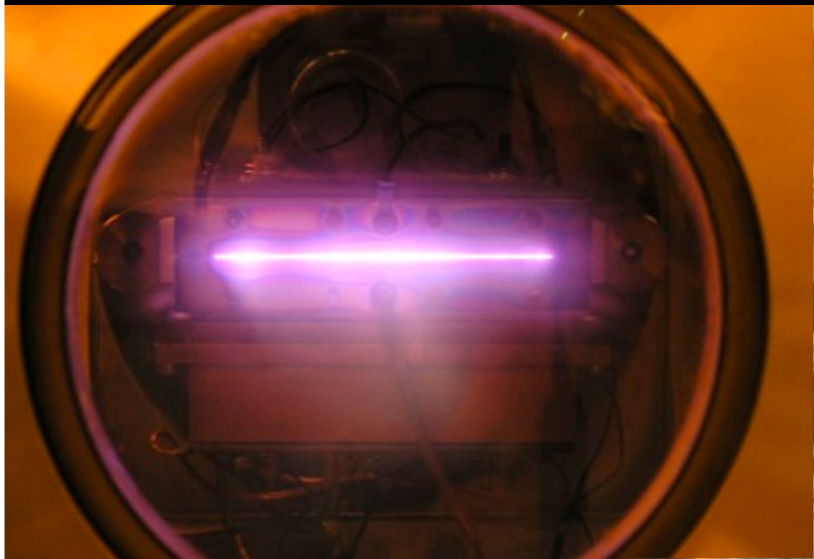
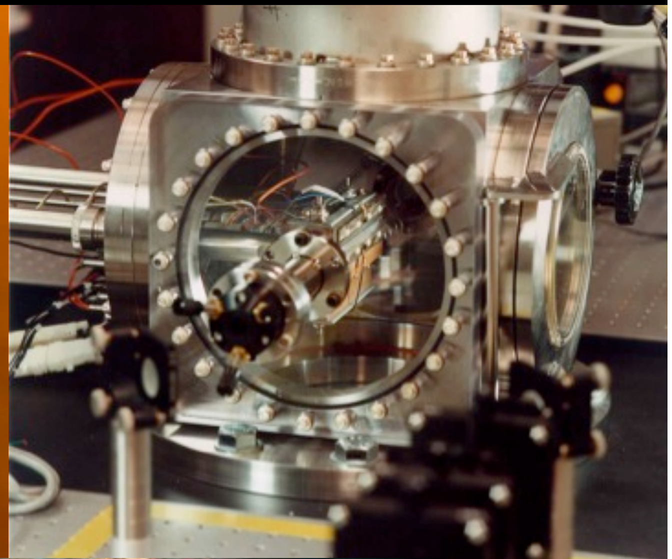
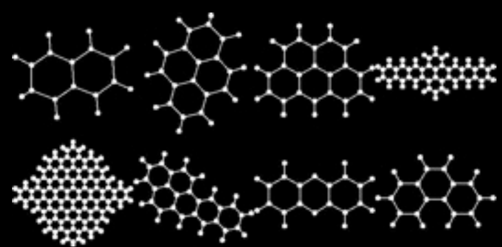
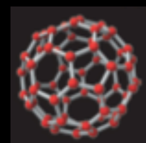
Organic Carbon in the Molecular Universe
Laboratory Astrophysics Studies of Cosmic Dust Analogs





Farid Salama
NASA Ames Research Center





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Ames Research Center


Space Environments
Interstellar Medium &
Star-Forming Regions
Earth-Moon System, Outer Planets & Moons
(Titan) and Interplanetary Space
Laboratory & Space Exposure
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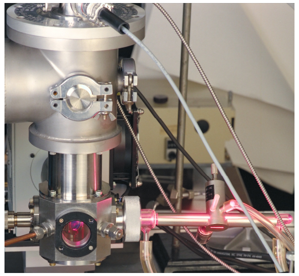

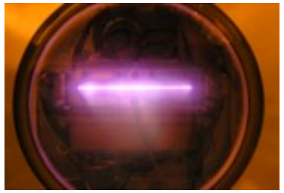

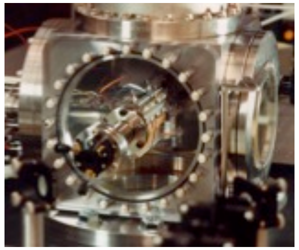

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Laboratory Astrophysics & Astrochemistry: Cosmic Simulation Chamber (COSmIC) UV-Vis-NIR, MS Lab Facility

Simulation Chambers for the Formation/Processing and the Analysis of Interstellar, Planetary and Lunar materials

Research Theme: The Molecular Universe

Current Research Projects:

Astrophysics & Astrochemistry:

- Search for the signature of carbon molecules (PAHs, fullerenes, ...) UV/Vis/NIR
- Nature molecular carriers contributing to Galactic and Extragalactic extinction
- Molecular carriers of the Diffuse Interstellar Bands (DIBs) UV/Vis/NIR (HST/COS; JWST; VLT/EDIBLES)
- Formation of circumstellar and interstellar carbon grains from molecular precursors (HST/COS; JWST).
- Complex organic molecules in space (ISS/EXPOSE-R/EXOcube).

Solar System:

- Formation of aerosols in the atmosphere of Titan (Cassini).
- Complex organic molecules in space (ISS/EXPOSE-R/EXOcube).

Lunar:

- Dust Activation/Mitigation (surface reactivity).

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Astrophysics:

- Energy budget and signature of aromatic carbon molecules
- PAHs & Grain formation

Planetary:

- Titan’s atmosphere (haze)

ISS:

- Exposure experiments on complex organic molecules

Astrophysics:

- Energy budget and signature of aromatic carbon molecules
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ISS:

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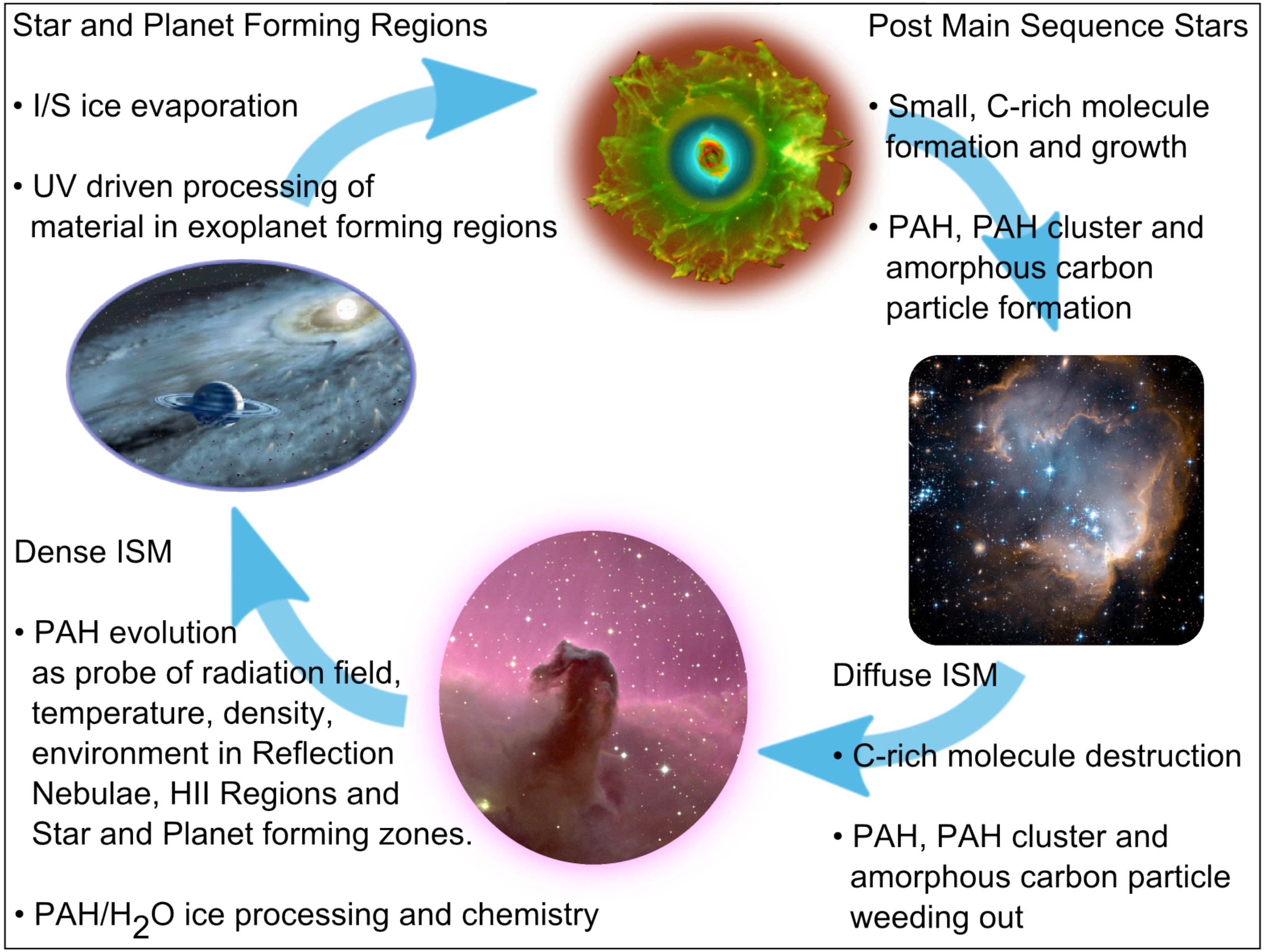
The Stellar Life Cycle and Evolution of Cosmic Carbon



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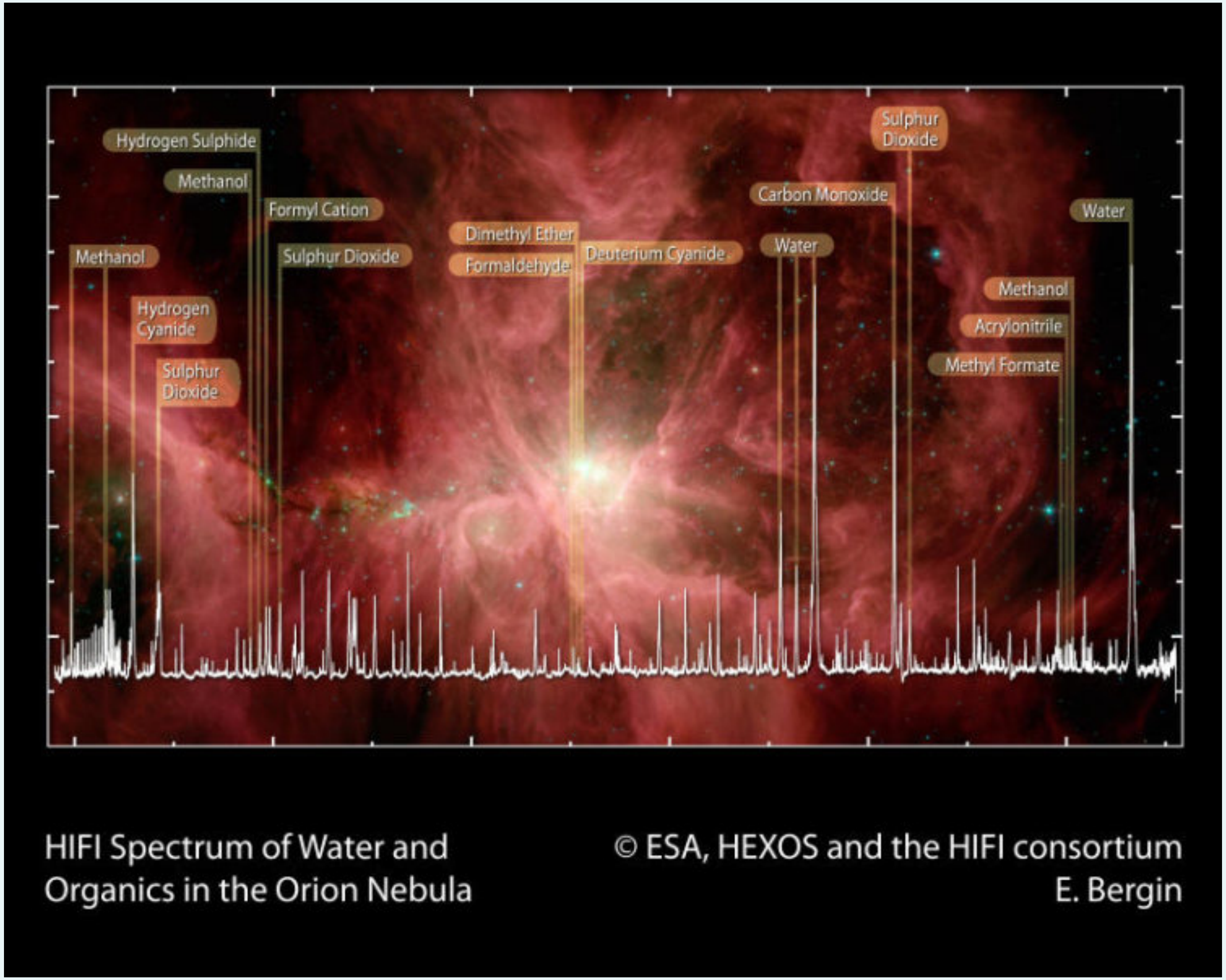
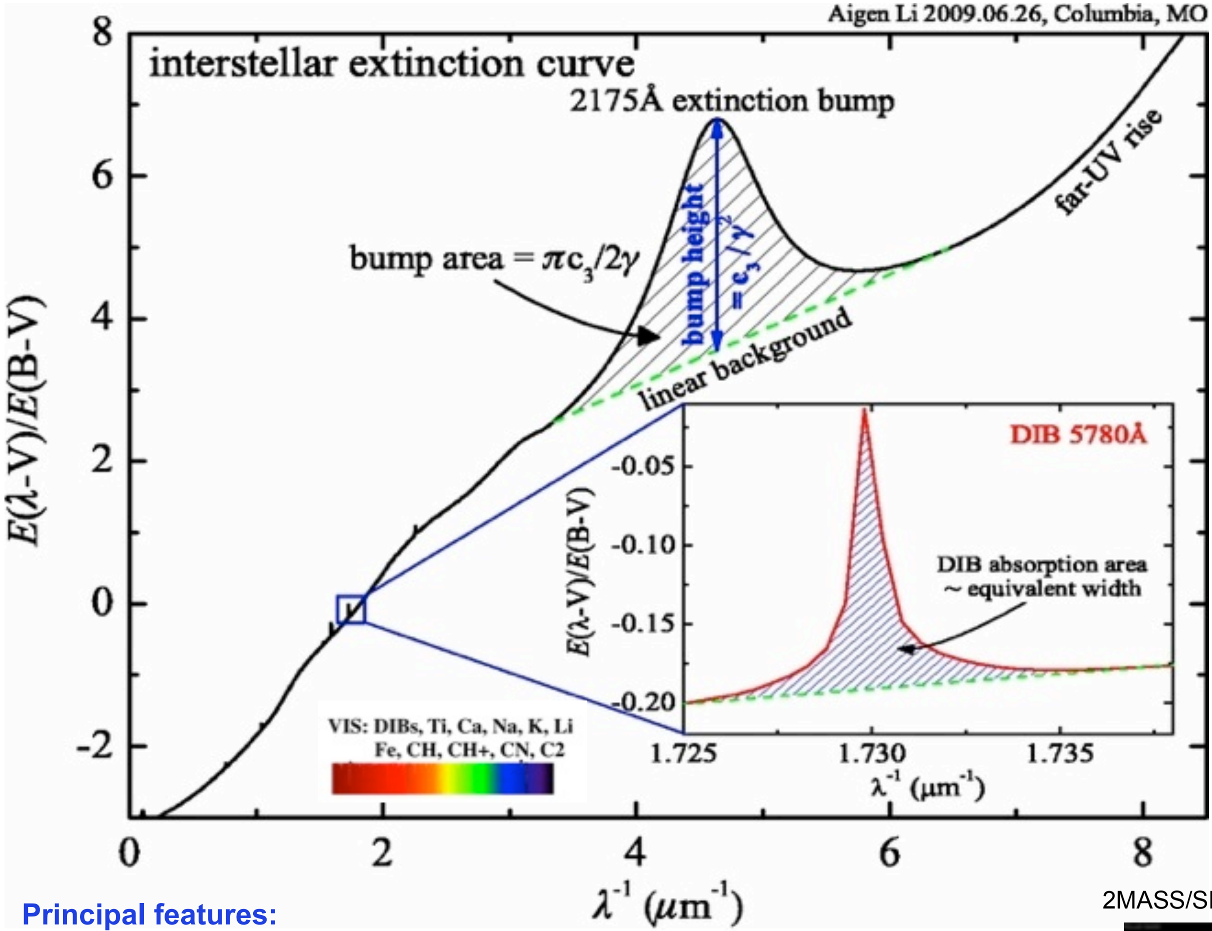
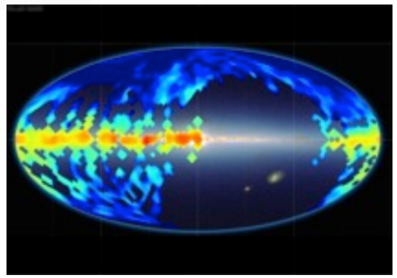

Hydrogen Sulphide
Methanol
Formyl Cation
Sulphur Dioxide
Methanol
Hydrogen Cyanide
Sulphur Dioxide
Dimethyl Ether
Formaldehyde
Deuterium Cyanide
Carbon Monoxide
Water
Sulphur Dioxide
Water
Methanol
Acrylonitrile
Methyl Formate
HIFI Spectrum of Water and Organics in the Orion Nebula
© ESA, HEXOS and the HIFI consortium
E. Bergin

Composition of IS Dust: Observed Spectral Features

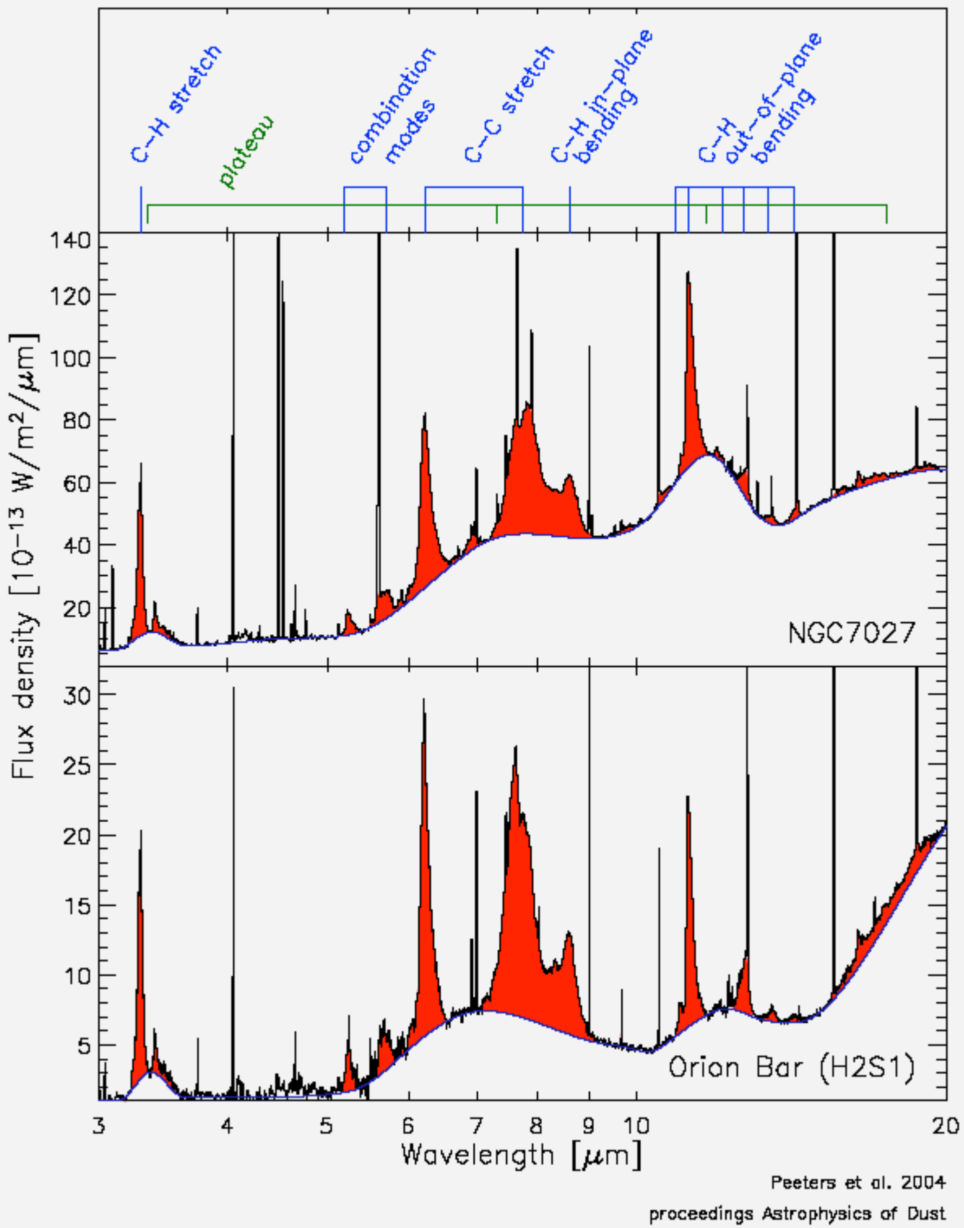


2MASS/SDSS MW DIB survey H Band



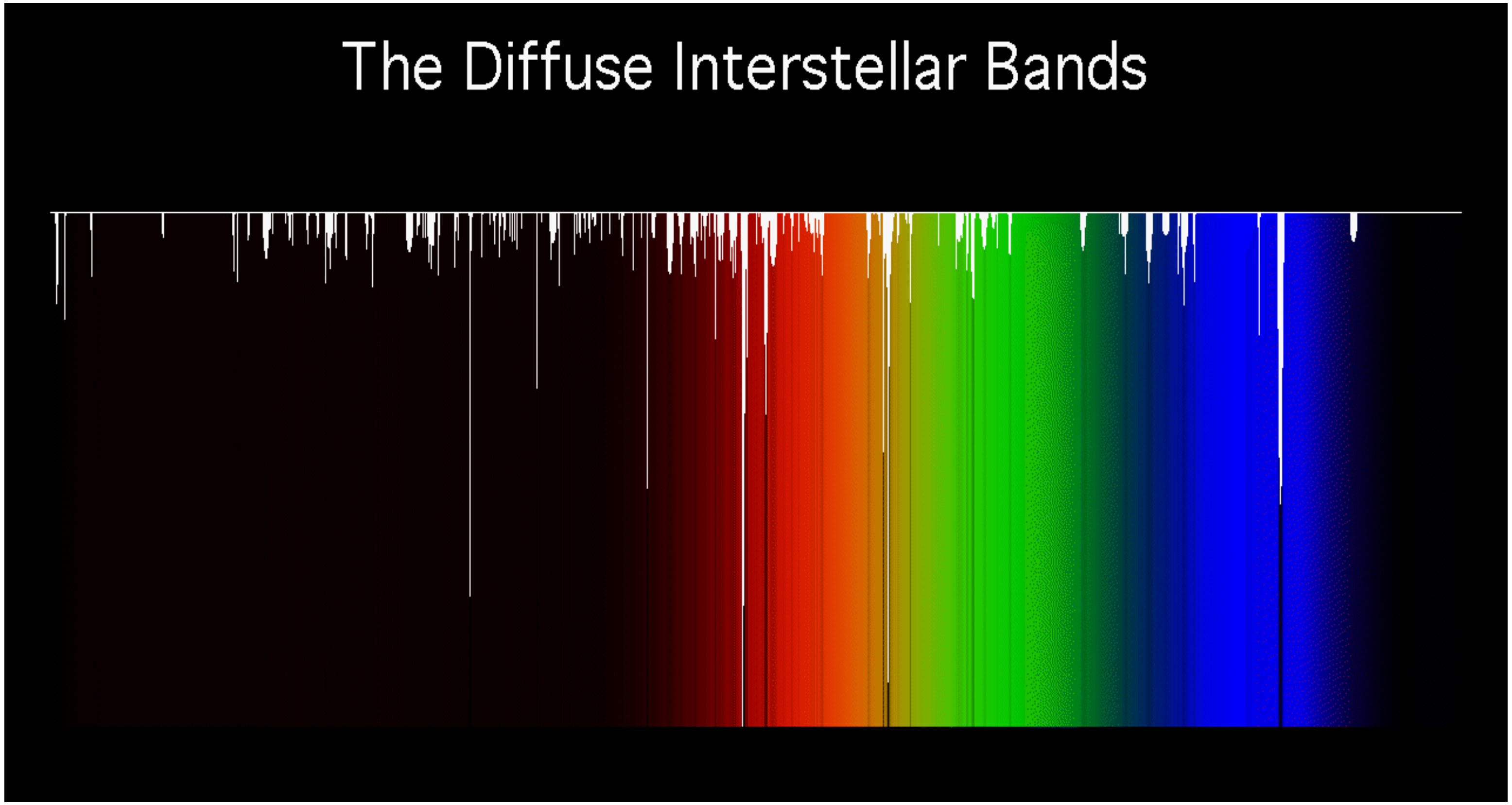
Principal features:

– General rise from IR to VUV (~ 0.1 µm)
– 18 µm and 10 µm: O-Si-O bend and Si-0 stretch in amorphous silicates
– 3.4 µm: C-H stretch in hydrocarbons
– 0.2175 µm (~4.6 μm^{-1}): “2200 Å bump”. Probably $\pi \rightarrow \pi^*$ electronic transition in sp2-bonded carbon (e.g., graphite or PAH)
– > 400 weak features – the Diffuse Interstellar Bands (DIBs) – still unidentified.



The IS emission spectra represent the composite emission of a complex mixture of aromatic compounds. The features are not resolvable, but show subtle variations.

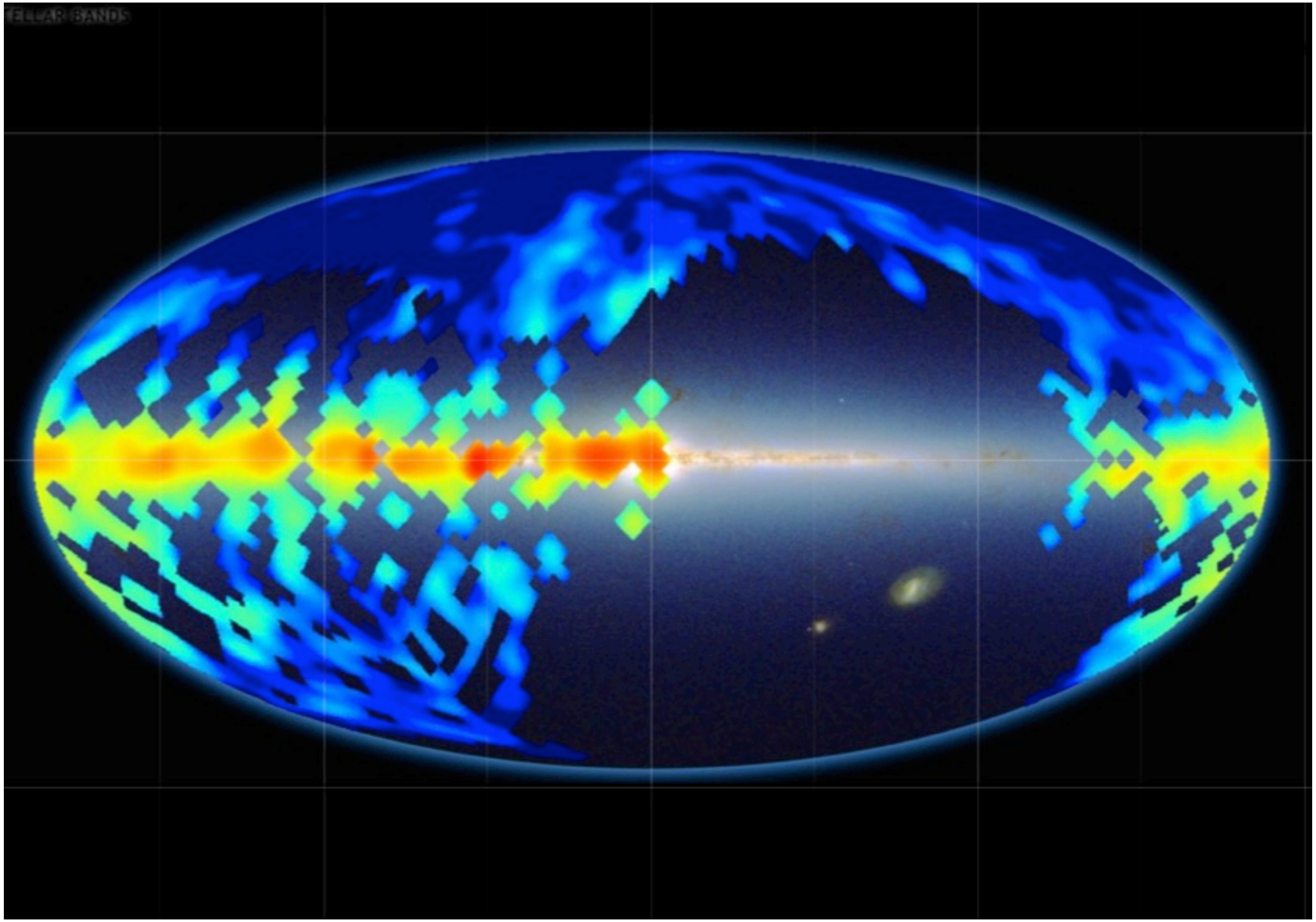
The ISO-SWS spectra of the planetary nebula NGC 7027 and the Photo-Dissociation region at the Orion Bar illustrate the richness and variety of the UIR spectrum. Also indicated are the aromatic mode identifications of the major UIR features (Adapted from Peeters *et al.*, 2004, Astrophysics of Dust)



- First discovered in 1922
- Of interstellar origin - ubiquitous carrier(s) - very stable
- Currently > 300 known DIBs (Narrow: 1-2 Å to Broad: 20 Å)
- DIBs fall at constant wavelengths
- Spectral fingerprint of molecules in space
- Superimposed on IS extinction curve

- 1922: Heger 2
- 1934: Merrill 4
- 1975: Herbig + 39
- 1995: Herbig + 127
- 2000: O' Tuairisg + 226
- 2003: York > 400

Map of the Diffuse Interstellar Bands in the Milky Way



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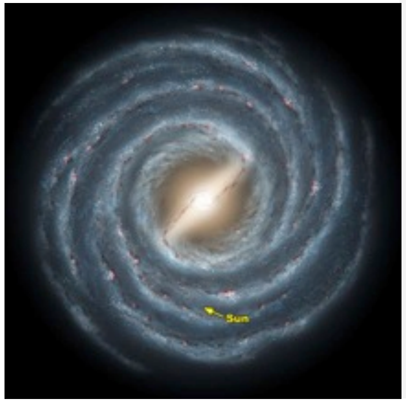
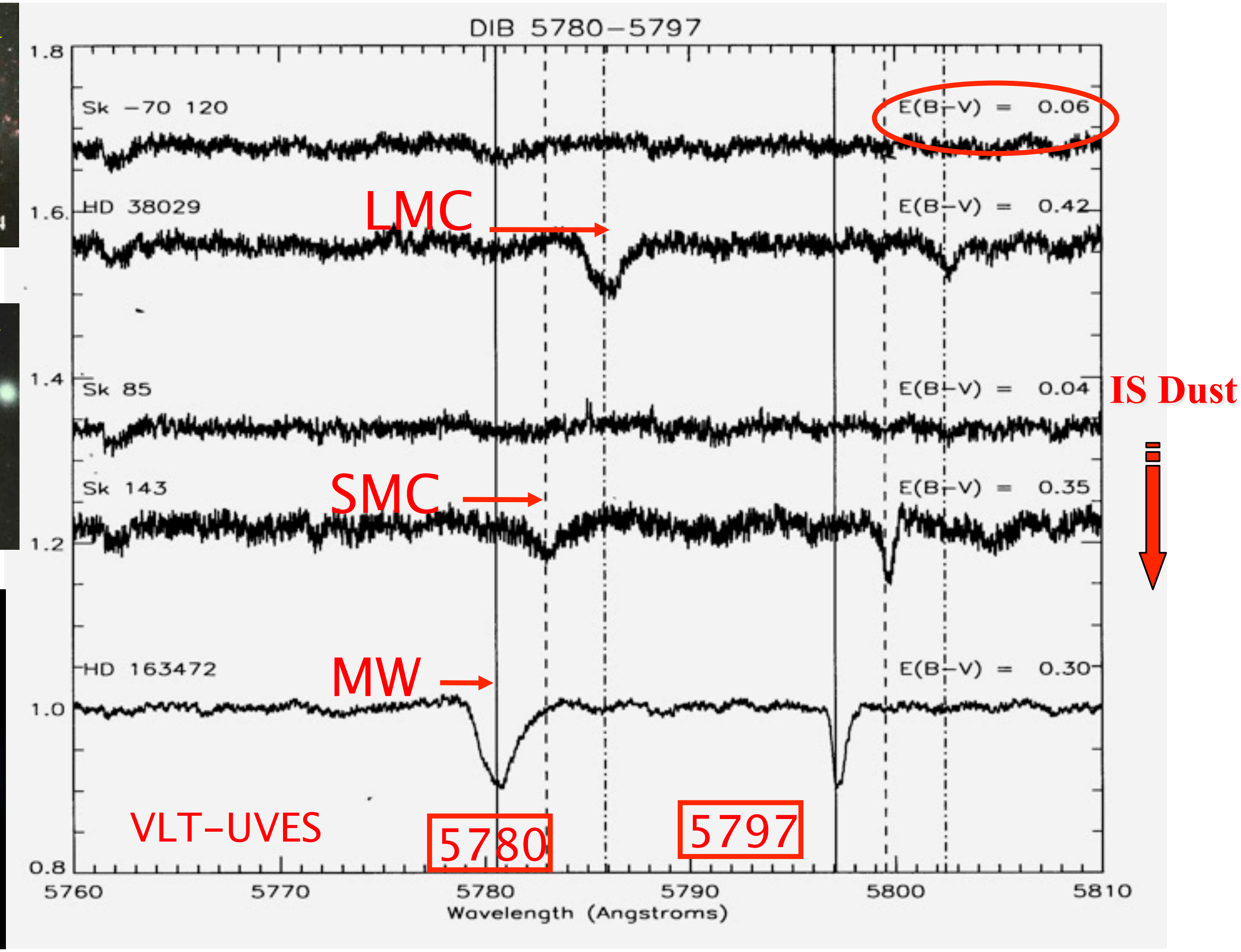
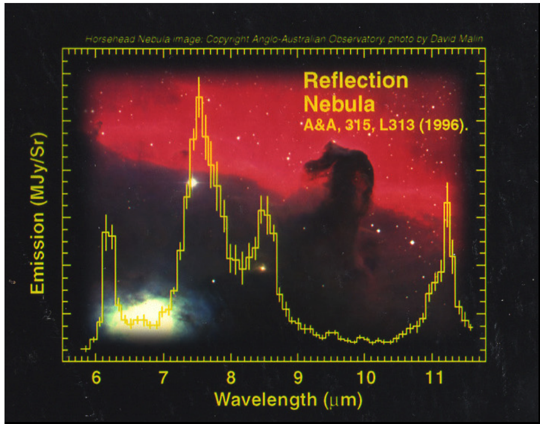
Diffuse Interstellar Bands in the Magellanic Clouds



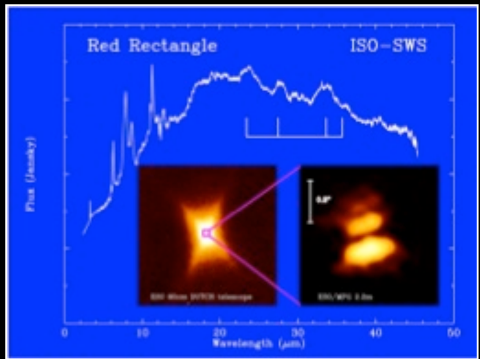


Salama et al. ApJ 1999; Ehrenfreund et al. ApJ 2002

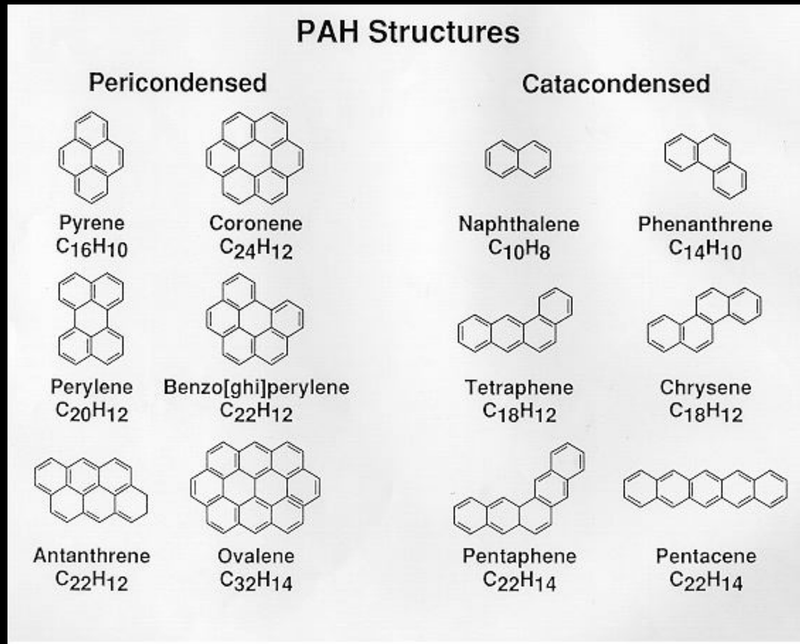
Polycyclic Aromatic Hydrocarbons

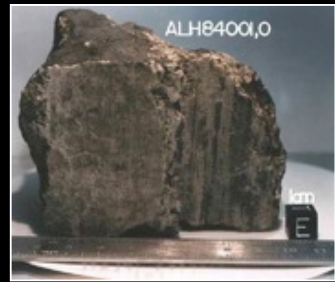


ISM Infrared Emission

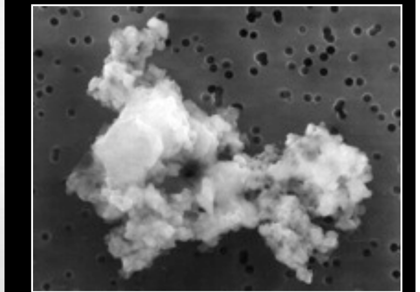


RR Blue Luminescence

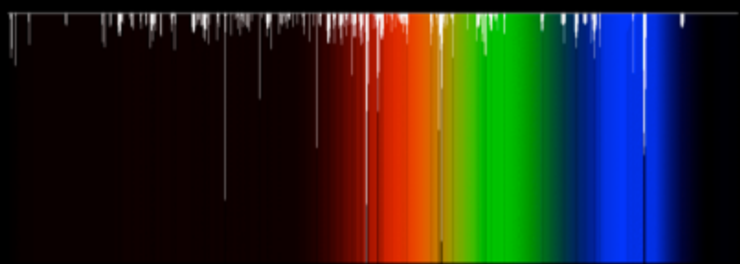




Meteorites

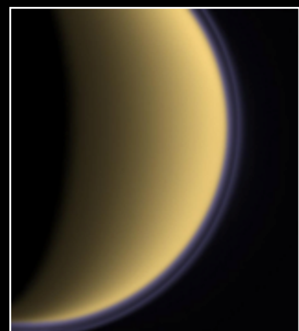


IDPs



DIBs

Comets



Planetary Atmospheres,
Rings & Surfaces

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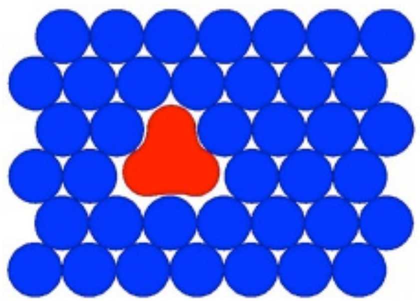
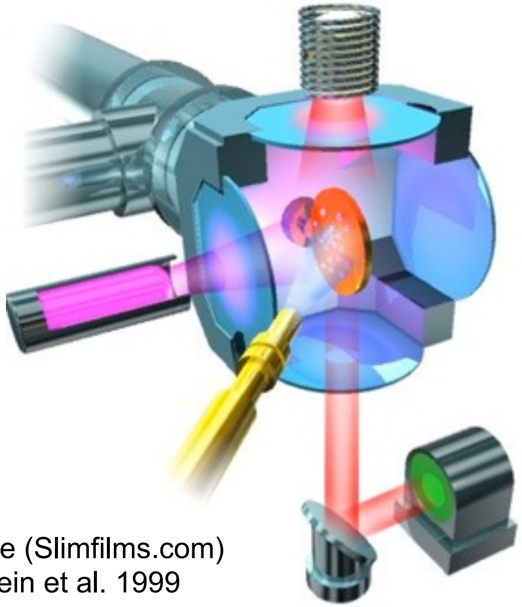
Measuring laboratory spectra under astrophysically relevant conditions -

Requirements: Molecules & Ions: 1: Free - 2: Cold - 3: Exposed to VUV photons



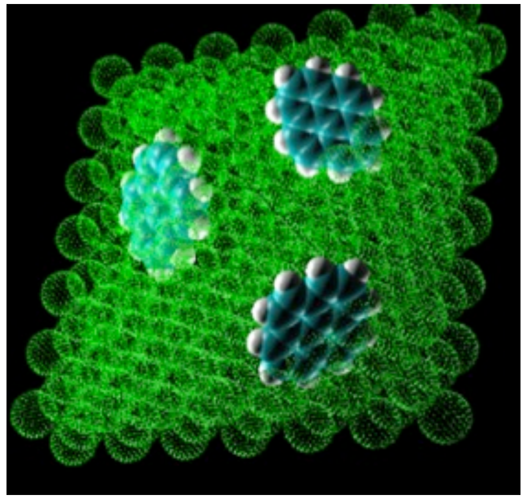
Matrix Isolation Spectroscopy (MIS) provides:

- Low temperature (5 K)
- Low density (molecule/ion fully isolated)
- High-energy photons (VUV)
- Solid phase



A. Christie (Slimfilms.com)
in Bernstein et al. 1999

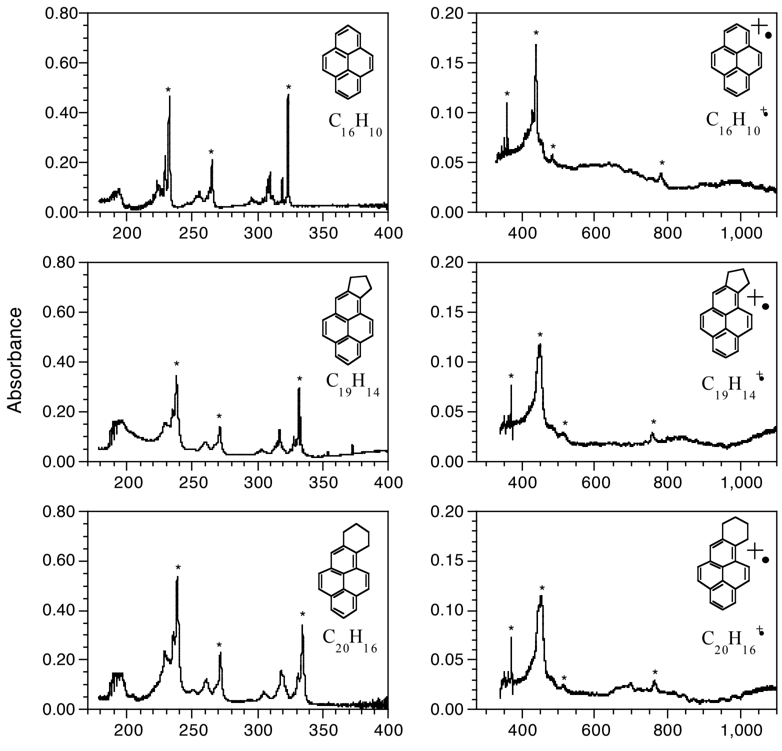
Ne Matrix-embedded molecules

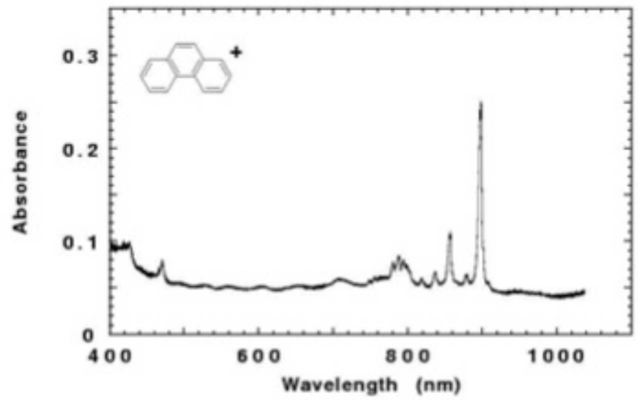


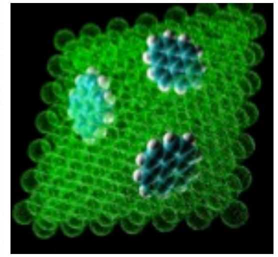
Adapted from Honeycutt et al. 2003

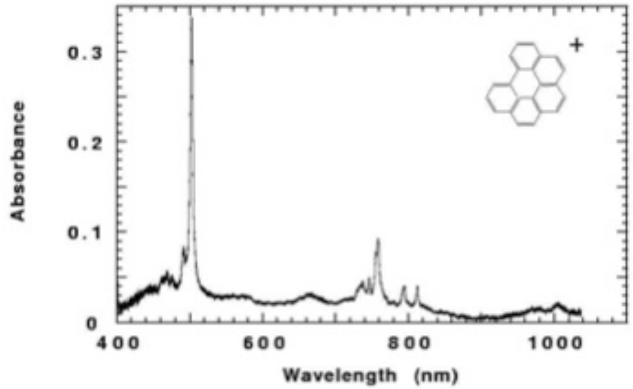
Matrix Isolation Spectroscopy (MIS) Chamber

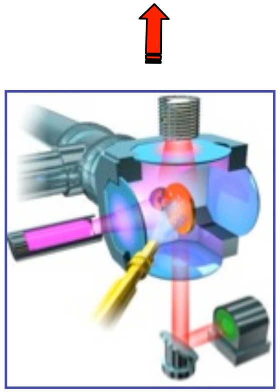
Preparatory Investigations: MIS Electronic Absorption Spectra of PAH Neutrals & ions

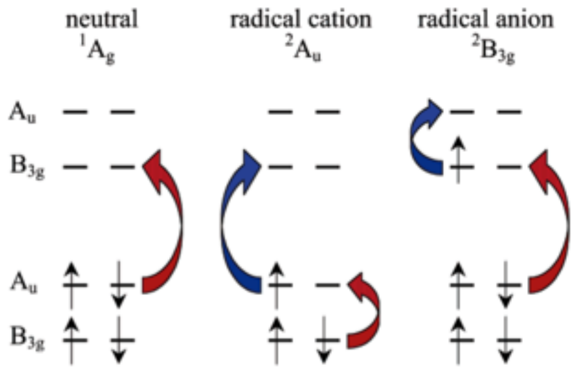


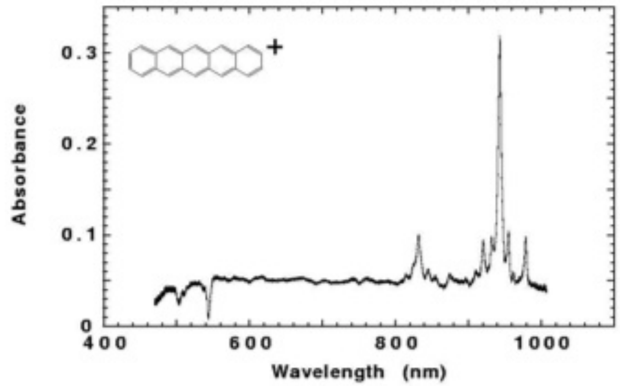












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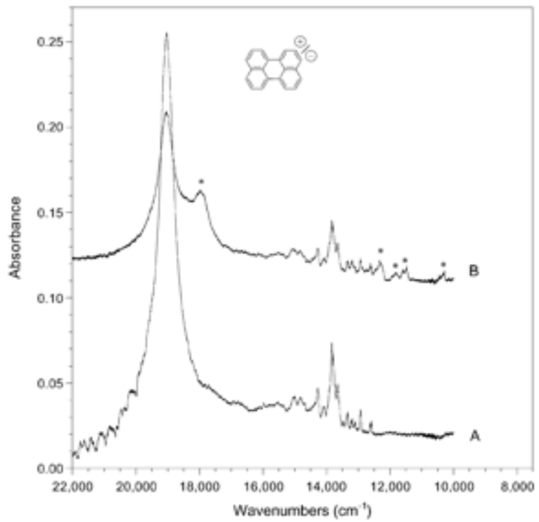
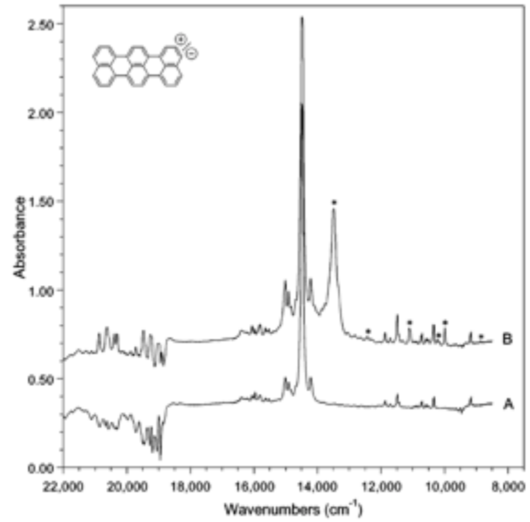
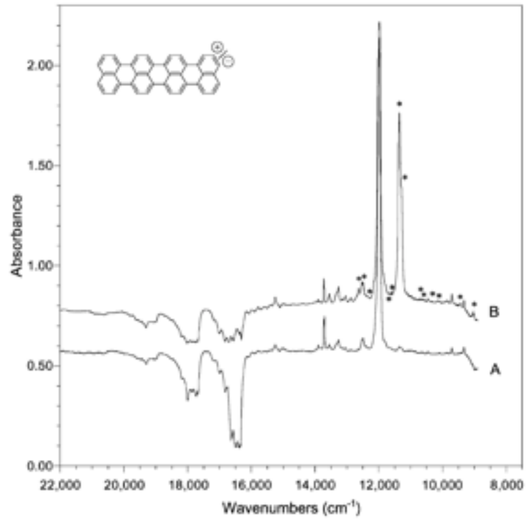
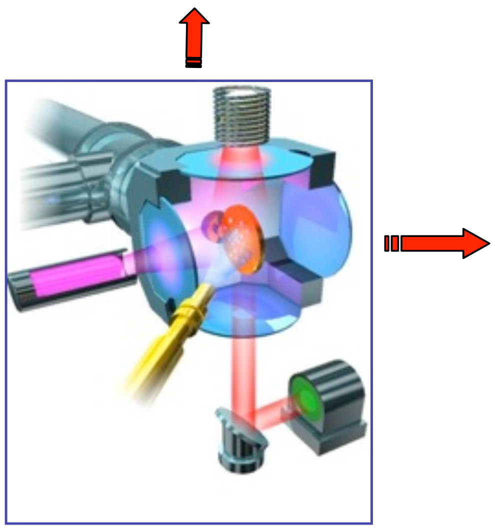
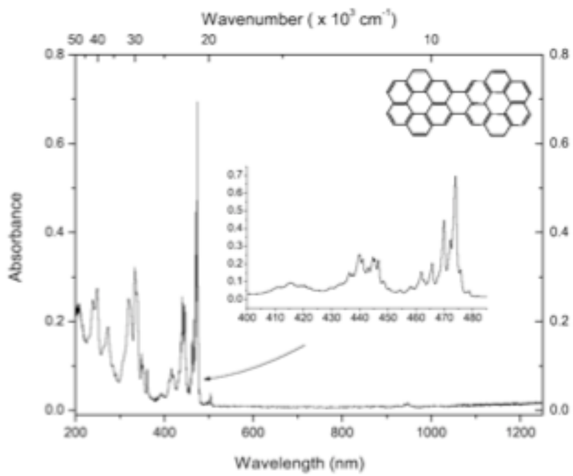
Preparatory Investigations: MIS Electronic Absorption Spectra of $C_{20}H_{12}$, $C_{30}H_{16}$, $C_{40}H_{20}$ and $C_{48}H_{20}$ Cations (+) and Anions (-)

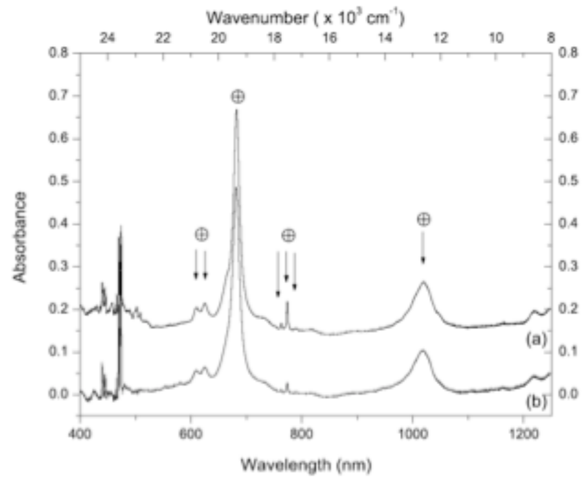












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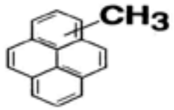
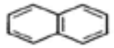
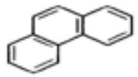
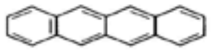
Ruiterkamp et al. A&A 2002; Halasinski et al. JPC 2003; Weisman et al. ApJ 2003

Comparison of DIBs with the Absorption Bands of PAH Cations Isolated in Neon Matrices

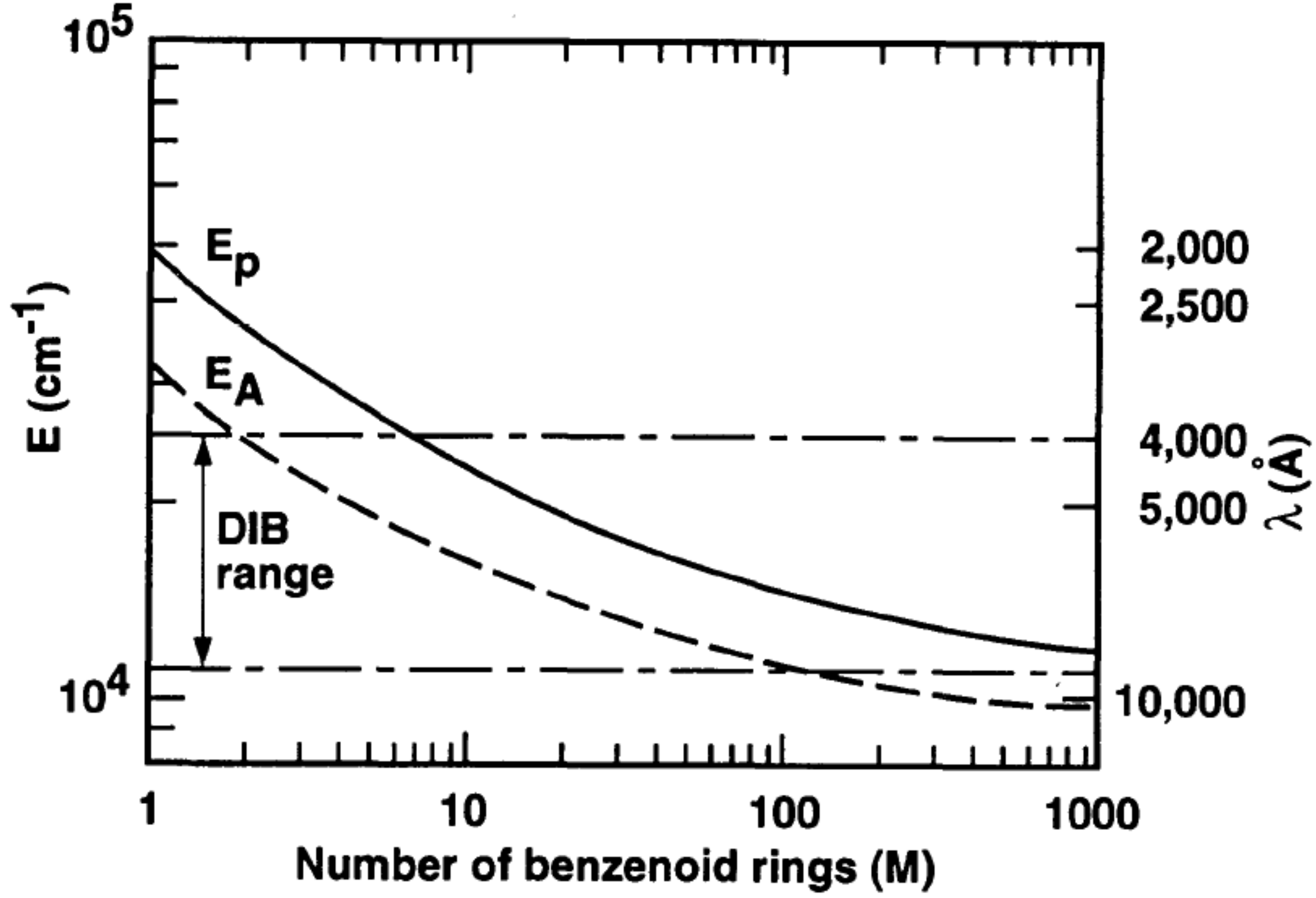
λ PAH$^+$ (Ne matrix data)	HD 207198 Sp = O9 Iie $E(B-V) = 0.60$	BD +40°4220 Sp = O7e $E(B-V) = 1.96$	HD 195592 Sp = O9.5 Ia $E(B-V) = 1.14$	HD 190603 Sp = B1.5 Iae $E(B-V) = 0.72$	HD 187459 Sp = B0.5 I $E(B-V) = 0.41$
3442 TetracB	...	...	...	...	...
4227 B(e)pyrA	Blended with interstellar Ca I (4226.734), 9.5%, 18 mÅ	...	...	Interstellar Ca I 4226.73, 5.5%, 4 mÅ	Interstellar Ca I 4226.73, 10 mÅ
4395 PyreneA	...	...	...	...	...
4442 1MePyrA	DIB 4428.88, 6.5%, 450 mÅ	...	...	DIB 4428.88, 4.5%, 400 mÅ	DIB 4428.88, 3%, 200 mÅ
4456 4MePyrA	...	...	...	...	...
4499 COHPyrA	DIB 4501.8, 4%, 140 mÅ	...	DIB 4501.8 blended with stellar lines	DIB 4501.8, 3.5%, 100 mÅ	DIB 4501.8, 2.5%, 63 mÅ
4580 4MePyrB	...	...	...	...	...
4590 CoronA	...	...	...	...	...
4987 COHPyrB	DIB 4963.96, 4.5%, 31 mÅ DIB 4969.67, 1.2%, 10 mÅ DIB 4984.73, 3%, 13 mÅ	Low S/N (here and above)	DIB 4963.96, 5.5%, 30 mÅ DIB 4969.67, 2%, 30 mÅ DIB 4984.73, 2%, 30 mÅ	DIB 4963.96, 1.5%, 15 mÅ DIB 4969.67, 1.3%, 10 mÅ DIB 4984.73, 1%, 8 mÅ	DIB 4963.96, 2%, 15 mÅ DIB 4984.73, 1.5%, 3 mÅ
5022 b(ghi)perA	...	New feature 5025, 7%, 2 mÅ	...	...	...
5251 PerylA	...	...	...	...	...
6120 NaphtB2 (projected value)*	DIB 6116.65, 2.5%, 19 mÅ	DIB 6116.65, 3.3%, 28 mÅ	...	DIB 6116.65, 2%, 9 mÅ	...
6489 NaphtB1*	...	DIB 6491.88, 2.5%, 22 mÅ	DIB 6491.88, 3%, 22 mÅ	DIB 6491.88, 4.5%, 22 mÅ	...
6706 NaphtA*	DIB 6699.37, 4%, 23 mÅ DIB 6701.98, 2.2%, 4 mÅ	DIB 6699.37, 4.7%, 35 mÅ DIB 6701.98, 3.5%, 10 mÅ	DIB 6699.37, 3%, 15 mÅ	DIB 6699.37, 2%, 19 mÅ	DIB 6699.37, 3%, 20 mÅ DIB 6701.98, 1%, 6.5 mÅ
7229 peryIB1	...	DIB 7249.26, 2.8%, 43 mÅ DIB 7257.35, 1%, 15 mÅ	DIB 7224.18, 19%, 200 mÅ	DIB 7224.18, 15%, 200 mÅ	DIB 7224.18, 8%, 125 mÅ
7256 peryIB2	...	DIB 7249.26, 2.8%, 43 mÅ DIB 7257.35, 1%, 15 mÅ DIB 7276.7, 6%, 33 mÅ	DIB 7224.18, 19%, 200 mÅ DIB 7276.7, 3%, 15 mÅ	DIB 7224.18, 15%, 200 mÅ DIB 7276.7, 2.5%, 20 mÅ	DIB 7224.18, 8%, 125 mÅ
7580 1MePyrB	DIB 7585.63, 1.8%, 30 mÅ (Stellar C III?)	DIB 7581.24, 5%, 39 mÅ	DIB 7562.24, 6%, 100 mÅ	DIB 7558.5, 1.5%, 26 mÅ	DIB 7562.24, 3.5%, 30 mÅ
			DIB ~7580 as one, 2%, 70 mÅ DIB 7585.63, 1.5%, 30 mÅ	DIB 7562.24, 3%, 70 mÅ DIB 7579.17, 2%, 32 mÅ DIB 7581.24, 2%, 29 mÅ DIB 7585.63, 1%, 18 mÅ	
7584 b(ghi)perB	See above	See above	See above	See above	See above
7588 4MePyrC	See above	See above	See above	See above	See above
8321 PentacB	DIB 8283.45, 1.5%, 44 mÅ	DIB 8283.45, 5.3%, 55 mÅ New feature DIB 8321, 6.3%, 44 mÅ	DIB 8283.45, 3.5%, 60 mÅ	DIB 8283.45, 3%, 31 mÅ	...
8508 PhenantB*	...	...	...	...	...
8648 TetracA	DIB 8621.23, 4.5%, 290 mÅ	DIB 8621.23, 16.6%, 600 mÅ	DIB 8621.23, 7%, 440 mÅ	DIB 8621.23, 7%, 447 mÅ	DIB 8621.23, 6.5%, 650 mÅ
8839 1,2benzanthA	...	...	...	...	...
8919 PhenantA*	...	...	...	...	...
9124 B(e)pyrB	...	...	...	...	...
9310 MePhenA	...	...	...	...	...
9433 PentacA	...	...	...	...	...
9470 CoronB	...	...	...	...	...
	...	DIB 9577, 10%, 380 mÅ DIB 9632, 11%, 280 mÅ	DIB 9577, 9%, 300 mÅ DIB 9632, 7.5%, 215 mÅ	DIB 9577, 5%, 200 mÅ DIB 9632 blended with Mg II, 7%, 180 mÅ	...

Salama et al. 1999

Comparison of DIBs with PAH Cation Bands.
PAHs Isolated in Neon Matrices

PAH^+		λ_{peak} (nm)	DIBs (nm)
Pyrene ($C_{16}H_{10}^+$)		439.5 (443.0 in Ar)	442.9
1-Methylpyrene ($CH_3 - C_{16}H_9^+$)		444.2	442.9
4-Methylpyrene ($CH_3 - C_{16}H_9^+$)		(457.7) 482.8 757.6	 482.4 758.1
Naphthalene ($C_{10}H_8^+$)		674.2 652.0	674.1 652.0
Phenanthrene ($C_{14}H_{10}^+$)		898.3 856.8	 857.2
Tetracene ($C_{18}H_{12}^+$)		864.7	864.8
Benzo(ghi)perylene ($C_{22}H_{12}^+$)		502.2 758.4 755.2 794.3	503.9 (?) 758.1; 758.6 755.8 (?); 756.2 793.5 (prob.)
Coronene ($C_{24}H_{12}^+$)		459.0 946.5	459.5 946.6

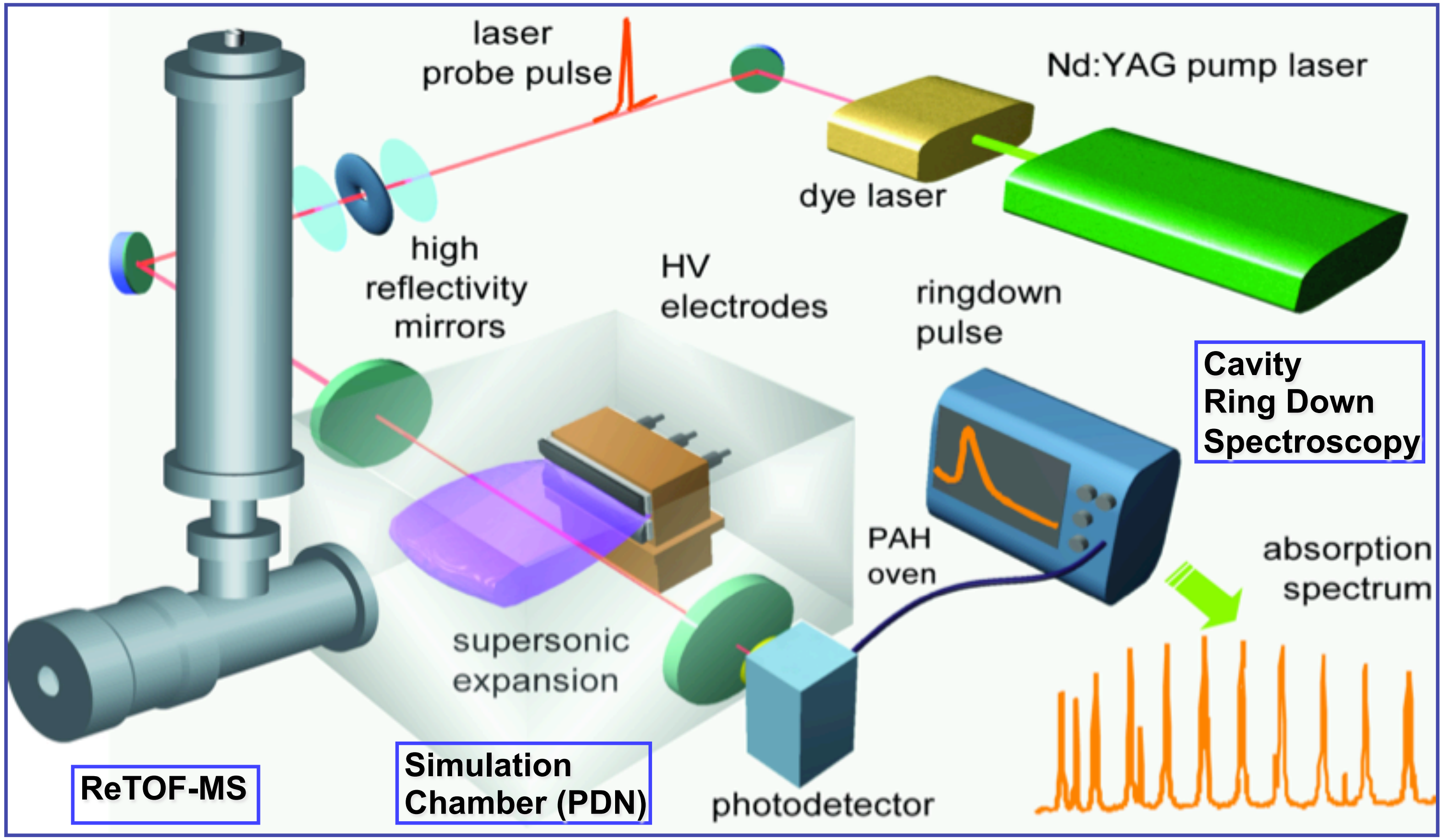
+ General conclusions: - spectral characteristics as function of charge state, molecular size and structure (compact vs. non-compact; etc…).



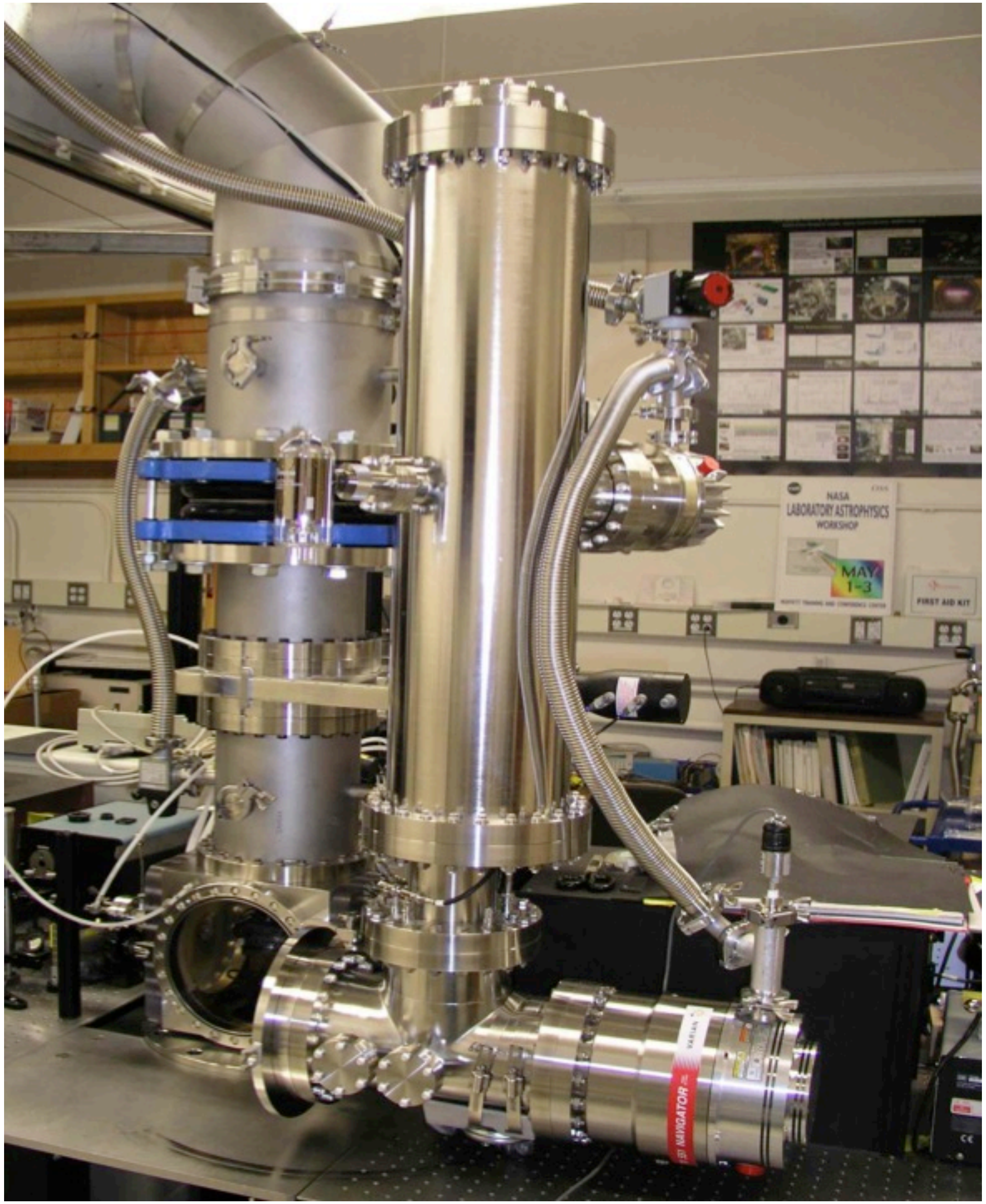
Salama et al. ApJ 1996

Measuring Laboratory Spectra Under Astrophysically Relevant Conditions:

Combine PDN + CRDS + o-ReTOF-MS: Free jet expansion + cavity ringdown spectroscopy + time-of-flight mass spectrometry



- ➲ High column density (10 cm-long slit)
- ➲ High pressure (1 bar) and temperature (300 C) reservoir
- ➲ Generates intense short gas pulses
- ➲ Generates (plasma) and stabilize (supersonic expansion) transient species



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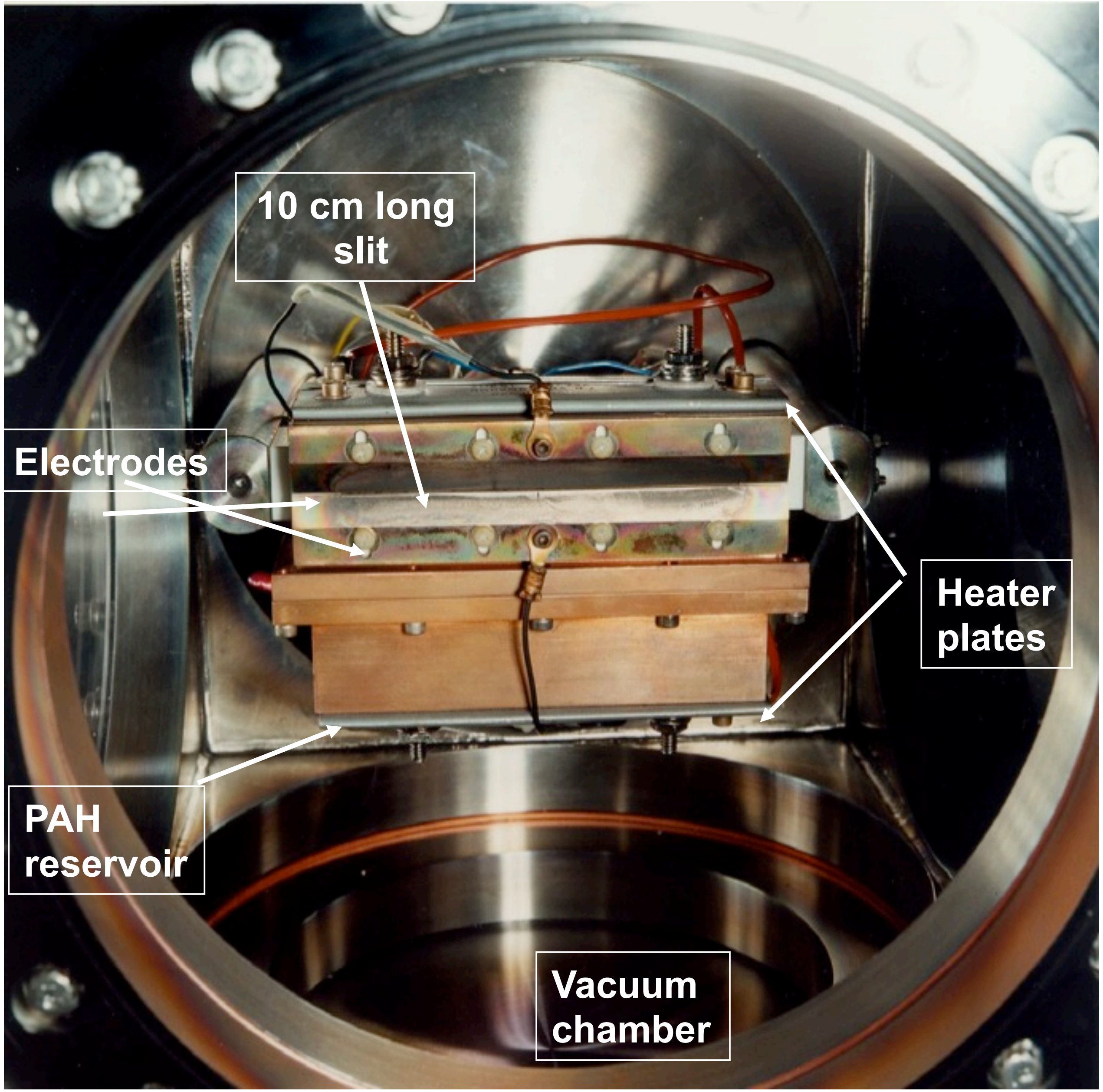
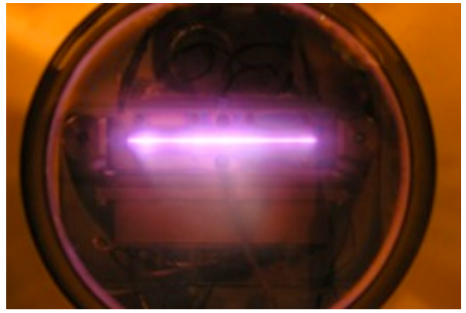
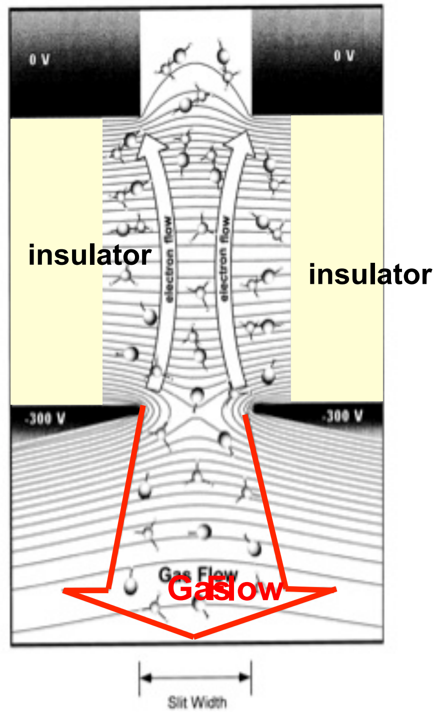
Simulation Chamber







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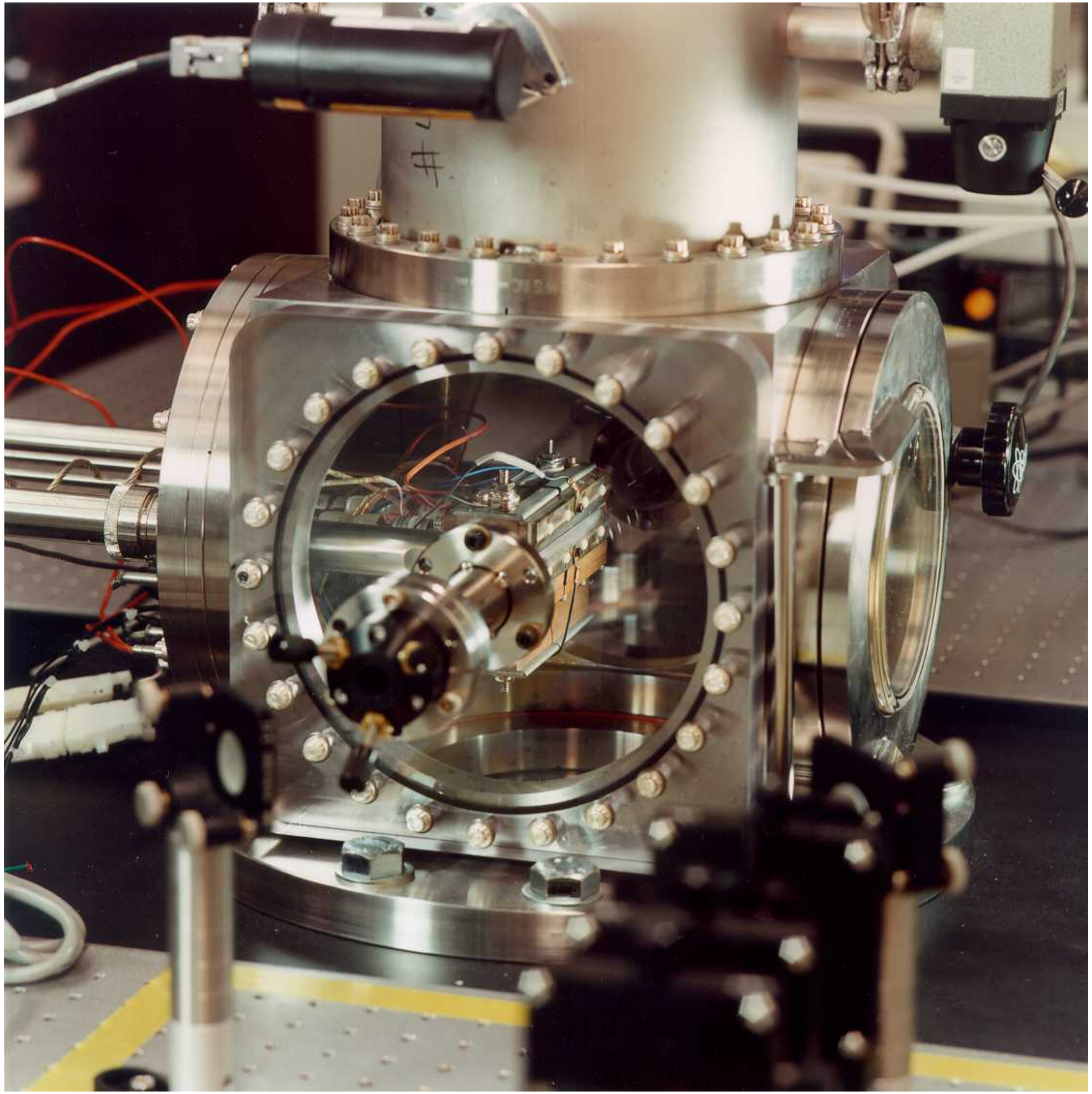
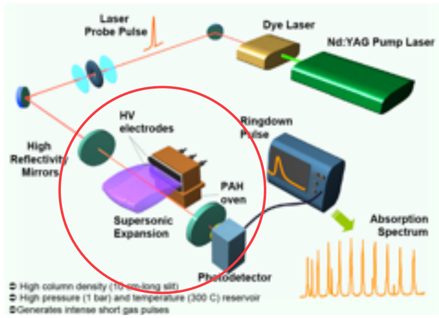
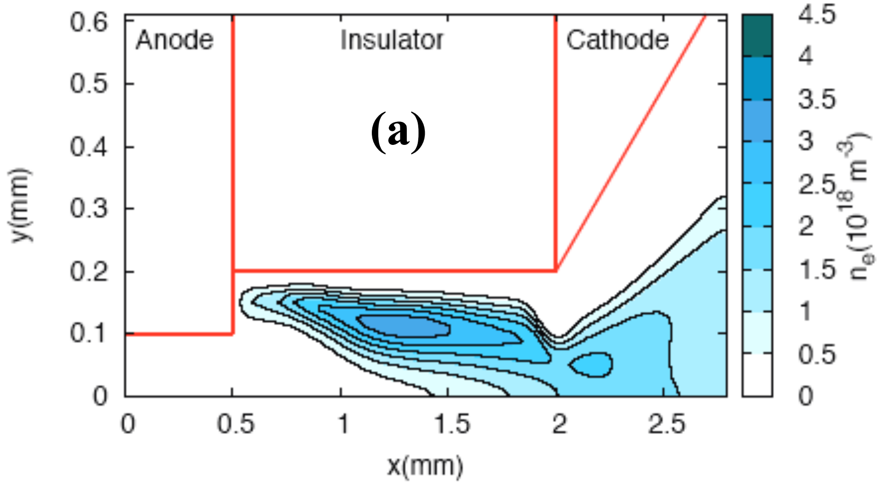
TOOLS

Simulation Chamber

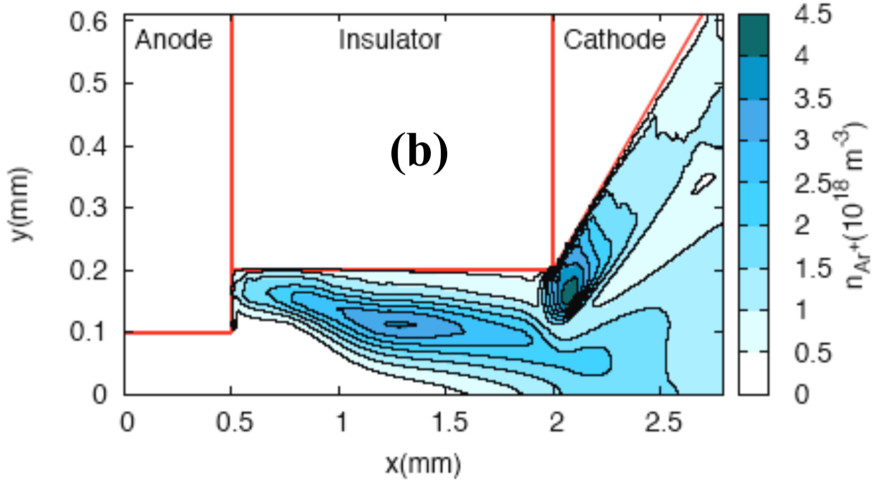


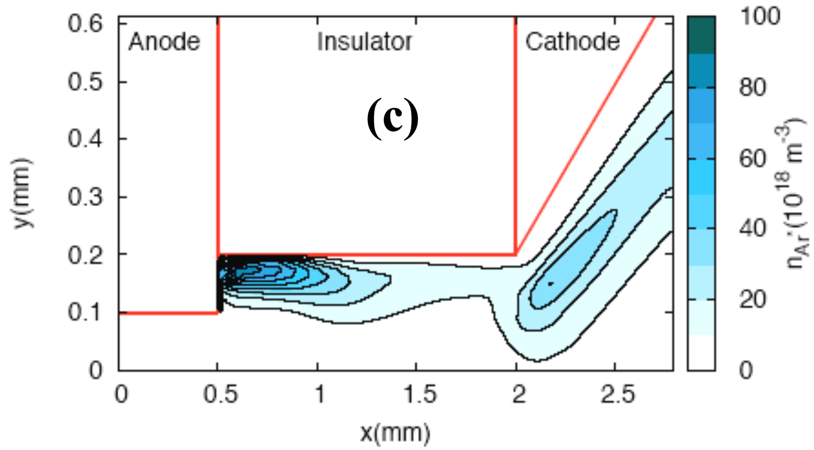


Results: Simulation of the Plasma → Glow Discharge



The (a) steady-state electron density, (b) Ar^+ density and (c) Ar^* density of the pulsed discharge nozzle for a source voltage of -500 V.

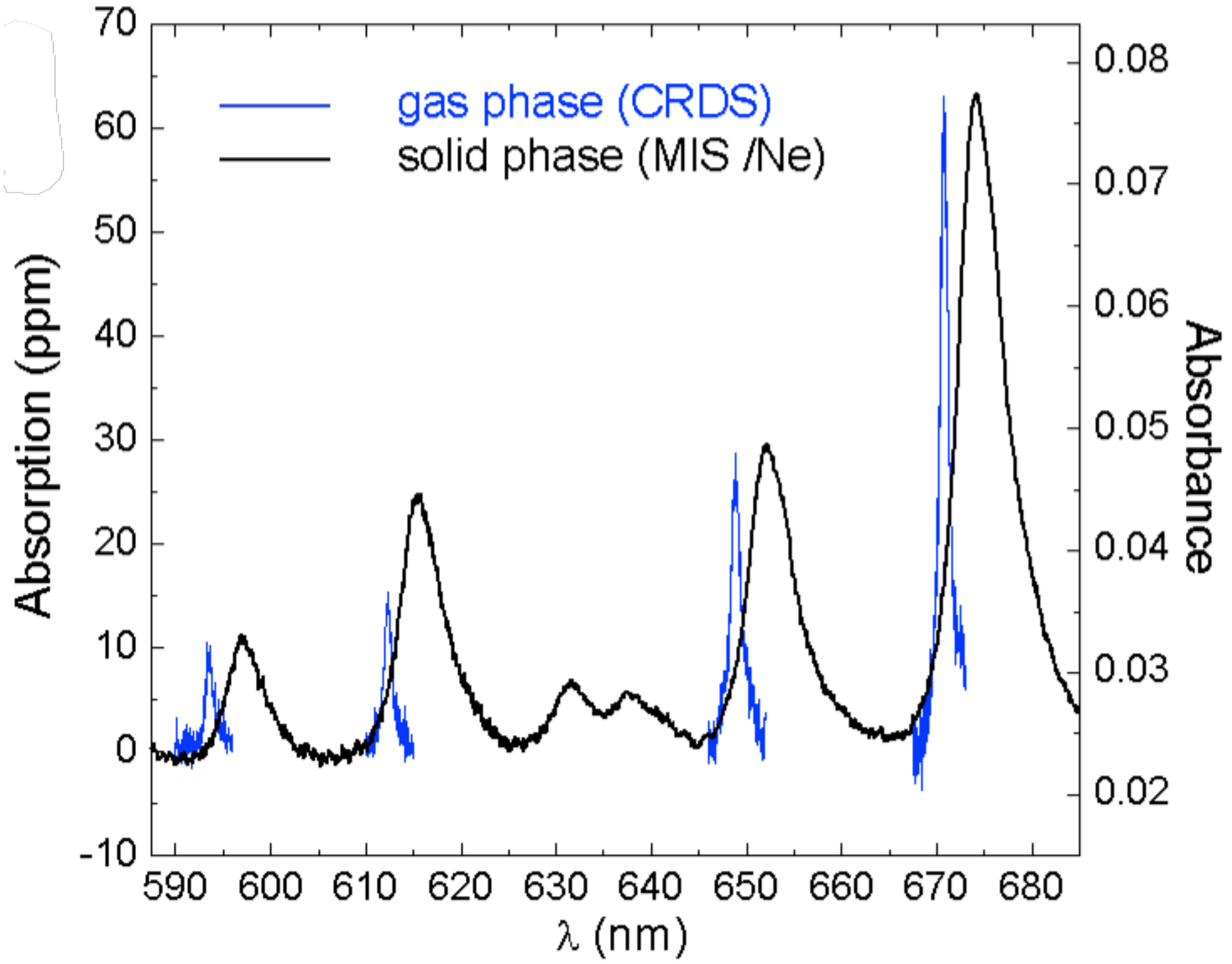


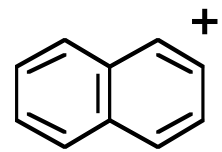


Ar* atoms in the expansion region >> electrons and ions. PAH ions are dominantly formed through Penning ionization of the neutral molecular precursors seeded in the supersonic expansion of Ar gas.

Remy, Biennier, Salama, IEEE 2005; Benidar, Biennier, Salama, Chem. Phys. 2006; Broks et al., Phys. Rev. E 2005; Broks et al. Spectrochim. Acta A 2005

Cavity Ringdown Gas-Phase Spectra of the PAH Ions compared to MIS



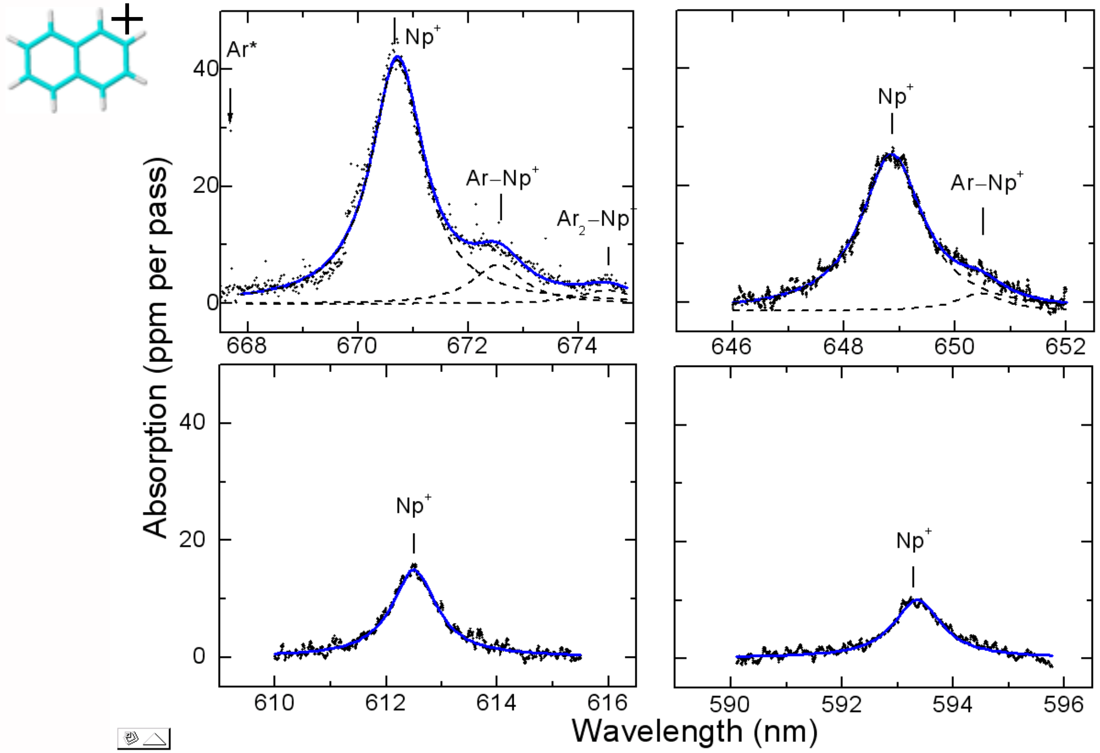


Bandwidths:
MIS: 120 cm^{-1}
Gas: 25 cm^{-1}

Biennier et al., JCP 2003

Intrinsic band profiles and peak positions can now be measured in the laboratory to search for specific PAHs (neutrals and/or ions) in interstellar and circumstellar spectra.

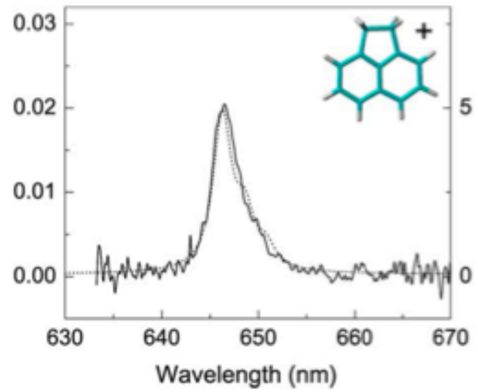
CRDS Electronic Absorption Spectra of PAH ions In the Gas Phase



Assignment	λ^e (nm)	ν^f (cm^{-1})	$\Delta\nu$ (cm^{-1})
0	670.70	14905.7	25
$\nu_9(a_g)$	648.89	15406.7	25
$\nu_4(a_g)$	612.52	16321.5	27
$\nu_9(a_g)+\nu_4(a_g)$	593.35	16848.8	31

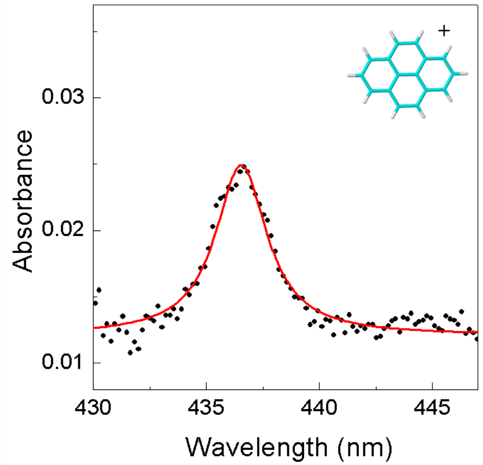
Biennier et al. 2003, 2004

The vibronic bands of PAH ions are broad.



$\Delta\nu$ = 55 cm^{-1}

	Ac^+	
	λ (nm)[a]	ν (cm^{-1})
PDN-CRDS[b]	646.27	15469.1
Photodepletion[c]	646.23±0.3	15470



Pyrene ion ($C_{16}H_{10}^+$)

Bandwidth: $\Delta\nu$ = 145 cm^{-1}

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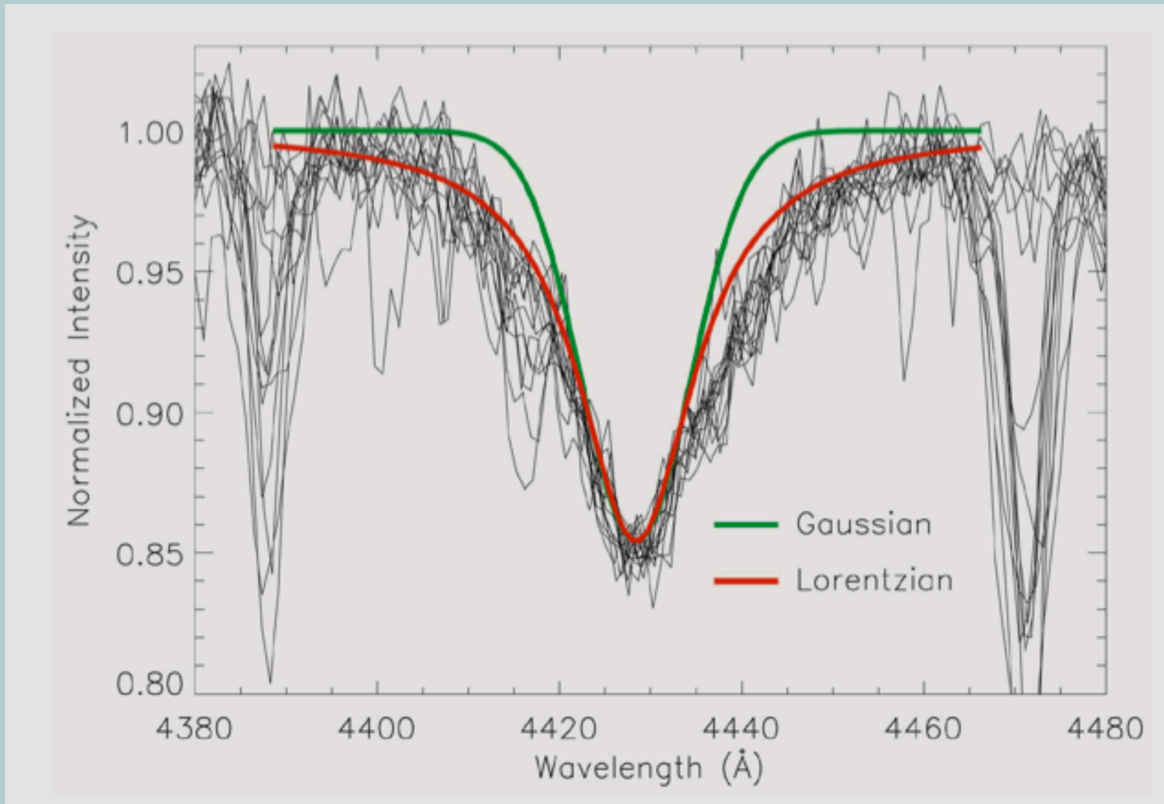
THE INTRINSIC PROFILE OF THE 4428 Å DIFFUSE INTERSTELLAR BAND



35 OB Stars
High extinction

Spectral Resolving Power ~2000

λ4428: 60 fs

Molecular carrier
Fast relaxation

Fit of λ4428 to the Gaussian and Lorentz profiles.

- The Lorentz profile is a perfect fit to the observations of the 4428 Å DIB.
- Proposal that the broad 4428 Å DIB is a molecular feature whose width is explained by very rapid internal conversion. (Snow et al. ApJ 2002)

Table 1. Electronic state peak positions and band widths of cold gas-phase PAH ions measured in the laboratory are compared to the characteristics of the strong broad 4428 ÅDIB

Molecular ion	Electronic State	$\lambda(\AA)$	$\Delta\lambda(\AA)$
Naphthalene$^+$ $[C_{10}H_8^+]^{a,1}$	D_2	6707.7	10
Naphthalene$^+$ $[C_{10}H_8^+]^{b,2}$	D_3	4548.5	19
Acenaphtene$^+$ $[C_{12}H_{14}^+]^{a,1}$	D_2	6462.7	22
Fluorene$^+$ $[C_{13}H_{10}^+]^{c,2}$	D_3	6201.7	53
Phenanthrene$^+$ $[C_{14}H_{10}^+]^{d,2}$	D_2	8919.0	12
Anthracene$^+$ $[C_{14}H_{10}^+]^{e,1}$	D_2	7087.6	47
Pyrene$^+$ $[C_{16}H_{10}^+]^{f,1}$	D_5	4362.0	28
Pyrene$^+$ $[C_{16}H_{10}^+]^{g,2}$	D_4	4803.3	30
Pyrene$^+$ $[C_{16}H_{10}^+]^{g,2}$	D_2	7786.6	97
Methylpyrene$^+$ $[C_{17}H_{12}^+]^{h,1}$	D_5	4411.3 (4413.3; 4409.3)	10
Pyrene(COH)$^+$ $[C_{17}H_{10}O^+]^{h,1}$	D_8	4457.8	20
Pyrene(COH)$^+$ $[C_{17}H_{10}O^+]^{h,1}$		4442.7	
Pyrene(COH)$^+$ $[C_{17}H_{10}O^+]^{h,1}$		4431.4	
4428Å DIB^i		*4428.4 ±1.4*	*17.3 ±1.64*

Also C78H26+

Salama, in *Molecules in Space* 2008

****PAH ions:**

- Band widths versus broad DIBs
- Naphthalene$^+$?
- Anthracene$^+$?
- Column densities ~ 10^{13}

****Hydrocarbons:**

- Diacetylene$^+$?
- Plasma product
- H_2CCC (l-C_3H_2)

**** Fullerenes**

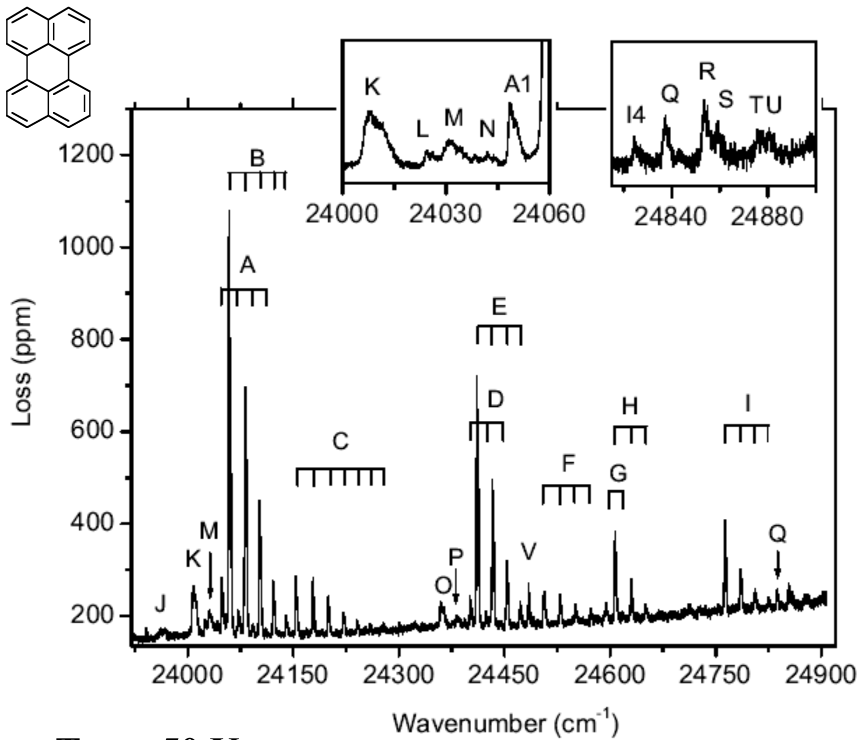
C60+

Criteria for Identification of Carrier:

2+ objects
absent in unreddened stars
1+ instrument confirmed
stationary (in spec. binary)
2+ transitions (preferred)
Match wavelength + profile

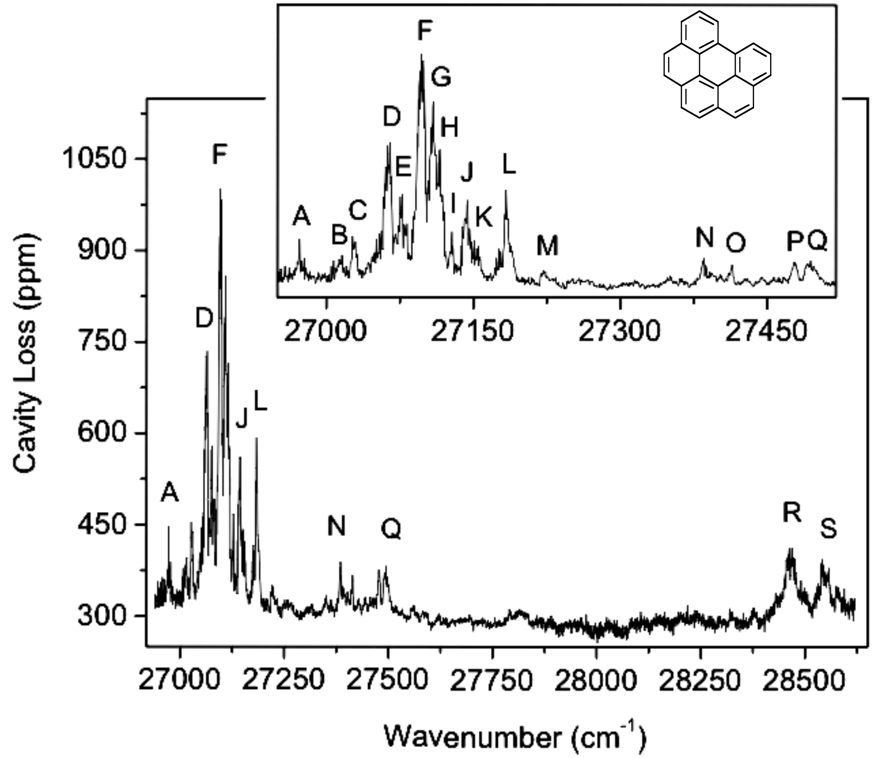
Electronic Absorption Spectra of Neutral PAHs In the Gas Phase

CRDS - Neutral Perylene ($C_{20}H_{12}$) & Neutral Benzoperylene ($C_{22}H_{12}$)



T_{ROT}: 50 K.

Range: 4000 – 4200 Å



Range: 3500 – 3700 Å

The vibronic bands of neutral PAHs range between 2 and 10 cm^{-1}.

Tan & Salama 2005; Rouillé et al. 2007

Stellar Data

Star HD	Sp/L	V	$B-V$	$E(B-V)$	$v\sin i$	rv[a]
110432	B2pe	5.3	0.26	0.47	200	+7.7
115842	B0.5 Iab	6.02	0.30	0.50	70	+8.7
136239	B2Iae	7.82	0.92	1.08	60	−14.0
144217	B0.5V	2.50	−0.07	0.17	100	−9.1
147165	B1 III	2.90	0.14	0.35	50	−4.4
147889	B2 V	7.90	0.84	1.05	100	−7.2
148184	B2 Ve	4.42	0.28	0.49	100	−10.8
148379	B2Iab	5.32	0.54	0.70	60	−11.3[b]
149404	O9 Iab	5.48	0.39	0.62	100	+1.7
149757	O9.5V	2.57	0.02	0.29	400	−14.7
151932	WN7	6.48	0.26	0.55		+2.0
152236	B1Iae	4.72	0.48	0.67	60	+2.2
152249	O9.5 Iab	6.47	0.20	0.43	80	+3.7
154368	O9.5 Iab	6.13	0.51	0.74	70	−1.7
154445	B1 V	5.62	0.14	0.37	130	−15.0
170740	B2 V	5.72	0.24	0.45	25	−7.6
163800	O7.5	6.98	0.28	0.57	138	−5.6

Notes.
[a] rv is the heliocentric radial velocity (km s^{-1}) of the main component of the interstellar CH 4300.31 Å band.
[b] Mid-position between two components.

Salama et al. ApJ 2011

Upper Limits of PAHs Abundance Measured in the Spectra of the Individual Program Stars of Table 1 and in the Average Spectrum in the Wavelength Region Corresponding to the Strongest PAH Absorption Feature(s)

HD	Acenaphthene[a] λ Peak: 3175.0 Å Δλ: 3174.55–3175.52 $f = 2.2E(-3)$[d]	Benzo[ghi]perylene[b] λ Peak: 3689.4 Å Δλ: 3685.9–3690.9 $f = 1.4E(-1)$[d]	2-Methylnaphthalene[a] λ Peak: 3152.7 Å Δλ: 3152.2–3153.2 $f = 2.3E(-3)$[d]	Pentacene[a] λ Peak: 5339.5 Å Δλ: 5336.2–5342.2 $f = 4.1E(-1)$[d]	Pentacene[a] λ Peak: 5362.8 Å Δλ: 5359.3–5365.0 $f = 4.1E(-1)$[d]	Perylene[c] λ Peak: 4155.0 Å Δλ: 4154.4–4155.7 $f = 2.4E(-1)$[d]
110432	330 0.0027 1.72907E13	840 0.0053 0.31295E12	410 0.0021 1.04052E13	1170 0.0050 0.48221E12		760 0.0014 0.38276E11
115842	330 0.0024 1.72907E13	880 0.0046 0.27162E12	470 0.0020 0.99098E13	1100 0.0077 0.74261E12		900 0.0014 0.38276E11
136239				940 0.0132 1.27304E12	1100 0.0385 0.36811E12	
144217	500 0.0018 1.72907E13	1100 0.0044 0.25981E12	640 0.0014 0.69368E13	1280 0.0052 0.50150E12	1550 0.0119 0.11378E12	970 0.0012 0.32808E11
147165	300 0.0028 1.57650E13	700 0.0060 0.35428E12	390 0.0022 1.09008E13			920 0.0014 0.38276E11
148184	280 0.0031 1.22052E13	700 0.0060 0.35428E12	350 0.0024 1.18917E13			980 0.0011 0.30074E11
148379				1000 0.0110 1.06087E12	1750 0.0311 0.29736E12	970 0.0011 0.30074E11
149404	210 0.0037 1.93248E13	640 0.0068 0.40152E12	280 0.0030 1.48647E13	1130 0.0073 0.70403E12	1390 0.0203 0.19409E12	840 0.0013 0.35542E11
149757	410 0.0021 1.11881E13	900 0.0044 0.25981E12	490 0.0019 0.94142E13	1100 0.0048 0.04629E12	1970 0.0073 0.06979E12	930 0.0012 0.32808E11
151932	260 0.0038 1.88163E13	600 0.0077 0.45466E12	370 0.0023 1.13962E13	1090 0.0073 0.70403E12	1600 0.0247 0.23616E12	740 0.0013 0.35542E11
152236	350 0.0024 1.62735E13	800 0.0056 0.33066E12	440 0.0020 0.99098E13		2750 0.0137 0.13099E12	1060 0.0012 0.32808E11
152249	260 0.0031 1.42394E13	730 0.0057 0.33657E12	350 0.0026 1.28827E13	1080 0.0070 0.67509E12	2050 0.0130 0.12430E12	890 0.0013 0.35542E11
154368	240 0.0034 0.91539E13	580 0.0075 0.44285E12	290 0.0033 1.63511E13	1160 0.0075 0.72332E12	1250 0.0124 0.11856E12	760 0.0014 0.38276E11
154445	250 0.0034 1.22052E13	660 0.0076 0.44876E12	430 0.0024 1.18917E13	1300 0.0060 0.57865E12	1400 0.0208 0.19887E12	710 0.0016 0.43744E11
170740	260 0.0034 1.37308E13	560 0.0080 0.47238E12	330 0.0027 1.33782E13			780 0.0014 0.38276E11
average	1000 0.0006 0.30513E13	2500 0.0021 0.12399E12	930 0.0010 0.49549E13	4100 0.0050 0.48221E12	4300 0.0236 0.22565E12	2100 0.0007 0.19138E11

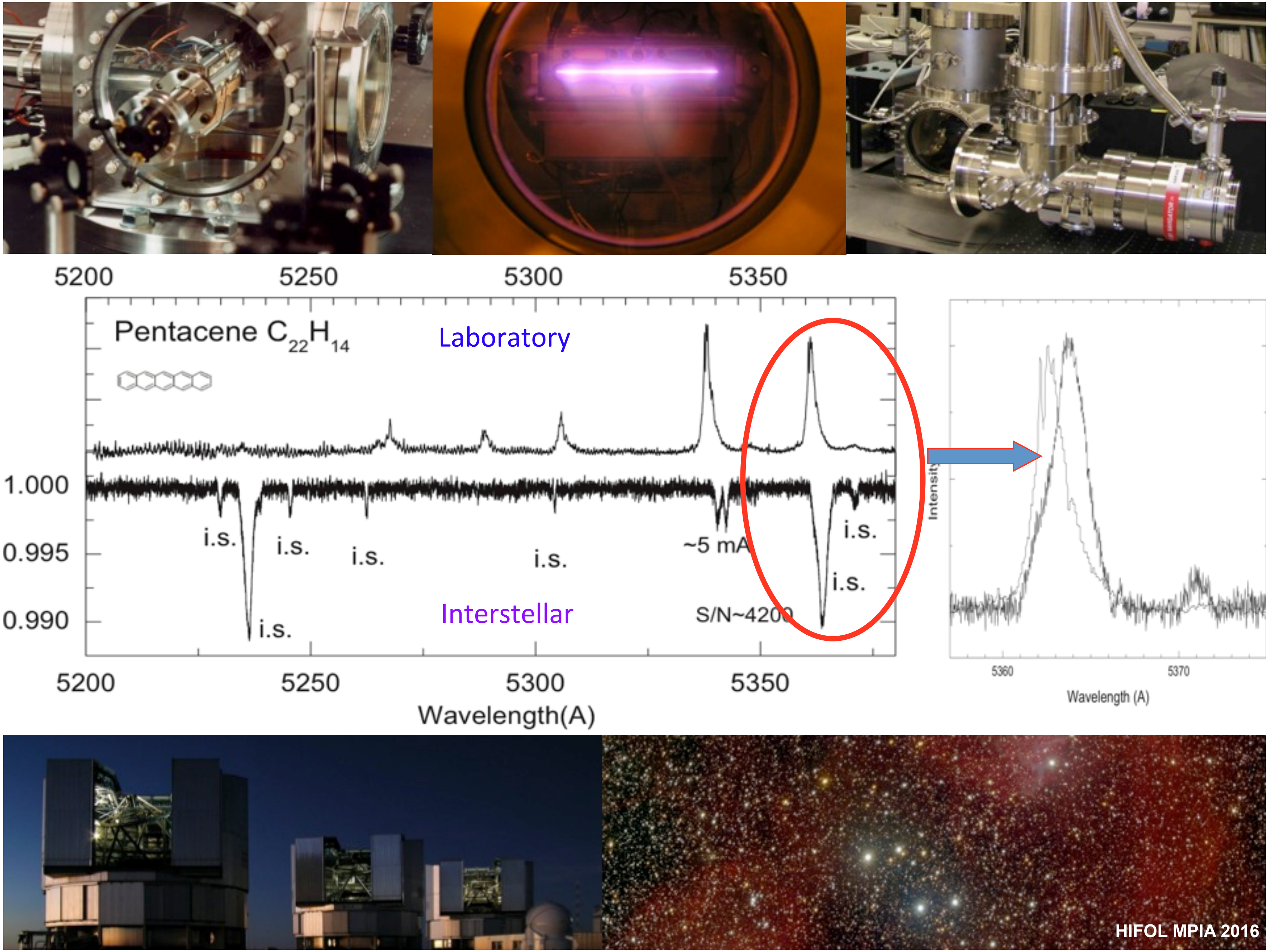
HD	Phenanthrene[a] λ Peak: 3408.4 Å Δλ: 3407.7–3409.1 $f = 2.3E(-2)$[d]	Pyrene[a] λ Peak: 3205.8 Å Δλ: 3199.0–3215.2 $f = 1.6E(-1)$[d]	$C_{42}H_{18}$[e] λ Peak: 4264.1 Å Δλ: 4263.35–4264.85 $f = 8.5E(-4)$	$C_{42}H_{18}$[e] λ Peak: 4335.2 Å Δλ: 4334.45–4335.95 $f = 2.4E(-4)$	Benzofluorene[f] λ Peak: 3345.1 Å Δλ: 3345–3345.2 $f = 2.4E(-2)$	Anthracene[g] λ Peak: 3611.8 Å Δλ: 3611.6–3612.0 $f = 1.0E(-2)$
110432	830 0.0015 0.63444E12	400 0.0359 0.24609E13	950 0.0013 9.46039E13	660 0.0020 4.92834E14	650 0.0003 1.26232E12	860 0.0004 3.46490E12
115842	845 0.0017 0.71903E12	430 0.0315 0.21593E13	950 0.0015 1.09158E14	610 0.0022 5.42116E14	560 0.0003 1.26232E12	780 0.0004 3.46490E12
136239			520 0.0026 1.89208E14	315 0.0041 1.01031E15	180 0.0012 5.04929E12	330 0.0011 9.52848E12
144217	1250 0.0009 0.38066E12	570 0.0250 0.17137E13	1110 0.0012 8.73267E13	680 0.0018 4.43551E14	1220 0.0002 8.41548E11	780 0.0004 3.46490E12
147165			850 0.0016 1.16436E14	500 0.0025 3.75786E14		450 0.0008 6.92981E12
148184	870 0.0015 0.63444E12		630 0.0023 1.67355E14	630 0.0019 2.85597E14	670 0.0004 2.75918E12	550 0.0008 6.92981E12
148379			1030 0.0013 9.46039E13	500 0.0024 3.60754E14	220 0.0009 6.20815E12	180 0.0021 1.81907E13
149404	760 0.0017 0.71903E12	300 0.0459 0.31464E13	860 0.0016 1.16436E14	590 0.0021 3.15660E14	440 0.0003 2.06938E12	670 0.0005 4.33113E12
149757	1100 0.0013 0.54985E12	480 0.0311 0.21319E13	1030 0.0014 1.01881E14	600 0.0023 3.45723E14	730 0.0003 2.06938E12	730 0.0004 3.46490E12
151932	840 0.0014 0.59214E12	370 0.0352 0.24129E13	910 0.0015 1.09158E14	550 0.0022 3.30691E14	535 0.0003 2.06938E12	580 0.0006 5.19735E12
152236	1020 0.0012 0.50755E12	420 0.0331 0.22690E13	1210 0.0011 8.00495E13	710 0.0018 2.70566E14	740 0.0002 1.37959E12	700 0.0004 3.46490E12
152249	910 0.0013 0.54985E12	370 0.0367 0.25158E13	880 0.0015 1.09158E14	510 0.0025 3.75786E14	545 0.0004 2.75918E12	620 0.0006 5.19735E12
154368	550 0.0024 1.01511E12	320 0.0414 0.28379E13	820 0.0017 8.23758E13	510 0.0026 3.90817E14	500 0.0004 2.75918E12	520 0.0007 6.06358E12
154445	880 0.0014 0.59214E12	380 0.0380 0.26049E13	930 0.0014 6.78392E13	500 0.0025 3.75786E14	570 0.0003 2.06938E12	580 0.0005 4.33113E12
170740	665 0.0019 0.80362E12	320 0.0425 0.29133E13	850 0.0015 1.09158E14	500 0.0027 4.05848E14	380 0.0005 3.44897E12	
average	2250 0.0005 0.21148E12	1000 0.0141 0.09665E13	2790 0.0011 8.00495E13	2000 0.0010 1.50314E14	1900 0.0001 6.89793E11	1730 0.0003 2.59868E12

Notes. Signal-to-noise ratio (S/N), equivalent width (EW in Å), and corresponding column density (c.d. in cm^{-2}) values are given for each PAH band. Δλ represents the wavelength range that was used to derive upper limits for the column densities of the strongest features.

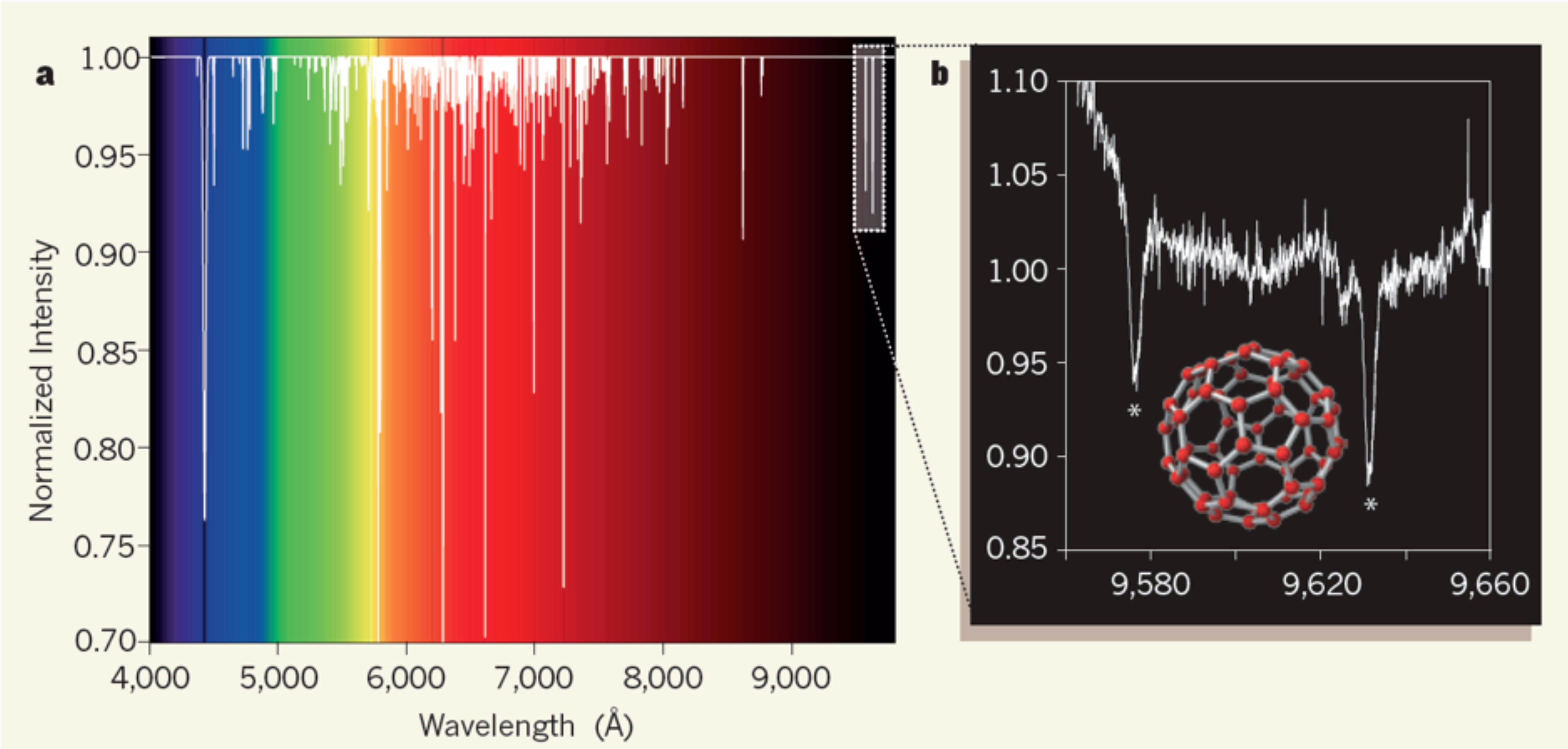
[a] This work; [b] Tan & Salama (2005b); [c] Tan & Salama (2005a); [d] Tan et al. (2010); [e] Kokkin et al. (2008); *f* value scaled according to Rouillé et al. (2009); [f] Staicu et al. (2006); [g] Hermine (1994).

Salama et al. ApJ 2011
Gredel et al. A&A 2011

S/N ~1000 - 2500
Typical fractional abundances: $10^{-10} – 10^{-8}$


5200
5250
5300
5350
Pentacene C22H14
Laboratory
1.000
0.995
0.990
i.s.
~5 mA
S/N~4200
Interstellar
Wavelength(A)
Intensity
5360
5370
Wavelength (A)
HIFOL MPIA 2016

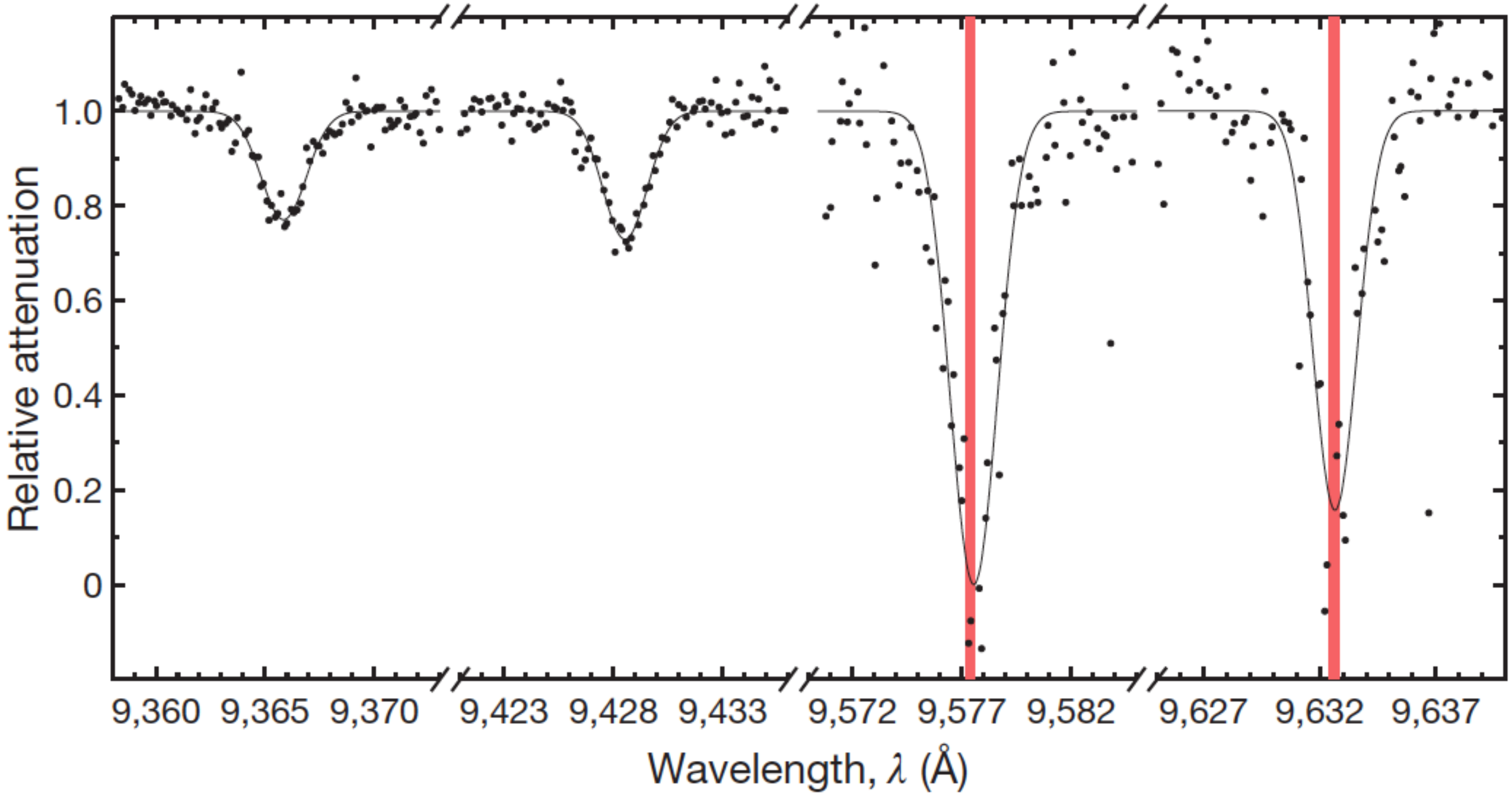
Fullerene solves an interstellar puzzle



Laboratory confirmation of C60+ as the carrier of two DIBs discovered in 1994

Ehrenfreund and Foing, Nature 523, 2015
E. K. Campbell, M. Holz, D. Gerlich & J. P. Maier, Nature, 523, 2015

Laboratory confirmation of C60+ as the carrier of two DIBs



E. K. Campbell, M. Holz, D. Gerlich & J. P. Maier, Nature, 523, 2015

Open Questions & Perspective

Carbon molecules are currently considered the most promising candidates for identifying the DIB carrier(s).

Alternative candidate carriers can not be dismissed, although the carriers are very likely **large carbonaceous gas phase molecules** that are **stable, UV resistant,** but **sensitive** to the **local cloud conditions**, in particular to the **UV radiation** field.

Multi-object line-of-sight high-resolution studies of **Local Group** galaxies are needed (EDIBLES).

Spectroscopic signatures in both the **UV** and the **NIR** are predicted for many (neutral/cation) **PAHs**.

Explore **new environments** other than diffuse/translucent ISM → **Circumstellar** envelopes of **evolved stars** (“PAH” factories)?

Observational verification of proposed candidates! e.g. **naphthalene+** detected in only 1 (peculiar) sightline.

DIB correlations: intrinsic scatter or measurement uncertainties?

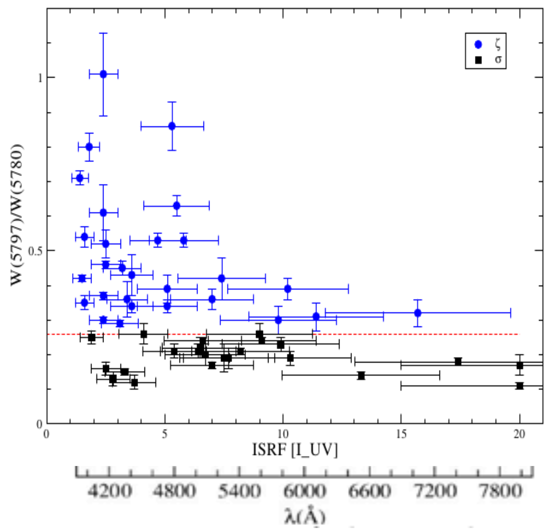
EDIBLES: ESO DIB Large Exploration Survey

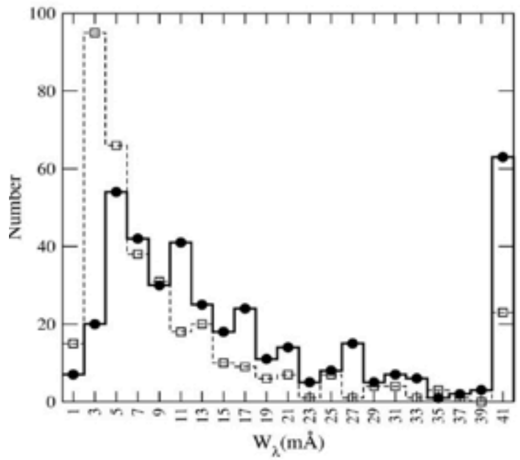
High-resolution, high-precision spectroscopic UV/optical survey (280 hours) of interstellar clouds with UVES@VLT.

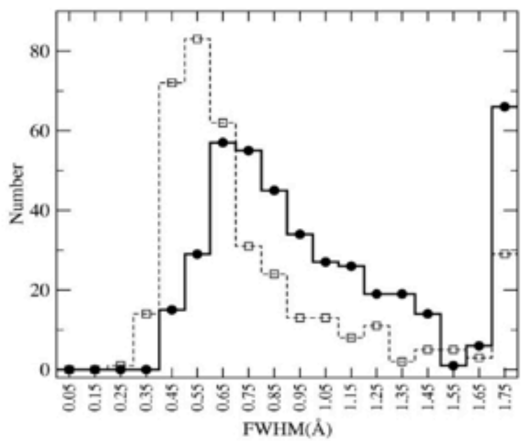
R ~ 120.000
S/N ~ 500-1000
~ 150
λ ~ 3300–10000 Å

Goals:

* Chemical make up: DIB carriers – ISM elemental abundances: depletion.
* Relation weak-strong DIBs: sequencing of 100+ DIBs.
* Effective DIB measurements to probe physical parameters.
* Identify physical-chemical parameters that influence DIB properties (PDR chemistry models).







Astrophysics:

Energy budget and signature of aromatic carbon molecules

PAHs & Grain formation

Planetary:

Titan’s atmosphere (haze)

ISS:

Exposure experiments on complex organic molecules

Sources of PAH Formation:

Outflows of carbon stars –

→ AGB stars are the dominant source of PAHs

- Lifetime of PAHs in ISM long enough (~ 10^8 years)
- PAH mixing into the ISM not complete

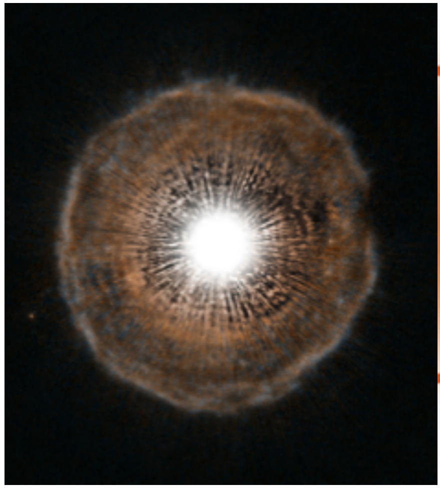
Other proposed mechanisms:

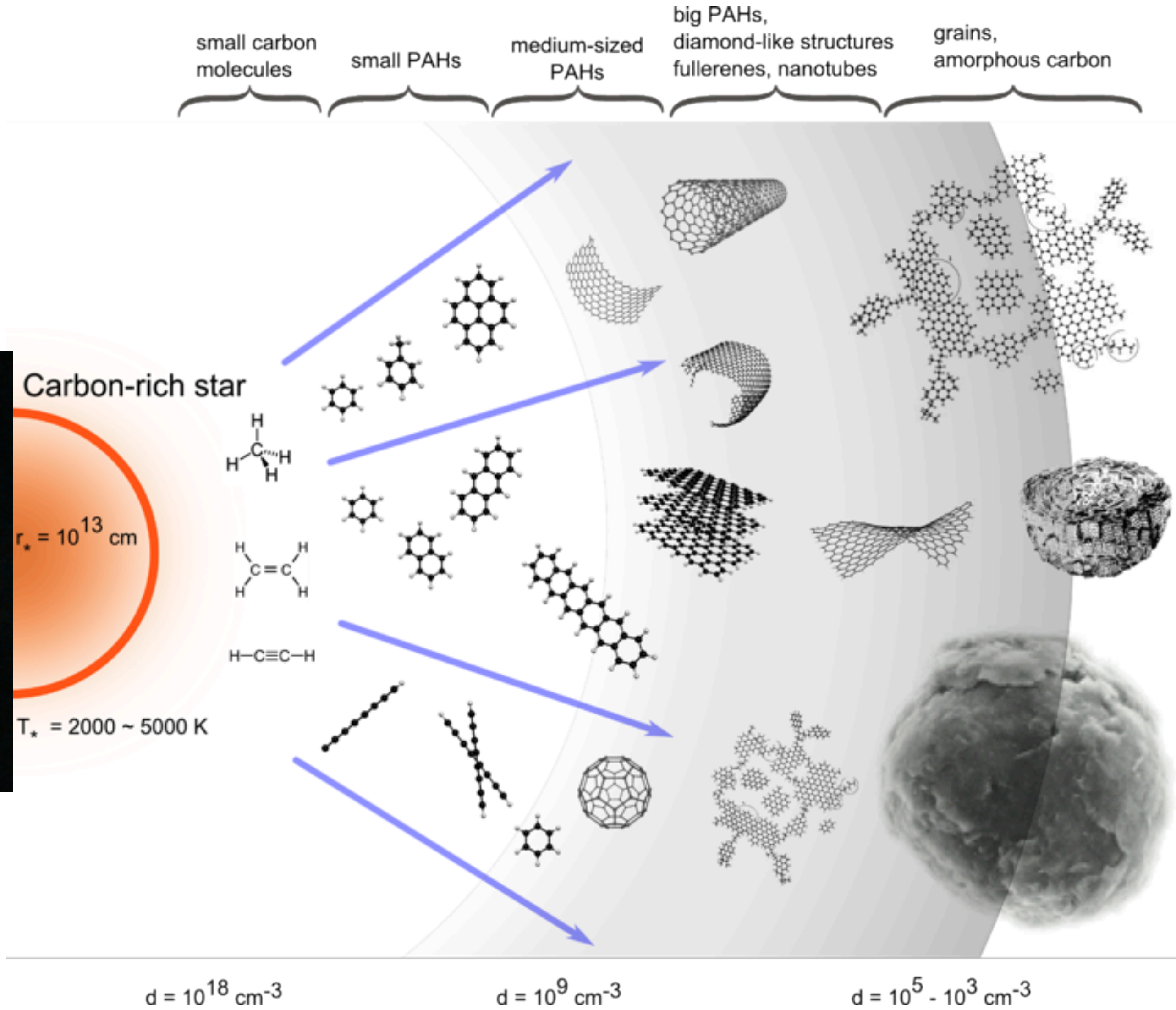
PAHs formed in UV photoprocessing of IS dust mantles

PAHs are the product of grain fracturing in shock waves

In situ formation of PAHs within dense IS clouds
(ion-molecule reactions)

Carbon in the Galaxy – Project 1 Investigations

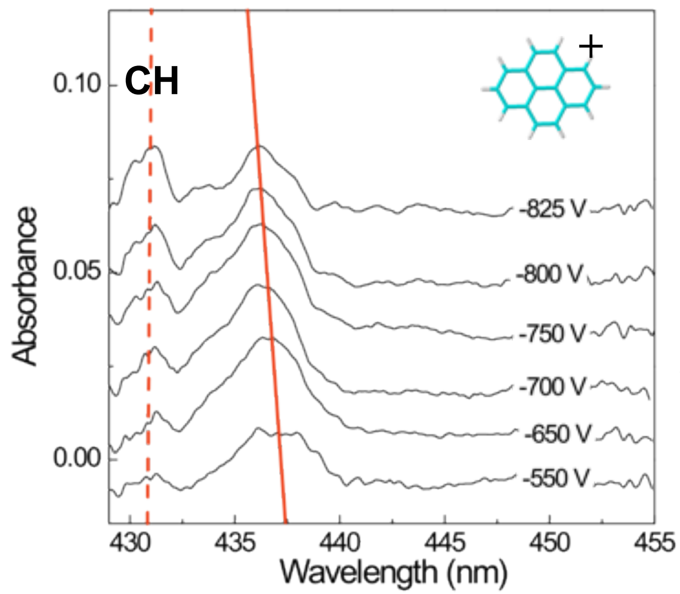




Contreras & Salama 2013 ApJS 208 (Adapted from Pascoli, Polleux, A&A 2000)

Monitoring fragment formation & detection of carbon particles

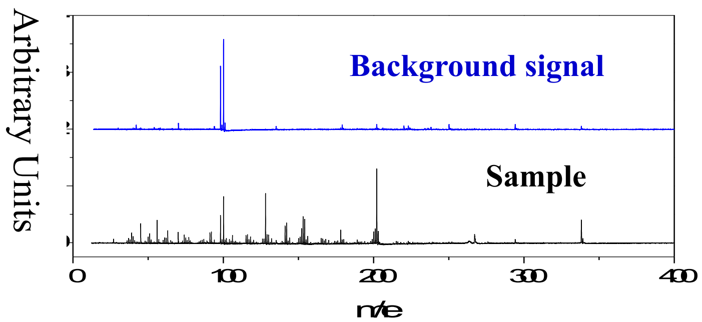
Spectrum of Pyrene ($C_{16}H_{10}$) seeded plasma versus discharge energy



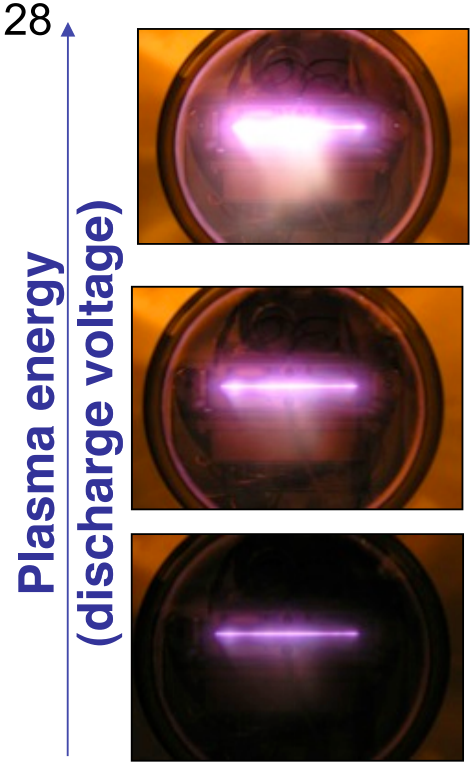
Observation of soot on the electrodes

Mass Spectrometry studies confirm the formation of larger particles: LDMS of soot formed from $C_{10}H_8$ (128 amu) precursor.

μL²MS of soot formed from $C_{12}H_{10}$ (154 amu) precursor



H. Sabbah, R. Zare, Stanford, 2006-2010



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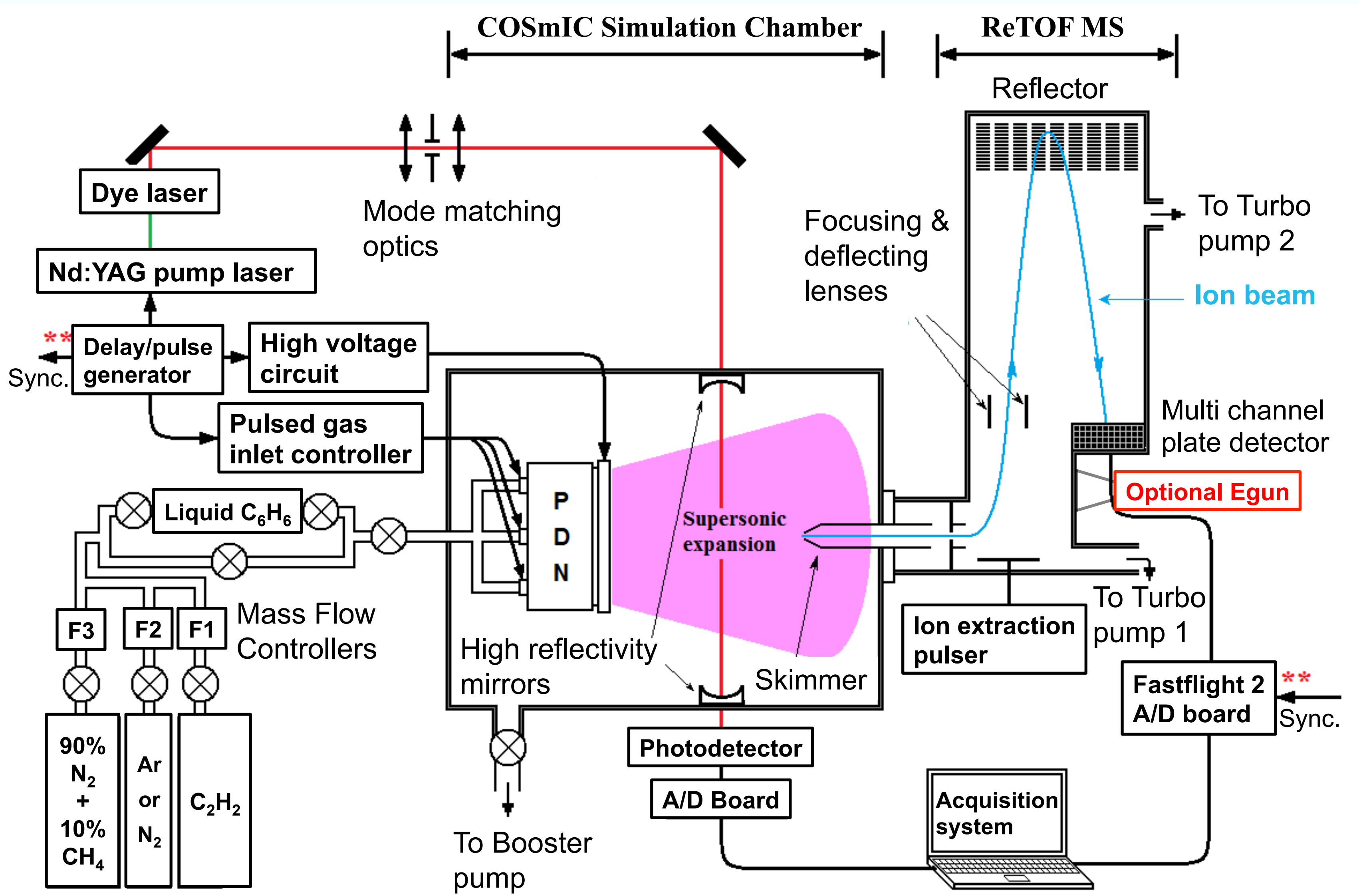
Pulsed Discharge Nozzle (PDN) + Cavity Ring-Down Spectroscopy + ReTOF Mass Spectrometer



Ricketts et al., 2011, Int. J. Mass Spectrom. Ion Processes, 300, 26

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ReTOF-MS Results - Summary of Experiments

Precursor category and types

Hydrocarbons

Alkanes
- Methane (CH_4)
- Ethane (C_2H_6)

Alkenes
- Ethylene (C_2H_4)

Alkynes
- Acetylene (C_2H_2)

Aromatics
- Benzene (C_6H_6)
- Toluene ($C_6H_5CH_3$)
- Pyridine (C_5H_5N)

Polycyclic Aromatic Hydrocarbons

Homogenous PAHs
- Naphthalene ($C_{10}H_8$)
- 1-Methylnaphthalene ($C_{10}H_7CH_3$)
- Acenaphthene ($C_{12}H_{10}$)

Heterogeneous PAHs
- Quinoline (C_9H_7N)
- 2,3-Benzofuran (C_8H_6O)
- Thianaphthene (C_8H_6S)

Mixtures of Precursors

Benzene Analogs & Hydrocarbons

Benzene (C_6H_6) &
- Methane (CH_4)
- Ethane (C_2H_6)
- Ethylene (C_2H_4)
- Acetylene (C_2H_2)

Toluene ($C_6H_5CH_3$) &
- Methane (CH_4)
- Ethylene (C_2H_4)
- Acetylene (C_2H_2)

Pyridine
- Methane (CH_4)
- Acetylene (C_2H_2)

PAH & Hydrocarbons

Naphthalene ($C_{10}H_8$) &
- Methane (CH_4)
- Ethane (C_2H_6)
- Ethylene (C_2H_4)
- Acetylene (C_2H_2)

1-Methylnaphthalene ($C_{10}H_7CH_3$)
- Methane (CH_4)
- Ethane (C_2H_6)
- Ethylene (C_2H_4)
- Acetylene (C_2H_2)

Acenaphthene ($C_{12}H_{10}$) &
- Methane (CH_4)
- Ethane (C_2H_6)
- Ethylene (C_2H_4)
- Acetylene (C_2H_2)

Quinoline (C_9H_7N) &
- Acetylene (C_2H_2)

2,3-Benzofuran (C_8H_6O) &
- Acetylene (C_2H_2)

Thianaphthene (C_8H_6S) &
- Acetylene (C_2H_2)

Contreras and Salama, ApJ Supplement, 2013

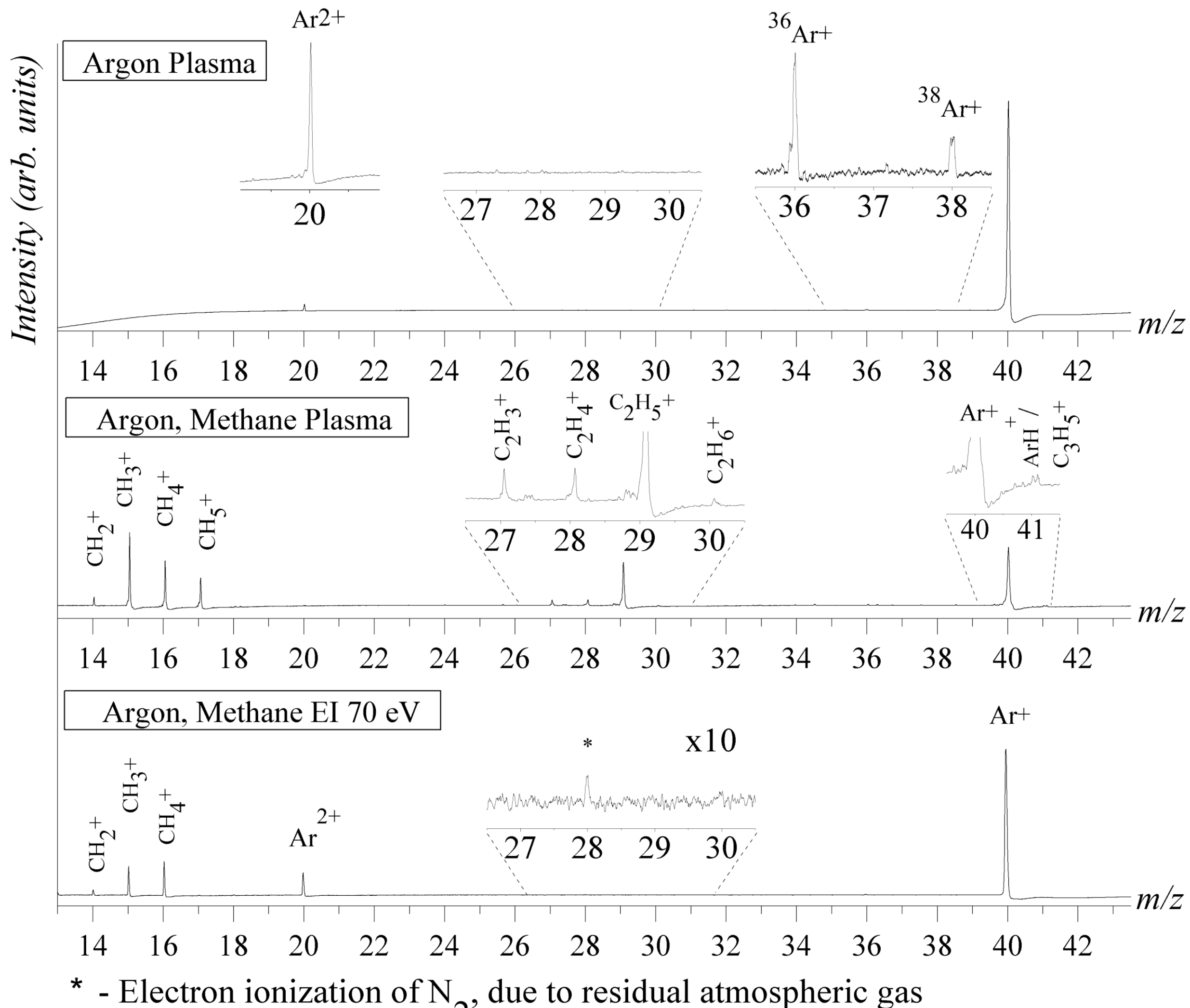
ReTOF-MS Results – Hydrocarbons: Methane

Comparison of Mass Spectra between ionization types

Plasma –

Major products for Methane:
By addition of CH_x

EI – Electron Ionization
No recombination products (expected)

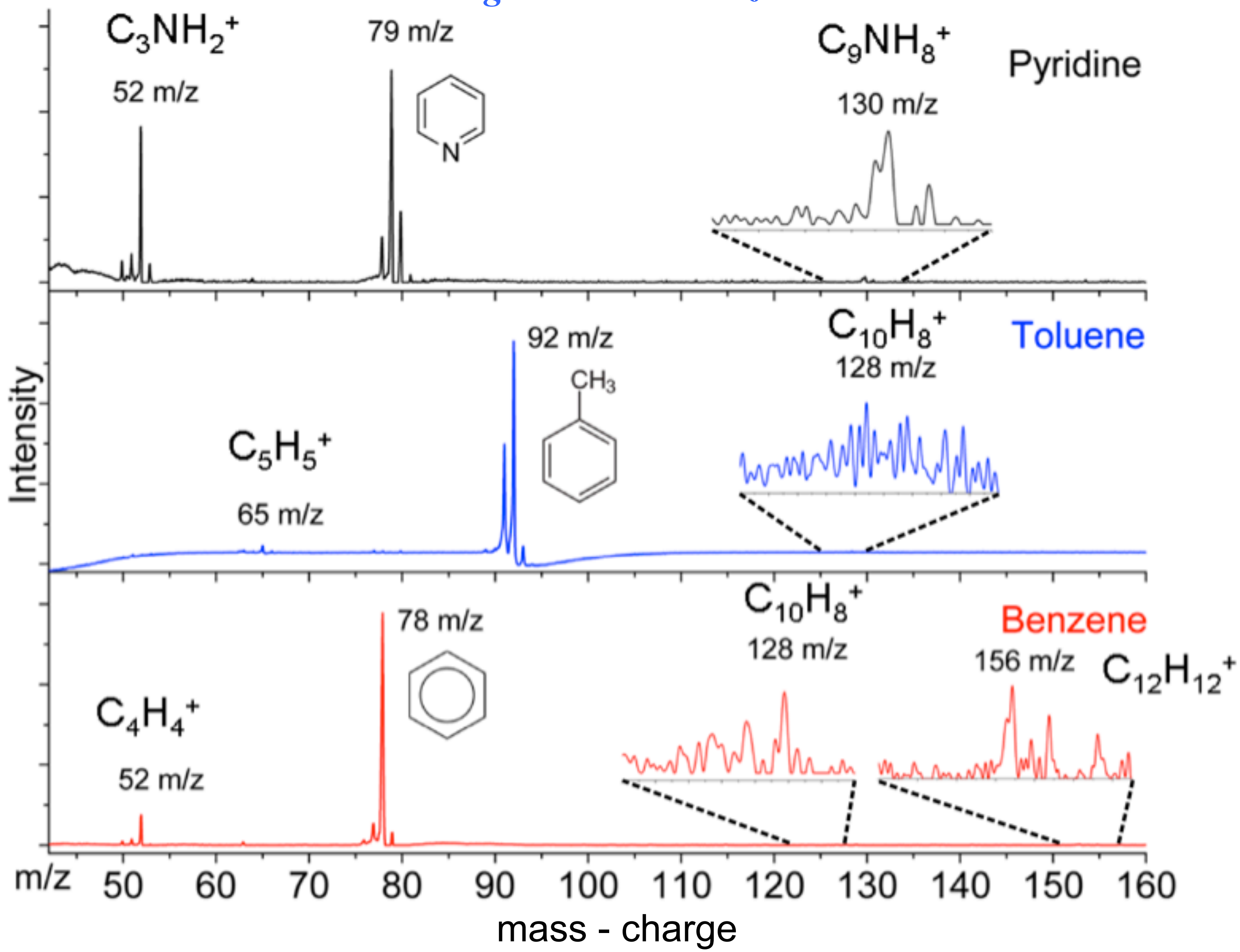


* - Electron ionization of N_2, due to residual atmospheric gas

Contreras and Salama, ApJ Supplement, 2013

ReTOF-MS Results – Single Ring Aromatics

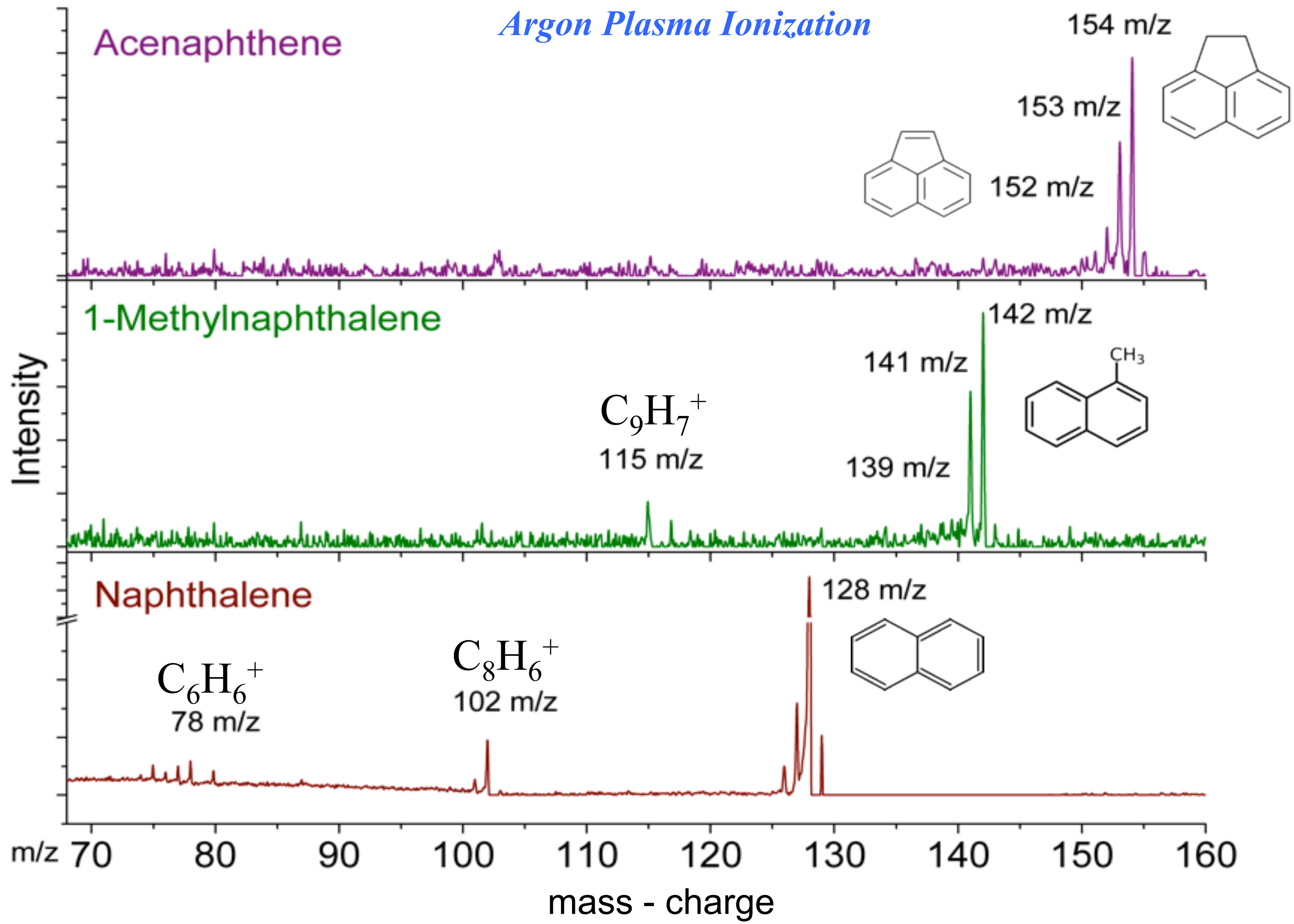
Argon Plasma Ionization



Contreras and Salama, ApJ Supplement, 2013

ReTOF-MS Results – Homogeneous PAHs

Argon Plasma Ionization



Contreras and Salama, ApJ Supplement, 2013

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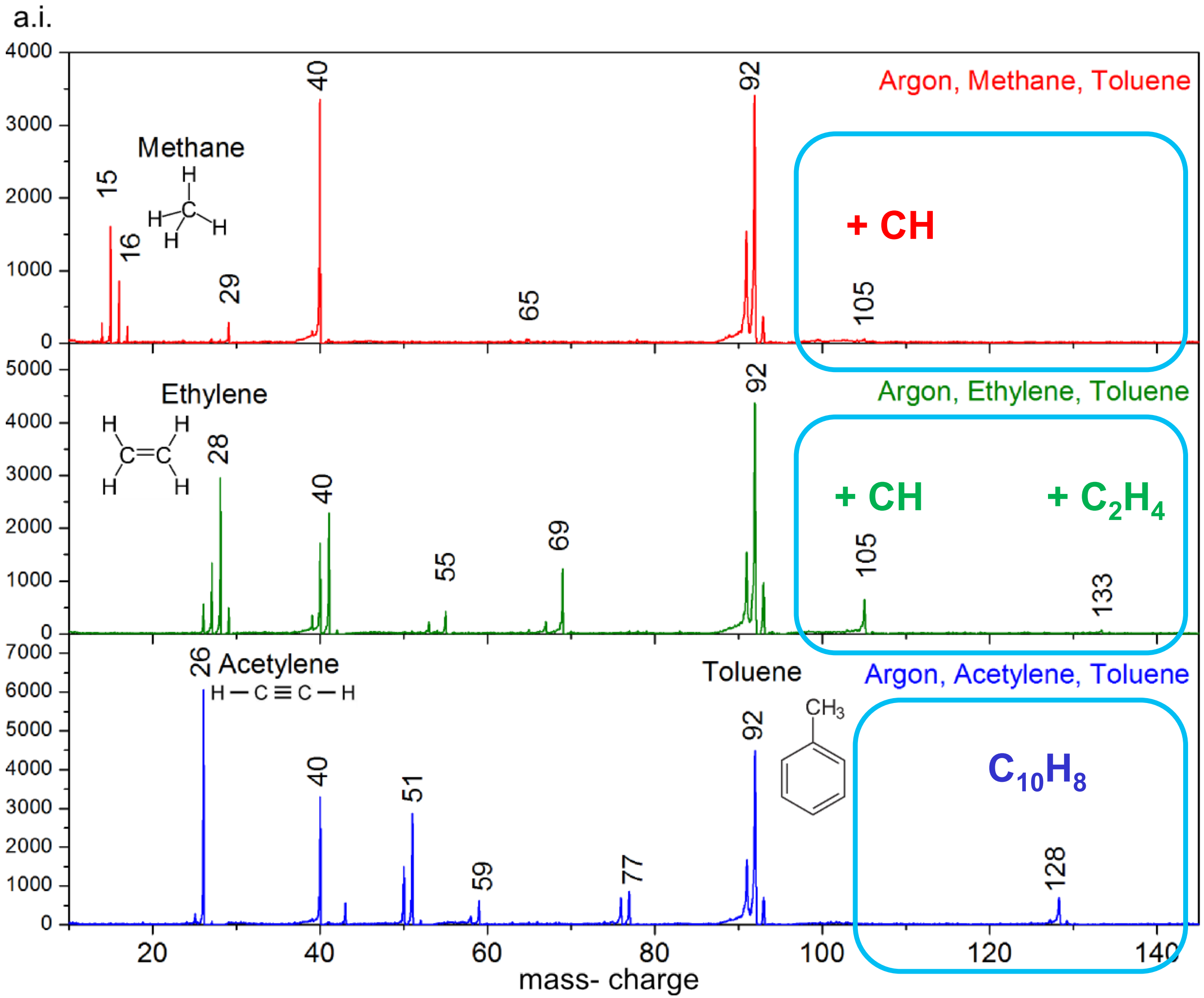
ReTOF-MS Results – Mixtures: Toluene/Hydrocarbons

Distinct chemistry occurs with each different hydrocarbon starting compound



Contreras & Salama, ApJ Supplement, 2013

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ReTOF-MS Summary

Hydrocarbons

- Methane, Ethane, Ethylene show sequential CH_x growth
- Acetylene major growth involves C_2 groups
- Acetylene experiments show growth up to C_6H_5 ions

Single-ring aromatics

- Benzene, toluene, pyridine all show recombination product ions
- Benzene forms ions $C_{10}H_8^+$ (128m/z) and $C_{12}H_{12}^+$ (156 m/z)
- Toluene also forms $C_{10}H_8^+$ (128 m/z)
- Pyridine has an analogous ion at 130 m/z, $C_9H_8N^+$

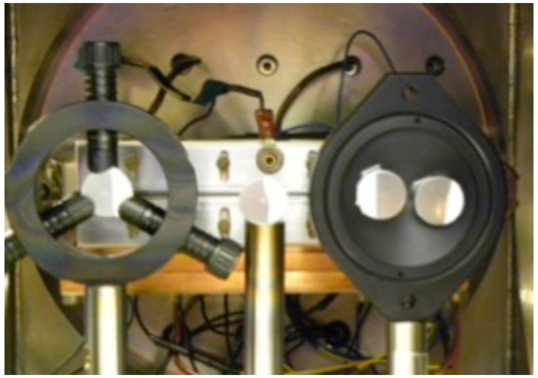
PAHs

- Acenaphthene shows 2 H losses
- 1-Methylnaphthalene shows further fragmentation and ring cleavage
- Naphthalene fragment peaks are comparable to benzene, toluene, acetylene

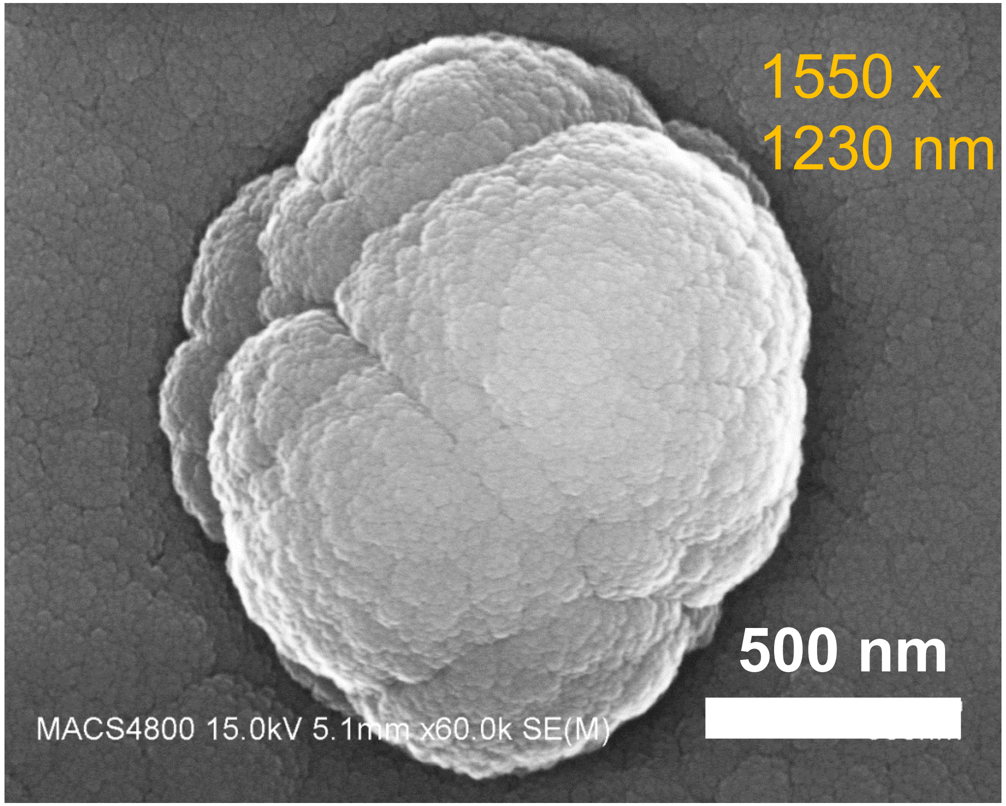
Mixtures

- Product ions seems dependent on the type of hydrocarbon precursor used.

Formation of carbon grain analogs in COSmIC



Characterization of soot nanoparticles and micrograins from the plasma experiments with SEM (Hitachi S4800), x80k – 200k magnification.



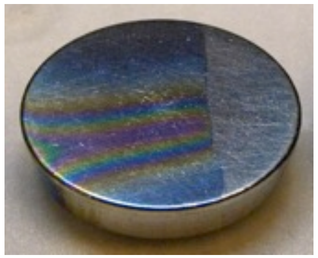
~ 1.5 µm aggregate of nanograins produced from HC precursors

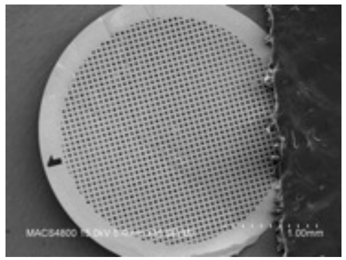
Precursors:

- Ar-Methane (CH_4)
- Ar-Acetylene (C_2H_2)
- Ar-Methane-Acetylene

Substrates:

- Aluminum SEM disc
- Aluminum foil on disc
- TEM copper grid w/ C web





Astrophysics:

- Energy budget and signature of aromatic carbon molecules
- Grain formation

Planetary:

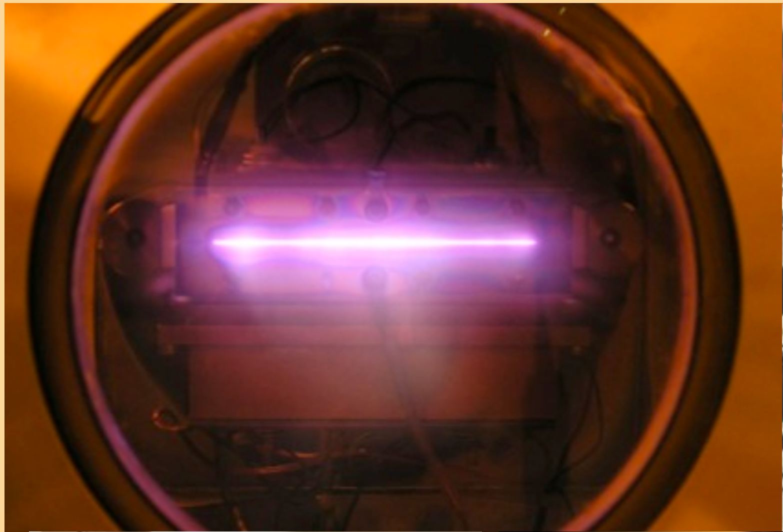
- Titan's atmosphere (haze)

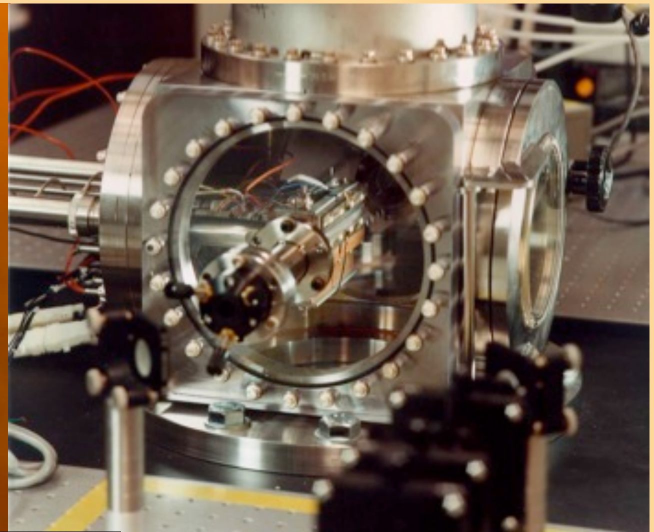
ISS:

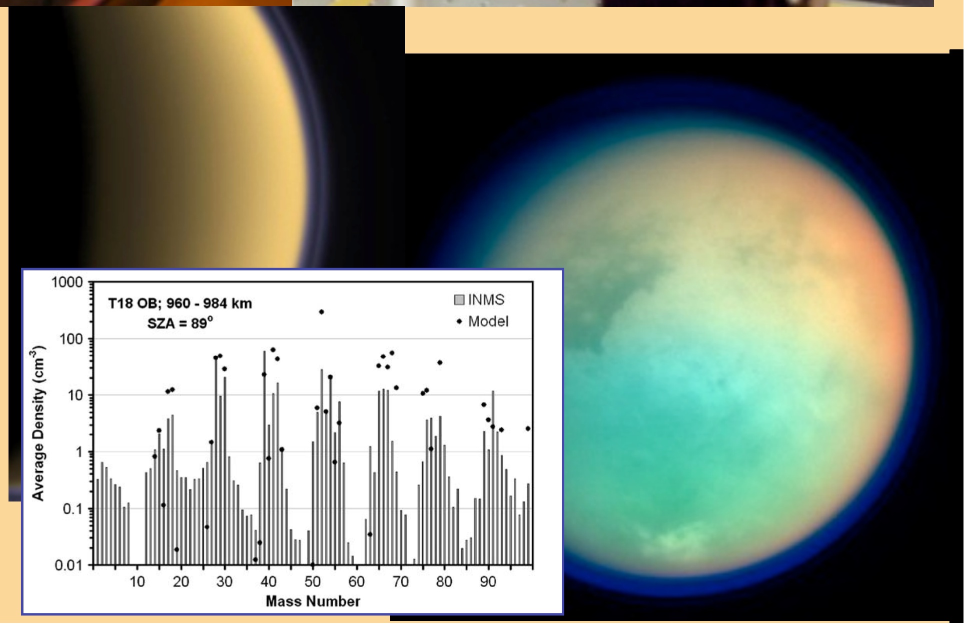
- Exposure experiments on complex organic molecules

Formation of Carbon Aerosols on Titan

Ion Neutral Mass Spectrometer (INMS) - Cassini.







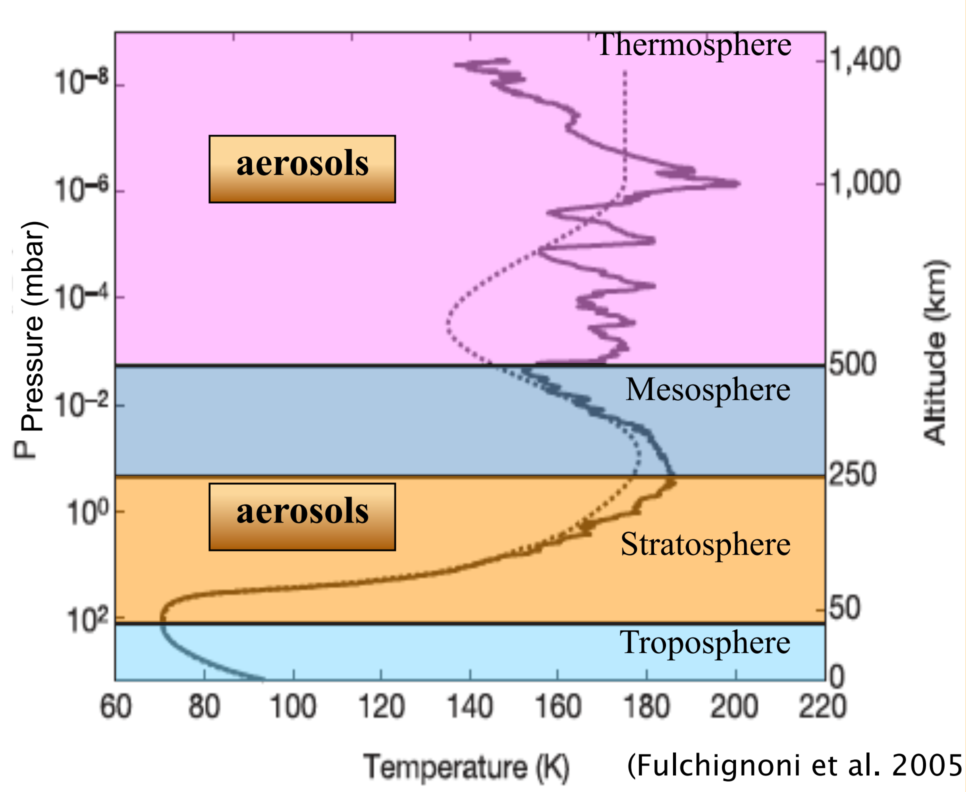
Ames Research Center

Motivation: Titan's atmospheric chemistry

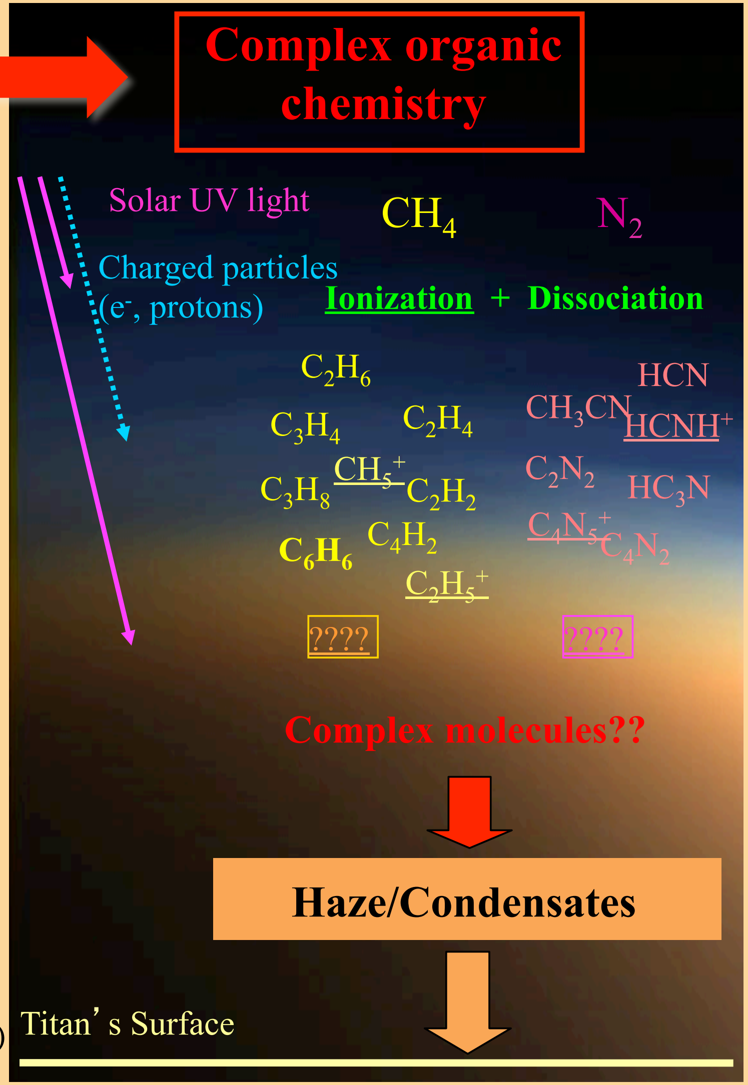
Major components: N_2 (95-99%)
CH_4 (2-5%)

(UV, e-)

Atmospheric temperatures: 70 K < T < 180 K



(Fulchignoni et al. 2005)



Motivation: Titan's atmospheric chemistry

Major components: N_2 (94-98%) CH_4 (1.8-6%) *(UV, e-)* → **Complex organic chemistry** → **aerosols**

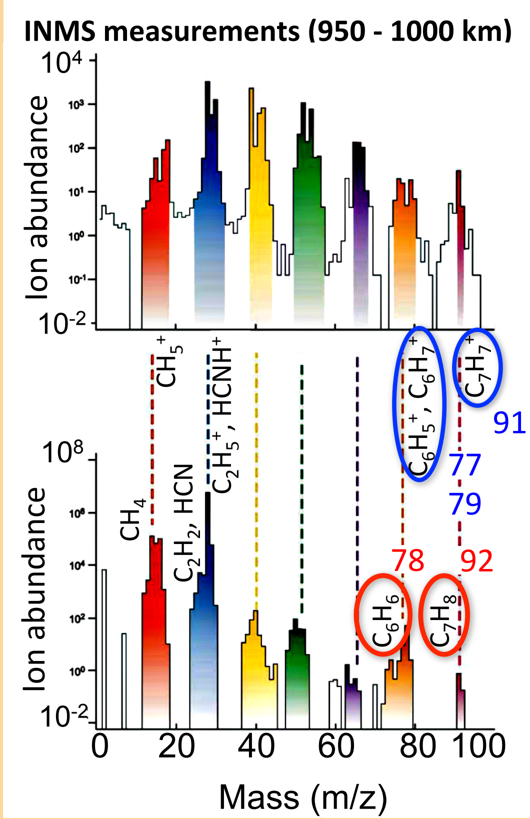
Atmospheric temperatures: **70 K < T < 180 K**

Detection of benzene and toluene (precursors of Polycyclic Aromatic Hydrocarbons (PAH)) **and heavy ions by Cassini/Huygens in Titan's upper atmosphere.** *(Waite et al. 2007, Vuitton et al. 2008)*

+ Results from numerical models *(Ricca et al. 2001, Wilson & Atreya 2003, Lebonnois 2005, Vuitton et al. 2007, Lavvas et al. 2011)*

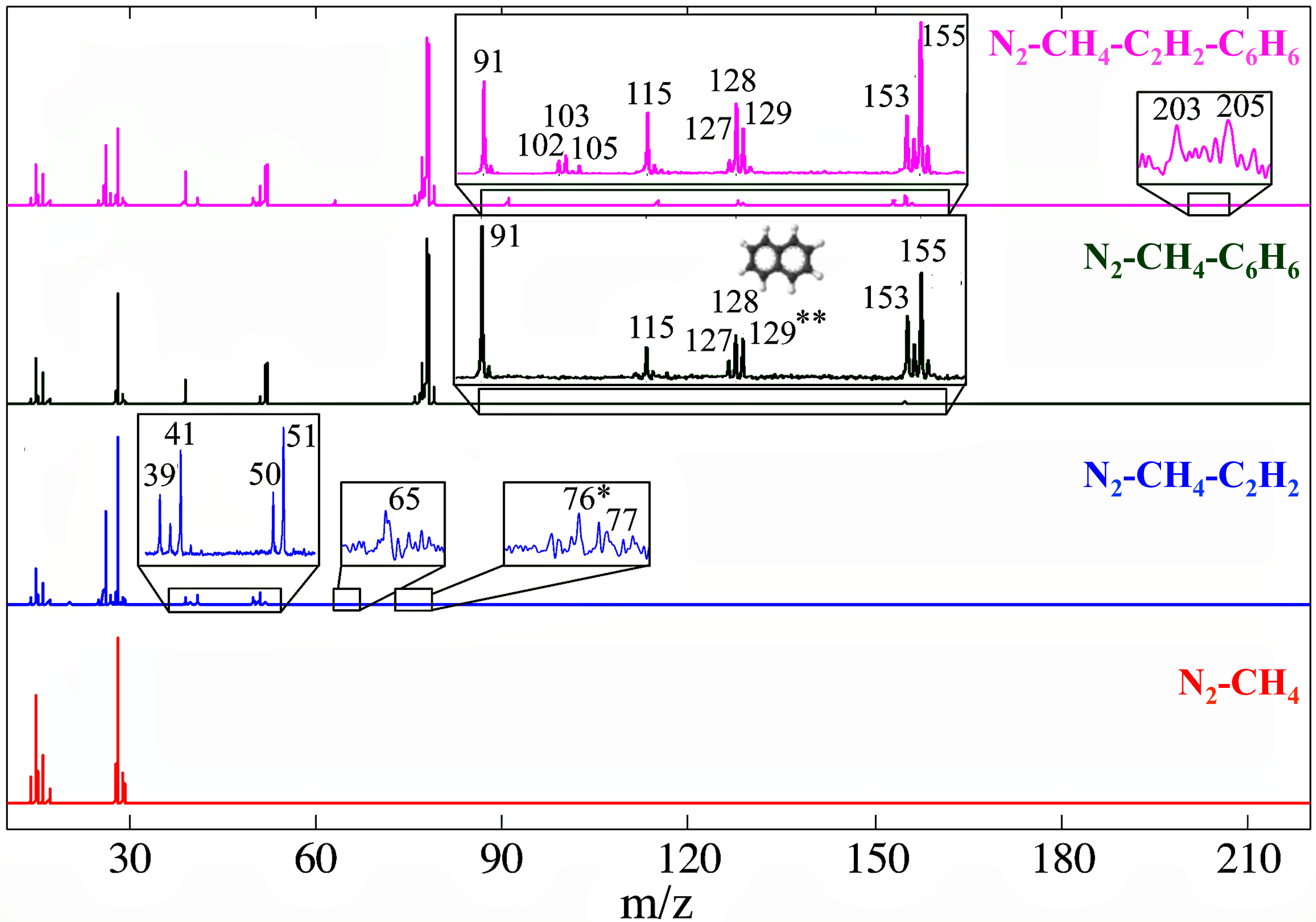
+ Results from experimental simulation *(Khare et al 2002, Imanaka et al. 2004, Trainer et al. 2004, Gautier et al. 2011)*

→ **suggest that PAHs and PANHs might play a role in the formation of aerosols.**



GAS PHASE: ReTOF-MS analysis

Probing the first and intermediary steps of Titan's chemistry:



→ **up to 205 m/z**

+ new peaks at 102-105 m/z

→ **up to 156 m/z**

(91 = ion associated with formation of toluene?
*** 129 = protonated naphthalene?)*

→ **up to 77 m/z**

(77 = ion associated with formation of benzene?
** 76 = cyclic $C_6H_4^+$?)*

→ **up to 42 m/z**

Due to short residence time in pulsed plasma

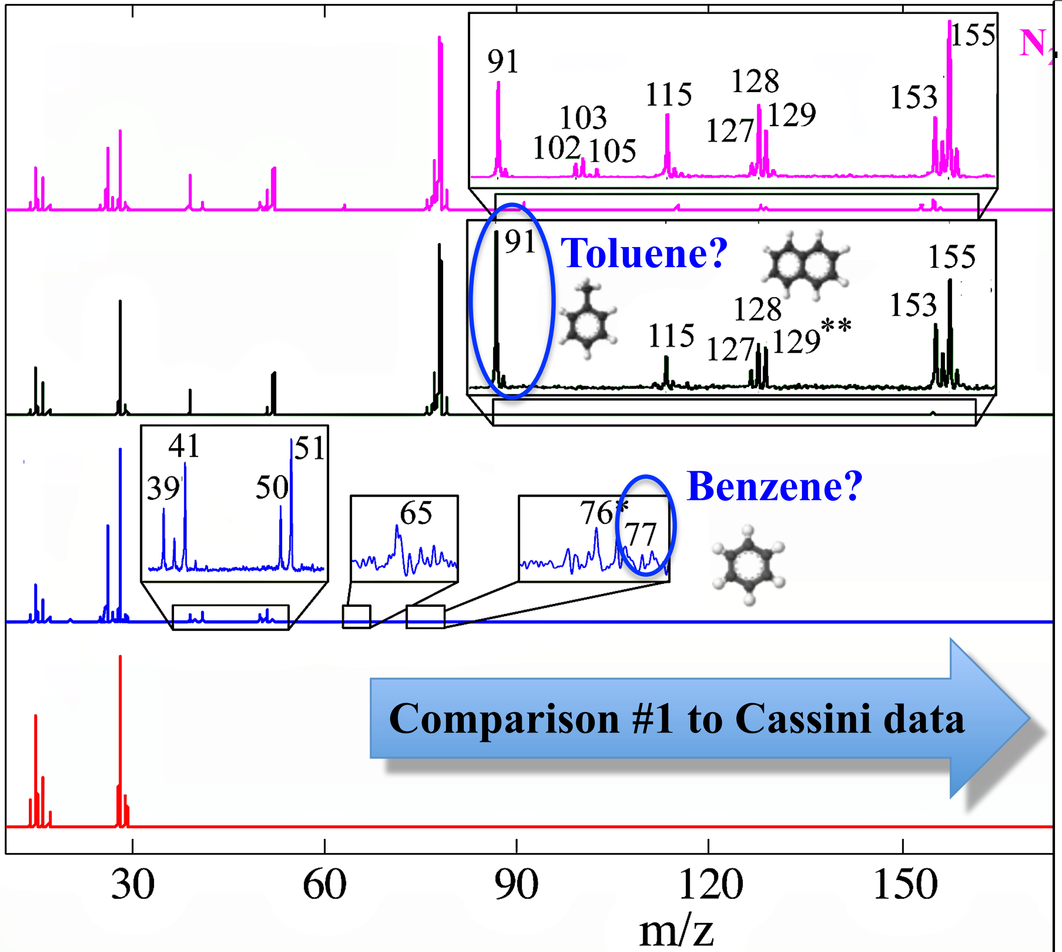
Chemical growth evolution

Sciamma-O'Brien, Rickets and Salama, Icarus, 2014

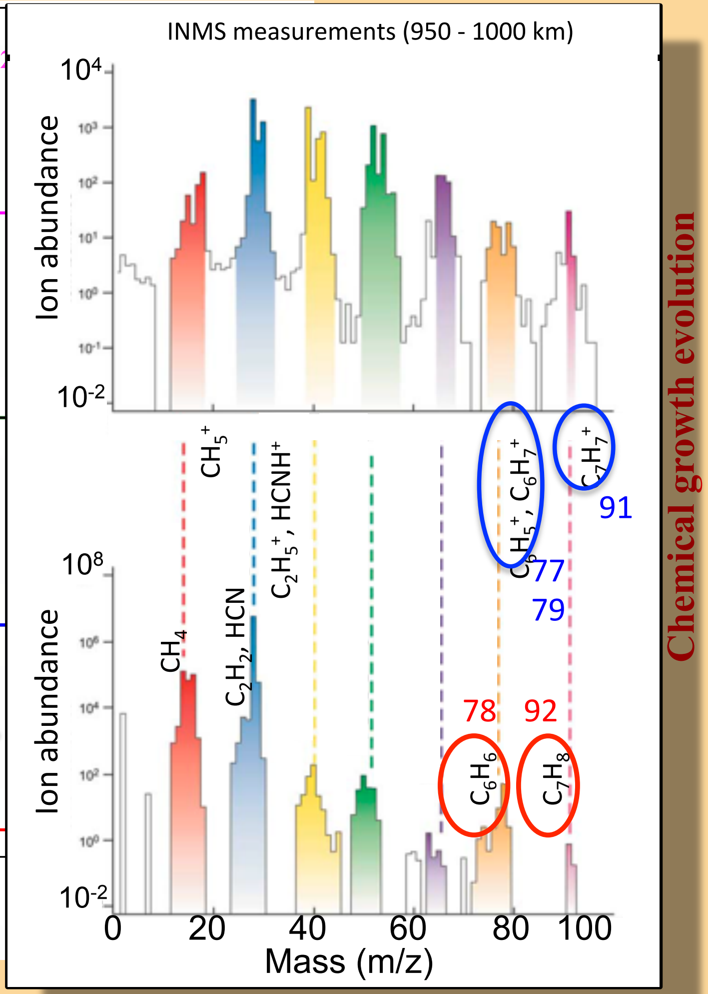
HIFOL MPIA 2016

GAS PHASE: ReTOF-MS analysis

Probing the first and intermediary steps of Titan's chemistry:



Sciamma-O'Brien, Rickets and Salama, Icarus, 2014



(Waite et al., 2007)

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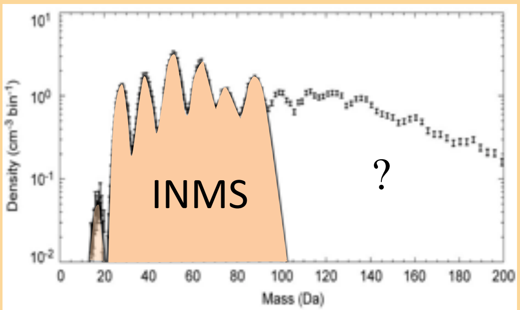
GAS PHASE: ReTOF-MS analysis

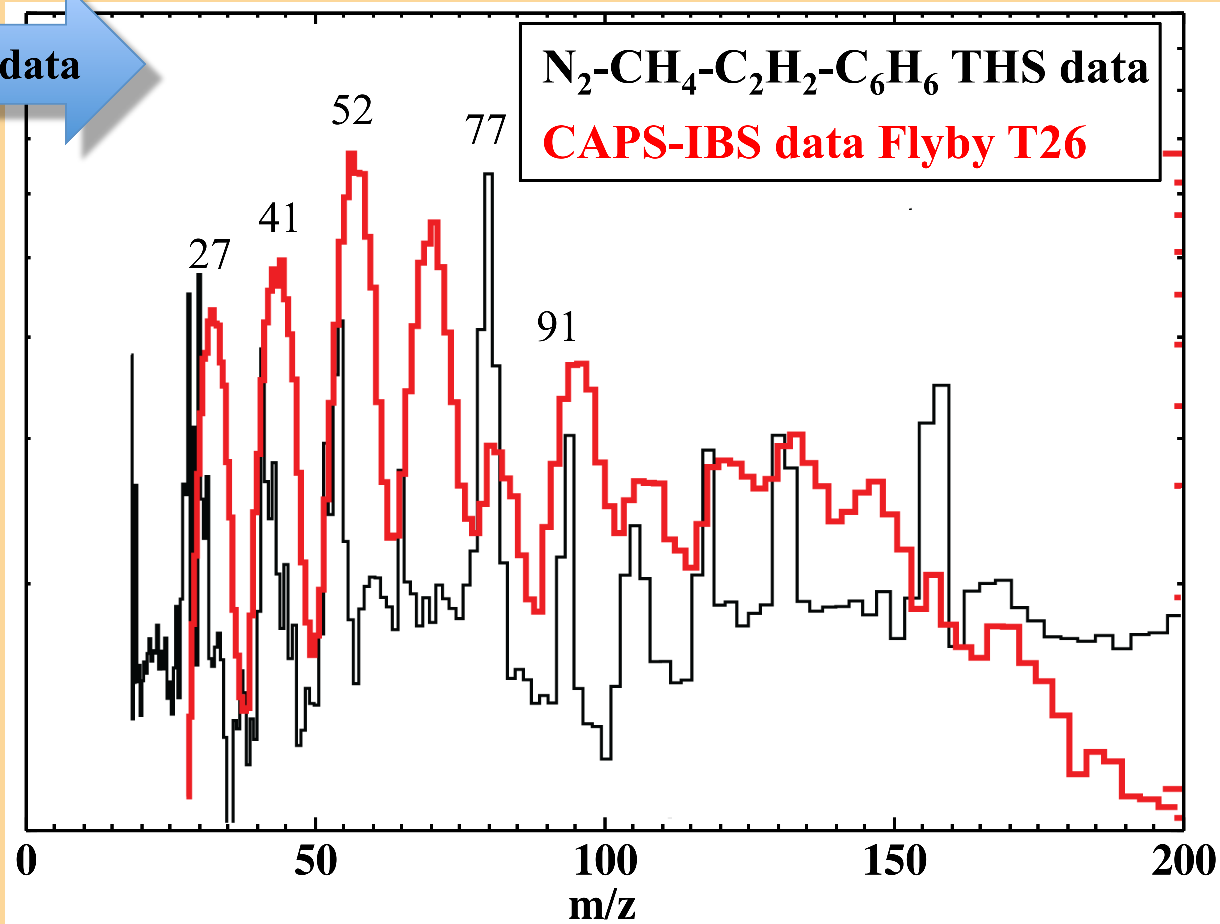
Comparison to CAPS – IBS: best match

Comparison #2 to Cassini data

Peaks observed in THS experiments match regions of positive ion spectrum in CAPS-IBS:

- **below 100 m/z** (also in agreement with INMS)





(CAPS-IBS data - Crary et al., 2009)

Sciamma-O'Brien, Rickets and Salama, Icarus, 2014

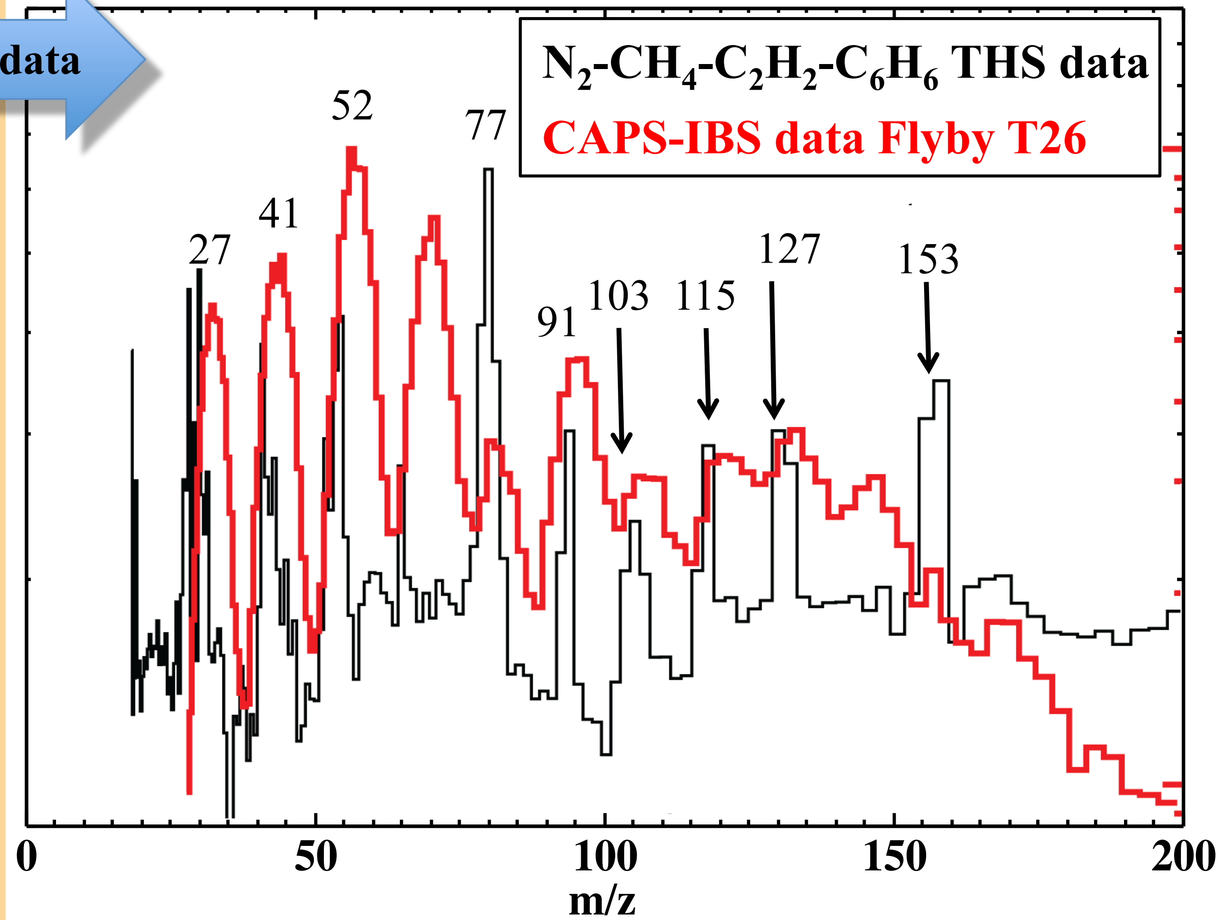
GAS PHASE: ReTOF-MS analysis

Comparison to CAPS – IBS: best match

Comparison #2 to Cassini data

Peaks observed in THS experiments match regions of positive ion spectrum in CAPS-IBS:

- **below 100 m/z** (also in agreement with INMS)
- **above 100 m/z** (not achieved in gas phase experiments at low temperature before) ,
  → most probably due to aromatic compounds



Sciamma-O'Brien, Rickets and Salama, Icarus, 2014

(CAPS-IBS data - Crary et al., 2009)

GAS PHASE: ReTOF-MS analysis

Comparison to CAPS – IBS: best match

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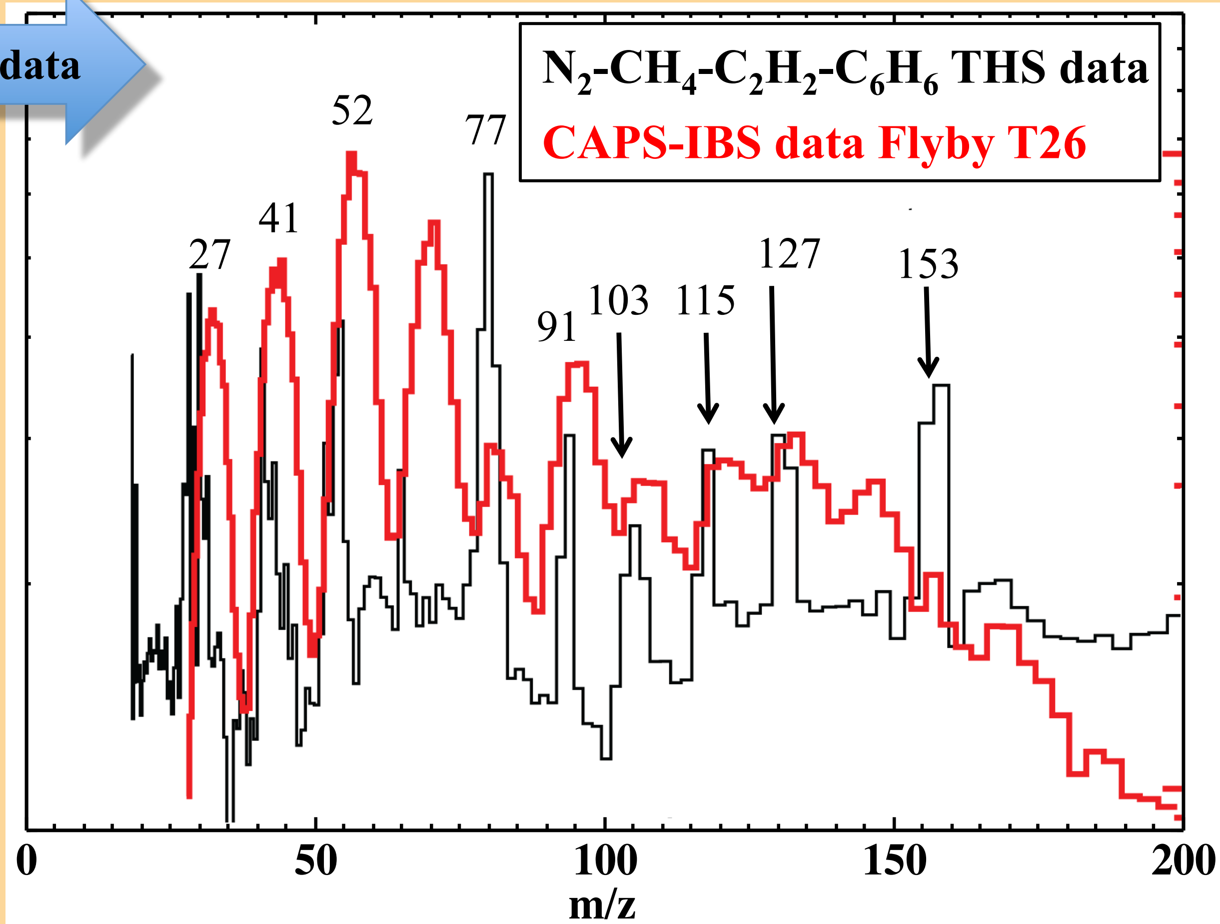
Peaks observed in THS experiments match regions of positive ion spectrum in CAPS-IBS:

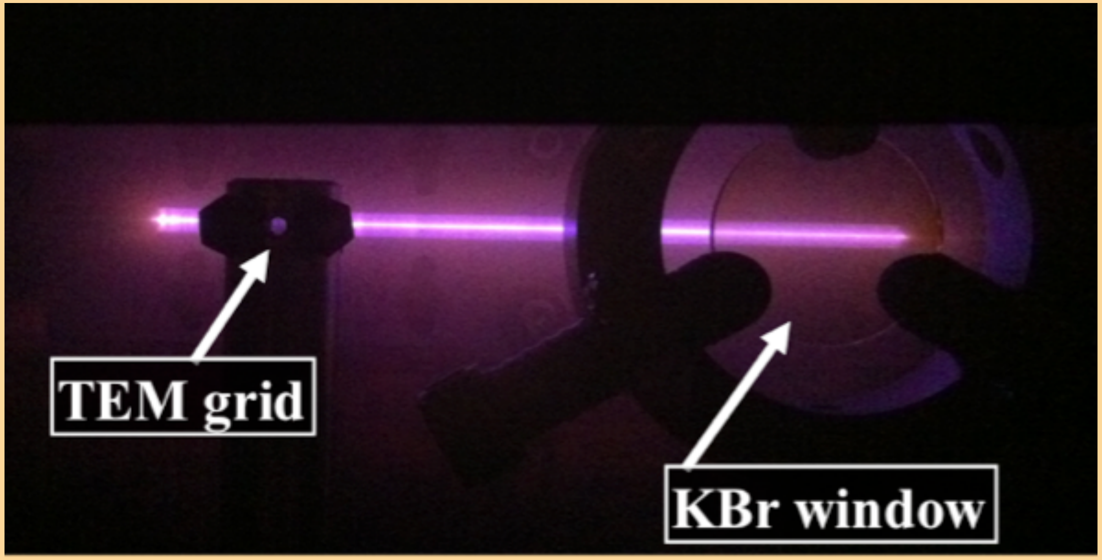
- **below 100 m/z** (also in agreement with INMS)
- **above 100 m/z** (not achieved in gas phase experiments at low temperature before) ,
  → most probably due to aromatic compounds

NEXT:
- **Missing regions: due to aliphatic compounds?**



(CAPS-IBS data - Crary et al., 2009)

SOLID PHASE: Tholin deposition



Substrates: → **Ex situ analyses:**

KBr window → IR spectroscopy

UHV Al foil → NMR spectroscopy, Mass Spectrometry

TEM grid → Scanning Electron Microscopy

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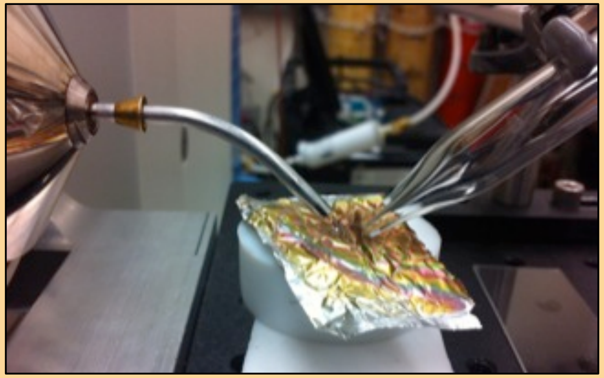
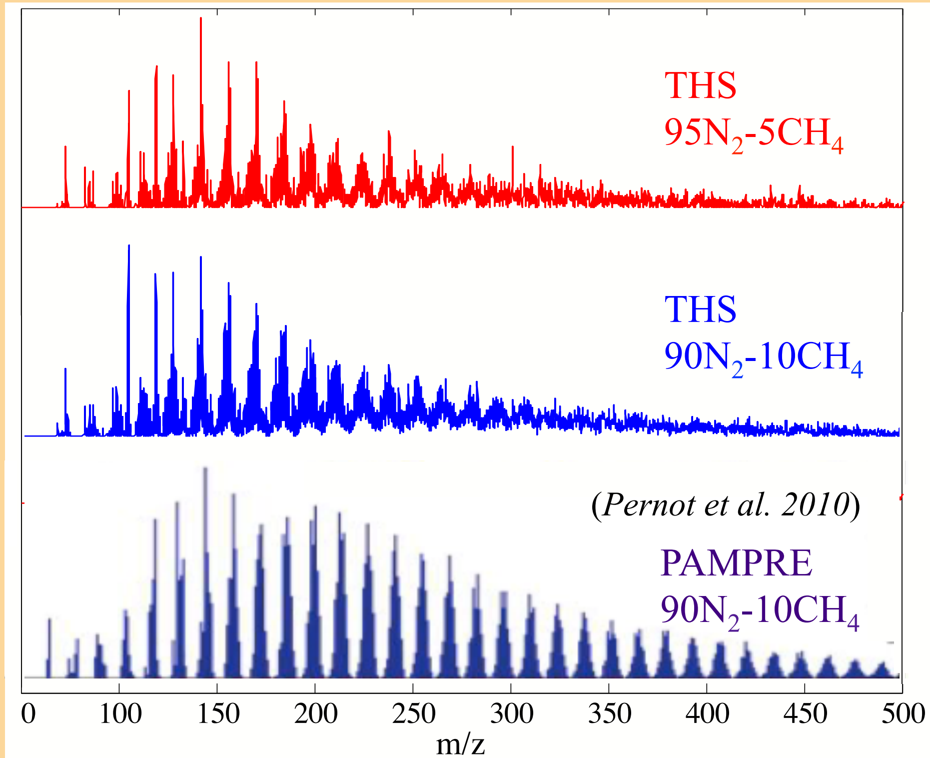
SOLID PHASE: Tholin ex situ analysis

Mass Spectrometry (UHV Al foil)

Direct Analysis in Real Time (DART)



Soft ionization method (no fragmentation) operating at **atmospheric pressure** and ambient conditions.



Common Tholin mass spectra
→ forest of peaks with periodicity

Early chemistry: made of less complex molecules than other Titan simulants (PAMPRE)

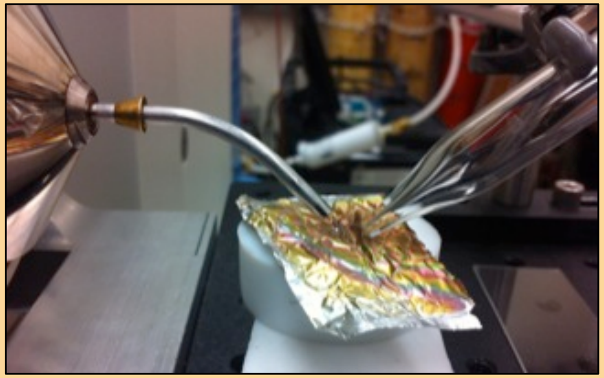
⇒ **CONSISTENT WITH GAS PHASE RESULTS**

Upton, Beauchamp et al. 2014

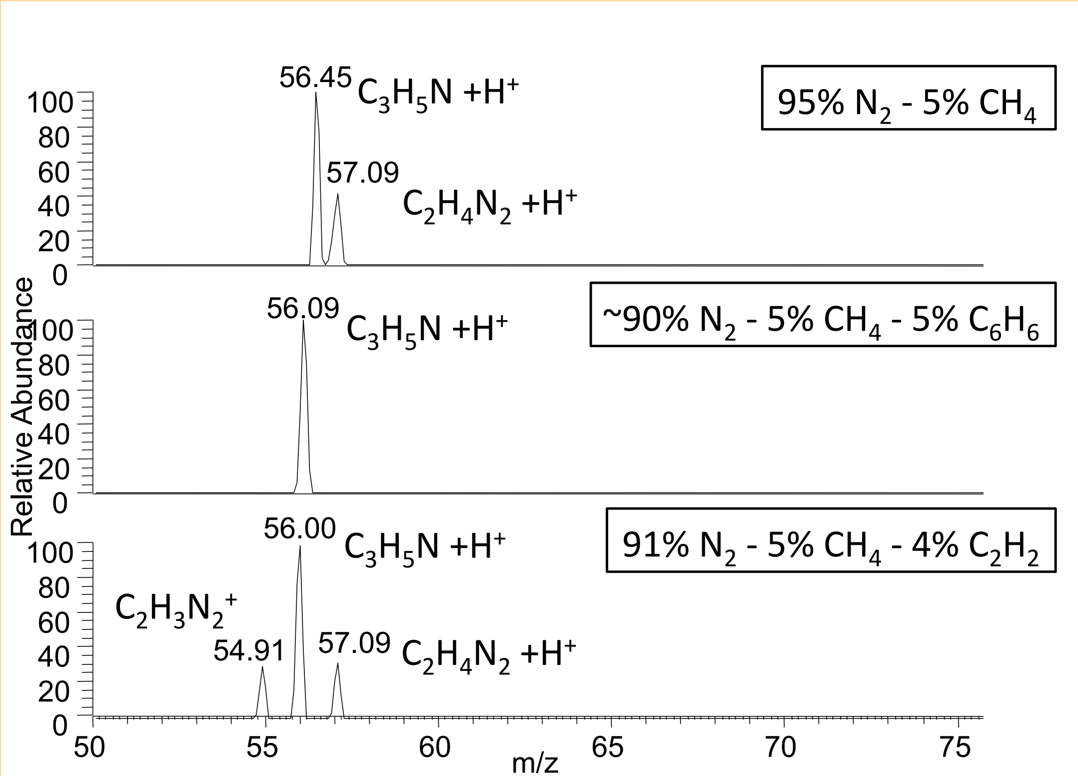
SOLID PHASE: Tholin ex situ analysis

Mass Spectrometry (UHV Al foil)

Direct Analysis in Real Time (DART)



Soft ionization method (no fragmentation) operating at **atmospheric pressure** and ambient conditions.



MS/MS data of peak at 77 m/z

→ shows production of aminoacetonitrile ($C_2H_4N_2$)

Upton, Beauchamp et al. 2014

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SOLID PHASE: Tholin ex situ analysis

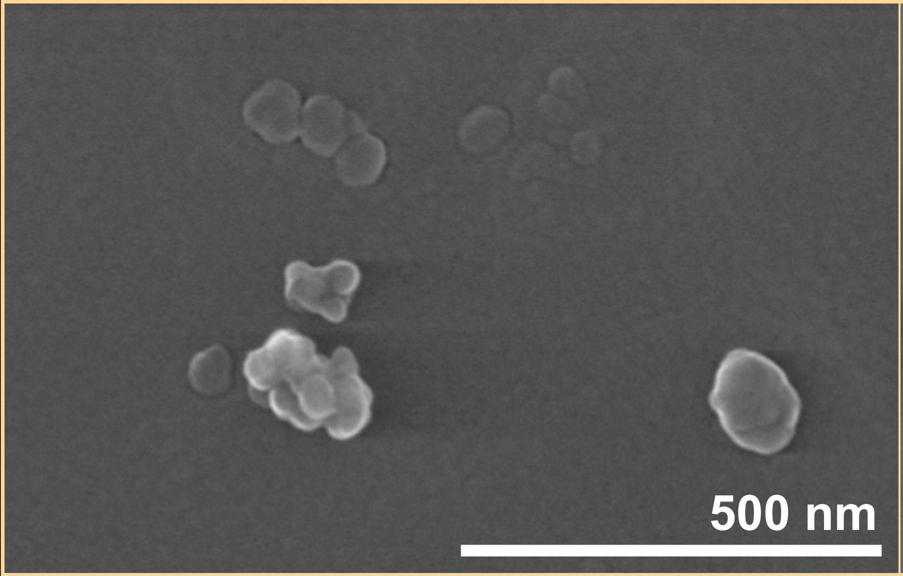
Scanning Electron Microscopy (TEM grid)

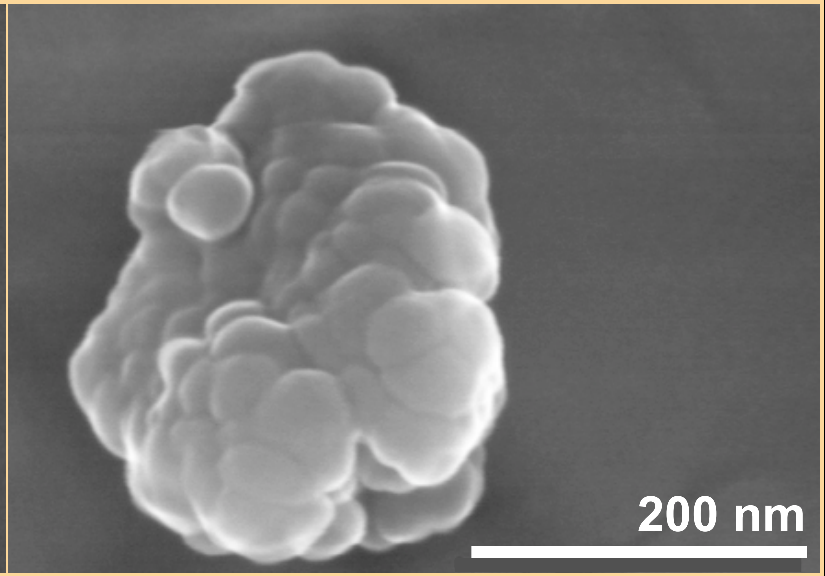
→ Can look at growth structure / morphology

N_2-CH_4 (95:5)

Substrate covered with impacted 10-50 nm nanoparticles

Grains: **100-300 nm** in diameter made of ~10-50 nm sized nanoparticles





SOLID PHASE: Tholin ex situ analysis

Scanning Electron Microscopy (TEM grid)

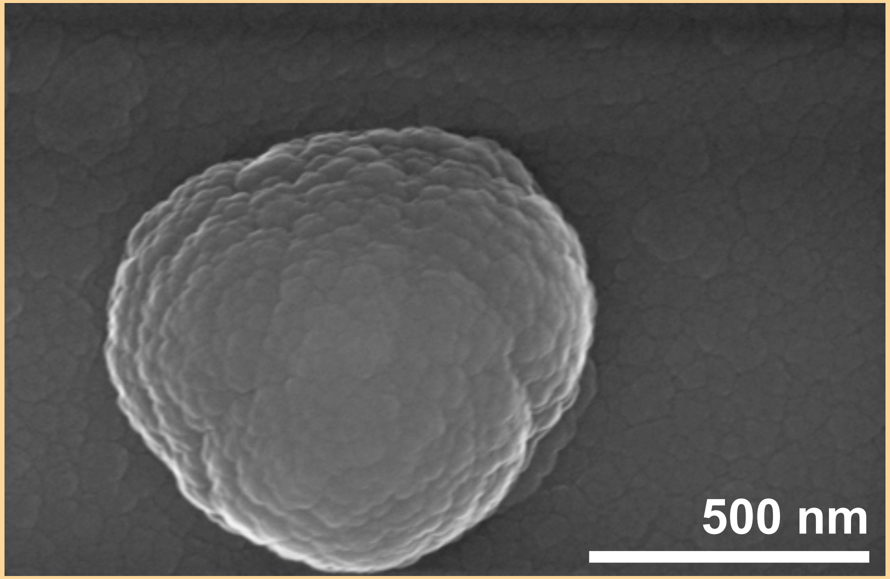
→ Can look at growth structure / morphology

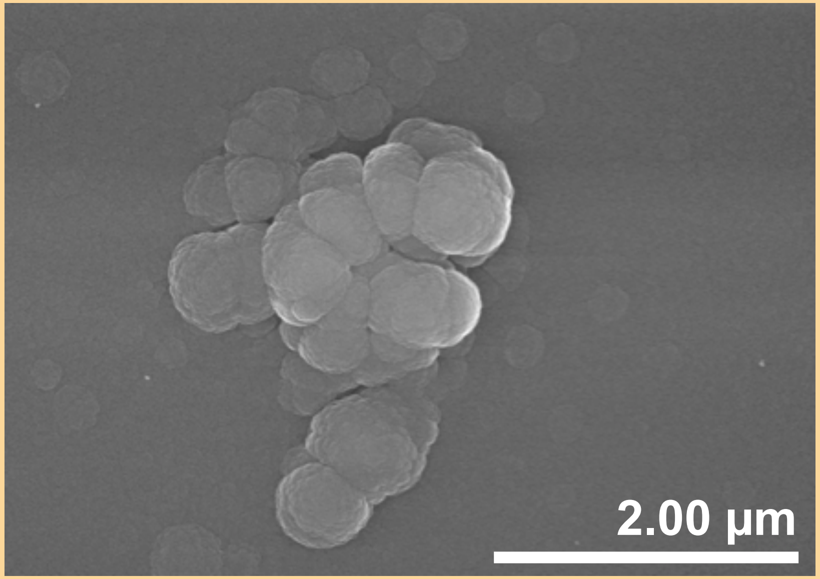
N_2-CH_4-C_2H_2 (90:5:5)

Substrate covered with impacted 10-50 nm nanoparticles

Grains: **300 to 500 nm** in diameter made of ~10-50 nm sized nanoparticles

Aggregates: **up to 3000 nm** in diameter made of 500 nm sized grains





SOLID PHASE: Tholin ex situ analysis

Scanning Electron Microscopy (TEM grid)

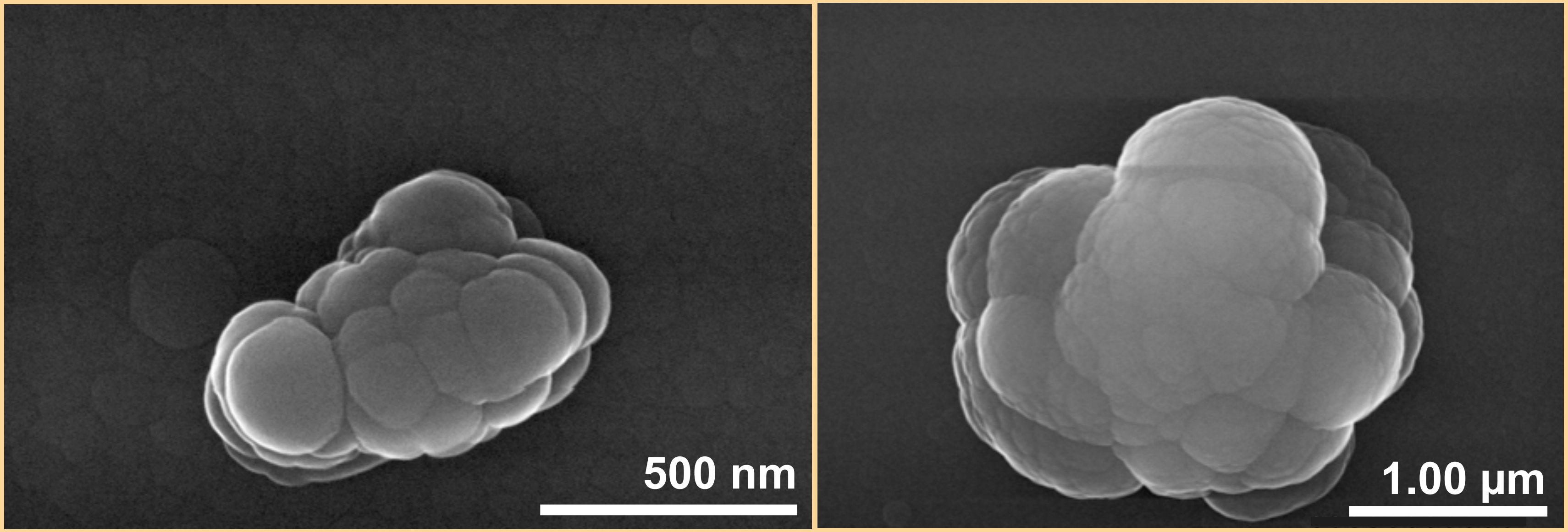
→ **Can look at growth structure / morphology**

N_2-CH_4-C_6H_6 (90:5:5)

Substrate covered with impacted 10-50 nm nanoparticles

Grains: **300 to 500 nm** in diameter made of ~10-50 nm sized nanoparticles

Aggregates: **up to 3000 nm** in diameter made of 500 nm sized grains



SOLID PHASE: Tholin ex situ analysis

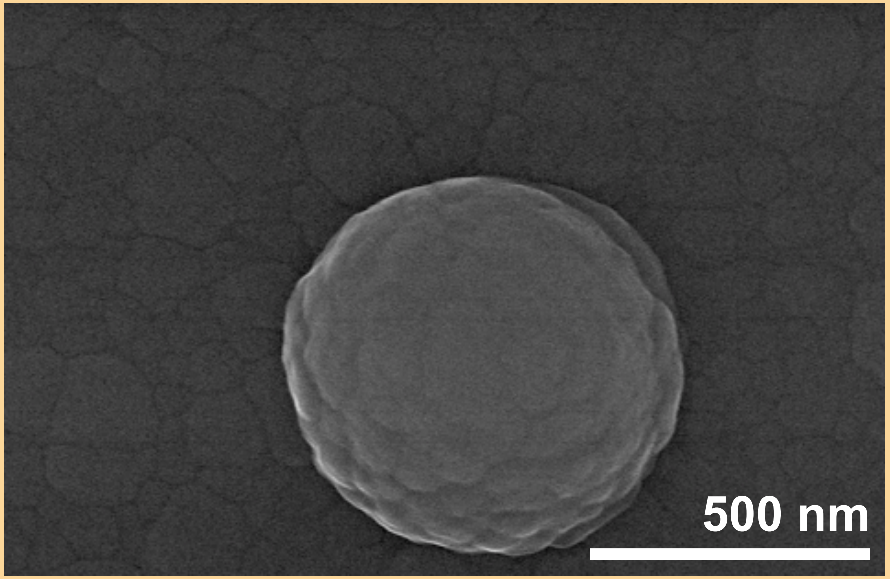
Scanning Electron Microscopy (TEM grid)

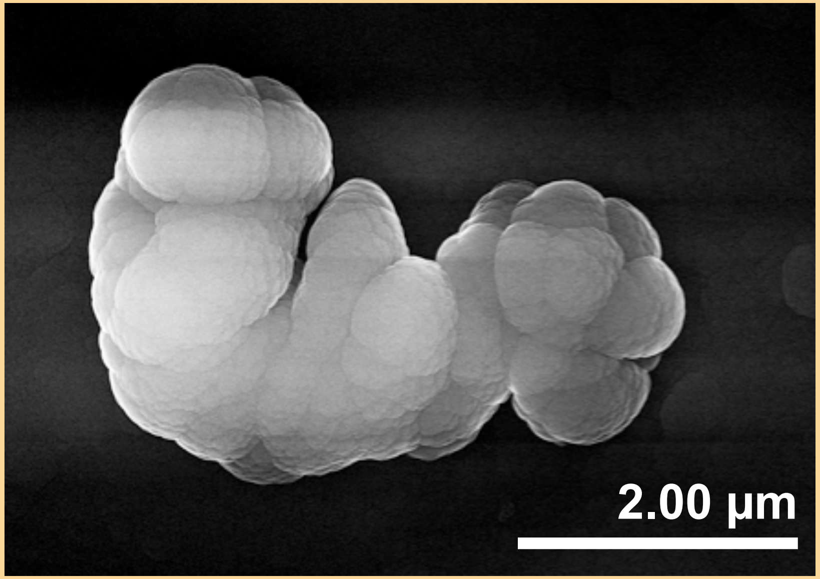
→ **Can look at growth structure / morphology**

N_2-CH_4-C_2H_2-C_6H_6 (85:5:5:5)

Substrate covered with impacted 10-50 nm nanoparticles

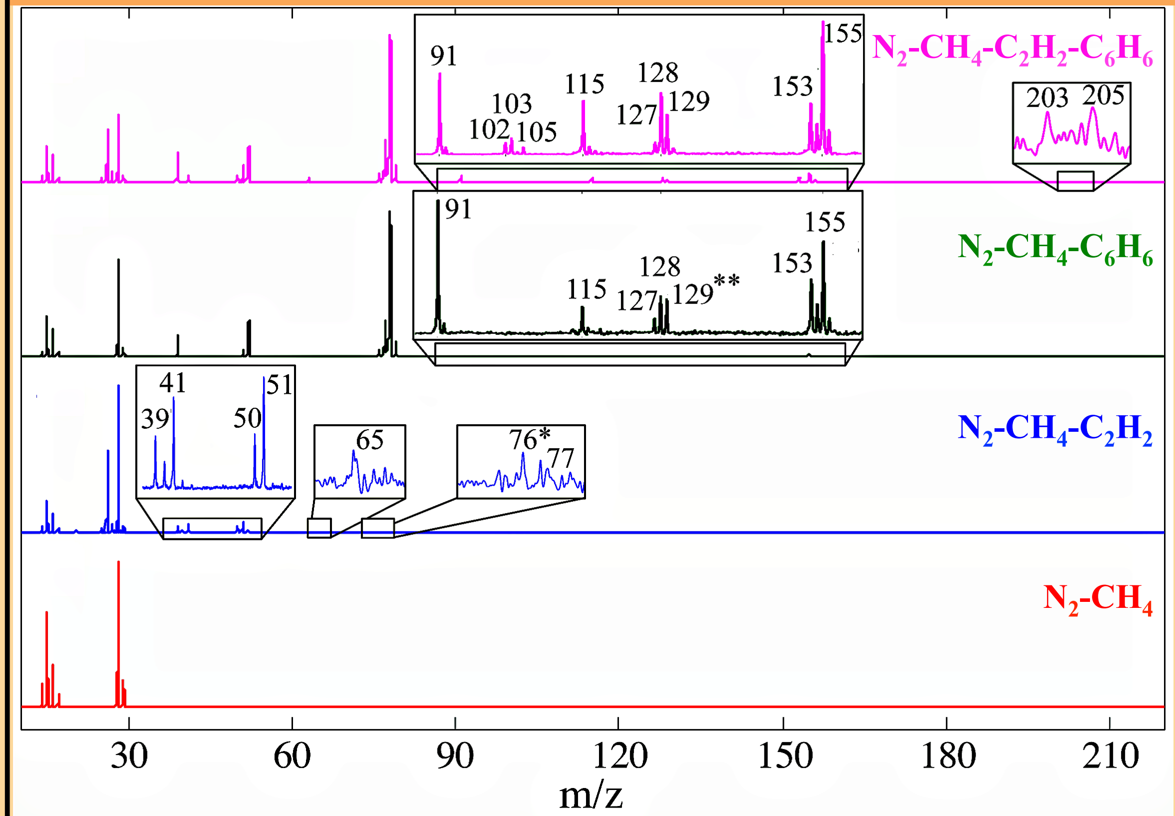
Grains: 300 to 500 nm in diameter made of ~10-50 nm sized nanoparticles
Aggregates: up to 5000 nm in diameter made of 500 nm sized grains

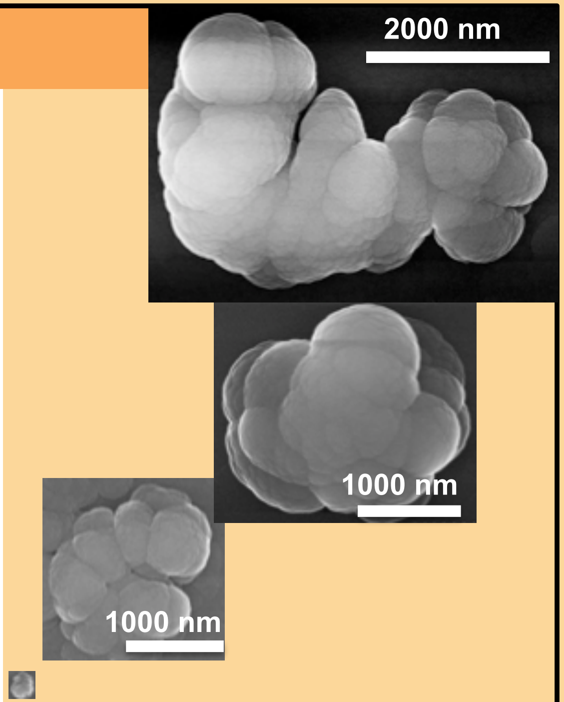




SOLID PHASE coherent with GAS PHASE

Scanning Electron Microscopy





(Same scale)

⇒ **Heavier precursors => larger aggregates => CONSISTENT WITH GAS PHASE**

+ **substrate covered with impacted 20/50 nm particles**

⇒ **Grains grow in the expansion and are then jet deposited on the substrate**

CONCLUSION

Probing different steps of the Titan chemistry at low temperature

The THS experiment can be used to **monitor different time and chemical windows** in the chain of chemical reactions in Titan's atmospheric chemistry.

First steps

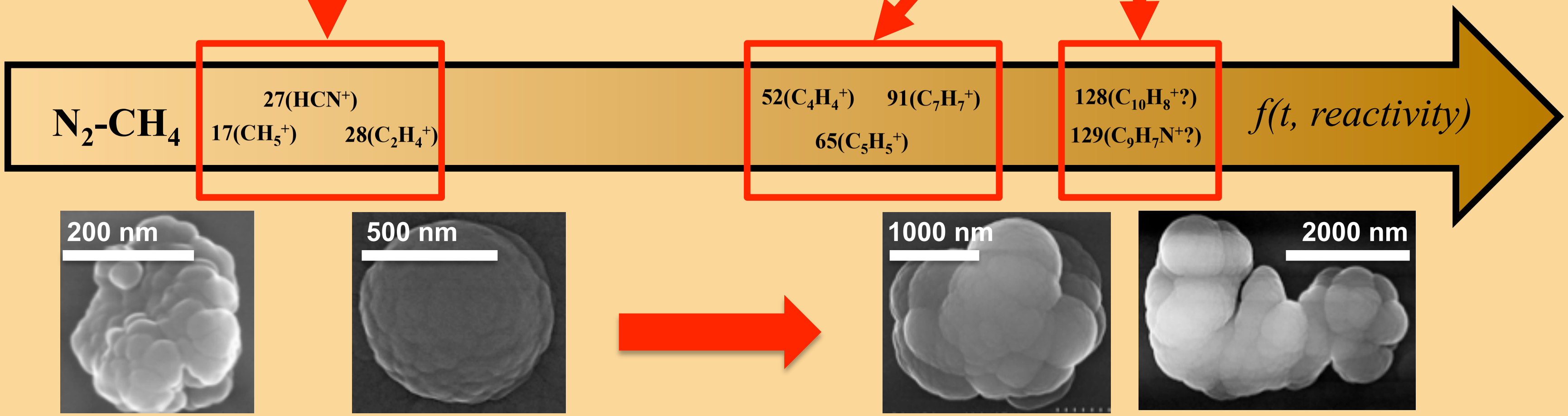
Short plasma + N_2 - CH_4 mixture:

⇒ **Probing the initial products of the N_2 - CH_4 chemistry**

Intermediary steps

N_2 - CH_4 - C_6H_6/C_2H_2 (and other) mixtures:

⇒ **probing next steps of chemistry and specific chemical pathways**



100 - 500 nm grains HIFOL MPIA 2016 **1000 - 5000 nm grains**

Astrophysics:

- Energy budget and signature of aromatic carbon molecules
- Grain formation

Planetary:

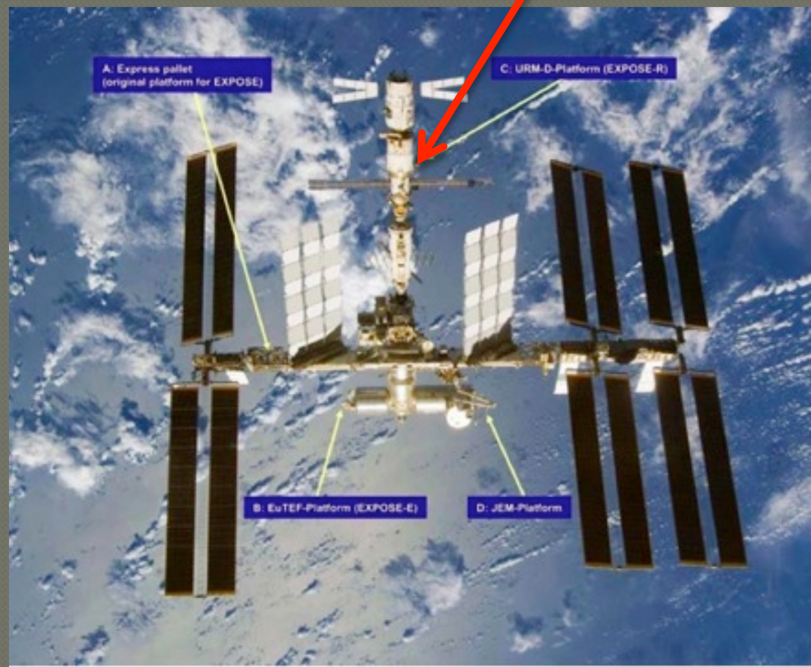
- Titan’s atmosphere (haze)

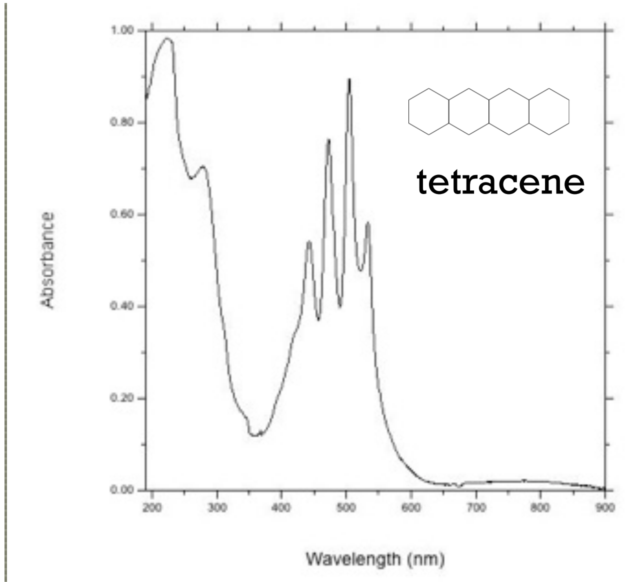
ISS:

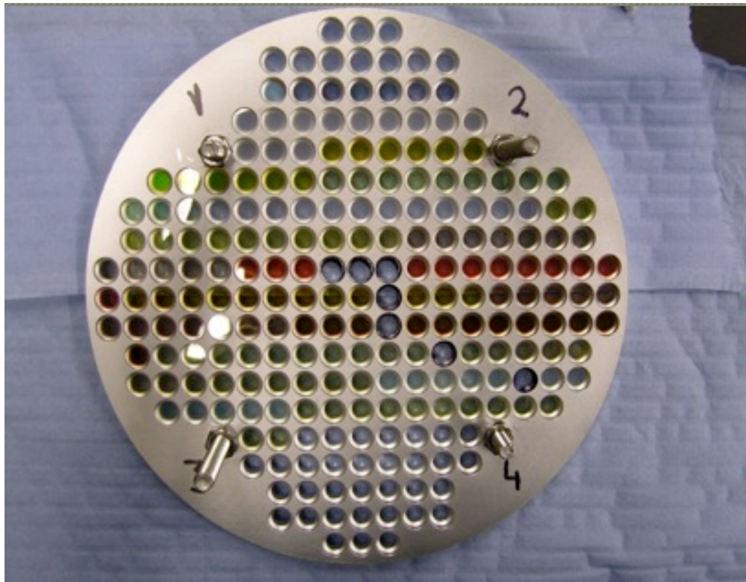
- Exposure experiments on complex organic molecules

EXPOSE-R Facility

- Second mission of the EXPOSE family
- Adapted on Universal Workplace D (URM-D platform), one of the four external platforms of the Russian Zvezda-Module of the ISS
- Provides space for astrobiology samples, sensors, heating systems, electronics for data collection, storage, telemetry and telecommand, and mechanical and electronic interfaces to the ISS platform
- Hosts 10 international astrobiology experiments

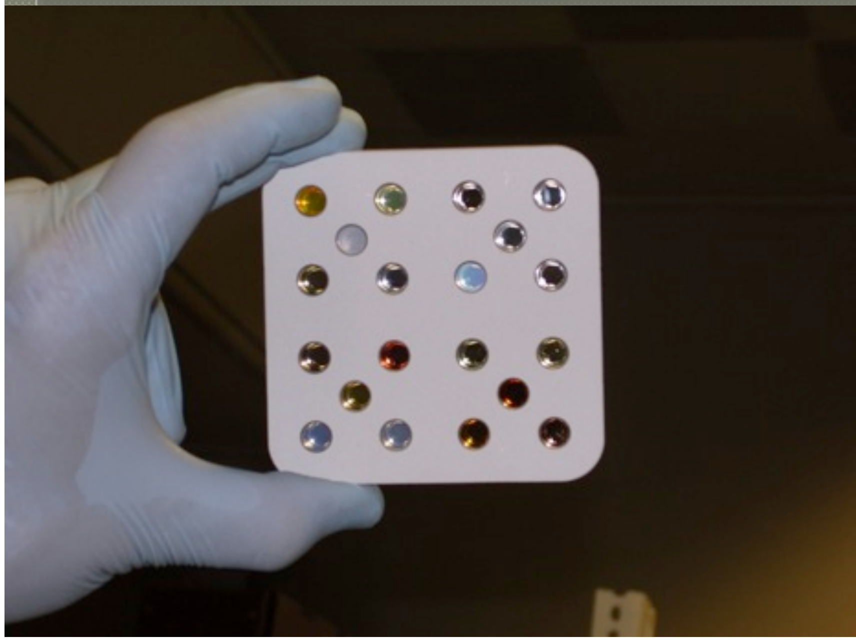


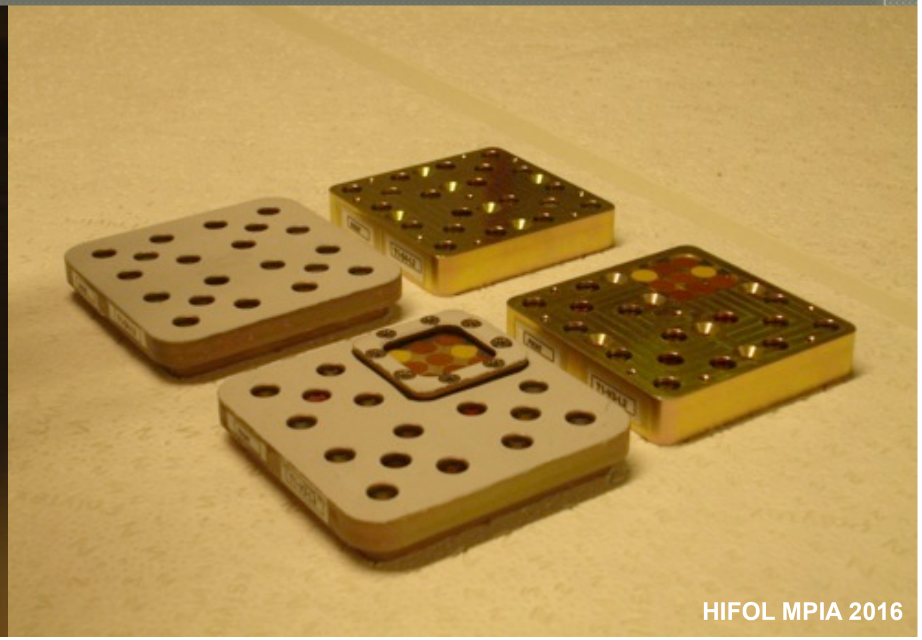




EXPOSE-R

PAH samples Cells and Carriers

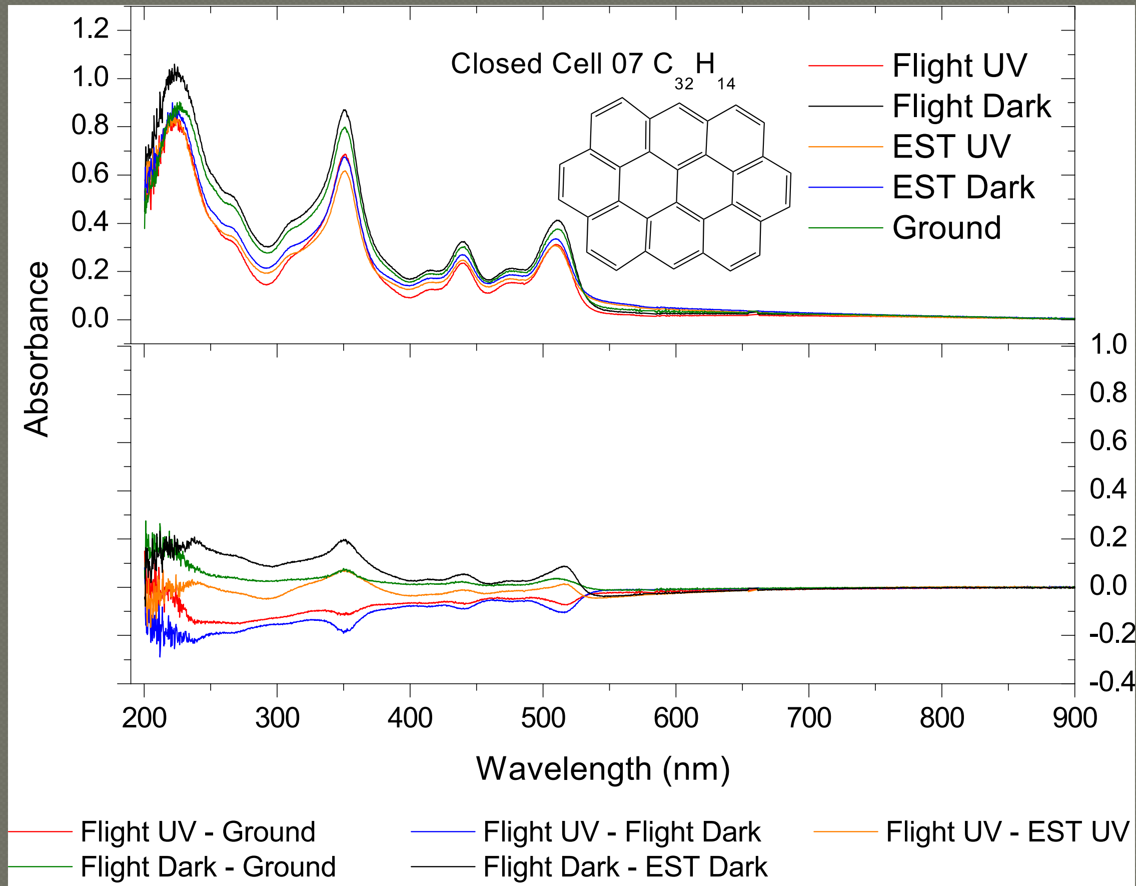




Space Exposure

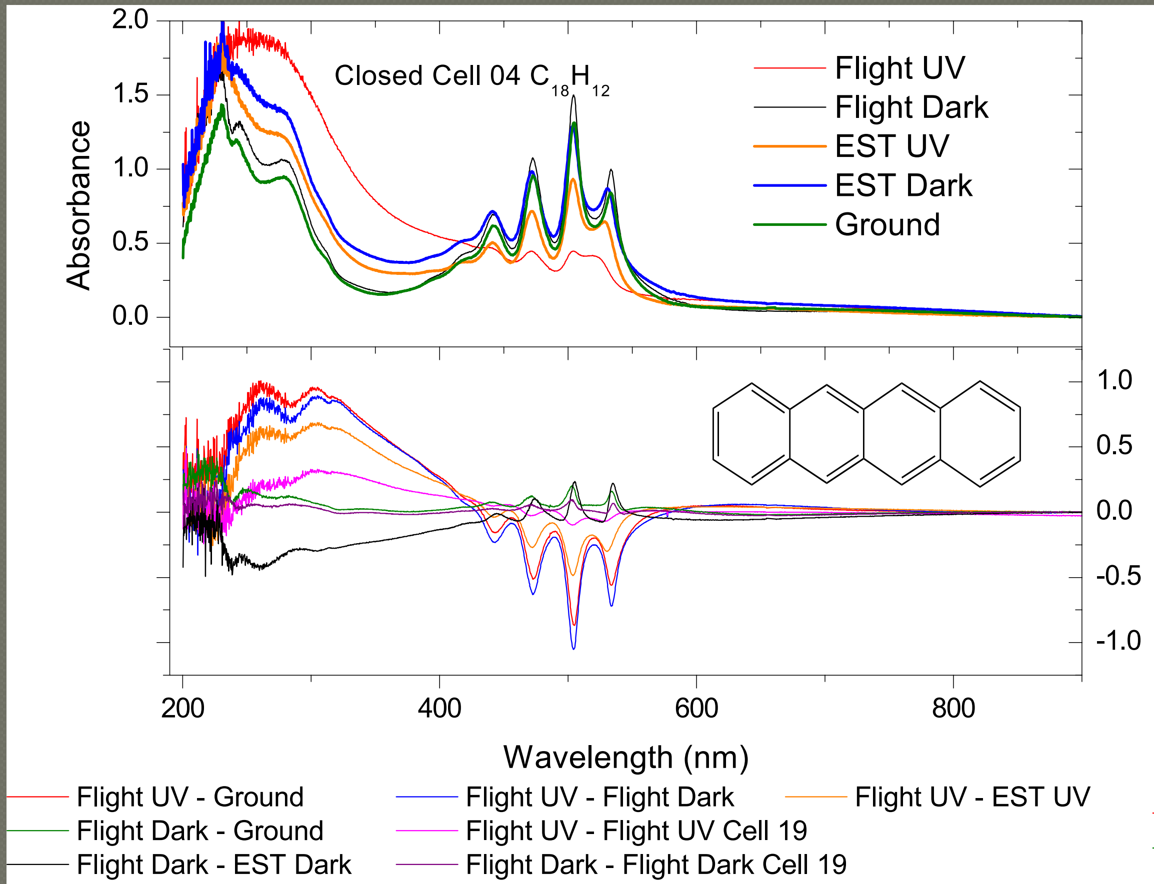
- ORGANIC on Biopan exposed
  - 58 h effective over 380 h flight
  - total fluence of 602.45 kJ m^{-2} for photons in the range 170-280 nm
- ORGANIC on EXPOSE-R exposed
  - irradiation dose of the order of 14000 MJ m^{-2} over 2900 h of unshadowed solar illumination

Compact PAH



Bryson et al., Int. J. Astrobiol., 2015

Non-Compact PAH



Bryson et al. 2015

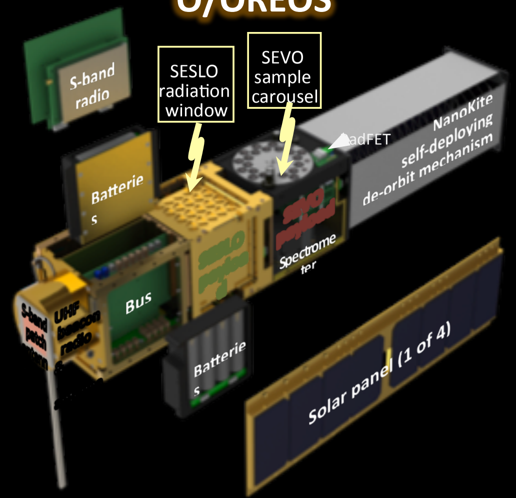
ORGANIC on EXPOSE-R RESULTS

- Limited spectral changes
- Known trend in the stability of PAH species according to molecular structure
  - Compact PAHs most stable (below 10% depletion)
  - Then non-compact PAHs
  - Least stable PAHs containing heteroatoms, the last category being the most prone to degradation in the space environment
- Extreme case – tetracene (smallest, non-compact PAH sample)
  - Estimated depletion rate of the order of 85 ± 5 % over the 17 equivalent weeks of continuous unshadowed solar exposure
- Future Experiments
  - Interactions with inorganic substrates
    - OREOcube: ORganics Exposure in Orbit Experiment

EXOcube - EXposure of Organisms/Organics cube

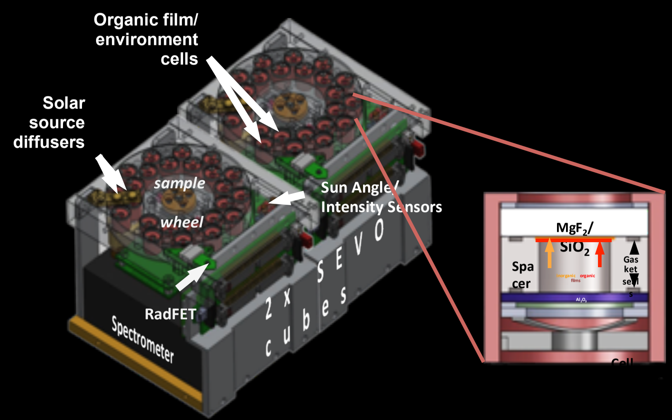
EXOcube heritage

O/OREOS



- O/OREOS (NASA Astrobiology Small Payloads (ASP)):
- Develop and fly small astrobiology payloads, from single-cube free flyers to suitcase-sized payloads, to address fundamental astrobiology objectives, using a variety of launch opportunities
- O/OREOS (Organism/Organics Exposure to Orbital Stresses) is the first technology demonstration mission for ASP
- Launched: November 19, 2010
- Nominal performance in orbit, 146 days
- http://ooreos.engr.scu.edu/dashboard.htm

OREOcube



- selected for Definition Phase by the European Space Agency (ESA) to be installed on the ISS.
- designed to perform *in situ* UV-Vis spectroscopy to study the chemistry of biomolecules in Low Earth Orbit.
- sample cell gas compositions and relative humidity can be controlled to create space and planetary "micro-environments".
- measures changes in organic samples and provides insight into the kinetic details of photochemical reactions.
- will be used to study radiation induced modification of astrobiologically relevant organics by mineral and catalytic surfaces.
- can be used to investigate carbon chemistry that relates to planetary surface conditions and the interstellar space environment.

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