Line profiles of water for the non-uniform density distribution in a cometary coma

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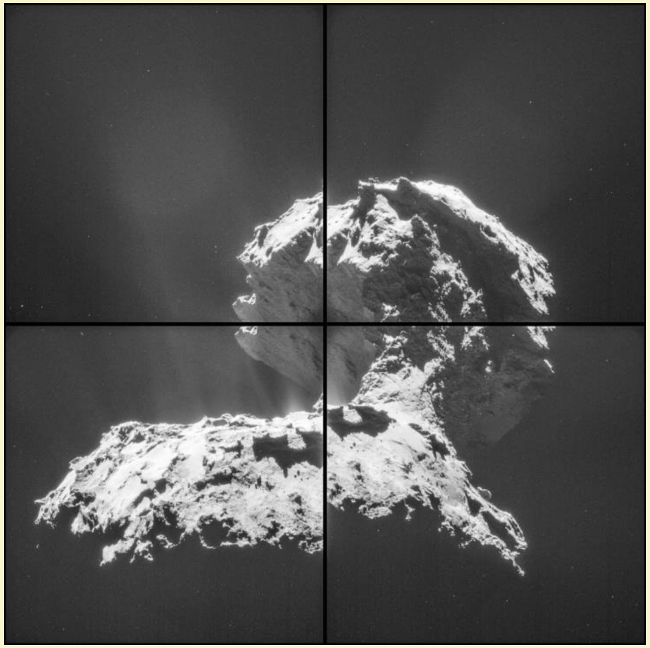
Zakopane, 12-15 May 2015

Comets

Cometary nucleus:

- **typical size ~ 1 – 10 km**
- **density is low ~250 – 600 kg/m^3, indicating that it is loosely bound icy material – high porosity**
- **very low albedo ~ 4%**
- **gas evaporating from the comet comes from active regions on only ~ 5-20% of the surface;**
  active regions – exposed or subsurface ices,
  rest of the surface is covered with a thick dust crust, through which gas cannot escape.
- **major volatiles components: water - dominant parent molecule (80%), carbon monoxide, carbon dioxide, methanol, formaldehyde, methane, ammonia, hydrogen sulfide, acetylene, ethane, hydrogen cyanide (easy detected).**

1P/Halley (Giotto 1986)
size: 15.3 × 7.3 × 7.2 km
$Q_{H2O} = 8 \cdot 10^{29}$ mol/s



Comet P/67 Churyumov-Gerasimenko dust and gas jets, 26 November 2014
Two active jet areas:
one narrow collimated group of jets to the upper left originating in the north polar area of the comet and another broad jet to the lower left arising in the large equatorial plain on the larger comet body.

Comets

Cometary activity depend on intrinsic composition of the nucleus and distance from the Sun.

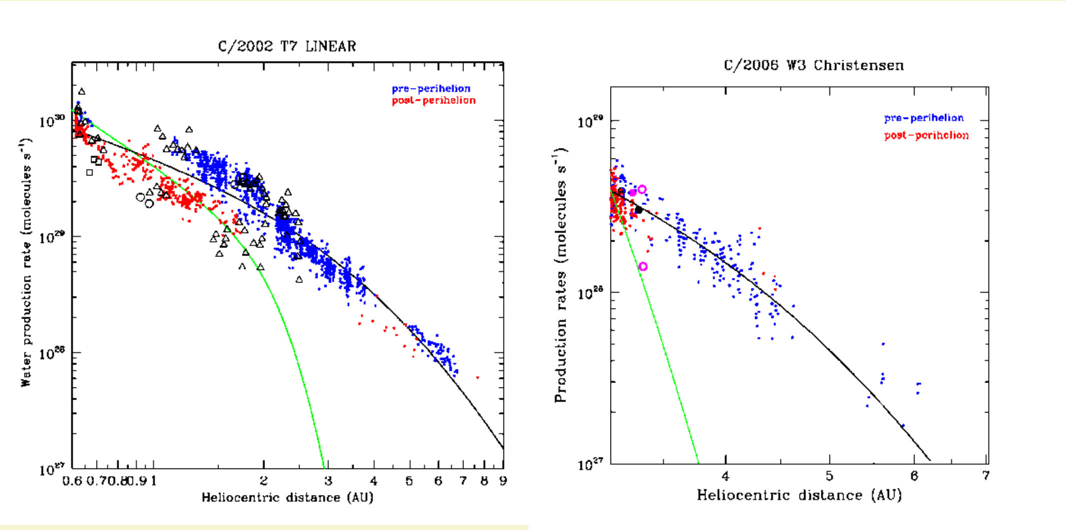
Solar heating →
sublimation of ices

Water begins to sublimate at about 3 AU.

Water production is estimated from the ground through products of photodissociation (OH radical), water high vibrational bands

First detections of water in comets from space:

- **bands of water:**
  ISO (0.6m; 1995-1998)
- **ground-state water line:**
  SWAS (0.7m; 1998-2005),
  Odin (1.1m; 2001-2006),
- **several rotational transitions:**
  Herschel (3.5m; 2009-2013)



Evolution of water production curves with heliocentric distance.

Small symbols denote values derived from heliocentric magnitudes. Big symbols represent measured production rate using different techniques

$Q_{H2O} = 5 \cdot 10^{28}\ s^{-1} = 1500\ kg\ s^{-1}$ (C/2006 W3 Christensen)

$Q_{H2O} = 8 \cdot 10^{29}\ s^{-1} = 24000\ kg\ s^{-1}$ (C/2002 T7 LINEAR)

Modelling of the radio line profile – physics of cometary coma

The line intensity depends on the spatial distribution of the molecules within the telescope beam and on their rotational excitation (population distribution):

- **in inner coma: collisional processes (with neutrals and electrons)**
- **in outer coma: fluorescent equilibrium governed by the Sun infrared radiation.**

The line profile depends on:

- **the molecular space density which is related to the outgassing pattern.**

In the standard models of isotropically expanding coma the density follows the standard Haser distribution.

Model

The proposed model is based on a non-uniform density distribution and the escape probability method for treating radiation transfer.

a) **The anisotropic component (jet) related to the discrete active area is accompanied by some uniform (isotropic) distribution of the material emitted from the dust covered - inactive parts of the nucleus or related to the distributed sources (icy grains). The gas density profile in the region of enhanced activity (jet) is described by a density function for emission into the cone. The temperature, the density and the expansion velocity outside the cone can differ from those within the cone.**

b) **The excitation model includes collisions with water and electrons, and infrared pumping. The equations of statistical equilibrium are solved in every cells of the coma with constant properties like density, temperature, and expansion velocity. In some directions two different parts of the coma (material inside the cone and outside it) can be radiatively coupled, it occurs when the material have the same projected velocity.**

Outgassing

The outgassing pattern assumes emission within and outside a cone. The density within the cone can be constant or vary as a function of the angle, θ, with respect to the outgassing axis. The outgassing is described by the density function:

$$\rho(\mathbf{r}, \theta) = \frac{\mathrm{Q}}{\mathrm{v} 4 \pi \mathrm{r}^2} \mathrm{e}^{-\mathrm{r}/\mathrm{v}\tau_1}\ \rho(\theta)$$

where v is v_{jet} or v_{iso} - the velocity emission within or outside a cone, r is the distance from the cometary nucleus, τ_l is the dissociation time for water molecule, Q is the production rate – number of molecules which are emitted from the nucleus per second.

Space density of molecules at any point at a distance r is described by:

$$\rho(\theta) \sim f(\theta)\, f$$

where f is contribution of the anisotropic or isotropic part in the total emission.

A numerical model for the simulation of water line emission o-H_2O (1_{10}–1_{01}) at 557 GHz in cometary coma

Model parameters :

Isotropic part:

gas temperature T = 20 K, gas expansion velocities: v_{exp}= 0.5 km s^{-1}

Anisotropic part:

gas temperature T = 30 K, gas expansion velocities: v_{exp}= 1 km s^{-1}

Density scaling factor for electrons: x_{ne}=0.15 (Biver et al. 2012)

Production rate : Q =10^{28} mol s^{-1}

Orientation of the rotation axis of the nucleus (rotation axis is perpendicular to the line of sight) : α_R =270°, δ_R = 90°

Location of the jet with respect to the rotation axis: colatitude β=0°

Heliocentric distance = 1 AU, Distance to the observer = 1 AU

Telescope beam= 38 arcsec (Herschel/HIFI beam at 557 GHz)

Spacing for maps= 16 arcsec

Considered models:

Model I (reference) – isotropic - uniform activity - $f(\theta)= 1$ for $0 < \theta < \pi$,

T=30 K, v = 1 km **s^{-1} or T= 20 K, v = 0.5 km s^{-1}**

Model A: $f_{jet}(\theta)= \cos^n(\theta)$

n=0.5, f_{jet} =1, 0.9, 0.8, 0.7

n=1., f_{jet} =1, 0.9, 0.8, 0.7

n=2., f_{jet} =1, 0.9, 0.8, 0.7

T_{jet}=30 K, v_{jet} = 1 km s^{-1}, T_{iso}= 20 K, v_{iso} = 0.5 km s^{-1}

Model B: $f_{jet}(\theta)= \cos^n(\theta)+1$

n=0.5, f_{jet} =1, 0.9, 0.8, 0.7

n=1., f_{jet} =1, 0.9, 0.8, 0.7

n=2., f_{jet} =1, 0.9, 0.8, 0.7

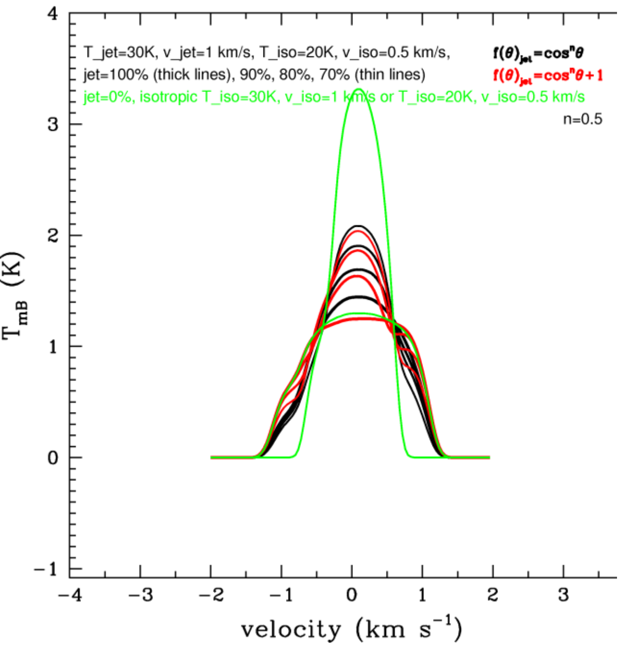
T_{jet}=30 K, v_{jet} = 1 km s^{-1}, T_{iso}= 20 K, v_{iso} = 0.5 km s^{-1}

Series of models with f_{jet} from 1 to 0.55 and with power law *n* from 0.3 to 2.

Simulated spectra for water at 557 GHz

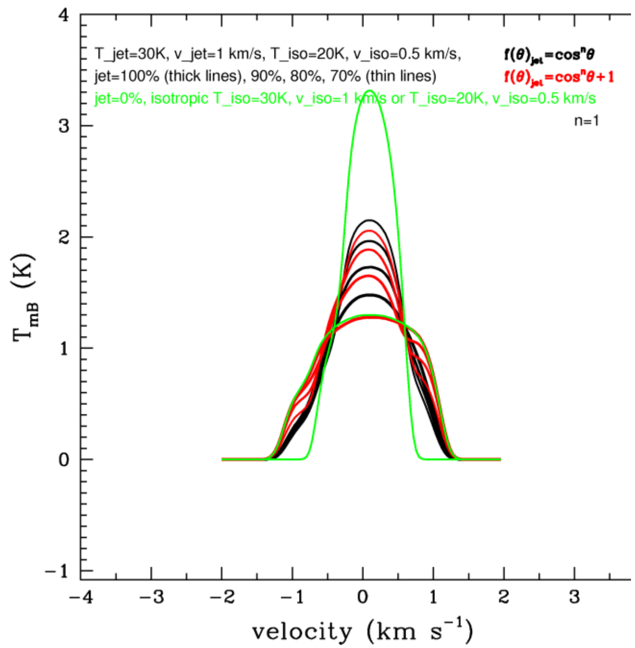
$f_{jet}(\theta) = \cos^{0.5}(\theta)$

$f_{jet}(\theta) = \cos^{0.5}(\theta)+1$



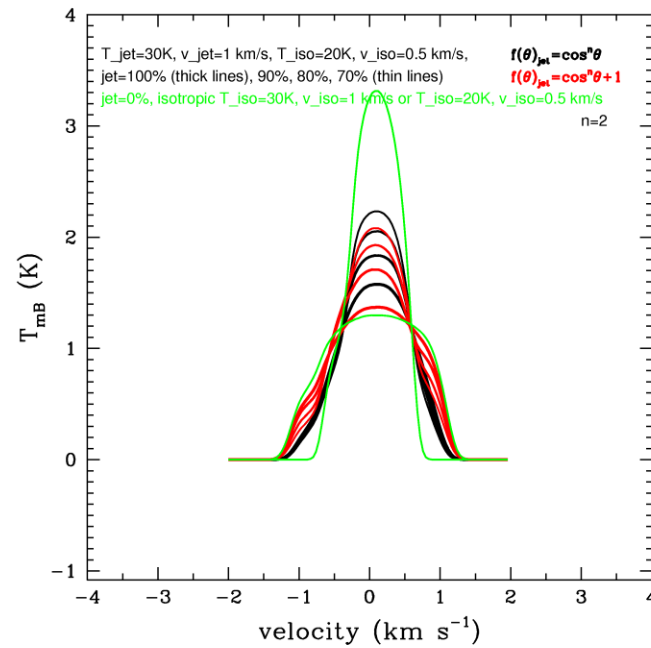
$f_{jet}(\theta) = \cos(\theta)$

$f_{jet}(\theta) = \cos(\theta)+1$

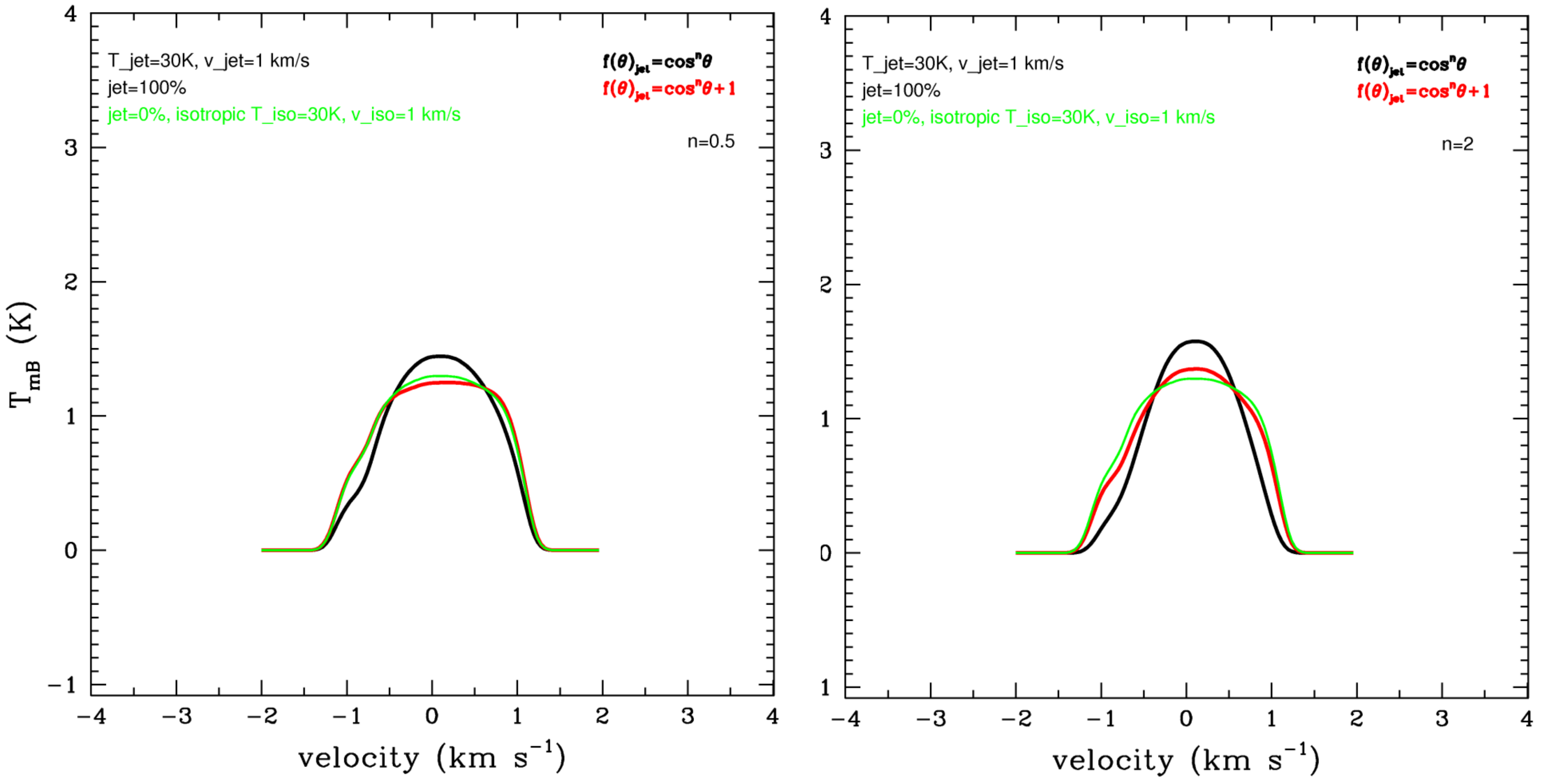


$f_{jet}(\theta) = \cos^{2}(\theta)$

$f_{jet}(\theta) = \cos^{2}(\theta)+1$



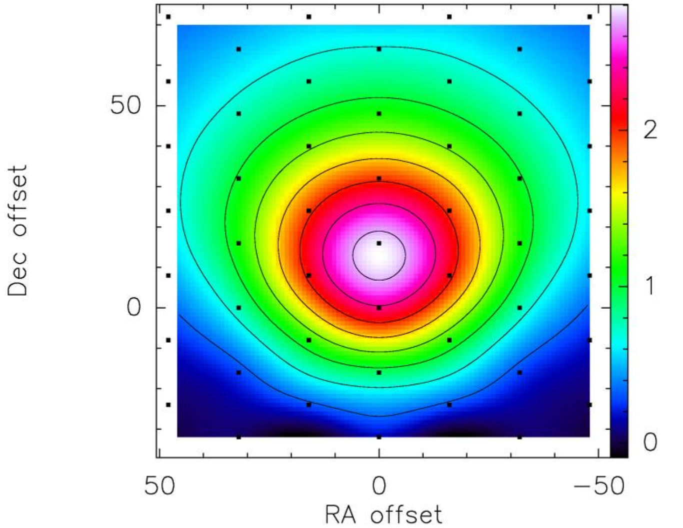
Simulated spectra for water at 557 GHz



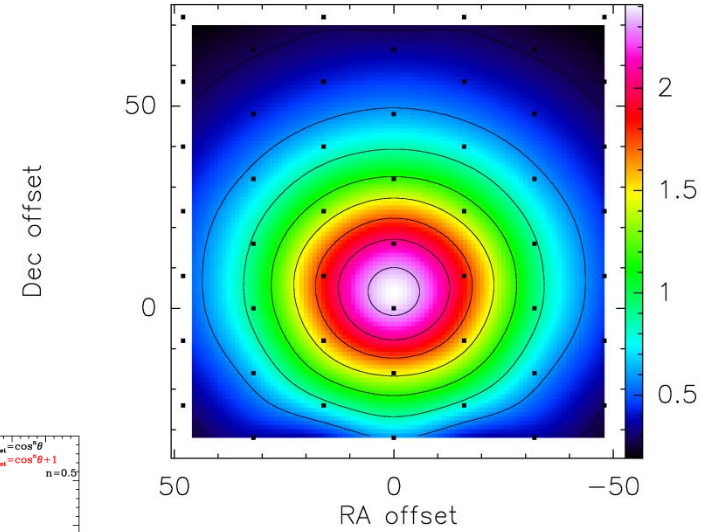
Simulated maps for water at 557 GHz

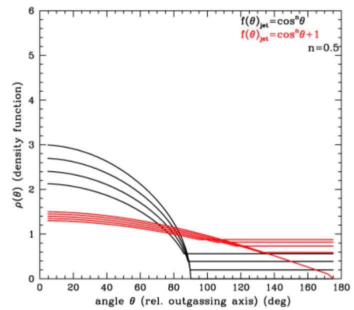
$\cos^{0.5}\theta$

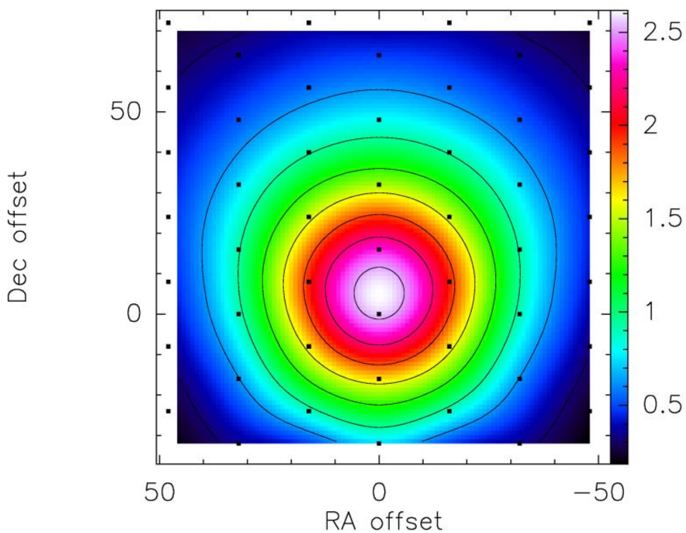
$\cos^{0.5}\theta + 1$



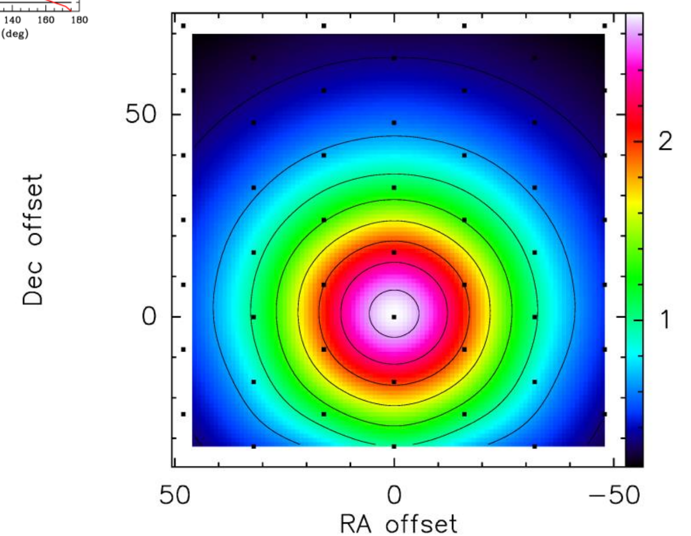
$f_{jet}=1$







$f_{jet}=0.7$

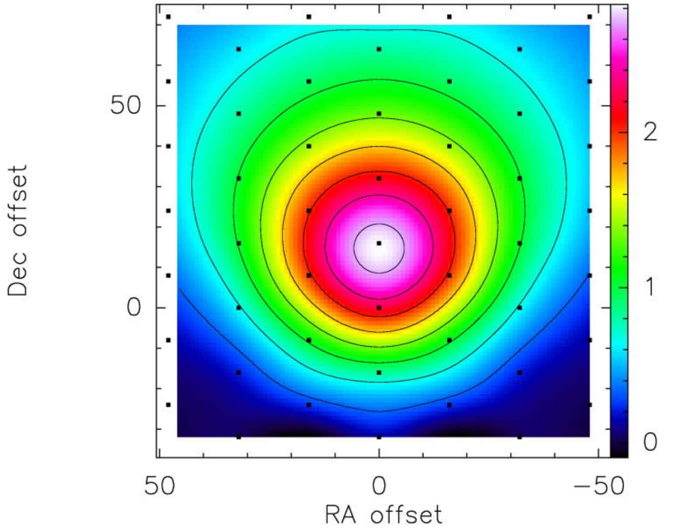


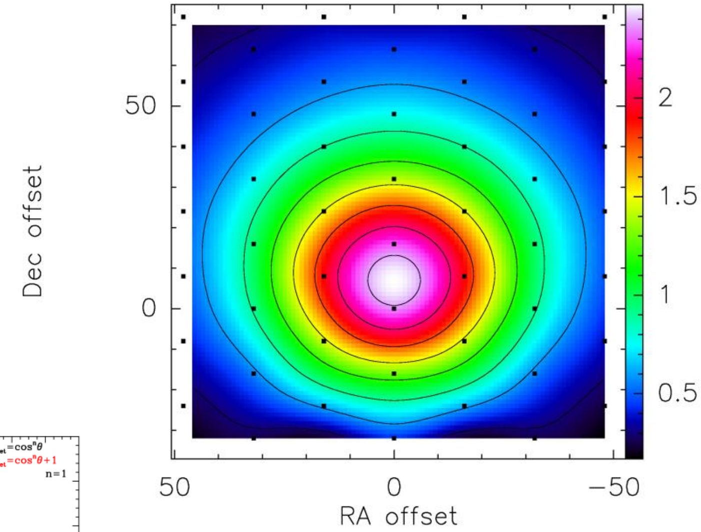
Simulated maps for water at 557 GHz

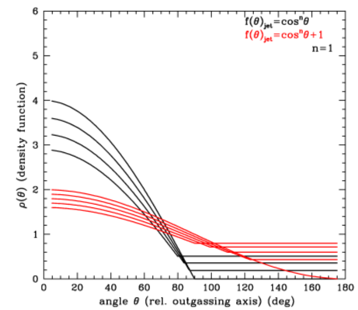
cosθ

cosθ+1

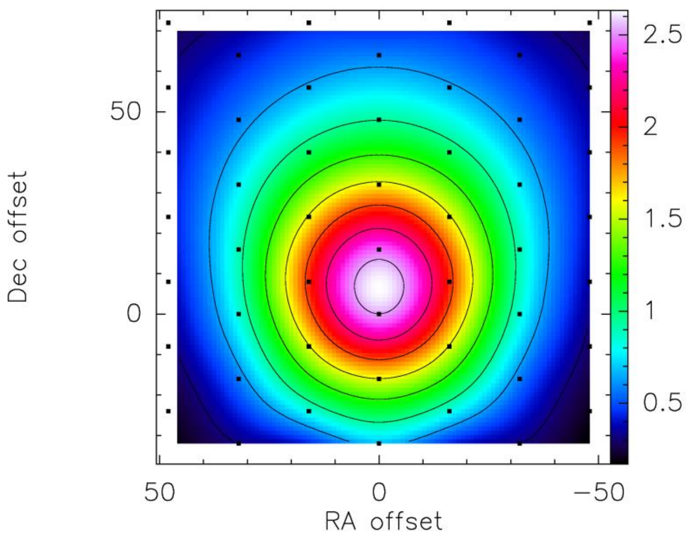
f_{jet}=1

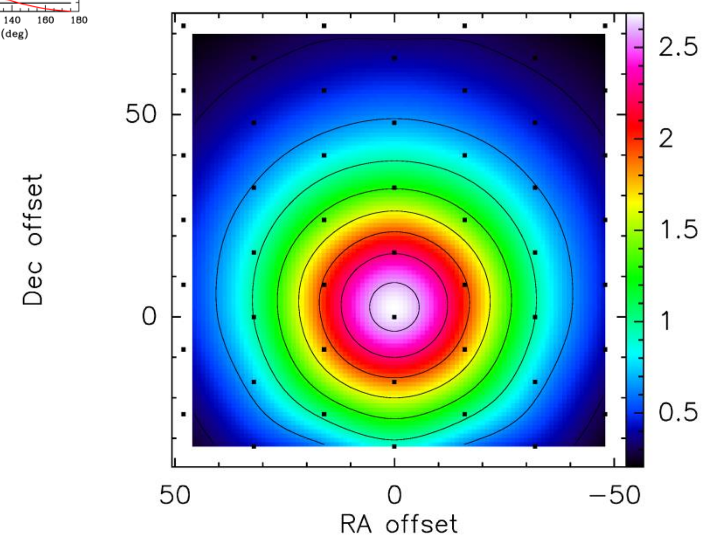






f_{jet}=0.7

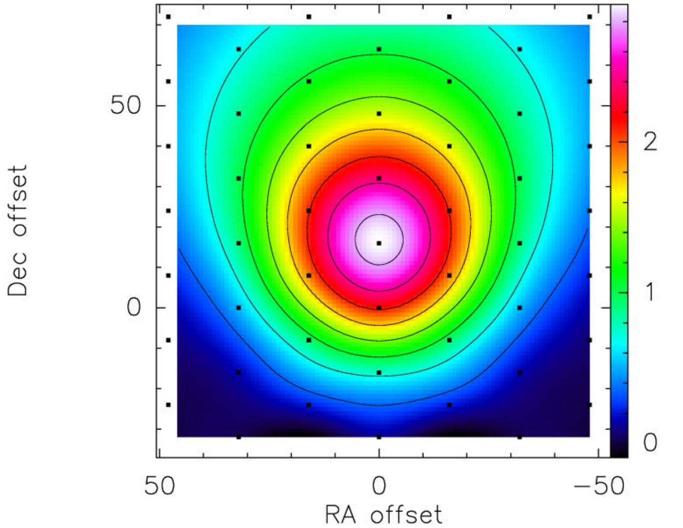




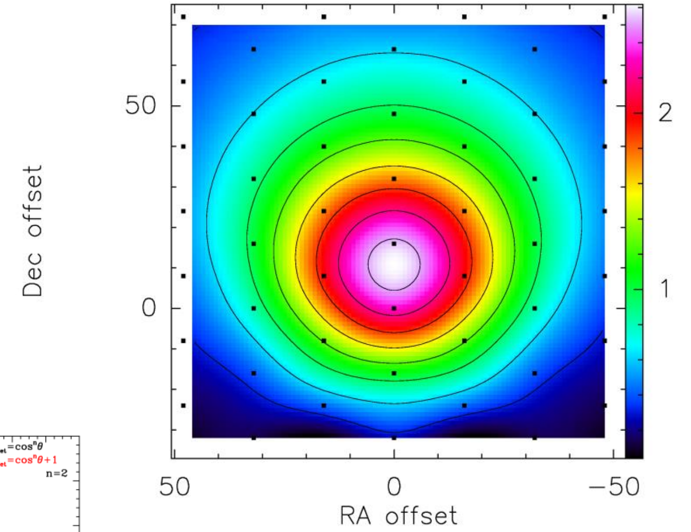
Simulated maps for water at 557 GHz

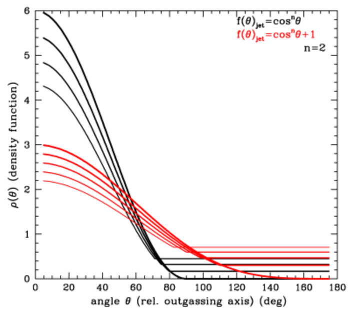
$\cos^2 \theta$

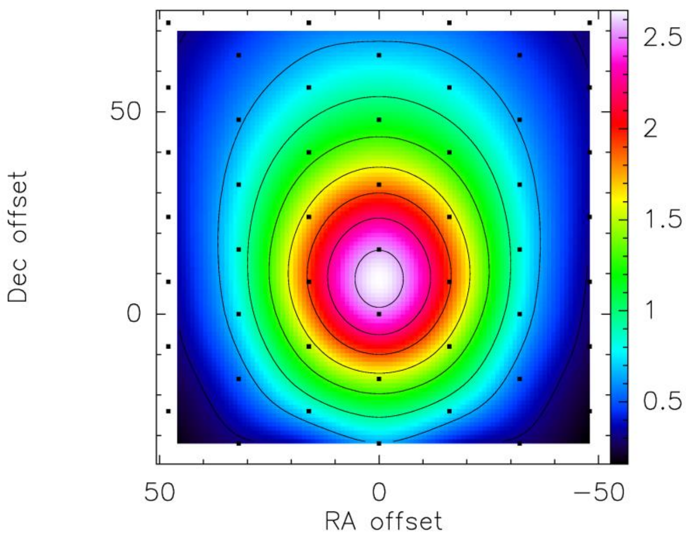
$\cos^2\theta + 1$



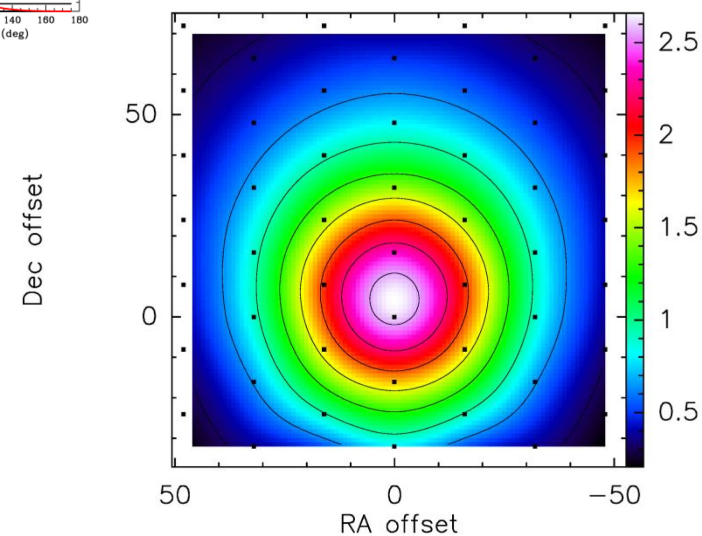
f_{jet}=1

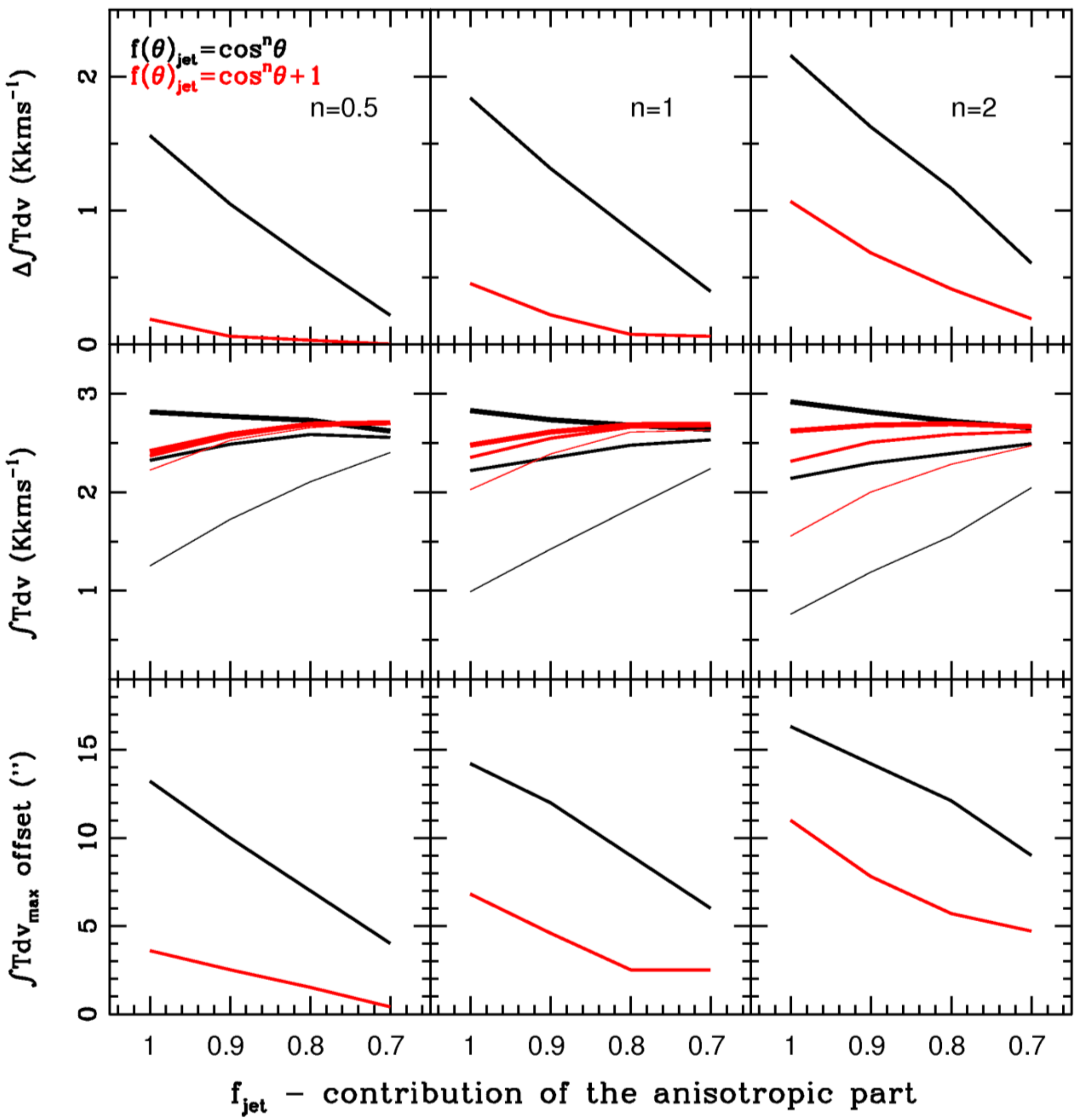




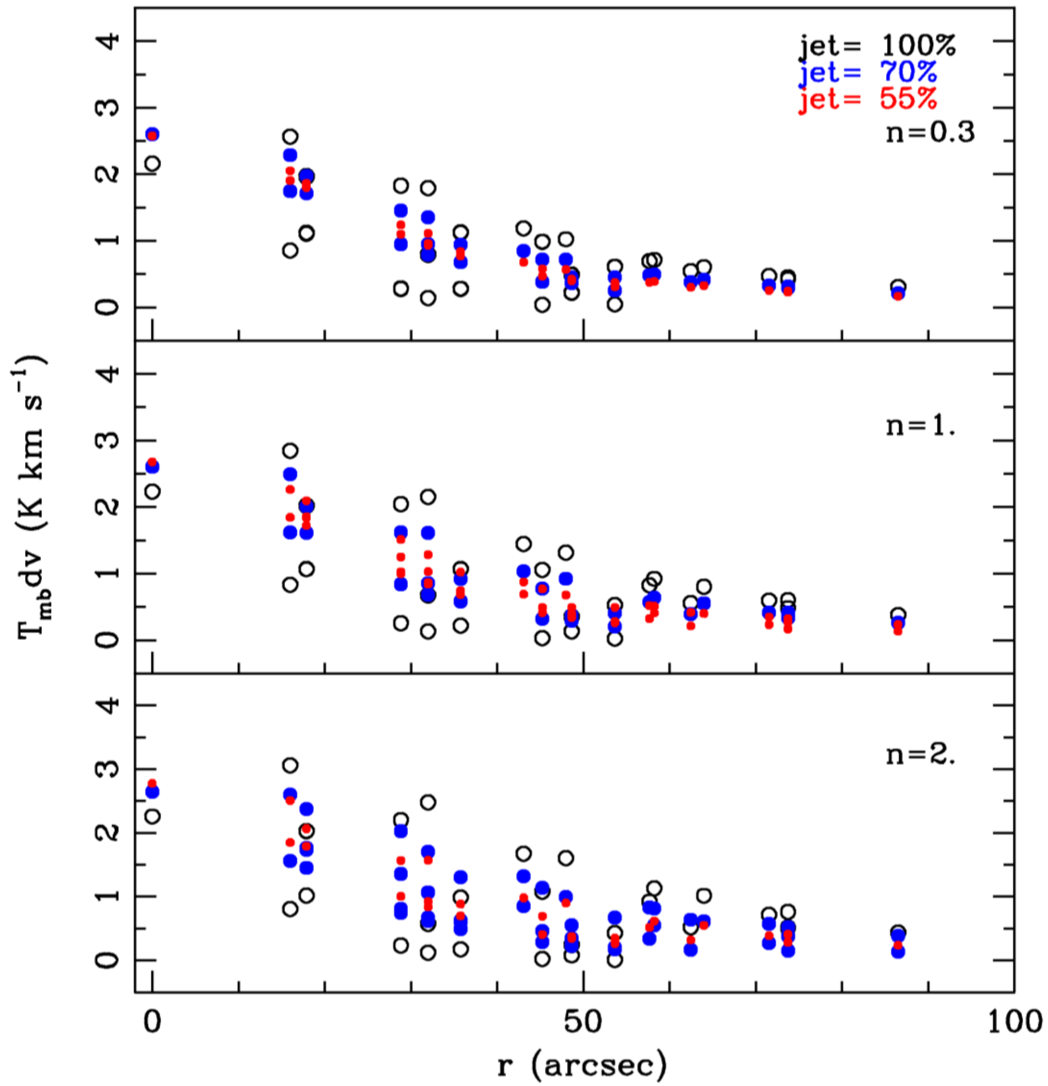


f_{jet}=0.7





f(θ)jet=cos^nθ
f(θ)jet=cos^nθ+1
n=0.5
n=1
n=2
Δ∫Tdv (Kkms^-1)
∫Tdv (Kkms^-1)
∫Tdvmax offset ('')
fjet − contribution of the anisotropic part



Radial profiles of the water emission with respect to the center of the emission, for the nine models: f_{jet} =1 (black open circles); f_{jet} = 0.7 (blue circles); f_{jet} =0.55 (red circles); power low *n* equals to 0.3, 1. and 2. (top, middle and bottom panel). - $f_{jet}(\theta)= \cos^n(\theta)$.

Practical implication – Comet 10/Tempel 2

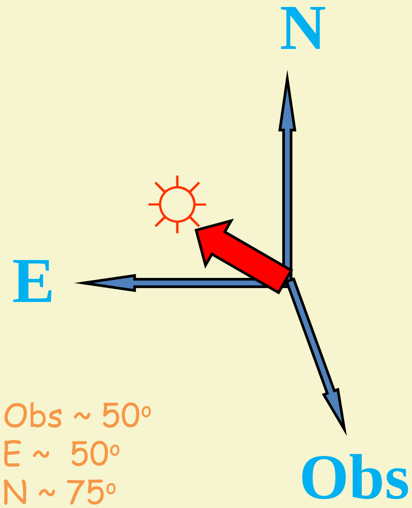
Comet 10P/Tempel 2 was observed with the Herschel Space Observatory in the framework of the Herschel guaranteed time key project "Water and related chemistry in the Solar System" (Hartogh et al., 2009)

HSO observations :
-short-term monitoring of the water lines; several ortho- and para-water transitions: **o-H_2O (1_{10}–1_{01}) at 557 GHz, o-H_2O (2_{12}–1_{01}) at 1669 GHz, p-H_2O (2_{02}-1_{11}) at 987 GHz, p-H_2O (1_{11}–0_{00}) at 1113 GHz**

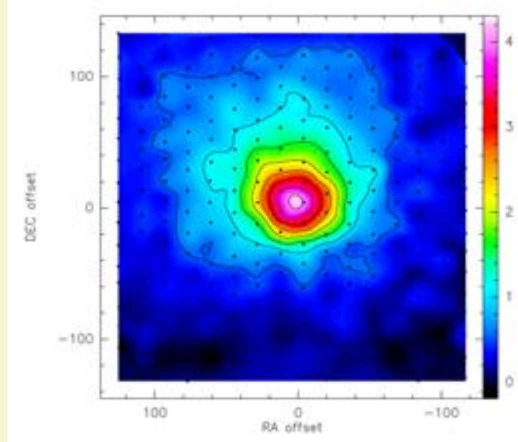
- three maps at **557 GHz ,** one map at **988 GHz**

The line shapes and the OTF maps taken with the high-resolution instrument Herschel/HIFI allowed to localize active region.

Model parameters:
x_{ne} = 0.15
v_{exp}= 0.9 km s^{-1}, T= 31 K – anisotropic emission
v_{exp}= 0.5 km s^{-1}, T= 20 K – isotropic emission
orientation of the rotation axis: **RA= 162º , Dec= 58º** (Knight et al.,2012)
rotation period: **P = 8.95 h**
location of the active region: colatitude, longitude contributions of the isotropic and anisotropic part: f_{iso} , $f_{jet.}$

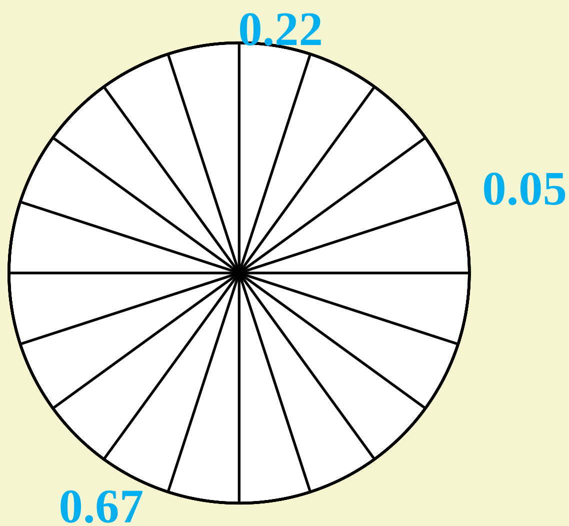


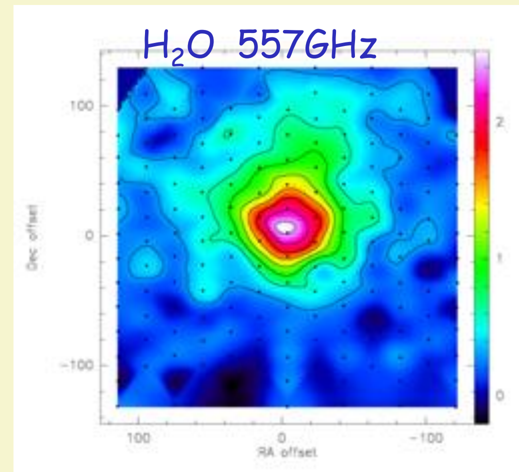
Sun - Obs ~ 50°
Sun - E ~ 50°
Sun - N ~ 75°

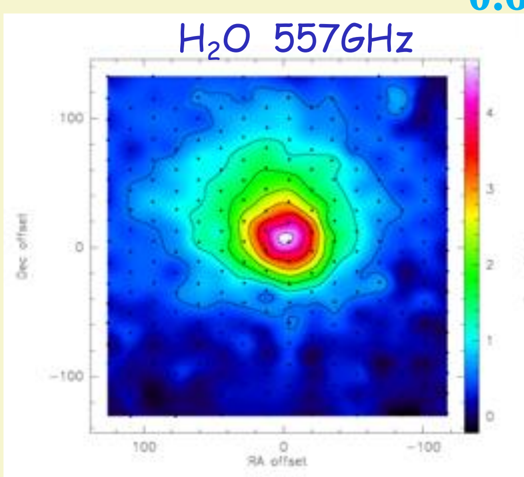


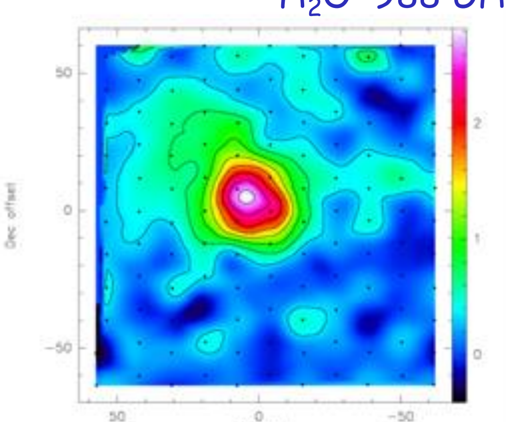
H_2O 557GHz

On-the-fly maps of the 557 GHz and 987 GHz lines obtained with HIFI/Herschel - versus rotational phase.









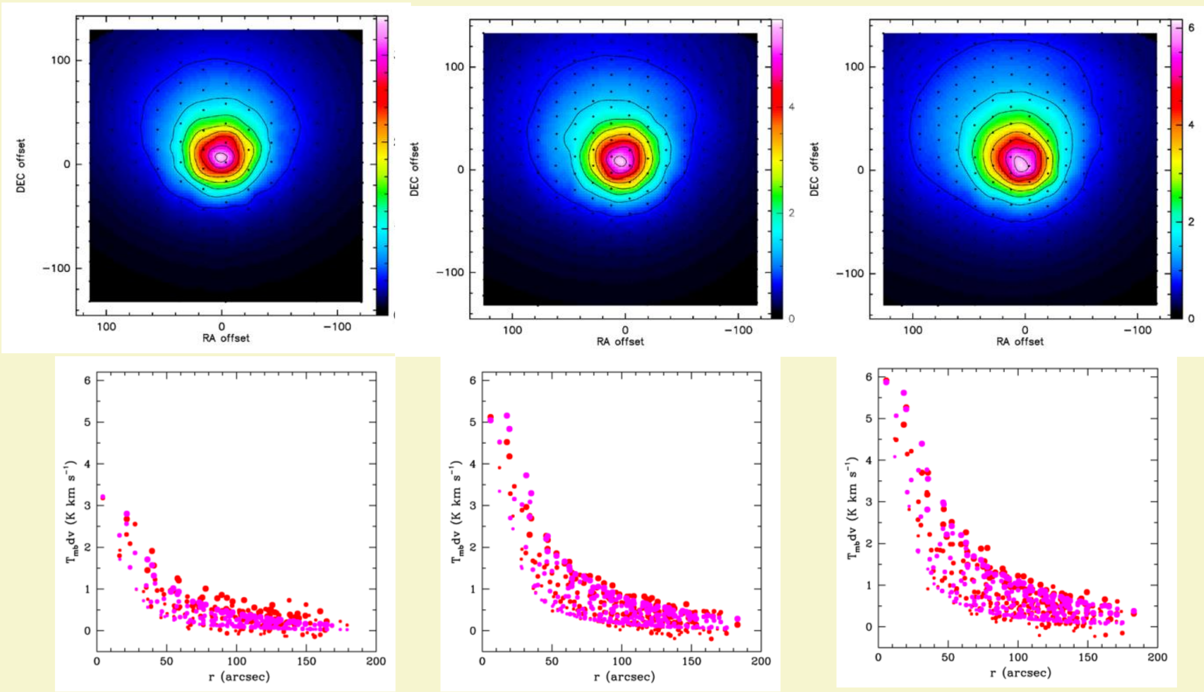
H_2O 988 GHz

10P/Tempel 2

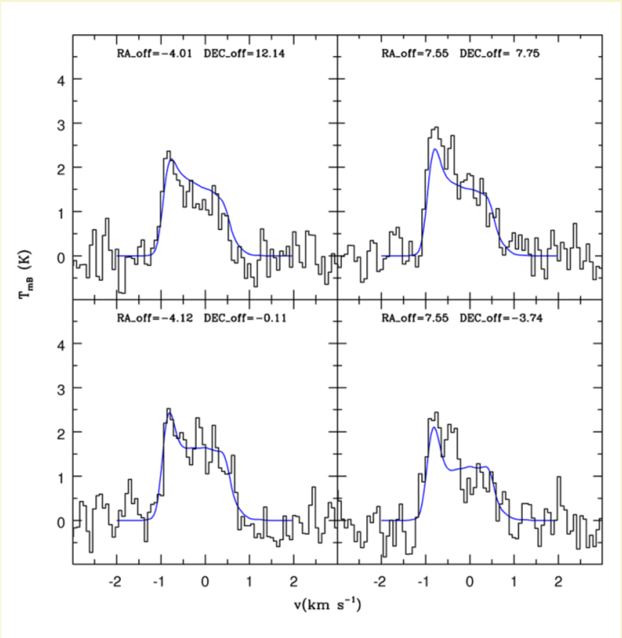
Szutowicz et al., 2012

10P/Tempel 2

The active region is located at the northern hemisphere: colatitude = 26^o , longitude = 276^o , contribution of the jet to the total outgassing is f_{jet} = 0.75



(Top) Modeled maps of the **H_2O (1_{10}–1_{01}) at 557 GHz.** Contours levels are 0.4 to 3.2 K km s^{-1} (June 15), 0.6 to 5.2 K km s^{-1} (July 19) and 0.8 to 6 K km s^{-1} (July 29). (Bottom) Comparison of radial profiles of the water emission for three OTF maps (observed – red, simulated- magenta).



Spectra of the water lines **H_2O (2_{02}-1_{11}) at 987 GHz** (July 7) taken at four points of the map; Blue lines show simulated spectra.

Szutowicz et al. 2014

Summary:

- Synthetic line profiles of water (ground rotational transition) as seen with Herschel telescope beam are computed at various off-set positions. The comet is assumed to be a source of *isotropic* and *anisotropic* emission. It is shown that the gas density distribution influences the lines shape and absorption and emission signal in the line profile.
- For the non-uniform density distribution the emission peak is shifted with respect to nucleus - observer direction. The effect depends on the density distribution.
- A model for the simulation of water lines emission in cometary coma allowed to constrain the geometry of the non-uniform density distribution for Comet 10P/Tempel 2 and retrieve localization of the active region.