Lessons to learn from Solar System studies for exoplanets

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Plan: Lessons to learn from Solar System

1. Transits and occultations in the Solar System
2. Complexities in radiative transfer of planets: inhomogeneities, aeronomy of upper atmospheres
3. Difficulties and errors in planetary spectroscopy
4. An unusual journey in the Solar System
Objectives of the course

After decades of space exploration, the Solar System objects are today known with high accuracy, to the point that Earth sciences are dominant in the study of planets, more than astronomy!

This knowledge can be translated to exoplanets only if we extrapolate from the physical mechanisms, even if average parameters of exoplanets are NOT similar to our planets!

The main objective of the course will also to remember all the errors made in planetology during decades, to try not to repeat them in exoplanets study.
Today, known planets plotted as a function of distance to the star (up to 20 au) and planetary radii (in Earth masses). Temperature of the host stars is given through the color grid.
Histogram of planetary radii
SUPER-EARTHS OR MINI-NEPTUNES?
Philosophical context

1) The Earth is **not** at the center of the (planetary) universe
Paradigm: Earth-like planets around Sun-like stars are not the most common planets...

2) The Solar System planets are **not** the representative templates for exoplanets study: superEarths/subNeptunes are the most common (and we don’t know much about them)!

3) Why do we need to study Solar System planets? Not as templates, but for the physical mechanisms which are universal
1. Transits and eclipses in the Solar System

• Transit observable from Earth only for inner planets! Mercury & Venus transits
Lomonosov discovery of the atmosphere of Venus (1761)

Lomonosov’s drawing of Venus transit across the Sun’s disc

1. Entering the solar disk in B
2. Colors caused by refraction
3. & 4. Bulge as Venus leaves the Sun

Marov, 2004, IAU proceedings
Transit of Venus in 2012 observed by Hinode

Observation of Venus Transit in 2012

Satellite Hinode (JAXA)

Credit: JAXA/NASA/Hinode
Transits and eclipses in the Solar System

- Transit observable from Earth only for inner planets! Mercury & Venus transits

- For any planets (and small bodies...), a powerful tool for investigation is the star occultation

An interesting example: the Jupiter spectral occultation in 1999 by HIP9369
Solar occultation by space missions

Many observations available:
- Titan, Saturn – VIMS/Cassini
- Mars: Auguste/Phobos 2 – SPICAM/Mars Express
- Venus: SPICAV/SOIR Venus Express
VIMS Titan occultation observations

Series of spectra during Titan solar occultation

(15 January 2006)

Bellucci et al., Icarus, 2009
Occultation of Star HIP9369 by Jupiter
10 October 1999

Emersion: 7:45:10 UTC

Immersion: 6:25:11 UTC
Raynaud, Drossart et al, Icarus 2003
Observations and data reduction:

Disentangling star and planetary spectra
CH₄ observations and simulations for different CH₄ profiles

CH₄ vertical profiles vs $K_{\text{eddy}}$
Equation of diffusion in an atmosphere

Mass conservation equation for the flux of a $i^{th}$ constituent in the atmosphere:

$$\frac{d\varphi}{dz} = 0$$

(in the absence of chemical/photochemical sources & loss, see O. Venot course)

Lower atmosphere: turbulent mixing $\Rightarrow$ one scale height $H_a = \frac{RT}{M_ag}$

Molecular diffusion: one scale height per constituent $H_i = \frac{RT}{M_ig}$
General Equation of diffusion

\[ \phi_i = n_i \left[ -D_i \left( \frac{1}{n_i} \frac{dn_i}{dz} + \frac{1}{H_i} + \frac{1}{T} \frac{dT}{dz} \right) - K \left( \frac{1}{n_i} \frac{dn_i}{dz} + \frac{1}{H_a} + \frac{1}{T} \frac{dT}{dz} \right) \right] \]

Variation of number density in molecular regime
\( D_i \gg K \)

Variation of number density in turbulent regime
\( D_i \ll K \)
Molecular diffusion coefficient

From the kinetic gas theory we have:

• \( D_i = A T^s / n \)
• \( K \sim n^{-0.5} \)

Therefore the \( D \) coefficient will dominate at high altitude.

\( K = D_i \) defines the homopause.
Plan : Lessons to learn from Solar System

1. Transits and occultations in the Solar System

2. Complexities in radiative transfer of planets: inhomogeneities, auroral effects and non-LTE phenomena in the upper atmospheres of giant planets
2.1 Inhomogeneities in planetary atmospheres

- Spatial inhomogeneities: horizontal or vertical

(a) UVI 0.33 µm  
(b) LIR 8-12 µm  
(c) IR2 2 µm
Jupiter

A. Simon (Goddard Space Flight Center), M. H. Wong (University of California, Berkeley) and the OPAL team. HST, 25 August 2020. Credit NASA, ESA

Karkoshka, Icarus, 1996
Auroral phenomena in giant planets

Importance of particle precipitations in a H$_2$/He atmosphere

H and H$_2$ UV emission :
• Lyman & Werner band for H2,
• Lyman alpha for H

Infrared emissions :
• H$_3^+$ emission in the ionosphere
• Infrared emissions : hydrocarbon emissions (CH$_4$, C$_2$H$_2$, ...)

Dynamic phenomena

Heating of the thermosphere
The magnetosphere of Jupiter
Auroral emissions

Precipitation of particles from the magnetosphere:
- Primary or secondary emissions: H Ly$_\alpha$ & H$_2$ Lyman and Werner bands
- Chemical modifications
- Thermal heating of the upper stratosphere
- Dynamical effects
**Auroral emissions on Jupiter**

- **Similar morphology on the global scale**
  - Blurring of ground-based $\text{H}_3^+$ images by atmospheric “seeing” local features associated to magnetospheric precipitating beams structure **undiscernable**. Instrumental effect.

- **Short-term variability (min) only visible in UV**, direct excitation by particle precipitation. IR emission, indirectly excited, depend on intermediate processes (lifetime, thermalisation, ..). Physical effect.

*Sinclair et al 2019*

A brightening of Jupiter’s auroral 7.8-μm CH 4 emission during a solar-wind compression
Rotational temperature retrieval

$2\nu_2$ band of $\text{H}_3^+$ (1st detection) – 2 µm (K band)

$\nu_2$ band 4 µm

L band

FTS spectra of Jupiter – R ~ 20,000
Maillard et al, 1990

September 2023

FTS spectra of Jupiter – R ~ 20,000
Drossart et al, 1989
Vibrational temperature retrieval

VLT/ISAAC observations (12/14/2000)

$H_3^+ 2\nu_2 - \nu_2$ emission

$\Rightarrow$ vibrational temperature
Kinetic temperature retrieval

CFHT/FTS spectral resolution of 115,000 – line resolved spectroscopy

Least square fit
Tk = 1150 K
Trot = 1250 K

*Drossart et al.,* APJ Lett. 1993
Non-LTE effects

Figure 6. (a) Departure from thermal population of the $nv_2$ levels. (b) Emission from $2v_2^2 R(6, 6)$ line as a function of altitude for LTE and non-LTE models. From Melin et al. (2005).
From spectrum to planetary physics

Measurable parameters:

- **Temperature** of the ionosphere
- **H$_3^+$ column density**
- **H$_3^+$** as a wind tracer (from Doppler shift)
- Spatial / temporal **variability**
- **Altitude** of emission from limb observations
- **Multiwavelength**: X-ray, UV, IR, radio
  => correlations with other processes
  (magnetosphere, solar wind, internal dynamics)
2.2 Non-LTE mechanisms in planetary atmospheres

Venus, VIRTIS/Venus Express, 2006
Observation of CO$_2$ fluorescence at 4.3 µm
Radiative transfer equation in LTE conditions

Formal radiative transfer equation \( dL(\psi, s) = -e_n \left[ L(\psi, s) - J(\psi, s) \right] ds \)

\( L = \) radiance ; \( e = \) extinction coeff. ; \( n = \) density of absorber ; \( J = \) source term

*The complexity is hidden in the source term...*

True thermal equilibrium:

\( J(\psi) = B(\psi) \) and \( L(\psi) = B(\psi) \): blackbody condition \( \Rightarrow \) 1 temperature \( T \)

Local Thermal Equilibrium \( \Rightarrow J(\psi) = B(\psi) \) but \( L(\psi) \neq B(\psi) \)

Observed when thermal collision ensures that all form of energy equilibrate the temperatures (vibrational, rotational, kinetic). Partial LTE possible (rotational vs vibrational, etc.)

Limitations of LTE sounding in infrared emission for dynamical purposes:

- dependence in limited number of atmospheric parameter (temperature profile \( T(z) \))
- vertical resolution = weighting function in the RT equation
- optical depth \( \tau \) \( \sim \) 1 sounding \( \Rightarrow \) limitation to stratospheric levels
Radiative transfer non-LTE scheme

Non-LTE regime:

\[ J_\nu \neq B_\nu \]

Thermal collision time > radiative time

Collisional, chemical processes to be taken into account to calculate the source function

Fig. 3.3 Processes affecting the populations of vibrational levels.
Some non-thermal processes

1. Vibrational-vibrational energy transfer.
   Example: CO$_2$ molecule; exchange with N$_2$

2. Electronic to vibrational energy transfer.
   Example: O($^1$D) state exciting the N$_2$ vibrational modes

3. Chemical recombination or chemiluminescence
   Example: ozone bands at 10 µm

4. Photochemical reactions
   Example: O$_2$ emissions at 1.27 µm

5. Dissociative recombination (O$_2^+$ + e- $\rightarrow$ O$^*$ + O)

6. Collisions with charged particles (auroral processes)
A conceptual picture of $O_2$ ($\Delta$) production and airglow on Venus

$$O + O + M \rightarrow O_2^* + M$$
O₂ average emission

O₂ emission
altitude: ~95 km

Soret, Lauriane; et al. The OH Venus nightglow spectrum: Intensity and vibrational composition from VIRTIS—Venus Express observations Planetary and Space Science,. 2012
Giant Planets:
Cassini/VIMS CH$_4$ emissions at 3.3 $\mu$m
Mid-latitude spectra

- **Jupiter thermal profile**
  - Temperature vs. Pressure (bar)
  - Key features: 
    - $H_3^+$
    - CH$_4$ fluorescence
    - Upper cloud

- **BS1380 spectrum**
  - **CH$_4$ fluorescence** $\nu_3+\nu_4 - \nu_4$ band
  - **Cloud reflection**

- **Mid-latitude spectra**

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September 2023 Biarritz, 2023 - Pierre Drossart
Comparison of synthetic spectra with ISO/SWS observations
vibration/rotation bands: \( \text{CH}_4 \)

- \(7.8 \, \mu\text{m}\)
- \(3.3 \, \mu\text{m}\)
- \(2.3 \, \mu\text{m}\)
- \(1.8 \, \mu\text{m}\)

Dyad
- 2 vibrational states
- 2 sublevels

Pentad
- 5 vibrational states
- 9 sublevels

Octad
- 8 vibrational states
- 20 sublevels

Tetradecad
- 14 vibrational states
- 60 sublevels

Simplified scheme of fluorescence in \( \text{CH}_4 \) in planetary atmospheres

- grouping stretching/ bending levels of \( \text{CH}_4 \)
- \( \text{CH}_4 \) radiative transitions:
  - \( \nu_4 \)(7.8\( \mu \)m) \( \nu_3 \)(3.3\( \mu \)m)
  - \( \nu_3 + \nu_4 \)(2.3\( \mu \)m) \( \nu_3 + 2 \nu_4 \)(1.7\( \mu \)m)
Fit of HD 189733b in L band
A summary of historical errors or difficulties

A summary of historical errors or difficulties

• Detection of chlorophylle on Mars (Sinton, 1957)
• Spectral confusion absorption/emission – « doublet » 3.52 micron

Ballester et al. 1994 claiming for unknown emission features
Re interpretation Drossart et al. 1995 as CH₄ features and cloud deck reflection between absorption
A summary of historical errors or difficulties

• Detection of chlorophyll on Mars (Sinton, 1957)
• Spectral confusion absorption/emission – doublet 3.52 micron (Ballester et al. 1994 / interpretation Drossart et al. 1995)
• Methane on Mars: where is the CH₄?
A story of CH₄ detections on Mars

• Mars Express/PFS Formisano et al, ground based observations – intermittent detection from orbit 0-30 ppbv
  *Formisano, Vittorio; Atreya, Sushil; Encrenaz, Thérèse; Ignatiev, Nikolai; Giuranna, Marco Detection of Methane in the Atmosphere of Mars 2004Sci...306.1758F*

• Curiosity Chemcam : sporadic detection 5 to 21 ppbv local on Gale crater

• Exomars TGO and ACS : CH₄ less than 0.06 ppbv
  *Knutsen, Elise W.; Villanueva, Geronimo L.; Liuzzi, Giuliano et al. Comprehensive investigation of Mars methane and organics with ExoMars/NOMAD 2021lcar..35714266*
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• Phosphine on Venus: where is the PH$_3$?
A story of PH$_3$ detections on Venus

• Greaves, Jane S.; Richards, Anita M. S.; Bains, William et al. Phosphine gas in the cloud decks of Venus 2021NatAs...5..655G


• Snellen, I. A. G.; Guzman-Ramirez, L.; Hogerheijde, M. R. et al. Re-analysis of the 267 GHz ALMA observations of Venus. No statistically significant detection of phosphine

• Encrenaz, T.; Greathouse, T. K.; Marcq, E. et al. A stringent upper limit of the PH$_3$ abundance at the cloud top of Venus 2020A&A...643L...5E
A summary of historical errors or difficulties

• Detection of chlorophylle on Mars (Sinton, 1957)
• Spectral confusion absorption/emission – doublet 3.52 micron (Ballester et al. 1994 / interpretation Drossart et al. 1995)
• Methane on Mars : where is the CH$_4$ ?
• Phosphine on Venus : where is the PH$_3$ ?
• Sodium in HD209458 : where is Na ?
A story of Na detection on HD209458b

• Charbonneau, David; Brown, Timothy M.; Noyes, Robert W.; Gilliland, Ronald L. *Detection of an Extrasolar Planet Atmosphere* 2002ApJ...568..377C

• Casasayas-Barris, N.; Pallé, E.; Yan, F. et al. *Is there Na I in the atmosphere of HD 209458b? Effect of the centre-to-limb variation and Rossiter-McLaughlin effect in transmission spectroscopy studies* 2020A&A...635A.206C

• Morello, G.; Casasayas-Barris, N.; Orell-Miquel, J.; Pallé, E.; Cracchiolo, G.; Micela, G. *The strange case of Na I in the atmosphere of HD 209458 b. Reconciling low- and high-resolution spectroscopic observations.* 2022A&A...657A..97M
Concluding remark

Thou shouldst be careful before announcing any molecular detection on a planet. Especially if the molecule is of biological interest.