H2O in Protoplanetary Disks: the snow line and the planet's nest

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Abstract

Protoplanetary disks represent the stage between the pre-stellar collapse of the molecular cloud and the formation of a planetary system surrounding a main sequence star. The goal of the DIANA FP7 project (P.I.: P.Woitke) is to investigate the disks in multiwavelengths, considering available data of photometry and spectroscopy, in order to define the properties of these objects. DIANA will work on a sample of 85 selected targets in different evolutionary stages and surrounding stars of different spectral type. At NIR-MIR wavelengths, it is possible observe many lines of water. Water is one of the main cooling agents of the disk, due to its abundance and the presence of energy levels with excitation temperatures from few tens to few thousands of Kelvin.

Water can also exist in condensate phase (frozen on dust) outside the so-called "snow line", which increases the surface density of solid material and therefore helps the formation of planets. Using a range of water lines, we can scan the disk surface, thus probing the disk from the lowest to the highest temperature regions and potentially indirectly detect the presence of the "snow line". Spectroscopic data from Spitzer and Herschel is used to investigate the spatial distribution and the synthesis of water, in the context of the thermophysical structure of the disk. This study is carried out with the code ProDiMo, producing different models of disks and investigating the diagnostic power of the different water lines in understanding the disk appearance and structure. The work is done as part of the FP7 DIANA project.

Why can we not see the lines?

Spitzer IRS, Herschel PACS & HIFI water lines of TW Hya

[1] Zhang, Pontoppidan et al. 2013 in press
[2] W.-F., Thi et al. 2010 A&A 518, L152; Kamp, I., et al. 2013 submitted
[3] Hogerheijde et al. 2011 Science 334, 338

Species	Transition	λ [μm]	flux [$10^{-18} W/m^2$]	Ref.
o-H_2O	$11_{39} - 10_{010}$	17.23	<163.7	[1]
p-H_2O	$11_{29} - 10_{110}$	17.36	<617.3	[1]
o-H_2O	$8_{36} - 7_{07}$	23.82	4669±364*	[1]
p-H_2O	$9_{81} - 8_{72}$	23.86	4669±364*	[1]
o-H_2O	$9_{82} - 8_{71}$	23.86	4669±364*	[1]
o-H_2O	$8_{45} - 7_{16}$	23.90	4669±364*	[1]
o-H_2O	$11_{66} - 10_{55}$	23.93	4669±364*	[1]
p-H_2O	$11_{56} - 10_{47}$	23.94	4669±364*	[1]
p-H_2O	$8_{53} - 7_{44}$	30.47	3750±317*	[1]
p-H_2O	$7_{61} - 6_{52}$	30.53	3750±317*	[1]
o-H_2O	$7_{62} - 6_{51}$	30.53	3750±317*	[1]
o-H_2O	$8_{54} - 7_{43}$	30.87	1883±287*	[1]
o-H_2O	$6_{34} - 5_{05}$	30.87	1883±287*	[1]
o-H_2O	$8_{18} - 7_{07}$	63.32	<7.2	[2]
o-H_2O	$7_{07} - 6_{16}$	71.95	<6.4	[2]
p-H_2O	$8_{17} - 8_{08}$	72.03	<35.4	[1]
o-H_2O	$4_{23} - 3_{12}$	78.74	<6.0	[2]
p-H_2O	$6_{15} - 5_{24}$	78.93	<6.4	[2]
p-H_2O	$3_{22} - 2_{11}$	89.99	5.6±0.9**	[2]
p-H_2O	$4_{13} - 3_{22}$	144.52	<6.6	[2]
o-H_2O	$2_{12} - 1_{01}$	179.53	<7.9	[2]
p-H_2O	$1_{11} - 5_{24}$	269.27	0.610±0.038	[3]
p-H_2O	$1_{10} - 1_{01}$	538.29	0.1700±0.0075	[3]

* blended transitions ** blend with CH^+ at 90.02μm

For TWHya Zhang (et al. 2013 ApJ 766:82) successfully model the Spitzer IRS lines and FIR lines (Herschel PACS/HIFI) using a parametrized model with a snow line at 4.2-6 AU. Kamp et al. (2013 submitted) employ a thermochemical disk model and find that the gas-to-dust ratio in the inner disk has to be higher than in the outer disk to explain the low and high-excitation water lines seen with Herschel. This is consistent with a depletion of gas phase water in the outer disk region. Generic disk models that take into account the water chemistry and the ice formation suggest that this is a general phenomenon in disks. (Meijerink et al. 2009 ApJ 704: 1471-1481)

Status for water in disks:

- Spitzer and Herschel have detected many lines, with Tex 58-4800K, however there is no correlation between the Spitzer and Herschel detections (Carr et al. 2008, Science 319, 1504; Pontoppidan et al. 2009, ApJ 704, 1482; Riviere-Marichalar et al. 2012, A&A 538, L3; Hogerheijde et al. 2011 Science 334, 338; Podio et al. 2013, ApJL 166, L5).

- Gas phase water can be depleted outside 0.5-few AU, because of water ice formation (Woitke et al. 2010).

Questions

- Why is the line detection not correlated in Spitzer and Herschel observations of a meaningful sample of disks?

- Is the non detection connected with dry reservoirs in some objects, and so differences in the local physical conditions and chemistry between the disks?

- Can it be that the water spectroscopy is affected by the disk geometry and / or global physical parameters?

Three water reservoirs

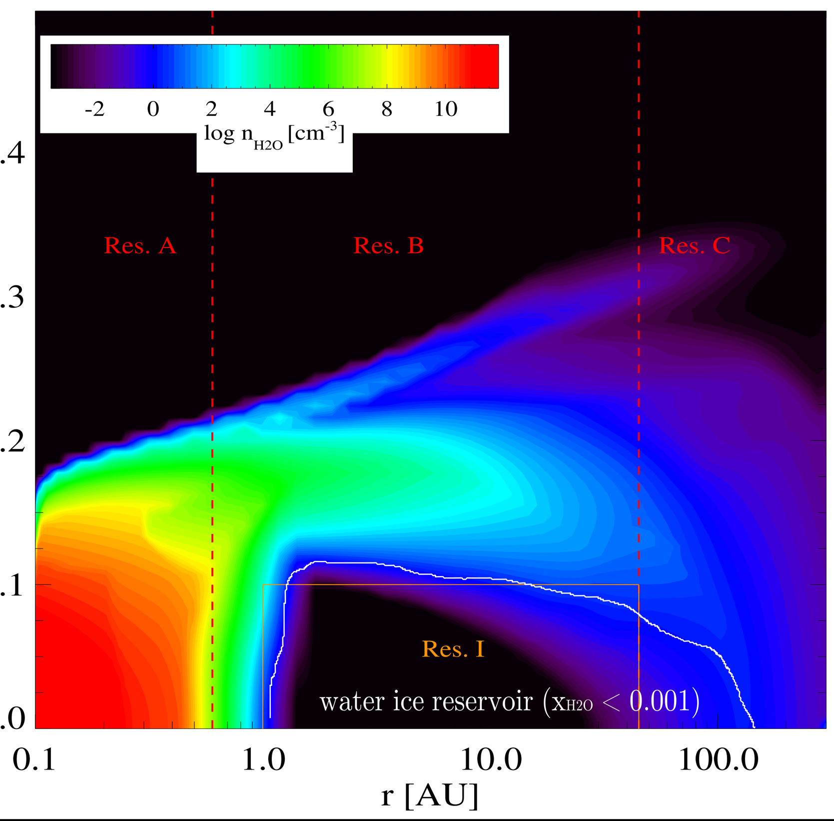
TTauri disk (parametrized structure):
$M_{disk} = 0.01 M_{sun}$
$r_{in} = 0.1AU$
$r_{out} = 300AU$
beta = 1.13
$H(r_{in}) = 3.548E-3$
d/g = 0.01
$a_{min} = 0.05$ um
$a_{max} = 1$ mm
$r_{taper} = 200AU$
epsilon = 1.0
$f_{PAH} = 0.01$
d=140pc

Parametrized hydrostatic scale height

$$H(r) = H_0 * \left(\frac{r}{r_0}\right)^\beta * e^{\left(\frac{-r}{r_{tap}}\right)^k}$$

Parametrized surface density

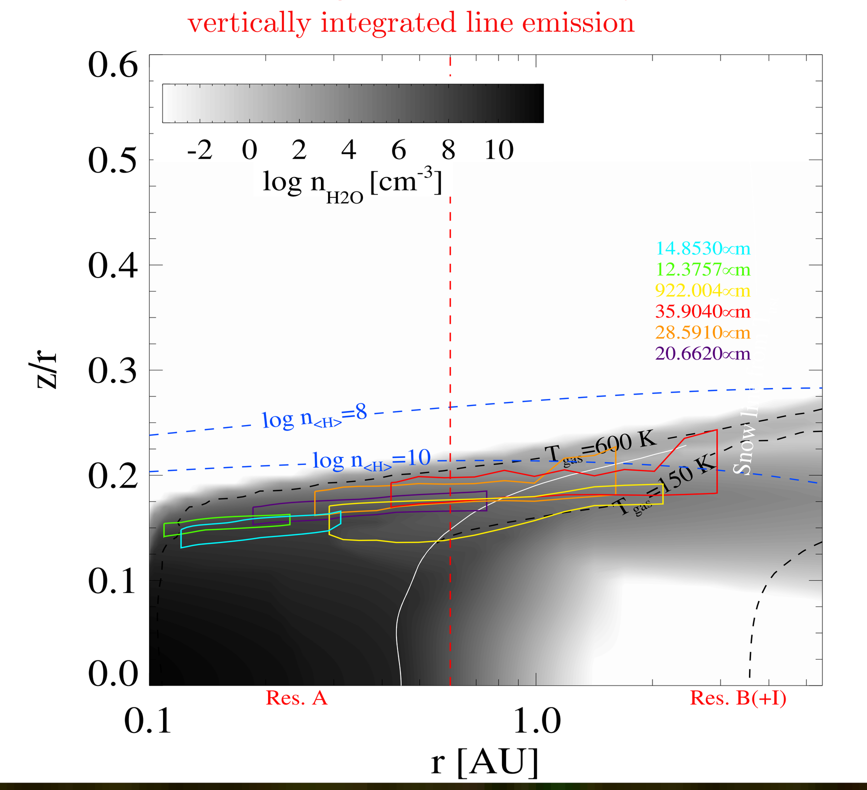
$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^\epsilon$$



Name	Radial extension [AU]	Vertical extension z/r	n_{H_2O} (relative fraction) [cm^{-3}]
Reservoir A	0.1-0.6	0-0.18	$\geq 10^9$ ($\geq 10^{-4}$)
Reservoir B	0.6-45	0.1-0.25	10^2-10^7 (10^{-6}-10^{-7})
Reservoir C	45-300	0-0.4	$\leq 10^2$ ($\simeq 10^{-9}$)
Reservoir I	0.5-45	0-0.2	$< 10^{-2}$ ($< 10^{-9}$)

Line origins

Contour region of 15-85% radially and vertically integrated line emission

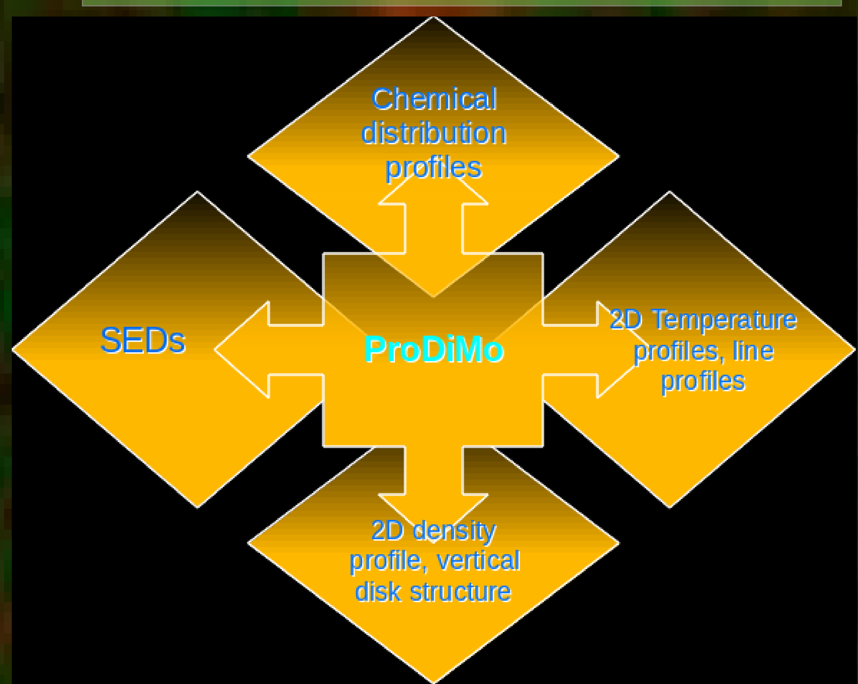


ProDiMo: PROtoplanetary DIsk MOdeling, radio-thermochemical code for circumstellar disks (Woitke, Kamp & Thi 2009 A&A 501, 383)

Reservoirs A & B:

E_{up} max: 4948K
upper level: 0,0,0 15,5,10 (v_1,v_2,v_3 J,K_a,K_c)

E_{up} min: 469.9K
upper level: 0,0,0 5,1,5 (v_1,v_2,v_3 J,K_a,K_c)

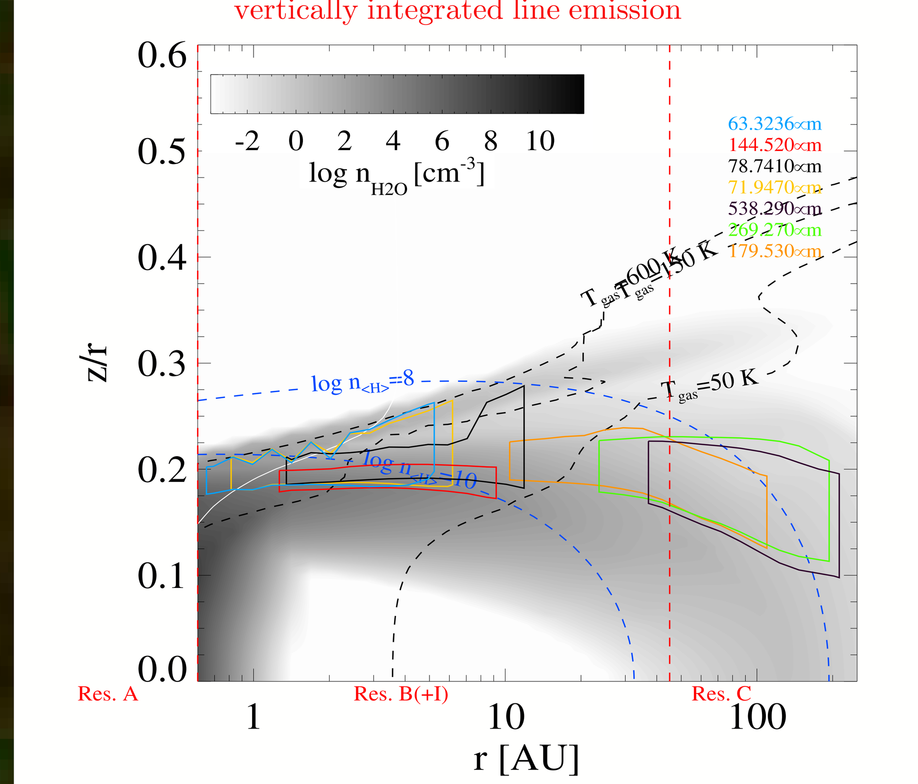


Reservoirs B & C:

E_{up} max: 843.5K
upper level: 0,0,0 7,0,7 (v_1,v_2,v_3 J,K_a,K_c)

E_{up} min: 53.43K
upper level: 0,0,0 1,1,1 (v_1,v_2,v_3 J,K_a,K_c)

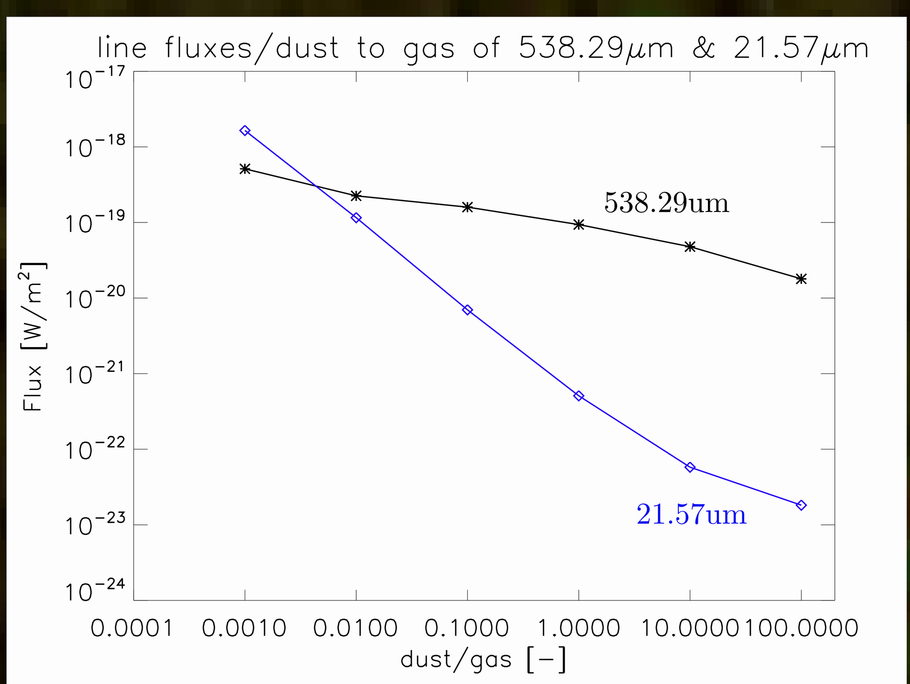
Contour region of 15-85% radially and vertically integrated line emission

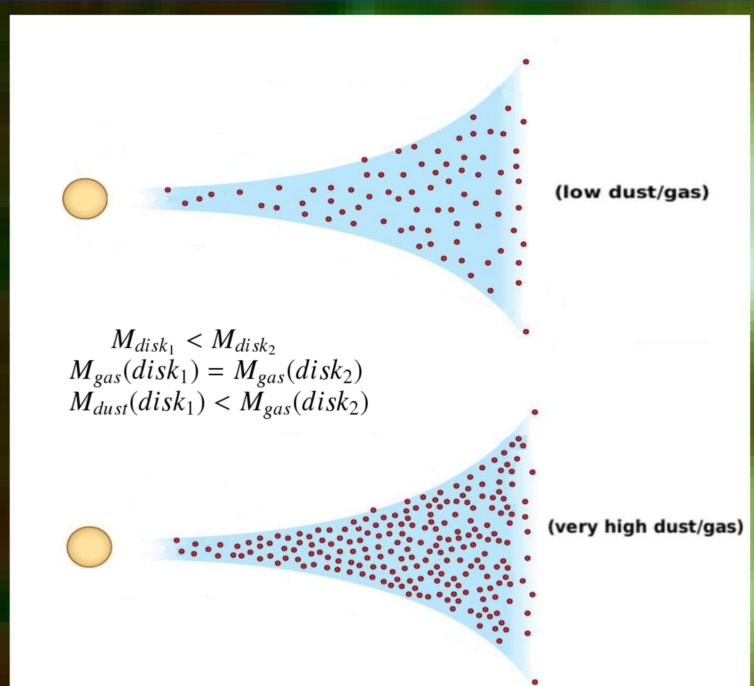


How does the line flux depend on the disk properties? Which parameters influence the line fluxes?

Effect of the dust to gas ratio on the HIFI transition 1,1,0 -> 1,0,1 (J,K_a,K_c), produced in the Reservoir B/C and on the Spitzer transition 7,7,0 -> 7,4,3, (J,Ka,Kc), produced in the Reservoir A

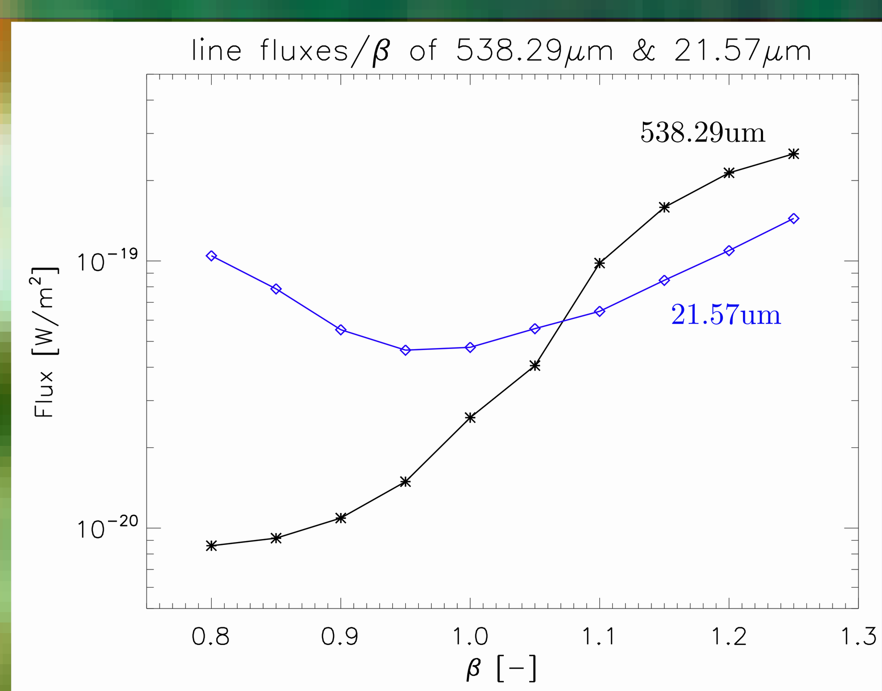
...The meaning of dust/gas...

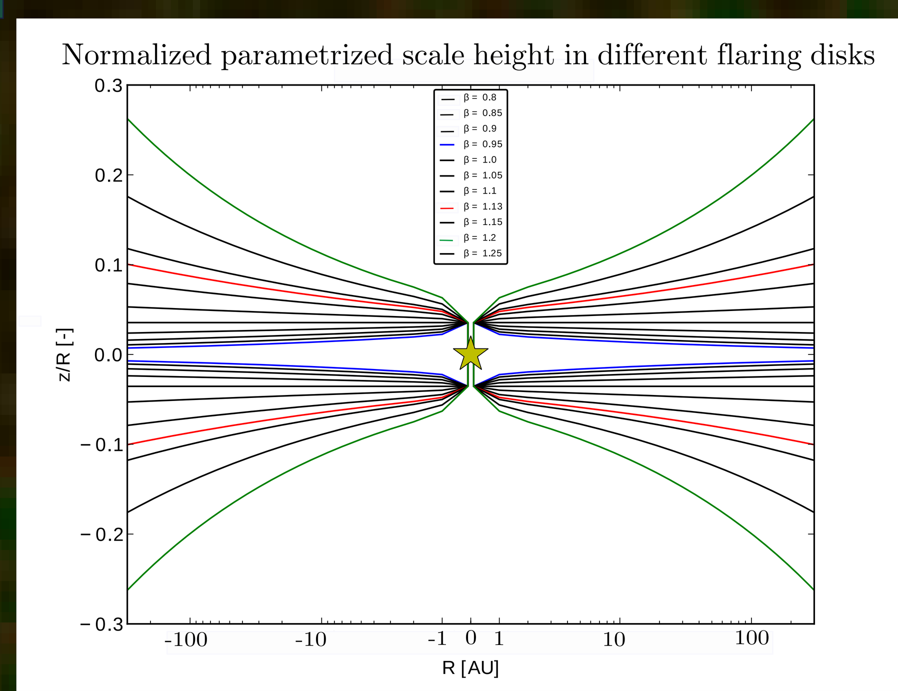




Effect of the flaring parameter on the HIFI transition 1,1,0 -> 1,0,1 (J,K_a,K_c), produced in the Reservoir B/C and on the Spitzer transition 7,7,0 -> 7,4,3, (J,Ka,Kc), produced in the Reservoir A

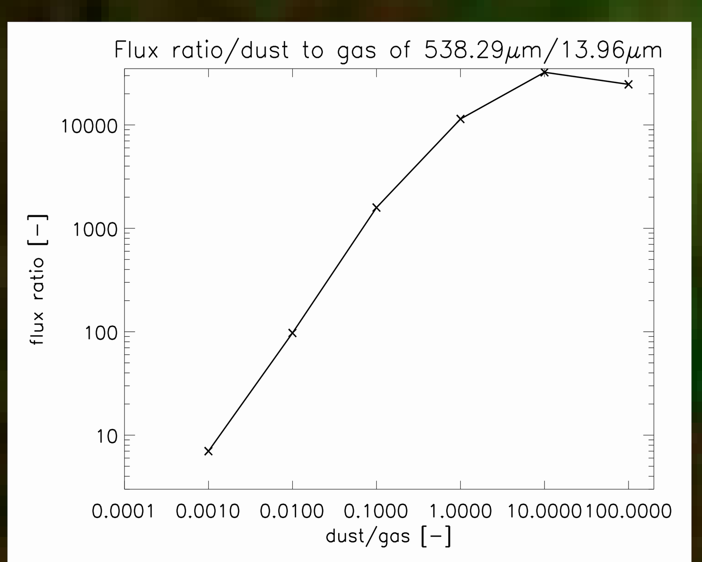
...The meaning of flaring...



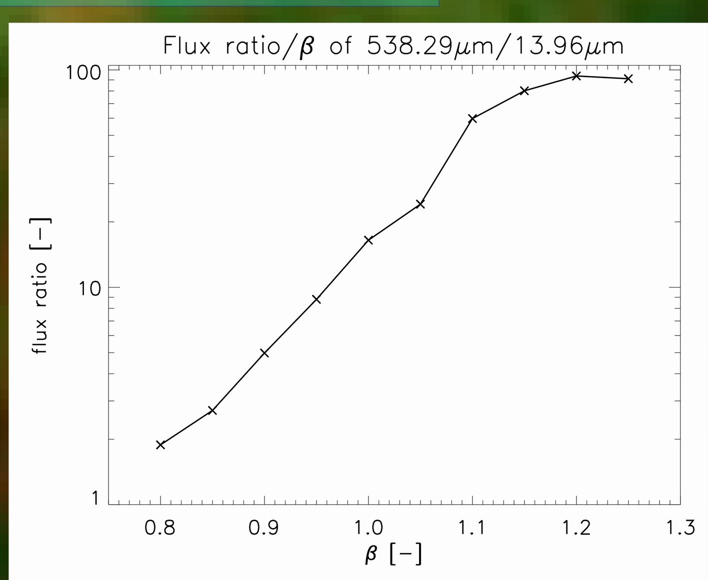


What about Herschel vs Spitzer line fluxes?

Variation of the ratio of the line fluxes with the dust to gas ratio of the transitions:
- o-H2O 538.29um, HIFI line from Reservoir B/C
- p-H2O 13.96um, Spitzer line from Reservoir A



Variation of the ratio of the line fluxes with the flaring parameter of the transitions:
- o-H_2O 538.29um, HIFI line from Reservoir B/C
-p-H_2O 13.96um, Spitzer line from Reservoir A



In progress...

...to be analyzed...

1) Chemistry in the emitting region:
- gas phase reactions
- solid phase reactions
- photochemistry
2) Local thermophysical conditions and radiation field:
- pumping thermal background IR radiation field
- statistical equilibrium
3) Quantitative correlation of the physical parameters with the line fluxes in the emitting region

Log into DIANA