Herschel observations of water in AGB and post-AGB stars

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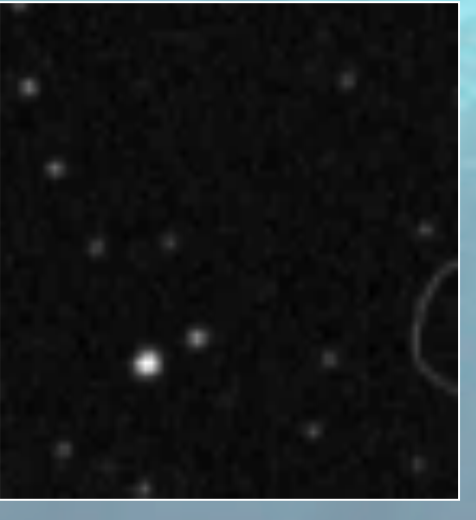
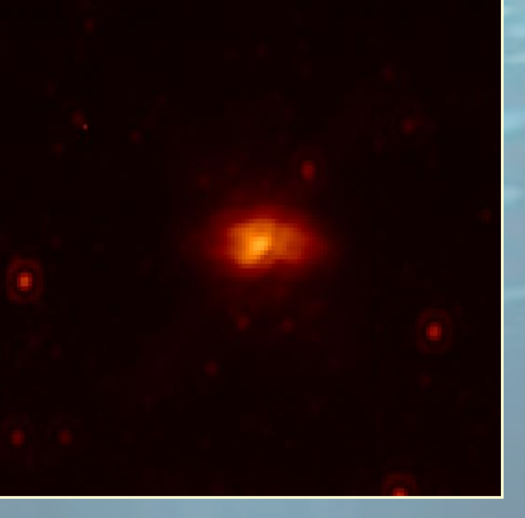
Introduction (I)

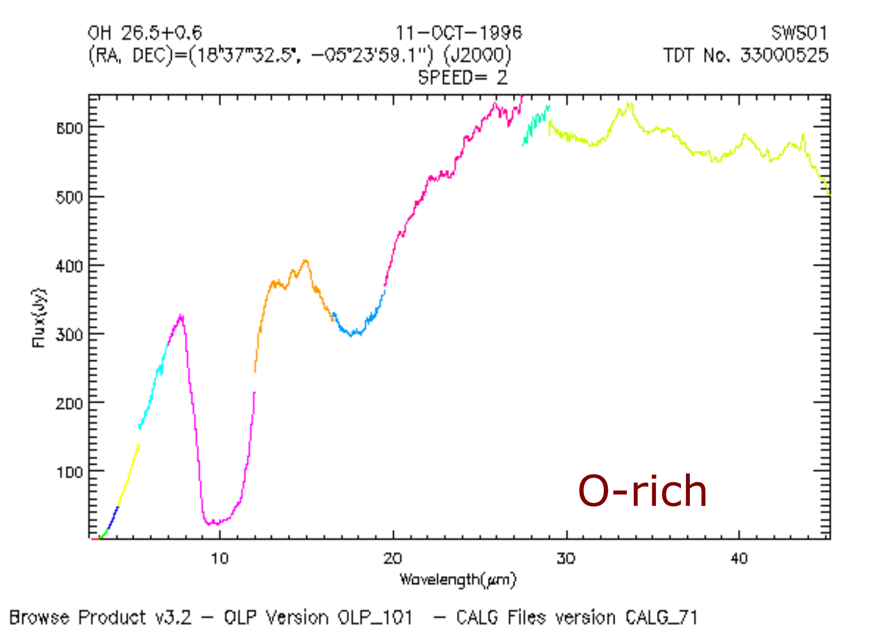
- Low- and intermediate-mass evolved stars (1-8 $M_{\odot}$) in the transition from the late AGB (Asymptotic Giant Branch) phase to the PN (planetary nebula) stage are among the brightest sources in the sky in the infrared, before they become white dwarfs.
- Strong mass loss (10^{-4} – 10^{-5} $M_{\odot}$/yr) as a consequence of periodic thermal pulses at the end of the AGB generates thick circumstellar shells of gas and dust, which sometimes completely obscure the light coming from the central star in the optical, associated to high velocity outflows that can help developing bipolar/complex morphologies

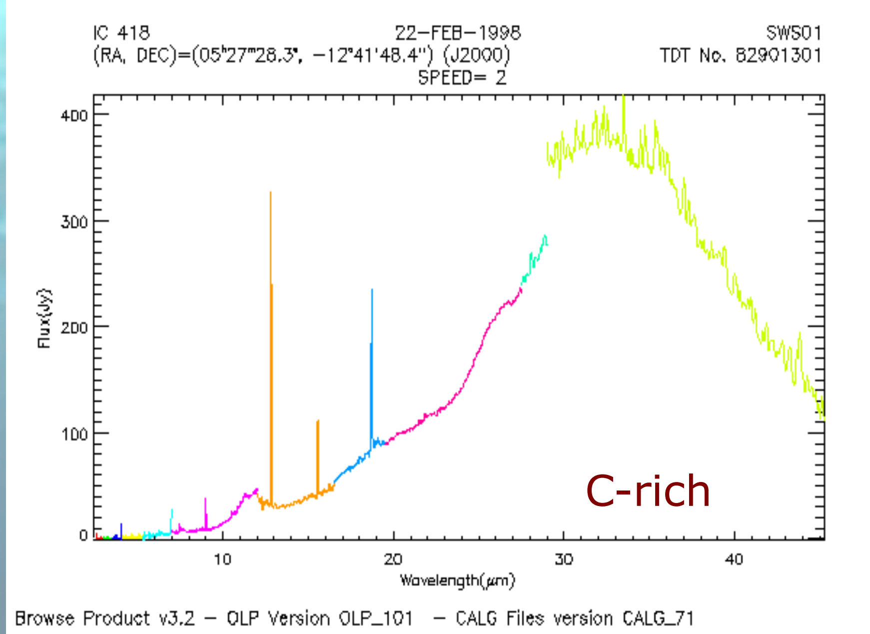




Introduction (II)

- Chemical composition of the shell reflects the nucleosynthesis experienced by the central star. Of major importance here is the C/O ratio, as it determines the formation of totally different chemical species and dust grains (C-rich vs. O-rich chemistry)
- Previously studied with ISO/SWS, Spitzer/IRS and AKARI/IRC, mainly at mid-infrared wavelengths, resulting in significant progress on the understanding of how molecules form and evolve to complex structures (e.g. PAHs, fullerenes) and the detection of many new dust features (crystalline silicates, HACs, ..)





What can we learn with Herschel?

- Extend the analysis to far-infrared wavelengths at higher resolution and more extended coverage in wavelength than other facilities in the past (mainly ISO/LWS: 43-197μm), providing complementary information to what can be obtained from ground-based sub-mm facilities (IRAM, JCMT, .. ALMA more recently).

- All instruments onboard Herschel can contribute: PACS (57-210μm, with R=1000-5000), SPIRE (194-672μm, with R=40-1000) and HIFI (157-212μm, 240-625μm with R as high as 10^7!)
  - Thermal continuum emission of the cool dust component – mass loss history
  - Important molecular lines (CO, OH, H_2O,..) – specially those formed at the warm inner layers of the shell
  - Solid state dust spectral features – extension of ISO/Spitzer findings
  - Kinematics, from HIFI spectroscopy – high velocity outflows

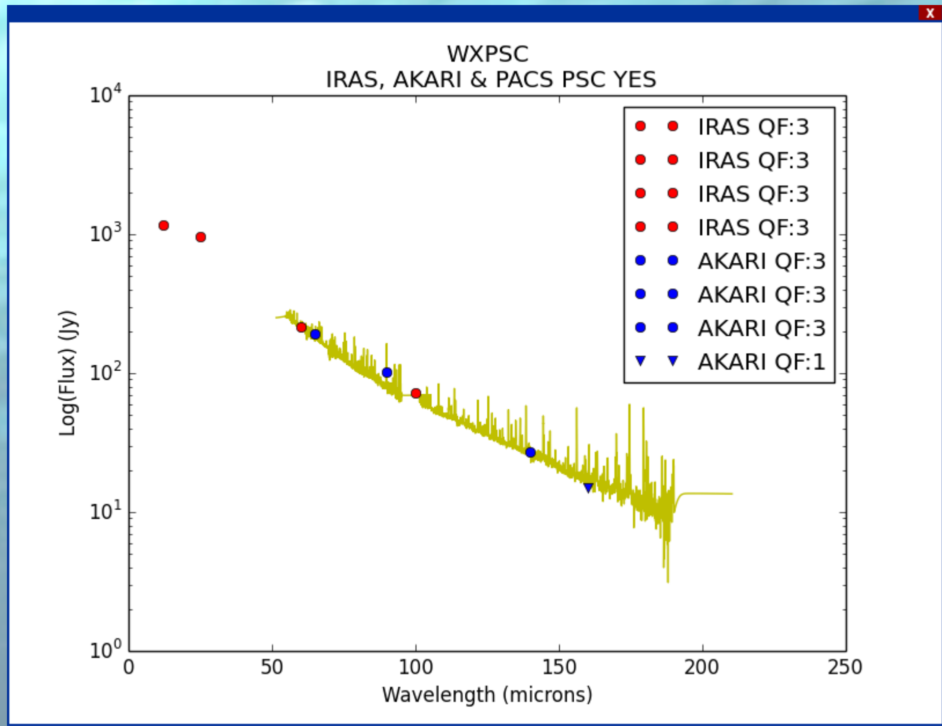
THROES: A caTalogue of HeRschel Observations of Evolved Stars

- A catalogue of fully reprocessed, homogenously reduced PACS/SPIRE spectra of all evolved stars observed with Herschel (more than 200 sources, originally part of more than 40 different research programmes)

- Covering the whole evolutionary stage from the AGB to the PN stage, including some massive red supergiants and LBVs, all chemistries

- Complemented with ancillary data taken by other facilities (IRAS, AKARI photometry, when available)

- Will be made publicly available through the Herschel Science Archive and also through a dedicated web-based interface



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Object class (?)	---
Mass Classification (?)	---

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288.8476	-7.0471	19:15:23.440	-7:02:49.90	W_AQL	PacsRangeSpec	2	Evolved low-intermediate mass star	S star	SED	CSV	FITS
16.6082	12.598	1:06:25.980	12:35:53.00	WX_PSC	PacsRangeSpec	2	Evolved low-intermediate mass star	O rich AGB	SED	CSV	FITS
259.8745	-45.6399	17:19:29.900	-45:38:23.90	WR_90	PacsRangeSpec	1	Evolved massive star	WR star	---	---	---
160.4096	-58.7718	10:41:38.320	-58:46:18.70	WR_23	PacsRangeSpec	1	Evolved massive star	WR star	---	---	---
308.0125	41.2556	20:32:03.020	41:15:20.50	WR_144	PacsRangeSpec	1	Evolved massive star	WR star	---	---	---
305.4347	37.3751	20:21:44.350	37:22:30.60	wr_142	PacsRangeSpec	1	Evolved massive star	WR star	---	---	---
305.1165	43.8545	20:20:27.980	43:51:16.30	WR_140	PacsRangeSpec	1	Evolved massive star	WR star	---	---	---
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122.3831	-47.3365	8:09:31.950	-47:20:11.70	wr11	PacsRangeSpec	1	Evolved massive star	WR star	---	---	---
73.7936	-68.3416	4:55:10.480	-68:20:29.80	WOH_G64	PacsLineSpec/PacsRangeSpec	2	Evolved massive star	Red Supergiant star	---	---	---
162.9052	-21.25	10:51:37.250	-21:15:00.30	V_HYA	PacsRangeSpec	2	Evolved low-intermediate mass star	post-AGB	SED	CSV	FITS
310.3261	48.1413	20:41:18.270	48:08:28.80	V_CYG	PacsRangeSpec	2	Evolved low-intermediate mass star	C rich AGB	SED	CSV	FITS
280.4766	17.6856	18:41:54.390	17:41:08.50	V821_Her	PacsLineSpec	2	Evolved low-intermediate mass star	C rich AGB	---	---	---
258.6657	11.0694	17:14:39.780	11:04:10.00	v438_oph	PacsRangeSpec	1	Evolved low-intermediate mass star	O rich AGB	SED	CSV	FITS
167.1669	-60.7143	11:08:40.060	-60:42:51.70	V432_Car	PacsRangeSpec	1	Evolved massive star	Blue supergiant star	---	---	---
51.6229	47.5301	3:26:29.510	47:31:48.60	V384_Per	PacsLineSpec/PacsRangeSpec	3	Evolved low-intermediate mass star	C rich AGB	SED	CSV	FITS
280.6028	-2.2903	18:42:24.680	-2:17:25.20	V1417_Aql	PacsLineSpec	2	Evolved low-intermediate mass star	C rich AGB	---	---	---

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76.3488	1.1776	5:05:23.720	1:10:39.50	W
207.2583	-28.3676	13:49:02.000	-28:22:03.50	W
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160.4096	-58.7718	10:41:38.320	-58:46:18.70	W
308.0125	41.2556	20:32:03.020	41:15:20.50	WR
305.4347	37.3751	20:21:44.350	37:22:30.60	wr
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162.9052	-21.25	10:51:37.250	-21:15:00.30	V
310.3261	48.1413	20:41:18.270	48:08:28.80	V
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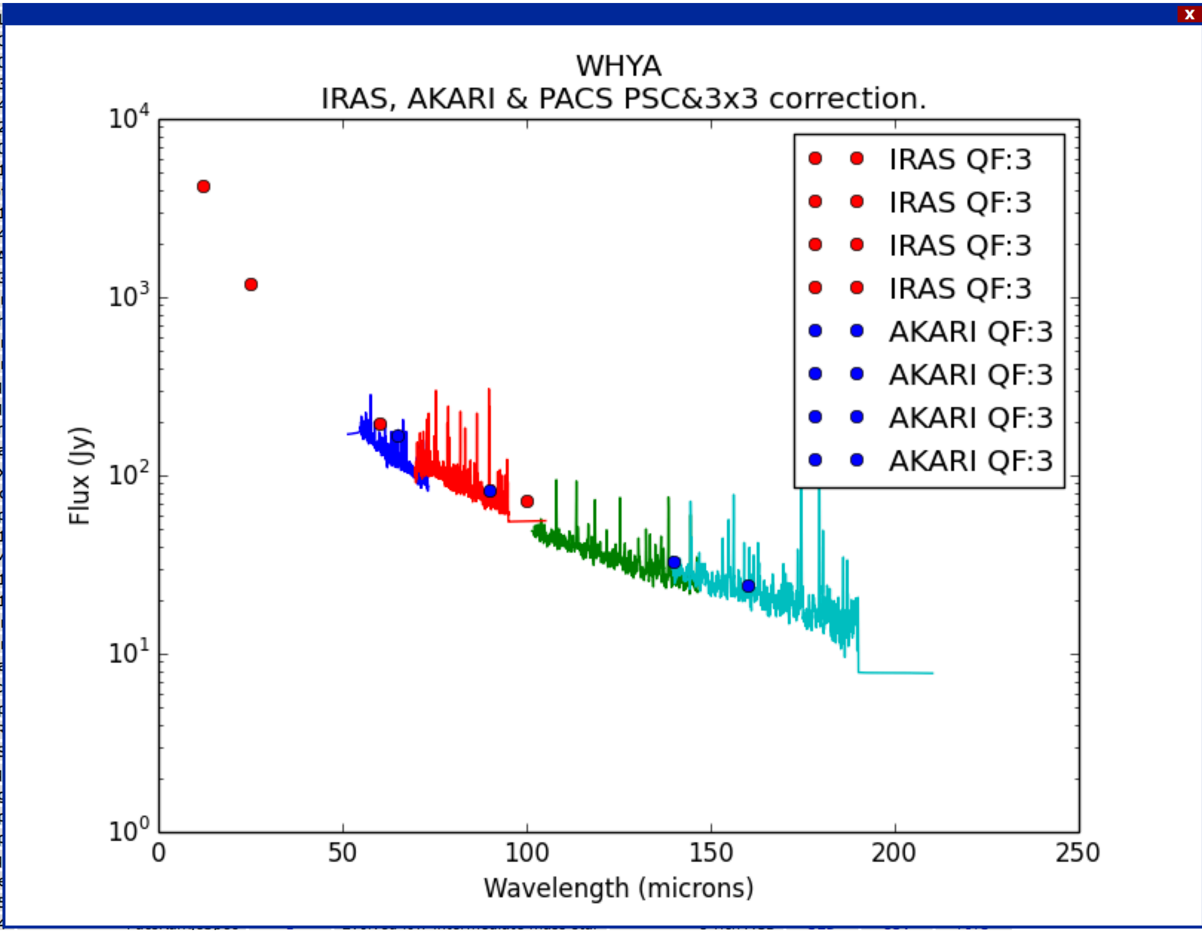
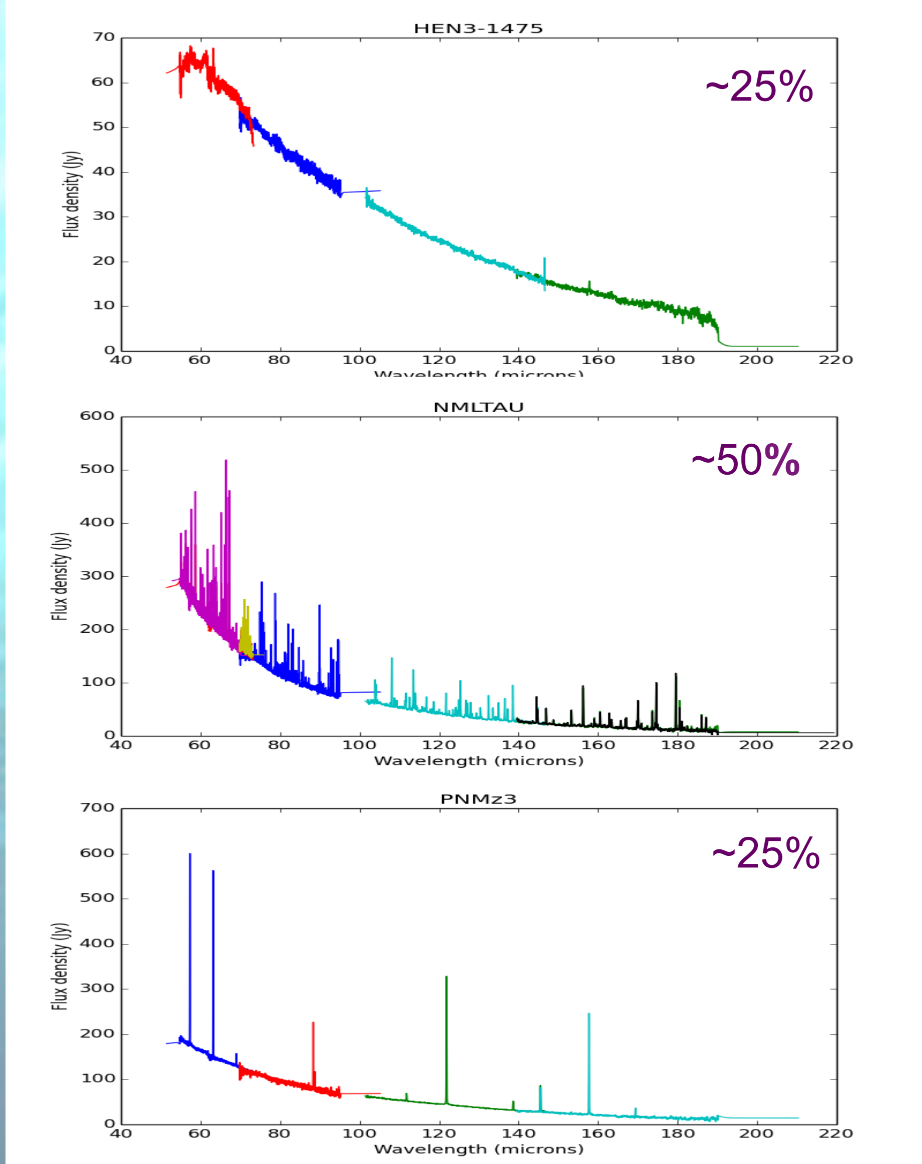


THROES: A caTalogue of HeRschel Observations of Evolved Stars

- 124 sources observed full-SED with PACS
  - O-rich AGB stars (24)
  - C-rich AGB stars (16)
  - S-type AGB stars (6)
  - OH/IR stars (16)
  - Post-AGB stars (32)
  - Planetary Nebulae (30)

- 87 sources observed with SPIRE
  - O-rich AGB stars (14)
  - C-rich AGB stars (8)
  - OH/IR stars (6)
  - Post-AGB stars (22)
  - Planetary Nebulae (37)
  -

- Among them, 60 with both PACS and SPIRE spectra available



Molecular lines in evolved stars

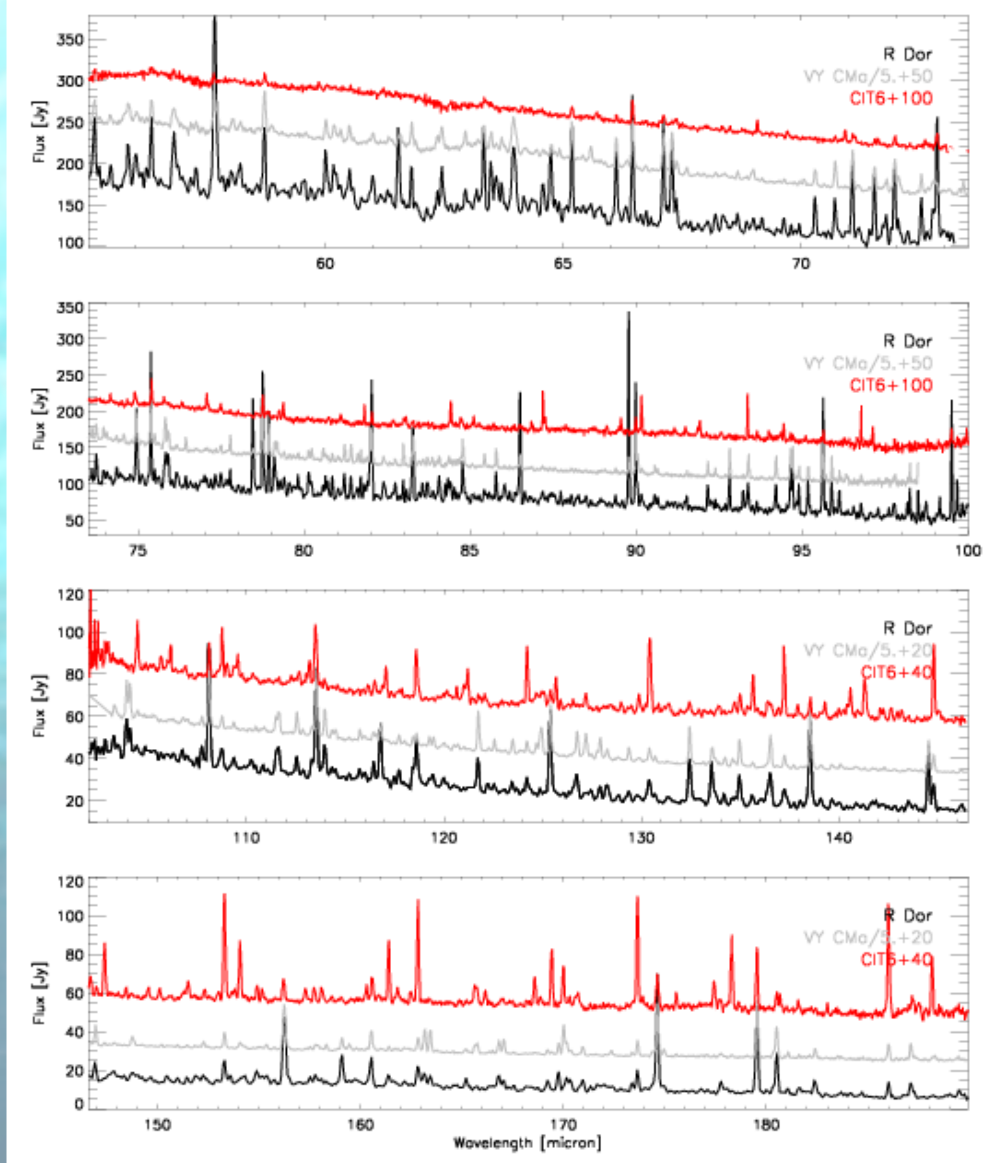
- To date, more than 70 molecules identified in evolved stars (mainly IRC+10216)

- Wealth of molecular lines, mainly CO (high-J rotational lines), OH and H_2O; HCN in C-rich stars

- Hundreds of lines need to be modelled simultaneously; non-LTE needed

- Evidence for new effects that need to be considered in the modelling

- Strikingly homogeneous spectra!



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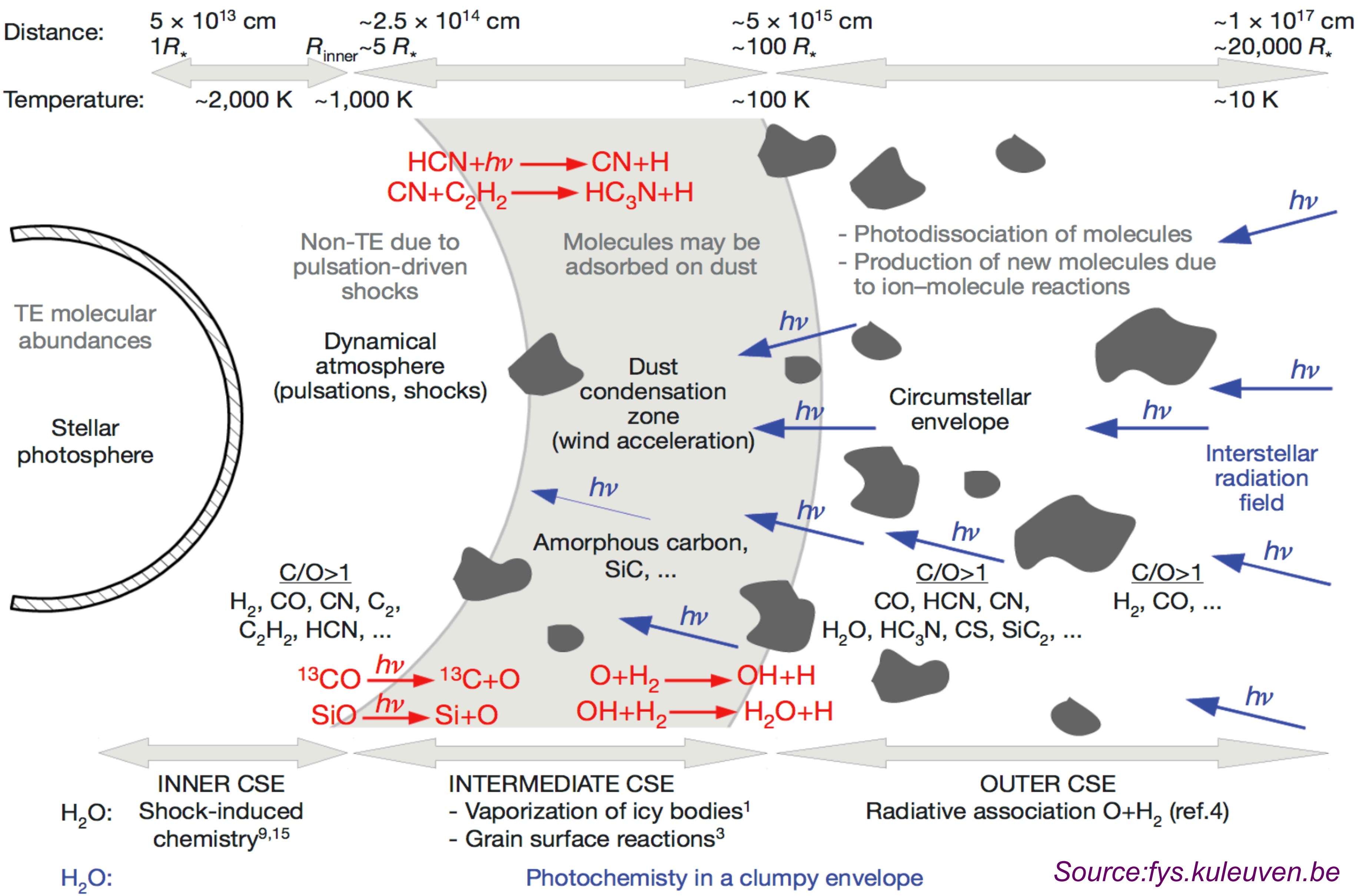
Chemical processs in C-rich AGB stars



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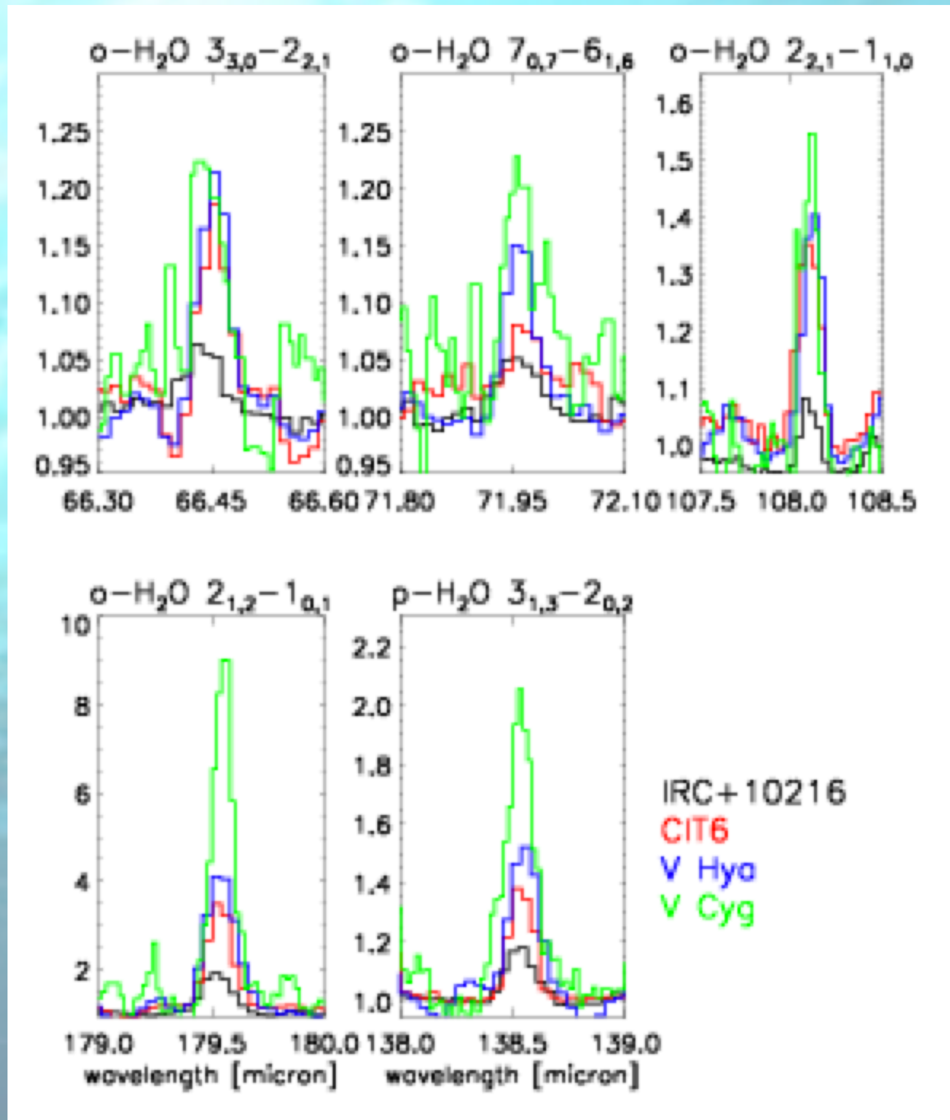
Water in C-rich AGB stars

– Detection of warm water vapour in C-rich AGB stars (Decin et al. 2010) suggests a non-equilibrium shocked chemistry in the inner regions of the circumstellar shell (Cherchneff 2011)

–Originally thought to be produced via photochemical processes in the outer envelope; now clear with Herschel that water and other O-rich molecules originate in the inner layers of C-rich stars

–Water vapour is now detected in ALL ~~(but one)~~ C-rich stars observed by Herschel

- Abundances anticorrelated with mass loss rate (Lombaert 2016)



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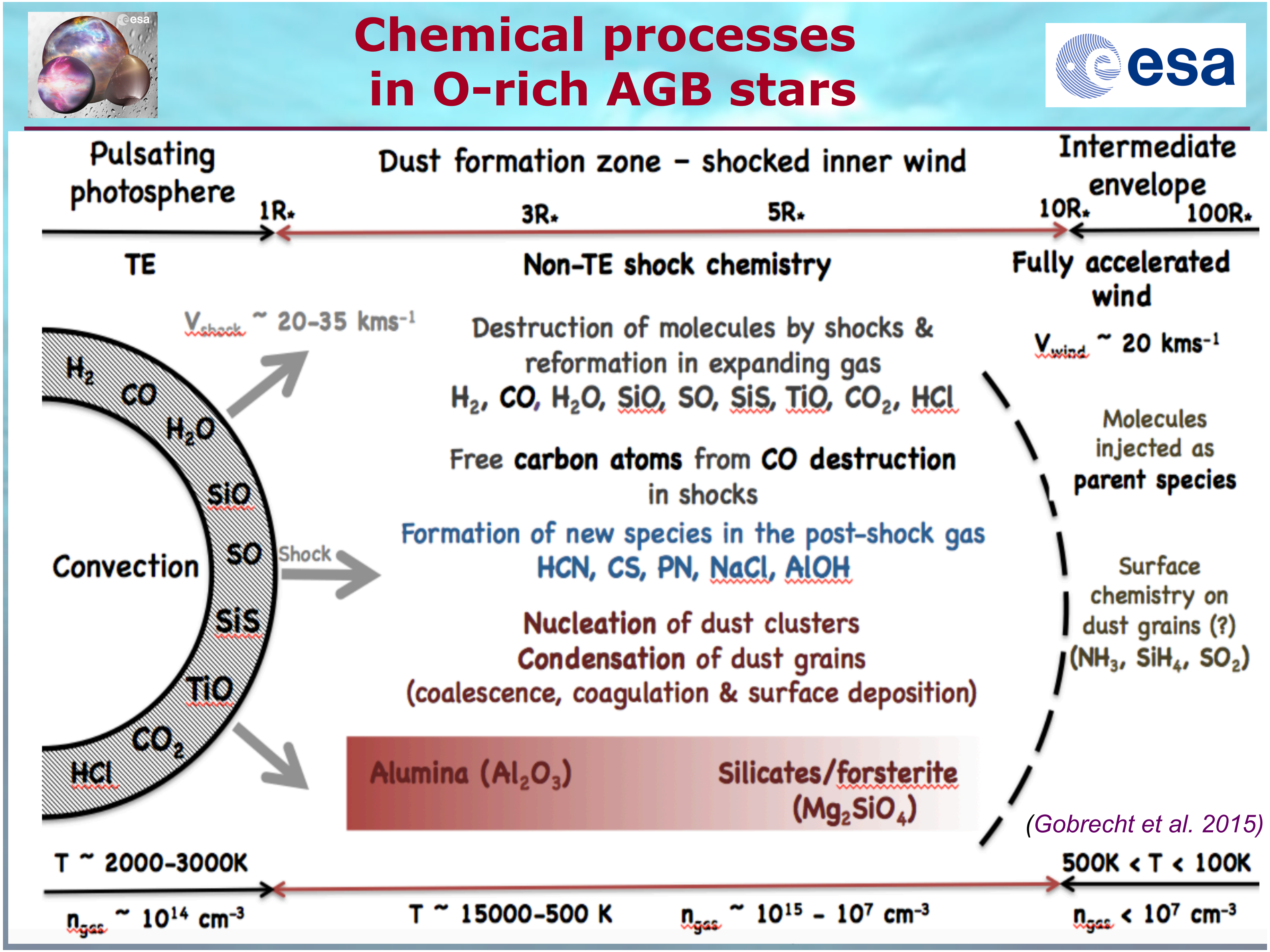

Chemical processes in O-rich AGB stars
esa
Pulsating photosphere
Dust formation zone – shocked inner wind
Intermediate envelope
1R*
3R*
5R*
10R*
100R*
TE
Non-TE shock chemistry
Fully accelerated wind
V_{shock} ~ 20-35 kms^{-1}
Destruction of molecules by shocks & reformation in expanding gas
H_2, CO, H_2O, SiO, SO, SiS, TiO, CO_2, HCl
V_{wind} ~ 20 kms^{-1}
H_2
CO
H_2O
SiO
SO
SiS
TiO
CO_2
HCl
Convection
Shock
Free carbon atoms from CO destruction in shocks
Molecules injected as parent species
Formation of new species in the post-shock gas
HCN, CS, PN, NaCl, AlOH
Surface chemistry on dust grains (?)
(NH_3, SiH_4, SO_2)
Nucleation of dust clusters
Condensation of dust grains
(coalescence, coagulation & surface deposition)
Alumina (Al_2O_3)
Silicates/forsterite (Mg_2SiO_4)
(Gobrecht et al. 2015)
T ~ 2000-3000K
500K < T < 100K
n_{gas} ~ 10^{14} cm^{-3}
T ~ 15000-500 K
n_{gas} ~ 10^{15} – 10^{7} cm^{-3}
n_{gas} < 10^{7} cm^{-3}

Water in O-rich AGB stars

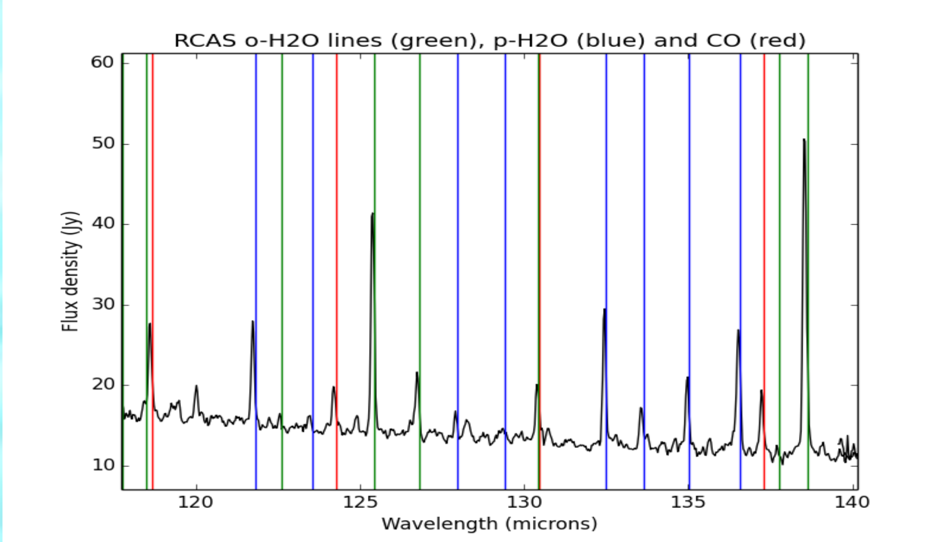
- Many similarities with C-rich AGB stars

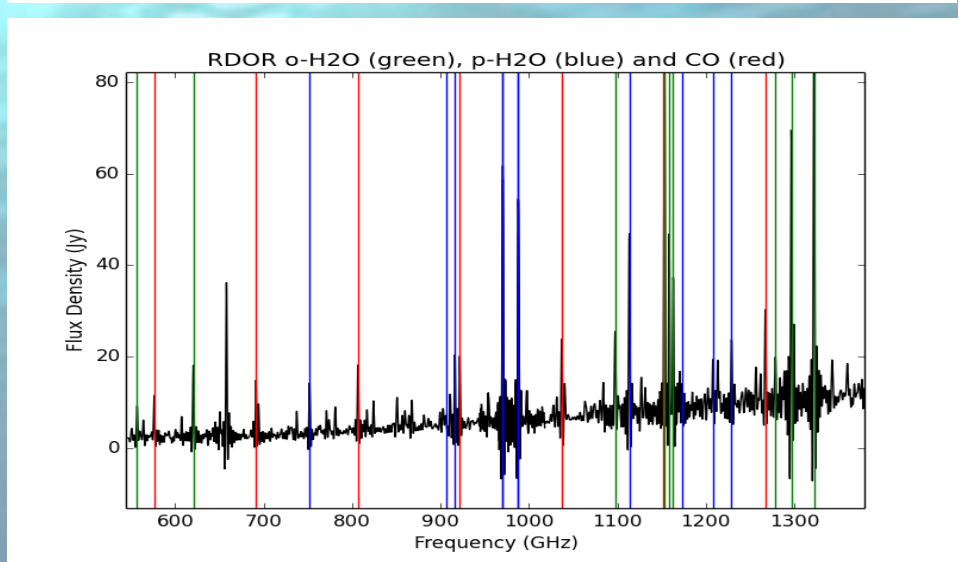
- Most O-rich AGB stars observed also display high-J CO lines + many ortho- and para- lines of warm water vapour

- Again, it suggests a non-equilibrium shocked chemistry in the inner regions of the circumstellar shell

- Rotational diagrams of CO and H_2O cannot be fit with one single temperature component

- Different lines form at different regions of the envelope





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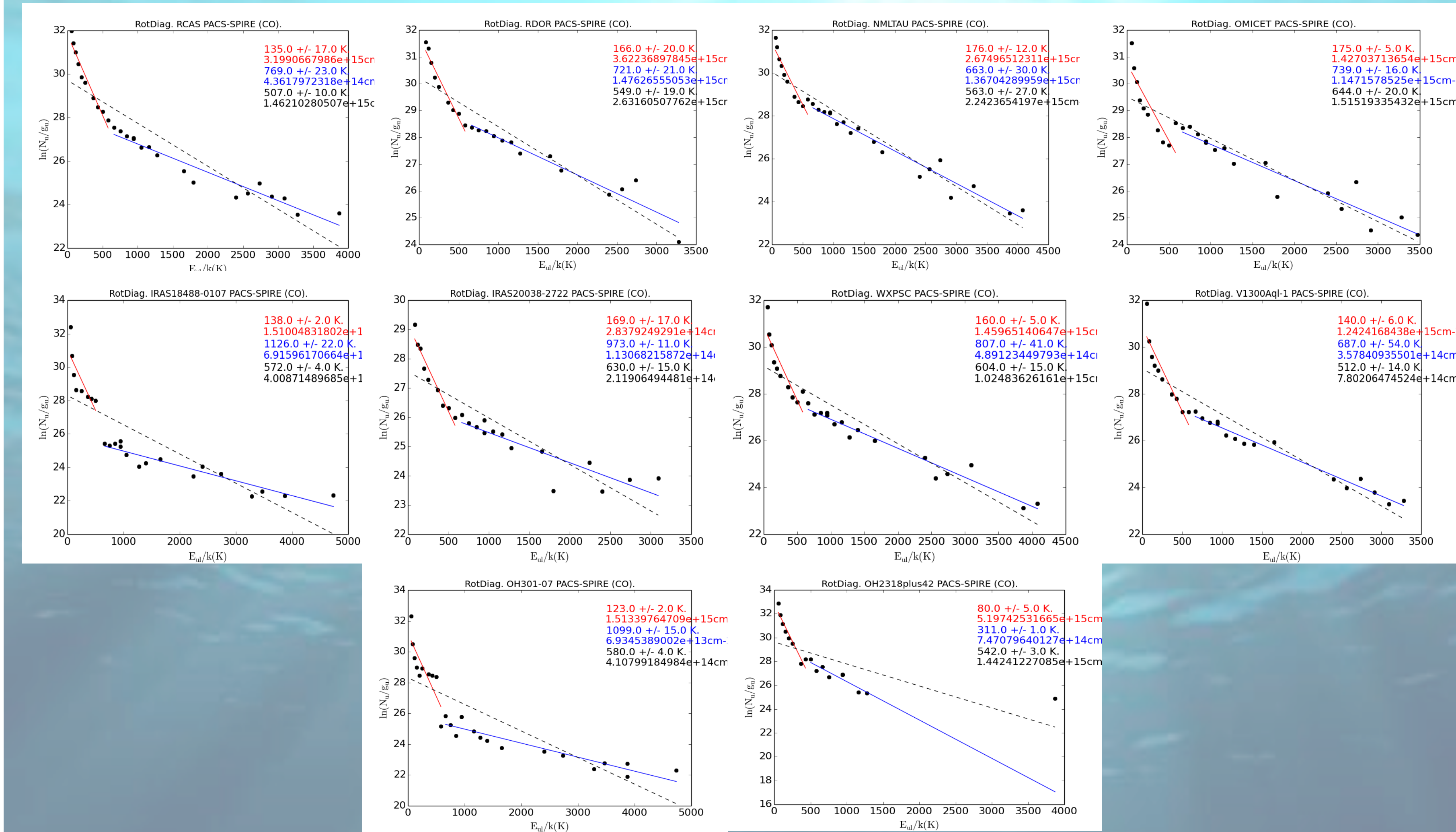
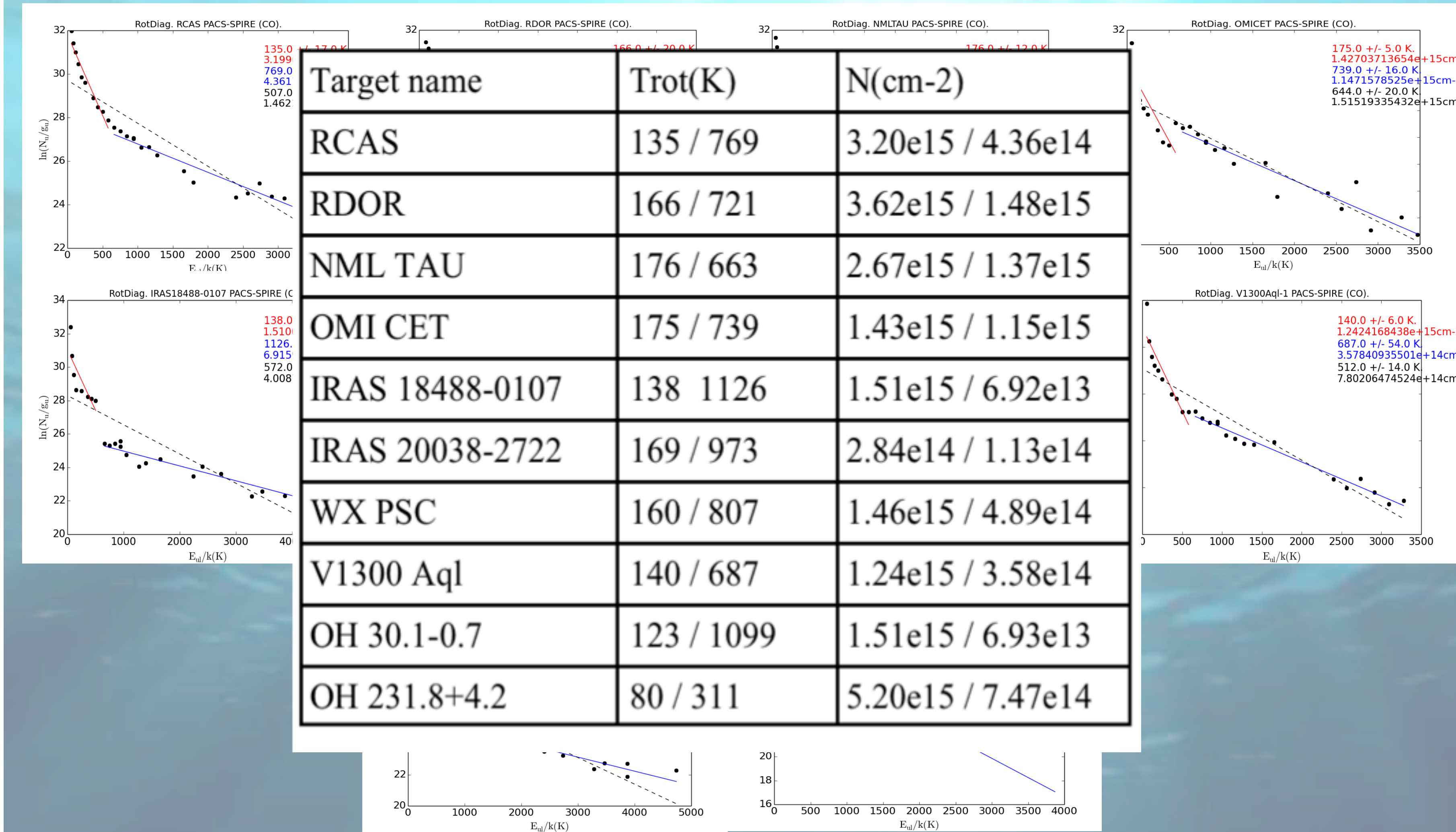
CO rotational diagrams



CO rotational diagrams



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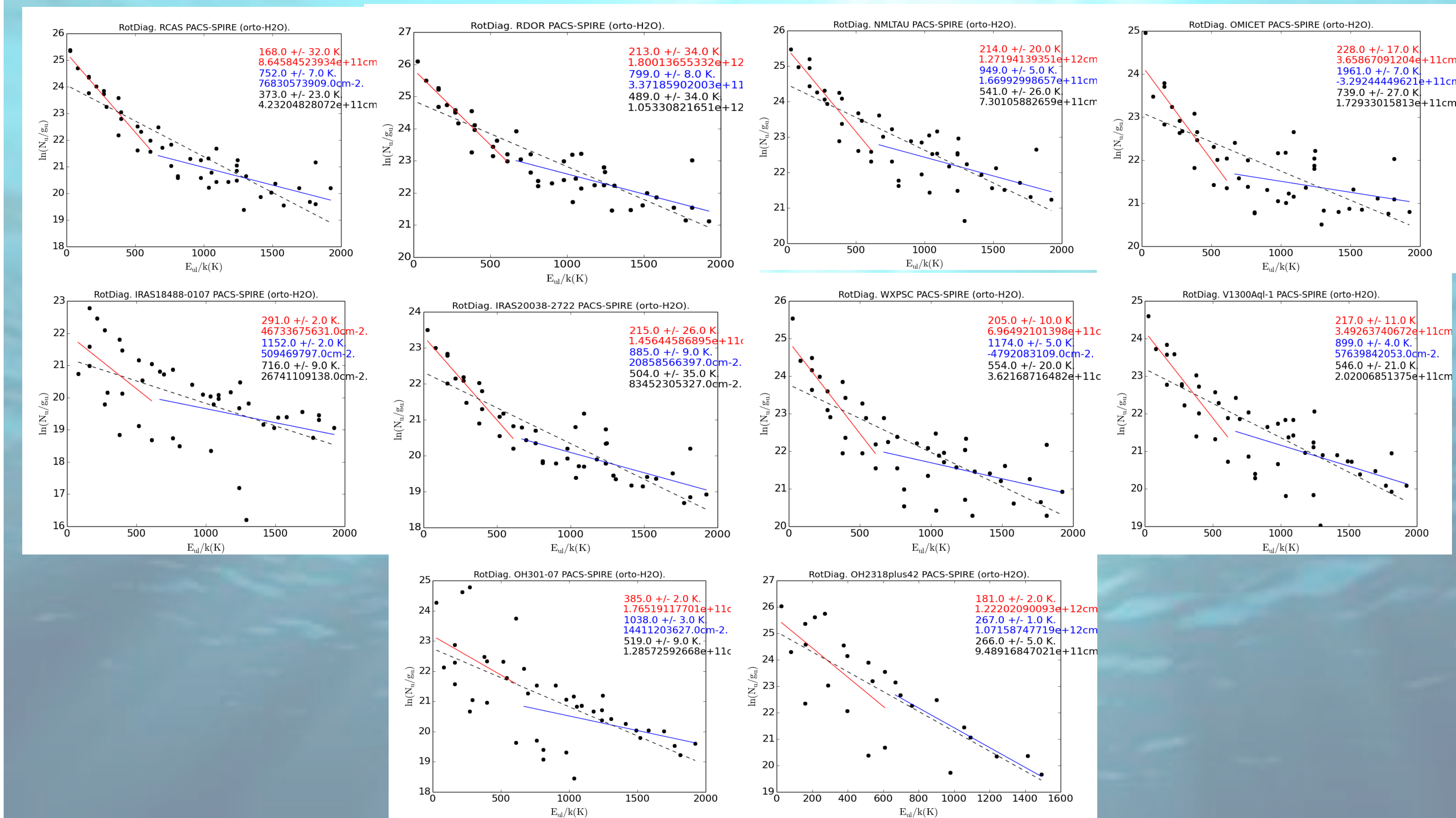
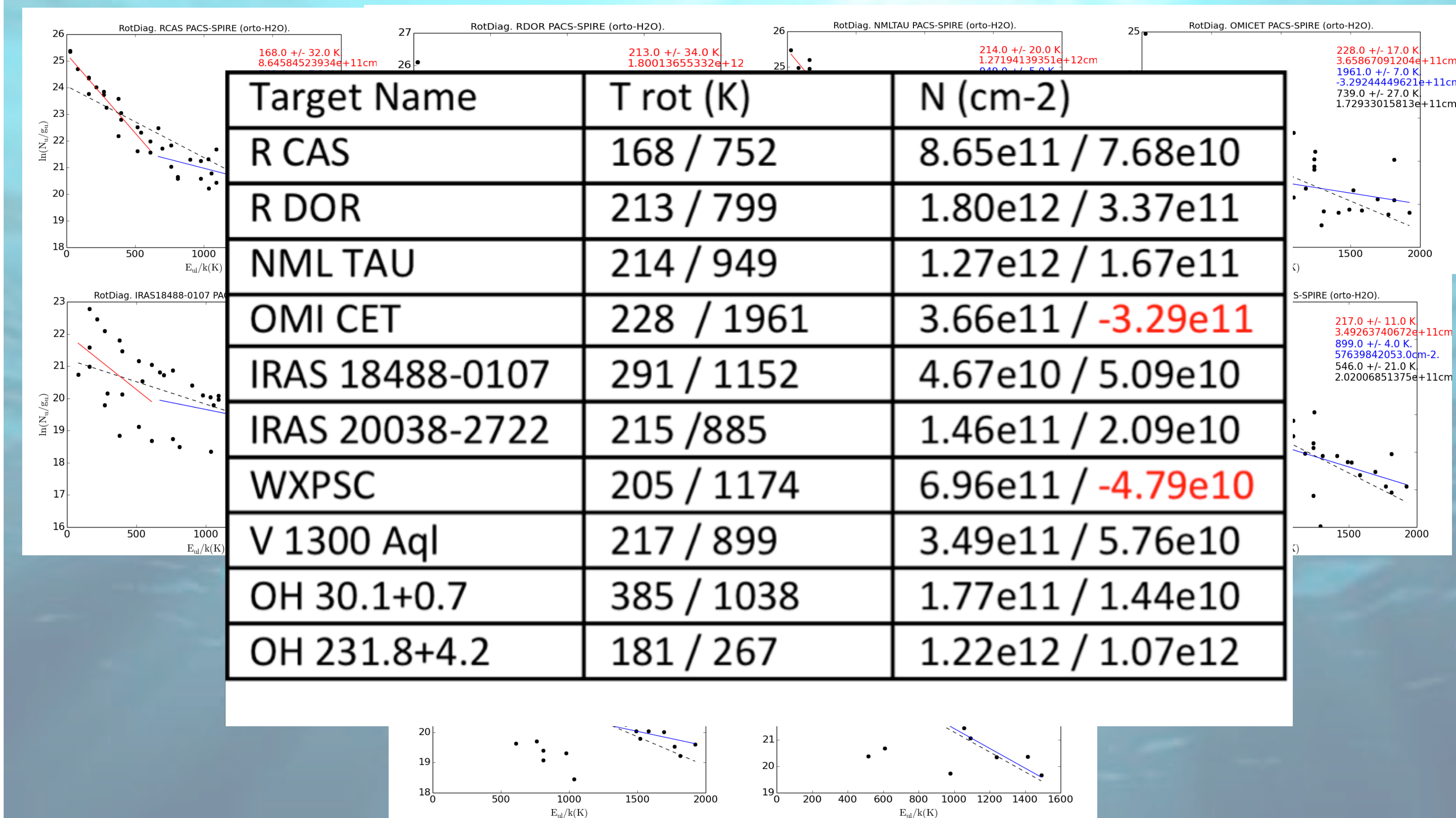
RCAS	135 / 769	3.20e15 / 4.36e14
RDOR	166 / 721	3.62e15 / 1.48e15
NML TAU	176 / 663	2.67e15 / 1.37e15
OMI CET	175 / 739	1.43e15 / 1.15e15
IRAS 18488-0107	138 1126	1.51e15 / 6.92e13
IRAS 20038-2722	169 / 973	2.84e14 / 1.13e14
WX PSC	160 / 807	1.46e15 / 4.89e14
V1300 Aql	140 / 687	1.24e15 / 3.58e14
OH 30.1-0.7	123 / 1099	1.51e15 / 6.93e13
OH 231.8+4.2	80 / 311	5.20e15 / 7.47e14

o-H_2O rotational diagrams



o-H_2O rotational diagrams



Target Name	T rot (K)	N (cm-2)
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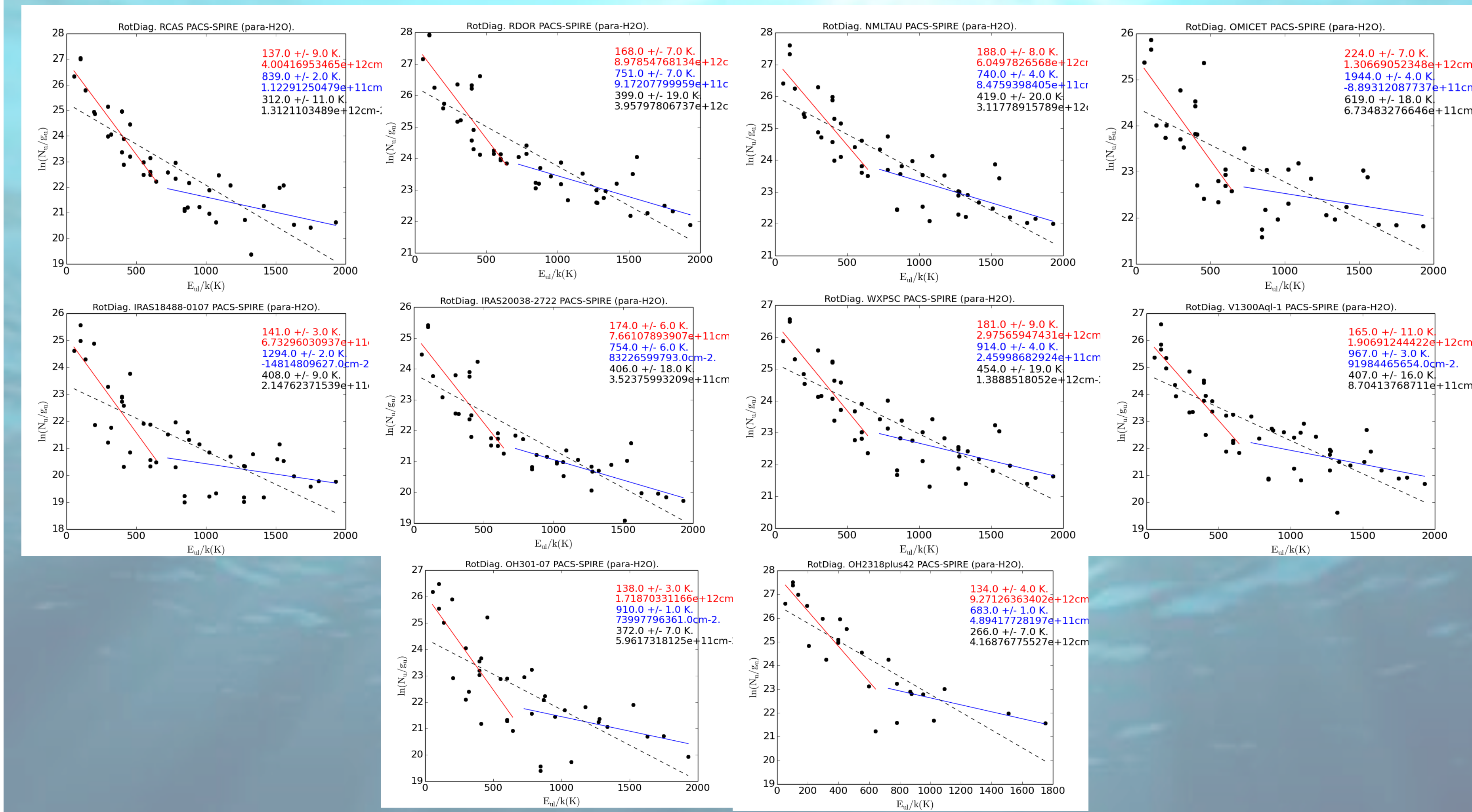
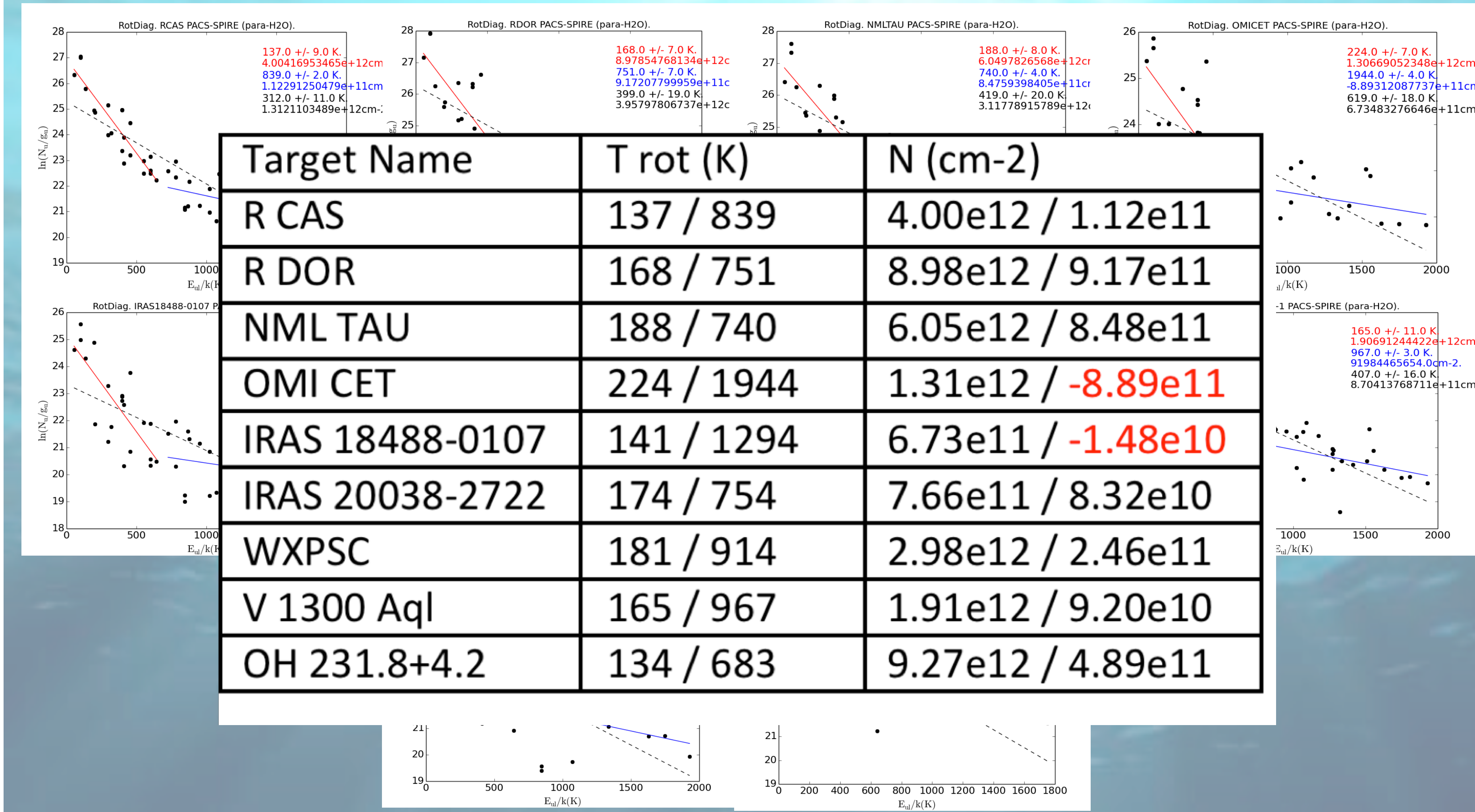
R DOR	213 / 799	1.80e12 / 3.37e11
NML TAU	214 / 949	1.27e12 / 1.67e11
OMI CET	228 / 1961	3.66e11 / -3.29e11
IRAS 18488-0107	291 / 1152	4.67e10 / 5.09e10
IRAS 20038-2722	215 /885	1.46e11 / 2.09e10
WXPSC	205 / 1174	6.96e11 / -4.79e10
V 1300 Aql	217 / 899	3.49e11 / 5.76e10
OH 30.1+0.7	385 / 1038	1.77e11 / 1.44e10
OH 231.8+4.2	181 / 267	1.22e12 / 1.07e12

p-H_2O rotational diagrams

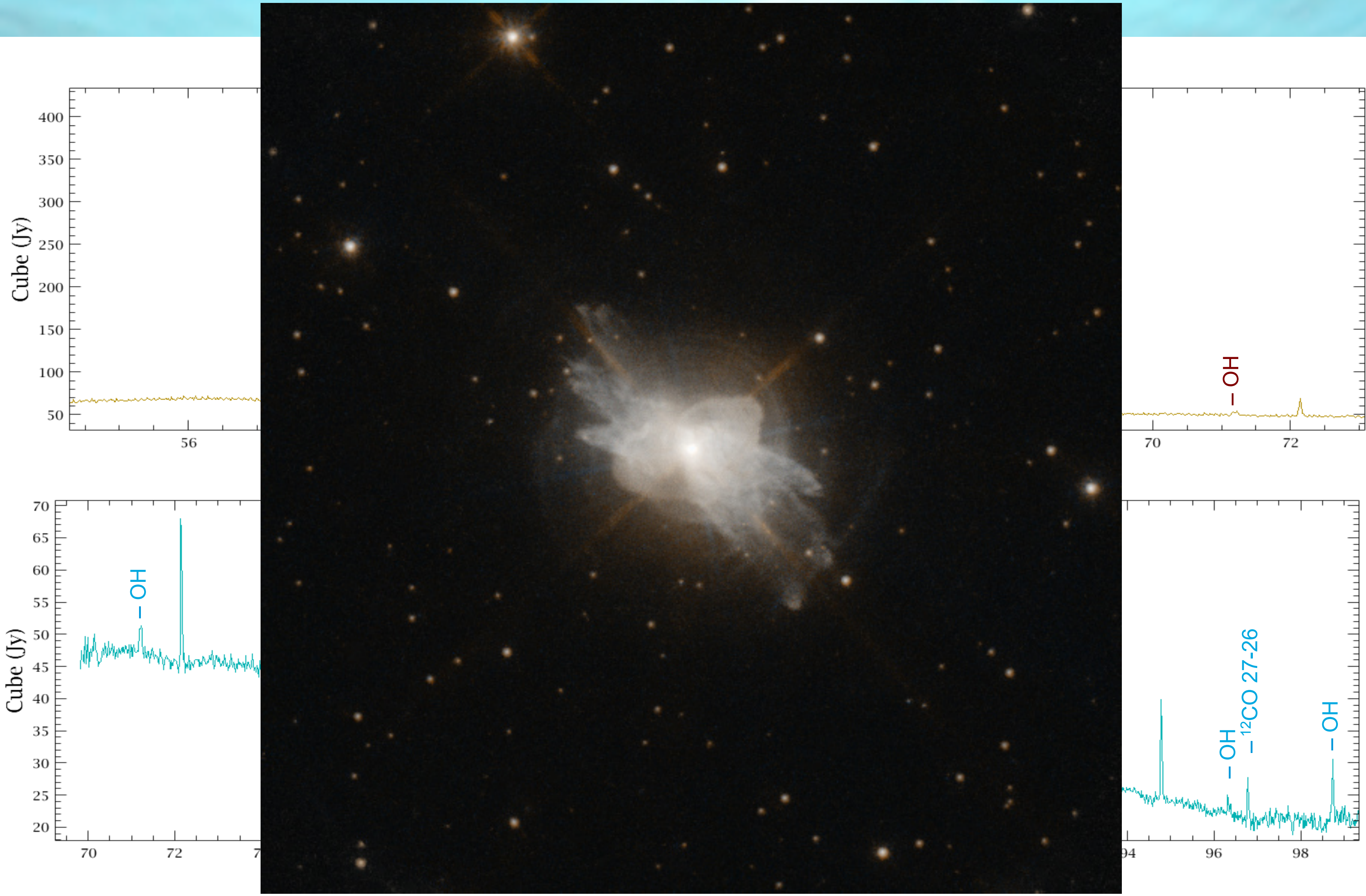


p-H_2O rotational diagrams



Target Name	T rot (K)	N (cm-2)
R CAS	137 / 839	4.00e12 / 1.12e11
R DOR	168 / 751	8.98e12 / 9.17e11
NML TAU	188 / 740	6.05e12 / 8.48e11
OMI CET	224 / 1944	1.31e12 / -8.89e11
IRAS 18488-0107	141 / 1294	6.73e11 / -1.48e10
IRAS 20038-2722	174 / 754	7.66e11 / 8.32e10
WXPSC	181 / 914	2.98e12 / 2.46e11
V 1300 Aql	165 / 967	1.91e12 / 9.20e10
OH 231.8+4.2	134 / 683	9.27e12 / 4.89e11

High-J CO and water in post-AGB stars (IRAS 16594-4656)



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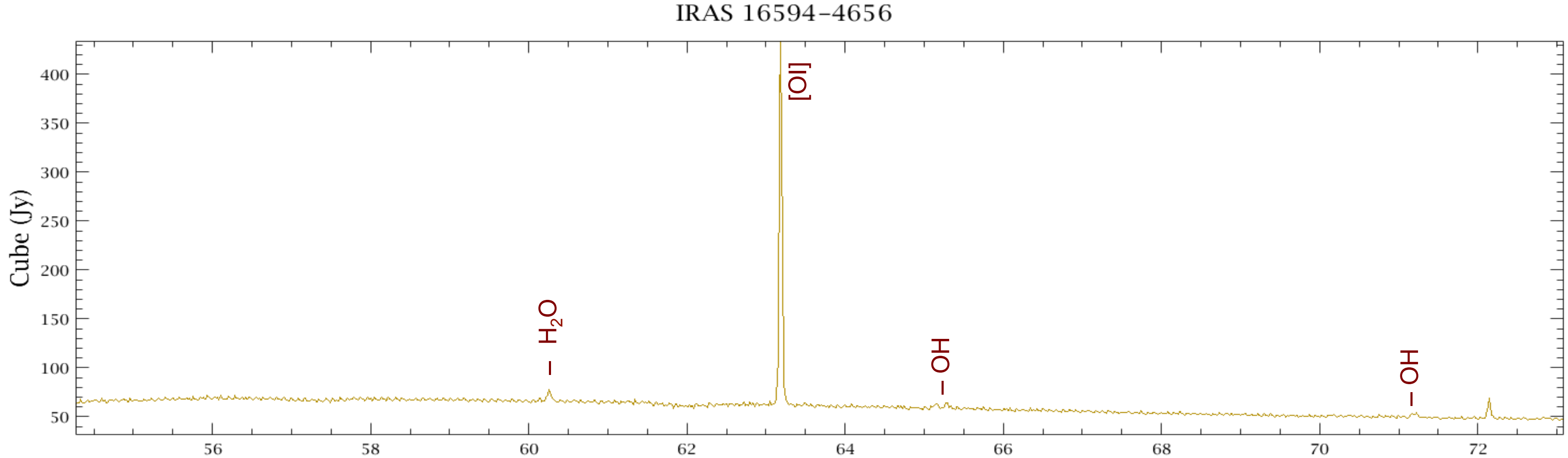

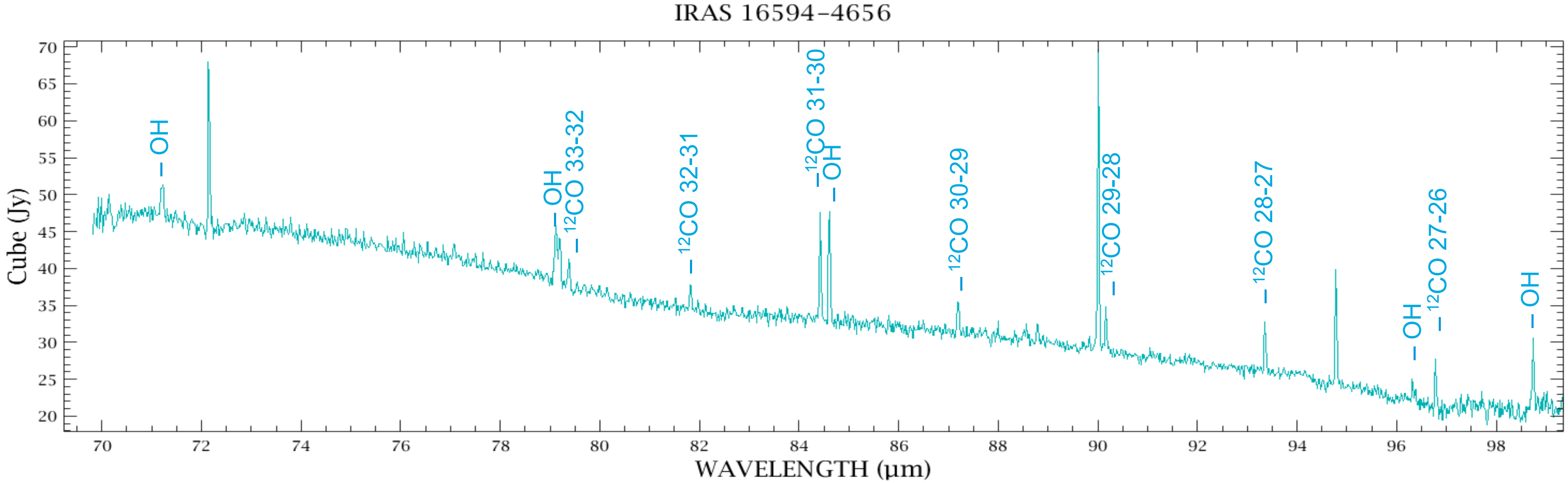

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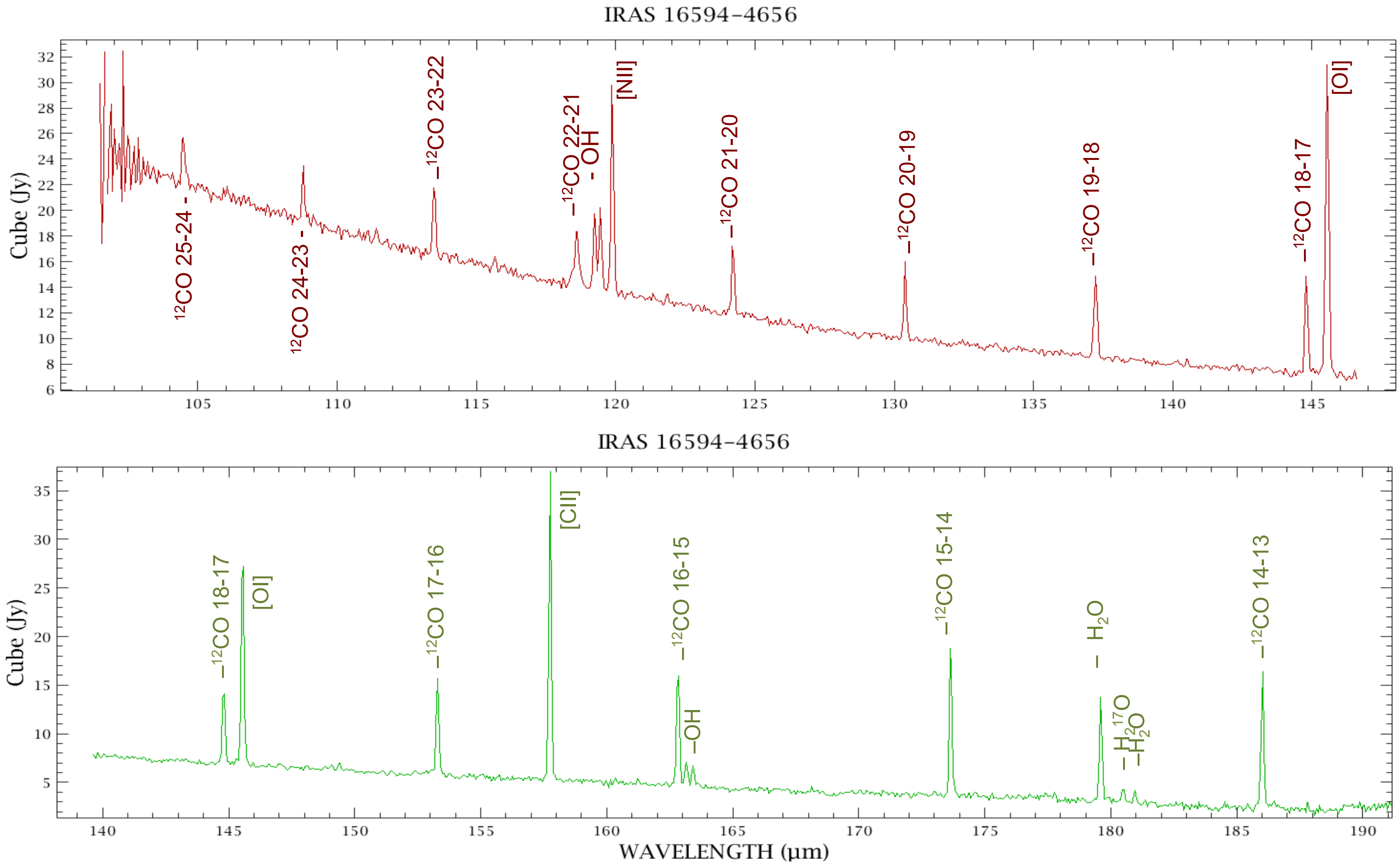
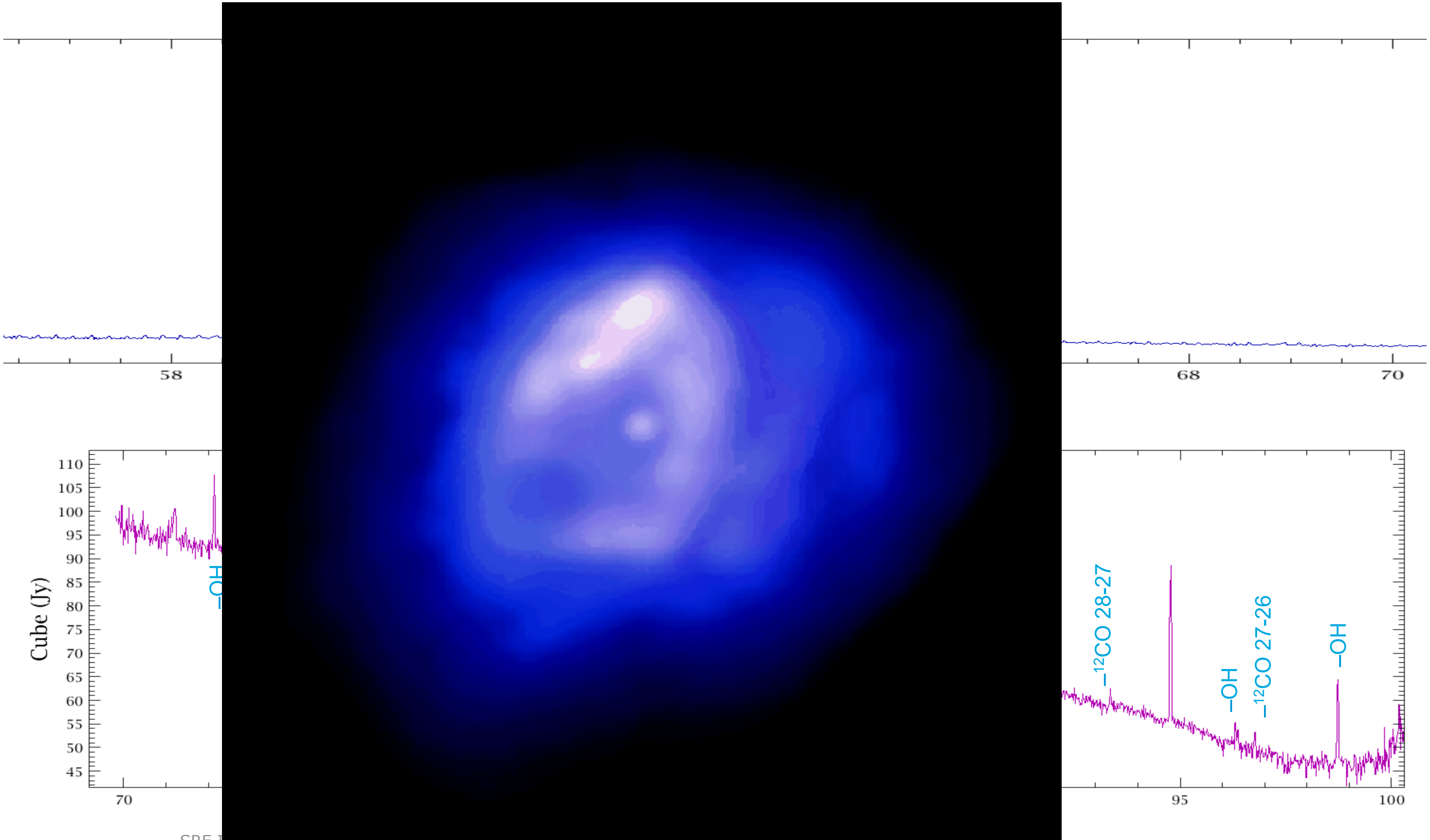
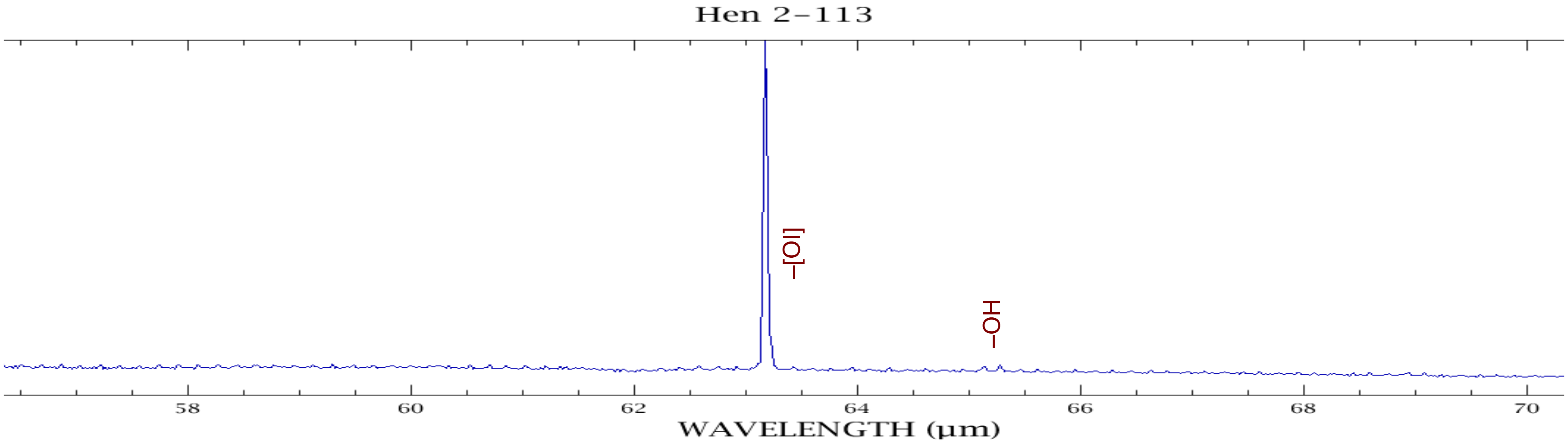
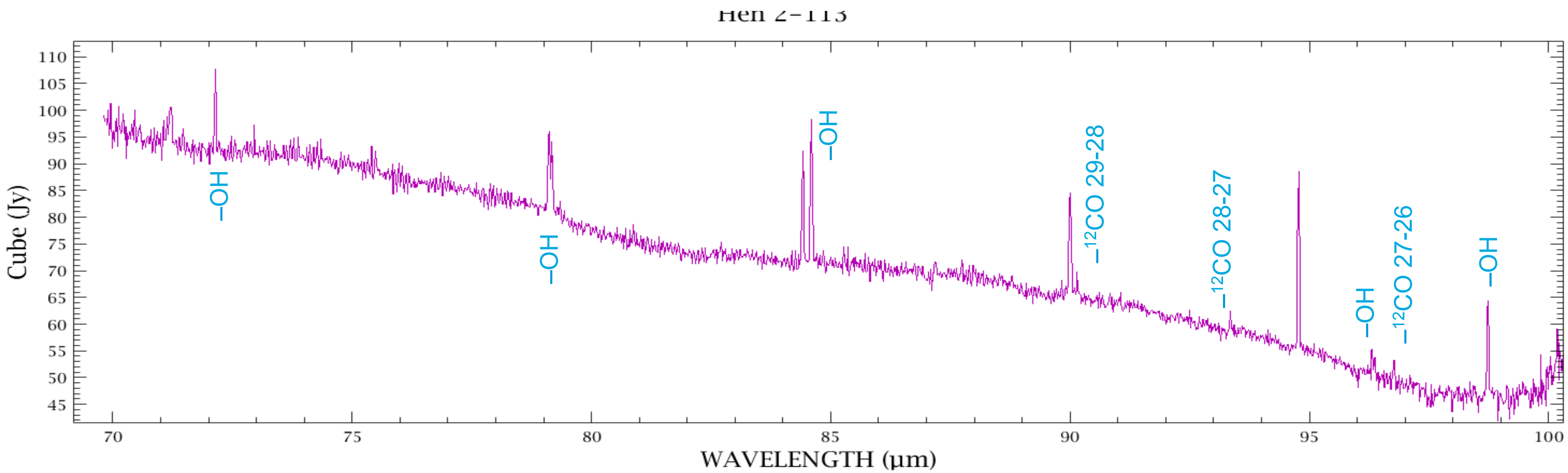


High-J CO and water in young PNe (Hen 2-113)

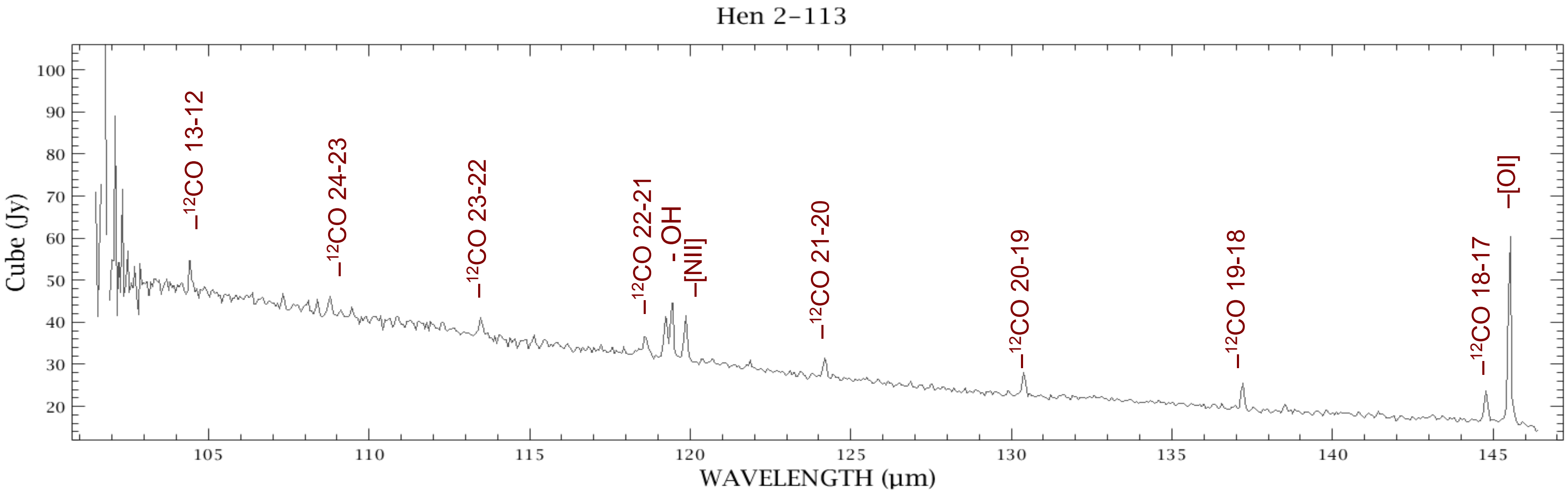


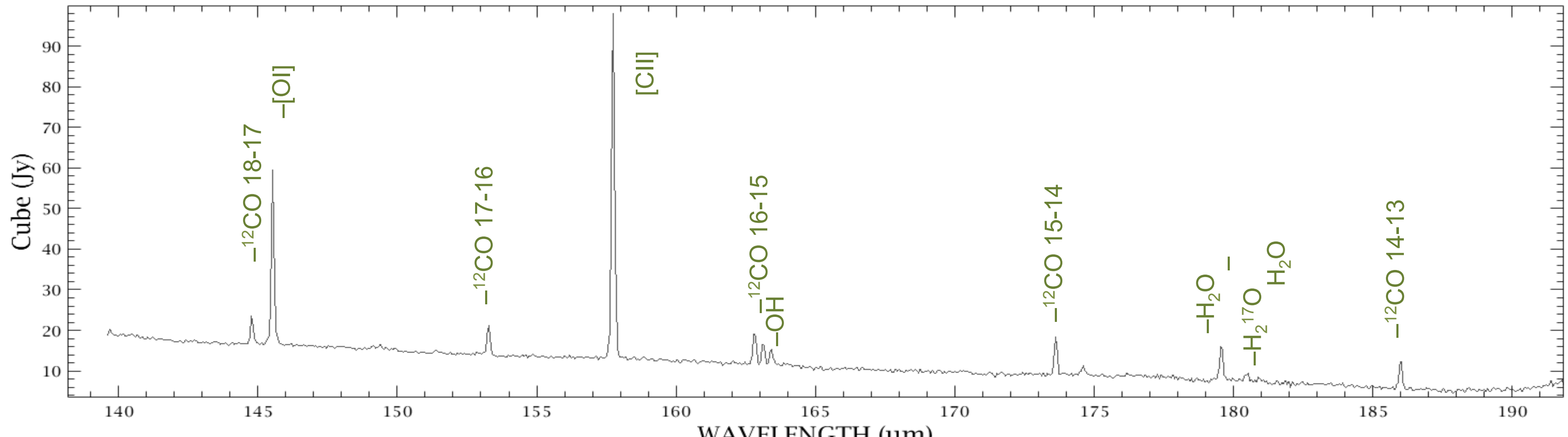
High-J CO and water in young PNe (Hen 2-113)





Herschel spectroscopic results (Hen 2-113)





Conclusions

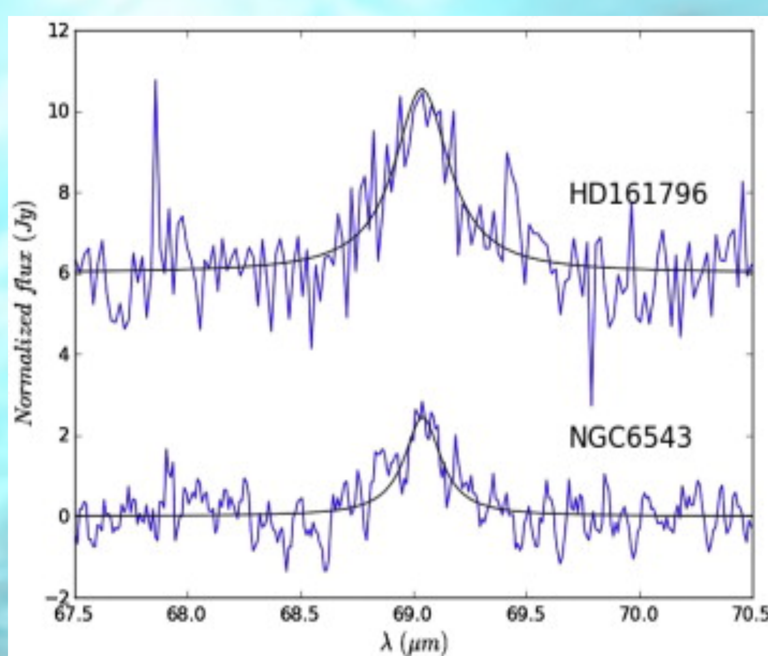
- We have presented the detection of a large number of water vapour emission lines in the Herschel spectra of evolved stars, including high-excitation lines which can only be explained if the water is formed in the warm inner regions of their envelopes. The high-J rotational CO lines detected in these sources seem to trace the same inner regions of the circumstellar envelope.
- A plausible explanation for the warm water observed appears to be the out-of-equilibrium shock chemistrydominating in the regions close to the central star induced by their pulsation, while photodissociation in the outer regions of the envelope by the interstellar UV field may be responsible for the formation of the lower excitation water emission associated to lower temperatures.
- The analysis of a large sample of evolved stars with THROES may provide the wide picture missing if we restrict our analysis to only a few individual sources; it is important to determine the relevance of the dominant chemistry, mass loss rate and evolutionary stage in the water abundances observed.
- It would be interesting to further investigate the anti-correlation of the water abundance with mass loss in connection with a scenario in which the formation of SiO and H_2O are competing in the presence of shocks. SiO would form preferentially at higher mass-loss rates. These shocks could also be the responsible to transform amorphous silicate into crystalline silicate in the envelopes of O-rich AGB stars.

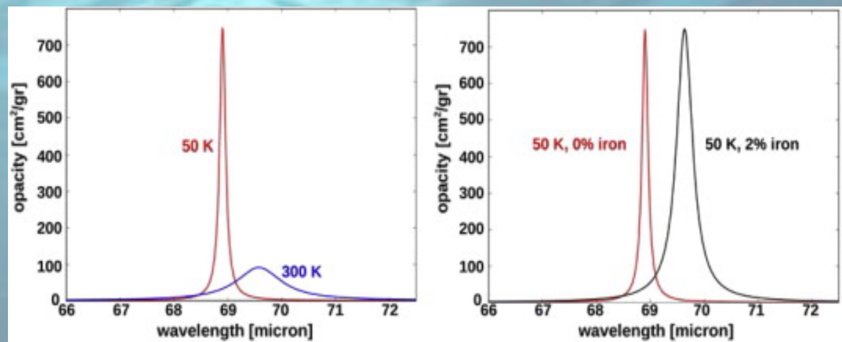
Appendix: solid state features

- Herschel/PACS overlaps with ISO/ LWS range, providing much higher S/N and better spectral resolution

- However, so far, only the detection of forsterite at 69μm has been confirmed in most O-rich transition sources observed
- Variable shape and central wavelength used as a dust thermometer and to determine the content of Fe in these grains (de Vries et al. 2011)

- Other features not found so far
  - Crystalline water ice at 61μm
  - Hibonite at 78μm
  - Calcite at 92.6μm
  - PAHs?





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