Stellar Mass loss and Cosmic Dust

SE 280460

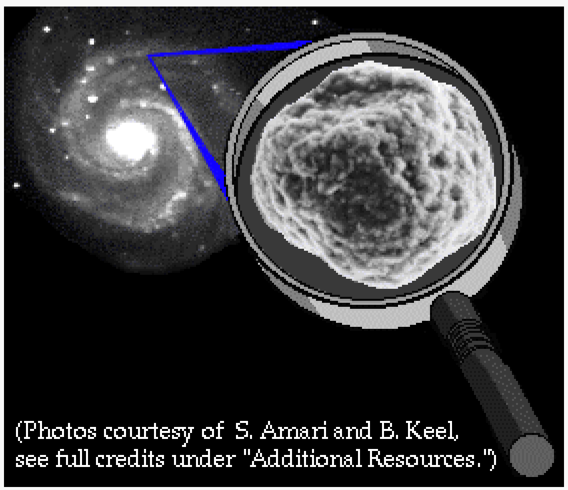
Unit 1: 5th October 2010

I. ***A short history*** *of the discovery and investigation of cosmic dust*

II. *Dust in the* ***cosmic cycle of matter***

III. ***Effects and evidences*** *of cosmic dust*

IV. ***Contents*** *of the seminar and recommended* ***literature***



Scale bar is 1 μm. (Photo courtesy of S. Amari.)

Picture credits: S. Amari – J. Alves, ESO, E. Tolstoy , R. Fosbury (ST-ECF), R. Hook (ST-ECF), VLT

Content of this seminar:

Cosmic dust in a broad sense, but focusing on circumstellar dust around AGB stars

17th century	interplanetary dust
≈1930	interstellar dust
1960s	circumstellar dust
1980s	relation of different dust populations, evolution within the cosmic cycle of matter

What follows is a loose compilation of historical data (in somewhat chronological order) which appear interesting in the context of "*Stellar Mass Loss & Cosmic Dust*"

We make no claim to be complete – but rather an appetizer for the upcoming semester

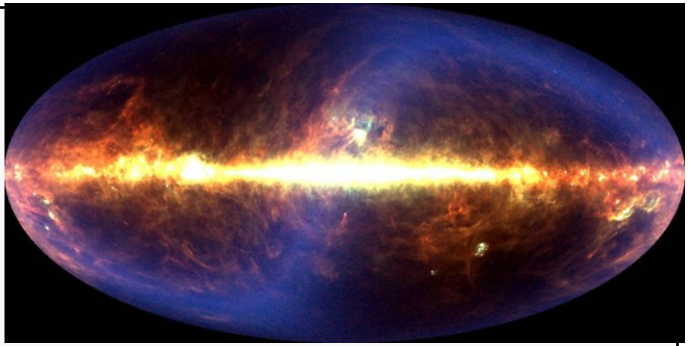
Further reading *(detailed references – see Sect. IV):*

Dorschner, 2003, in "Astromineralogy", Springer, ch.1

Habing & Olofsson, 2004, in "Asymptotic Giant Branch stars", Springer, ch.1

Fechtig et al., 2001, in "Interplanetary Dust", Springer, ch.1

Interplanetary dust particles – Zodiacal light



Picture credit: COBE

Observable (naked eye) along the ecliptic plane

Brighter than the Milky Way in its brightest parts
→ ancient Egypt representations, documented sightings by Aztecs
Named „Wings of aurora“ in the Bible

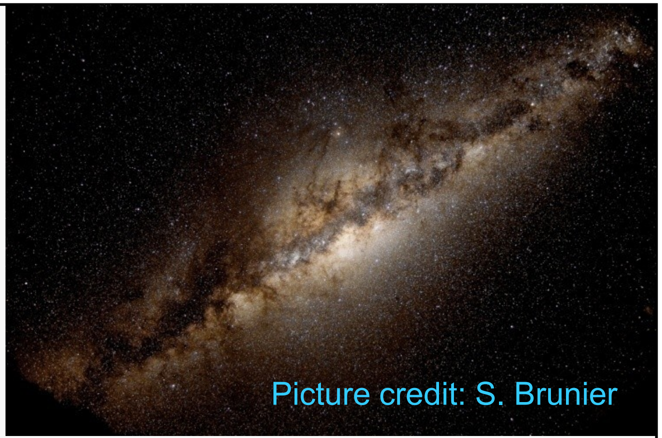
1683: first scientific discussion by Giovanni Domenico Cassini

Correct interpretation as reflected sunlight from dust particles circling the sun by his disciple Nicola Fatio de Duilliers

→Unit 11

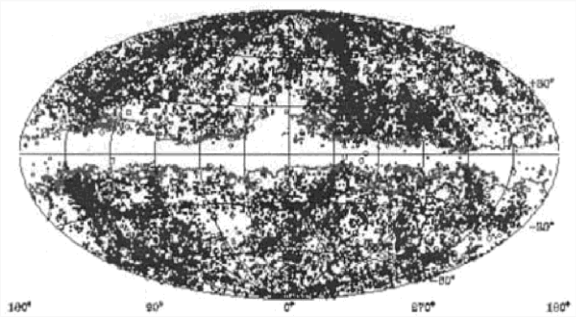
Picture credit: R. Dobesberger

Interstellar extinction:



1785: William Herschel notes existence of dark regions
along the galactic plane of the Milky Way
interpretation = starvoids, i.e. no stars exist in this direction
dominated till the end of 19th century

1878: R. Proctor "zone of avoidance"
(missing deep sky objects towards galactic equator)



1889: E.E. Barnard (pioneer in photographic techniques applied to astronomy) identifies and describes
"dark clouds without any visible star"

→Unit 10

beginning of 20th century: "holes in the sky" → "obscuring clouds" (A. Clerke 1903, M. Wolf 1904)

Pannekoek (1920): obscuration due to Rayleigh scattering by gas rejected as not efficient enough

Interstellar extinction:

Trümpler (1930):

extensive photographic studies of open clusters

☺ are at low gal. latitudes where dust is, covering all longitudes, allow accurate distance determinations

distances derived from main-sequence fitting >< geometrical distances derived from angular diameters

(assumed: linear diameter = const. for all clusters)

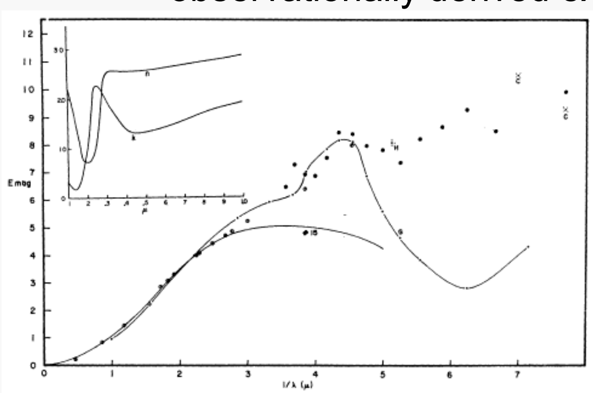
proved a general (i.e. not only for dark clouds) interstellar extinction law with A_V = 0.67 mag. / kpc

stars with given spectral type show increasing colours → extinction = f (λ)

1930+: it became clear that extinction of starlight because of interstellar dust grains is most plausible explanation

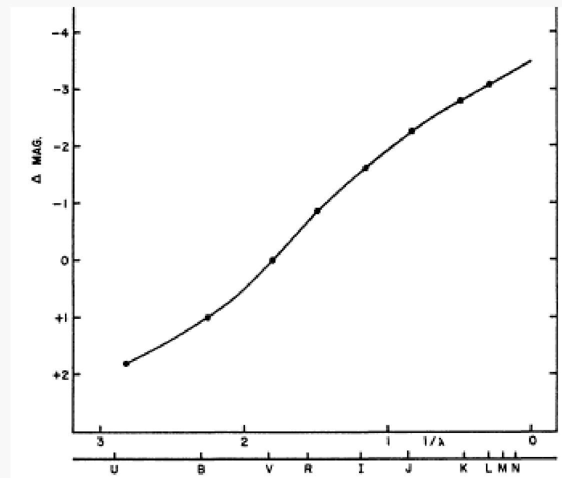
→Unit 10

1950-70s: intensive efforts in modeling interstellar dust to explain observationally derived extinction curves



Boggess & Borgman (1964),
Stecher & Donn (1965):
UV rocket measurements

Johnson (1965):
UBVRIJKLMN photometry



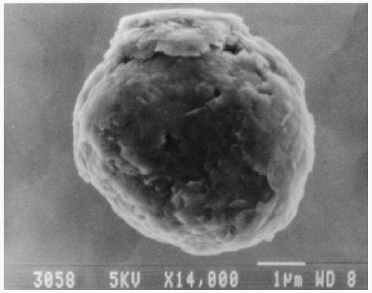
≈1960+: Research on interstellar dust & circumstellar dust (stellar winds) interleaved
trial-and-error (e.g. occurring dust species)
Advent of UV-/IR-spectroscopy → enabled detection of characteristic features of grain materials

Deutsch (1956): observed binary system α Her with common circumstellar envelope, circumstellar absorption lines of red giant (MI) also seen in spectra of companion → important evidence for mass loss
estimated expansion velocity, MLR
Reimers (1975): same for several systems (Reimers law)

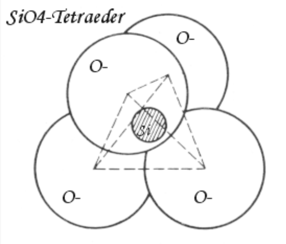
Auer & Woolf (1965): Hyades cluster with several white dwarfs (< 1.4$M_\odot$) but MS stars with M > 2$M_\odot$
→ indirect evidence for mass loss

Individual species investigated: (a) to explain extinction curve if constitute interstellar grains
(b) whether it is able to form in outer layers of stars

e.g. graphite grains suggested to constitute ISM dust by models of Hoyle & Wickramasinghe (1962)
extinction bump at 217nm attributed (e.g. Stecher & Donn 1965)
suggested as catalyst for stellar wind for 1st time (Wickramasinghe 1966)
[→ ≈*DMAs*]



Picture credit: S. Amari



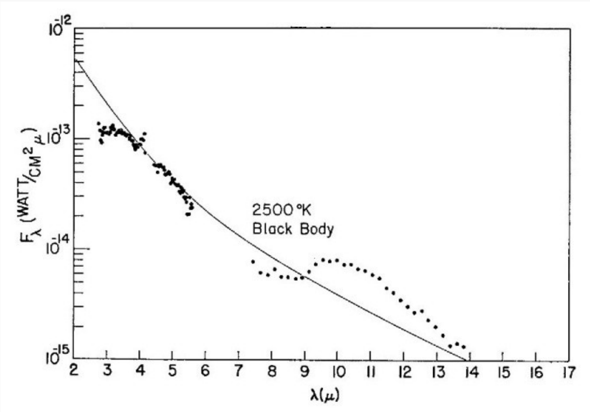
Silicates – the most important dust species:

Kamijo (1963): first appearance of silicate grains in models, suggested to condense in the extended envelopes of M-type LPVs
(expelled particles should serve as condensation seeds for "dirty ice grains" → later discarded)

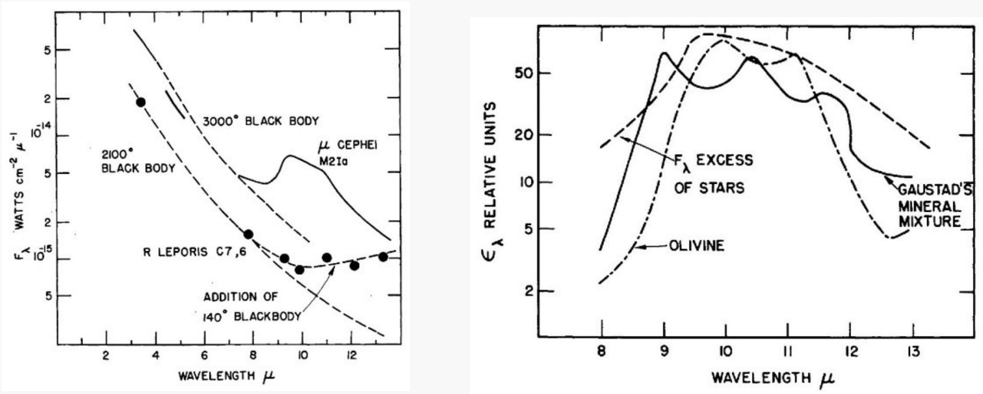
Knacke (1968): calculated extinction cross-sections for silicate grains → could explain the observed curve for interstellar extinction of Borggess & Borgman (1964) reasonably
also noted that silicates should produce strong spectral features at ≈10μm

→Units 6-8

Gillet et al. (1968), Woolf & Ney (1969): first observational evidence in spectra of M-type giants
Low & Swamy (1970): detection of the second feature at ≈18μm → confirms silicate identification



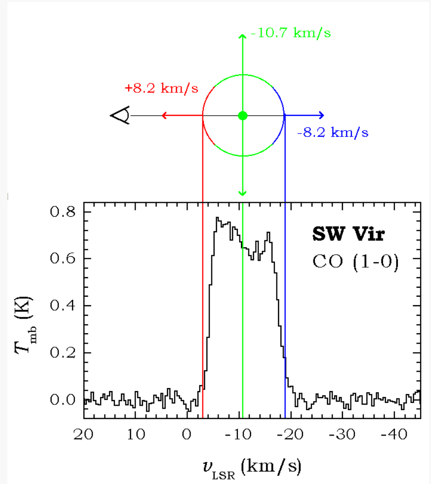
Picture credit: Gillet et al. (o Cet)



Picture credit: Woolf & Ney

Molecular emission lines:

- first detection of circumstellar maser lines (OH, 1612MHz=18cm) towards red supergiant NML Cyg (Wilson & Barrett 1968), line profiles interpreted with wind models → proof for mass loss
- later also H_2O/SiO maser lines for AGB stars,
- CO "normal" emission lines (2.6mm) for CW Leo (Solomon et al. 1971)



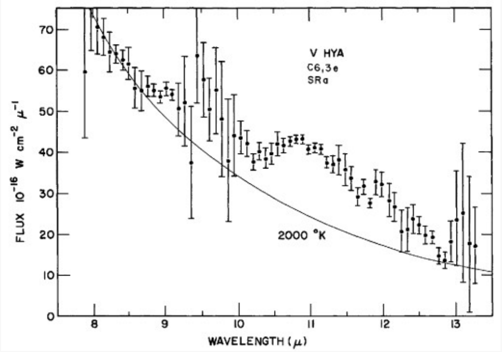
Picture credit: F .Kerschbaum

Neugebauer & Leighton (1969):

Two-micron sky survey, catalog with thousands of IR-bright objects, some without a counterpart in the visual (e.g. IRC+10216) → optically thick dust envelopes

SiC emission in C star spectra (→ atmospheric chemistry relevant also for occurring dust species):

proposed to exist based on model calculations (Friedemann 1969)
later observationally confirmed with 11.3µm-feature (Hackwell 1972)



Picture credit: Hackwell

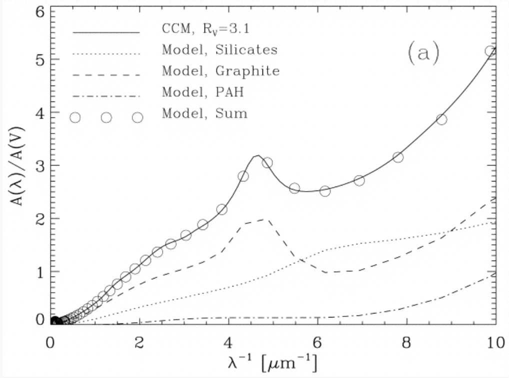
Gehrz & Woolf (1971): first estimations of MLRs for evolved red giants

based on (then newly) available IR photometry
10^{-6} to 10^{-7} $M_{\odot}$/yr (relatively low)

Later also high enough rates MLRs derived which are needed for explaining

pronounced reddening of OH/IR- or IR-carbon stars
(Engels et al. 1983, Baud & Habing 1983)

From 1970 on it was clear that:

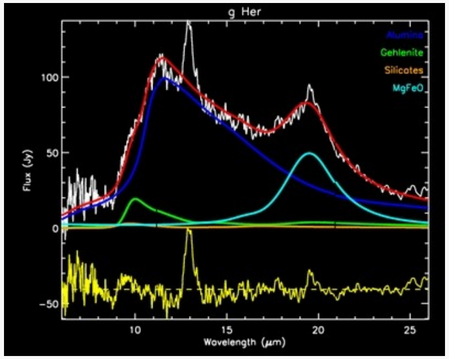


Misselt et al. (2001)

- A multi-component mixture of interstellar dust grains is needed to explain observed interstellar extinction curve (Gilra 1971)
- "*At least part of the interstellar dust is a by product of the phenomenon of stellar evolution*" (Herbig 1970), i.e. produced in ejecta of evolved stars
- Radiation pressure on circumstellar dust grains may provide key to understand AGB mass loss (Wickramasinghe 1966, Gehrz & Woolf 1971)

1970: **Laboratory astrophysics** started
investigation of analogue materials in the lab, enables (reliable) identification of observed spectral features, i.e. cosmic dust species

→Unit 5



Picture credit: J. Cami

≈1980+: Perception of cosmic dust changes,
matter cycling through different dust populations within a galactic system, and evolutionary connections between these
(cf. Dorschner 1992, Dorschner & Henning 1995)

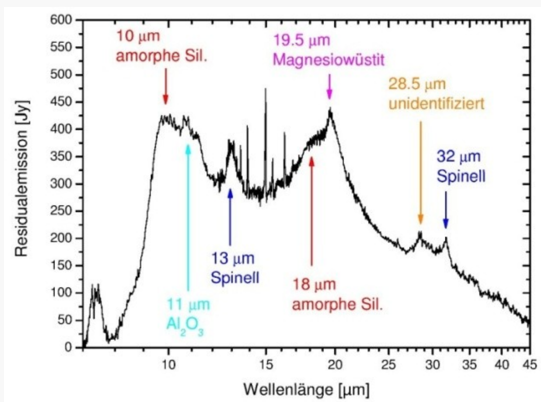
Space observatories:

→Units 6+8

1983 IRAS: survey of full sky,
photometry at 12/25/60/100μm + low-res spectroscopy at 8-22μm
few 10^6 objects detected, incl. many AGB stars
1800 / 300 O-rich objects with silicate dust features in emission / absorption
500 C-rich objects with SiC dust features
→ large observational data basis for AGB research

1996-98 ISO: pointed observations for selected objects
photometry at 2.5-17μm, spectroscopy at 2.4-200μm (R=150-2000)
→ opened a new era in astromineralogy
many new (O-rich) circumstellar dust species discovered

species	formula
amorphous olivine	$Mg_{2x}Fe_{2(1-x)}SiO_4$
crystalline forsterite	Mg_2SiO_4
amorphous pyroxene	$Mg_xFe_{1-x}SiO_3$
crystalline enstatite	$MgSiO_3$
silica	SiO_2
corundum	Al_2O_3
spinel	$MgAl_2O_4$
magnesio-wüstite	$Mg_xFe_{1-x}O$
silicon carbide	SiC
magnesium sulphide	MgS
iron	Fe-Ni-alloy
carbon	C



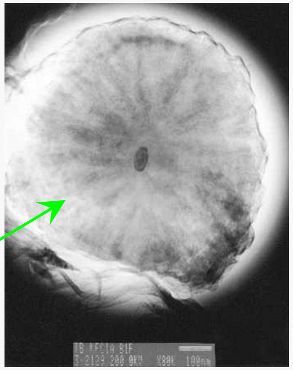
Picture credits: I. Hodous, ESA, H.-P. Gail

Studying cosmic dust "hands-on":

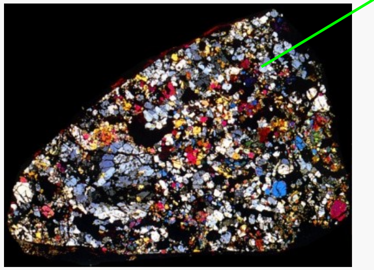
→ Unit 11

1987: for the first time pre-solar grains isolated from primitive meteorites in the lab

dust particles of interstellar origin incorporated into solar system bodies during planetary formation process ("fossil record") can be attributed to AGB winds via isotopic anomalies



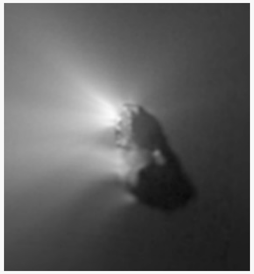
Th. Bernatowicz
graphite + TiC-core / ≈1μm



thin section of meteorite

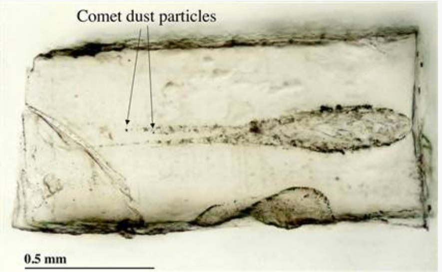
In-situ measurements of dust particles from spacecrafts:

E.g. 1986 ESA mission Giotto to comet Halley
→ images, dust detectors with mass spectrometer
(masses, elemental composition, etc.)



A. Mirecki, ESA

1999-2006 NASA mission Stardust, comet sample-return mission, collected matter during fly through coma of comet 81P/Wild-2 from which forsterite particles could be extracted



NASA

Dust in the cosmic cycle of matter – Synopsis:

→Unit 4

- No direct condensation of dust grains from gas phase of ISM
  dust nucleation (i.e. steps from molecules over macromolecules to tiny solids) needs much higher ρ / P

- Seed particles originating in cooling environments of stellar outflows (red giants) or explosive events (SNe,Novae) during late stages of stellar evolution are essential !

The major contributors are cool winds of AGB stars (SNe remain uncertain)

- Dust grains injected into the surrounding ISM and heavily reprocessed there physically and chemically (e.g. destruction by SN shocks, change of crystallinity)

- Grains become part of cool and dense molecular clouds (=starting points of next generation of stars and planetary systems) where they start to grow via condensation of refractory elements
  → biggest mass fraction of whole interstellar dust is material formed by accretion in molecular cloud, much more abundant than the “original” stardust (at most a few percent)

- Gravitational collapse accompanied by formation of accretion disk, protostellar dust undergoes pronounced reprocessing within protoplanetary disks and is incorporated in newly formed planetary system
  dust particles = starting point for formation of planetesimals/planets
  remaining grains → interplanetary dust component (zodiacal light)

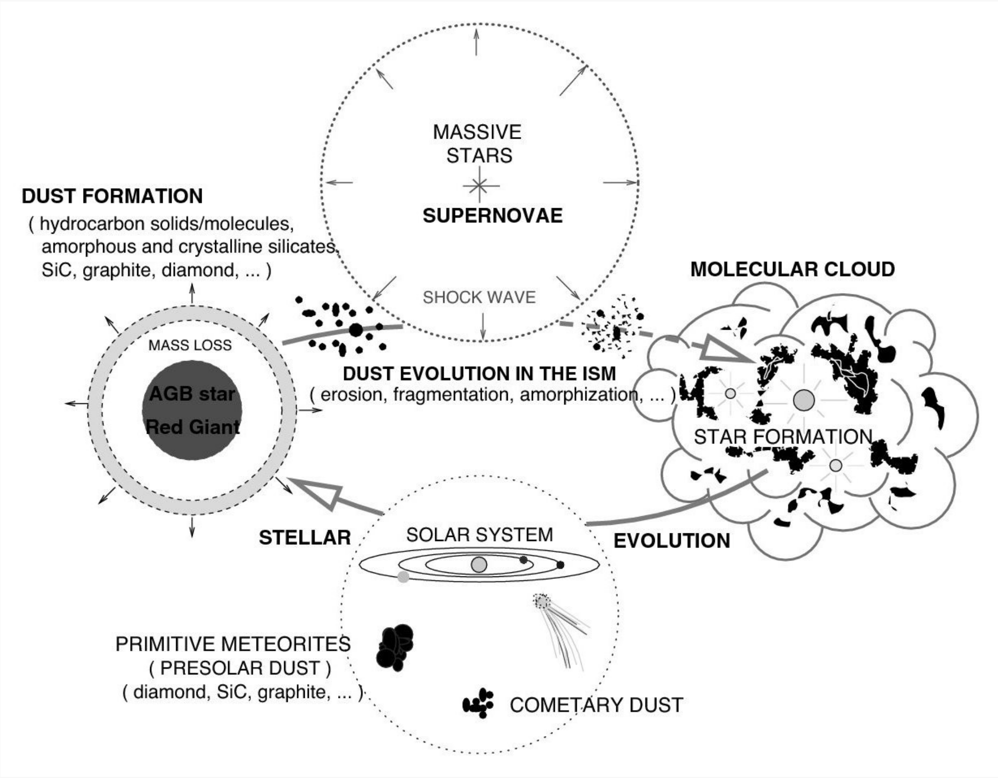
→Unit 9

Dust in the cosmic cycle of matter:

- Matter cycles through the phases of the ISM by star formation and mass return
- Condensed matter (liquids, solids) constitute only 1% of baryonic matter in universe
- Dust grains enable formation of terrestrial planets and life on earth

processing

formation of seed particles

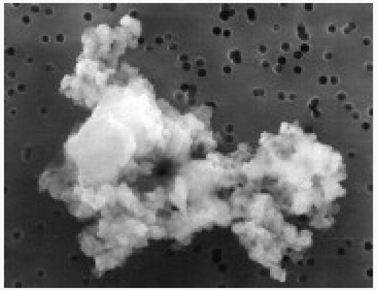


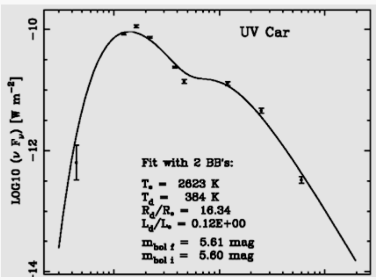
growth

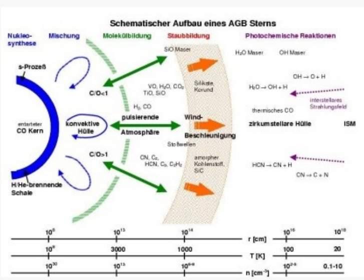
The lifecycly of dust in the ISM
Picture credit: A. Jones (2004)

"Cosmic dust evolved from interstellar nuisance to a necessary agent of formation of terrestrial planets"

Essential functions of cosmic dust







Picture credits:
J. Bradley; F. Kerschbaum;
J. Hron

(1) The formation of condensed matter (dust, ices, …) creates
2-dimensional surfaces
A universe without solids/liquids = a universe without surfaces.
This would mean: No life and much less chemistry than in our universe

(2) Dust grains can efficiently
redistribute energy
due to their lattice structures, due to their internal degrees of freedom
They can „thermalize“ UV and visual radiation, re-emitting it in the IR.
Many structures (e.g. H_2) can only form due to a thermalizing agent.

(3) Dust grains can
take up momentum from radiation fields
and transfer it to the much larger masses of gas in their vicinities
thereby initiating mass loss processes

(4) Dust grains may serve as
catalysts for chemical reactions

Phenomenon / Effect	Interpretation
Zodiacal light	„Large“ (µm-sized) interplanetary dust particles
Extinction and reddening of starlight, $\sim 1/\lambda$	Solid interstellar grains, sizes in the range of λ_{vis}
Polarization of starlight	Asymmetric particles, partially aligned
Reflection nebulae near stars (e.g. NGC 1435)	Scattering by dust grains
Local UV extinction peak near 220nm	(Carbonaceous) interstellar dust
Infrared bands seen in AGB (& other) stars	Circumstellar dust grains: silicates, oxides, carbonaceous dust, ices, …
IR continuum emission of AGB (& other) stars	Re-emission of stellar radiation (from UV and visual ranges)
Depletion of elements in the ISM	Some elements consumed by dust formation
Molecular hydrogen H_2 in the ISM	Dust catalysed reactions
IR absorption by dirty ice	Reactions on dust grain surfaces
IR absorption by solid CO	CO accreted from gas on cold dust
Presolar grains in meteorites	Original stardust surviving solar system formation

Partly according to: T.J. Millar & D.A. Williams, Dust and Chemistry in Astronomy.

Institute of Physics Publishing, Bristol and Philadelphia, 1993. Tab. 1.3, p. 4

The Zodiacal light

- Strongest glow along the ecliptic and close to the Sun
- Colour corresponds to solar spectrum
- Previously thought to be extended solar atmosphere

Physics of the zodiacal light

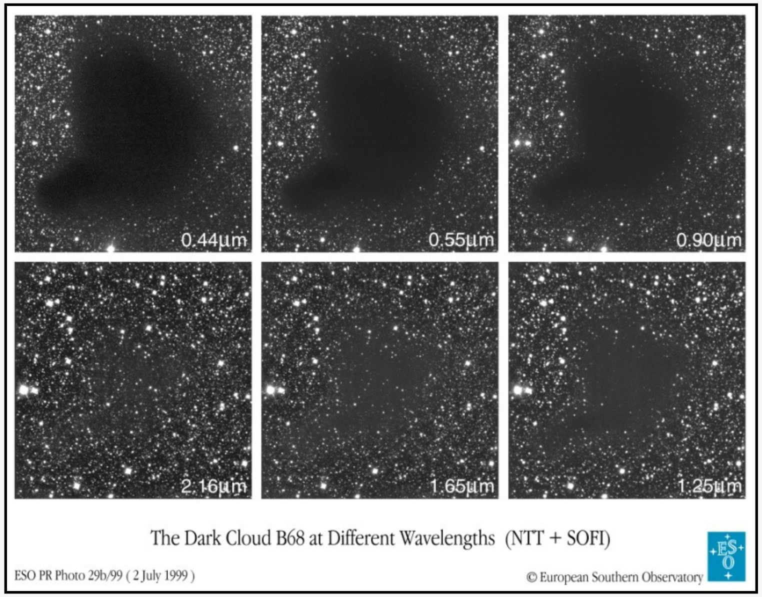
- Scattering of sunlight
- Scattering particles cannot be much smaller than λ_{vis} otherwise its colour would be blue
- Additionally, re-emission of absorbed radiation in the IR
- Silicate particles are dominant species
- Most particles are even much bigger than 1µm

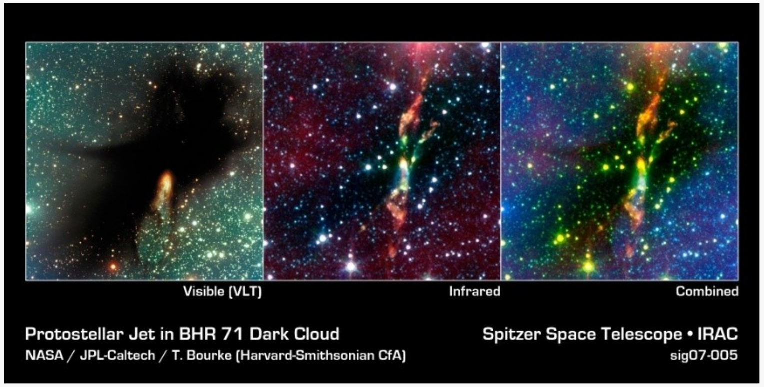
Further reading:

E. Grün et al. (eds.), 2001, Interplanetary Dust. Chapters 1-2

W.T. Reach et al., 1996, A&A 315, L 381, Mid Infrared Spectrum of the zodiacal light

Picture credit: ESO / Yuri Beletsky, 19 Nov. 2009





Picture credits: ESO (Alves et al.) / NASA
(Picture above 7x APOD since May 11, 1999)

Extinction and reddening:

- Causes structured appearance of the Milky Way
- Previously, dark regions thought to be holes in M.W.
- Extremely dense: “Bok globules” (B68, BHR 71)
- More extinction at shorter wavelengths
- Therefore, “reddening”

Physics of extinction:

- Extinction = Absorption + Scattering
- Absorption dominant for particle size a >> λ
- Then: Absorption efficiency $Q_{abs} \sim 1/\lambda$
- Exact description: Mie theory
- Dust absorbs up to 10.000 times more effectively than gas

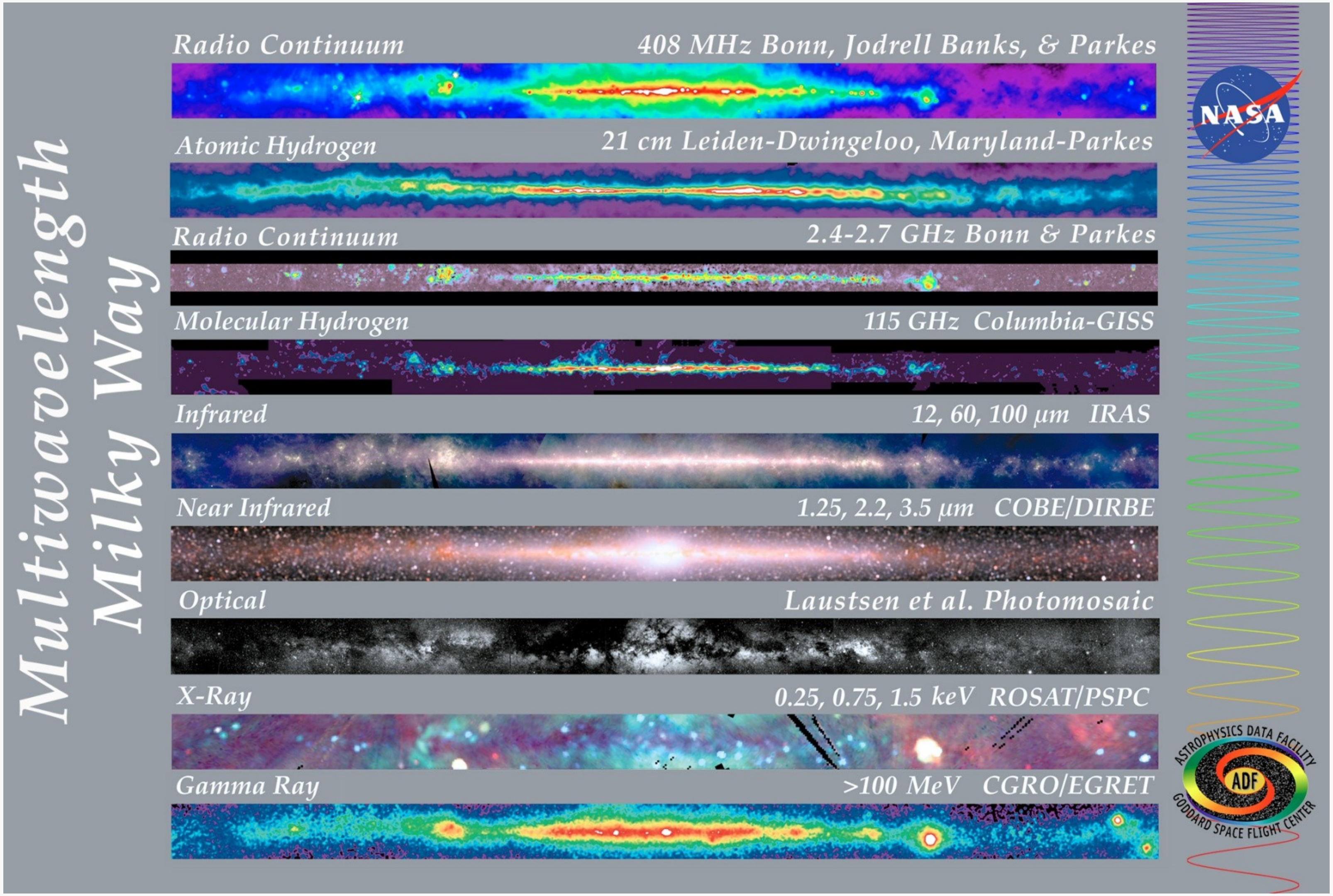
Further reading:

C.F. Bohren & D.R. Huffman, 1983, Absorption and Scattering of Light by Small Particles. Wiley, New York. Esp. Ch. 9-12.

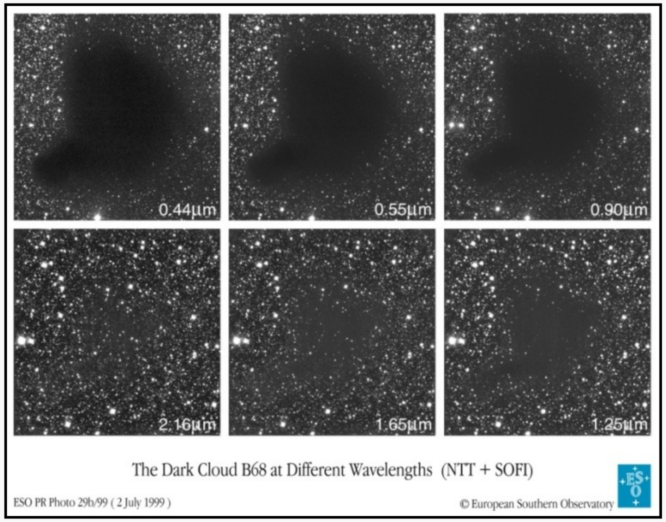
Short video on Barnard 68 available online at:

http://www.eso.org/public/archives/videos/old_video/eso9934a.mpg

Remember: extinction by interstellar dust does not occur at all wavelengths!



Picture credit: NASA Astrophysics Data Facility



The Dark Cloud B68 at Different Wavelengths (NTT + SOFI)


Picture credits: ESO (Alves et al.), NASA

Interstellar extinction - quantitative aspects

- Interstellar extiction: typically **A_V ~ 1 mag./kpc** at λ = 500nm
- Which matter density is needed to account for that?
- In case of electrons (Thomson scattering): 300 / cm³
- In case of atoms/molecules and Rayleigh scattering: 10.000 / cm³
- In case of dust grains: about 1/100 proton masses per cm³
  $\rho \sim 2 \times 10^{-26}$ g /cm³

How much interstellar matter is out there?

Upper limit (called 'Oort limit') of the average matter density near the Sun, derived from gravitational acceleration of stars perpendicular to the galactic plane:

$\rho \sim 4 \times 10^{-24}$ g /cm³ (~2.4 proton masses per cm³)

→ Atoms and molecules cannot account for observed extinction!

→ Dust grains, even if present at the 1% level of the total ISM mass, can easily account for the observed extinction.

This is due to the much higher absorption efficiency of solid grains compared to molecules or atoms.

Reference: K.S. Krishna Swamy, Dust in the Universe, Singapore 2005, p. 63- 71

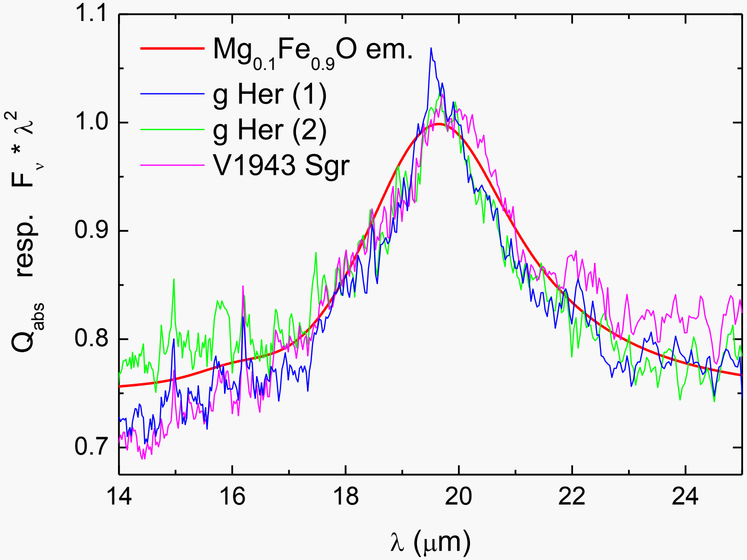
The Phenomenon of "Reflection Nebulae":

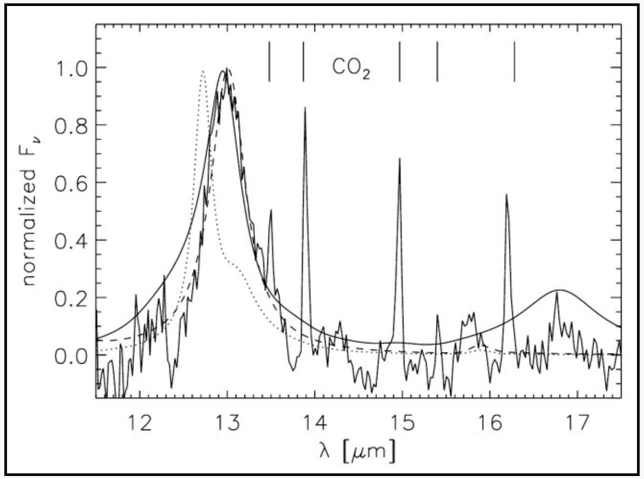
- Some stars (mostly B stars) show bluish diffuse nebulae in their vicinity
- A well-known example is NGC 1435 around 23 Tau (Merope) in M 45 (The Pleiades) – see picture on the top.
- Combinations with dark nebulae may occur, such as in the case of NGC 1999 (picture on the bottom).
- The bluish color is important to differentiate between reflection nebulae which typically show reddish or green glow.

Physics of Reflection nebulae (RN):

- The colourful light from emission nebuale (e.g. Lagoon Nebula) comes from excited atoms of gas
- By contrast, the bluish haze of RN is due to interstellar dust
- *Forward scattering* dominates, as expected for ~ λ sized grains
- Scattering dust is not outflow from star whose light is scattered

Picture credits:
Top: NGC 1435 by Yuugi Kitahara;
Bottom: NGC 1999 by Hubble Heritage Team (STScI) and NASA





IR bands of AGB (&other) stars:

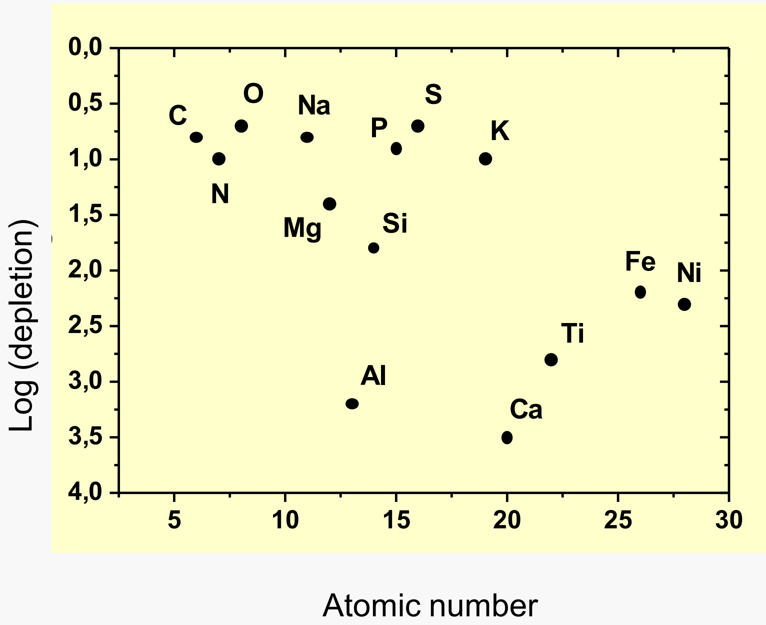
- Detected primarily at λ > 8µm
- Bands much broader than molecular lines
- Features seen in emission and absorption
- Featureless spectra also occur

→ Units 2,6,7

Physics of IR bands:

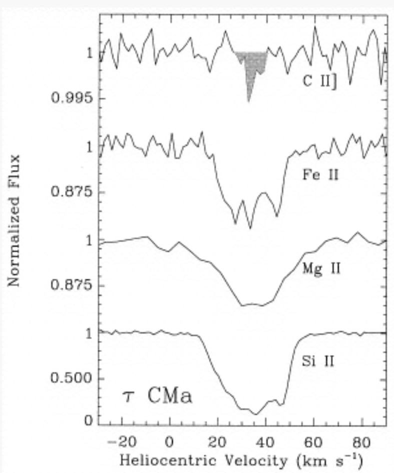
- Vibrations of ions (quantized vibrations = phonons) excited by photons, eg. Si-O or Al-O stretching vibration
- Vibrations of larger lattice parts can also occur
- Dipole moment must be induced to generate strong IR bands
- Requires at least diatomic species (e.g. FeO, but not pure carbon)

Picture sources: Top: Posch et al. 2002, A&393, L7-L10
Bottom: Posch et al. 1999, A&A 352, p. 609-618



Depletion of elements in the ISM:

- Spectroscopy shows: some elements are „missing“ in the ISM (compared to average „cosmic“ elemental abundances)
- Most strongly depleted in interstellar gas:
  Ti (by a factor ~600)
  Al (by a factor ~1600)
  Ca (by a factor ~3200)
- Explanation: Depleted elements are now in solid phase (dust, ice)



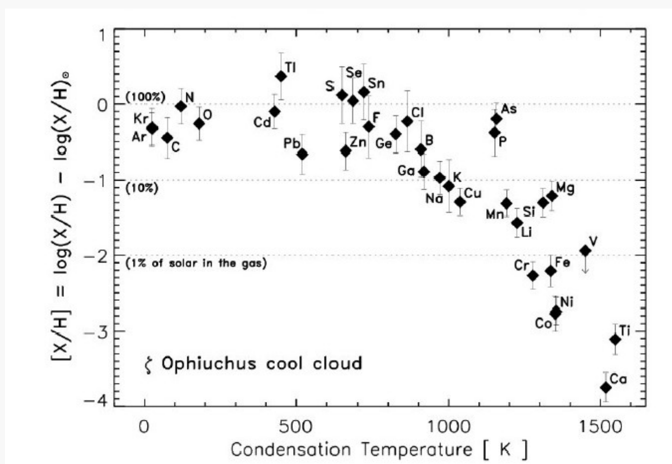
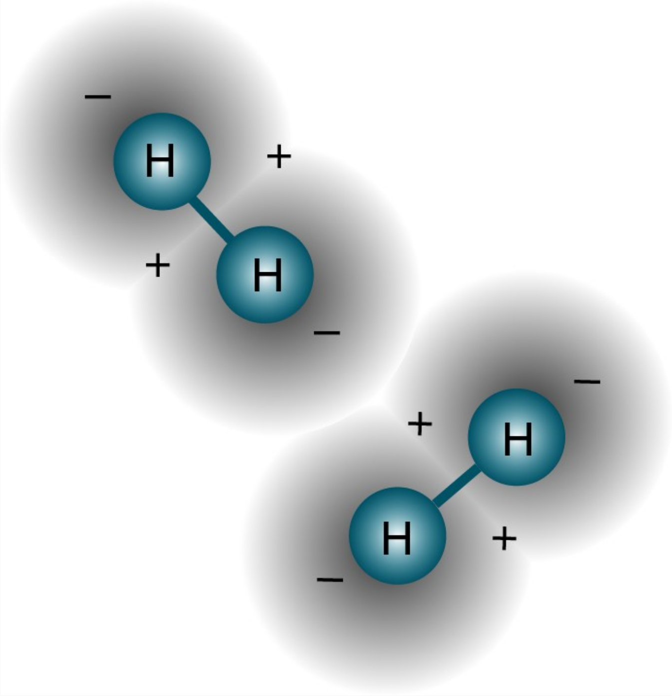


Image credits:
Top: Posch, 2005, Astromineralogy […], Data from Salpeter 1977, ARAA 15, 267
Bottom left: Sofia et al., 1997, ApJ 482, L105
Bottom right: Palme & Jones, 2004, in: Meteorites, Comets and Planets, Treatise on Geochemistry, Vol. 1, ed. A. M. Davis (Amsterdam: Elsevier), p. 4



Picture credit:
Univ. of Zurich, Physics Institute

Text source:

T.J. Millar & D.A. Williams, Dust and Chemistry in Astronomy. Chapter 1.

Molecular Hydrogen (H_2) in the ISM:

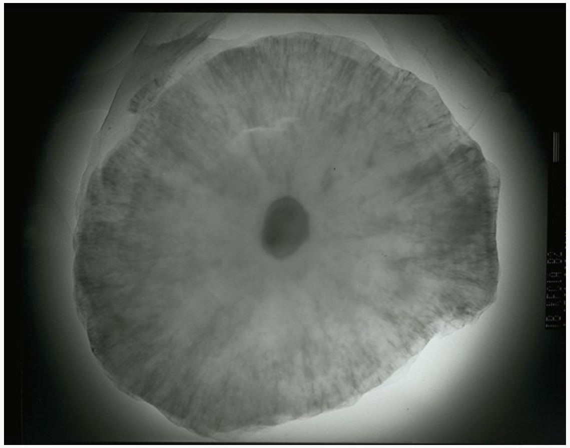
- Has UV absorption lines
- These were found by a rocket-borne experiment in 1970 in ISM spectra
- H_2 has also IR vibrational lines that were found as well
  → Much of the interstellar hydrogen is molecular, esp. in regions of modest extinction by dust („Diffuse interstellar clouds“)

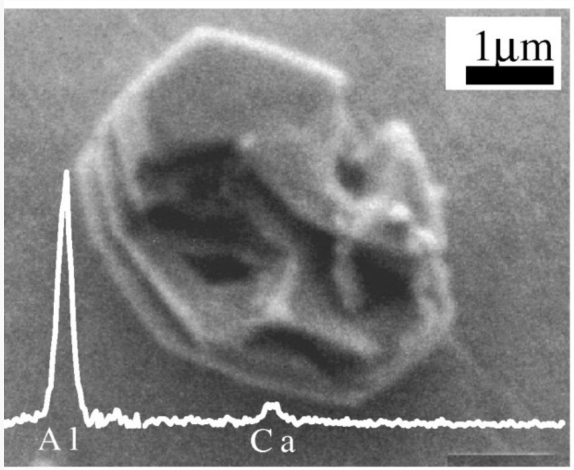
Physics and Chemistry of H_2 in the ISM:

- How can H_2 form in the ISM? Two gas phase routes:

1) $H + e \text{ -----> } H^- + h\nu$
   $H^- + H \text{ -----> } H_2 + e$
2) $H + H^+ \text{ -----> } H_2^+ + h\nu$
   $H_2^+ + H \text{ -----> } H_2 + H^+$

- But: Formation by these gas phase reactions does not work
- Reason: H_2 cannot get rid of its energy radiatively
- Reactions of H‘s on solid surfaces required
- Dust needed as catalyst for H_2 formation





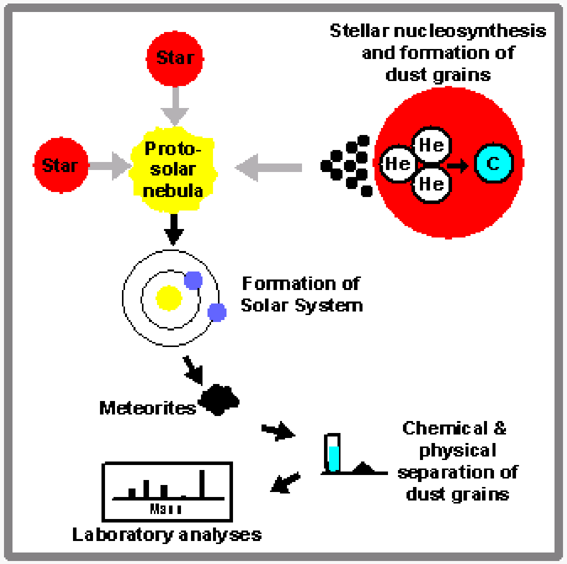
Picture credits:
Top: E. Zinner, Washington Univ. / St. Louis
Bottom: Choi, Wasserburg & Huss, ApJ 522, L133-L136

Presolar Grains (PSGs):

-Tiny (sub-µm sized) inclusions esp. in carbonaceous chondrites
- Sometimes individual crystals (e.g. hibonite below)
- Highly refractory minerals, e.g. SiC, corundum, spinel, diamond…
- Extraction and identification = highly sophisticated process

Physics of PSGs:

- Most primitive, unprocessed material in meteorites. Age > 4.6 Ga
- Isotope abundances strongly deviating from solar system values
- Explained by nucleosynthesis mainly in AGB stars & Supernovae



Further reading:

Th. Henning (ed.), 2003, Astromineralogy, Ch. 7 (by U. Ott)
H.Y. McSween & G.R. Huss, 2010, Cosmochemistry, Ch. 5

Picture credit:
P. Hoppe, MPI f. Chemistry, Mainz

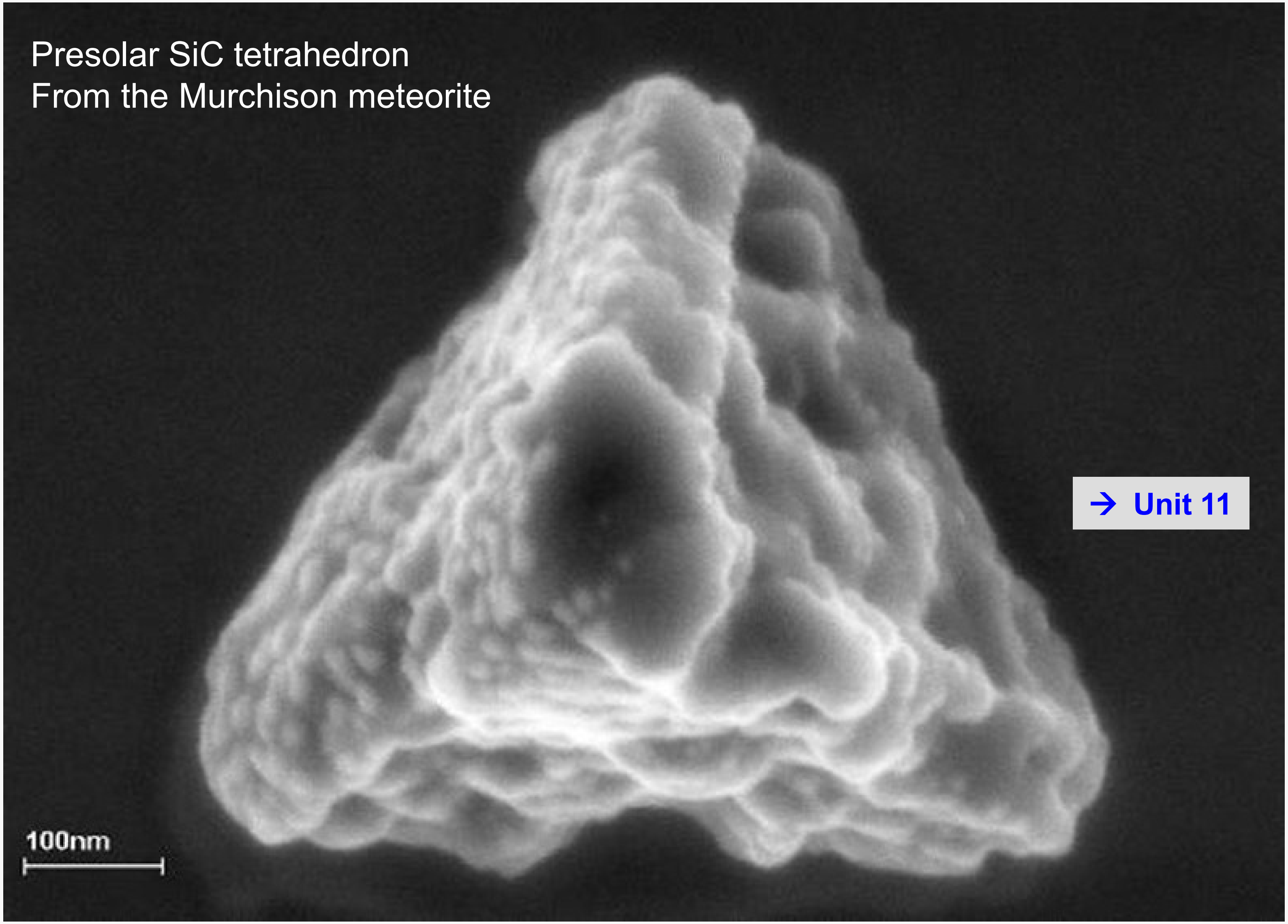


Photo credit :P. Hoppe, Max-Planck-Institute for Chemistry, Mainz
See ASP Conf. Ser., vol. 414 (2009), p. 148-156

Schedule and topics of the seminar sessions:

Unit	*Date*	*Topic*
(U1)	05.10.2010	Introduction
(U2)	12.10.2010	Empirical evidences for cosmic dust
(U3)	09.11.2010	Radiation from cosmic dust
(U4)	16.11.2010	Dust formation and processing: How and Where
(U5)	23.11.2010	Studying dust analogs in the laboratory
(U6)	30.11.2010	Dust in stellar outflows
(U7)	07.12.2010	Dust around AGB stars (1)
(U8)	14.12.2010	Dust around AGB stars (2)
(U9)	11.01.2011	Dust in protoplanetary disks
(U10)	18.01.2011	Dust in the Interstellar Medium
(U11)	25.01.2011	Dust in the solar system

Recommended literature:

Books (all available in the Astronomy library):

- D. Apai & D.S. Lauretta (Hg.), Protoplanetary Dust. Astrochemical and cosmochemical perspectives. Cambridge University Press, 2010.
- C.F. Bohren & D.R. Huffman, Absorption and Scattering of Light by Small Particles. New York 1983.
- E. Grün et al. (eds.), Interplanetary Dust. Springer-Verlag Berlin Heidelberg New York 2001. esp. Chap.1: „Historical Perspectives“; Last Chapter: „Interstellar Dust and Circumstellar Dust Disks“
- Th. Henning (ed.), Astromineralogy. Springer Verlag, Berlin Heidelberg 2003.
-Th. Henning, E. Grün & J. Steinacker (eds.): Cosmic Dust – Near and Far. ASP Conf. Ser. vol. 414 (2009)
- H.Y. McSween & G.R. Huss, Cosmochemistry. Cambridge University Press, 2010. esp. Chapter 5, „Presolar grains“ (p. 120-156)
- T.J. Millar &D.A. Williams, Dust and Chemistry in Astronomy. Bristol and Philadelphia, 1993. esp. Ch. 1, „Dust and Astrochemistry: an Introduction” (p. 1-8)
- K.S. Krishna Swamy, Dust in the Universe. World Scientific, Singapore 2005.

Review-Artikel:

- Th. Henning: Cosmic Silicates. Annual Review of Astronomy and Astrophysics, vol. 48 (2010), p. 21-46
- J. Dorschner & Th. Henning, Dust metamorphosis in the galaxy. The Astronomy & Astrophysics Review, vol. 6 (1995), p. 271-333