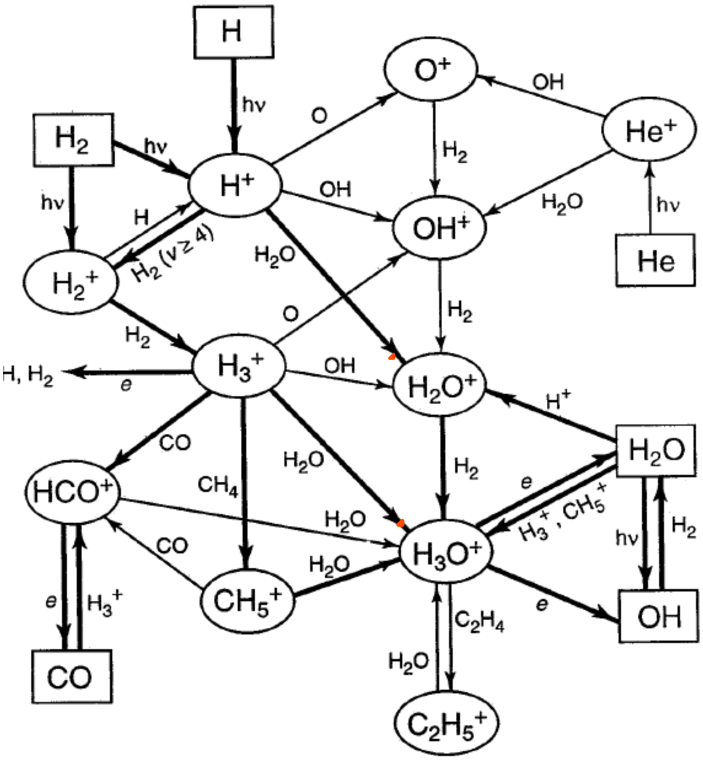
Photochemistry in Gas Giant atmospheres

$H^+ + H_2O \rightarrow H_2O^+ + H$
$k_2 = 8.2 \times 10^{-9}$ cm^3 s^{-1}

$H_2O^+ + H_2 \rightarrow H_3O^+ + H$
$k_3 = 7.6 \times 10^{-10}$ cm^3 s^{-1}

$H_3^+ + H_2O \rightarrow H_3O^+ + H_2$
$k_4 = 5.3 \times 10^{-9}$ cm^3 s^{-1}

$H_3O^+ + e^- \rightarrow$ neutral products
$\alpha_5 = 1.74 \times 10^{-5} \times Te^{-0.5}$ cm^3 s^{-1}
with Te in K.

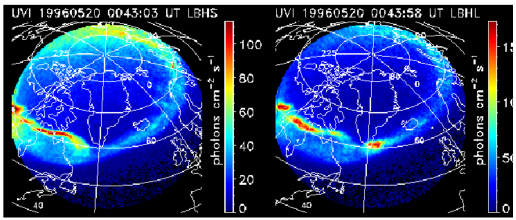


[Moses and Bass 2000]

AURORAL SPECTROSCOPIC ANALYSIS

- ➢ Identification of energetic particle type
- ➢ Assessment of (E_m, Q_{prec}) of energetic particles
- ✓ *Supported by comprehensive modeling*

POLAR UVI images



N_2 LBHS N_2 LBHL

COLOR RATIO	Earth	Jupiter, Saturn
Two spectral bands chosen in:	N_2 LBH	H_2 Lyman and Werner
One band strongly absorbed by:	O_2 (< 160 nm)	CH_4 (< 140 nm)
Electron energy range covered	0.2 – 20 keV	~10 to 200 keV
Type of aurora identified:	Electron aurora (discrete only)	Electron aurora (diffuse + discrete)

✓ *Similar techniques can be applied at various planets*
BUT different limitations on the product

[Fox et al. 2008]