Lecture 10: Dust and Surface Experiments

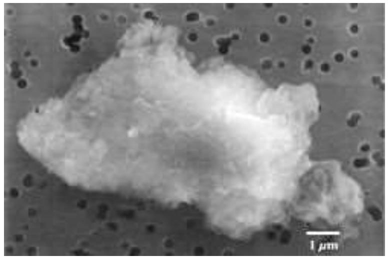

nature

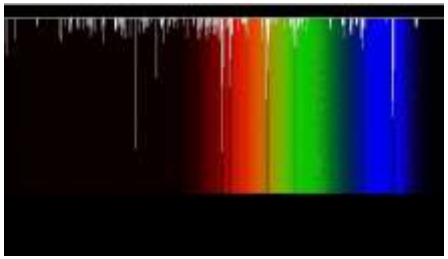
INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

A NEW FORM OF CARBON

UNDERSTANDING ANTARCTIC OZONE DEPLETION

The cellular defect behind cystic fibrosis



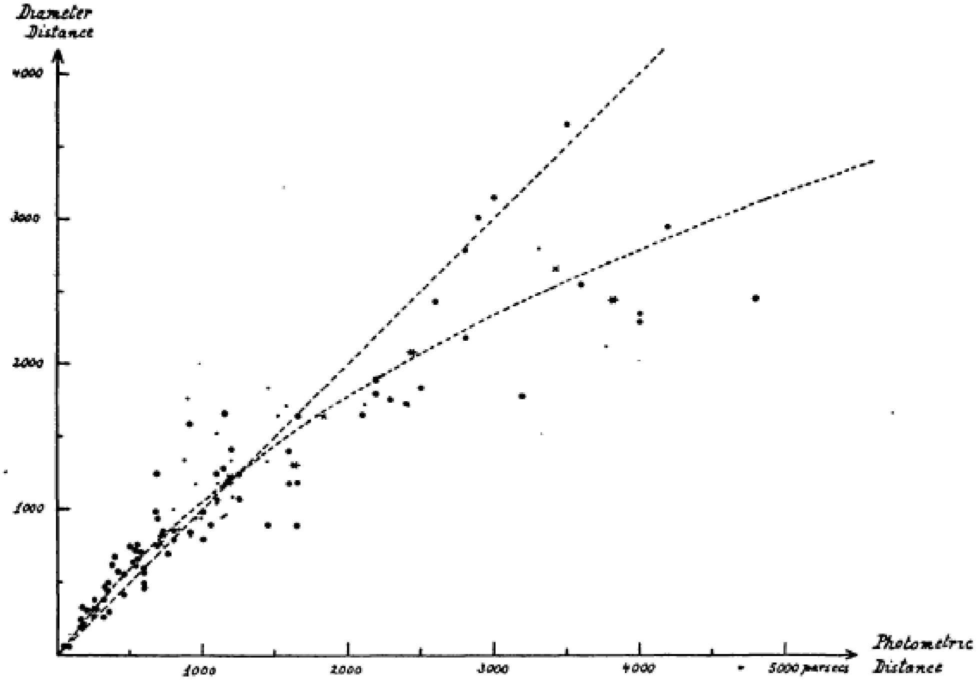


The term “dust grain” is understood here to extend down to molecules containing tens of atoms, as there is no discontinuity in the physics as the particle size decreases from microns to Angstroms.

B.T. Draine, “Interstellar Dust Grains”,
Annu. Rev. Astron. Astrophys. 2003, 41:241-89

Recap: first evidence for interstellar dust

Trumpler tries to determine distance of open clusters



"Unless we are willing to admit that the dimension of open clusters depend on their distance from the sun, we are led to the conclusion that the inverse square law on which the photometric distances are based does not hold and that a general absorption is taking place within our stellar system."

R.J. Trumpler, PASP 1930

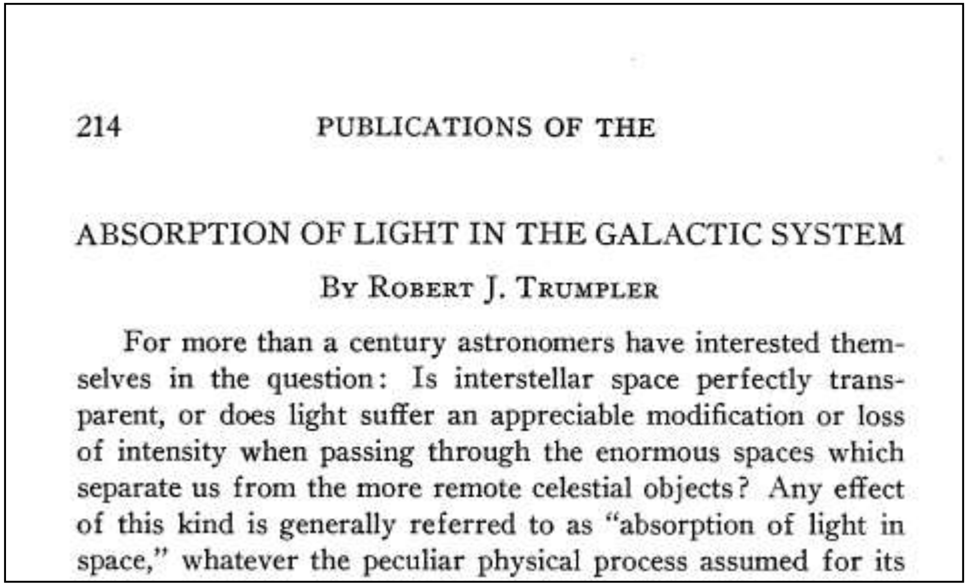
Recap: The First "Dark Matter"

Early observations showed **"Holes in the sky"**

- Interstellar voids?
- absorption of light in space by "ether"?

"The space absorption of light is thus immediately related to the question of the presence, distributions, and constitution of **dark matter in the universe."**

R.J. Trumpler, PASP 1930



214 PUBLICATIONS OF THE

ABSORPTION OF LIGHT IN THE GALACTIC SYSTEM

By Robert J. Trumpler

For more than a century astronomers have interested themselves in the question: Is interstellar space perfectly transparent, or does light suffer an appreciable modification or loss of intensity when passing through the enormous spaces which separate us from the more remote celestial objects? Any effect of this kind is generally referred to as "absorption of light in space," whatever the peculiar physical process assumed for its

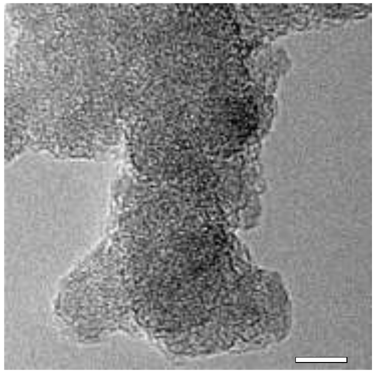
How to see cosmic dust with naked eyes?

According to some estimates up to 100 tons of cosmic dust fall to Earth every day

- Meteor showers
- 2017: August 12–13 (Perseids), November 17/18 (Leonids)

Outline: Challenges for Laboratory Astrophysics

1. Can we collect cosmic dust (since it seems to rain down on us)?
2. Can we simulate dust formation in the laboratory?
3. Can we understand its optical properties to make use of astron. data?
4. Can we test the formation of molecules (chemistry) on dust grains?



Can we simply collect cosmic dust?

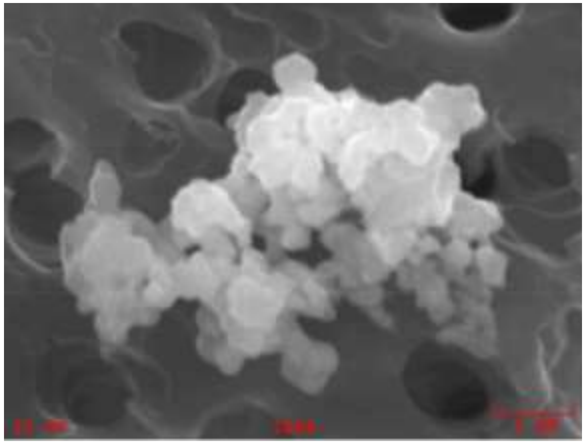
Dust collecting pool with magnetic filtering.

Source: wikipedia

But: human contamination from engines and power plants almost everywhere today (Feinstaub)

More professional: **NASA's Cosmic Dust Program: Collecting Dust Since 1981**

Figure 1 - Two round, large-area cosmic dust collectors deployed beneath the wing of a NASA ER-2 aircraft in flight.



http://elementsmagazine.org/2016/06/16/nasas-cosmic-dust-program-collecting-dust-since-1981/

Science

Cosmic dust left over from the dawn of the solar system found on rooftops in Paris

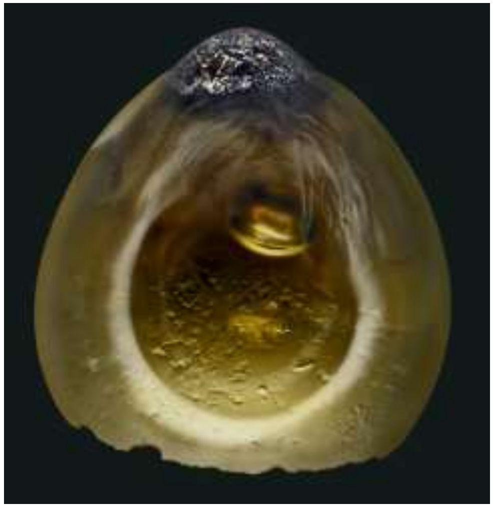
By **Sarah Knapton**, SCIENCE EDITOR

6 DECEMBER 2016 • 4:46PM

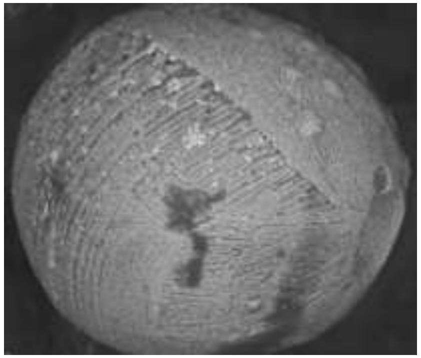
Tiny specks of cosmic dust which are left over from the formation of our solar system have been discovered on the rooftops of three European cities.

The space debris, which is falling constantly through the atmosphere, has previously only been found in Antarctica and the deep ocean.

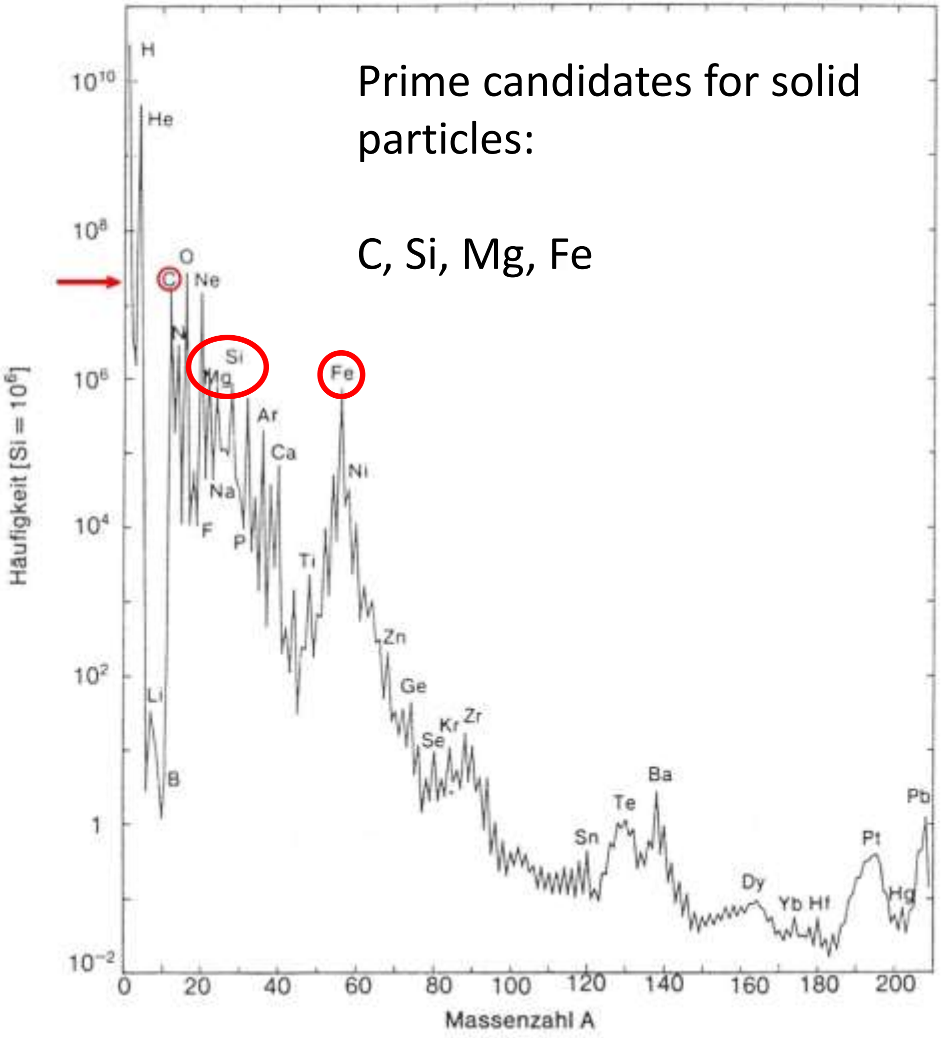
It was thought that it would never be found in cities because it would be so difficult to detect it amid the pollution, dust and grime in urban areas.



Amateur astronomer Jon Larsen



What is cosmic dust probably made of?
Check Elemental Abundances of non-volatiles



Prime candidates for solid particles:

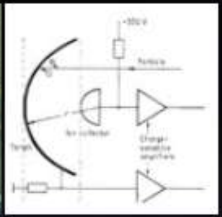
C, Si, Mg, Fe

Terms from mineralogy

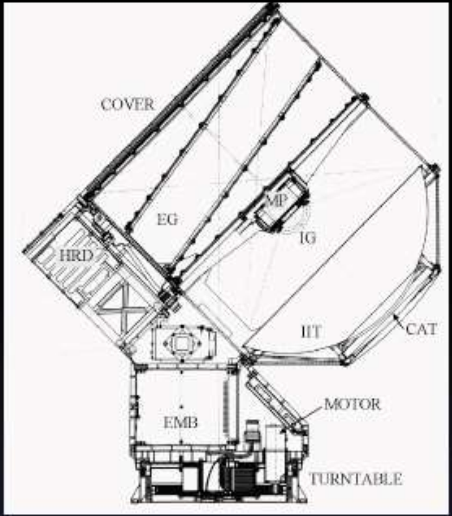
Dust Collectors (courtesy V. Sterken, ETH Zurich, former MPI-K Dust group)

Ballistic rockets in Kiruna (Sweden)

HEOS-2 @ Earth (apo 38 R$_E$)

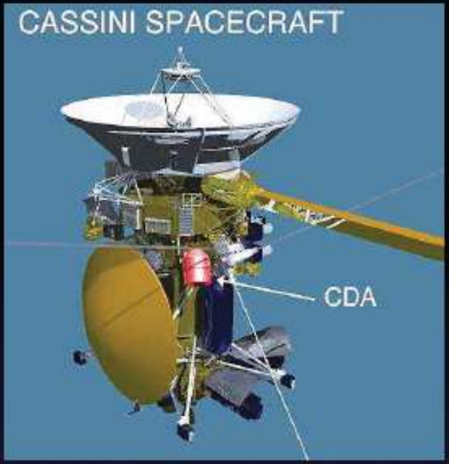


HELIOS @ Sun-Earth (apo 0.3 AU, peri 0.88 AU)

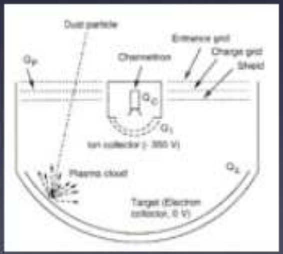


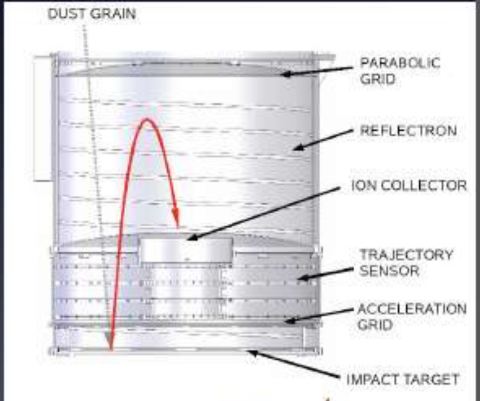
Galileo @ Jupiter (5 AU)

Cassini @ Saturn (10 AU)



Ulysses - around the Sun, out of the ecliptic plane! @ 1.3-5.4 AU (almost Jupiter)





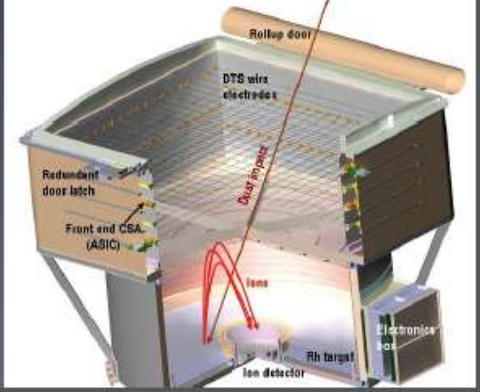
(1-3 AU)

J.Kissel with Stardust CIDA

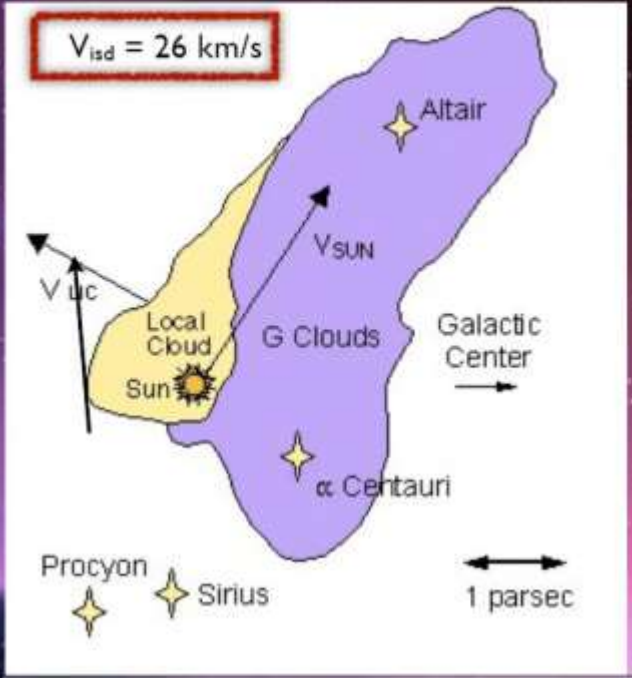
Rosetta mission to comet Landing in 2014

Giotto encounter with comet Halley 1986

Trajectory sensor for future missions: JUICE, SARIM+, DUNE,...



Interstellar Dust moves fast



Local Interstellar Cloud (LIC)

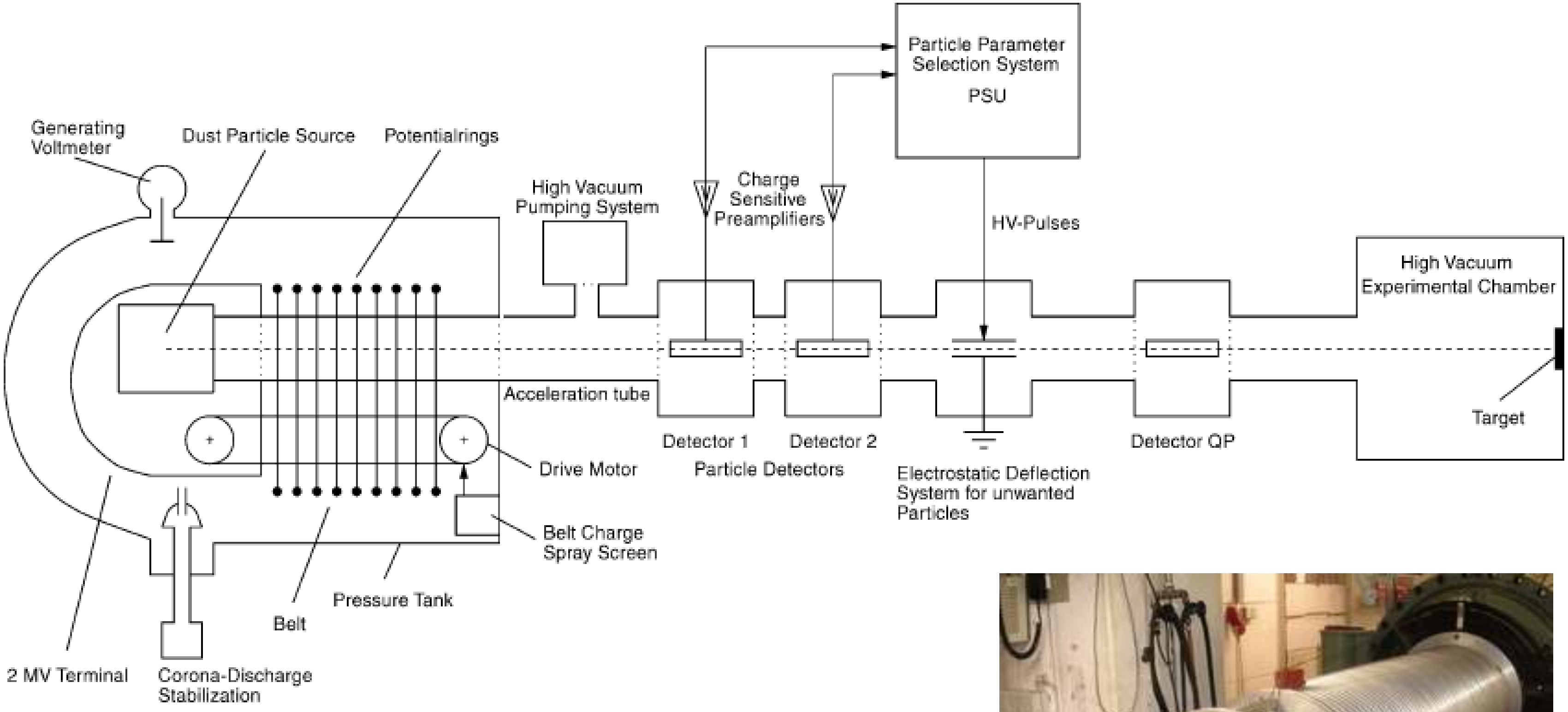
- The LIC: H, He and dust
- Dust comes from 259° Longitude, 8° latitude (Ecliptic frame), V_{rel} = 26 km/s
- Mainly silicates and carbons

What we're aiming for:
- Dust size distribution & abundances
- Chemical composition

1. Astronomical observations
2. Spacecraft in-situ measurements
3. From dust dynamics (comparing simulations to data)

Horsehead Nebula - 1500 ly
Credits: Hubble Space Telescope

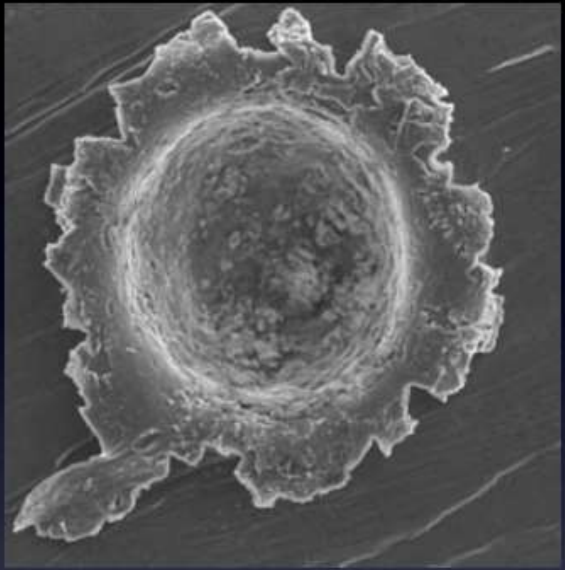
How to make dust move fast in the laboratory: The Heidelberg Dust Accelerator (1960-2016)

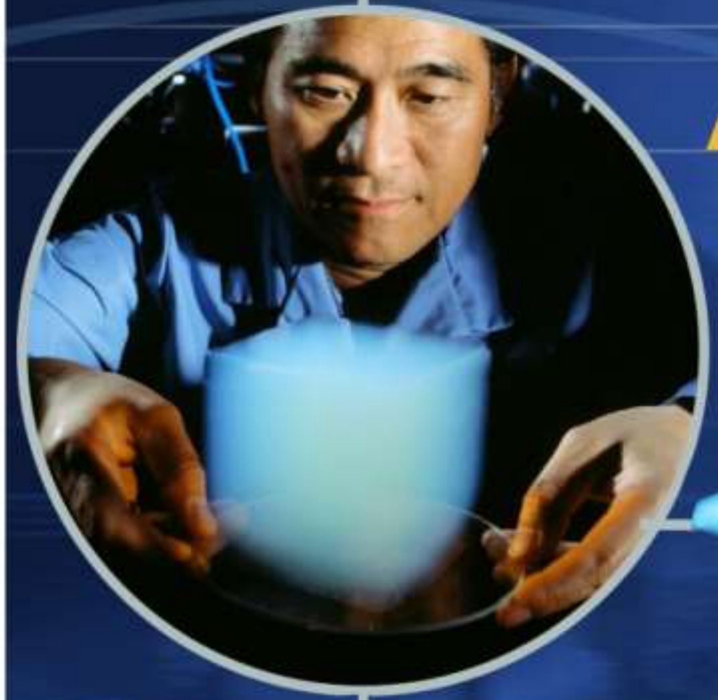


M. Stuebig et al., Planetary and Space Science 49, 853 (2001)

Testing & Calibration with the dust accelerator

Impacts on foils, aerogel, dust instruments, ...
Calibration of dust instruments
Using different dust "analogues"





Aerogel

Mystifying Blue Smoke

At first glance aerogel resembles a hologram. It's deceiving whether it's really there or not. A highly porous solid material, aerogel has the lowest density of any solid known to man. One thousand times less dense than glass, aerogel has earned the nickname, "solid blue smoke."

The crayons on top of the aerogel are protected from the flame underneath, and are not melting.

Aerogel will be used on the STARDUST spacecraft to capture comet particles from Comet Wild 2.

Aerogel is strong and easily survives launch and space environments. It has been used for the Mars Pathfinder and other rover missions.

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Chemistry

Mixed with silicon dioxide and a solvent, aerogel is 99.8% air, and is 1,000 times less dense than glass.

Capability

Particles traveling six times faster than a rifle bullet can be stopped by a block of aerogel.

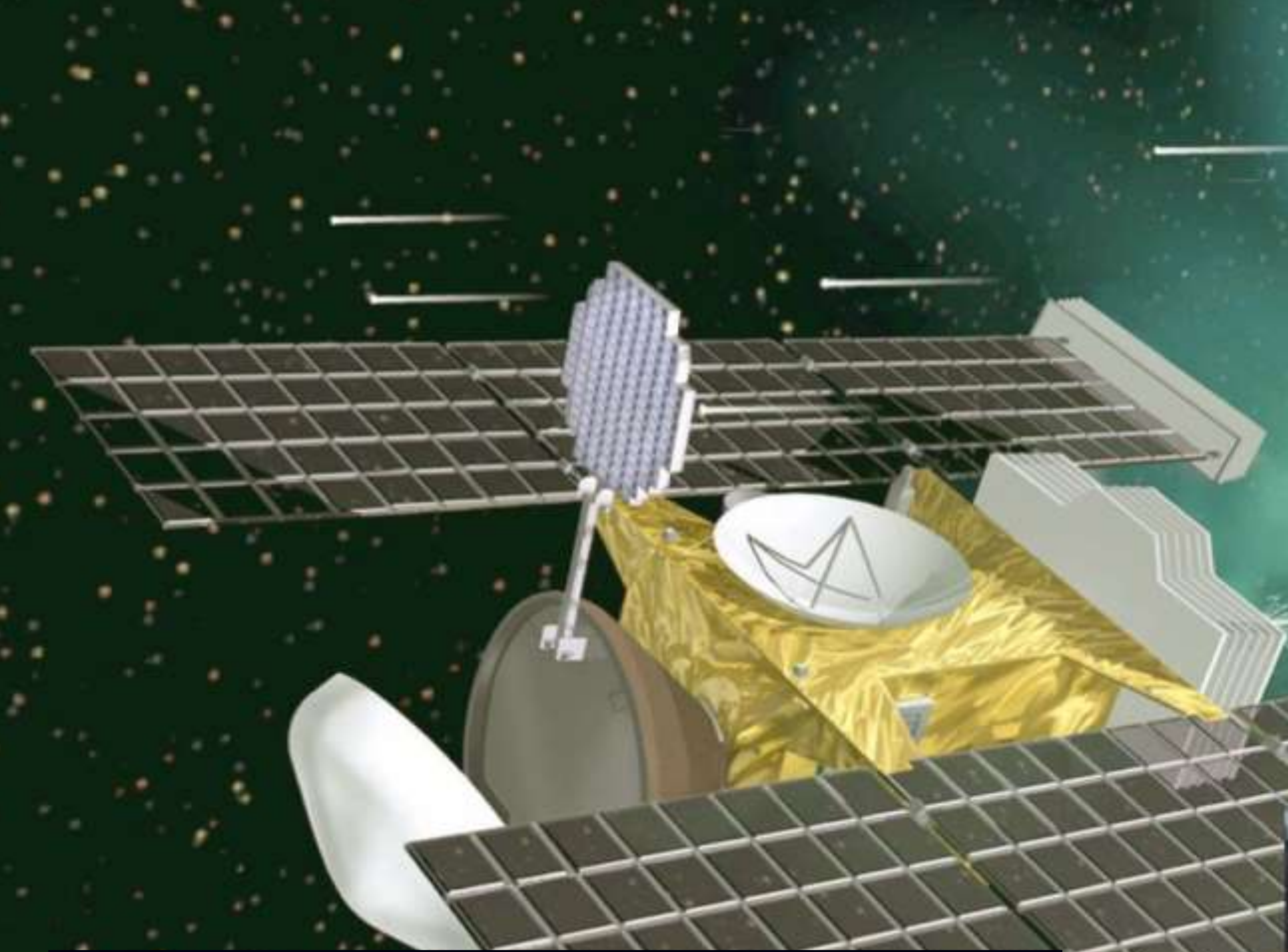
High Temperature

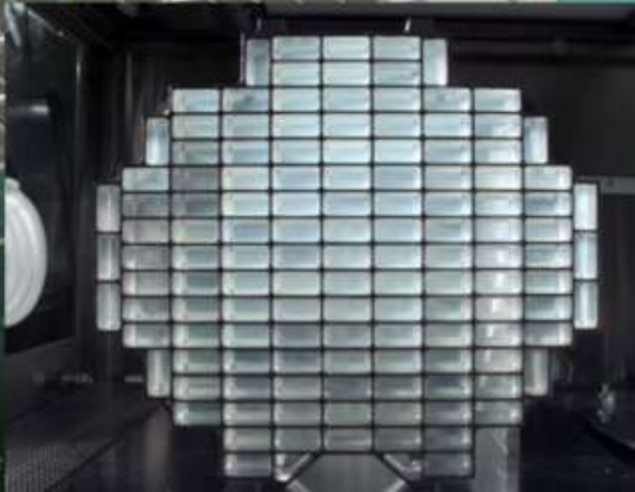
Aerogel can withstand high temperatures. Some types of aerogel provide 39 times more insulation than fiberglass.

Support

Despite weighing only 3 milligrams per cubic centimeter, aerogel can support up to 4,000 times its own weight.

Stardust (NASA mission)

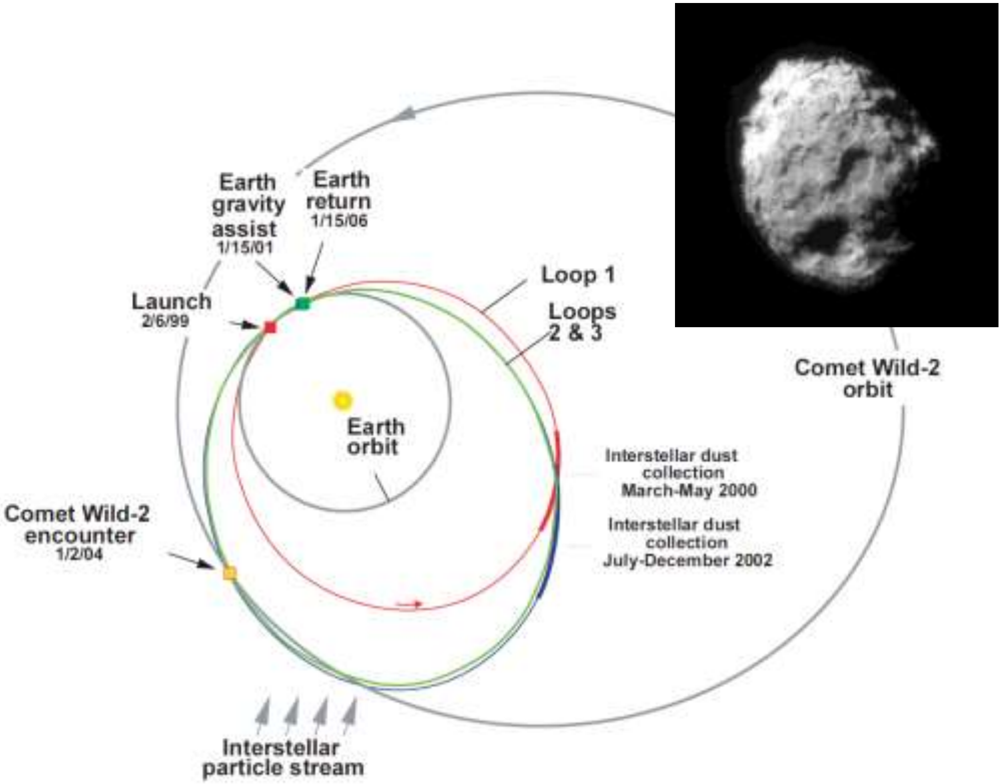




- Launch: 1999 (Delta II rocket, Florida)
- 2 ISD capture periods in 2000 & 2002
- Aerogel collector (2 sides)
- 2006: Earth return

Stardust

Mission trajectory



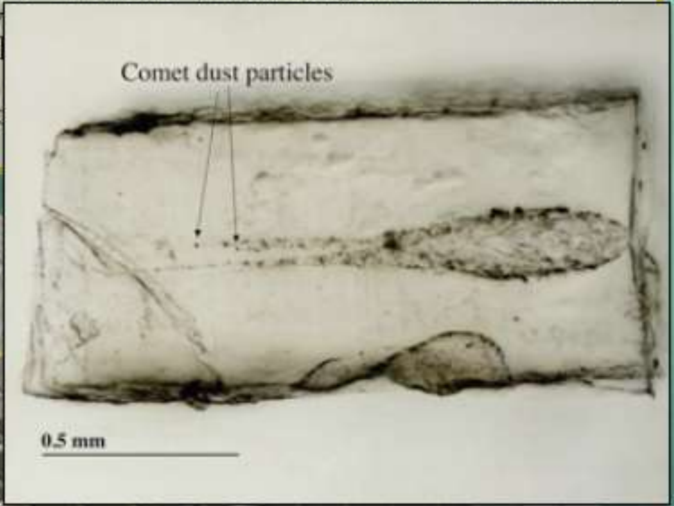
Return capsule

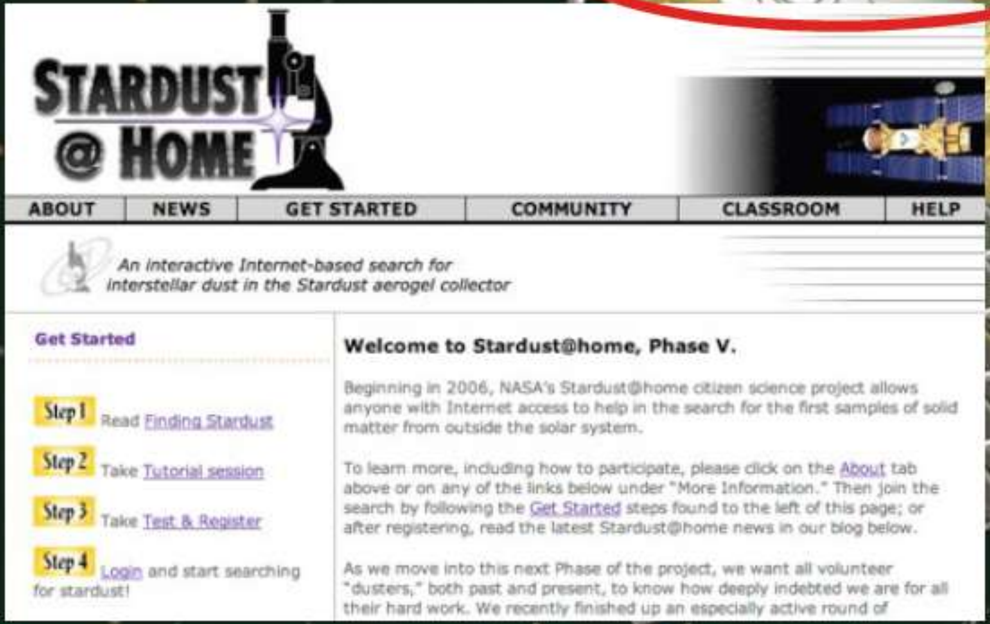
http://stardust.jpl.nasa.gov/home/index.html

Stardust

Impact speeds and directions of interstellar grains on the Stardust dust collector

Veerle J. Sterken[35], Andrew J. Westphal[1], Nicolas Altobelli[40], Eberhard Grün[18], Frank Postberg[29], Ralf Srama[34], Carlton Allen[2], David Anderson[1], Asna Ansari[3], Sasa Bajt[4], Ron S. Bastien[2], Nabil Bassim[5], H. A. Bechtel[6], Janet Borg[7], Frank E. Brenker[8], John Bridges[9], Donald E. Brownlee[10], Mark Burchell[11], Manfred Burghammer[12], Anna L. Butterworth[1], Hitesh Changela[13], Peter Cloetens[14], Andrew M. Davis[14], Ryan Doll[15], Christine Floss[19], George Flynn[16], Patrick Fougeray[17], David Frank[2], Zack Gainsforth[1], Philipp R. Heck[19], Jon K. Hillier[25], Peter Hoppe[20], Bruce Hudson[21], Gary Huss[22], Joachim Huth[28], Brit Hvide[4], Anton Kearsley[23], Ashley J. King[24], Barry Lai[25], Jan Leitner[28], Laurence Lemelle[26], Hugues Leroux[27], Ariel Leonard[19], Robert Lettieri[1], William Marchant[1], Larry R. Nittler[28], Ryan Ogliore[30], Wei Ja Ong[19], Mark C. Price[13], S. A. Sandford[30], Juan-Angel Sans Tresseras[14],
Sylvia Schmitz[31], Tom Schoonjans[32], Geert Silv
Sol e[14], Thomas Stephan[18], Julien Stodolna[1],
Trieloff[45], Peter Tsou[37], Akira Tsuchiyama[38],
Vincze[50], Joshua Von Korff[1], Naomi Wordsw
>30,000 Star- dust@home dusters[41]





An interactive Internet-based search for interstellar dust in the Stardust aerogel collector

Get Started

Step 1 Read Finding Stardust

Step 2 Take Tutorial session

Step 3 Take Test & Register

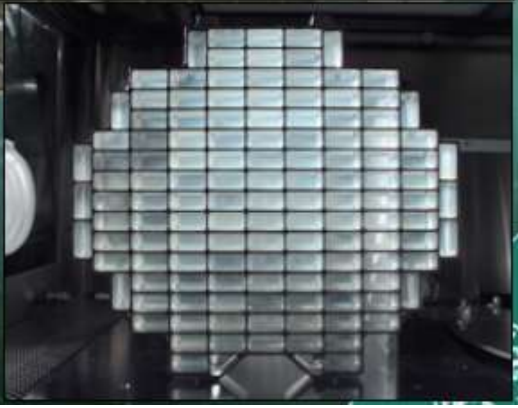
Step 4 Login and start searching for stardust!

Welcome to Stardust@home, Phase V.

Beginning in 2006, NASA's Stardust@home citizen science project allows anyone with Internet access to help in the search for the first samples of solid matter from outside the solar system.

To learn more, including how to participate, please click on the About tab above or on any of the links below under "More Information." Then join the search by following the Get Started steps found to the left of this page; or after registering, read the latest Stardust@home news in our blog below.

As we move into this next Phase of the project, we want all volunteer "dusters," both past and present, to know how deeply indebted we are for all their hard work. We recently finished up an especially active round of



Stardust@home: You can become a "duster" too!

Stardust Results

Westphal et al, (≈31000 co-authors)
Science 345, 786 (2014)

RESEARCH ARTICLE

INTERSTELLAR DUST

Evidence for interstellar origin of seven dust particles collected by the Stardust spacecraft

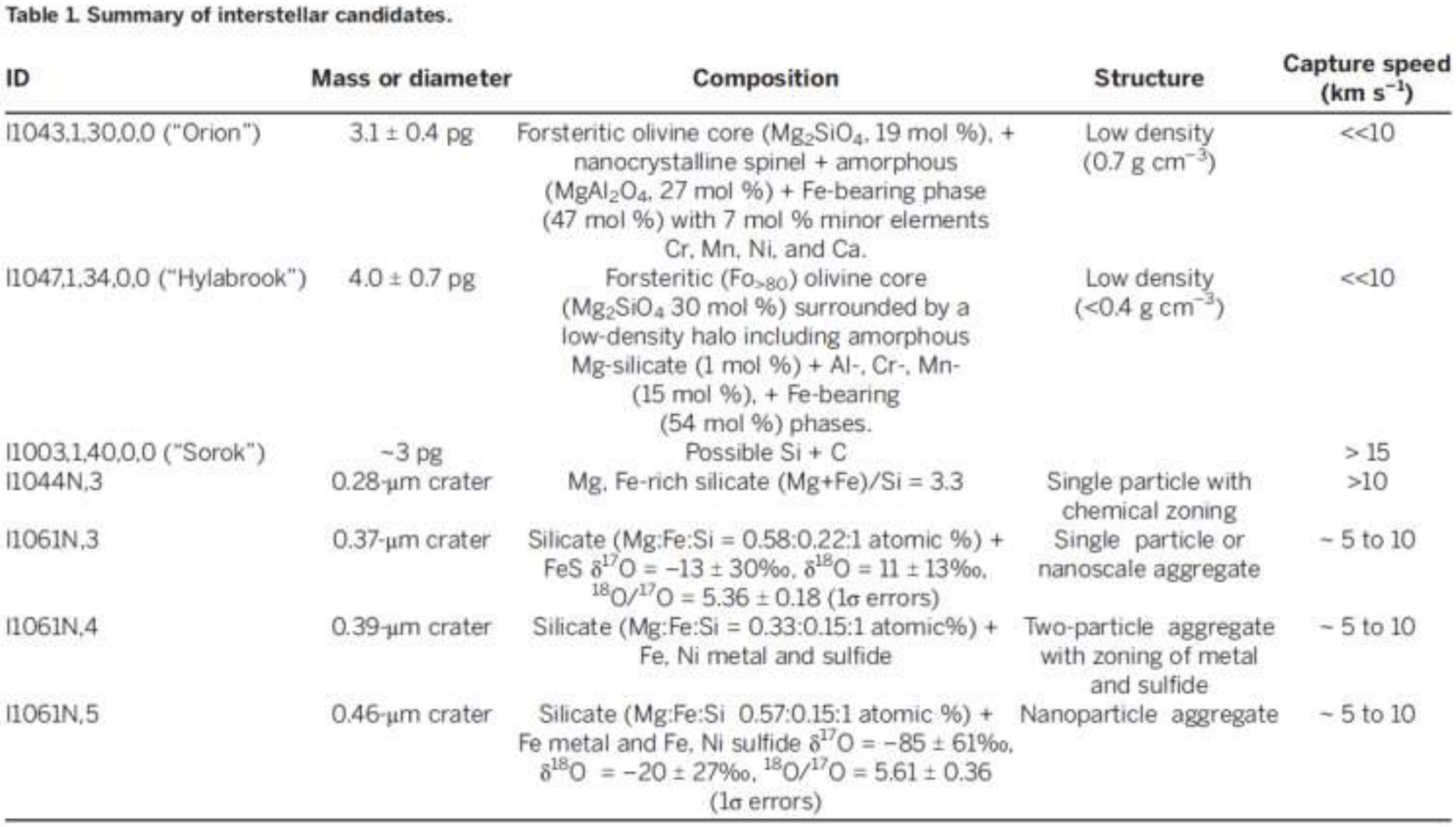
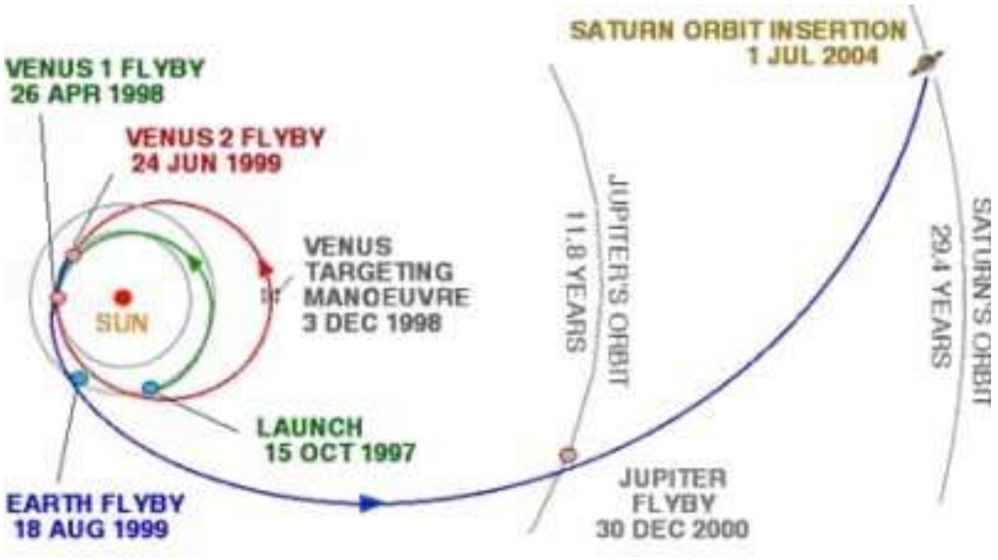


Table 1. Summary of interstellar candidates.

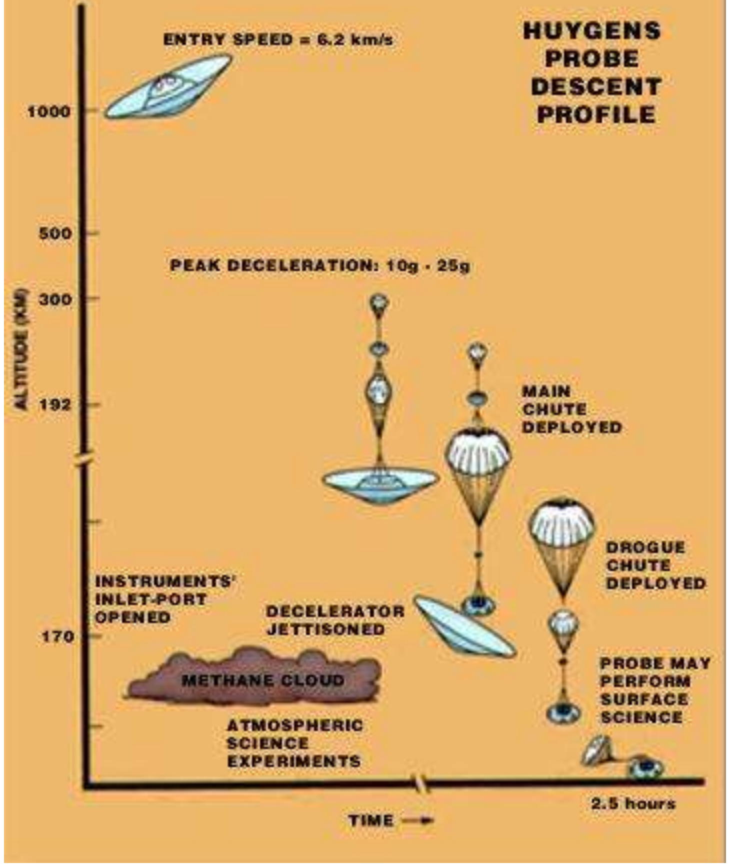
ID	Mass or diameter	Composition	Structure	Capture speed (km s^{-1})
I1043,1,30,0,0 ("Orion")	3.1 ± 0.4 pg	Forsteritic olivine core (Mg_2SiO_4, 19 mol %), + nanocrystalline spinel + amorphous ($MgAl_2O_4$, 27 mol %) + Fe-bearing phase (47 mol %) with 7 mol % minor elements Cr, Mn, Ni, and Ca.	Low density (0.7 g cm^{-3})	<<10
I1047,1,34,0,0 ("Hylabrook")	4.0 ± 0.7 pg	Forsteritic ($Fo_{>80}$) olivine core (Mg_2SiO_4 30 mol %) surrounded by a low-density halo including amorphous Mg-silicate (1 mol %) + Al-, Cr-, Mn- (15 mol %), + Fe-bearing (54 mol %) phases.	Low density (<0.4 g cm^{-3})	<<10
I1003,1,40,0,0 ("Sorok")	~3 pg	Possible Si + C		> 15
I1044N,3	0.28-μm crater	Mg, Fe-rich silicate (Mg+Fe)/Si = 3.3	Single particle with chemical zoning	>10
I1061N,3	0.37-μm crater	Silicate (Mg:Fe:Si = 0.58:0.22:1 atomic %) + FeS $\delta^{17}O = -13 \pm 30‰$, $\delta^{18}O = 11 \pm 13‰$, $^{18}O/^{17}O = 5.36 \pm 0.18$ (1σ errors)	Single particle or nanoscale aggregate	~ 5 to 10
I1061N,4	0.39-μm crater	Silicate (Mg:Fe:Si = 0.33:0.15:1 atomic%) + Fe, Ni metal and sulfide	Two-particle aggregate with zoning of metal and sulfide	~ 5 to 10
I1061N,5	0.46-μm crater	Silicate (Mg:Fe:Si 0.57:0.15:1 atomic %) + Fe metal and Fe, Ni sulfide $\delta^{17}O = -85 \pm 61‰$, $\delta^{18}O = -20 \pm 27‰$, $^{18}O/^{17}O = 5.61 \pm 0.36$ (1σ errors)	Nanoparticle aggregate	~ 5 to 10

7 interstellar candidates in micrometer range found! (Less than expected)

Cassini Huygens Mission to Saturn and its moons



Descend of the Huygens probe




Saturn

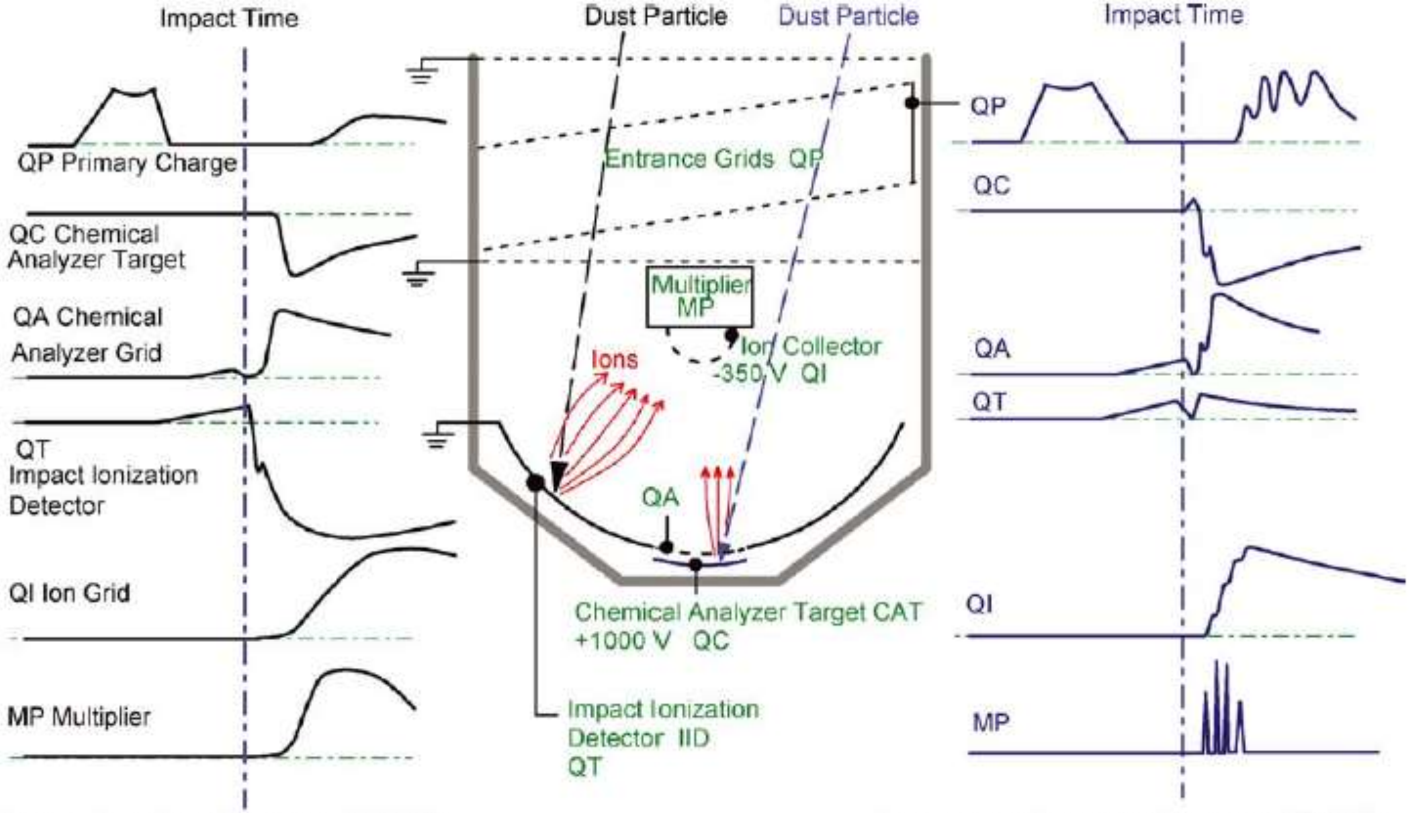

Surface Titan

Launch date:	15.10.1997
Orbiting Saturn:	01.07.2004
Huygens lands:	14.01.2005
Mission end:	15.09.2017

The Cassini Cosmic Dust Analyzer

Srama et al., Space Science Reviews 114: 465 (2004)

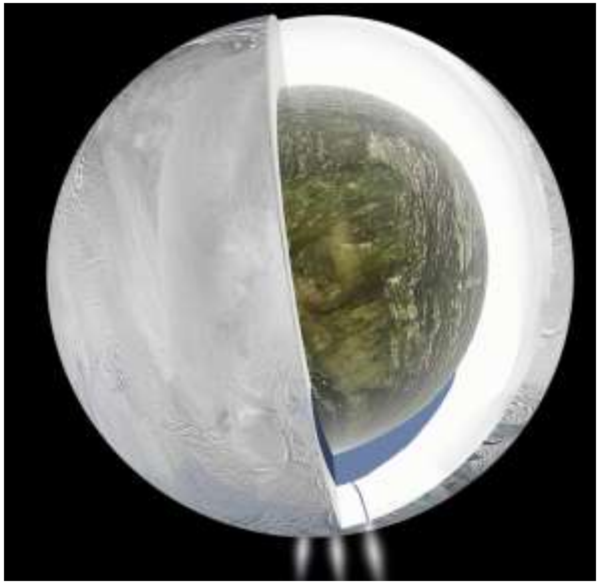
Cassini-Huygens probe launched in 1997,
reached Jupiter in 2004,
End of mission in 2017



Impact onto big target (IID)

Impact onto small target (CAT)

Salt Water Geysers on Enceladus (one of Saturn's moons)



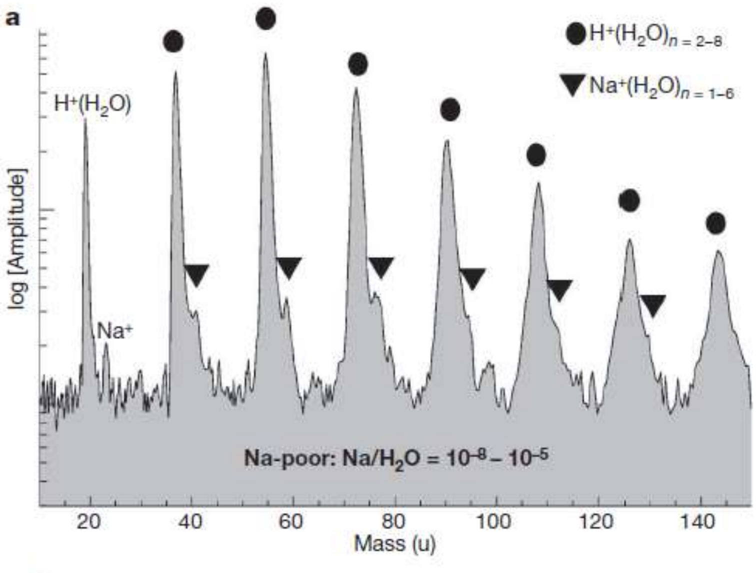
Enceladus is believed to be covered in a solid ice surface

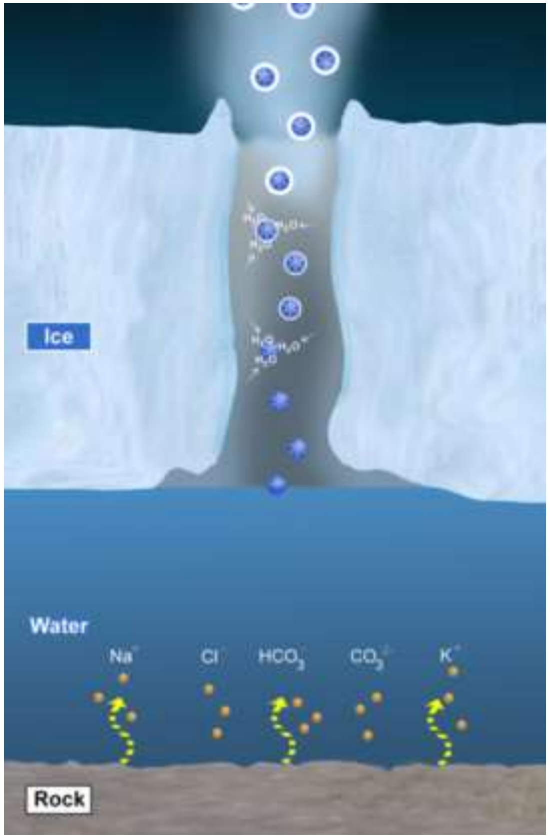
Evaporation plume

Credit : Cassini Imaging Team,
SSI, JPL, ESA, NASA

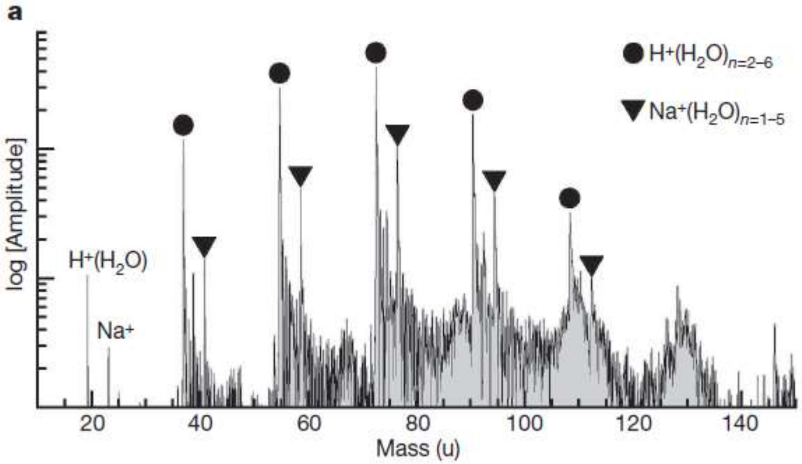
Underground Salt Water Ocean on Enceladus

Cassini
Dust Detector
(Enceladus Plume)





Laser dispersion
of salt water in
the laboratory



Postberg et. al,
Nature 459,
1098 (2009)

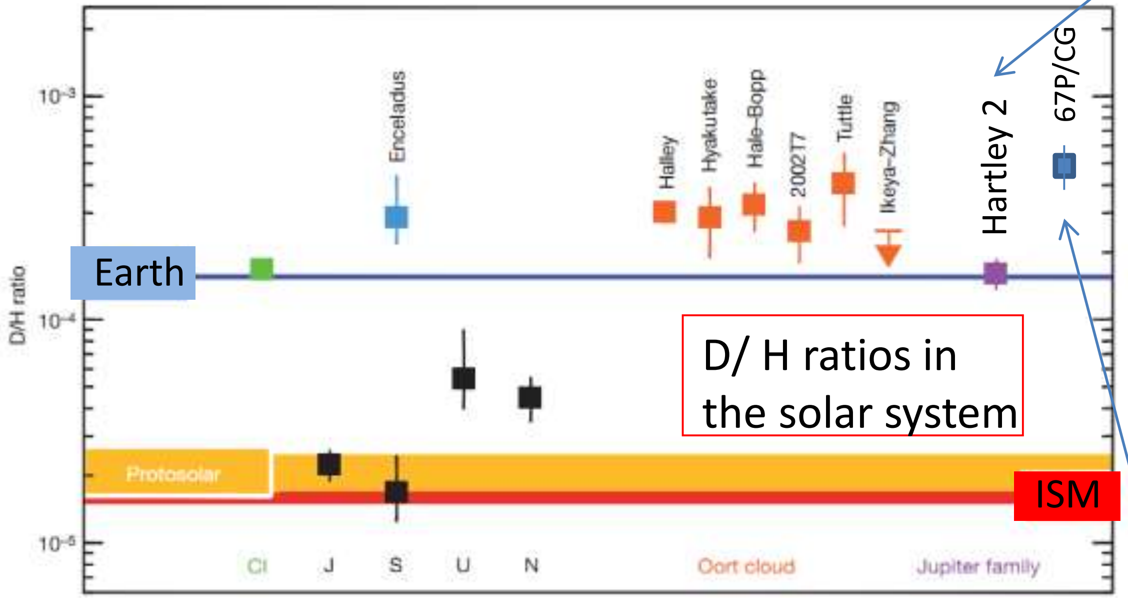
Comet:
Icy solar system body
„dirty snowball“

Landing on a comet: The Rosetta mission

https://blogs.esa.int/rosetta/2014/10/17/naming-rosetta-an-interview-with-eberhard-grun/

Where does Earth´s water come from?

Deuterium Fractionation and the Origin of Terrestrial Water



D/ H ratios in the solar system

Hartogh et al., Nature **478**, 218 (2011)

Altwegg et al. Science **347**, 6220 (2015)

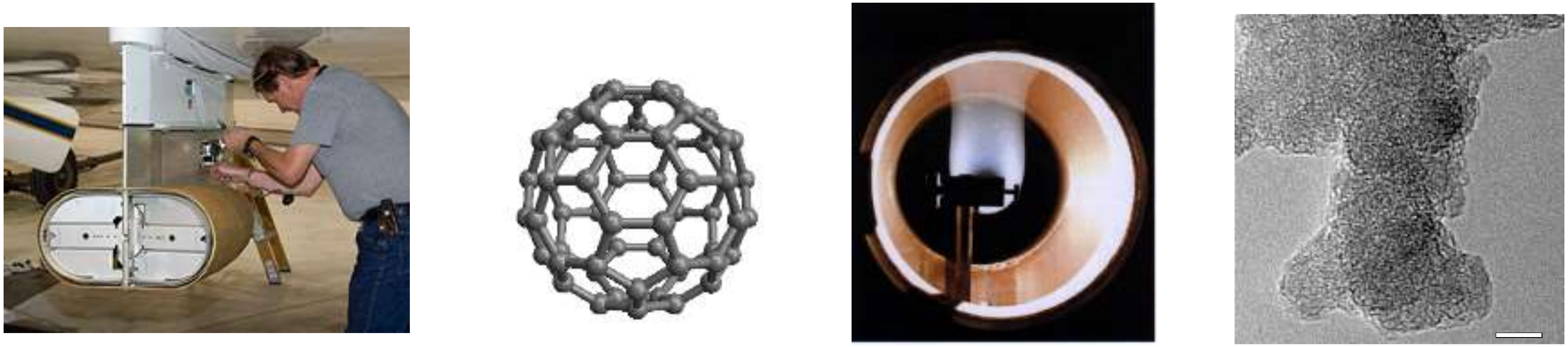
Outline: Challenges for Laboratory Astrophysics

1. Can we collect cosmic dust (since it seems to rain down on us)?
   Yes! But to identify interstellar dust is very hard (7 particles so far).

2. Can we simulate dust formation in the laboratory?

3. Can we understand it´s optical properties to make use of astron. data?

4. Can we test the formation of molecules (chemistry) on dust grains?



Where does the dust come from? Formed in the ISM? Estimate Grain Growth Rate in the ISM I

Average velocity of gas phase molecules with mass m_x:

$$v_{rms} = \left(\frac{3k\,T_{gas}}{2m_x}\right)^{1/2}$$

Collision rate with dust particle of cross section σ:

$$R = n_x \sigma \left(\frac{3k\,T_{gas}}{2m_x}\right)^{1/2}$$

Full, normalized Maxwell-Boltzmann Distribution:

$$f(v)dv = \left(\frac{2}{\pi}\right)^{1/2} \left(\frac{m_x}{kT_{gas}}\right)^{3/2} v^2 \exp\left(\frac{-m_x v^2}{2kT_{gas}}\right) dv$$

Collision rate integrated over all velocities, assuming geometric cross section $\pi\, a^2$:

$$R = \pi\, a^2 n_x \int_0^\infty v\, f(v) dv$$

Estimate Grain Growth Rate II

Solving the integral yields:

$$R = 4\pi\, a^2 n_x \left(\frac{k\, T_{gas}}{2\,\pi\, m_x}\right)^{1/2}$$

Mass change per time:
(introducing sticking probabilty S)

$$\frac{dm_{grain}}{dt} = 4\pi\, a^2 n_x m_x\, S \left(\frac{k\, T_{gas}}{2\,\pi\, m_x}\right)^{1/2}$$

General Ansatz,
mass linear to volume:
(introducing density ρ)

$$\frac{dm_{grain}}{dt} = \frac{d}{da}\left(\frac{4}{3}\,\pi\, a^3 \rho\right)\frac{da}{dt}$$

$$\frac{dm_{grain}}{dt} = 4\,\pi\, a^2 \rho \frac{da}{dt}$$

$$\frac{da}{dt} = \frac{n_x S}{\rho}\left(\frac{kT_{gas}\, m_x}{2\pi}\right)^{1/2}$$

Can be integrated, assuming all parameters are independent of t

Estimate Grain Growth Rate III

Radial growth with time:

$$a(t) = a_0 + \frac{n_x S}{\rho}\left(\frac{kT_{gas}\, m_x}{2\pi}\right)^{1/2} t$$

Solve for time t(a):

$$t(a) \sim \frac{a\rho}{n_x\, S}\left(\frac{2\pi}{k\, T_{gas} m_x}\right)^{1/2}$$

Diffuse interstellar medium:

- T = 50 K,
- Typical grain size: 0.1 µm
- assume mass of condensable Molecules: $m_x = 50\ m_H$
- assume grain density $\rho = 2.2\ \mathrm{g\ cm^{-3}}$
- $n_x = 1\mathrm{x}10^{-5}\ n_H = 1\mathrm{x}10^{-5}\ \mathrm{x}\ 100\ \mathrm{cm}^{-3}$

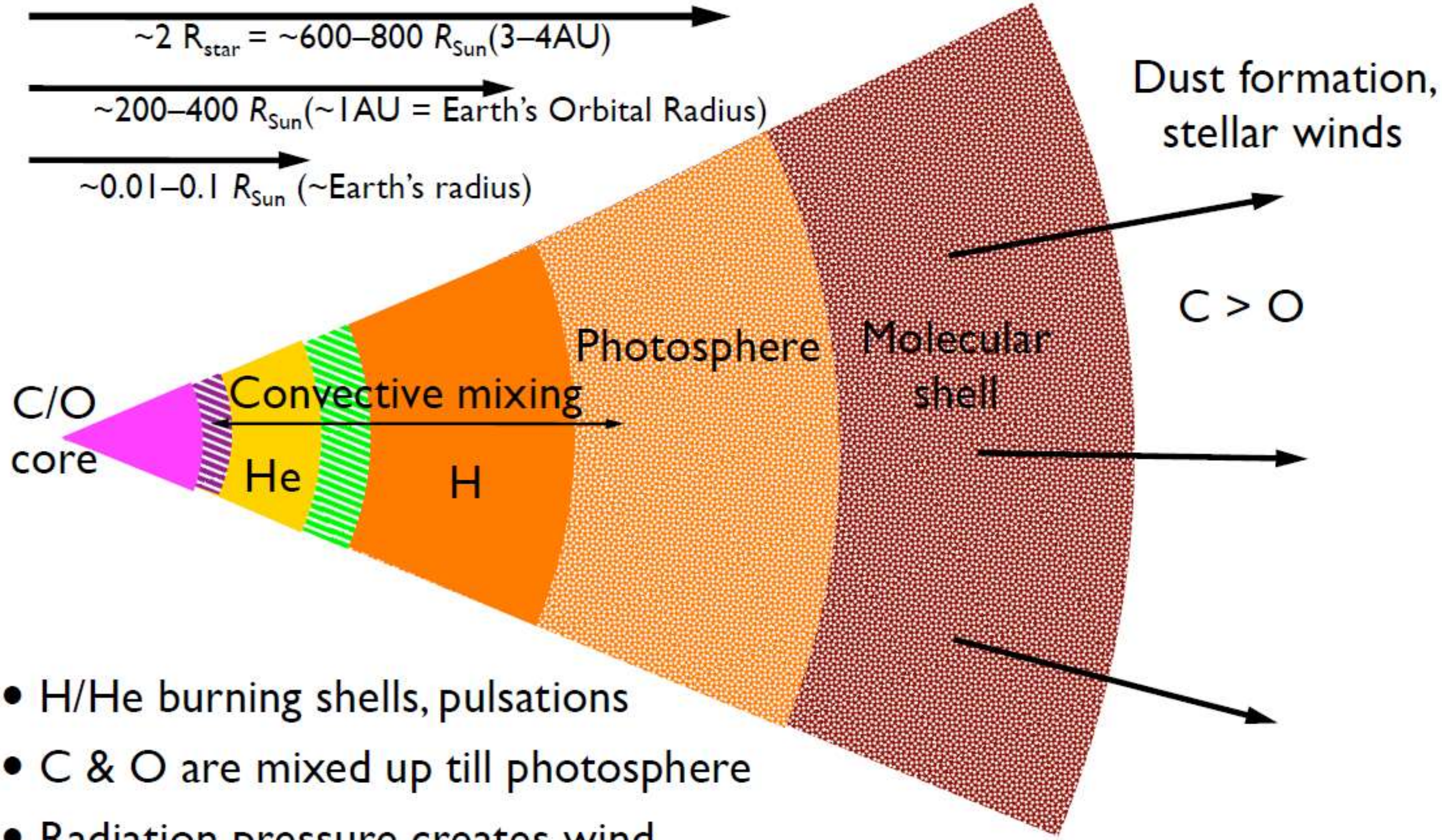
$$t \sim \frac{2\ x\ 10^9}{S}$$ years

Comparable to the age of the Universe!

Dust must form in regions of higher density, under conditions favorable for Condensation

Dust and molecules in shells of AGB stars

AGB: Asymptotic Giant Branch



~2 R_{star} = ~600–800 R_{Sun}(3–4AU)

~200–400 R_{Sun}(~1AU = Earth's Orbital Radius)

~0.01–0.1 R_{Sun} (~Earth's radius)

Dust formation, stellar winds

C > O

C/O core

Convective mixing

He

H

Photosphere

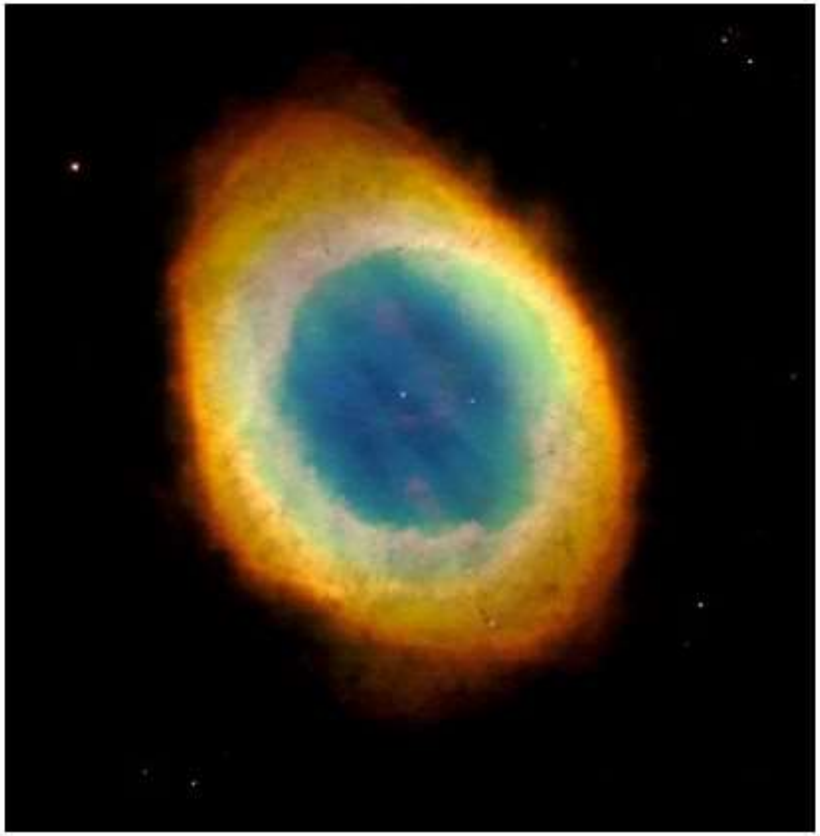
Molecular shell

- H/He burning shells, pulsations
- C & O are mixed up till photosphere
- Radiation pressure creates wind
- T goes down outward ⇒ at T < 3000 K condensation begins

The beautiful end of the Sun

The Cat's Eye nebula

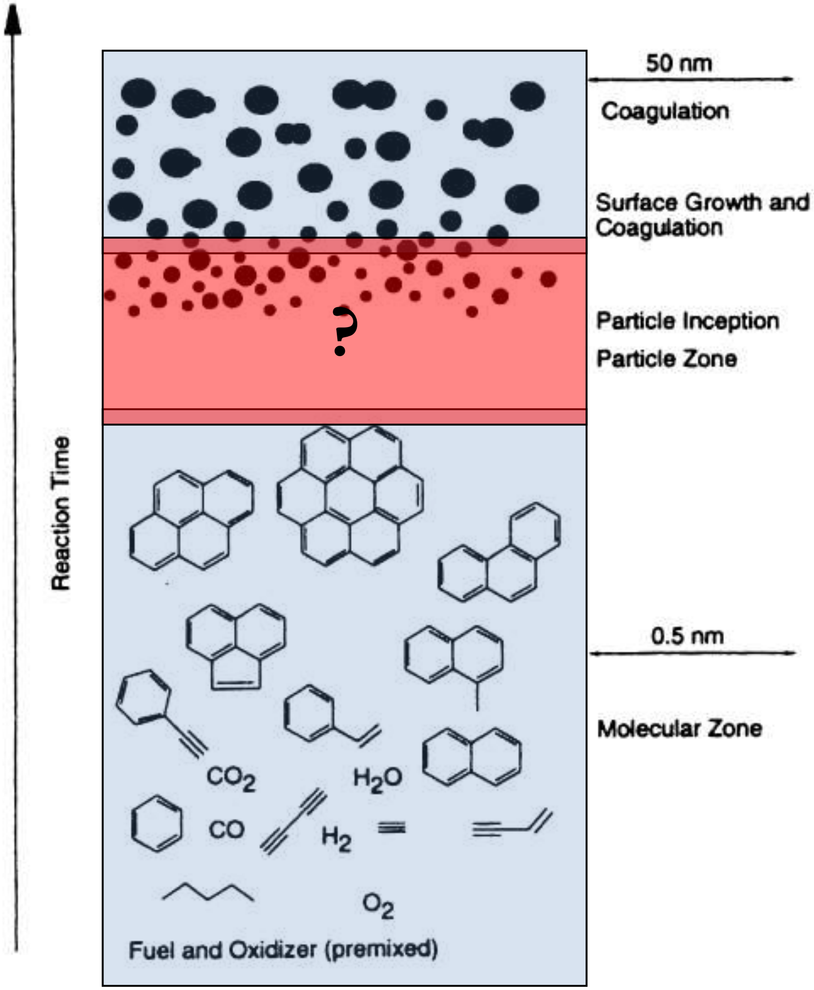
The Ring nebula



- Extended shells of gas + freshly condensed solids

Can we simulate dust formation in the laboratory?

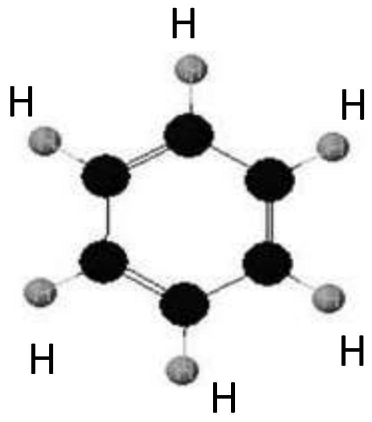
Formation pathways for solid carbon



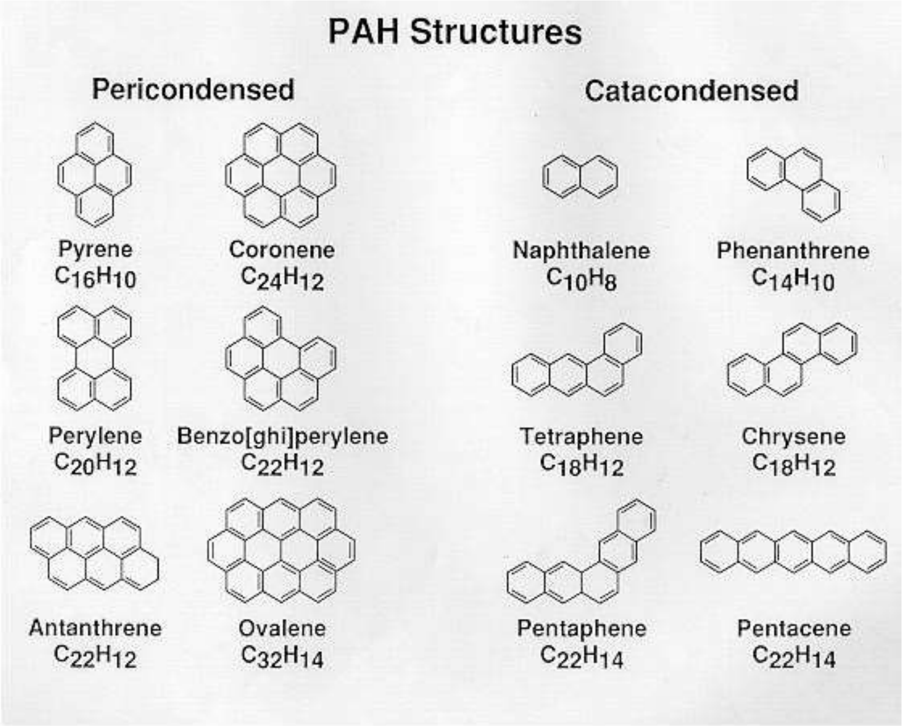
Terrestrial:

- most experimental data on the kinetics on soot formation were obtained in flames and shock waves
- there is a rough understanding of the processes of dust formation.
- Fullerenes versus PAHs

Polycyclic Aromatic Hydrocarbons (PAHs) and Fullerenes



Simple
aromatic
molecule:
C_6H_6

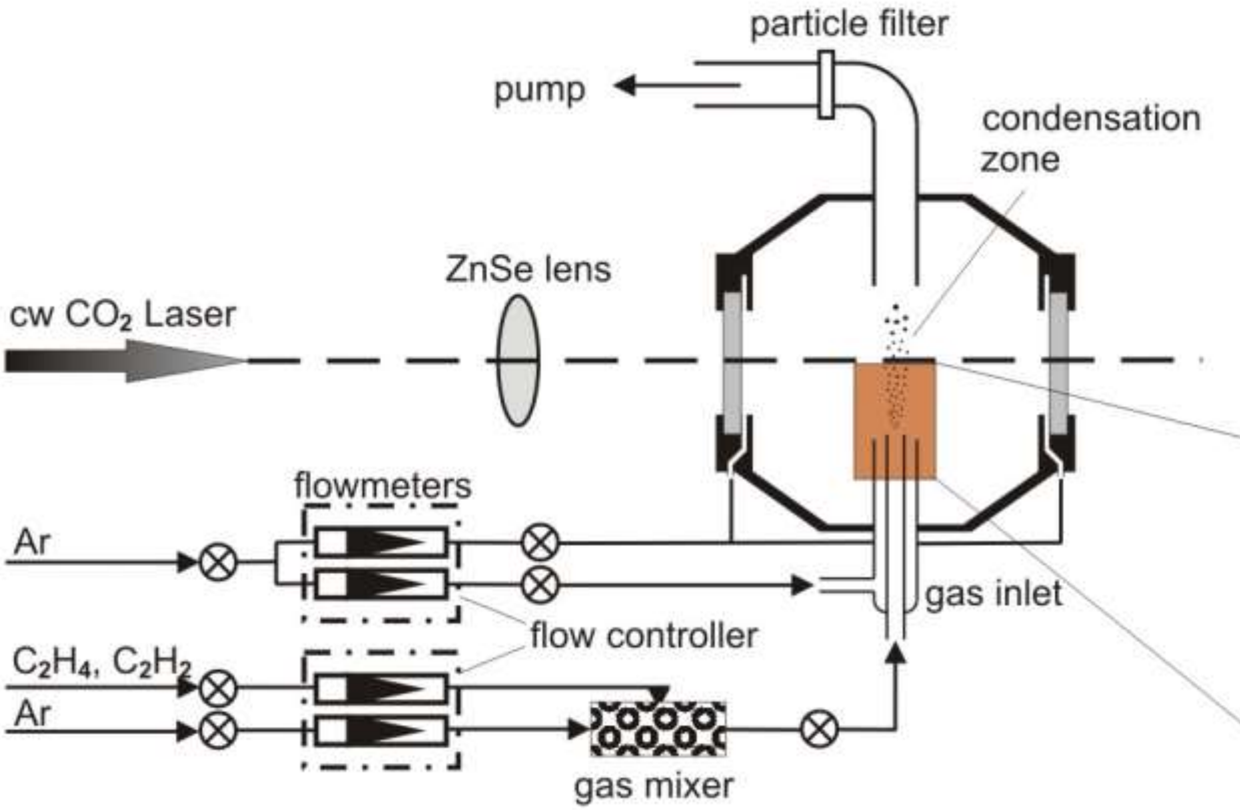


C_{60}

Fullerenes are molecules consisting of carbon atoms that are connected by single and double bonds so as to form a closed or partially closed mesh, with fused rings of five to seven atoms. The molecule may be a hollow sphere, ellipsoid, tube or many other shapes and sizes.

Gas-phase condensation by Laser Pyrolysis

Cornelia Jäger MPIA / Friedrich Schiller Universität Jena

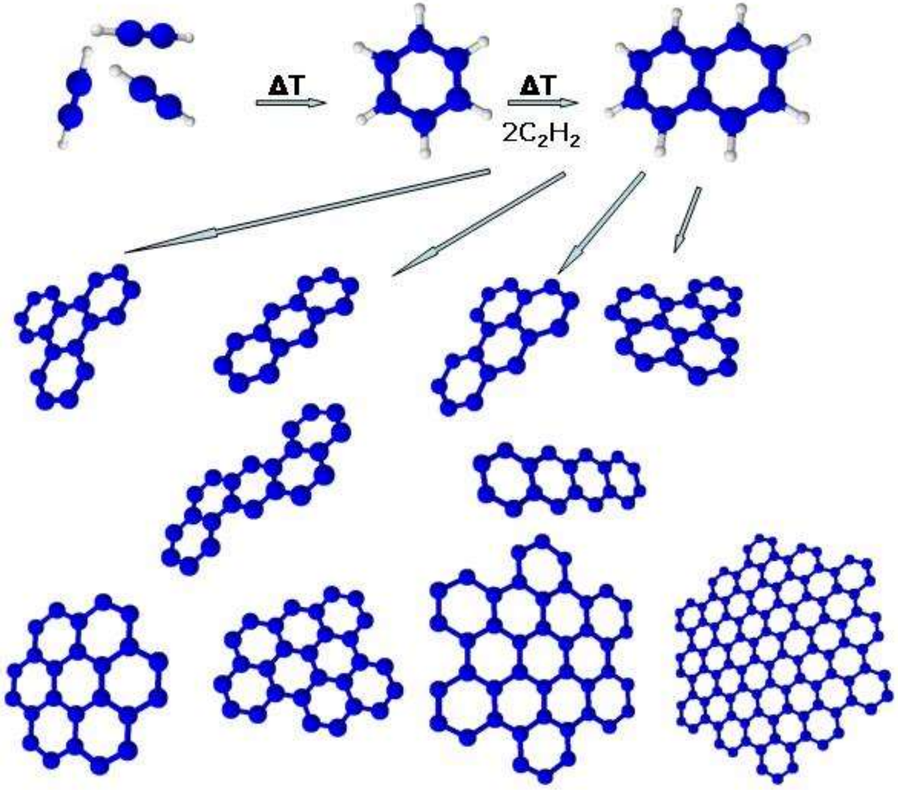


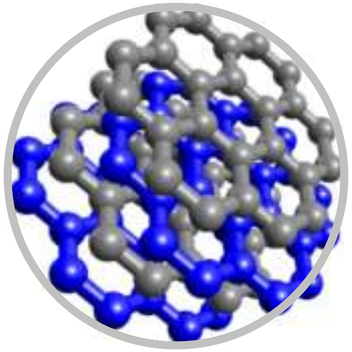
Condensate:
soot & PAHs

High-temperature condensation: **Laser pyrolysis or laser ablation** with a pulsed laser (T ≥ 3500 K); **Fullerene-like carbon grains**

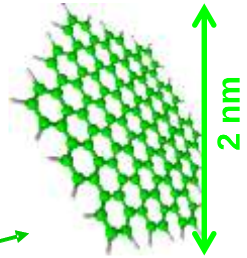
Low-temperature condensation: Laserpyrolysis with cw-laser (T ≤ 1700 K) **soot and PAHs**

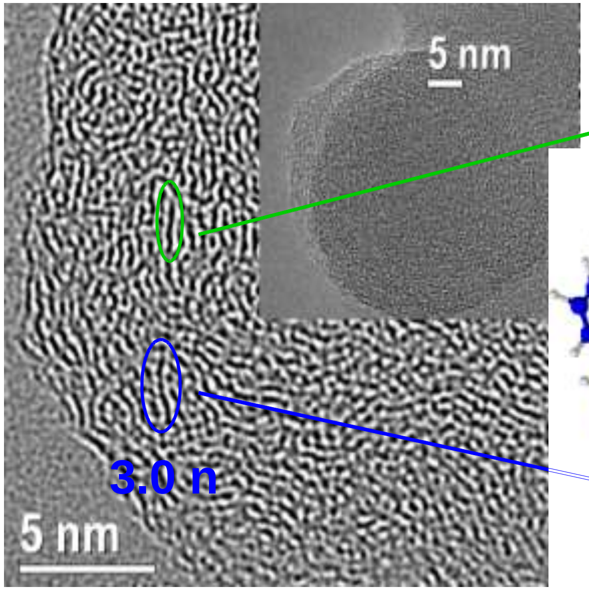
Low-temperature condensation process T ≤ 1700 K

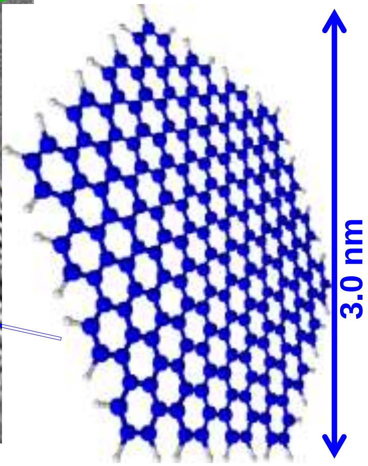




$C_{110}H_{32}$, 1352Da





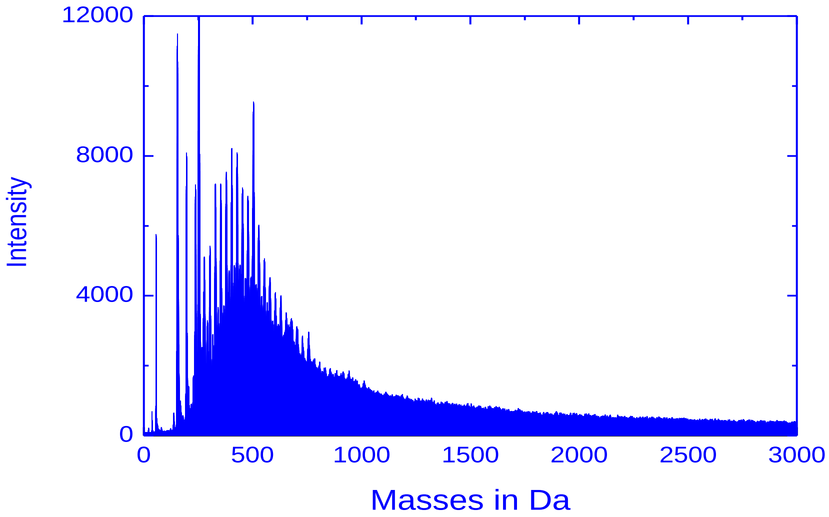


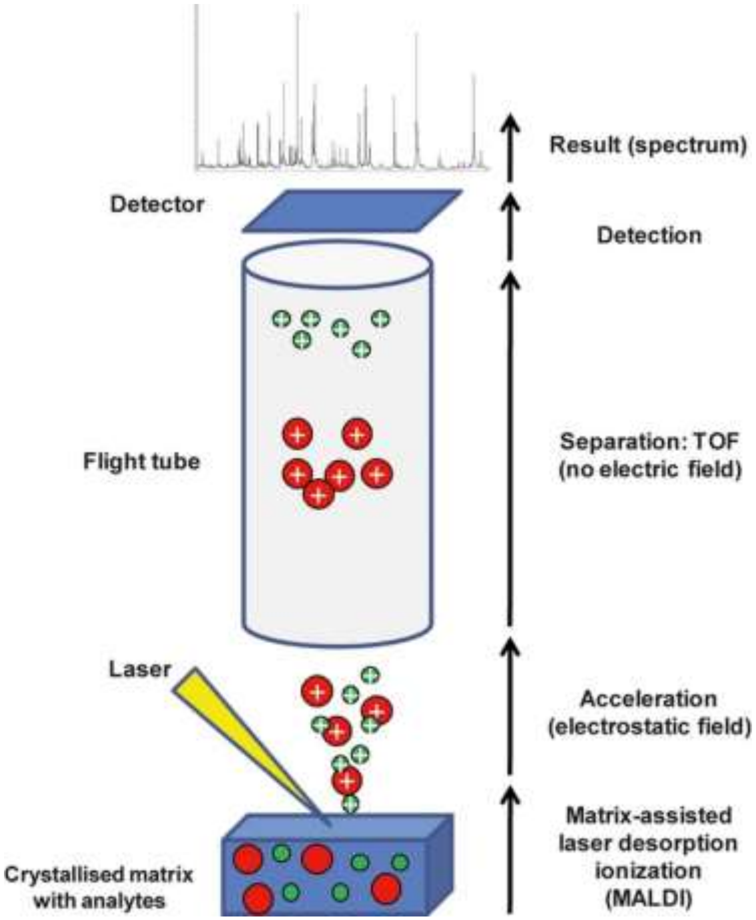
$C_{222}H_{42}$, 2700Da

Soot grains & PAHs
or only PAHs as condensates

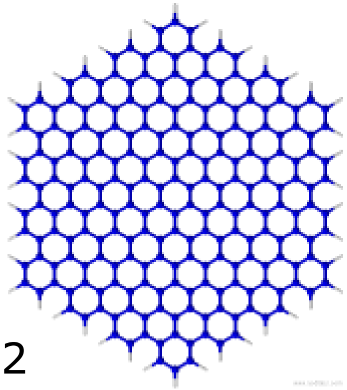
Characterisation of the low-temperature condensates

Matrix-Assisted-Laser Desorption and Ionization combined with mass spectrometry MALDI-TOF





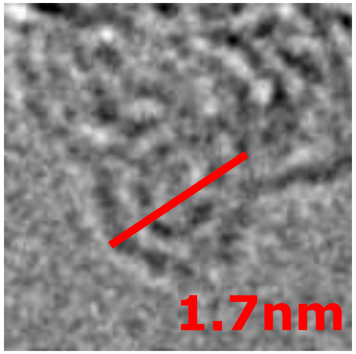
PAHs with masses up to 3000 Da



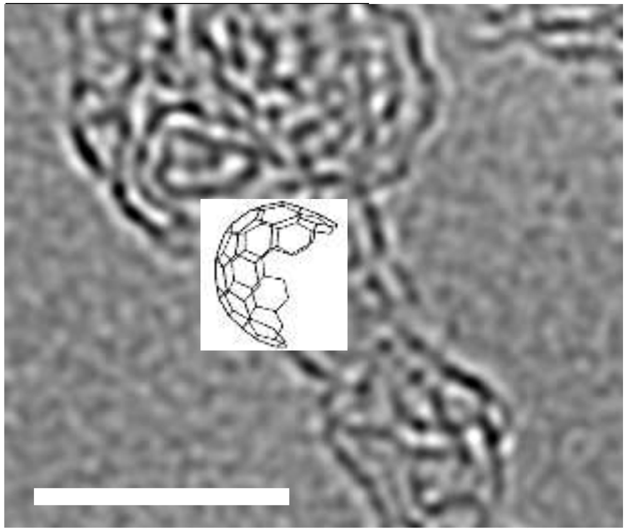
$C_{222}H_{42}$

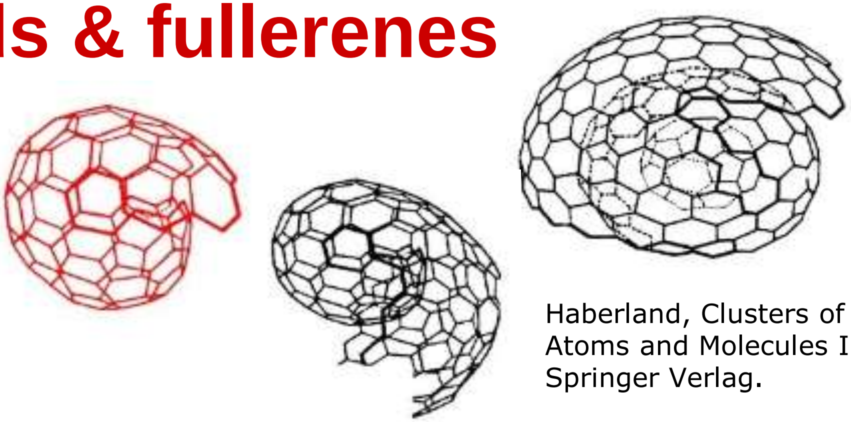
High-temperature condensation
T ≥ 3500 K

Fullerene-like carbon seeds & fullerenes

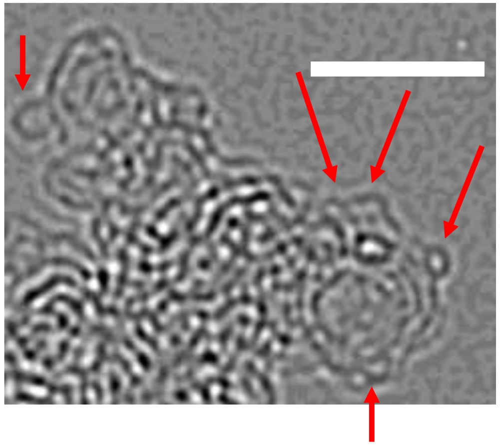


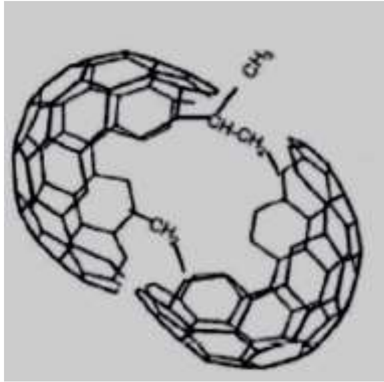
C_{240}@C_{60}

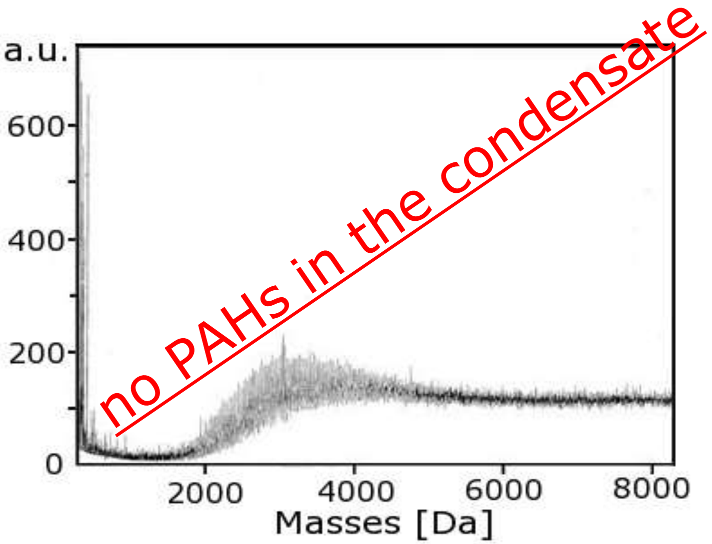




Haberland, Clusters of Atoms and Molecules I, Springer Verlag.



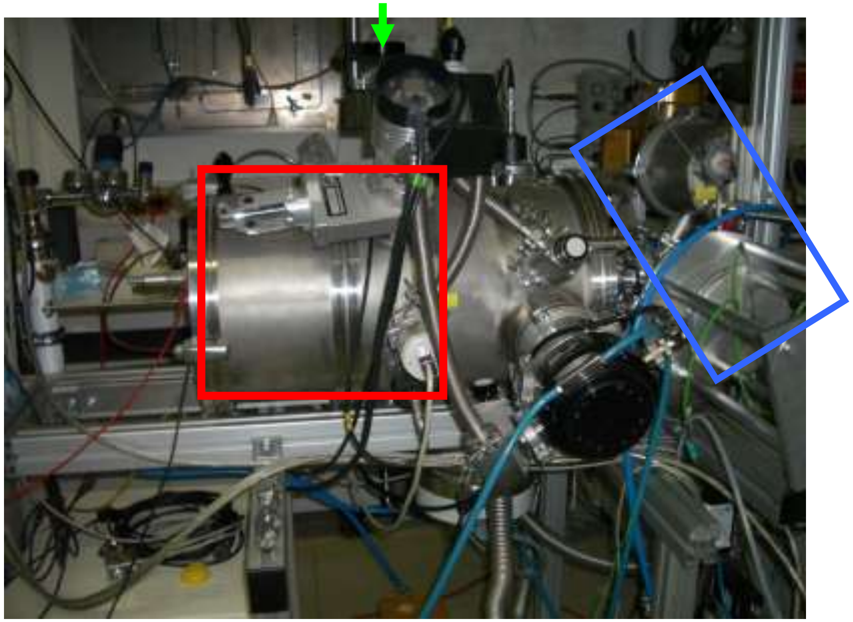


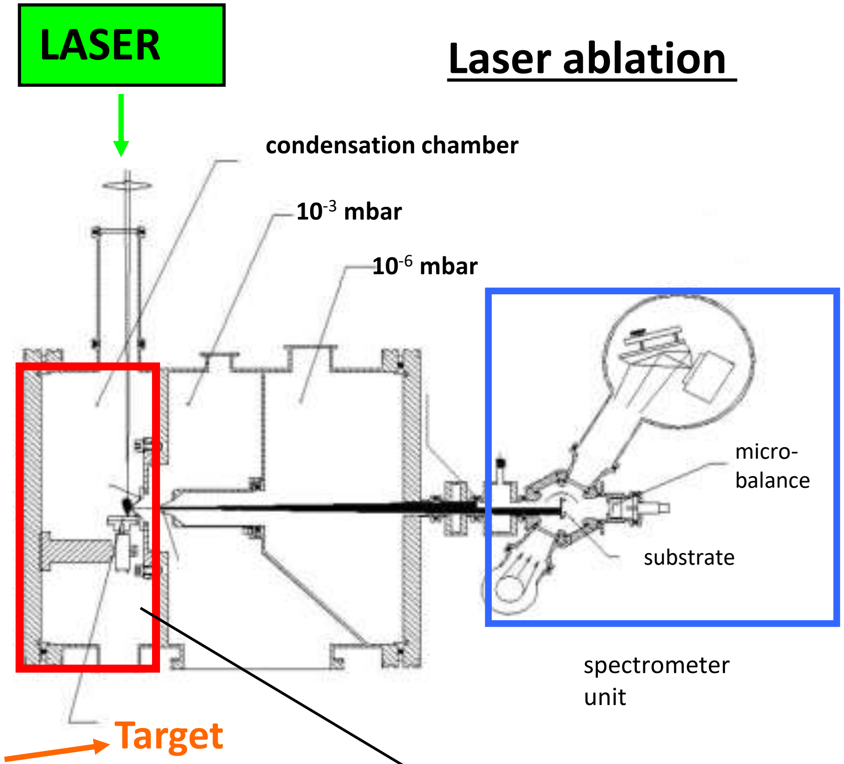


no PAHs in the condensate

Gas-phase condensation of silicate particles

Pulsed Nd:YAG laser, 532nm
30-240 mJ per pulse, 5ns

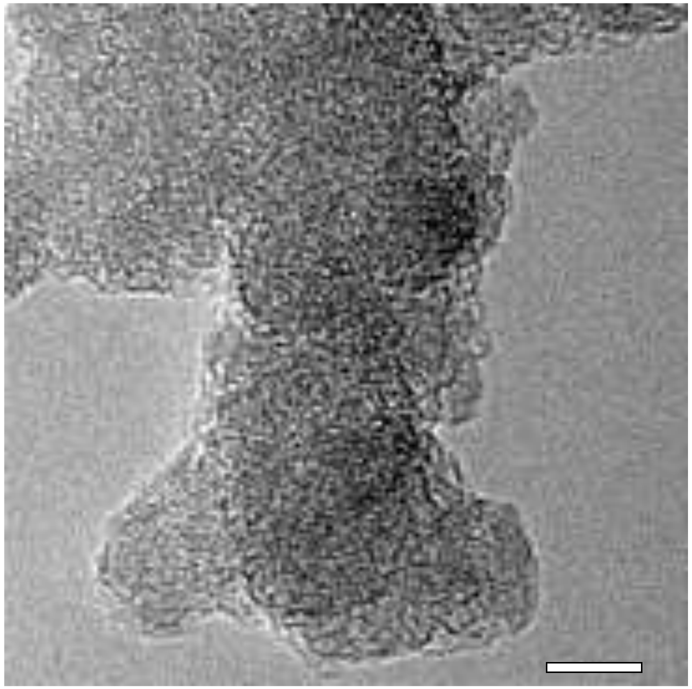




- **laser ablation** of Mg/Fe/Si, Mg/Si, Fe/Si mixed targets (olivine and pyroxene stoichiometry) and of an olivine crystal
- beam extraction, deposition on CaF2 substr.

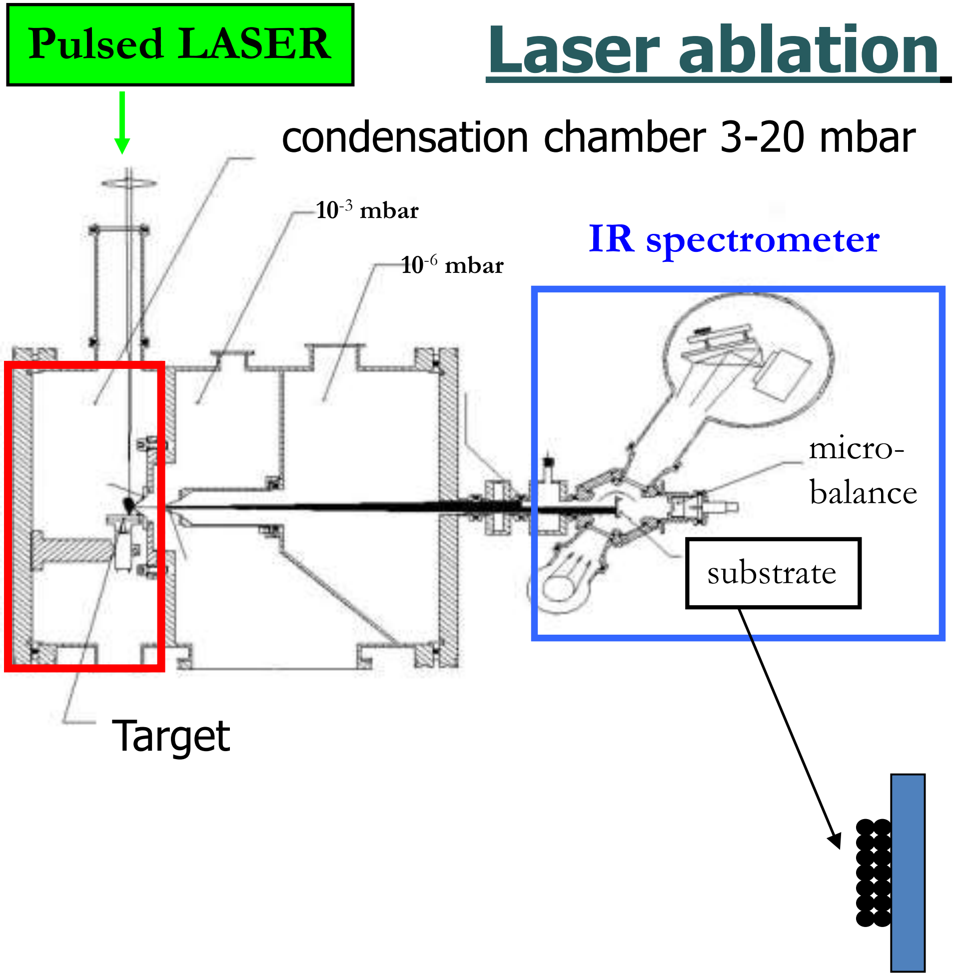
Quenching gas: He or He/O$_2$ mixtures

High-temperature gas-phase condensation of silicates or carbon from the laboratory



Particulate silicate (for example $MgFeSiO_4$ olivine) or carbon layer of definite thickness

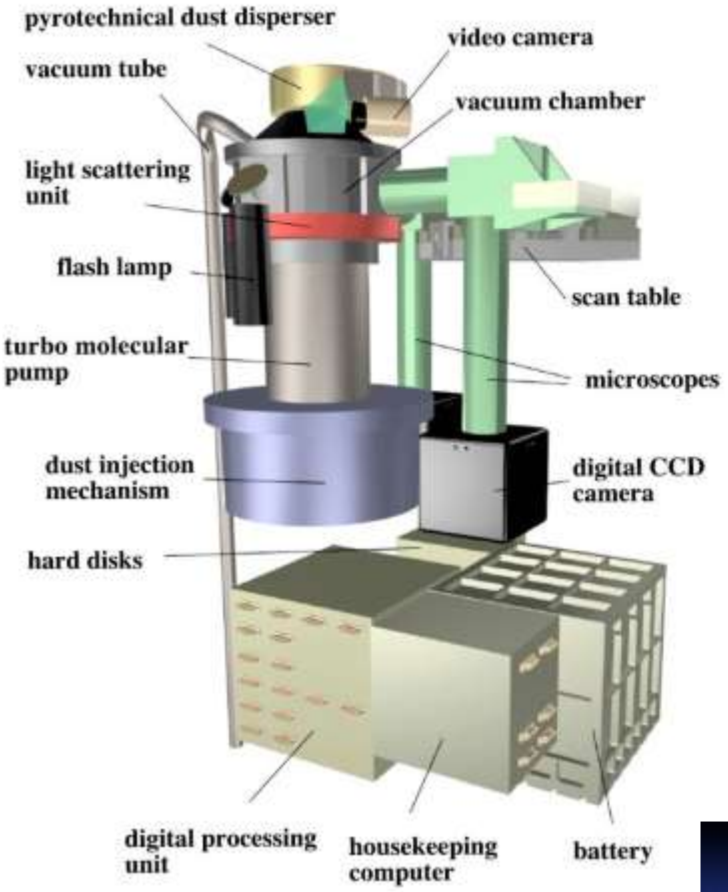
Laser ablation



Condensation temperature for carbononaceous particles ≥4000K

The cosmic dust aggregation experiment CODAG

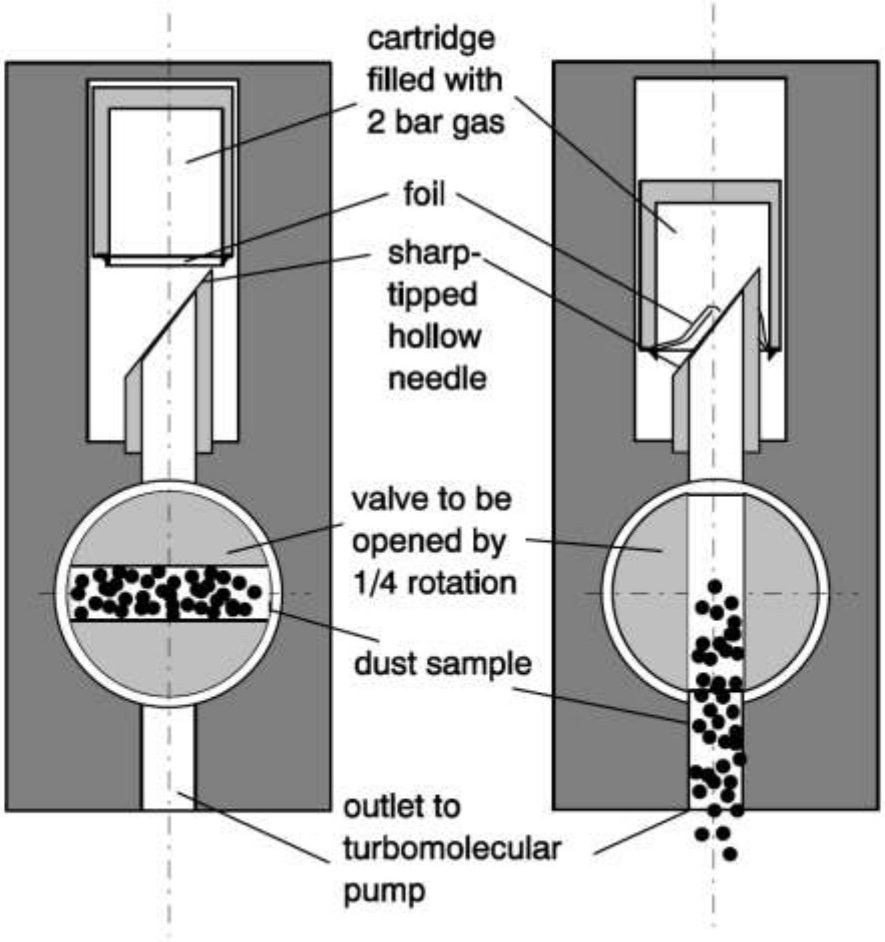
An encapsuled dust aggregation experiment onboard a space shuttle



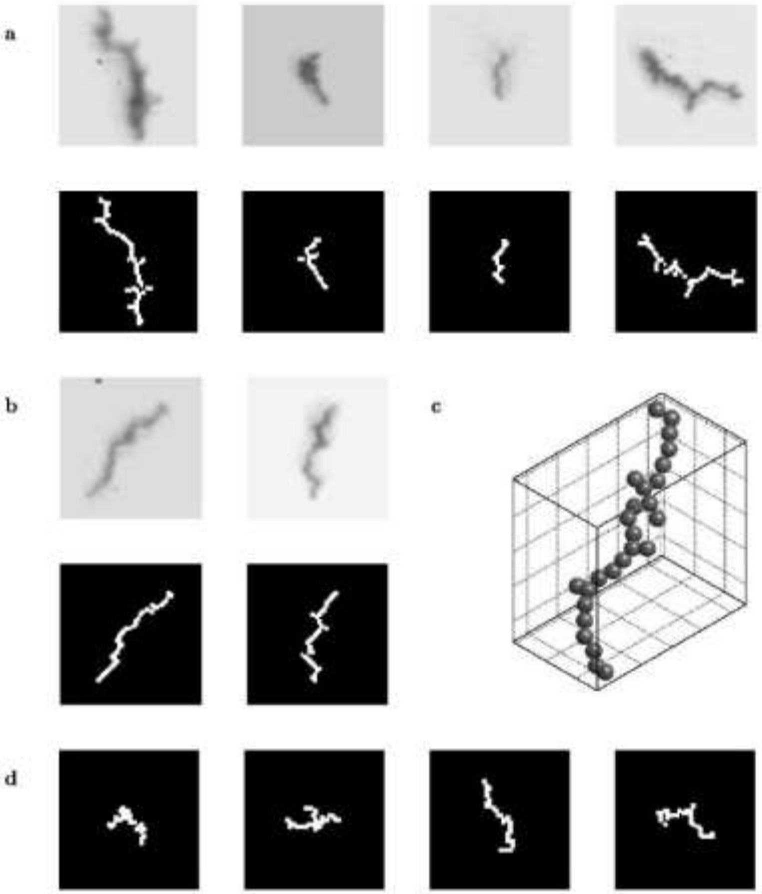
To rule out the influence of gravity -> go to low-gravity environment

J. Blum et al., Meas. Sci. Technol. 10 (1999) 836–844.

The cosmic dust aggregation experiment CODAG



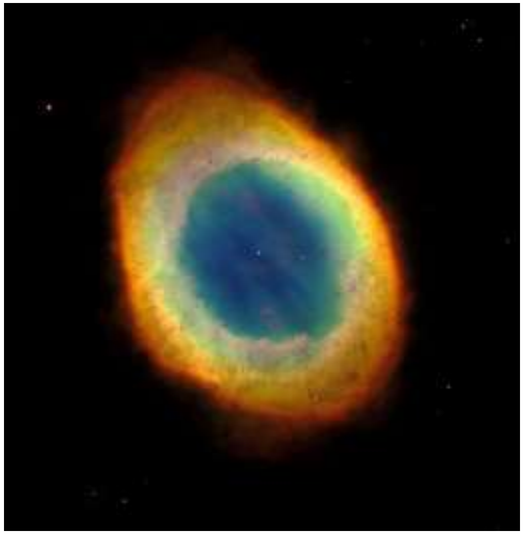
Dust injection device



Rapid growth of surprisingly open structures

J. Blum et al., Phys Rev. Lett. 85, 2426 (2000)

Interstellar Dust: Soot and Sand



Dust grains are produced in the
outflows of Stars and stellar envelopes

- Carbon-rich stars produce **carbonaceous grains (soot)**
- Oxygen-rich stars make **metalic oxides and silicates**

Nature of Interstellar Dust:

- Ranges in size from 1nm to 10µm
- Many more small grains than large
- The larger grains are likely to be non-spherical, perhaps porous, fluffy, even fractal
- Composition is likely to contain metallic silicates, carbonaceous material, and GEMS (glasses with embedded metal and sulfites)
- Mantles of ices (H_2O, CO, CO_2, CH_3OH) are found in dense regions

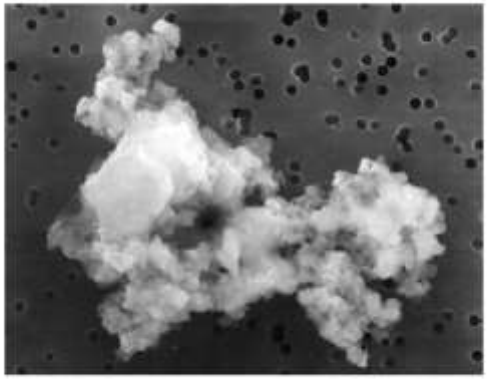


Fig. 5. A 10-µm interplanetary dust particle known as a Brownlee particle. Collected in the stratosphere, it is composed of glass, carbon, and mineral silicates. Acknowledgment is made to NASA for allowing reproduction of this picture from web site http://stardust.jpl.nasa.gov/science/sci2.html.

D.A. Williams, E. Herbst, “It’s a dusty Universe”, Surface Science 500 (2002) 823

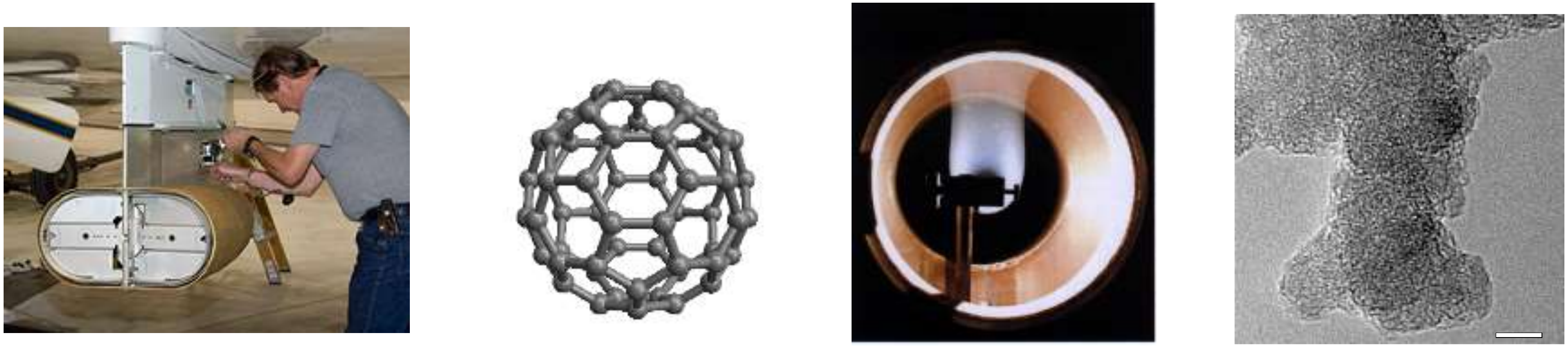
Outline: Challenges for Laboratory Astrophysics

1. Can we collect cosmic dust (since it seems to rain down on us)?
   Yes! But to identify interstellar dust is very hard (7 particles so far).

2. Can we simulate dust formation in the laboratory?
   Yes! One can condensate carbonaceous as well as silicate particles.
   But there is a lot of potential for complexity.

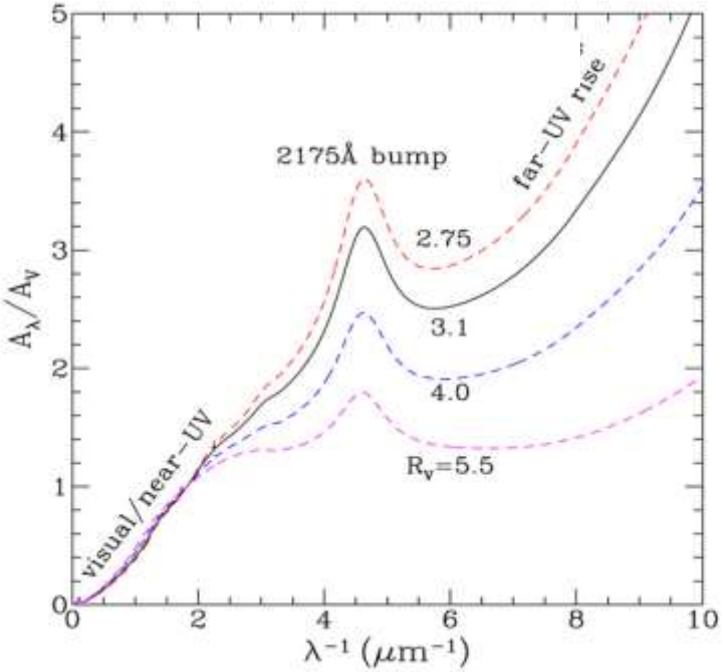
3. Can we understand it´s optical properties to make use of astron. data?

4. Can we test the formation of molecules (chemistry) on dust grains?



3. Can we understand the optical properties of dust?

Interstellar Extinction Curve



- Grain absorption and scattering processes at a certain wavelength λ are correlated with the size of the particle

- Rise towards the UV means that there are **a lot more small particles**

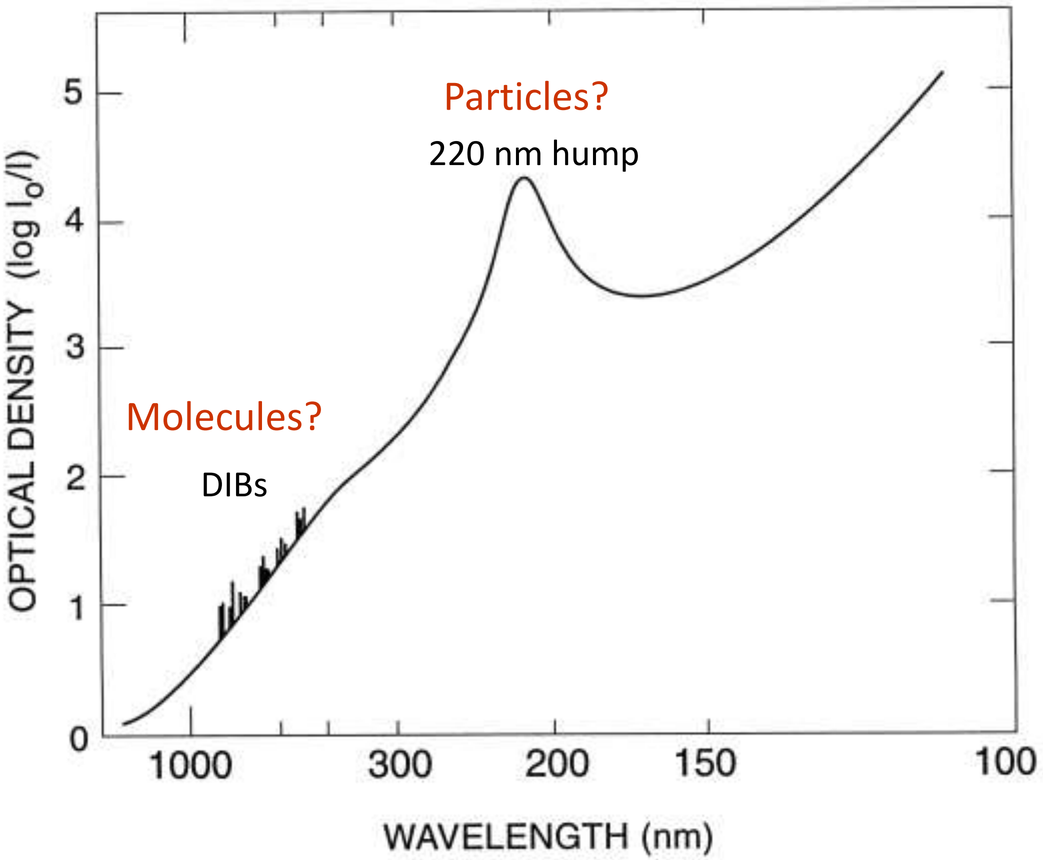
- General trend: more extinction at shorter wavelength ⟶ Reddening
- The shape of the curve is well-represented by a 7-parameter fit (Cardelli 1989):

$$\frac{A_\lambda}{A_V} = f(\lambda, R_v, C_1. C_2, C_3, C_4, \lambda_0, \gamma)$$

- It is possible to estimate all parameters, if R_v is known.

3. Can we understand the optical properties of dust?

The 220 nm Bump and the Discovery of the Buckminsterfullerene C_{60}



Particles?

220 nm hump

Molecules?

DIBs

nature

INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

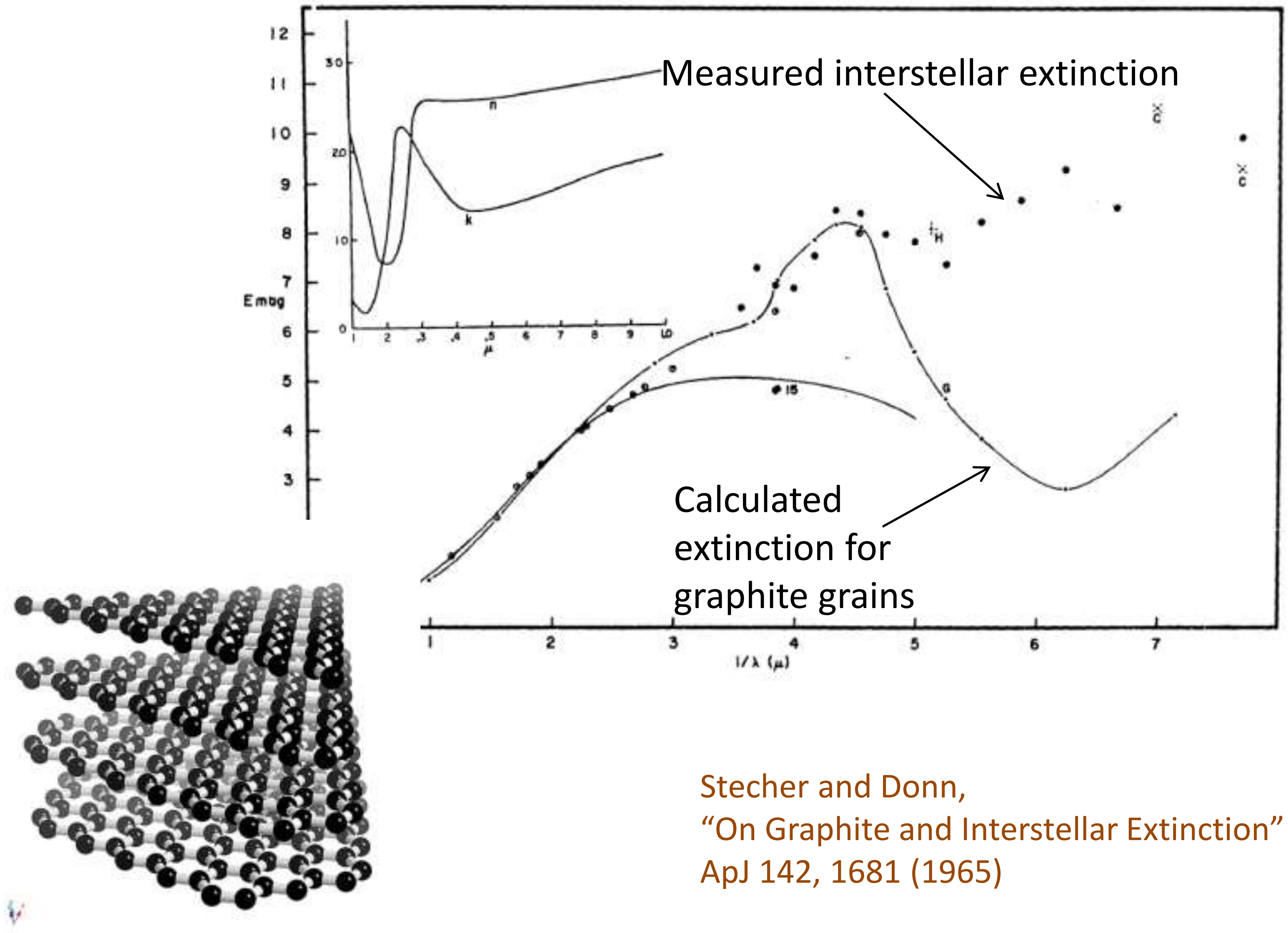
A NEW FORM OF CARBON

UNDERSTANDING ANTARCTIC OZONE DEPLETION

The cellular defect behind cystic fibrosis

The next slides courtesy of
Prof. Wolfgang Krätschmer (MPIK)

Early indications: 220 nm hump caused by Graphite?



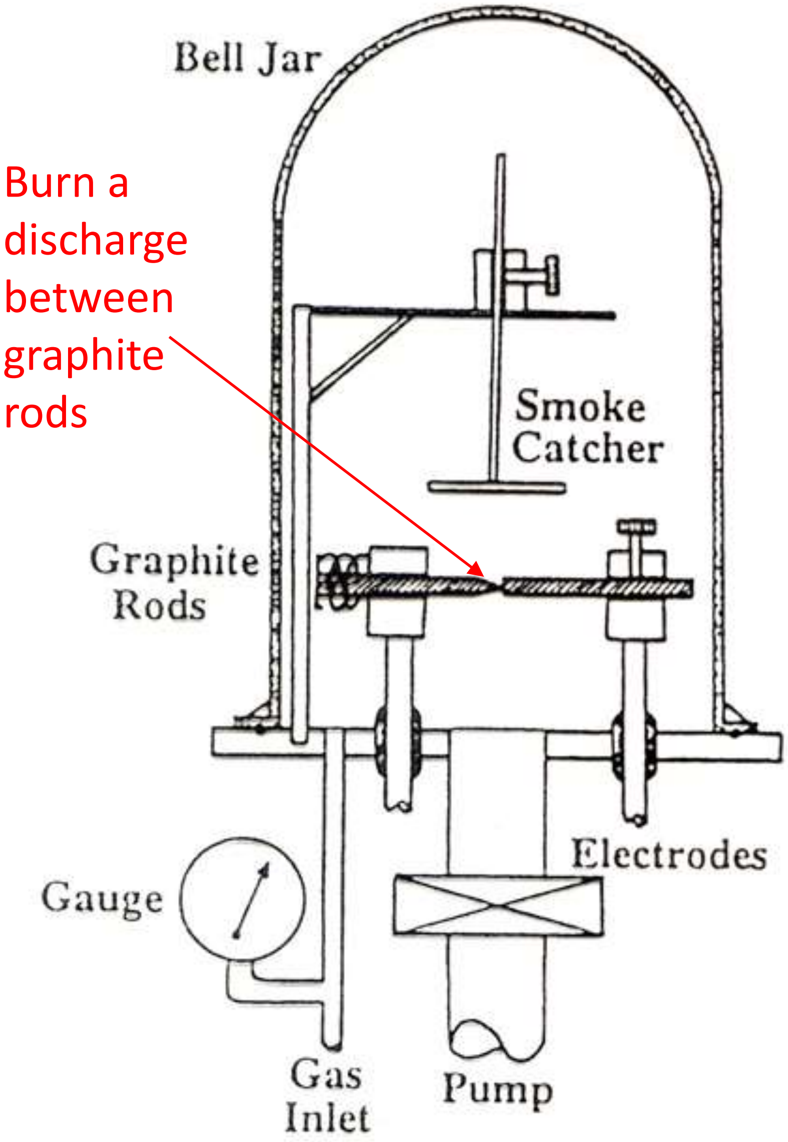
Measured interstellar extinction

Calculated extinction for graphite grains

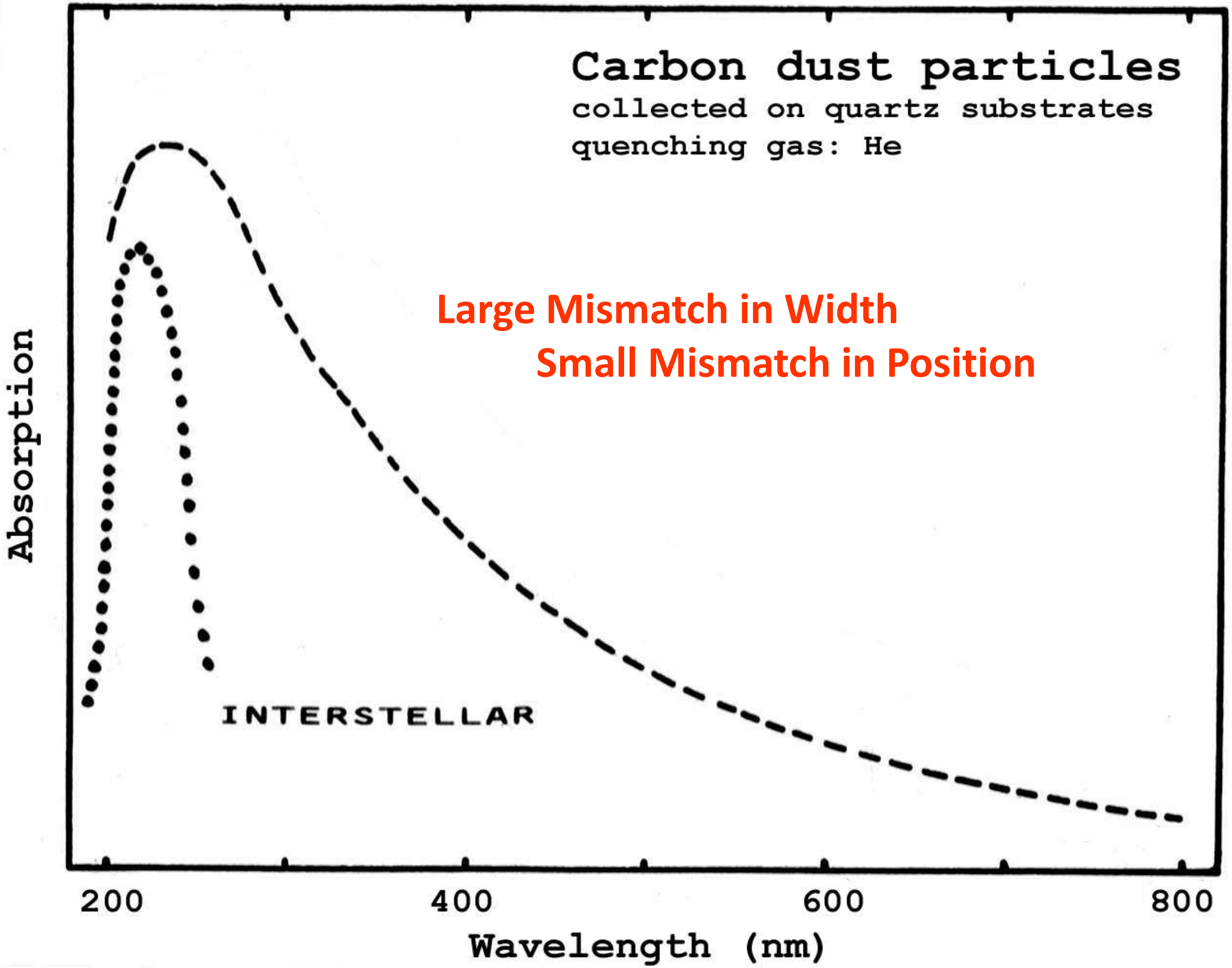
Stecher and Donn,
“On Graphite and Interstellar Extinction”
ApJ 142, 1681 (1965)

Experiment: how to condense carbonaceous material

Burn a discharge between graphite rods

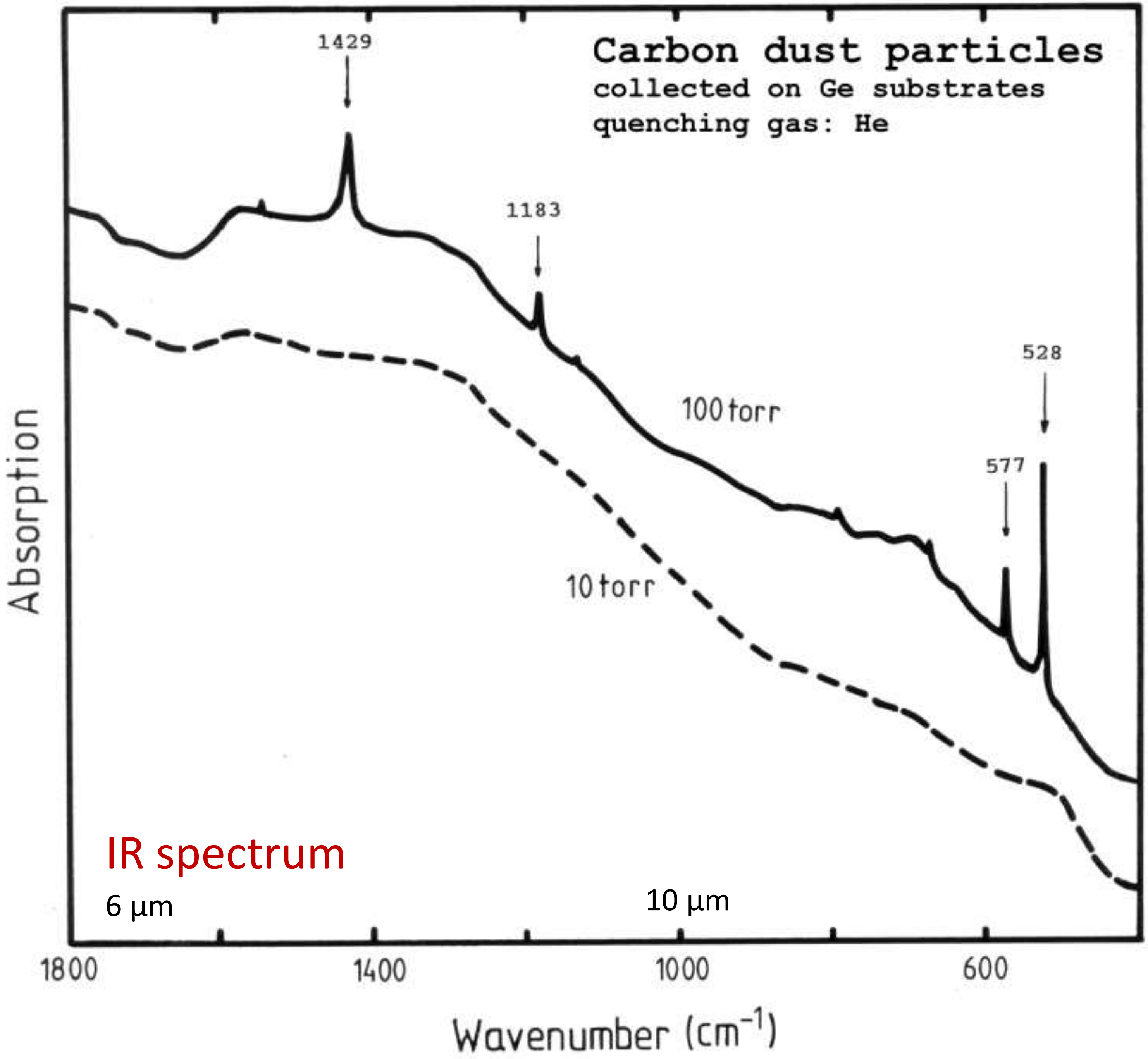



0,1 µm



Large Mismatch in Width

Small Mismatch in Position



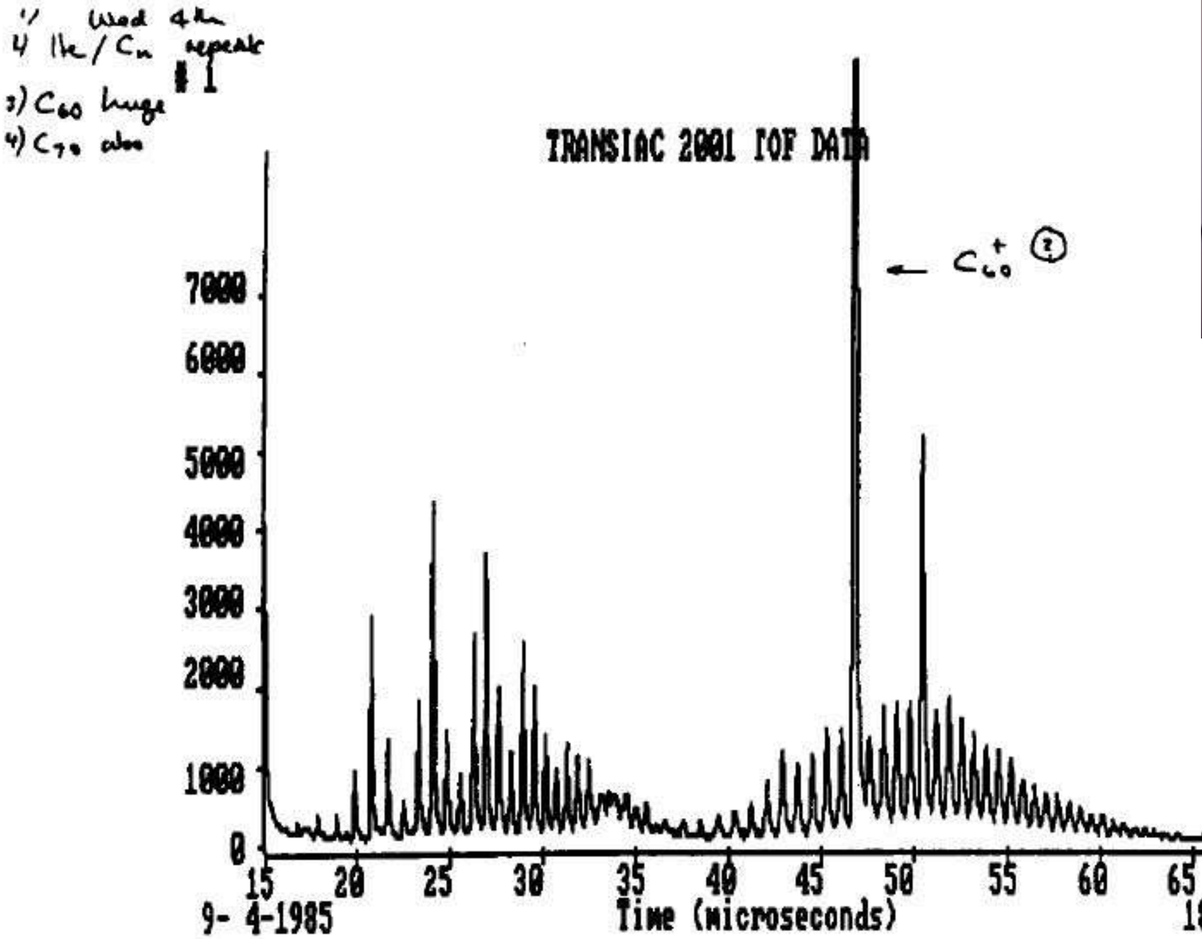
IR spectrum

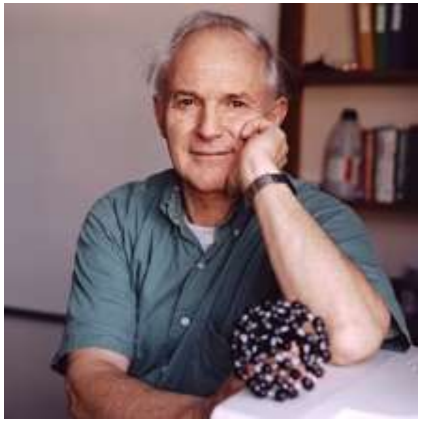
6 µm

10 µm

The discovery of C_{60}

Harry Kroto had been studying the formation of interstellar carbon chains since 1970

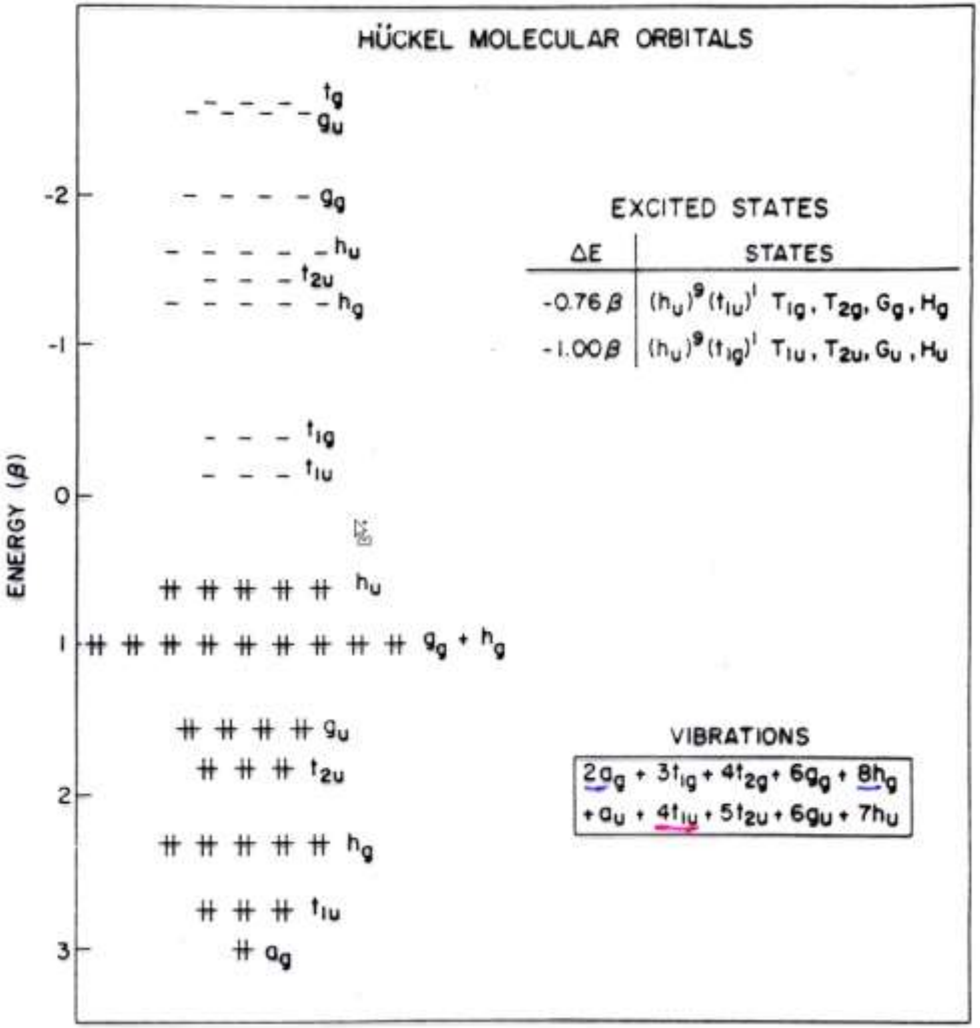




Rice University, Houston,Texas, 1985

Robert F. Curl, Richard E. Smalley, Harold Kroto

Theory: an obscure form of carbon

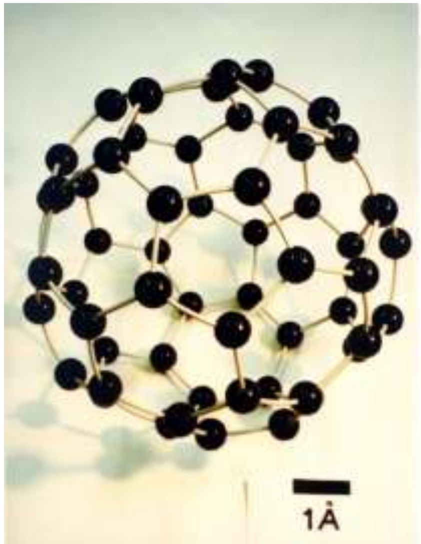


EXCITED STATES

ΔE	STATES
-0.76β	$(h_u)^9(t_{1u})^1$ T_{1g}, T_{2g}, G_g, H_g
-1.00β	$(h_u)^9(t_{1g})^1$ T_{1u}, T_{2u}, G_u, H_u

VIBRATIONS

$$\boxed{\begin{array}{l} \underline{2a}_g + 3t_{1g} + 4t_{2g} + 6g_g + \underline{8h}_g \\ + a_u + \underline{4t_{1u}} + 5t_{2u} + 6g_u + 7h_u \end{array}}$$



大澤映二

Eiji Osawa

Osawa predicts C_{60} in an article in 1970:
Superaromaticity (*Kagaku.* ***25****: 854–863).*

W Krätschmer et al. (MPI Kernphysik, Heidelberg)
developed a method to synthesize C_{60} in macroscopic quantities


nature

INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Volume 347 No. 6291 27 September 1990 £2.50

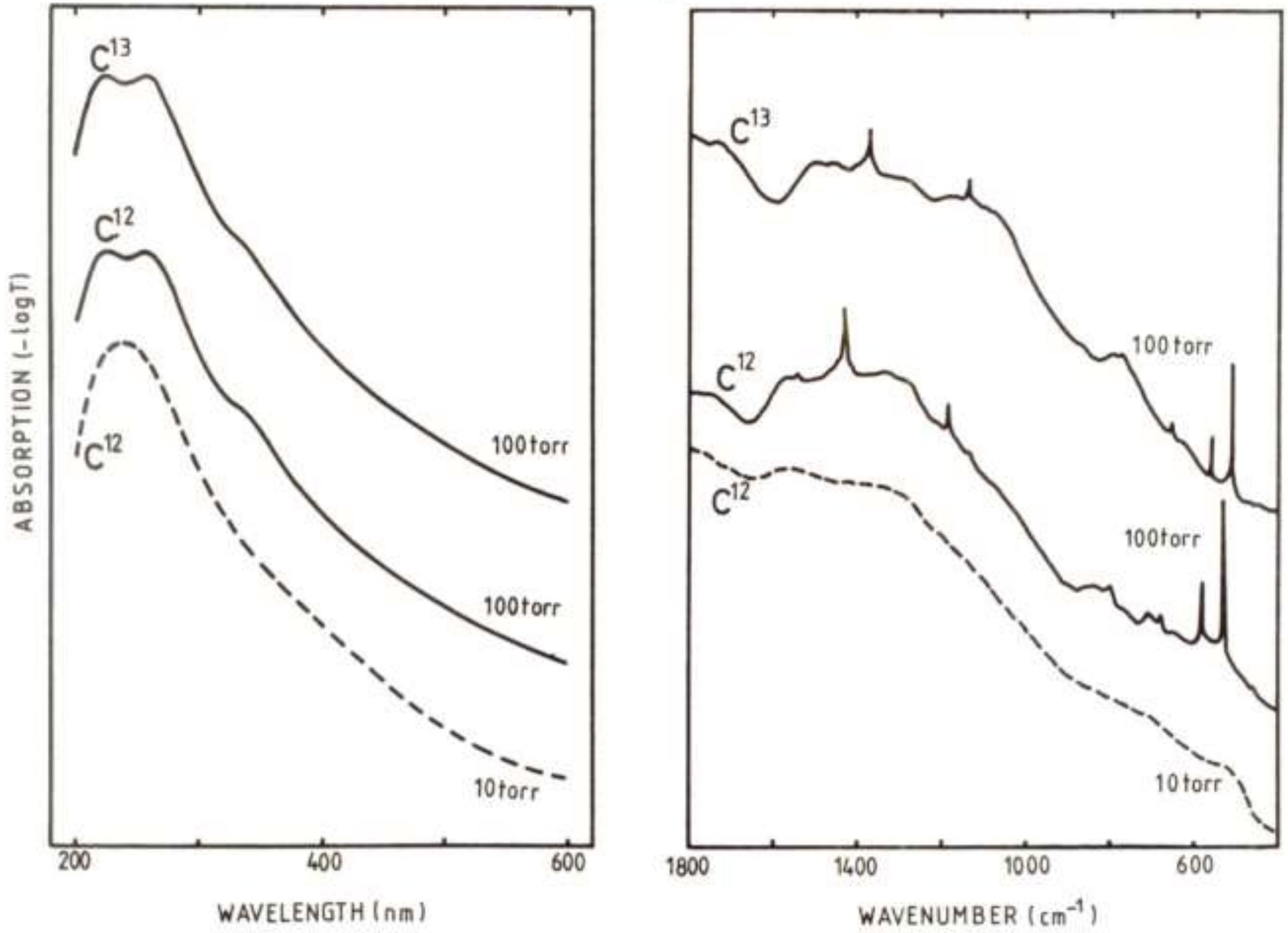
A NEW FORM OF CARBON

UNDERSTANDING ANTARCTIC OZONE DEPLETION

The cellular defect behind cystic fibrosis

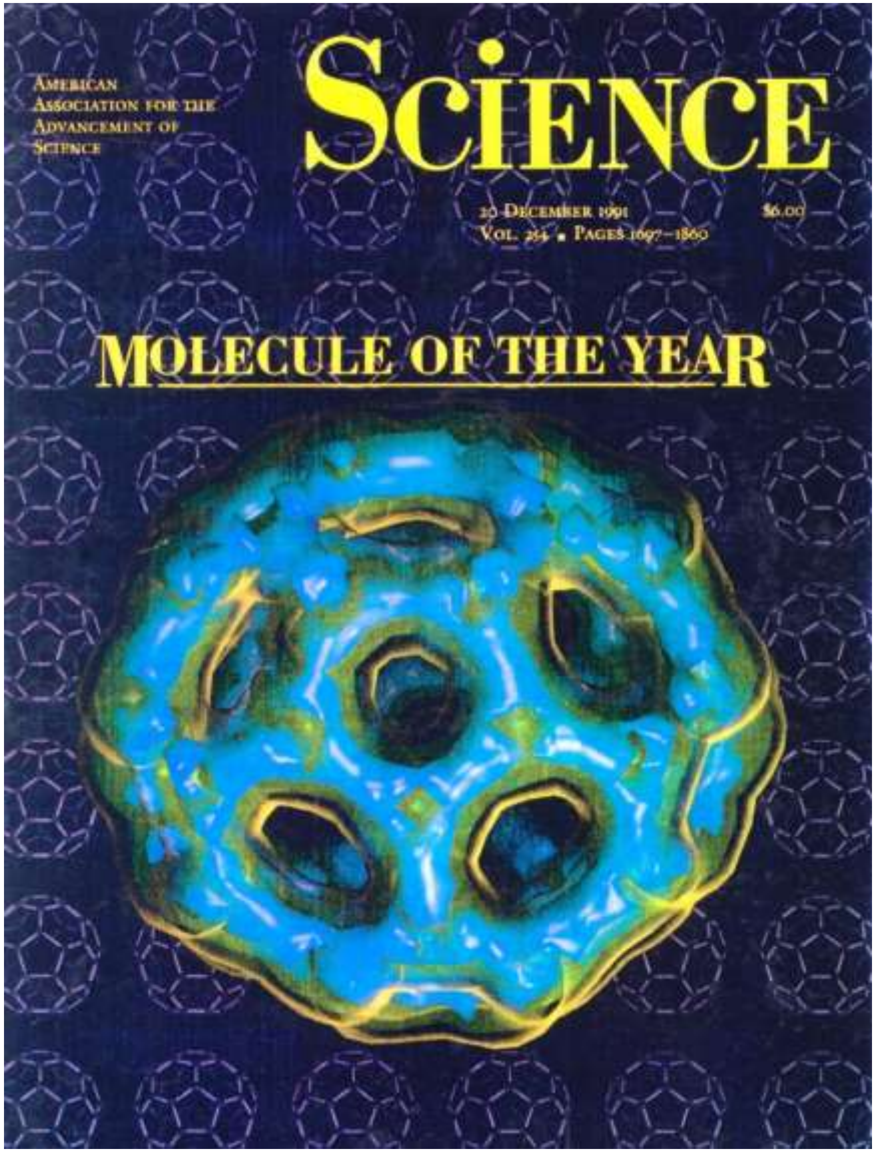
Carbon dust particles

quenching gas: He



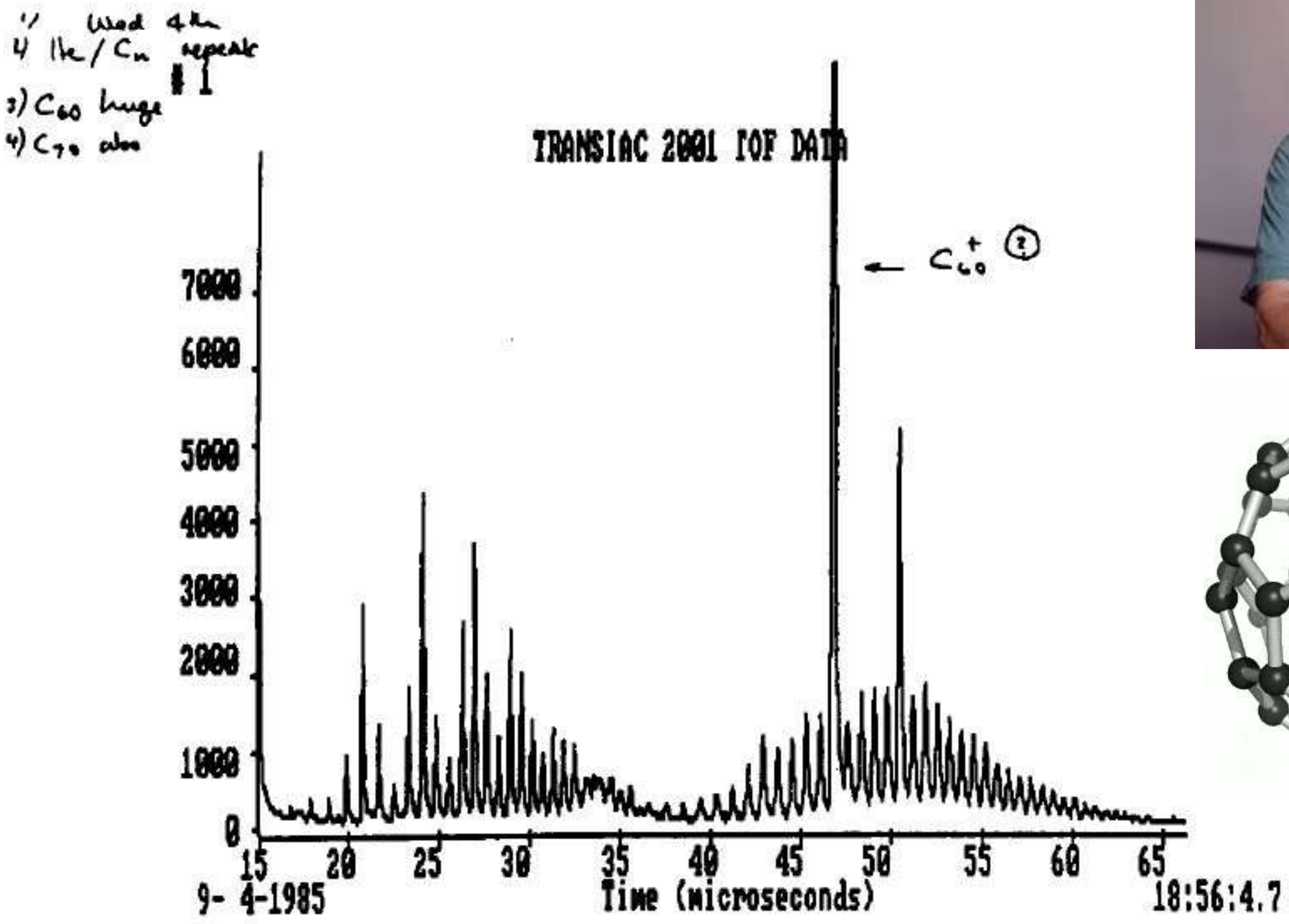
W.Krätschmer et al. Chem. Phys. Lett. 170, No.2,3 p.167 (1990)

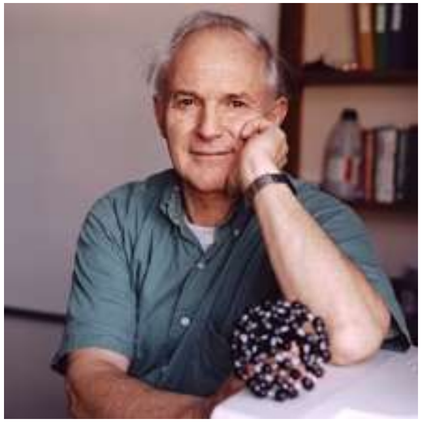
Molecular Hype

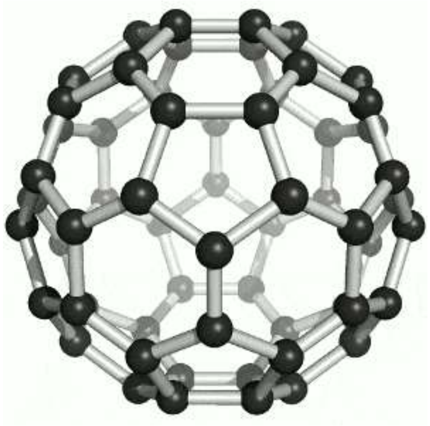


The discovery of buckyballs C_{60}

(Named after architect Buckminster Fuller)







Rice University, Houston,Texas, 1985

Robert F. Curl, Richard E. Smalley, Harold Kroto

Nobel prize
Chemistry
(1996)

Today at the „Deutsche Museum“ (Bonn)

Fulleren-Generator

Diese Apparatur dient der kostengünstigen Herstellung von Fulleren C60, einem fußballförmigen Molekül aus 60 Kohlenstoffatomen.

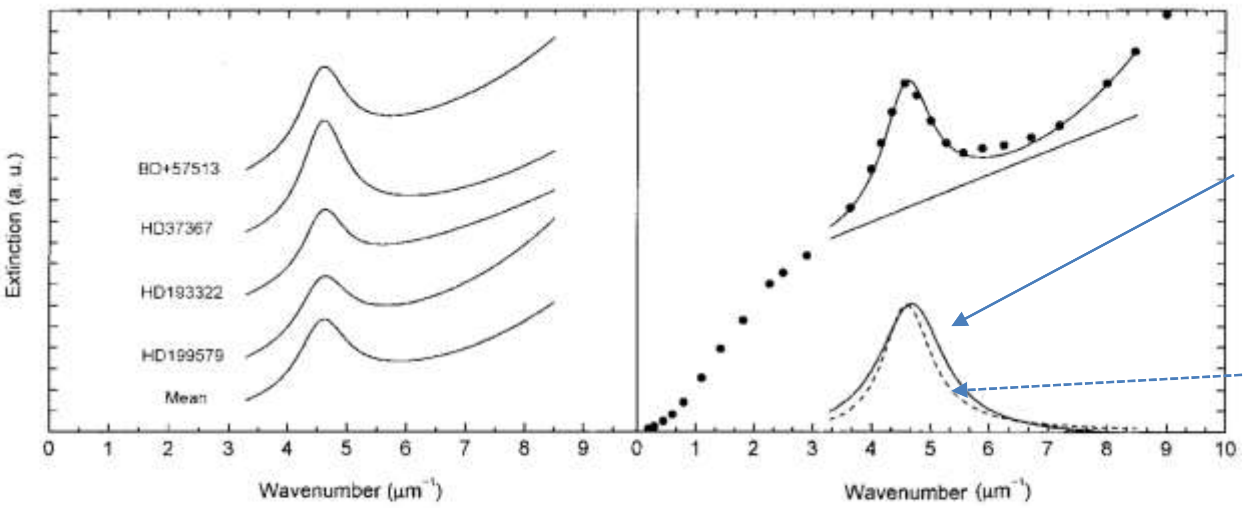
Im Inneren der Glasglocke verdampfen Graphitstäbe in einer Heliumatmosphäre zu heißem Kohlenstoffdampf, der anschließend durch das Edelgas Helium gekühlt wird. Der Dampf kondensiert dabei zu kleinsten Staubteilchen, die sich als Ruß an den Wänden der Apparatur absetzen. Der Ruß enthält neben anderen Fullerenen bis zu 15 % C60-Moleküle, die leicht zu isolieren sind.

In Fulleren-Molekülen sind Kohlenstoffatome in Fünf- und Sechsecken angeordnet und bilden zusammen eine Kugel. Dieser Aufbau gibt Fullerenen besondere Eigenschaften. Bisher waren nur zwei Kohlenstoffanordnungen bekannt: Kohlenstoffatome, die sich wie im Graphit als Schichtgitter oder wie im Diamant als Raumgitter aneinanderlagern.

Mehr Informationen:
→ www.deutsches-museum-bonn.de

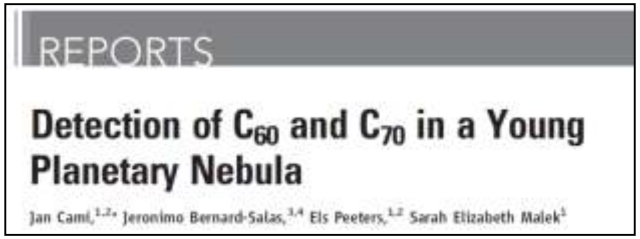
Epilogue: C_{60} and space and the 220nm bump

Henning & Salama Science 282, 2204 (1998)



Isolated profile 220nm feature

Experiment: Nanosized Carbon particles



REPORTS

Detection of C_{60} and C_{70} in a Young Planetary Nebula

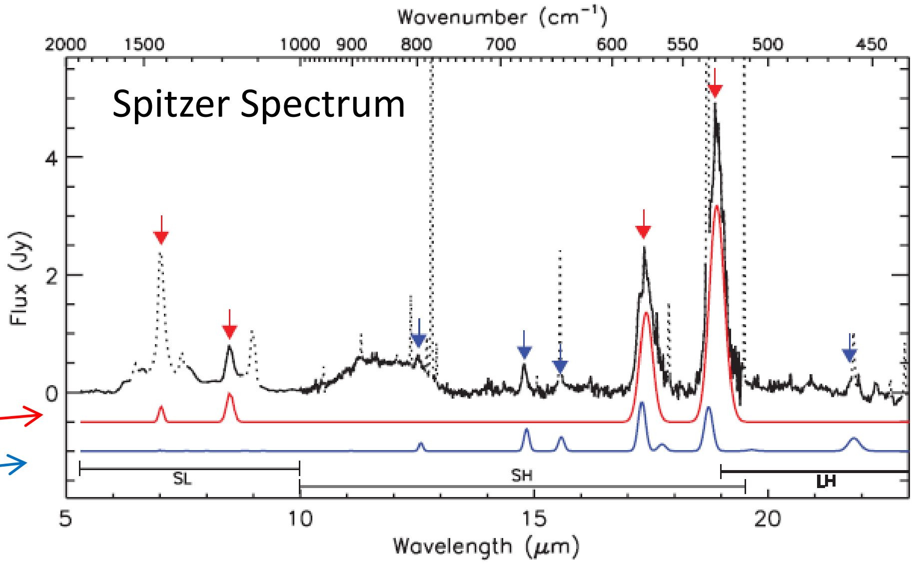
Jan Cami,[1,2*] Jeronimo Bernard-Salas,[3,4] Els Peeters,[1,2] Sarah Elizabeth Malek[1]

Cami et al., Science 329, 1190 (2010)

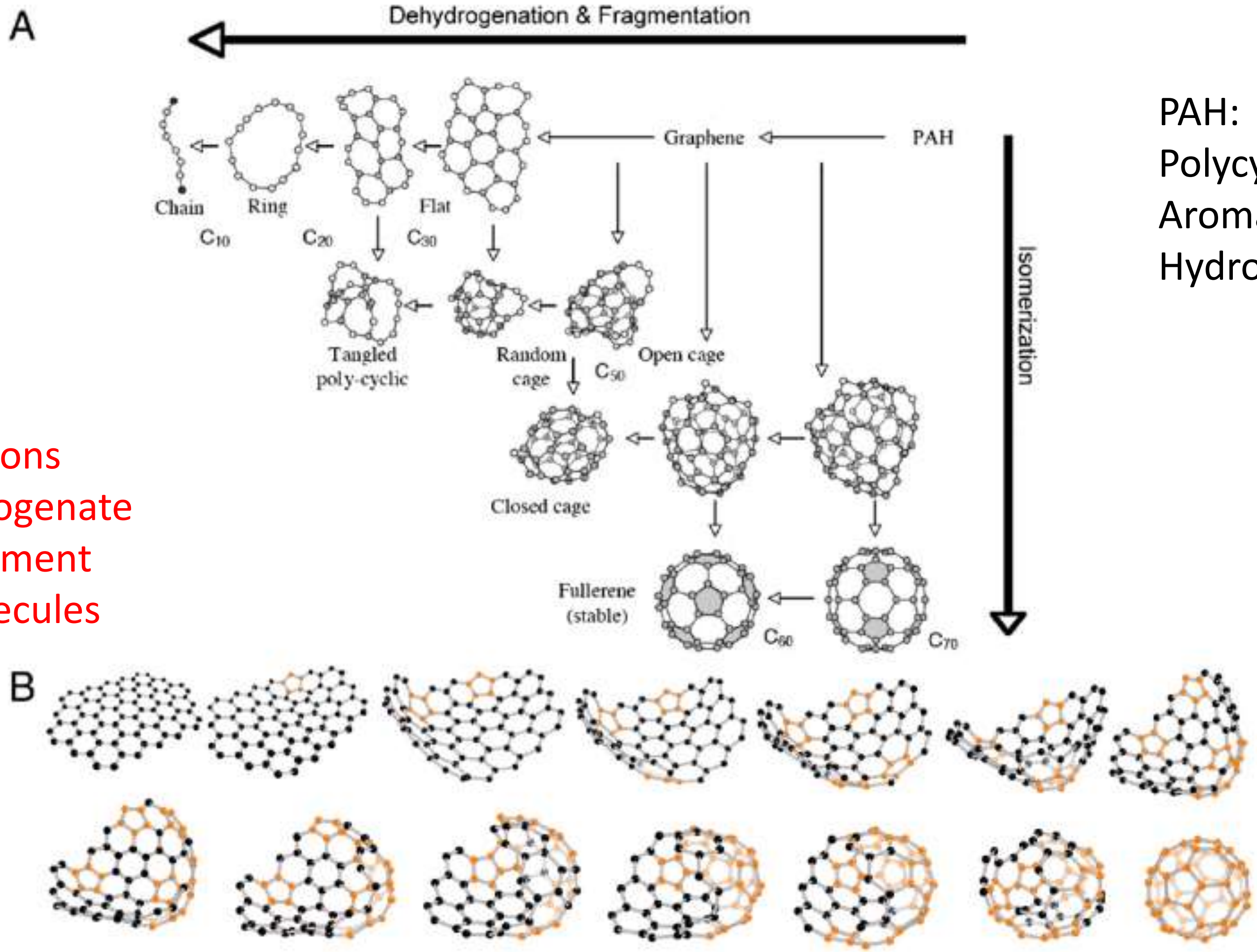
Thermal emission models

C_{60}

C_{70}


Spitzer Spectrum

Fullerene Production in Interstellar Space (Theory)

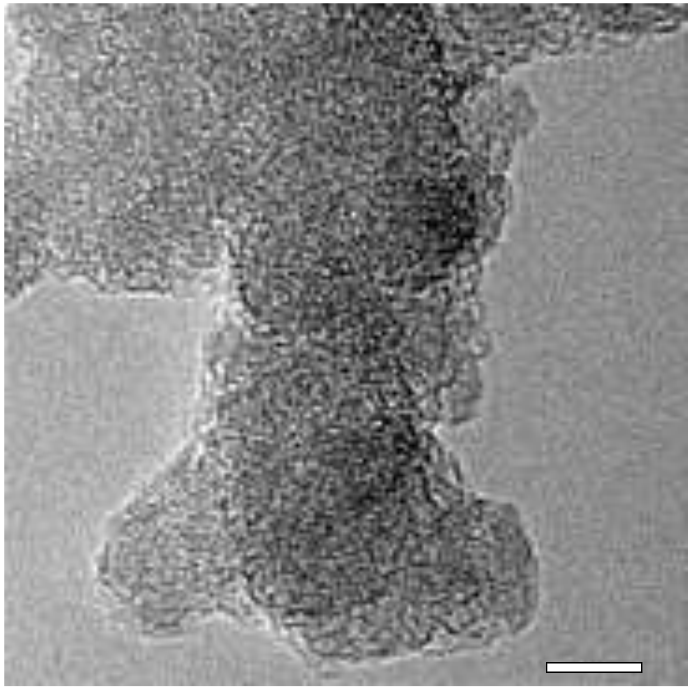


PAH:
Polycyclic
Aromatic
Hydrocarbon

UV photons
de-hydrogenate
and fragment
the molecules

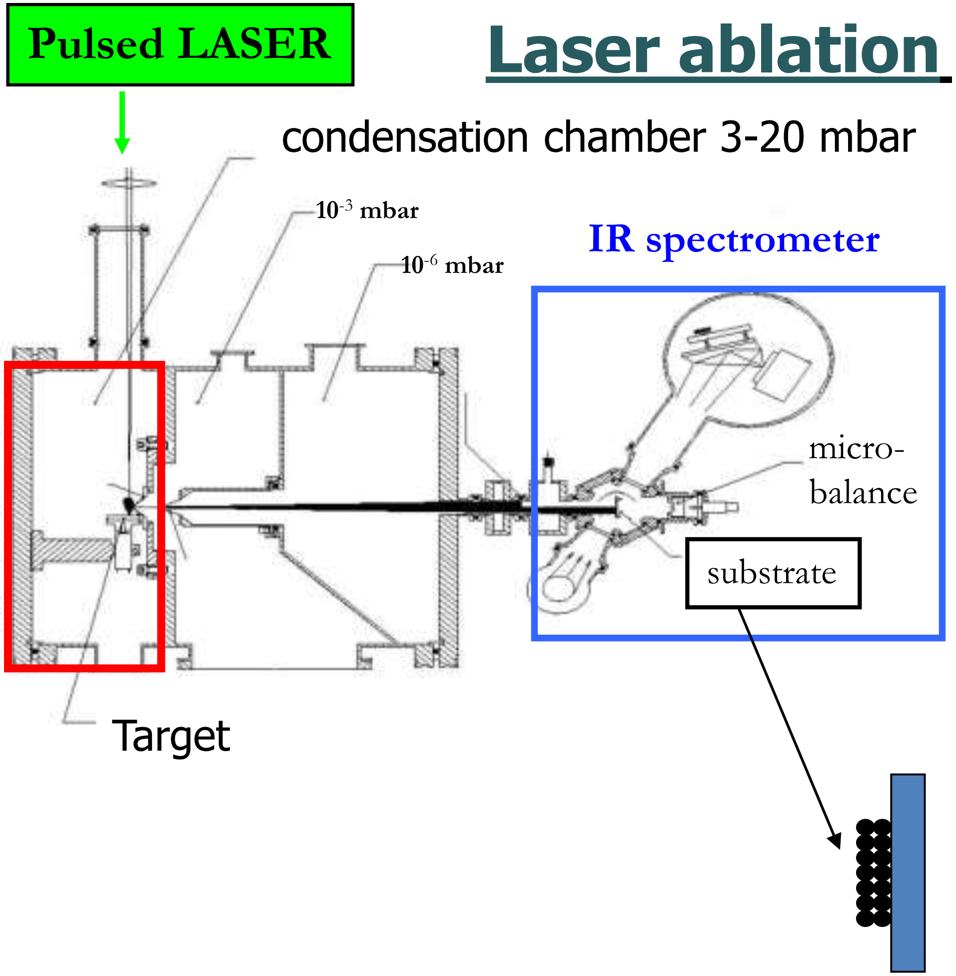
Berne and Tielens, “Formation of buckminsterfullerene (C_{60}) in interstellar space”, PNAS 2011

High-temperature gas-phase condensation of silicates or carbon from the laboratory



Particulate silicate (for example $MgFeSiO_4$ olivine) or carbon layer of definite thickness

Laser ablation

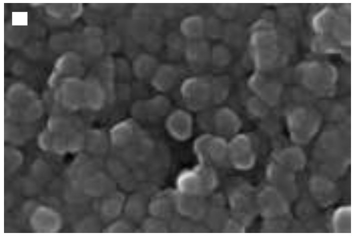


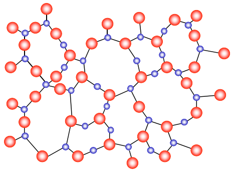
Condensation temperature for carbononaceous particles ≥4000K

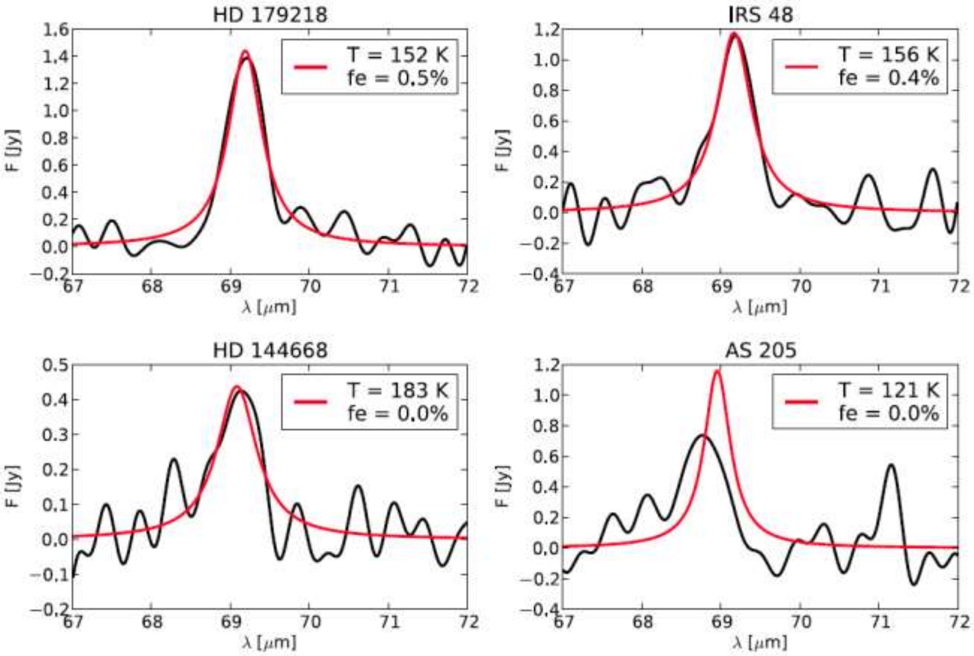
Spectrocopy of cosmic dust analogues in the laboratory

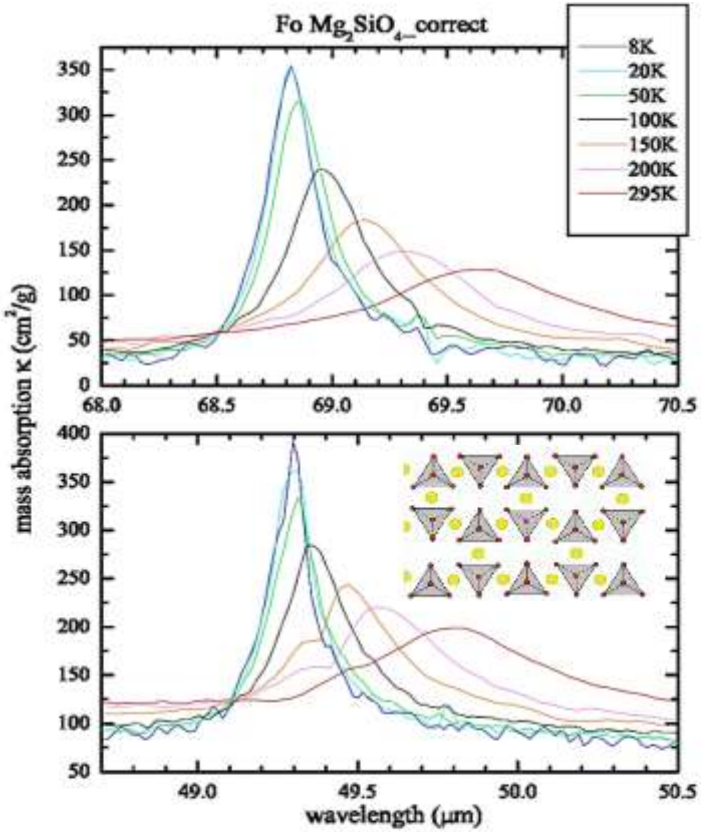
Herschel telescope / PACS

69 µm emission band of forsterite shows the existence of warm (~100–200 K), iron-poor grains in disks.









Sturm et al. 2013, A&A **553**, A5

Data Bases

CDMS AND HJPDOC

MOLECULAR/DUST SPECTROSCOPY CATALOGUES

CDMS

Cologne Database for Molecular Spectroscopy

S. SCHLEMMER, C. P. ENDRES, H. S. P. MÜLLER, P. SCHILKE, J. STUTZKI
I. Physikalisches Institut, Universität zu Köln

HJPDOC

Heidelberg - Jena - St.Petersburg - Database of Optical Constants for Cosmic Dust

C. JÄGER, H. MUTSCHKE, TH. HENNING, V.B. Il'IN, D. SEMENOV
MPIA Heidelberg, AIU Jena, AI St. Petersburg State Univ.

VAMDC consortium

AIU JENA

XSAMS
XML Schema for Atoms, Molecules, and Solids

Outline: Challenges for Laboratory Astrophysics

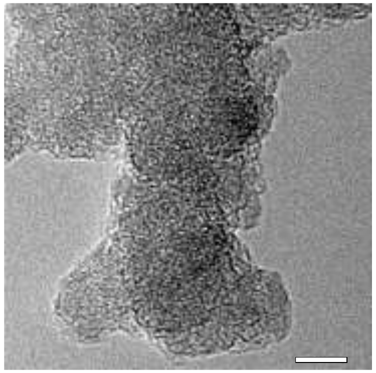
1. Can we collect cosmic dust (since it seems to rain down on us)?
   Yes! But to identify interstellar dust is very hard (7 particles so far).

2. Can we simulate dust formation in the laboratory?
   Yes! One can condensate carbonaceous as well as silicate particles.
   But there is a lot of potential for complexity.

3. Can we understand it´s optical properties to make use of astron. data?
   Yes! But it‘s a lot of work, the phase space is huge! There is a lot that remains to be done.

4. Can we test the formation of molecules (chemistry) on dust grains?

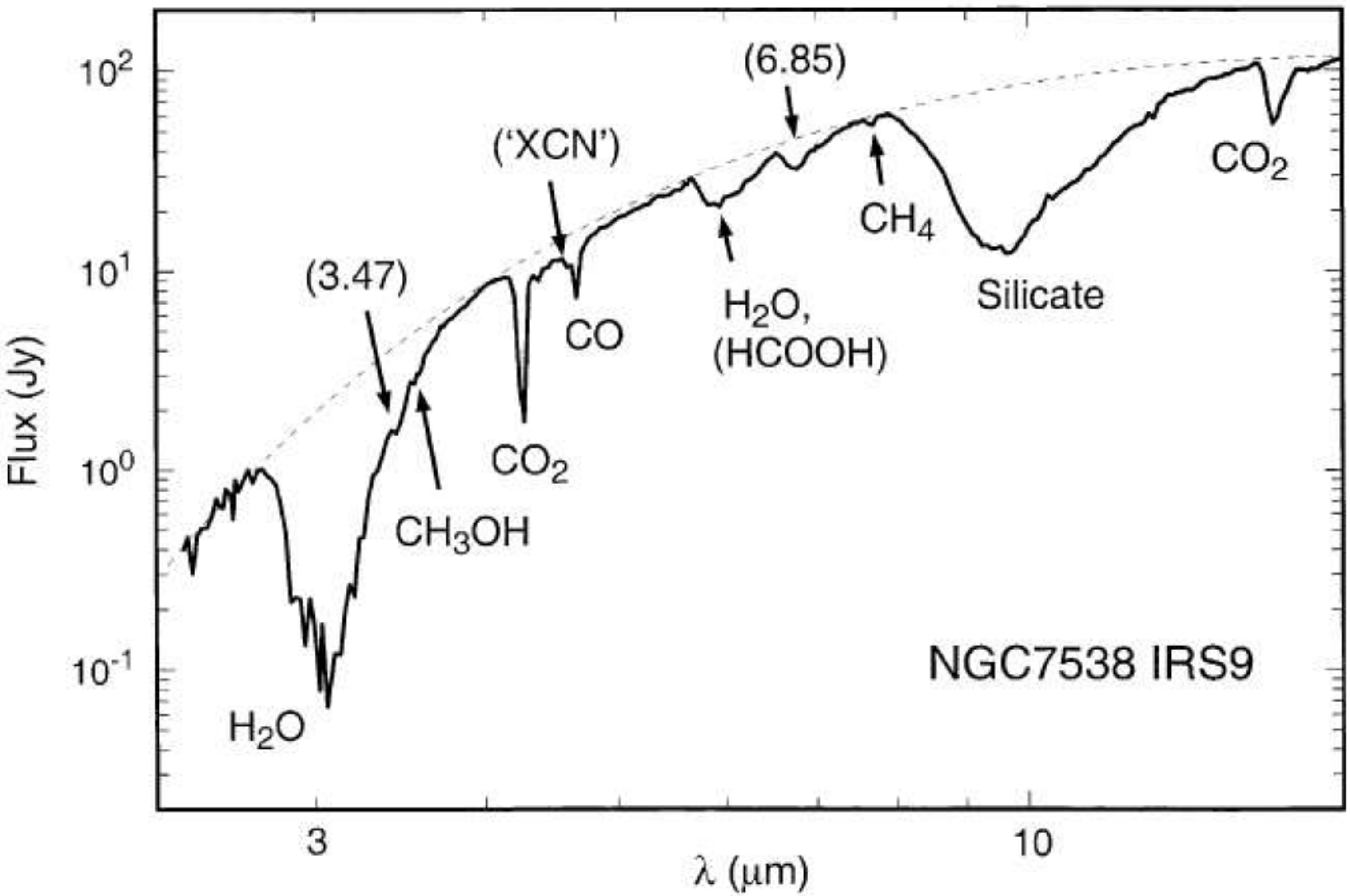


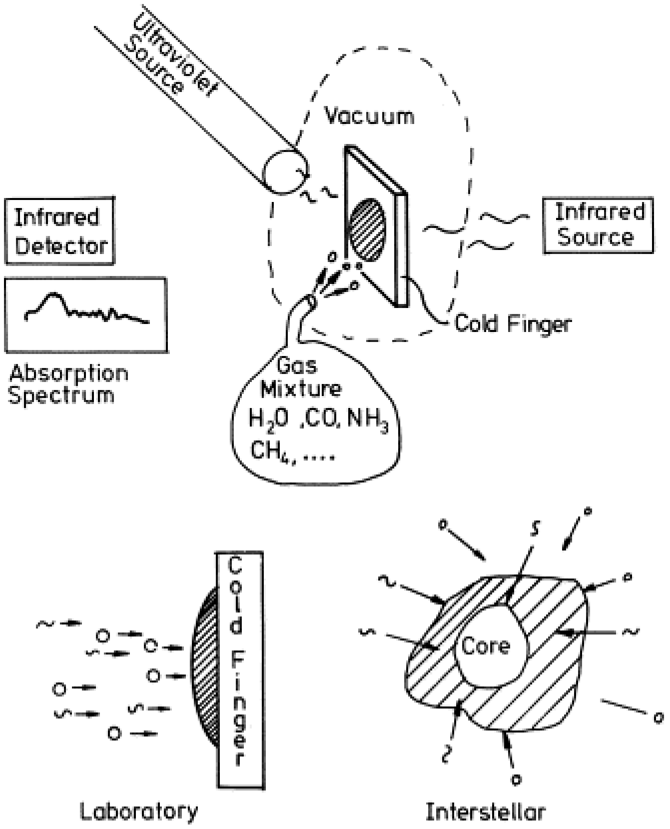
4. Can we test the formation of molecules (chemistry) on dust grains?

Even more features: Ices

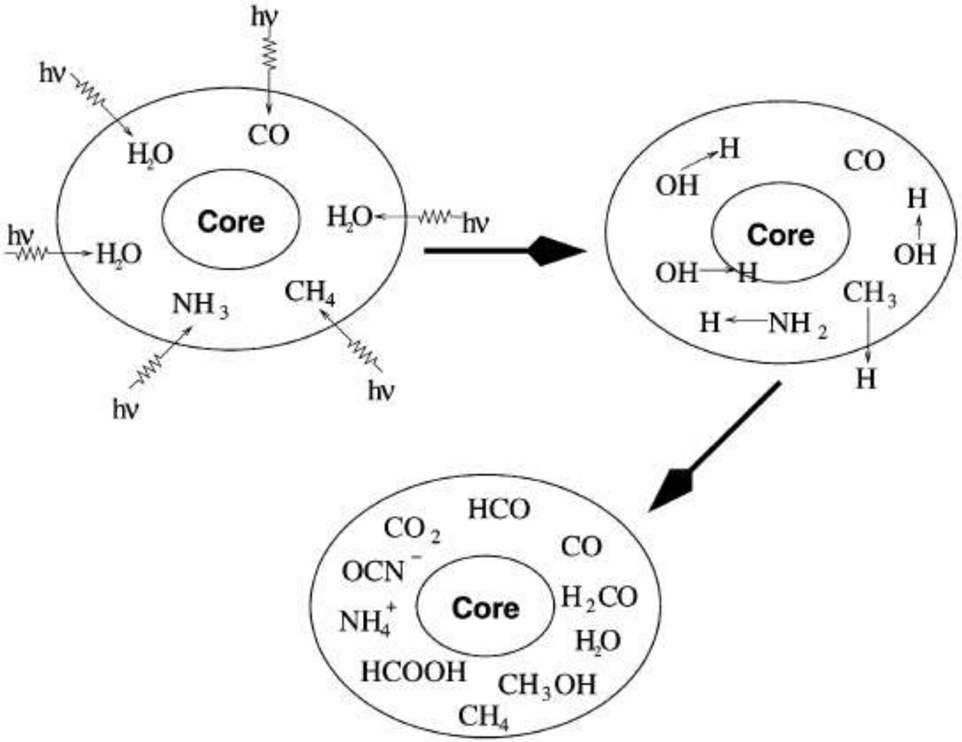
D.A. Williams, E. Herbst / Surface Science 500 (2002) 823–837



Generic Ice Experiments

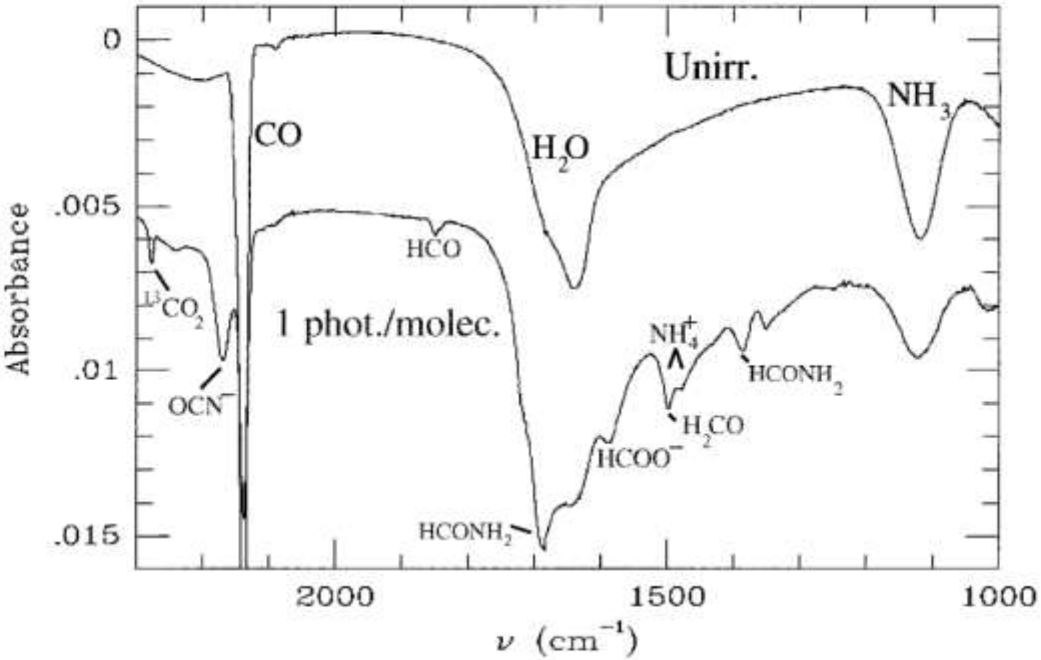


Processing of ice by radiation

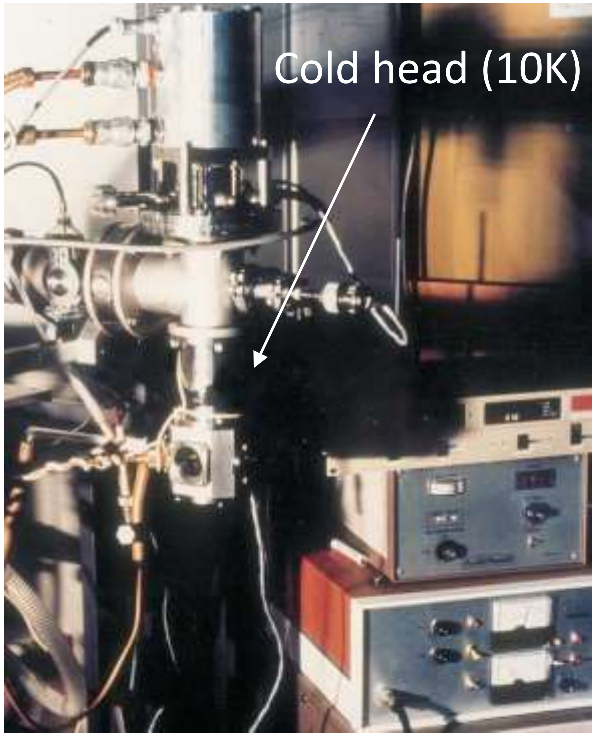


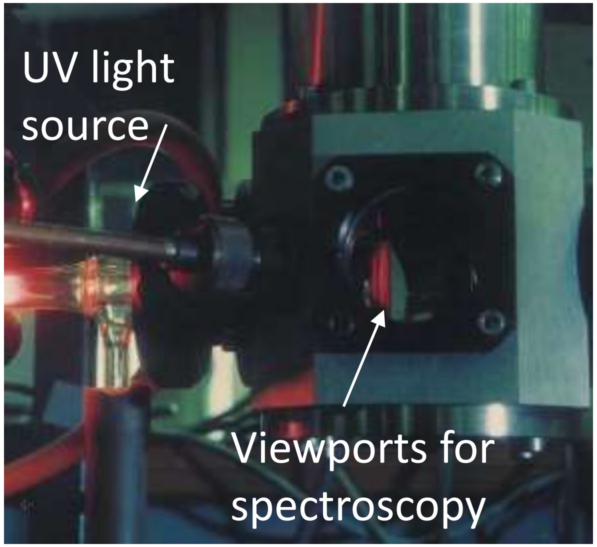
J.M. Greenberg, Surface Science 500, 793 (2002)

Ice processing experiment



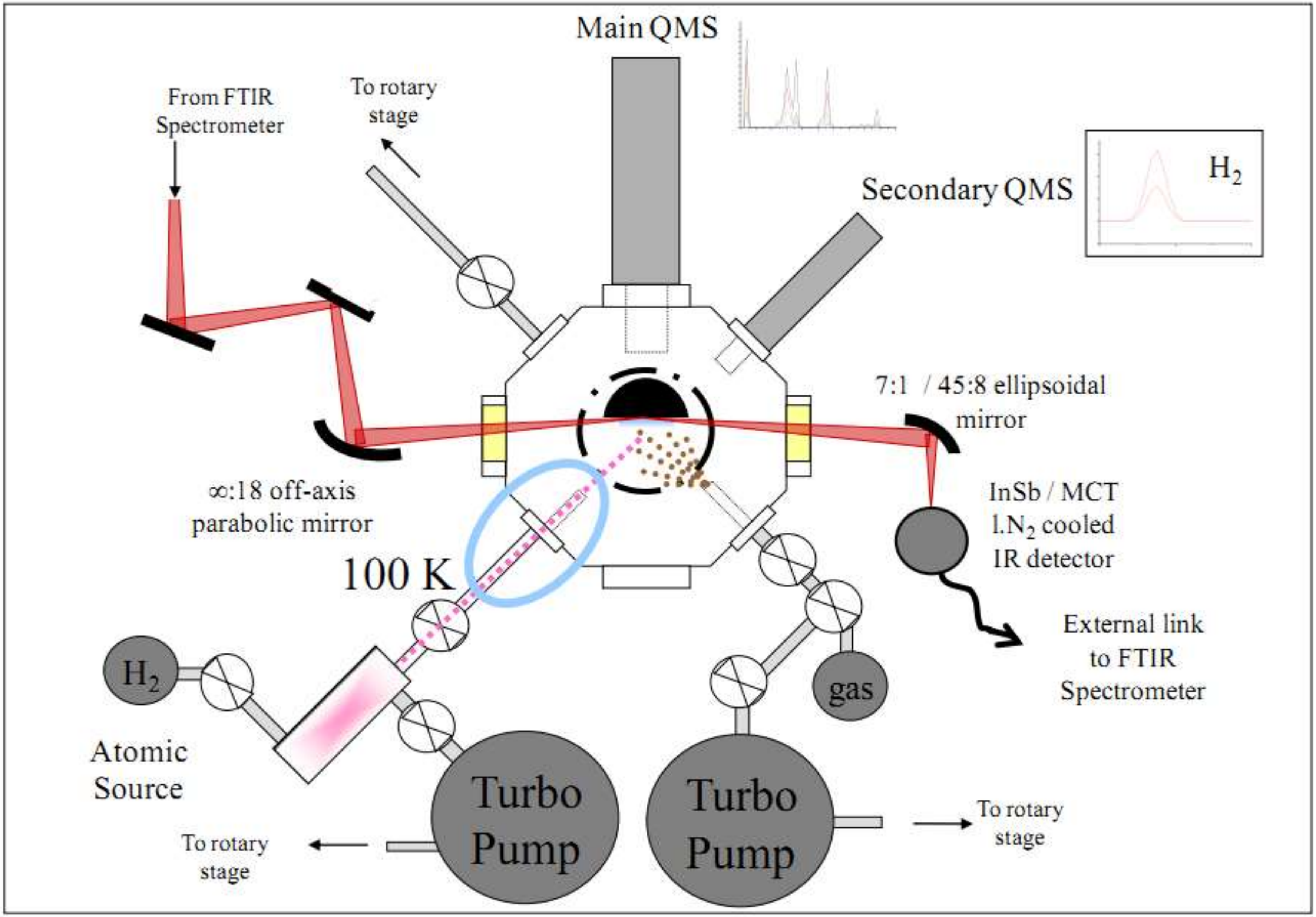
J.M. Greenberg, Surface Science 500, 793 (2002)


Cold head (10K)


UV light source

Viewports for spectroscopy

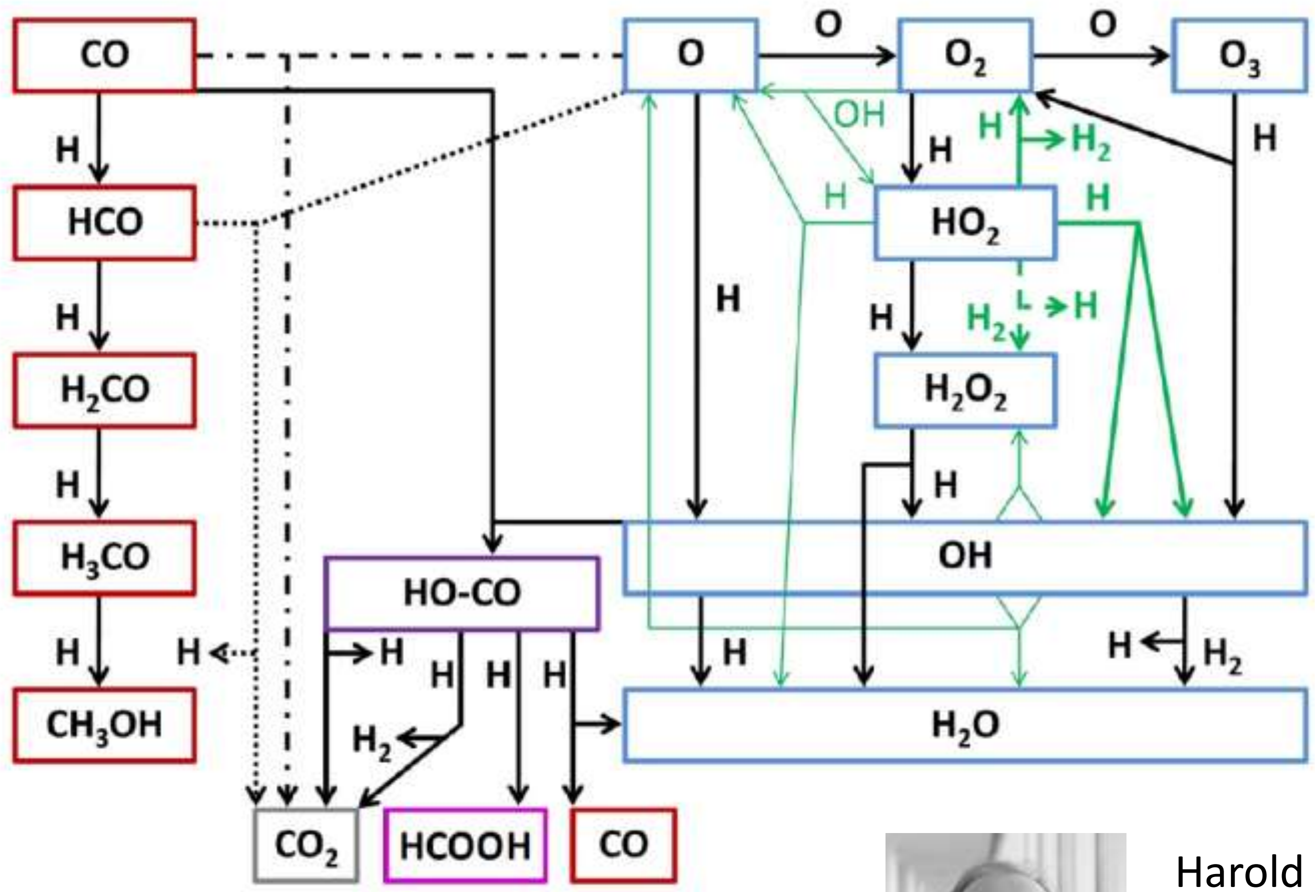
Sackler Laboratory: Leiden



E. Van Dishoeck / Lecture notes

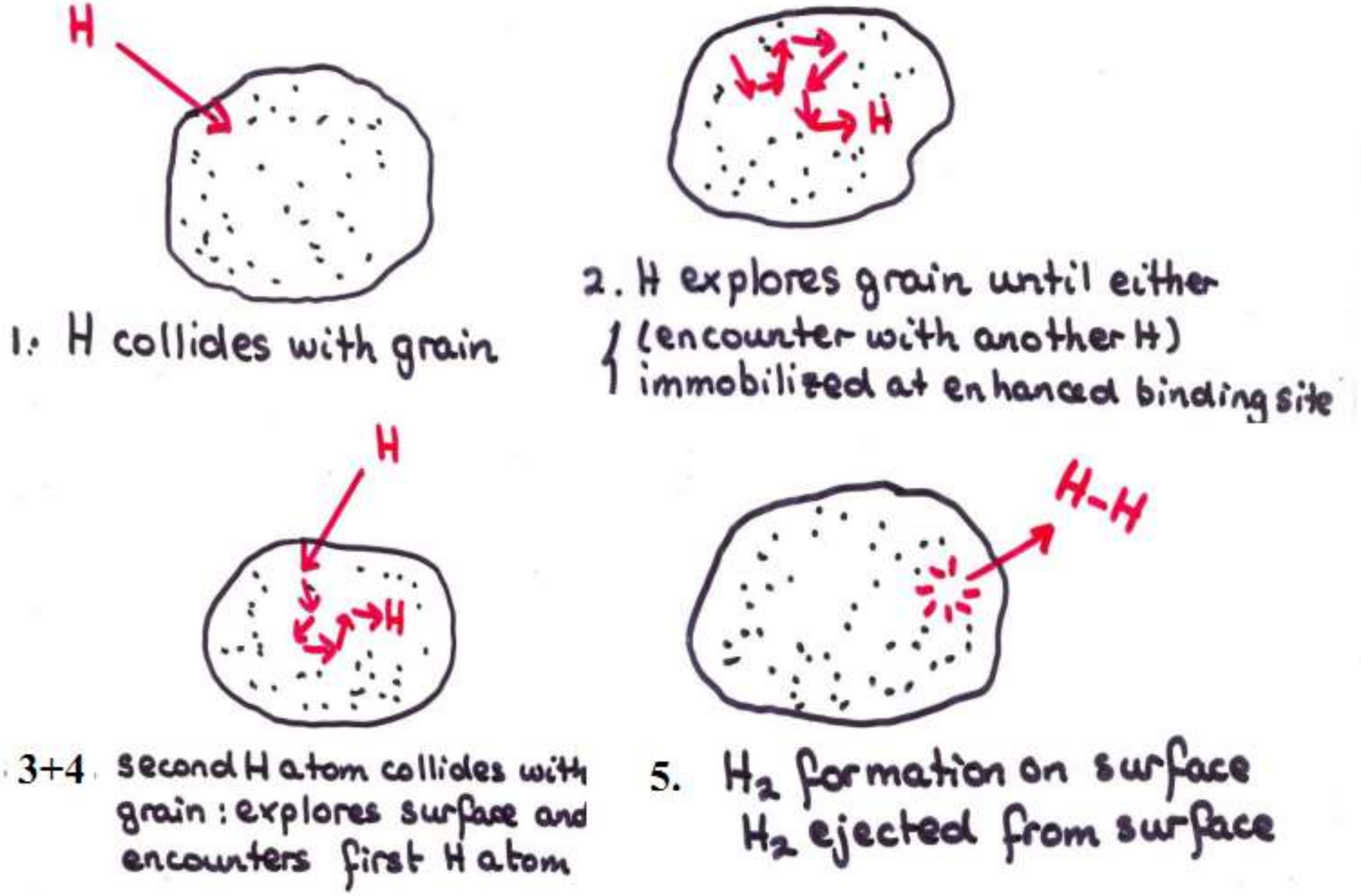
Atom Addition Reactions in interstellar Ice Analogues

Harold Linnartz, Intern. Rev. Phys. Chem. 34, 205-237 (2015)



Harold Linnartz
Leiden University

H_2 formation on grains



1. H collides with grain

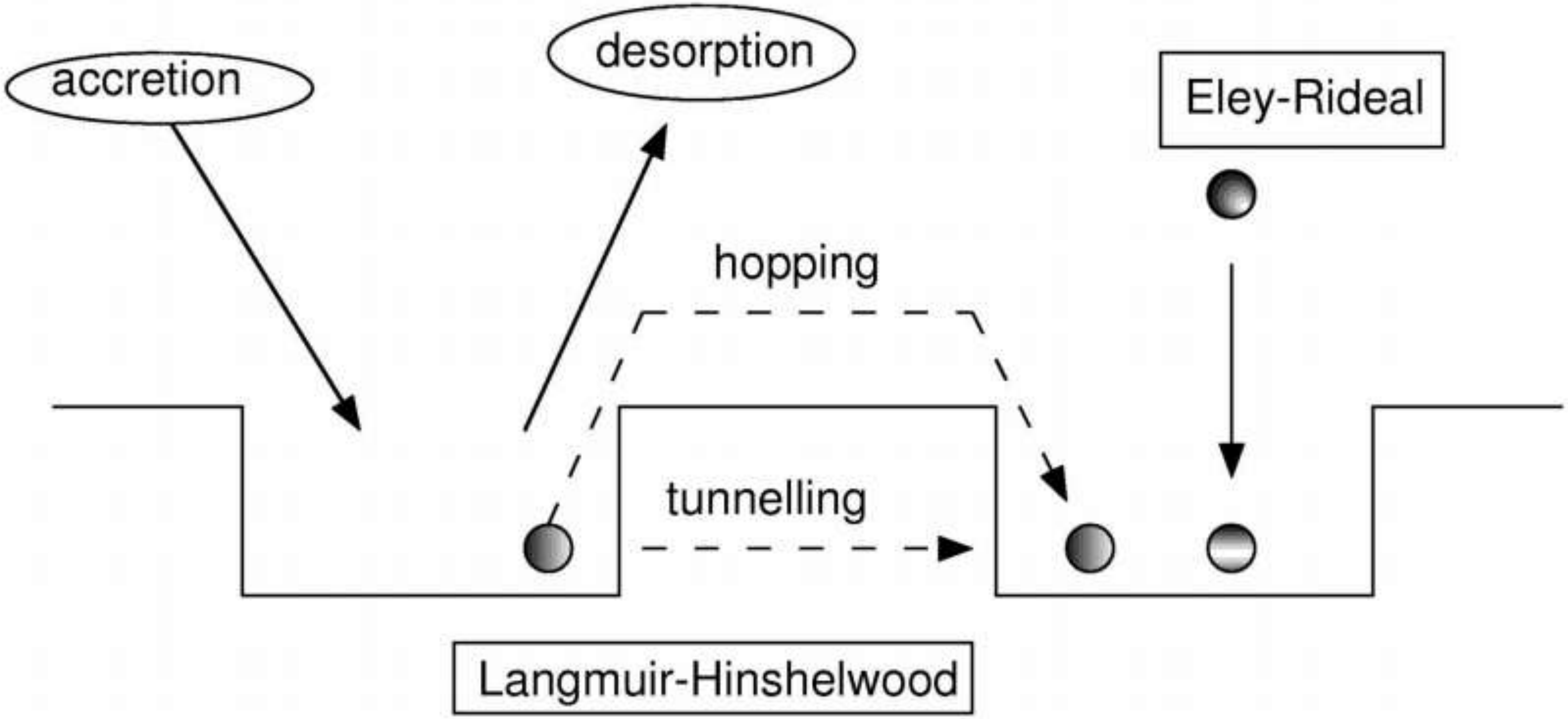
2. H explores grain until either
{ (encounter with another H)
immobilized at enhanced binding site

3+4 second H atom collides with grain: explores surface and encounters first H atom

5. H_2 formation on surface
H_2 ejected from surface

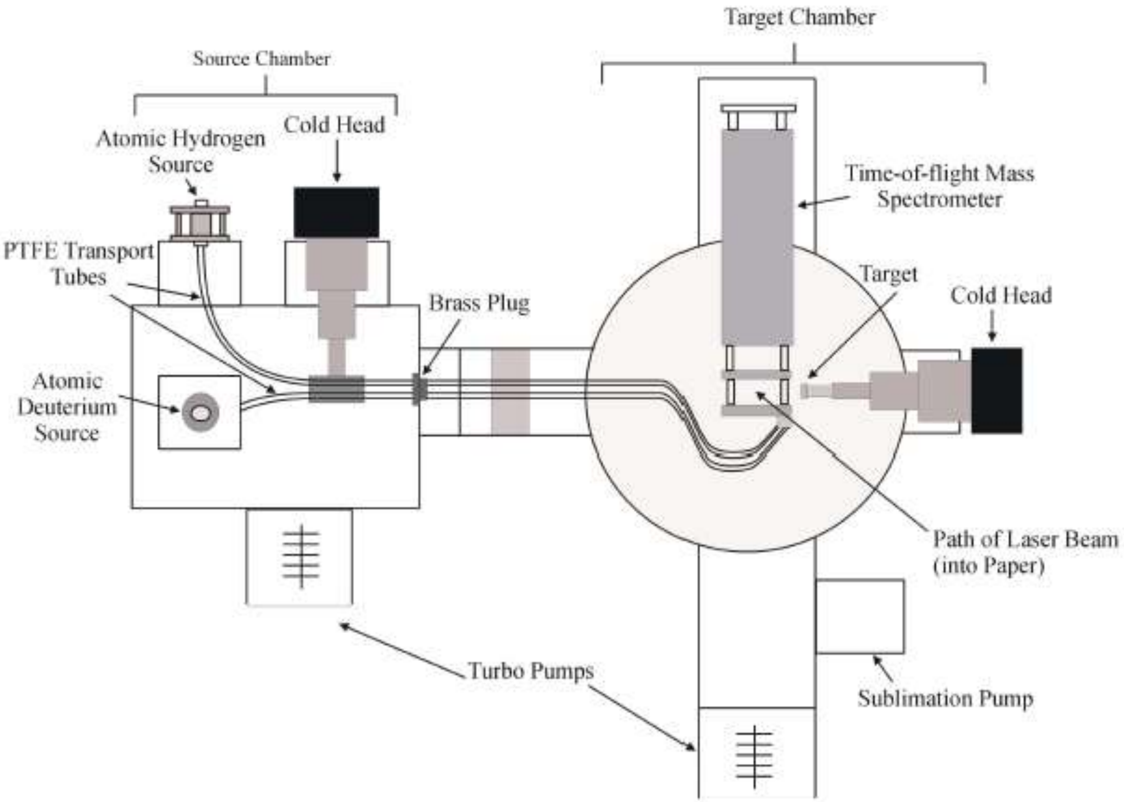
E. Van Dishoeck / Lecture notes

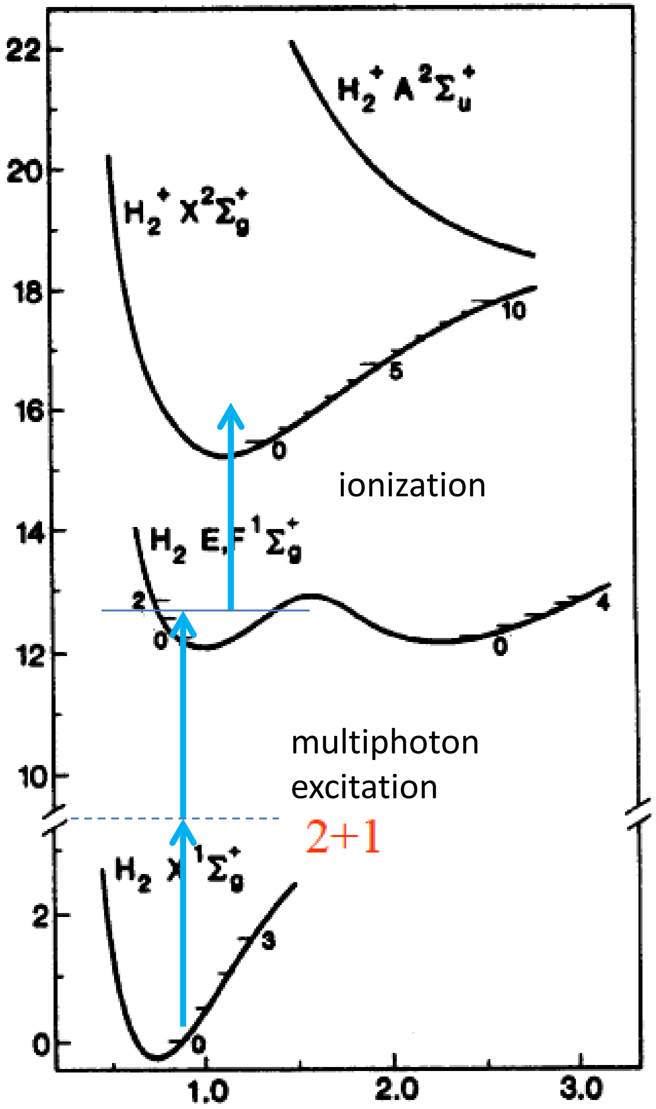
Gas grain processes: diffuse and direct



E. Van Dishoeck / Lecture notes

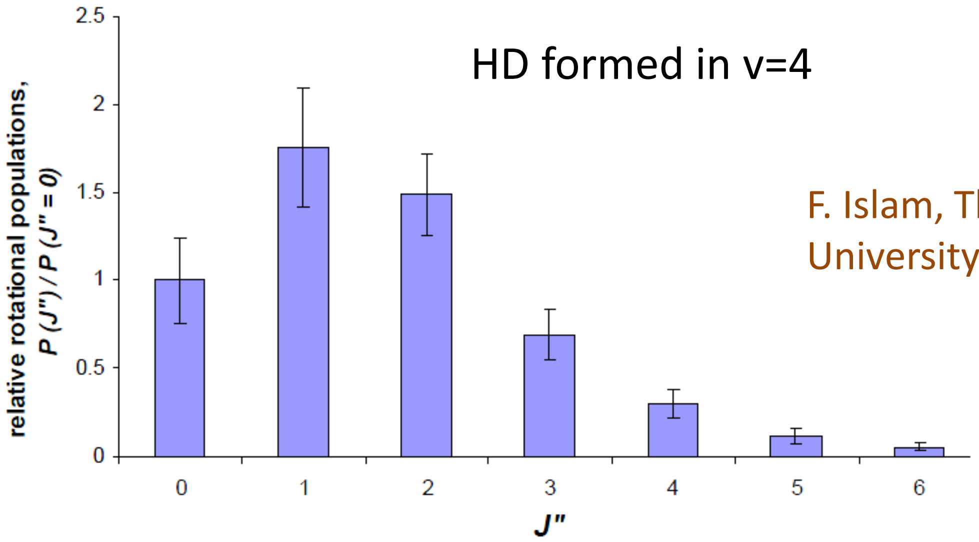
Ro-vibrational excitation in HD formation detected by Resonantly Enhanced Multiphoton Ionization (REMPI)





F. Islam, Thesis 2009 University College London

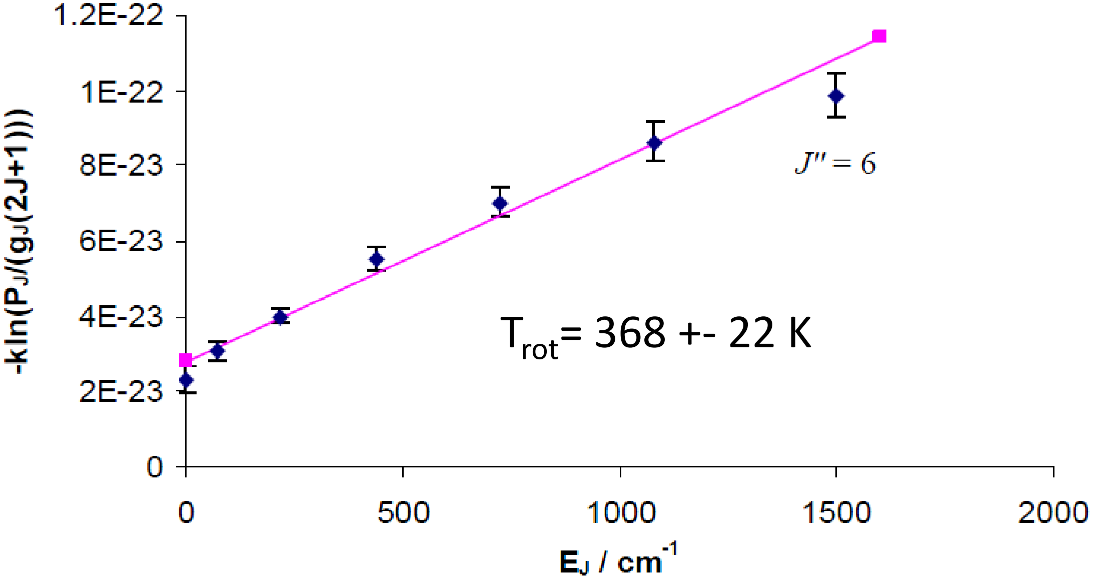
HD Formation and Ro-vibrational excitation



HD formed in v=4

F. Islam, Thesis 2009
University College London

Energy released in the formation may contribute to the non-thermal H_2 distribution observed in diffuse clouds



T_{rot}= 368 +- 22 K

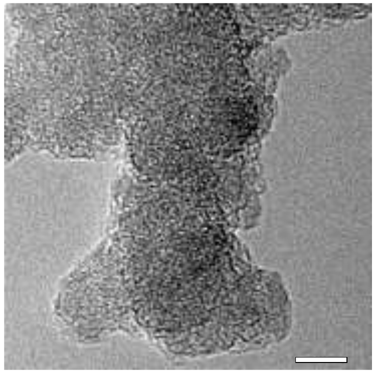
Outline: Challenges for Laboratory Astrophysics

1. Can we collect cosmic dust (since it seems to rain down on us)?
   Yes! But to identify interstellar dust is very hard (7 particles so far).

2. Can we simulate dust formation in the laboratory?
   Yes! One can condensate carbonaceous as well as silicate particles.
   But there is a lot of potential for complexity.

3. Can we understand it´s optical properties to make use of astron. data?
   Yes! But it‘s a lot of work, the phase space is huge! There is a lot
   that remains to be done.

4. Can we test the formation of molecules (chemistry) on dust grains?
   Yes! And a very rich chemistry is found.



Literature

J. M. Greenberg: “Cosmic dust and our origins”
Surface Science 500, 793-822 (2002)

B.T. Draine: “Interstellar Dust Grains”
Annu. Rev. Astron. Astrophys. 2003. 41:241-89

D.A. Williams
E. Herbst
“It’s a dusty Universe: surface science in space”
Surface Science 500, 823-837 (2002)