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

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This study was performed within an ESA-ESTEC study

Various research institutes have developed sophistical models to simulate radiative transfer and wave propagation.

Most of them are designed for rather narrow regions of the electromagnetic spectrum , for certain missions, for specific atmospheric conditions and/or for a specific planetary body, e.g., the Earth, certain planets etc.

Their demand in accuracy requires high sophistication.
So these codes **can be bulky**, **slow**, and **difficult to use**.

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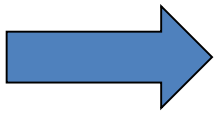
There is a need for having tools that can provide - with moderate to good accuracy - a quick estimation of the main microwave activity in the 0-3 THz.

The objective of this study was to design and build up a fast and easy-to-use propagation model available to ESA as an in-house tool supporting the definition of future missions for Earth (and/or) Mars, Venus or Jupiter.

ARTS-3
(**Earth** only)



ARTS-4 usable for **Earth (and/or) Mars, Venus or Jupiter** (in **a consistant way**)

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The ARTS-3 model (pre-planet)

- focus (but not exclusively limited):
  - mostly Earth atmosphere
  - environmental and climate related applications

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The ARTS model: Capabilities

State-of-the-art absorption model

Use the line-by-line catalogs (HITRAN, JPL, GEISA catalogs) and various continua and full absorption models)

Scattering (2 different methods available). Arbitrarily shaped, arbitrarily oriented (scattering) particles

Polarization (1-4 Stokes elements)

1D, 2D or 3D atmosphere. All observation geometries allowed

Analytical or semi-analytical Jacobians

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The ARTS model: Limitations

- no collimated beam source (solar source)
- no absorption models for UV/VIS
  - **microwave to thermal infrared only**

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Planet Adaptations – general considerations

	Venus	Earth	Mars	Jupiter
Main gases	CO_2 (96.5%) N_2 (3.5%)	N_2 (79%) O_2(21%) Water (tropo)	CO_2 (95.5%) N_2 (2.7%)	H_2 (86%) Helium (13.6%)

In ARTS-4:

Planetary "constants" (**planet size/shape**, **gravity constant**, …): **isotopologue ratios** are **user accessible variables**

For the **refractivity (particles)** , **line shape parameters (gases)** **each species** is treated as a **separate contributor**:

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Planet Adaptations –general considerations

ARTSCAT-3 → ARTSCAT-4

- 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 ARTSCAT-3** & the **new approach ARTSCAT-4** can be applied **in parallel**

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Planet Adaptations – Catalogue format

- applied approach determined by format of line catalogue
  - line catalogue files carry format tag
  - reading routine is adaptive

```
<?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>
```

classical ARTSCAT-3

```
<?xml version="1.0"?>
<arts format="ascii" version="1">
<ArrayOfLineRecord version="ARTSCAT-4" nelem="3">
@  HF-19     1232476234457.38 0.29624E-11 296  0.
@  HF-19     2370935635414.22 0.76459E-19 296  0.
@  HF-19     2463428114203.56 0.17631E-10 296  0.
</ArrayOfLineRecord>
</arts>
```

new approach ARTSCAT-4

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Planet Adaptations – Catalogue format

- **ARTSCAT-3**: Old format ⇔ for **Earth**….
  - similar to GEISA or HITRAN, but less restricted format

- **ARTSCAT-4**: (new format) planet generalised format for **Jupiter**, **Venus** , **Mars** (and **Earth**)

  Needs to hold further parameters (species-specific broadening & shift information)

- For gases (line by line) : pressure induced (**broadening** and **shift**) by :

N_2-, **O_2**-, **CO_2**-, **H_2O**-, **H_2**-, **Helium**- and **self**- are considered

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Molecules catalog for ARTSCAT-4

- Water ($H_2{}^{16}O$ and its associated other isotopic species)
- Methane (CH_4 and its associated other isotopic species)
- Carbon dioxide (CO_2)
- Carbon monoxide (CO)
- Formaldehyde (H_2CO)
- Hydrogen peroxide (H_2O_2)
- Hydroperoxyl radical (HO_2)
- Hydrogen chloride (HCl)
- Ozone (O_3)
- Hydrogen sulphide (H_2S)
- Carbonyl sulfide (OCS)
- Sulfur monoxide (SO)
- Sulfur dioxide (SO_2)
- Sulfuric acid (H_2SO_4)
- Molecular oxygen
- Ammonia (NH_3)
- Phosphine (PH_3)
- Propane (C_3H_8)

+ the remaining « usual » molecules (only) of Earth interest (ARTSCAT-3)

Several molecules of planetary interest (C_2H_4, C_2H_2 etc… do not have any MW signature)

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Line Catalogue

- Some examples…

Most of the time, informations on the pressure induced (**broadening** and **shift**) by **N_2**-, **O_2**-, **CO_2**-, **H_2O**-, **H_2**-, **Helium**-

…. are **missing** or concern just **several lines** in the whole 0-3 THz spectral region)

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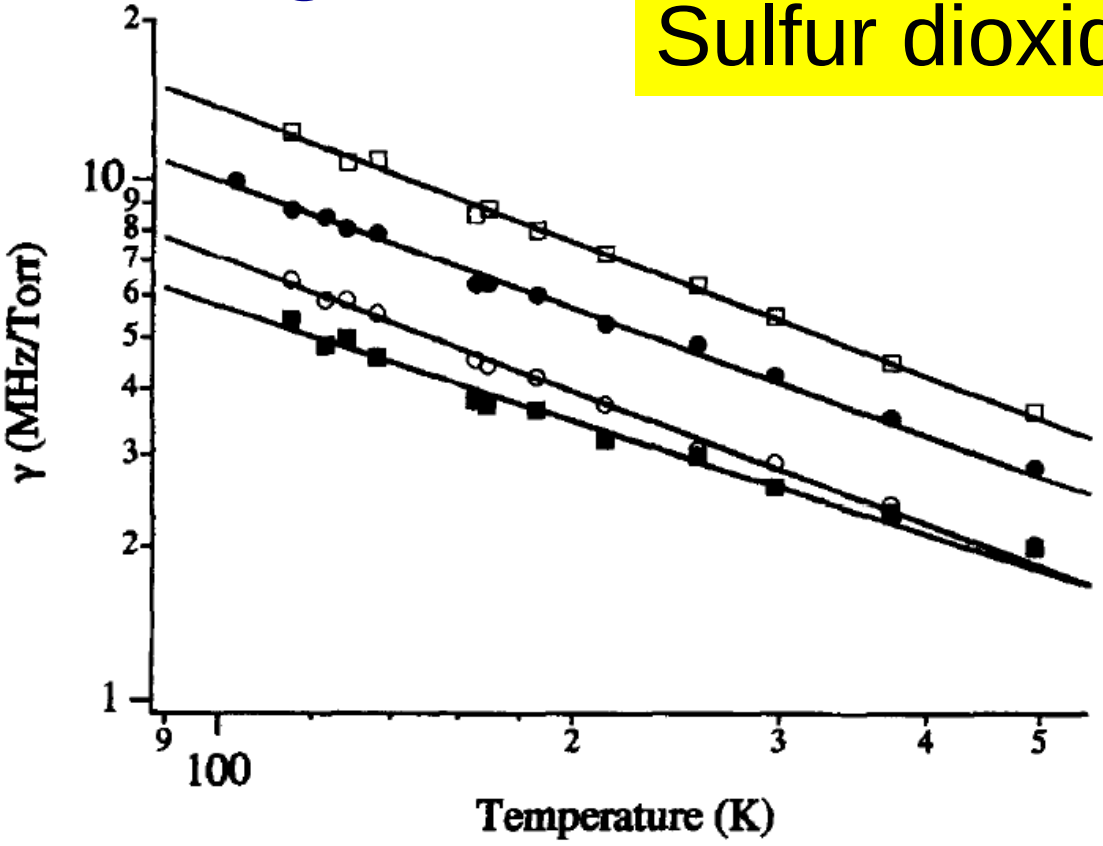
Line Catalogue

Sulfur dioxide (SO_2)



2. Measured N_2 (●), O_2 (○), He (■), and H_2 (□) pressure broadening parameters of the $18_{3,15}$–$18_{2,16}$ transition of SO_2 (logarithmic scale). (—) the result of a least-squares fit to Eq. (1).

Ball et al JQSRT 56, No. 1, pp. 109-117, 1996

Line shape parameters are available just for **several lines**…

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Line Catalogue

Ammonia (NH_3)

Several N_2, O_2 , H_2- and He- broadening parameters exist in the literature

¤Brown, L.R. and D.B.Perterson. An empirical expression for line widths of ammonia from far infrared measurements. J. Mol. Spectrosc. 168 pp 593-606 (1994).

¤S.Nouri, J.Orphal, H.Aroui, and J.M.Hartmann, Temperature dependence of pressure broadening of NH_3 perturbed by H_2 and N_2. J. Mol. Spectrosc. 227, pp60-66 (2004)

¤Pine, A.S.; Markov, V.N.; Buffa, G.; Tarrini, O. N_2, O_2, H_2, Ar and He broadening in the v_1 band of NH_3. JQSRT, 50, pp. 337-48 (1993).

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Line Catalogue

Hydrogen peroxide (H_2O_2): **line intensities**

Inconsistency of the H_2O_2 line intensities….

$$^{JPL}Int(296K) = 2 \times {}^{HITRAN}Int(296K)$$

- R.T. Clancy, B.J. Sandor, and G.H. Moriarty-Schieven. A measurement of the 362 GHz absorption line of **Mars** atmospheric **hydrogen peroxide** (**H_2O_2**). Icarus 168 (2004) 116–121 → **uses JPL**

- T. Encrenaz, T.K.Greathouse, F.Lefèvre, S.K.Atreya. **Hydrogen peroxide (H_2O_2)** on **Mars** Observations, interpretation and future plans. Planetary Space Science, (2011). → **Uses HITRAN**

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Line Catalogue

Water

For Water: two linelists exist in the literature for the γ_{CO2} and n_{CO2} line broadening parameters (Gamache et al 2011):

one prepared for **Mars**

the other one for **Venus** atmosphere:

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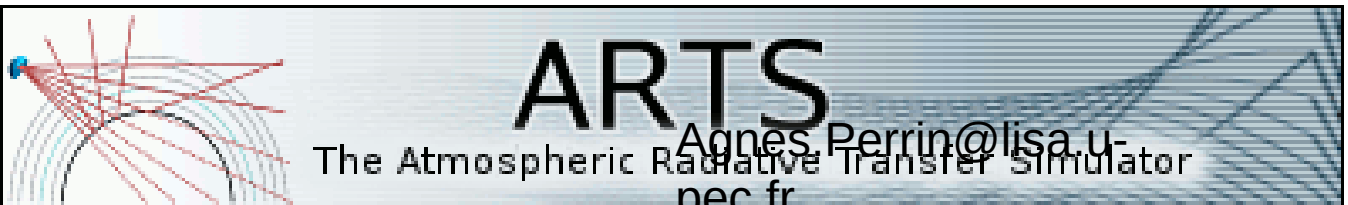
Gamache et al. Icarus 213 p720 (2011)
Brown et al. J. Mol. Spect 2007.



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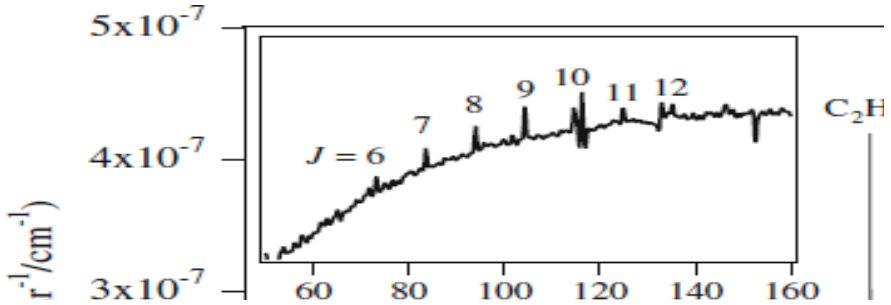
Methane (CH_4): lines
(V.Boudon)



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Planet Adaptations – CIA

- ARTS offers plenty of continuum models

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

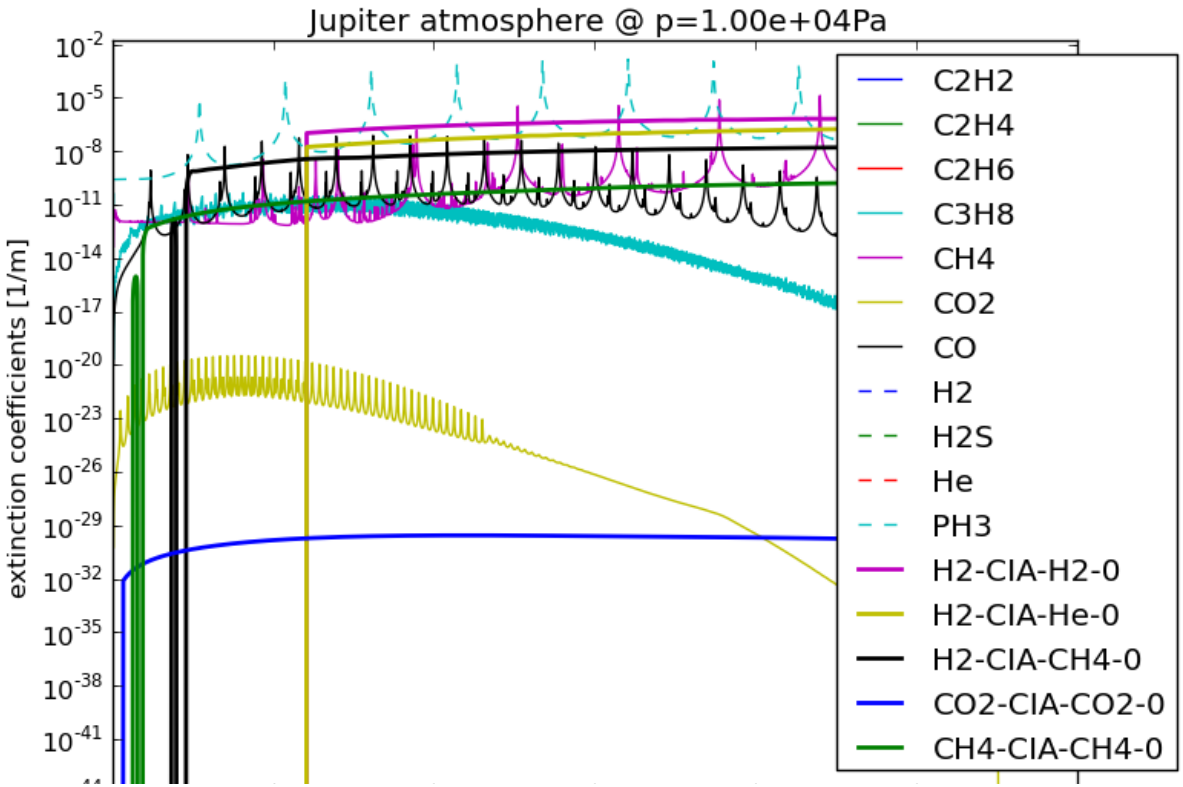
⇨implemented new continua

Planet Adaptations – CIA

(Richard et al. J.Q.S.R.T. 113, p1276 (2012)

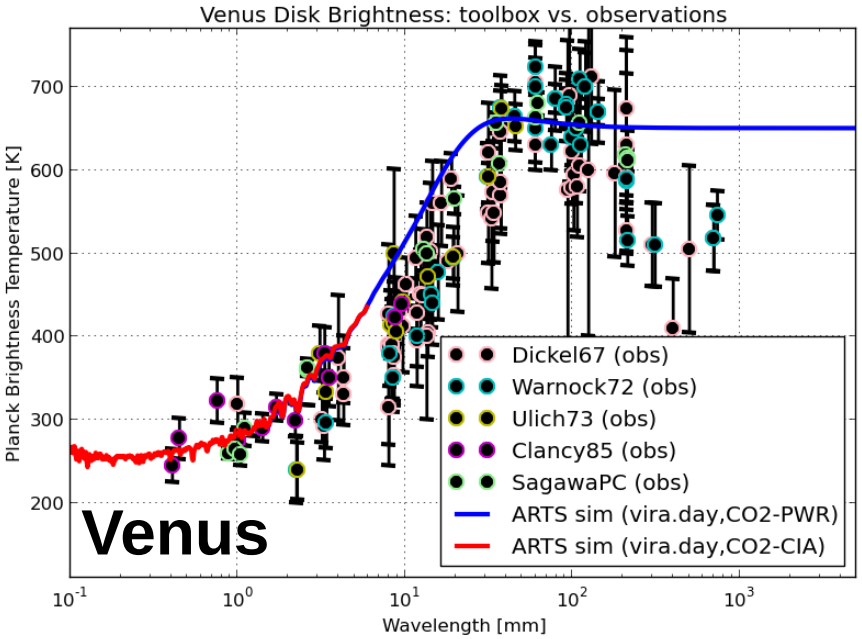
- Implemented **C**ollision **I**nduced **A**bsorption data

For each planet ⇔ different continua



Data are missing at low frequency (or are extrapolated from the infrared)

Results examples – Planet brightness



ARTS
The Atmospheric Radiative Transfer Simulator

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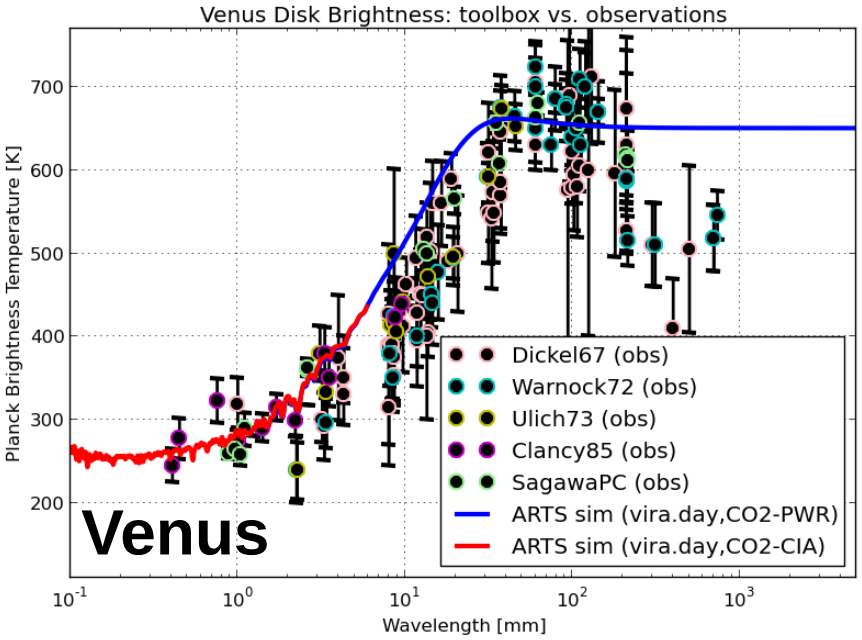
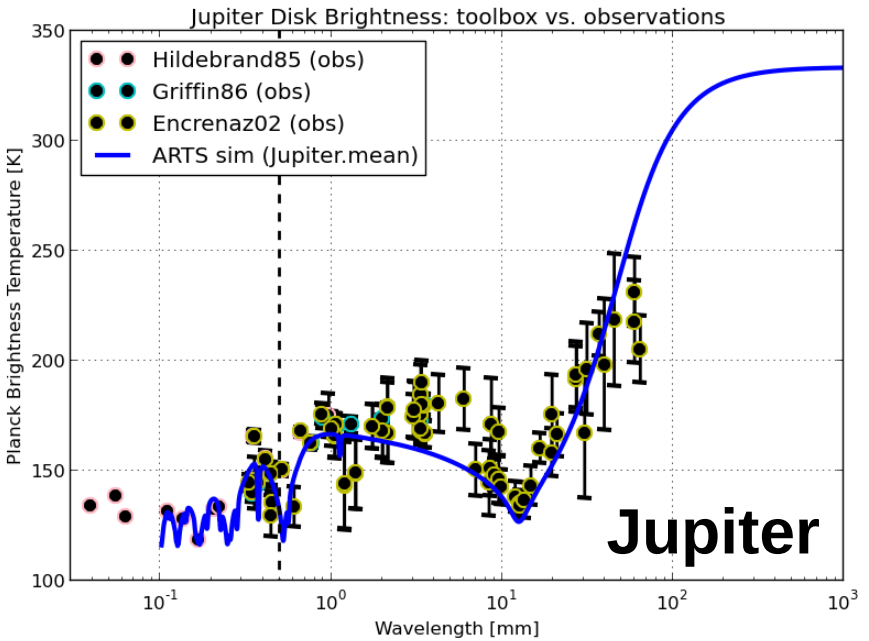
Results examples – Planet brightness





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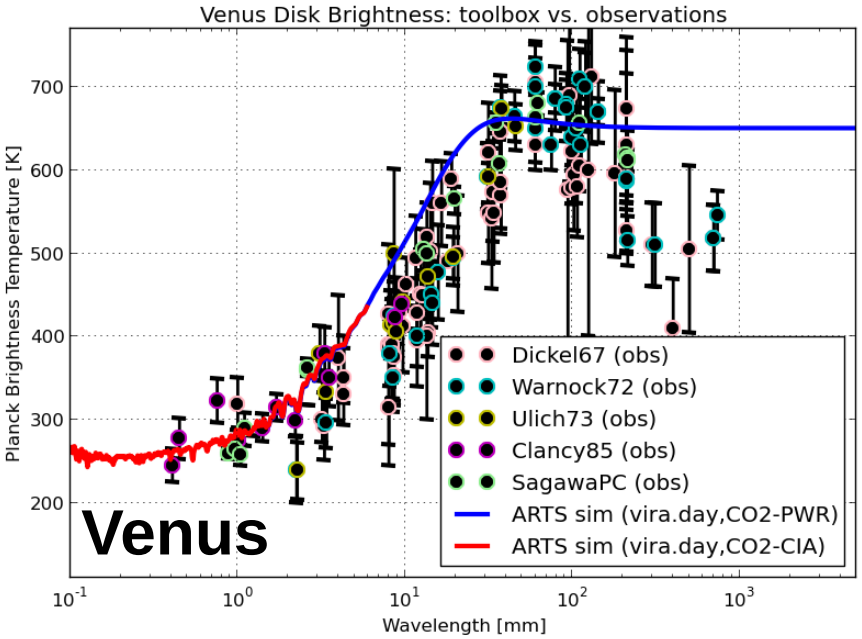
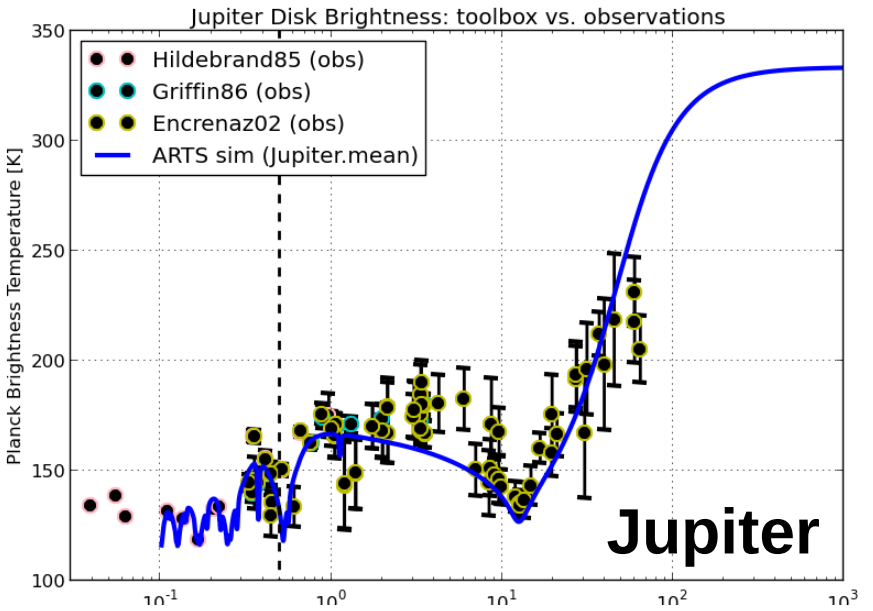
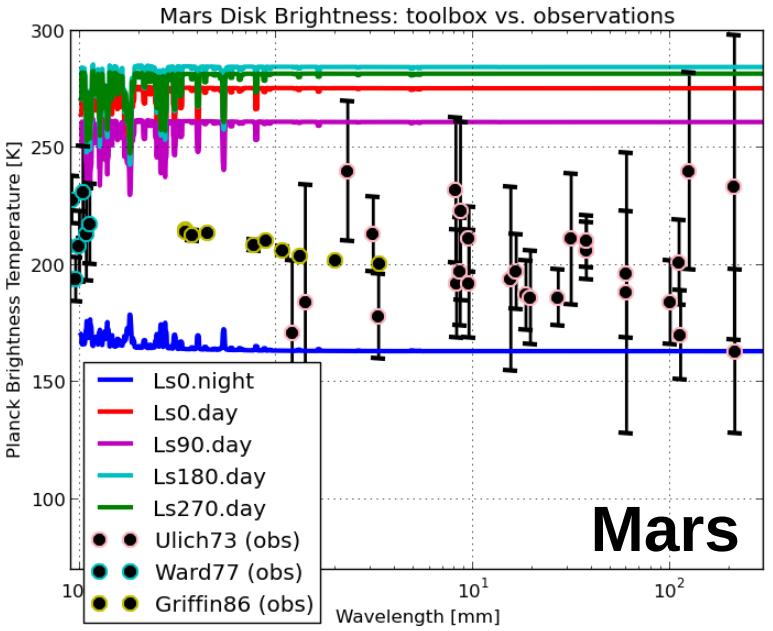
Results examples – Planet brightness







Summary

- ARTS revised for use with non-Earth planets
  - applying generalised approaches
  - major limitation from data availability
    - line data (compiled own catalogue for <3THz)

    ⇨reporting of species-specific broadening & shift parameters in line catalogues (**HITRAN)** is **highly desirable!**

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- ARTS 2.2 to be released June2014
  - planet generalised
  - extended features (wind, magnetic field & free electron effects; radio occultation & radio links, cloud radar)

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