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lisa

Atmospheric radiative transfer generalized for use on Earth and other planets: ARTS 2.2

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ARTS Workshop

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ARTS

The Atmospheric Radiative Transfer Simulator

Contents

- Background
- "Planetarization" adaptations
  - line modeling approach
  - refractivity
  - isotopologue ratios
  - CIA
  - planet parameters
- Further new ARTS features
- Data collection
- Summary

- theory and implementation
- user-interface

Background

- increasing interest in RT modeling for planet atmospheres

- sophisticated Earth RT models available, e.g. ARTS

- conditions on planets are different, i.e. adaptations required
  - specialised RT models (planet, spec. region)
  - generalized planetary model ⇨ **consistency!**

Background

- triggered by ESA project *"Microwave propagation toolbox for planetary atmospheres"*
  - Earth, Venus, Mars, Jupiter
  - frequencies <3THz
  - propagation modeling (passive+active) + data
- our solution approach: **revise & generalize ARTS**

Planet adaptations – What and why?

- common implicit assumptions (strictly) valid for Earth only
  - air = 79% N_2 + 21% O_2
  - parameters expressed in terms of (ambient) **total** pressure
- remove assumptions:
  - apply actual atmospheric composition
- allow to use and set planetary parameters for currently considered planet
- extend data to cover planetary conditions, e.g., continua

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Planet Adaptations – Line absorption

- expressed in terms of **total** pressure:
  - foreign pressure broadening
  - pressure shift
- the common formulation:

$$\gamma_L = x_{\mathrm{self}}\, p\, \mathrm{SGAM} \left(\frac{\mathrm{T\_GAM}}{T}\right)^{\mathrm{NSELF}} + (1 - x_{\mathrm{self}})\, p\, \mathrm{AGAM} \left(\frac{\mathrm{T\_GAM}}{T}\right)^{\mathrm{NAIR}}$$

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⇨ replace by formulation in terms of species-specific contributions

Planet Adaptations – Line absorption

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- the revised formulation:

$$\gamma_L = x_{\text{self}}\, p\, \text{SGAM} \left(\frac{\text{T\_I0}}{T}\right)^{\text{NSELF}} + (1 - x_{\text{self}})\, p\, \frac{\boxed{\sum_i \left[x_i\, \text{GAMMA}_i \left(\frac{\text{T\_I0}}{T}\right)^{\text{N}_i}\right]}}{\sum_i x_i}$$

Planet Adaptations – Line absorption

- some practical (implementation) issues
  - species-specific broadening/shift contributions implemented for limited set of species
  - model atmosphere allows total VMR<1

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⇨ rescale foreign broadening such that $VMR_{total(broad.spec.).}=1$

$$\gamma_{foreign} = (1 - VMR_{self})\, p \cdot \sum_{i=broad.spec.} \gamma_i \Big/ \sum VMR_i$$

- ensures consistency with "classical" approach

Planet Adaptations – Line absorption

- from the user side:
  - nothing specific to do by the user ☺
  - applied approach is determined by format of applied line catalogue (or the individual line record!)
  - classical and new approach can be applied in parallel
  - line catalogue files carry format tag
  - reading routine is adaptive

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```
<?xml version="1.0"?>
<arts format="ascii" version="1">
<ArrayOfLineRecord version="ARTSCAT-3" nelem="1">
@ O-6 2060067944638.33 0 2.87793884119732e-16 296
</ArrayOfLineRecord>
</arts>
```

```
<?xml version="1.0"?>
<arts format="ascii" version="1">
<ArrayOfLineRecord version="ARTSCAT-4" nelem="3">
@   HF-19     1232476234457.38 0.29624E-11 296   0.0
@   HF-19     2370935635414.22 0.76459E-19 296   0.7
@   HF-19     2463428114203.56 0.17631E-10 296   0.8
</ArrayOfLineRecord>
</arts>
```

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Planet Adaptations – Line catalogue

- generalized line modeling requires
  - extended set of spectroscopic parameters
  - revised line catalogue format
  - newly compiled line catalogue
    - here: for f<3THz, from literature
    - in future: extended-database-HITRAN

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Planet Adaptations – Catalogue format

- old format (ARTSCAT-3):
  - similar to HITRAN, but less restricted format

Col	Variable	Label	Unit
0	'@'	ENTRY	-
1	molecule & isotopologue tag	NAME	-
2	center frequency	F	Hz
3	pressure shift of F	PSF	Hz/Pa
4	line intensity per molecule	I0	m^2/Hz
5	reference temp. for I0	T_I0	K
6	lower state energy	ELOW	J
7	air broadened width	AGAM	Hz/Pa
8	self broadened width	SGAM	Hz/Pa
9	AGAM temp. exponent	NAIR	-
10	SGAM temp. exponent	NSELF	-
11	ref. temp. for AGAM, SGAM	T_GAM	K
12	number of aux. parameters	N_AUX	-
13	auxiliary parameter	AUX1	-
14	...		
15	error for F	DF	Hz
16	error for I0	DI0	%
17	error for AGAM	DAGAM	%
18	error for SGAM	DSGAM	%
19	error for NAIR	DNAIR	%
20	error for NSELF	DNSELF	%
21	error for PSF	DPSF	%

Planet Adaptations – Catalogue format

- planet generalized format(ARTSCAT-4):
  - needs to hold further parameters (species-specific broadening & shift information)

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3	line intensity	I0	Hz*m^2
4	reference temperature	T_I0	K
5	lower state energy	ELOW	J
6	Einstein A-coefficient	A	1/s
7	Upper state stat. weight	G_upper	-
8	Lower state stat. weight	G_lower	-
9	broadening parameter self	SGAM	Hz/Pa
10	broadening parameter N2	GAMMA_N2	Hz/Pa
11	broadening parameter O2	GAMMA_O2	Hz/Pa
12	broadening parameter H2O	GAMMA_H2O	Hz/Pa
13	broadening parameter CO2	GAMMA_CO2	Hz/Pa
14	broadening parameter H2	GAMMA_H2	Hz/Pa
15	broadening parameter He	GAMMA_He	Hz/Pa
16	GAM temp. exponent self	NSELF	-
17	GAM temp. exponent N2	N_N2	-
18	GAM temp. exponent O2	N_O2	-
19	GAM temp. exponent H2O	N_H2O	-
20	GAM temp. exponent CO2	N_CO2	-
21	GAM temp. exponent H2	N_H2	-
22	GAM temp. exponent He	N_He	-
23	F pressure shift N2	DELTA_N2	Hz/Pa
24	F pressure shift O2	DELTA_O2	Hz/Pa
25	F pressure shift H2O	DELTA_H2O	Hz/Pa
26	F pressure shift CO2	DELTA_CO2	Hz/Pa
27	F pressure shift H2	DELTA_H2	Hz/Pa
28	F pressure shift He	DELTA_He	Hz/Pa
29	Vib. & rotational assignments	VRA	-

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Planet Adaptations – Refractivity

- neutral gaseous atmosphere
  - commonly parametrized in terms of total pressure, e.g.

$$(n - 1) \times 10^6 = N = 77.6(P_a/T)Z_a^{-1} +$$

(Thayer74)

  - now: treat each species as separate contributor

- additionally: free electron contribution

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$$N = N_{\mathrm{ref},1}\frac{n_1}{n_{\mathrm{ref},1}} + N_{\mathrm{ref},2}\frac{n_2}{n_{\mathrm{ref},2}} + \cdots = \frac{273.15\,\mathrm{K}}{760\,\mathrm{Torr}}\left[N_{\mathrm{ref},1}\frac{p_1}{T} + N_{\mathrm{ref},2}\frac{p_2}{T} + \cdots\right]$$

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Planet Adaptations – Refractivity

- from the user side:
  - different approaches implemented as workspace methods
  - air refractive index provided by an agenda, used defines which methods/settings to apply:
  - pre-defined agendas provided (in agendas.arts), user just needs to copy the desired one.

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```
###
# Combination of Thayer + free electrons. OK for Earth and microwave.
#
AgendaSet( refr_index_air_agenda ){
  NumericSet( refr_index_air, 1.0 )
  NumericSet( refr_index_air_group, 1.0 )
  refr_index_airThayer
  refr_index_airFreeElectrons
}
```

```
###
# combined refraction from gases (Newell&Baird) and free electrons
# valid for arbitrary planetary atmospheres in microwave
#
AgendaSet( refr_index_air_agenda ){
  NumericSet( refr_index_air, 1.0 )
  NumericSet( refr_index_air_group, 1.0 )
  refr_index_airMWgeneral
  refr_index_airFreeElectrons
}
```

```
###
# no refraction (n==1.0)
#
AgendaSet( refr_index_air_agenda ){
  Ignore( f_grid )
  Ignore( rtp_pressure )
  Ignore( rtp_temperature )
  Ignore( rtp_vmr )
  NumericSet( refr_index_air, 1.0 )
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- set of isotopologue ratios “in code” as part of species definitions
  - required as HITRAN line strengths are scaled with isotopologue ratio
  - “in code” from HITRAN (where available), i.e., reflecting Earth conditions

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- now: user-accessible variable holding the isotopologue ratios to be applied in RT
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  - can be read from file (⇨ planets)

- files with isotopologue ratio data for each planet are part of the toolbox data package
- from modified D/H (all) and 15N/14N (Mars, Jupiter); others (13C/12C, 18O/16O, 17O/16O) within 5% of Earth

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<?xml version="1.0"?>
<arts format="ascii" version="1">
<SpeciesAuxData version="1" nelem="204" nparam="1">
@ H2O-161 0.997572947934
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@ H2O-171 0.000372095461312
@ H2O-162 5.23649842028e-05
@ H2O-182 1.05002501676e-07
@ H2O-172 1.95261577018e-08
@ H2O-262 6.37002016557e-10
@ H2O-SelfContStandardType nan
@ H2O-ForeignContStandardType nan
@ H2O-ForeignContMaTippingType nan
@ H2O-ContMPM93 nan
@ H2O-SelfContCKDMT100 nan
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Planet Adaptations – CIA

- ARTS offers plenty of continuum models
- for Earth, though (either empirical models or pressure parametrised with fix-air assumption)

- atm. conditions are different on other planets
  - incl. Venus and Jupiter with high pressures
- (completely) different species have significant continuum absorption

⇨ implemented new continua
  - namely HITRAN CIA data

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ARTS The Atmospheric Radiative Transfer Simulator

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Planet Adaptations – CIA

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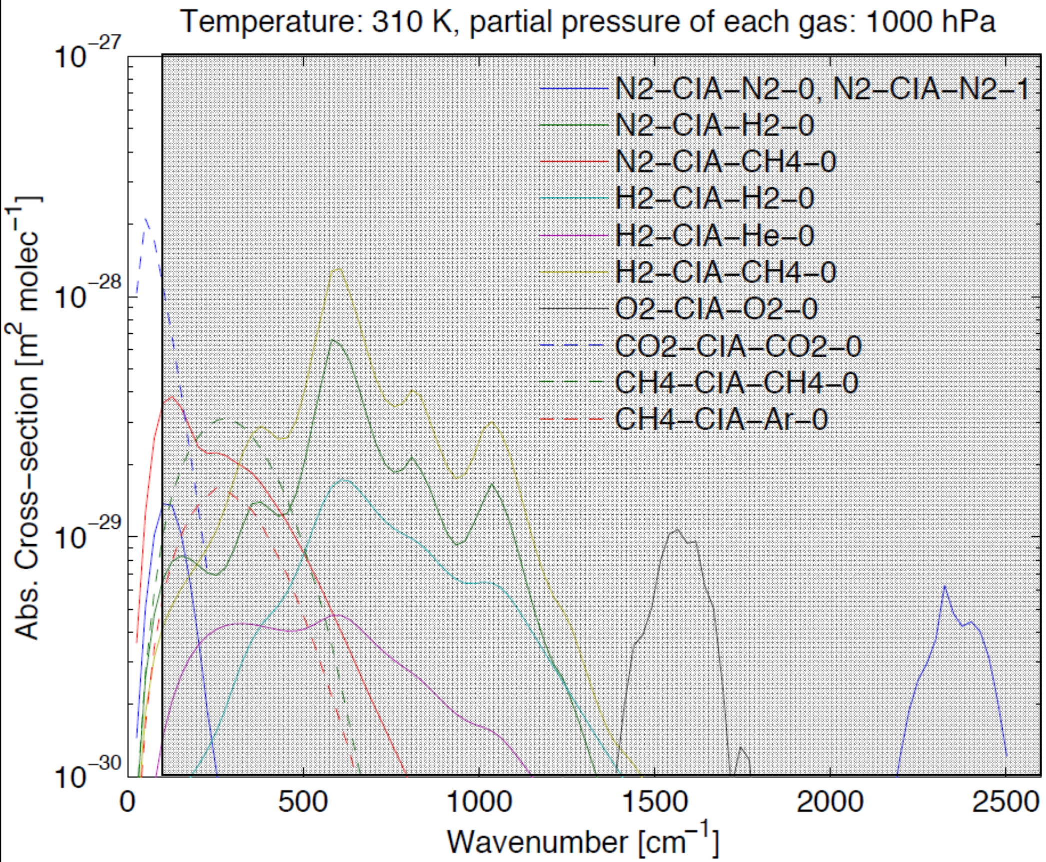
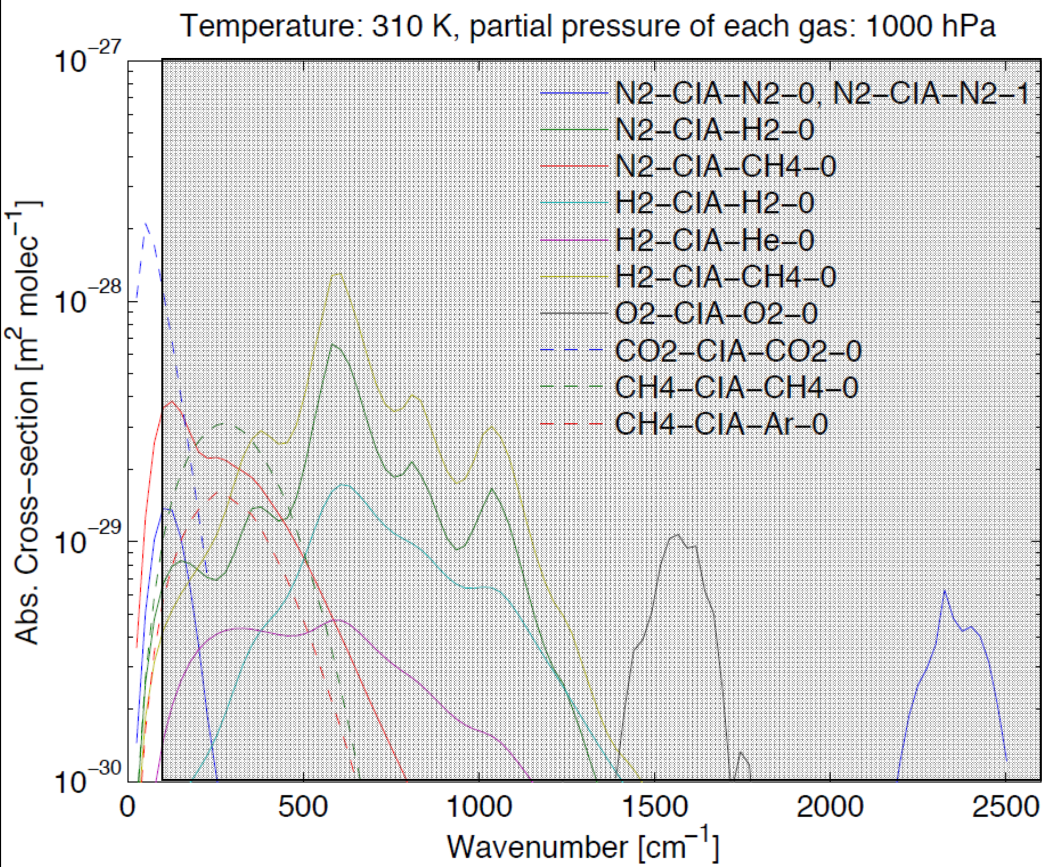
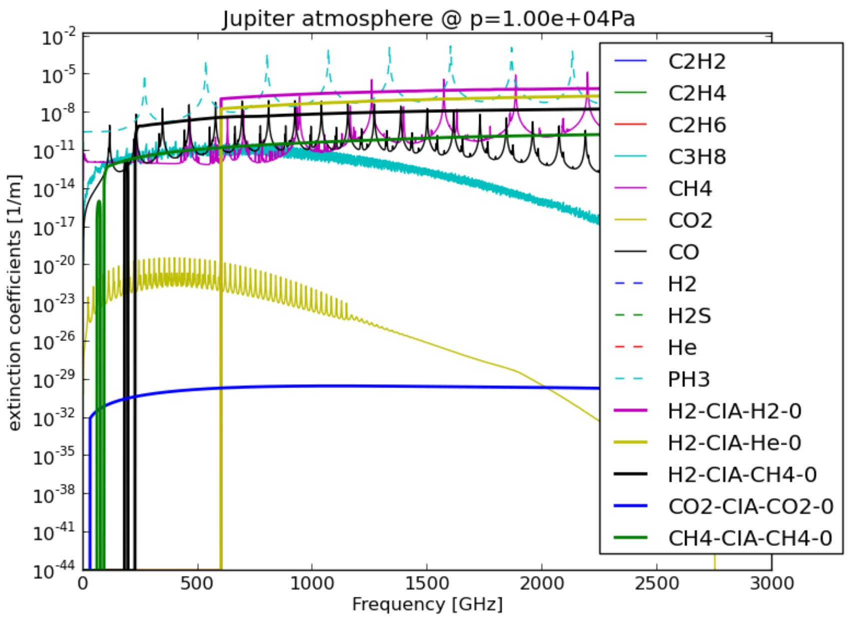


Planet Adaptations – CIA

- ⇨ implemented HITRAN CIA data
- other planets ⇨ other significant continuum species





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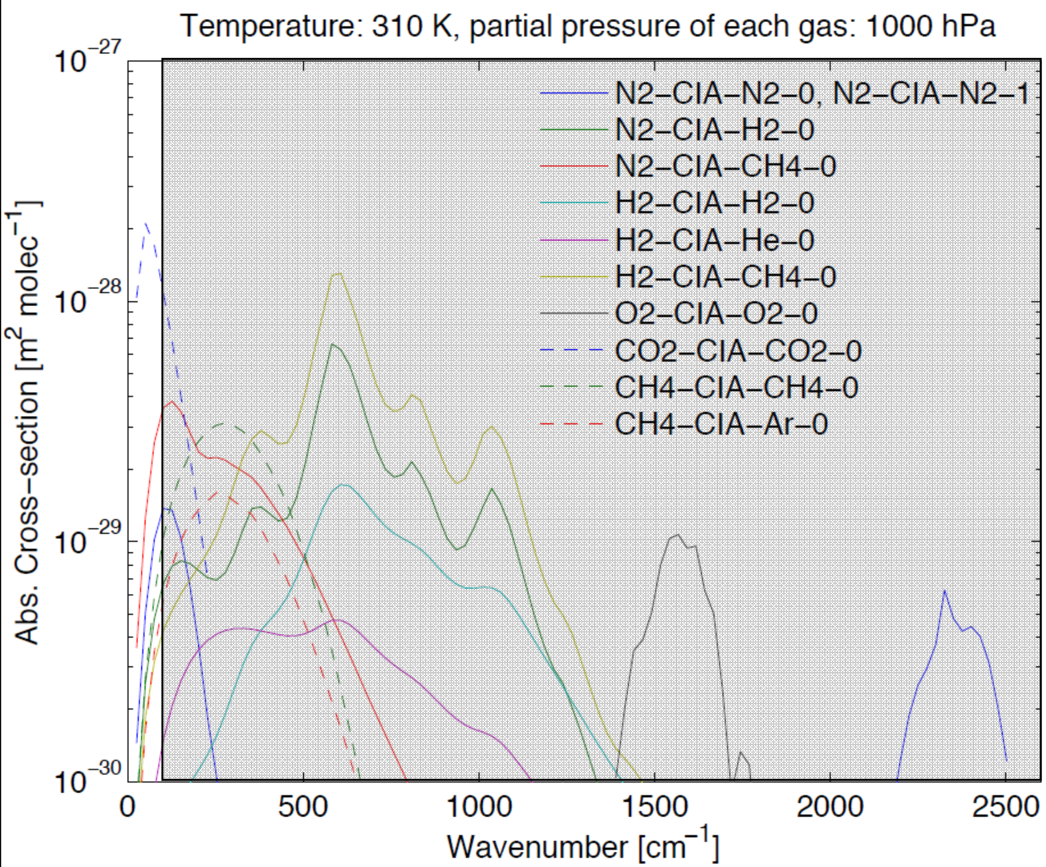

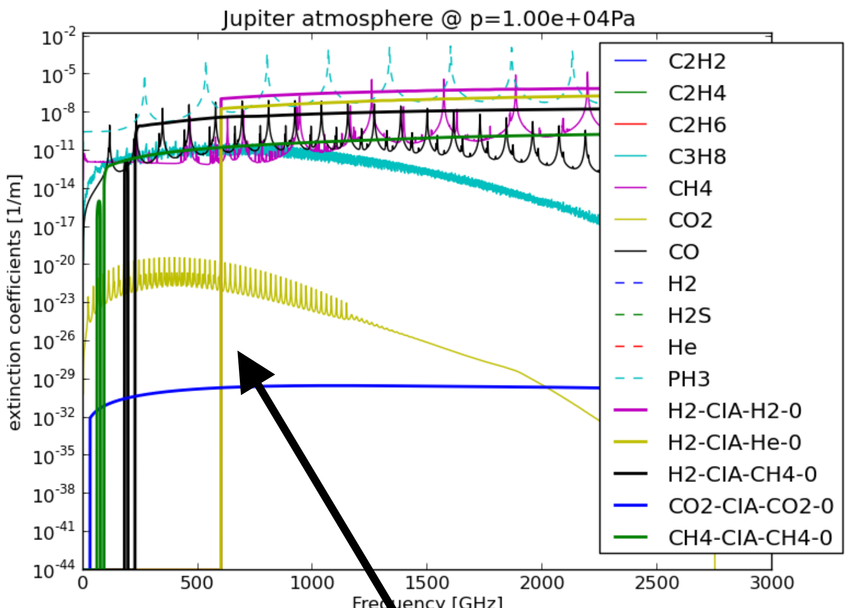

some data gap issues

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Adaptations – Basic planet parameters

- planet size and shape
- sidereal rotation period
- molar mass of dry air
- gravity constant

Adaptations – Basic planet parameters

- planet size/shape:
  - set manually from “basic” workspace method:

    `refellipsoidSet( refellipsoid, re, e )`

  - set by planet-specific workspace methods (“model” choices: sphere or ellipsoid):

    `refellipsoidMars( refellipsoid, model )`

Adaptations – Basic planet parameters

- explicitly manually set numeric:
  - sidereal rotation period
  - molar mass of dry air

- gravity constant
  - set by agenda (**`g0_agenda`**)
    - apply planet-specific workspace methods:

      `g0Mars( g0 )`
    - alternatively, set numeric manually

Adaptations – Basic planet parameters

- as support for the user, include file for each planet provided
  - **`controlfiles/general/planet_XXX.arts`**

- performing the settings for:
  - isotopologue ratios
  - reference ellipsoid (only as sphere, though!)
  - gravity
  - sidereal rotation period
  - molar mass of dry air

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New features

- active measurement techniques
  - radio link budgets, radio occultation
  - transmitter-receiver-path ray tracing
- Doppler shifts
  - wind, planet rotation, (sensor movement)
- polarized gas absorption
  - Zeeman splitting, Faraday rotation
- extended atmospheric characterization
  - magnetic field, electron density, wind
- Dispersion
- n^2-law of radiance
- auxiliary output

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New features – atmosphere

- new absorption species **`free_electrons`**
- electron density as **`vrm_field`** entry
- grid conversion by **`AtmFieldsCalc`**

- additional workspace variables
  - **`wind_u/v/w_field`**
  - **`mag_u/v/w_field`**
- explicit grid conversion of raw data required:
  `GriddedFieldPRegrid`,
  `GriddedFieldLatLonRegrid`

New features – Doppler

- wind Doppler
  - no user action required
  - considered when any of **`wind_u/v/w_field`** non-zero
  - horizontal winds (**`v/u`**) require 2D/3D
- planet rotation
  - modelled as pseudo-wind
  - via WSM **`wind_u_fieldIncludePlanetRotation`**
- wind Jacobians possible

New features – Faraday

- via WSM **`propmat_clearskyAddFaraday`**
  - e.g. as part of **`propmat_clearsky_agenda`**

- requires
  - absorption species **`free_electrons`**
  - **`mag_u/v/w_field`** being non-zero

New features – transmitter-receiver

- required for active meas. techniques
- direct path (!)

- specified by position
  - transmitter (**`transmitter_pos`**/**`rte_pos2`**)

  AND
  - receiver (**`sensor_pos`**/**`rte_pos`**)

- performed by applying **`ppathFromRtePos2`** in **`ppath_agenda`**

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New features – Auxiliary output

- intermediate variables that are usually not accessible on ARTS controlfile level, e.g.
  - along-LOS parameters: (per-species) absorption, T, iy
  - derived parameters: optical depth

- different per applied RT method
  - **`iyCalc`** or **`yCalc`** (no LOS decomp)
  - **`iy_main_agenda`** method (see built-in doc)

- output format: **`ArrayOfTensor4/Vector`**
- selected via **`iy_aux_vars`** (array of string identifiers)

New features – n^2-law

- implicitly handled by **`iyEmissionStandard`**

- no issue if
  - sensor in space (vacuum)
  - $n_{sensor} \approx 1$
  - output as Tb

- else: manual n^2 scaling by user required

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New features – Dispersion

- usually, all frequencies in parallel on identical ray path (no dispersion)

- to consider dispersion:
  - set **`iy_main_agenda`** as
    - **`AgendaSet( iy_main_agenda ){ iyLoopFrequencies}`**
  - set **`iy_sub_agenda`**
  - apply a dispersive refractive index
    - **`refr_index_airFreeElectrons`**

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Data collection

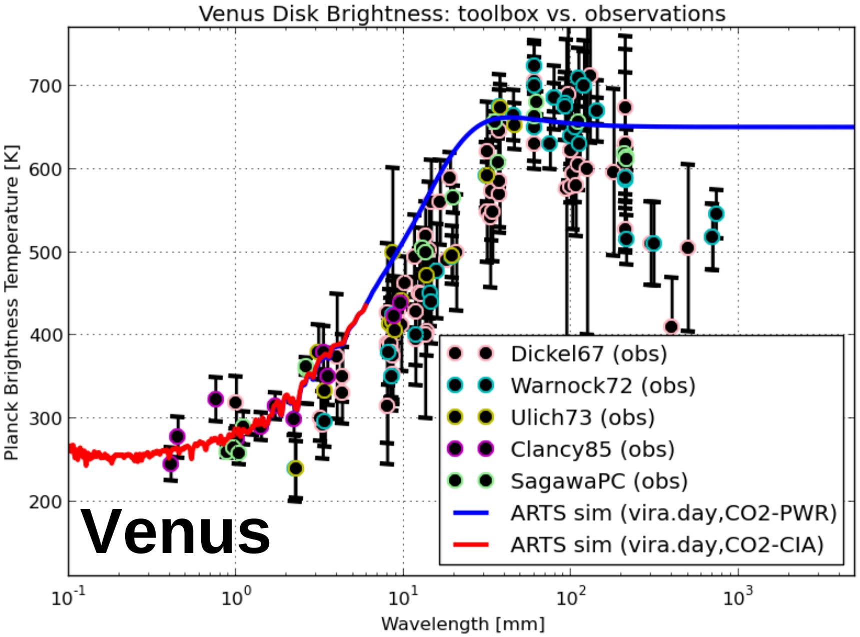
- in arts-xml-data package

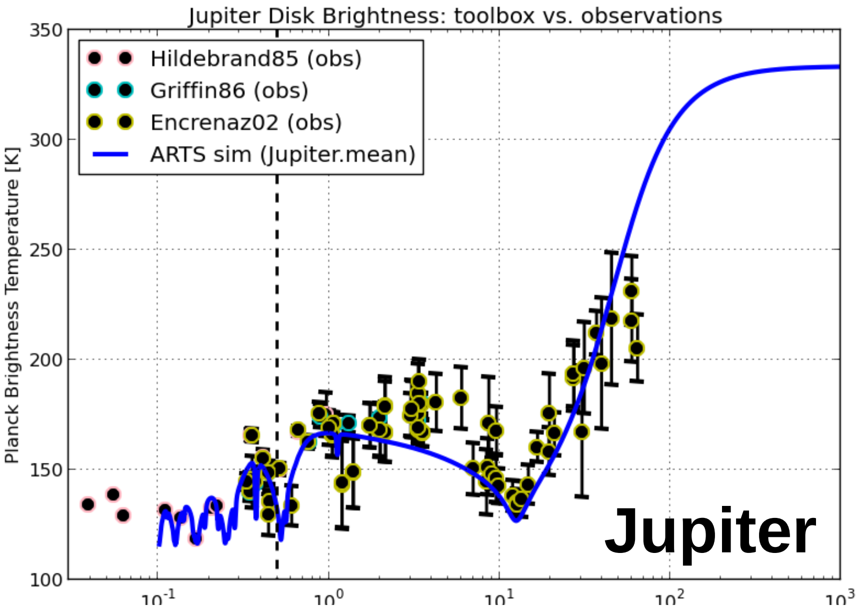
- spectroscopy
  - line catalogue, CIA data
- planet data
  - atmospheric scenarios: fields of z(p), T, VMRs, wind, N_e, B, clouds
  - surface data: e.g., T_{surf}, z_{surf}, n_{surf}
  - isotopologue ratios
- cloud optical properties

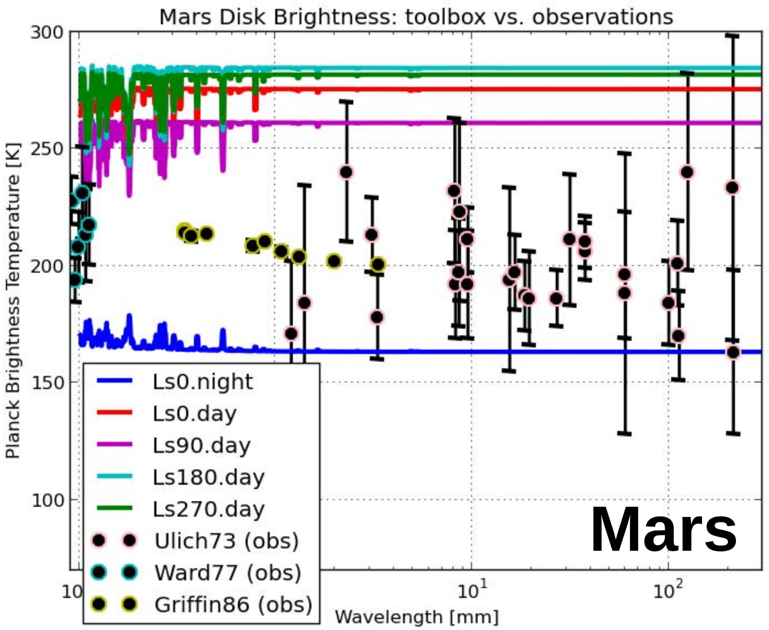
Demo cases

- in **`controlfiles/planetary_toolbox/`**
- template-like demos
  - easy to adapt (?)
  - setups reflect data available with toolbox

Results examples – Planet brightness







Summary

- ARTS revised for use with non-Earth planets
  - applying generalized approaches
  - some limitations apply
    - line data for f<3THz only
- extended modeling capabilities
- extended data collection

- all part of newly released ARTS 2.2