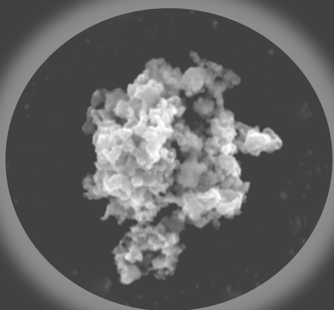
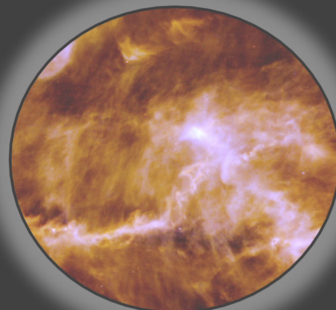
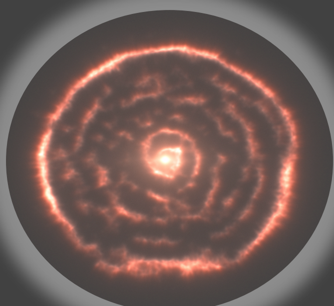
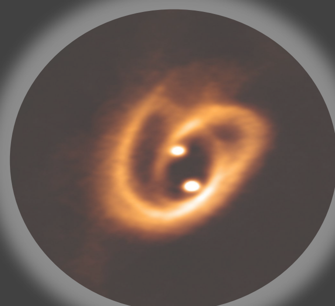
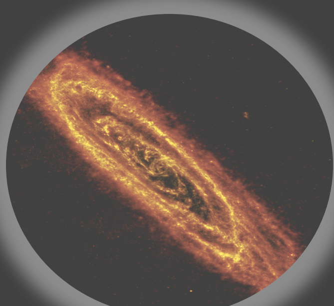
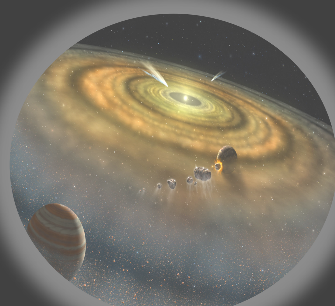
Life Cycle of Dust

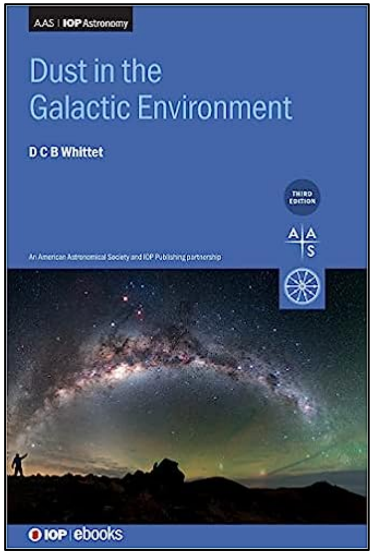







Introduction to dust astrophysics (I)

Álvaro Sánchez-Monge
Institute of Space Sciences (ICE-CSIC / IEEC)

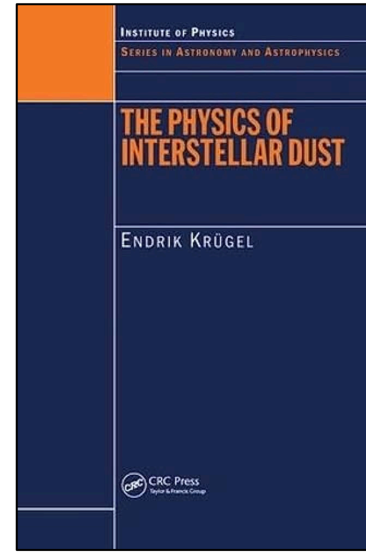
Institute of Space Sciences
EXCELENCIA MARÍA DE MAEZTU
CSIC
MINISTERIO DE CIENCIA E INNOVACIÓN
Financiado por la Unión Europea NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN

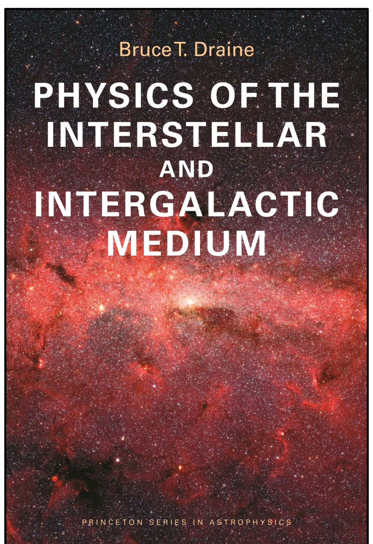
Bibliography



Dust in the Galactic environment
by Douglas C B Whittet

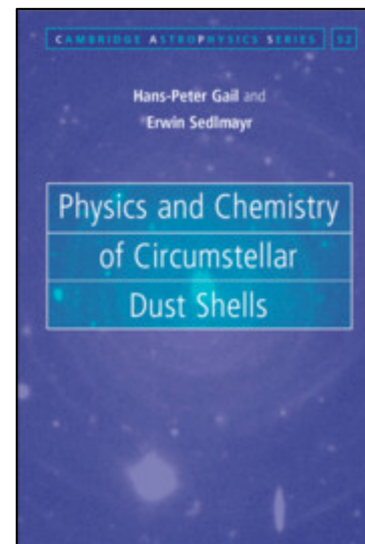
The physics of interstellar dust
by Endrik Krügel





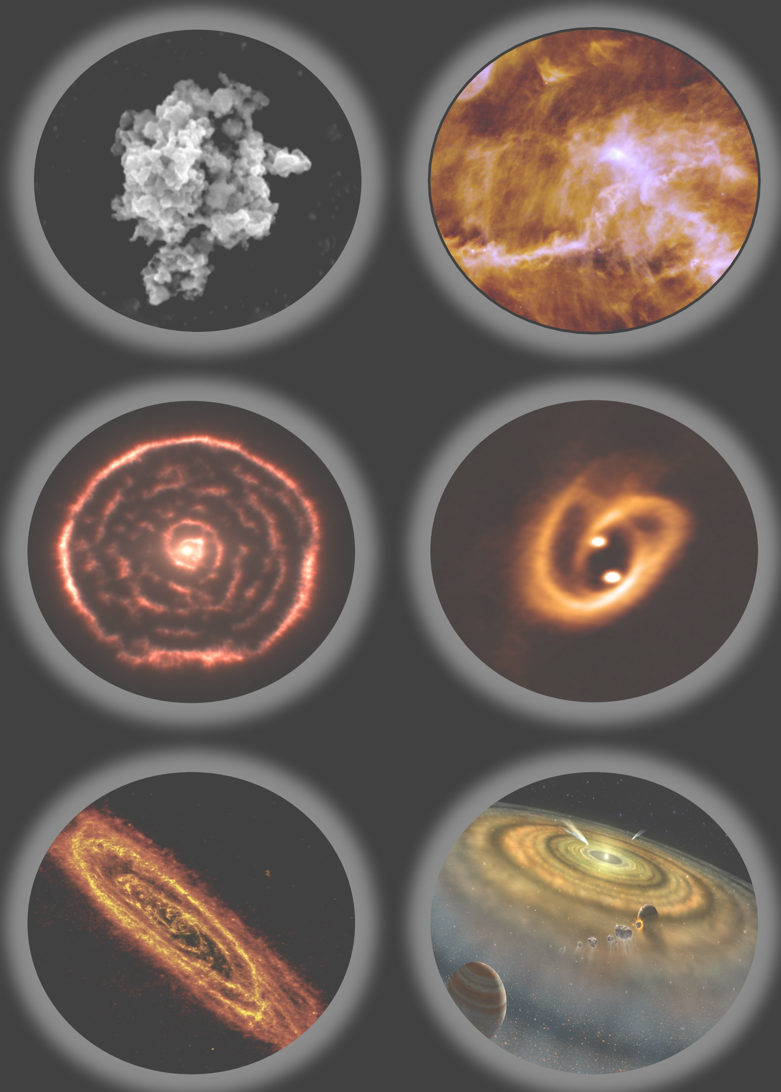
Physics of the interstellar medium
by Bruce T Draine

Physics and chemistry of circumstellar dust shells
by Hans-Peter Gail & Erwin Sendlmayr



Outline

Life Cycle of Dust



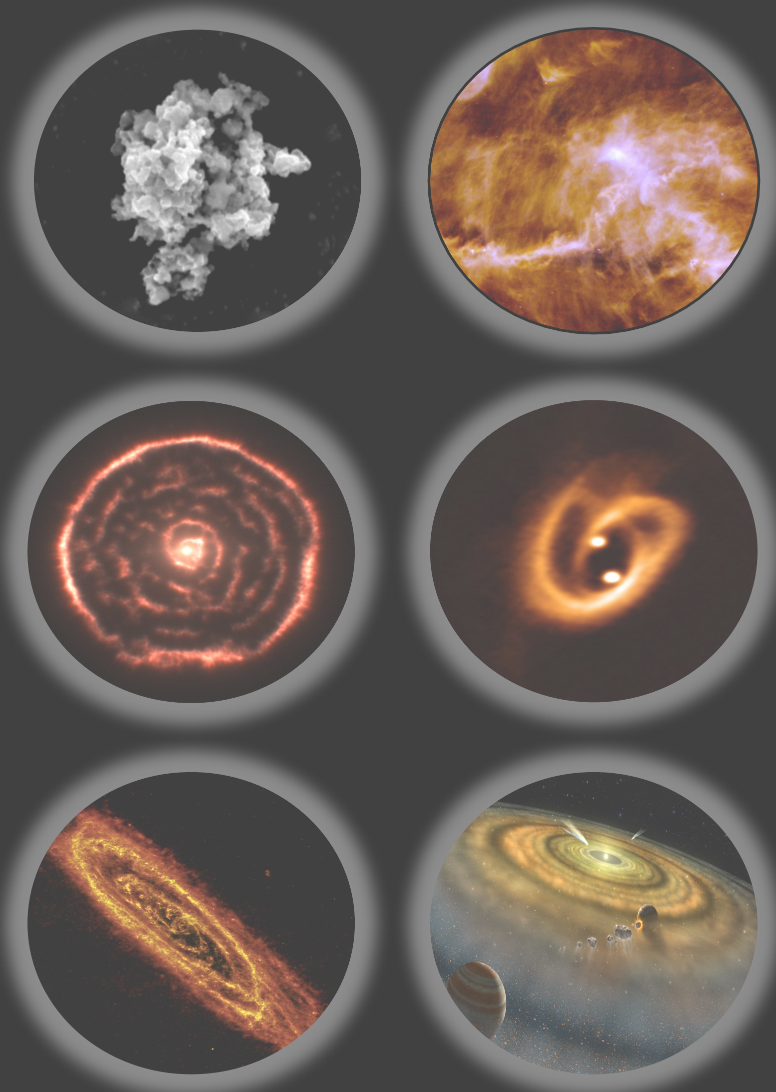
Existence of Interstellar Dust

Properties of the Interstellar Medium

Abundances, Depletion, Composition

Dusty astrophysical objects

Life Cycle of Dust



Outline

Existence of Interstellar Dust

Properties of the Interstellar Medium

Abundances, Depletion, Composition

Dusty astrophysical objects

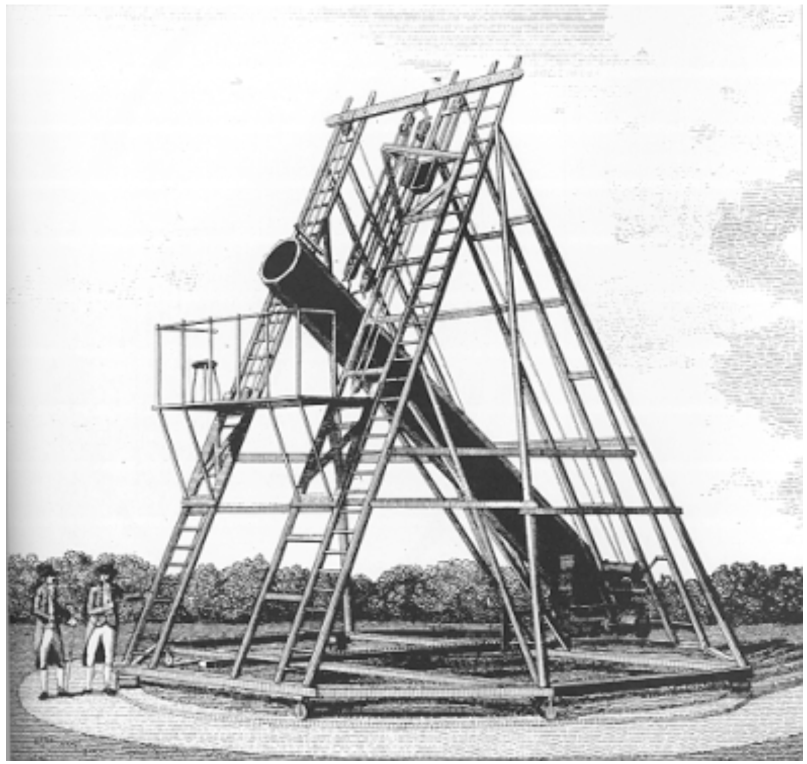
A historical perspective

Wide-angle photograph of the sky. W Schlosser and Th Schmidt-Kaler, Ruhr Universität, Bochum. Taken from La Silla, ESO

A historical perspective

… ein Loch im Himmel!

William **Herschel**
(1738-1822)



'Forty-foot' telescope

Caroline **Herschel**
(1750-1848)

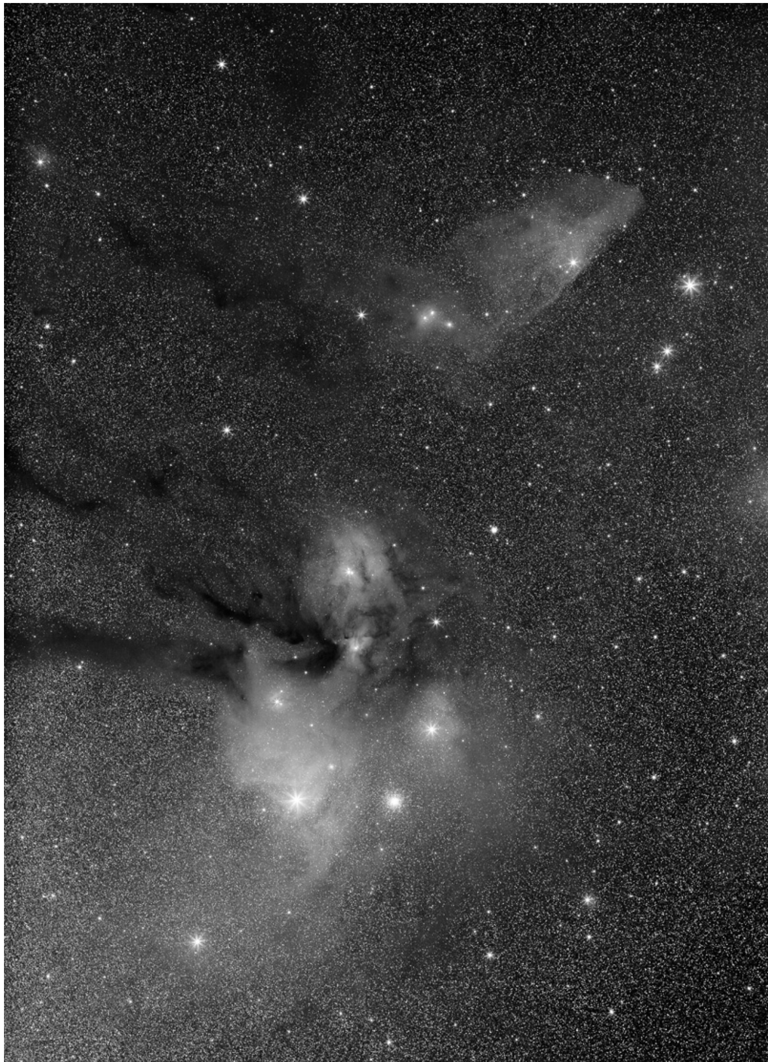
Based in part on talk in AAS 205th Meeting, 9-13 January 2005

A historical perspective

… ein Loch im Himmel!

"… for instance, in the body of the Scorpion is an opening, or hole, ... I found it while I was gauging in parallel from 112 to 114 degrees north of polar distance... As I approached the Milky Way the gauges were gradually running up ... when all of a sudden, they fell down to nothing..."

William **Herschel**
1785, Phil. Trans. LXXV, pp. 213-266



A historical perspective

… ein Loch im Himmel!

"… It is remarkable, that one of the richest and most compressed clusters [M80] of small stars I remember to have seen, is situated on the western border of it, and would almost authorise a suspicion that the stars, of which it is composed, were collected from that place and had left the vacancy."

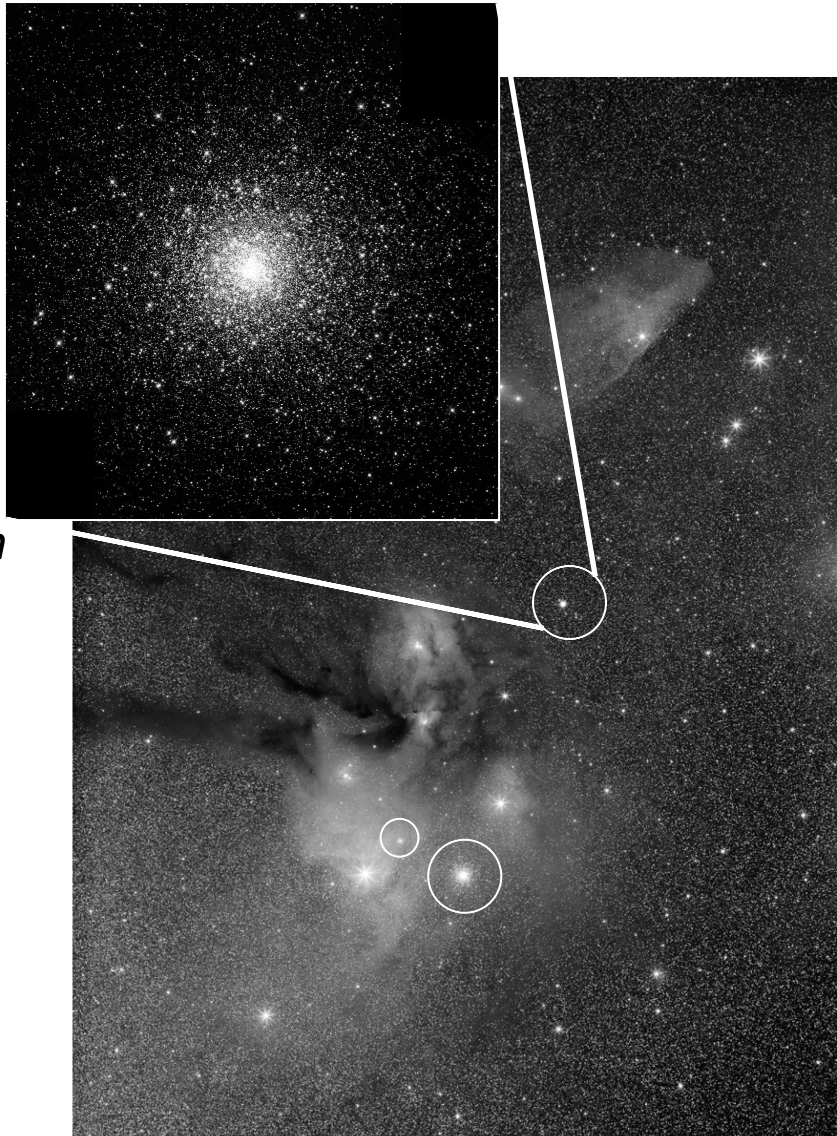
William **Herschel**
1785, Phil. Trans. LXXV, pp. 213-266

A historical perspective

… ein Loch im Himmel!

"What adds not a little to this surmise is, that the same phaenomenon is once more repeated with [M4] which is also on the western border of another vacancy and has moreover a small miniature cluster (NGC6144) … north following it, at no very great distance."

William **Herschel**
1785, Phil. Trans. LXXV, pp. 213-266

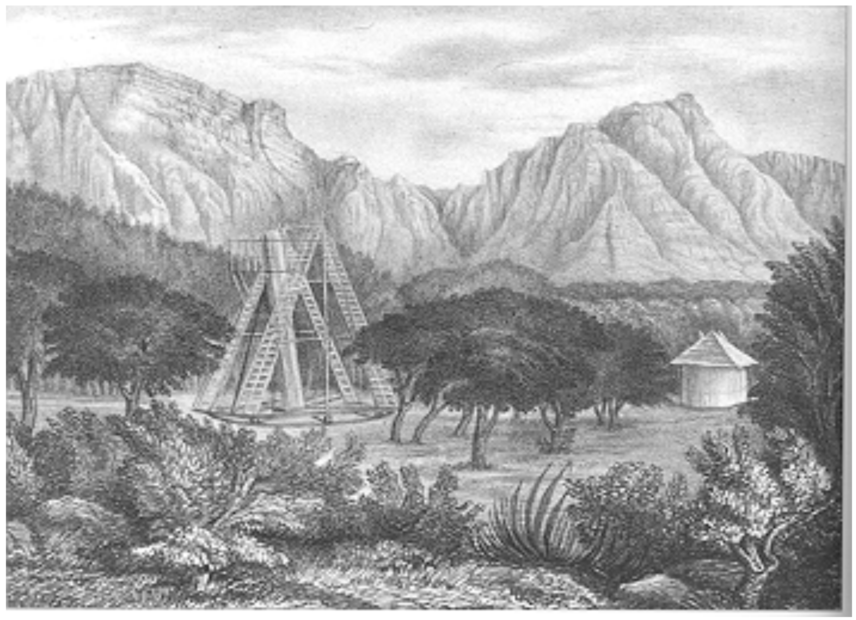


A historical perspective

… ein Loch im Himmel!

John **Herschel**
(1792-1871)

Feldhausen, South Africa (1834)

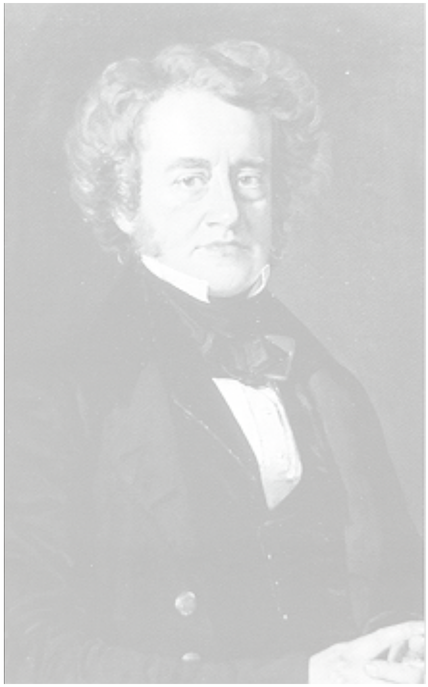


Caroline **Herschel**
(1750-1848)

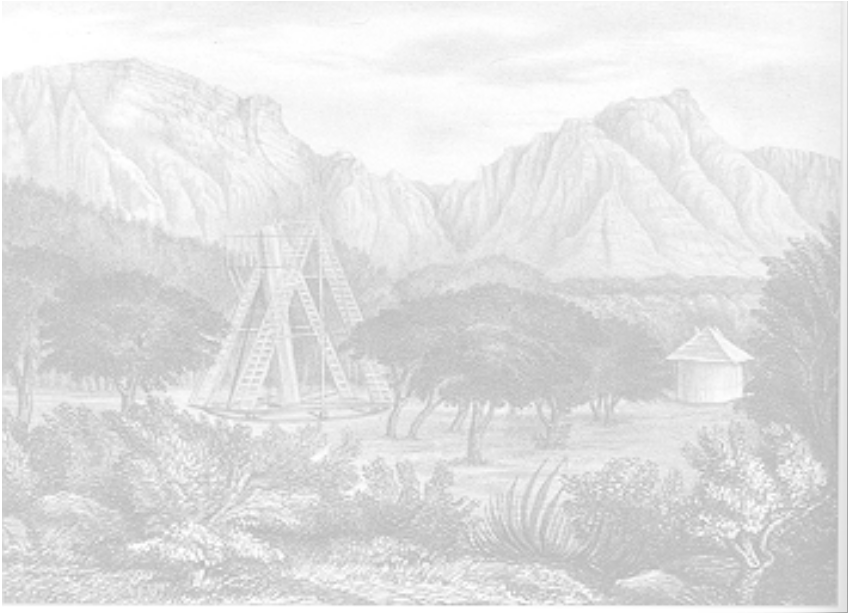
A historical perspective

… ein Loch im Himmel!

John **Herschel**
(1792-1871)



Feldhausen, South Africa (1834)



Caroline **Herschel**
(1750-1848)

August 1, 1833

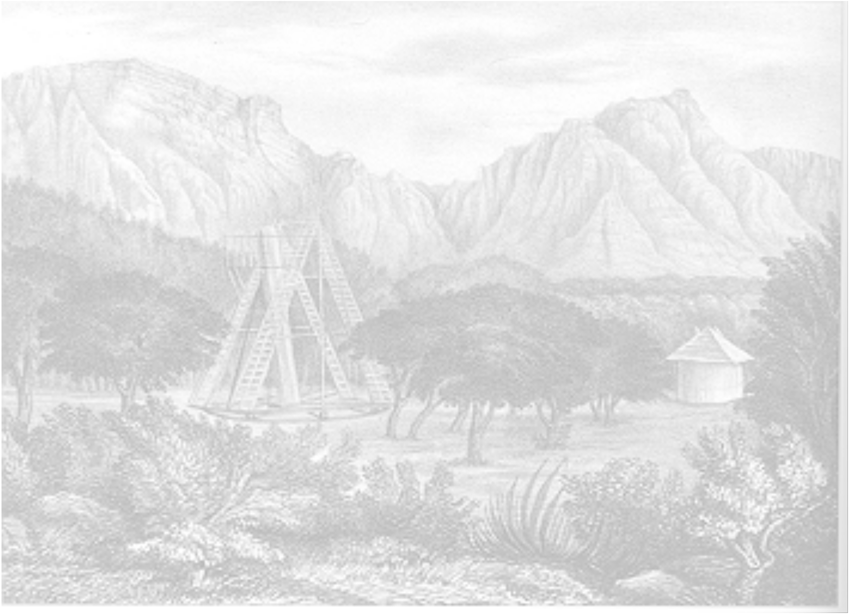
“Dear Nephew,
As soon as your instrument is erected I wish you would see if there is not something remarkable in the lower part of the Scorpion to be found…”

A historical perspective

… ein Loch im Himmel!

John **Herschel**
(1792-1871)

Feldhausen, South Africa (1834)



Caroline **Herschel**
(1750-1848)

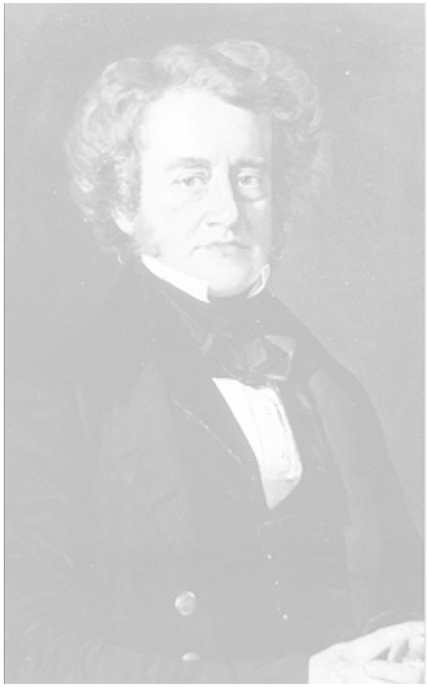
June 6, 1834

"… I have not been unmindful of your hint about Scorpio. I am now rummaging the recesses of that constellation and find it full of beautiful globular clusters."

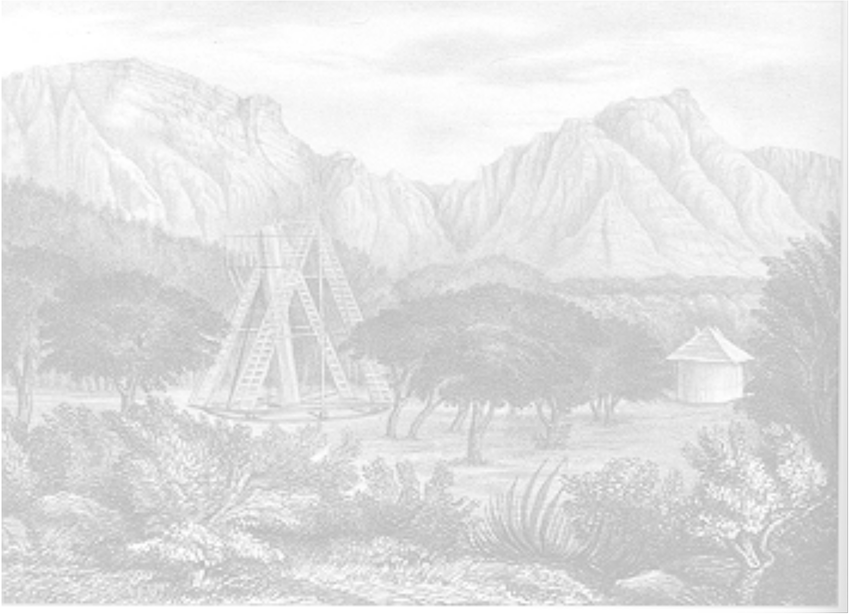
A historical perspective

… *ein Loch im Himmel!*

John **Herschel**
(1792-1871)



Feldhausen, South Africa (1834)



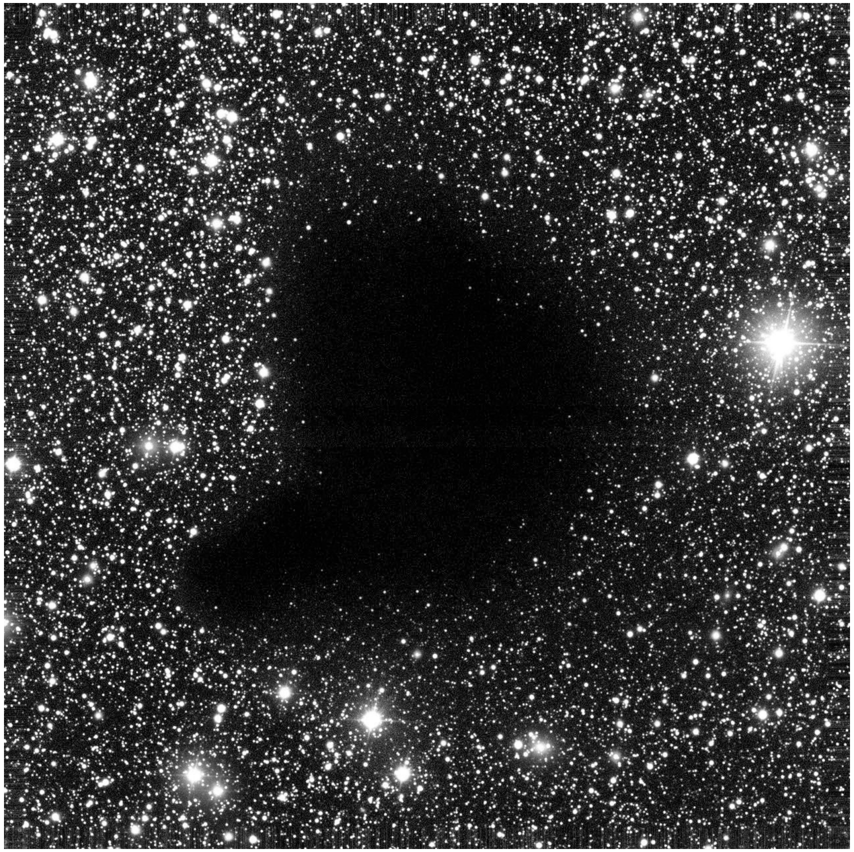
Caroline **Herschel**
(1750-1848)

*"It is not Clusters of Stars I want you to discover in the body of the Scorpion (or thereabouts) for that does not answer my expectation, remembering having once heard your father… exlaim, '**Hier ist wahrhaftig ein Loch im Himmel**!' "*

A historical perspective

... ein Loch im Himmel!

John **Herschel**
(1792-1871)



Caroline **Herschel**
(1750-1848)

February 22, 1835

“I have swept well over Scorpio and have many entries in my sweeping books of the kind you describe viz: blank spaces in the heavens without the smallest star.”

A historical perspective

First studies of dark nebulae

Catalogue of Nebulae and Clusters of Stars (**CN**), General Catalogue of Nebulae and Clusters of Stars (**GC**) … precursors of **NGC** catalogue

1912, The Scientific Papers of Sir William Herschel

(The Royal Society & Royal Astronomical Society), Vol II, pg 712

712 STAR-GAGES FROM THE 358TH TO THE 1111TH SWEEP

VACANT PLACES

[Extracted from the Sweeps. Places for the Year of Observation.]

Sweep.	R.A.	P.D.	Stars.	
383 Mar. 10 1785	16 5 22	109 25	0	
	16 6 22	109 20	0	
	16 6 32	109 31	0	
	16 7 22	109 49	0	
	16 7 42	109 12	0	
	16 11 52	110 17	0	
	16 12 22	109 11	0	
	16 12 40	110 25	0	
	16 13 0	111 29	2	
485 Dec. 7 1785	4 17 37	65 29		Upper border of a vacancy, but it is a very irregular one.
	4 18 30	65 27		Do.
	4 19 17	65 29		Do.
	4 21 35	64 31	0	
	4 22 26	64 22	0	
	4 23 53	64 4	0	and many such in the neighbourhood.
	4 25 17	..		There is a vacancy between the bright row of stars in the direction of Orion's belt and the Bull's head, Perseus' body and the Milky Way, and I am now in that vacancy.
	4 27 26	65 4	0	Intermixed with places that have many stars.
	4 28 6	64 10	0	
	4 28 42	65 11	0	
	4 29 24	65 15	0	
	4 30 54	65 16	0	
	4 37 51	65 16	0	
	4 39 16	..		The straggling stars of the Milky Way seem now to come on gradually, most small.
	4 43 20	..		They begin now to be intermixed with some larger ones.
516 Jan. 30 1786	5 32 16	98 30	0	Vacant spaces picked out, between stars sparingly and irregularly scattered.
	5 32 42	100 21	0	
	5 33 5	99 33	0	
	5 34 40	100 39	0	
566 May 26 1786	16 8 52	113 18		Vacant between these two places.*
	16 9 12	112 25		
	16 11 56	112 53		From this place to the bottom of sweep [113° 20′] vacant.
	16 16 8	112 36		From these places downwards vacant, the night very fine.
	16 17 6	112 37		
	16 18 25	112 27		
	16 20 32	112 54		

* [Compare Vol. I. p. 253.—Ed.]

A historical perspective

Wilhelm **von Struve**
(1793-1864)

Struve (1847) noticed that the apparent number of stars per unit volume of space declines in all directions receding from the Sun. He attributed this effect to 'interstellar absorption'.

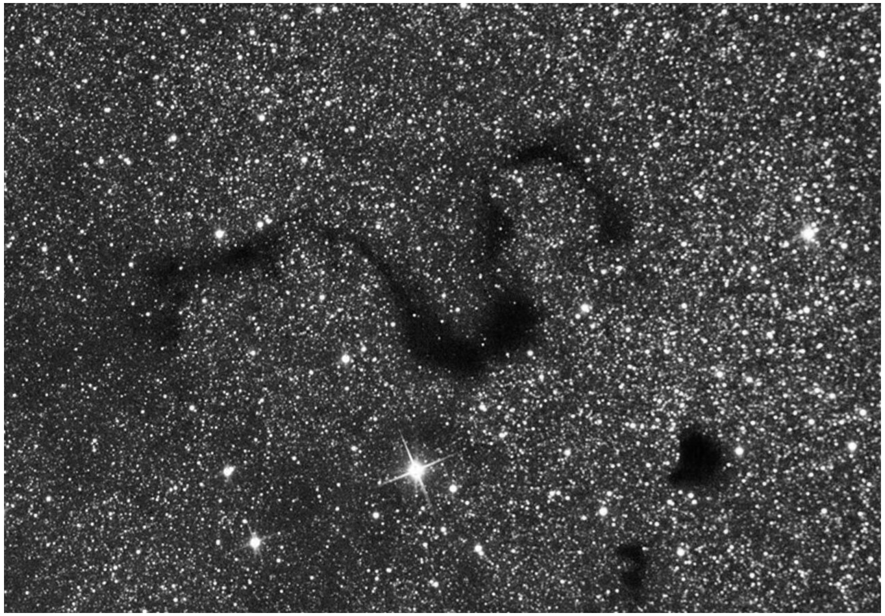
Jacobus **Kapteyn**
(1851-1922)

"Undoubtedly one of the greatest difficulties, if not the greatest of all, in the way of obtaining understanding of the real distribution of the stars in space, lies in our uncertainty about the amount of loss suffered by the light on its way to the observer"

A historical perspective

Edward Emerson
Barnard
(1857-1923)

"… my own photographs convinced me ... that many of these markings were not simply due to an actual want of stars, but were really obscuring bodies nearer to us than the stars."



"In a considerable number of cases no other explanation seems possible, but (that) some of them are doubtless only vacancies"

Barnard 1919, Astrophysical Journal, 49, 1

A historical perspective

Vesto **Slipher**
(1875-1969)

Slipher (1912) noticed that the diffuse nebulosity in the Pleiades shows a dark-line spectrum similar to that of the surrounding stars. He concluded that the nebula shines by reflected light.

"This observation of the nebula in the Pleiades has suggested to me that the Andromeda Nebula and similar spiral nebula might consist of a central star enveloped and beclouded by fragmentary and disintegrated matter"

Slipher 1912, Lowell Observatory Bulletin, 2, 26

A historical perspective

Robert Julius
Trumpler
(1886-1956)

R. J. Trumpler sought to determine the distances of open clusters by means of photometry and spectroscopy of individual member stars

Photometric distance

Spectral classification provides luminosity estimate

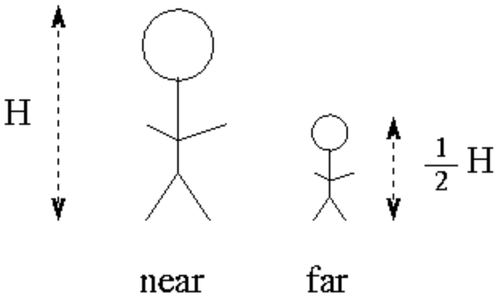
Distance obtained by comparing apparent and absolute magnitudes

$$V - M_V = 5 \log d' - 5$$

Diameter distance

Based on concentration of stars he divided clusters in two groups, and assumed that they should be about the same physical size.

Using the apparent size, it was possible to derive their distance

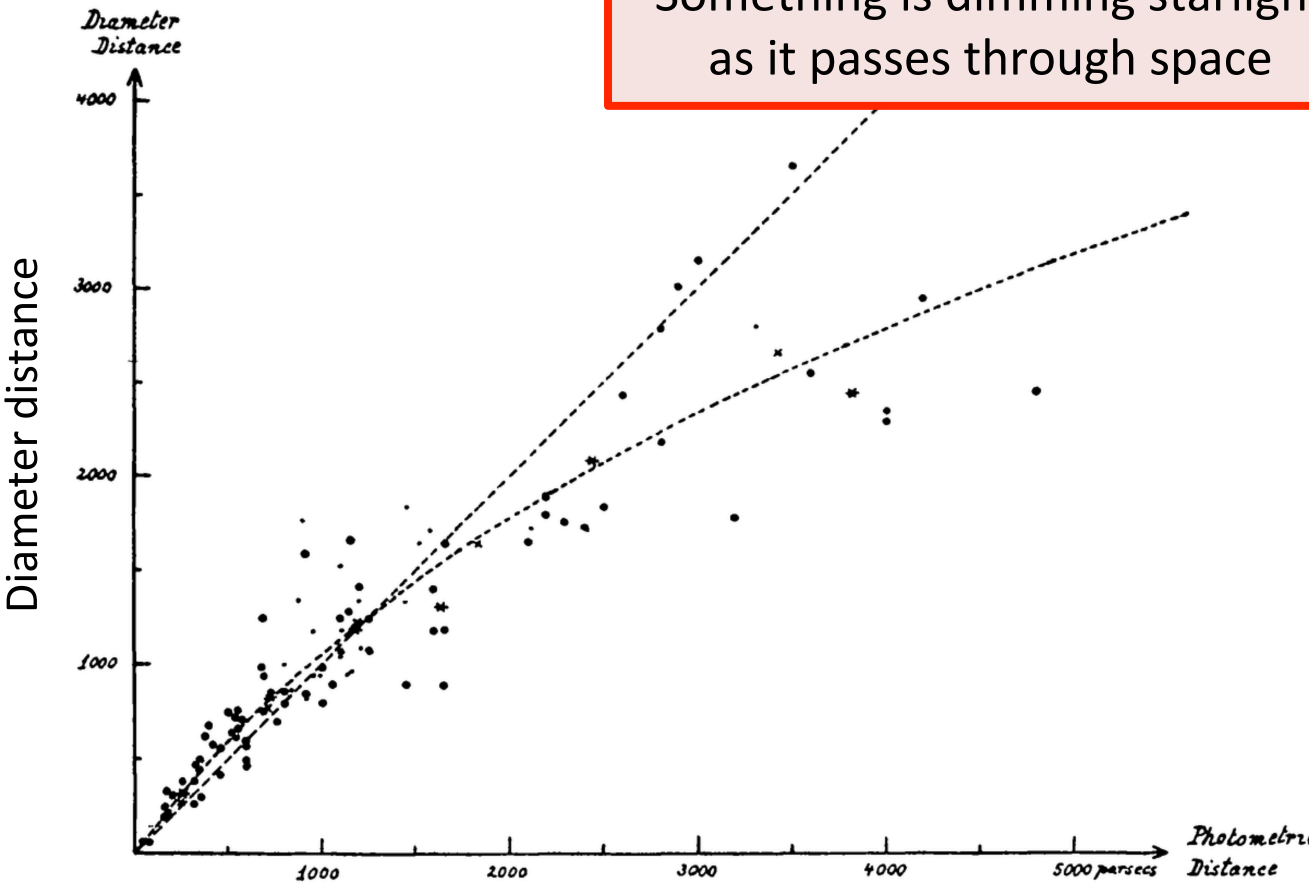


A historical perspective

Robert Julius
Trumpler
(1886-1956)

R. J. Trumpler sought to determine the distances of open clusters by means of photometry and spectroscopy of individual member stars

Something is dimming starlight as it passes through space



Trumpler 1930, PASP, 42, 248

A historical perspective

Robert Julius **Trumpler** (1886-1956)

R. J. Trumpler sought to determine the distances of open clusters by means of photometry and spectroscopy of individual member stars

When determining (photometric) distances…

$$V - M_V = 5 \log d' - 5$$

Presence of a systematic error due to obscuration in the interstellar medium, a distance-dependent correction must be applied:

$$V - M_V - A_V = 5 \log d - 5$$

A_V represents interstellar 'absorption'
in reality it is the combined effect of absorption and scattering

it tends to increase with distance (≈ 1 mag kpc^{-1})

A historical perspective

Robert Julius **Trumpler** (1886-1956)

R. J. Trumpler sought to determine the distances of open clusters by means of photometry and spectroscopy of individual member stars

Implications of this 'absorption' for the colors of stars…

There was an existing problem: stars close to the galactic plane appear redder than expected on the basis of their spectral types

$(B - V)$ color of a star, comparing magnitudes in two bands

$$E_{B-V} = (B - V) - (B - V)_0$$

degree of reddening 'selective extinction'

$$A_\lambda \propto \lambda^{-1}$$

interstellar extinction is a function of wavelength in the visible region of the spectrum

Implication: presence of solid particles with dimensions comparable to the wavelength of visile light
size ≈ 0.1 - 1 micron → smoke / dust particles

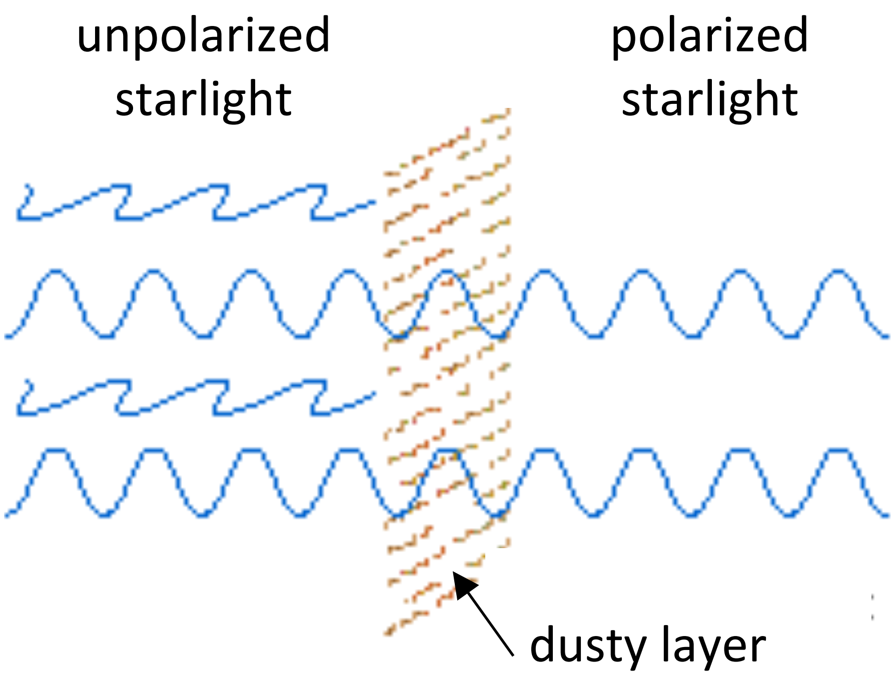
$$A_V = R_V E_{B-V} \qquad R_V \approx 3.05 \pm 0.15$$

Polarization of star light

William Albert **Hiltner** (1914-1991)

John Scoville **Hall** (1908-1991)

Hiltner 1949, Nature, 163, 283
Hiltner 1949, Science, 109, 165
Hall 1949, Science, 109, 166



Extinction by dust renders interstellar space a polarizing and attenuating medium
The light of reddened stars if partially plane polarized, at a typical 1-5 % level

Content of dark nebulae (interstellar matter)

Bart J. **Bok**
(1906-1983)

Following the discovery of HI emission at 21 cm (1951)
… Bart Bok studies the amount of HI in these dark nebulae

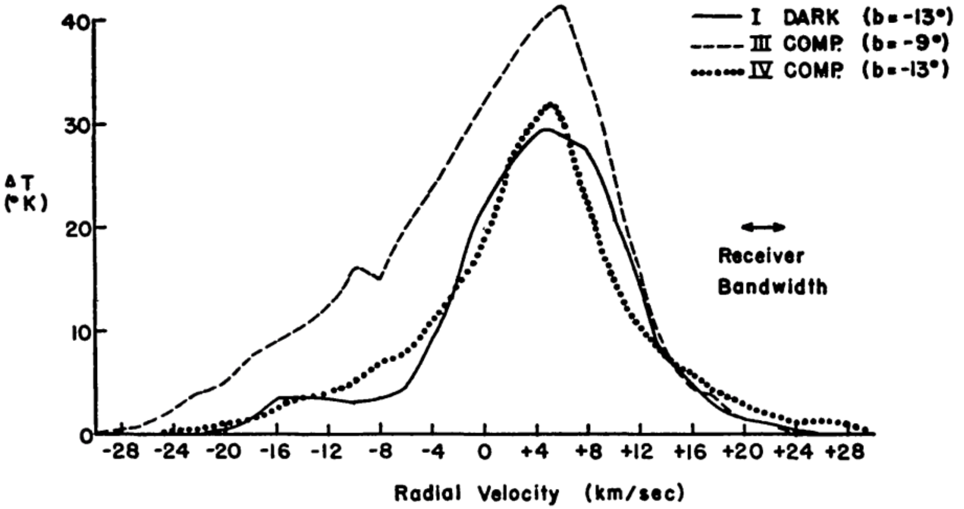


FIG. 4.—Reduced 21-cm profiles for the Ophiuchus Center and two comparison fields.

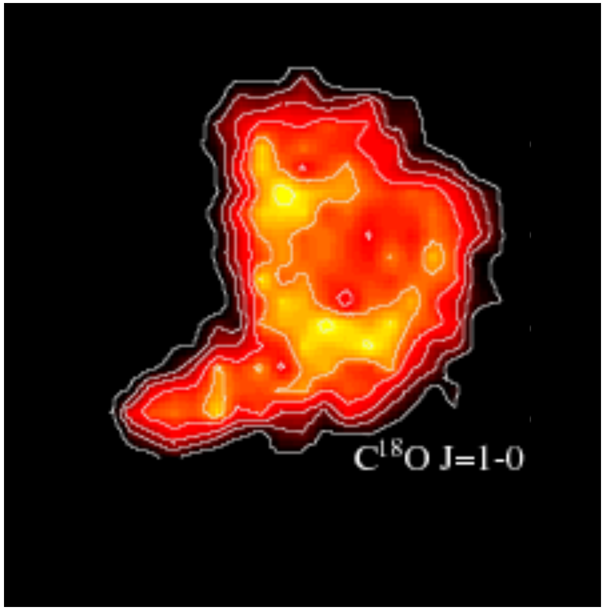
Bok, Lawrence & Menon, 1955, PASP, 67, 108

"There remains the possibility that the neutral hydrogen in the dark clouds is mostly in molecular form"

Content of dark nebulae (interstellar matter)

Barnard 68, in optical

Barnard 68, in $C^{18}O$



H_2 (molecular Hydrogen) is difficult to be observed (in most scenarios)

… but other molecular species can trace molecular gas (e.g., CO)

Take home messages

Existence of interstellar dust

For more than 200 years, many people have used telescopes and their knowledge to discover, study and understand the interstellar dust

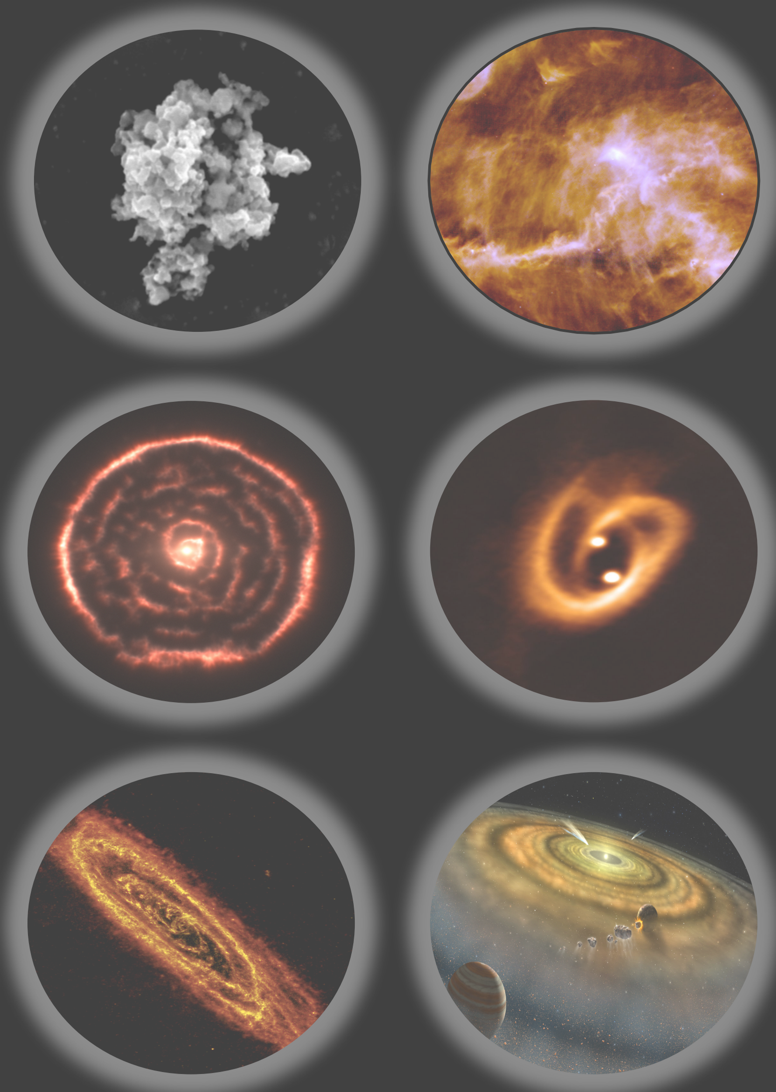
… and many others

Interstellar dust is composed of small particles 0.1 µm and associated with gas
Interstellar dust produces extinction, scattering and polarization

$$V - M_V - A_V = 5 \log d - 5$$

$$A_V = R_V E_{B-V} \qquad R_V \approx 3.05 \pm 0.15 \qquad A_\lambda \propto \lambda^{-1}$$

Life Cycle of Dust



Outline

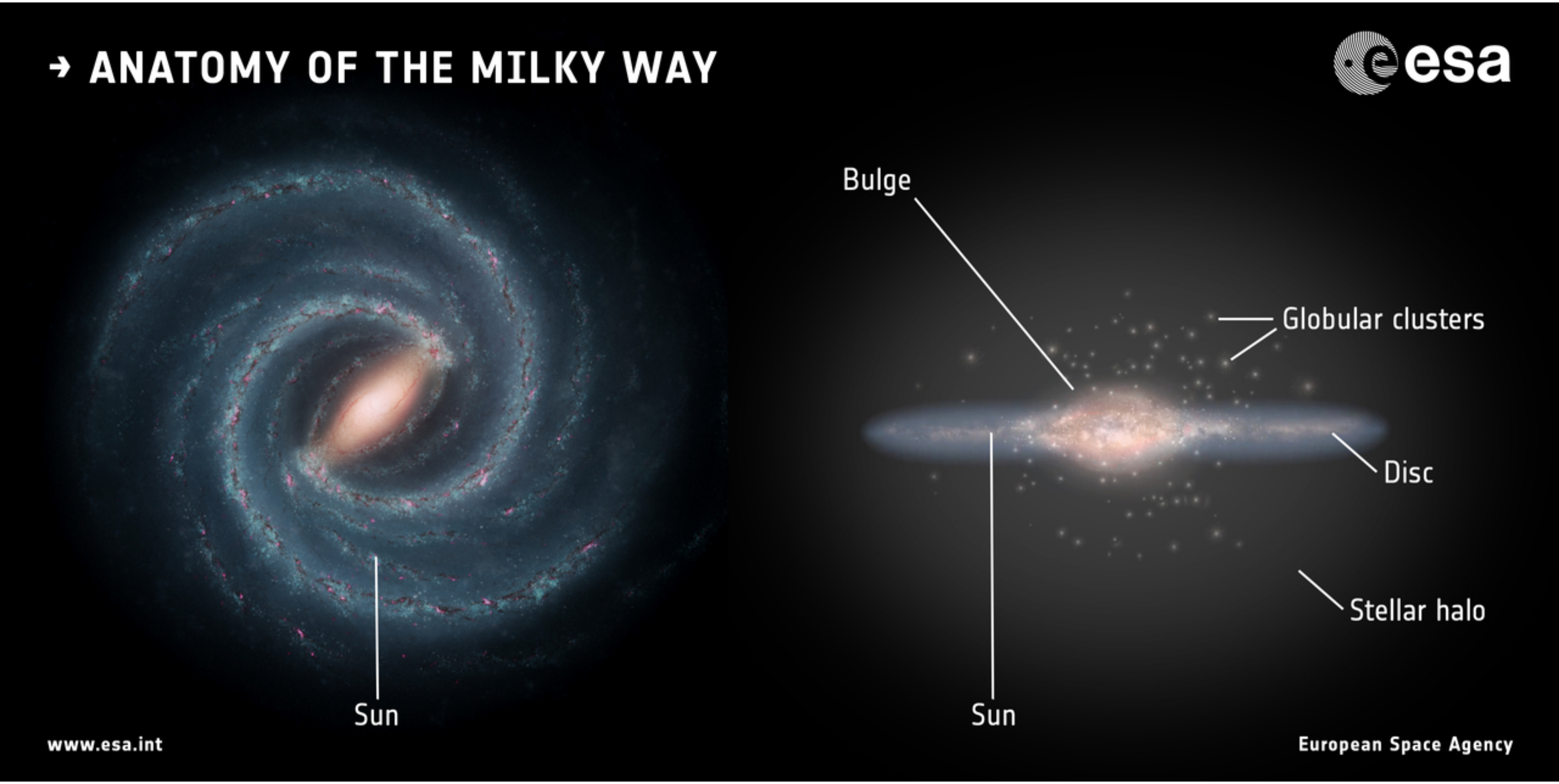
Existence of Interstellar Dust

Properties of the Interstellar Medium

Abundances, Depletion, Composition

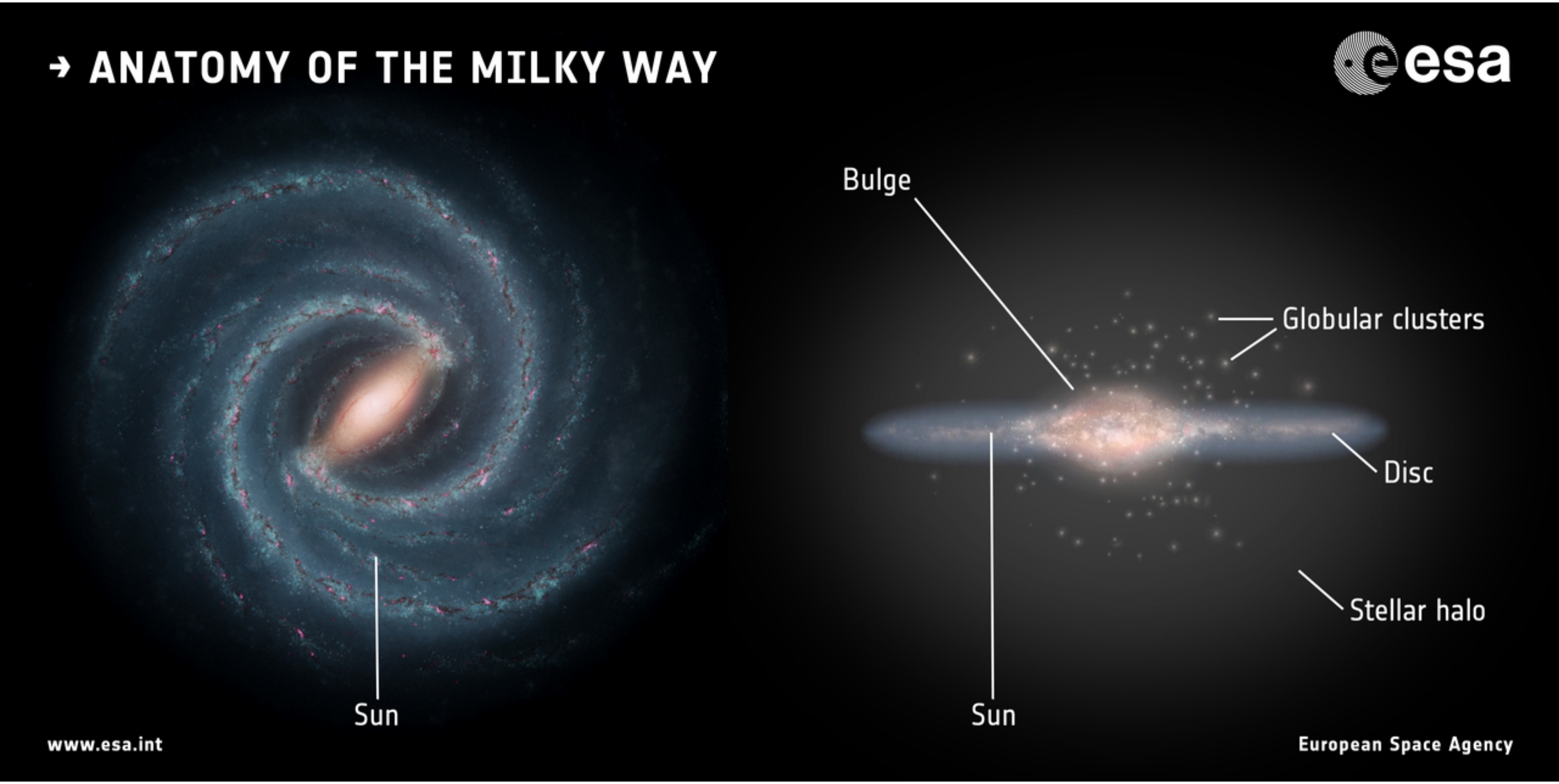
Dusty astrophysical objects

Properties of the interstellar medium



From star counts, most of the extinction material was concentrated in a continuous layer within the Galactic plane with a scale height ≈ 100 pc

Properties of the interstellar medium



On average, a column 1-kpc long in the Galactic disk intersects several (≈ 5) diffuse clouds and produces a typical reddening of $E_{B-V} \approx 0.6$

$$A_V = R_V E_{B-V} \longrightarrow \left\langle \frac{A_V}{L} \right\rangle \approx 1.8 \text{ mag kpc}^{-1}$$

Properties of the interstellar medium

Correlation between dust (extinction) and gas (hydrogen)

Following the first studies by Bok: connection between the dust and the gas?

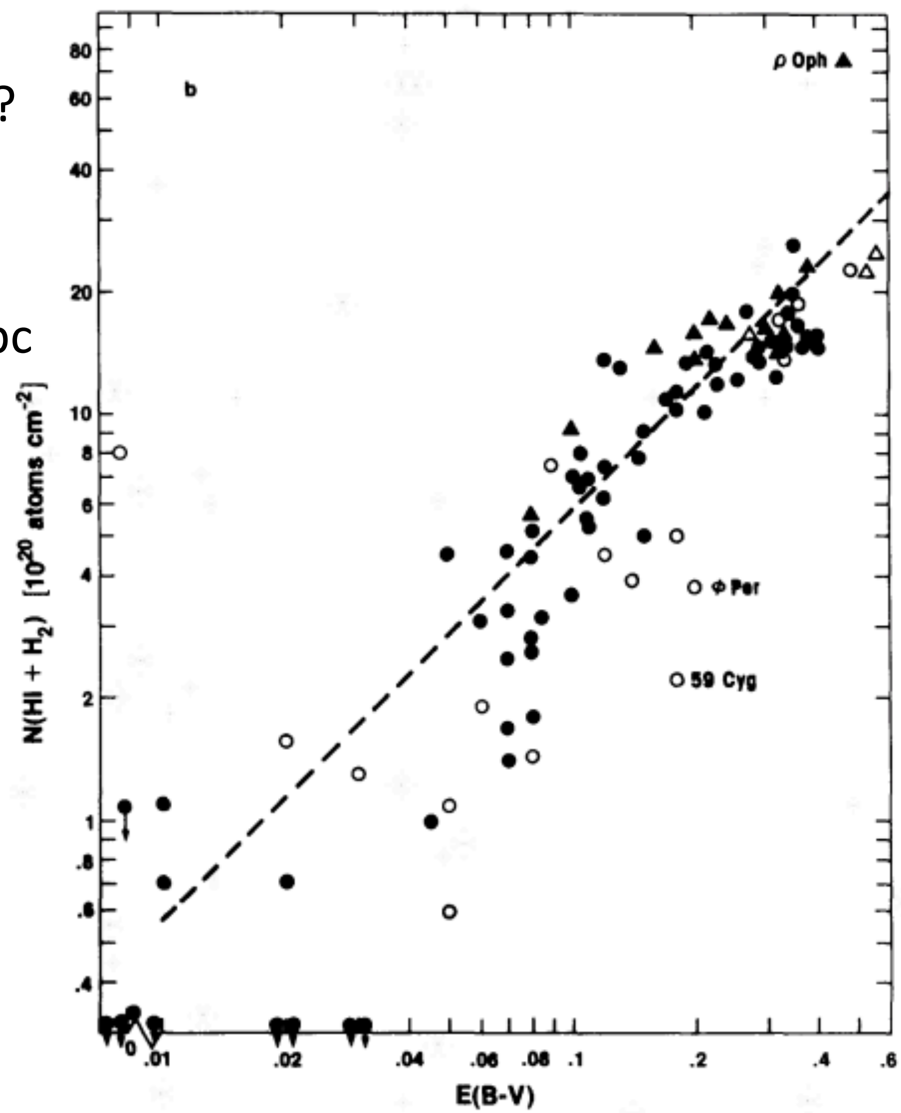
N(H) measured via UV absorption-line spectroscopy of reddened stars within 1 kpc

$$N_{\mathrm{H}} = N(\mathrm{H\ I}) + 2N(\mathrm{H}_2)$$

vs

$$E_{B-V} = (B-V) - (B-V)_0$$

$$\left\langle \frac{N_{\mathrm{H}}}{E_{B-V}} \right\rangle \approx 5.8 \times 10^{25}\ \mathrm{m}^{-2}\ \mathrm{mag}^{-1}$$



Savage, Bohlin et al 1977, ApJ, 216, 291
Bohlin, Savage et al 1978, ApJ, 224, 132

Correlation between dust (extinction) and gas (hydrogen)

$$\left\langle \frac{N_\mathrm{H}}{E_{B-V}} \right\rangle \approx 5.8 \times 10^{25}\ \mathrm{m^{-2}\ mag^{-1}} \qquad \left\langle \frac{N_\mathrm{H}}{A_V} \right\rangle \approx 1.9 \times 10^{25}\ \mathrm{m^{-2}\ mag^{-1}}$$

$$A_V = R_V E_{B-V}$$

For a typical extinction of 1.8 mag kpc^{-1}, we can derive a mean hydrogen number density:

$$\langle n_\mathrm{H} \rangle = \left\langle \frac{N_\mathrm{H}}{L} \right\rangle \approx 1.1 \times 10^{6}\ \mathrm{m^{-3}}$$

The mass density is then derived as:

$$\langle \rho_\mathrm{H} \rangle = m_\mathrm{H} \langle n_\mathrm{H} \rangle \approx 1.8 \times 10^{-21}\ \mathrm{kg\ m^{-3}}$$

The contribution of the hydrogen gas to the mass of the Galactic disk can be better characterize via the surface mass density:

$$\langle \sigma_\mathrm{H} \rangle = 2h \langle \rho_\mathrm{H} \rangle \approx 5.3\ \mathrm{M_\odot pc^{-2}}$$

using a scale height of 100 pc

Properties of the interstellar medium

Correlation between dust (extinction) and gas (hydrogen)

$$\langle\sigma_{\rm H}\rangle \approx 5.3\ {\rm M_\odot pc^{-2}}$$

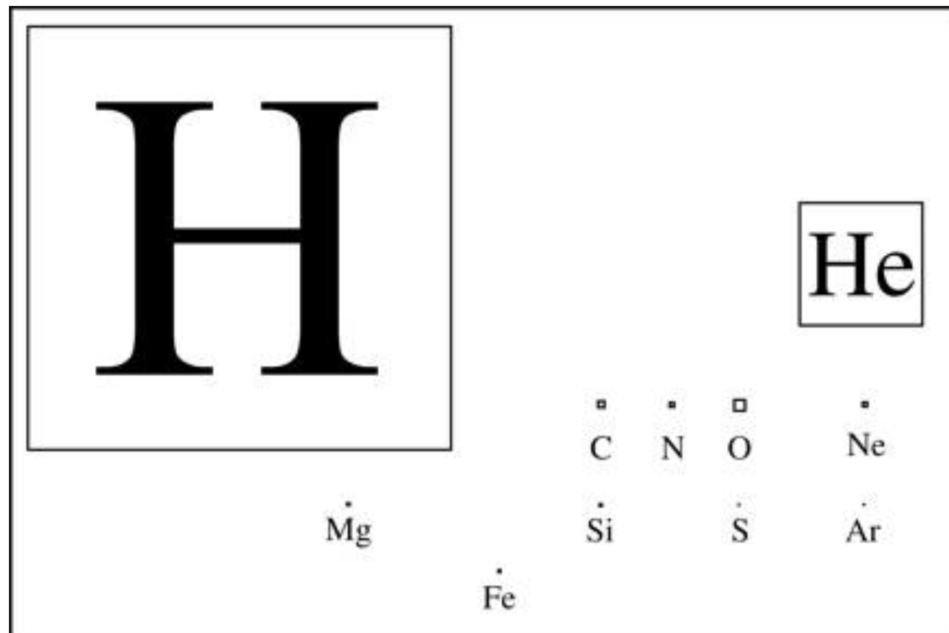
multiply by a factor 1.4 to account
for other elements in addition to hydrogen

$$\langle\sigma_{\rm ISM}\rangle \approx 7.4\ {\rm M_\odot pc^{-2}}$$

Compared to the
surface density of the mass in stars

$$\langle\sigma_{\rm stars}\rangle \approx 35\ {\rm M_\odot pc^{-2}}$$

The ISM mass is about 10-20 %
the stellar mass

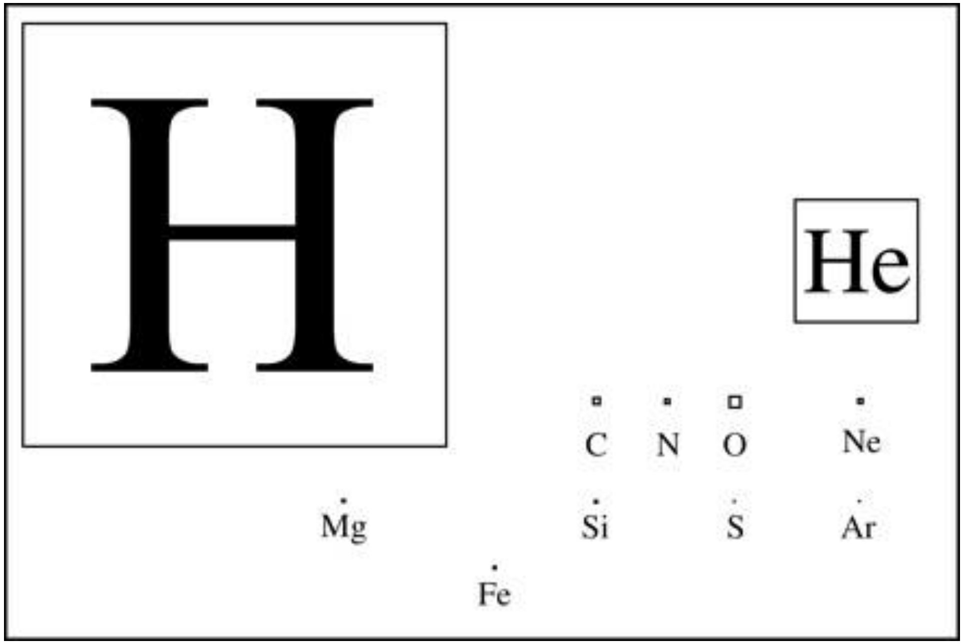


Hydrogen is the most abundant element (about 70% in mass),
followed by **helium** (about 25% in mass) and then other elements (**carbon**, **oxygen**, **nitrogen**)

Components of the interstellar medium

The gas (mainly hydrogen, as seen below) can be found in three main phases:

- **Atomic** H for hydrogen: 1 proton and 1 electron
- **Ionized** H^+ for hydrogen: 1 proton (electron has escaped)
- **Molecular** H_2 for hydrogen: 2 hydrogen atoms together



Hydrogen is the most abundant element (about 70% in mass), followed by **helium** (about 25% in mass) and then other elements (**carbon**, **oxygen**, **nitrogen**)

Properties of the interstellar medium

Components of the interstellar medium

		Phase	n_0^a (cm^{-3})	T^b (K)	ϕ_v^c (%)	M^d ($10^9\ M_\odot$)	$< n_0 >^e$ (cm^{-3})	H^f (pc)	Σ^g ($M_\odot$pc^{-2})
Hot	Ionized	Hot intercloud	0.003	10^6	~50.0	—	0.0015	3000	0.3
Warm	Atomic	Warm neutral medium	0.5	8000	30.0	2.8	0.1^h	220^h	1.5
							0.06^h	400^h	1.4
Warm	Ionized	Warm ionized medium	0.1	8000	25.0	1.0	0.025^i	900^i	1.1
Cold	Atomic	Cold neutral medium[j]	50.0	80	1.0	2.2	0.4	94	2.3
Cold	Molecular	Molecular clouds	>200.0	10	0.05	1.3	0.12	75	1.0
Hot	Ionized	HII regions	1–10^5	10^4	—	0.05	0.015^k	70^k	0.05

[a] Typical gas density for each phase.
[b] Typical gas temperature for each phase.
[c] Volume filling factor (very uncertain and controversial!) of each phase.
[d] Total mass.
[e] Average mid-plane density.
[f] Gaussian scale height, $\sim \exp[-(z/H)^2/2]$, unless otherwise indicated.
[g] Surface density in the solar neighborhood.
[h] Best represented by a Gaussian and an exponential.
[i] WIM represented by an exponential.
[j] Diffuse clouds.
[k] HII regions represented by an exponential.

Properties of the interstellar medium

Components of the interstellar medium

		Phase	n_0^a (cm^{-3})	T^b (K)	ϕ_v^c (%)	M^d ($10^9 M_\odot$)	$< n_0 >^e$ (cm^{-3})	H^f (pc)	Σ^g ($M_\odot$pc^{-2})
Hot	Ionized	Hot intercloud	0.003	10^6	~50.0	—	0.0015	3000	0.3
Warm	Atomic	Warm neutral medium	0.5	8000	30.0	2.8	0.1^h	220^h	1.5
							0.06^h	400^h	1.4
Warm	Ionized	Warm ionized medium	0.1	8000	25.0	1.0	0.025^i	900^i	1.1
Cold	Atomic	Cold neutral medium^j	50.0	80	1.0	2.2	0.4	94	2.3
Cold	Molecular	Molecular clouds	>200.0	10	0.05	1.3	0.12	75	1.0
Hot	Ionized	HII regions	$1–10^5$	10^4	—	0.05	0.015^k	70^k	0.05

Interstellar medium:
Its total mass is about **5x10^9 M$_\odot$** (it is only 1% of the total Milky Way mass), but it occupies almost all the volume of the Galaxy.
The gas is mainly hydrogen, which can be **atomic** (about 50% in mass), **molecular** (about 50% in mass) and **ionized**

Properties of the interstellar medium

Components of the interstellar medium

Are these different ISM phases in equilibrium?

$$p = nkT$$

Phase	n_0^a (cm^{-3})	T^b (K)	ϕ_v^c (%)	M^d ($10^9\ M_\odot$)	$< n_0 >^e$ (cm^{-3})	H^f (pc)	Σ^g ($M_\odot$pc^{-2})
Hot intercloud	0.003	10^6	~50.0	—	0.0015	3000	0.3
Warm neutral medium	0.5	8000	30.0	2.8	0.1^h	220^h	1.5
					0.06^h	400^h	1.4
Warm ionized medium	0.1	8000	25.0	1.0	0.025^i	900^i	1.1
Cold neutral medium^j	50.0	80	1.0	2.2	0.4	94	2.3
Molecular clouds	>200.0	10	0.05	1.3	0.12	75	1.0
HII regions	1–10^5	10^4	—	0.05	0.015^k	70^k	0.05

[a] Typical gas density for each phase.
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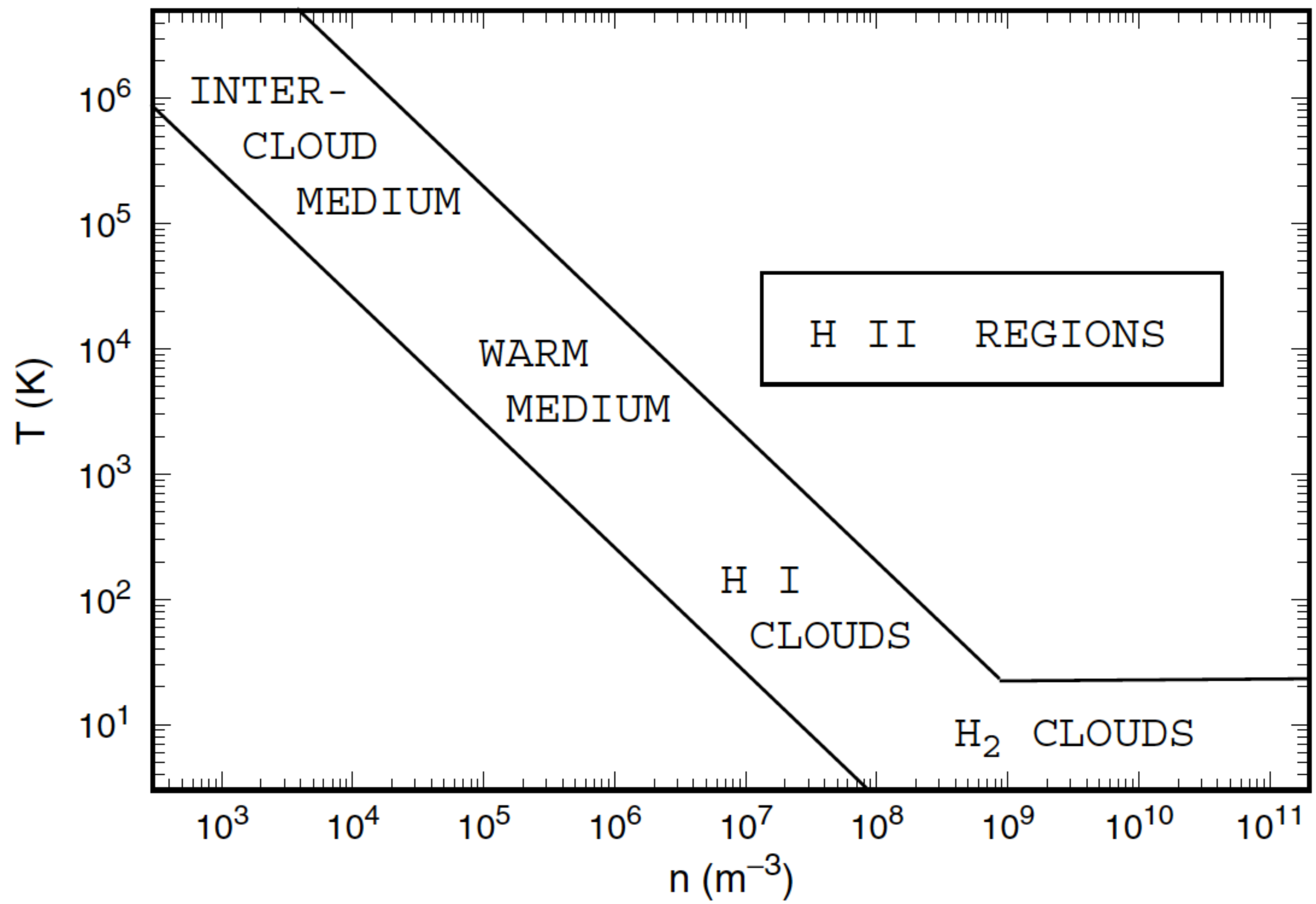
Components of the interstellar medium

Are these different ISM phases in equilibrium?

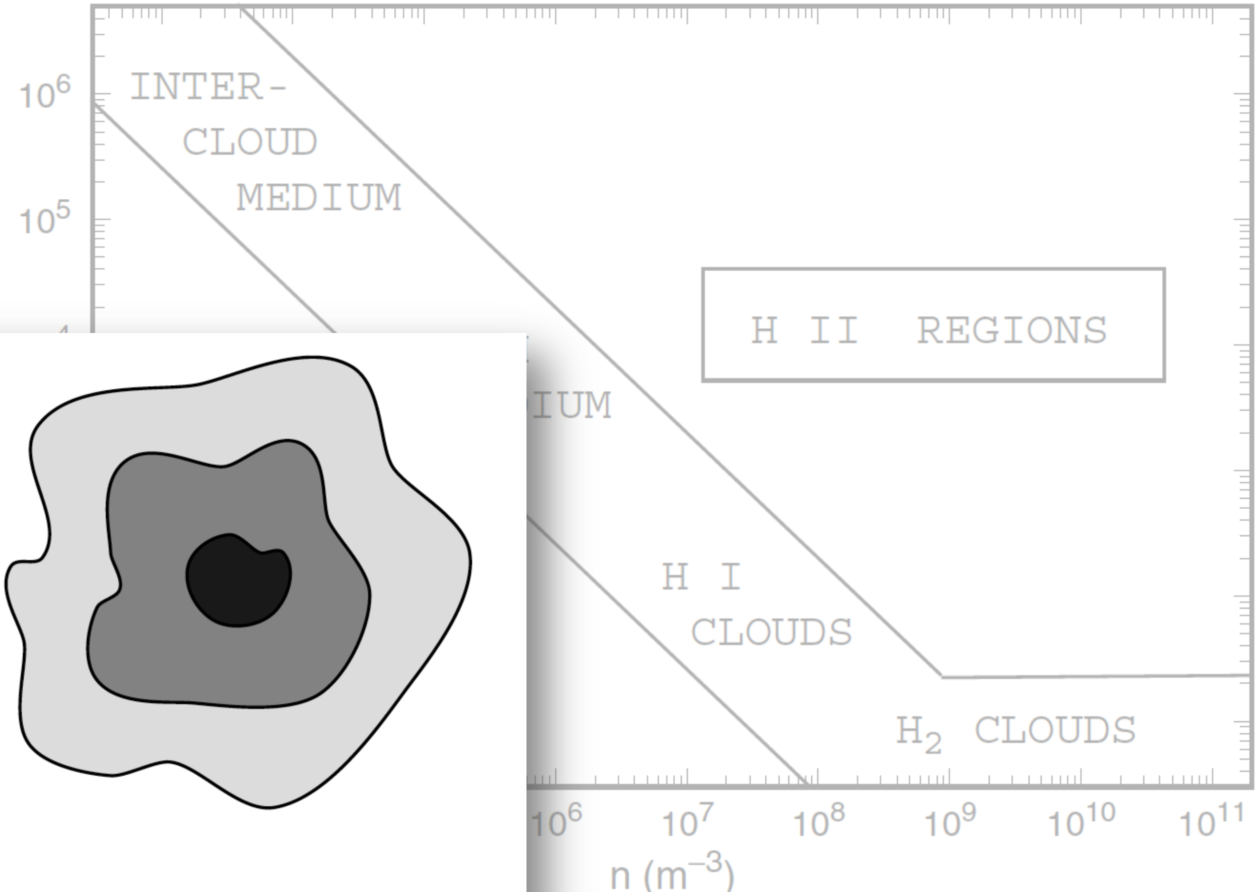
$$p = nkT$$

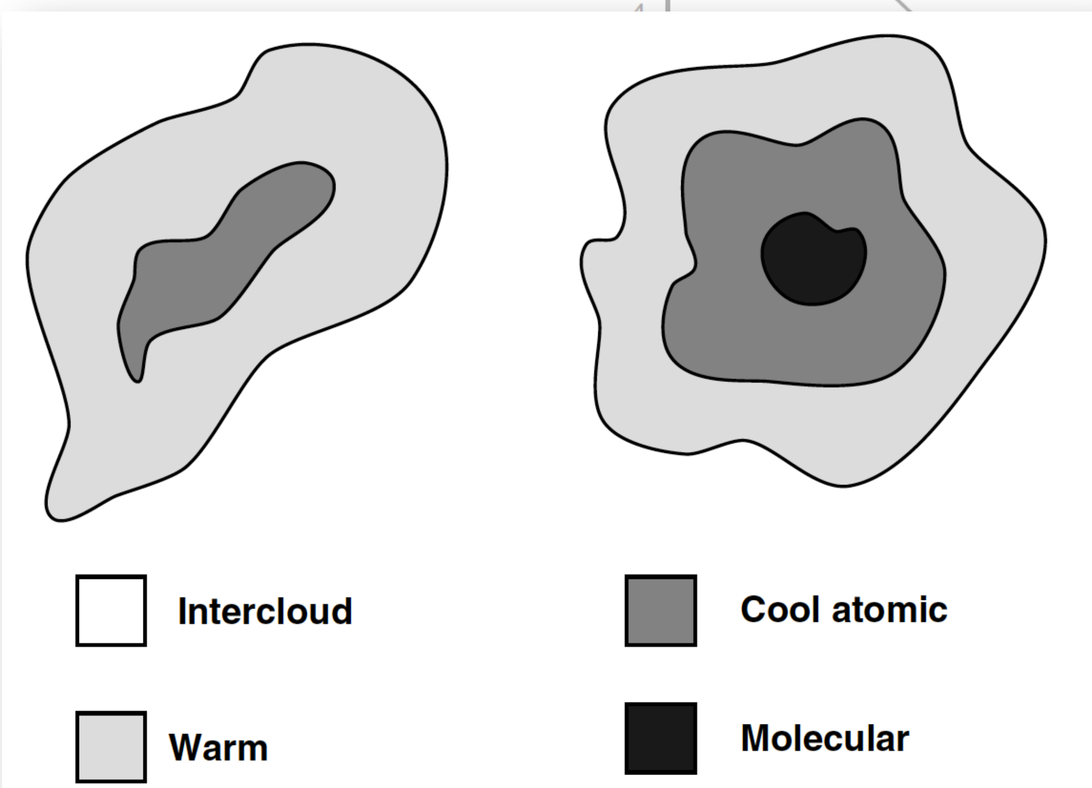


Most of the different phases are in equilibrium except HII regions which 'are expanding' and dense molecular clouds which 'are collapsing'

Components of the interstellar medium

Are these different ISM phases in equilibrium?





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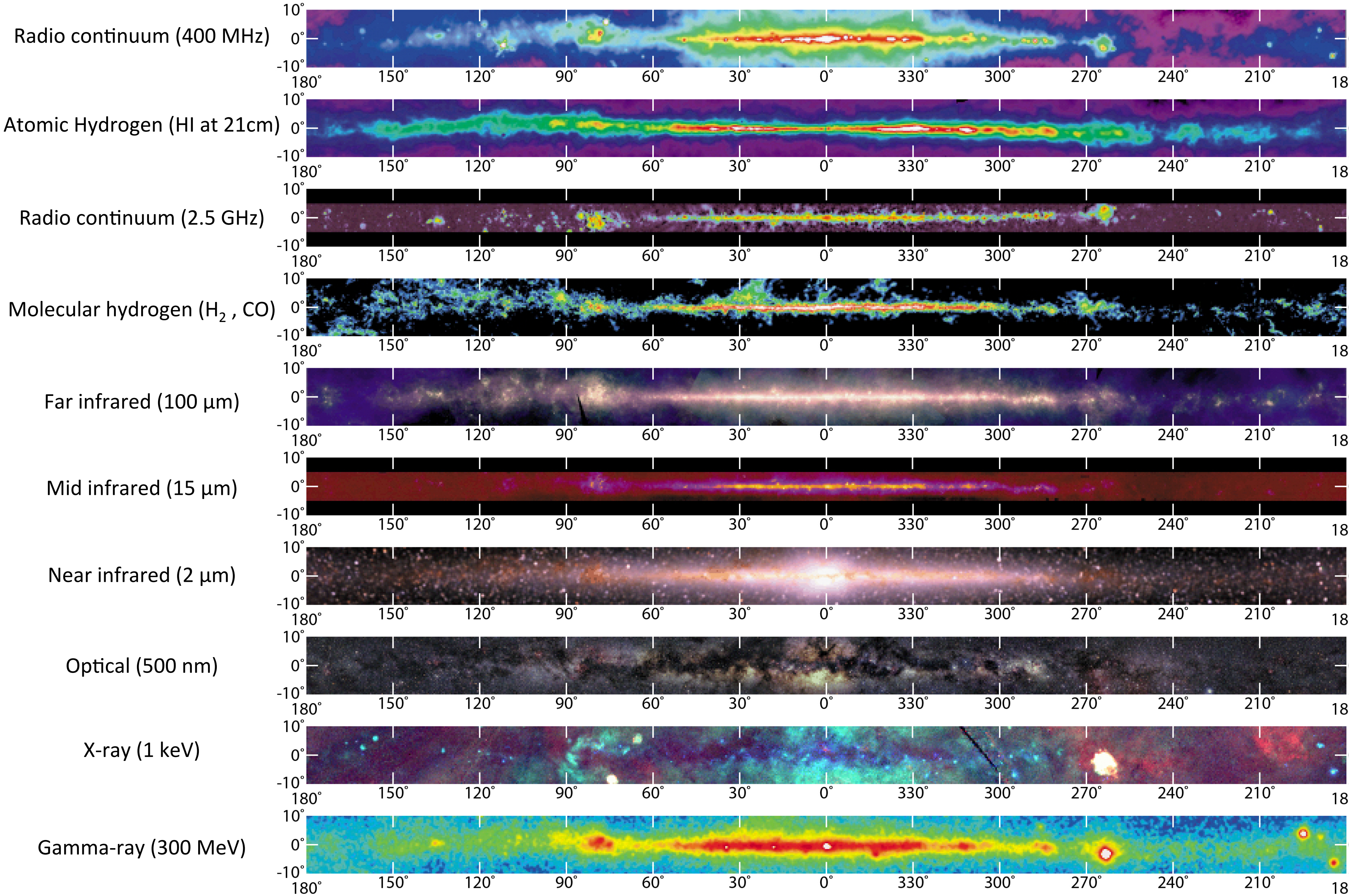
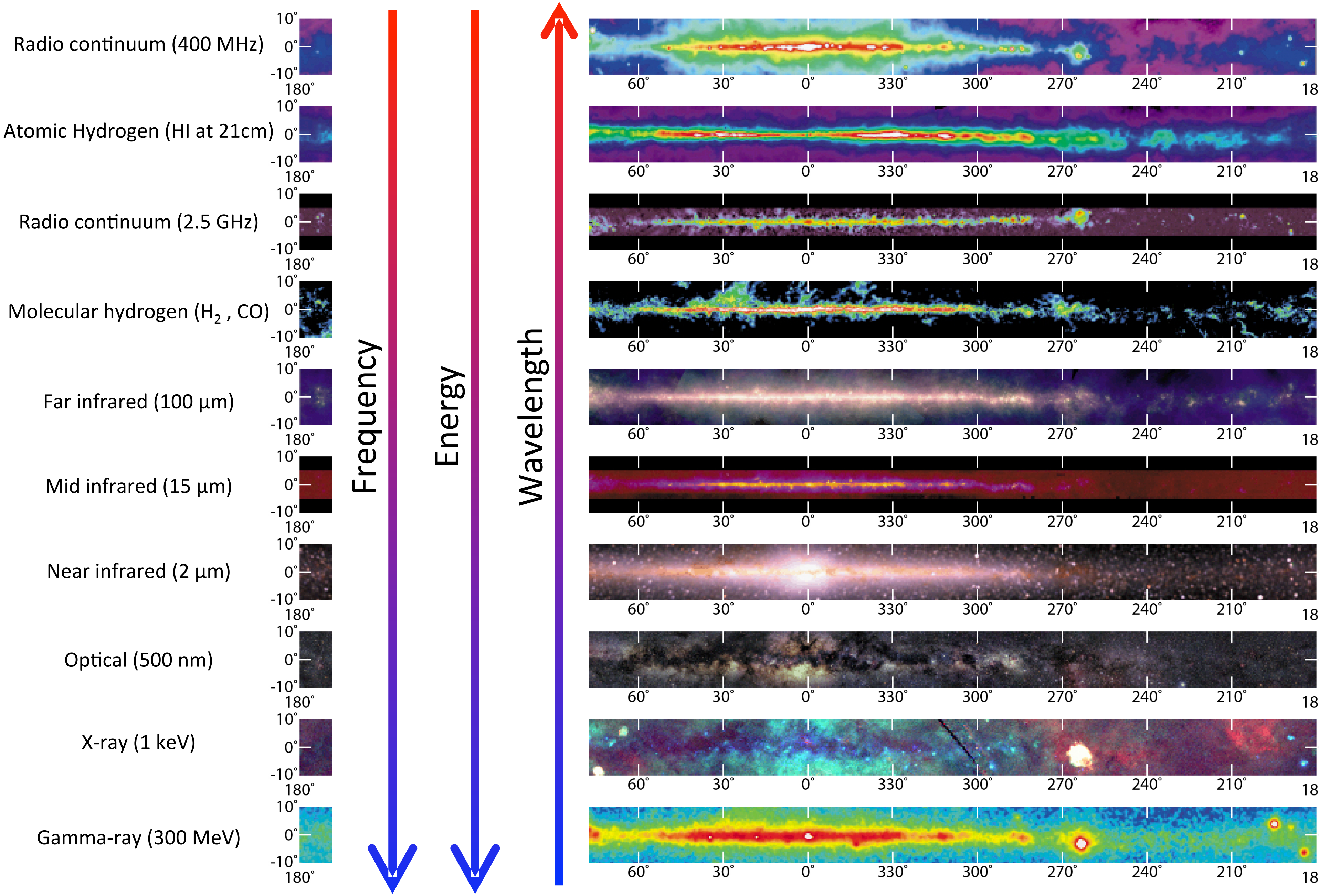
ions which ‘are expanding’
lar clouds which ‘are collapsing’

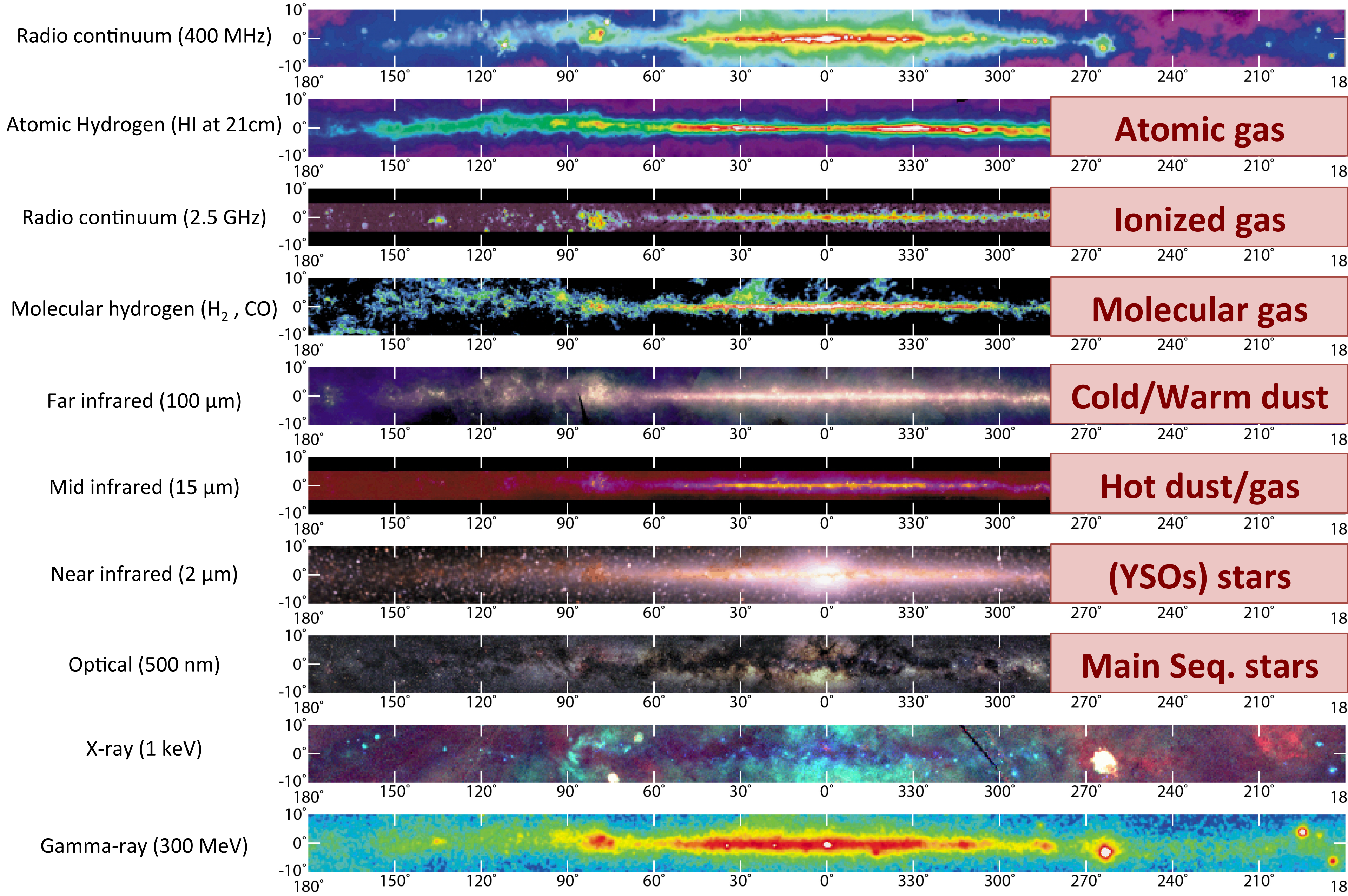
Properties of the interstellar medium



Properties of the interstellar medium



Properties of the interstellar medium



Properties of the interstellar medium

Interstellar medium: It is everything (e.g. matter and radiation) that exists in the space between stellar systems within galaxies

Components of the interstellar medium:

- Matter (dust and gas)
- Electromagnetic radiation
- Magnetic fields
- Cosmic rays (high energetic particles)
- Neutrinos
- Dark matter
- Gravitational waves

Take home messages

Properties of the interstellar medium

Most of the interstellar matter (producing extinction) is concentrated in the disk (with a scale height of about 100 pc)

Correlation between extinction properties (dust) and presence of gas (hydrogen)

The mass of the ISM is about 10-20 % of the mass of stars in the Milky Way

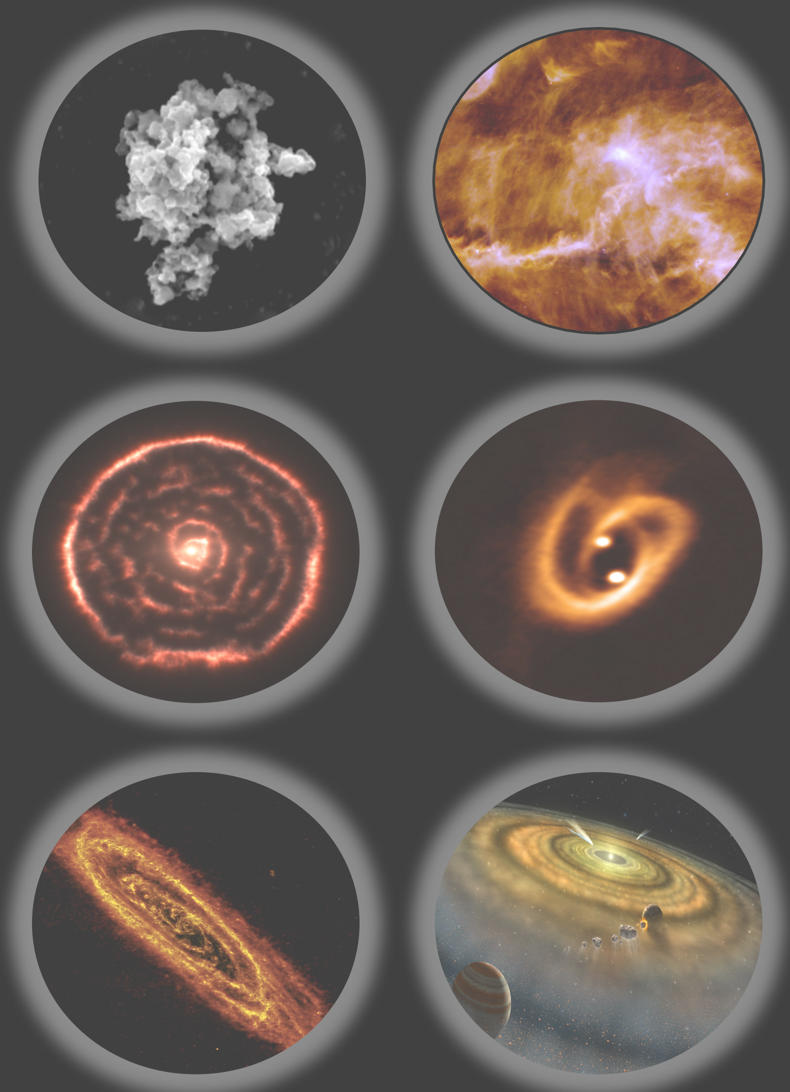
$M_{MW} \approx 1\text{x}10^{12}\ M_{\odot}$ (dark matter, stars and gas)

$M_{stars} \approx 5\text{x}10^{10}\ M_{\odot}$ (mass in stars)

$M_{ISM} \approx 5\text{x}10^{9}\ M_{\odot}$ (gas: 99% and dust: 1%)

The interstellar medium is everything in-between stars: matter (gas and dust), radiation, magnetic fields, cosmic rays, neutrinos, dark matter, gravitational waves

Life Cycle of Dust



Outline

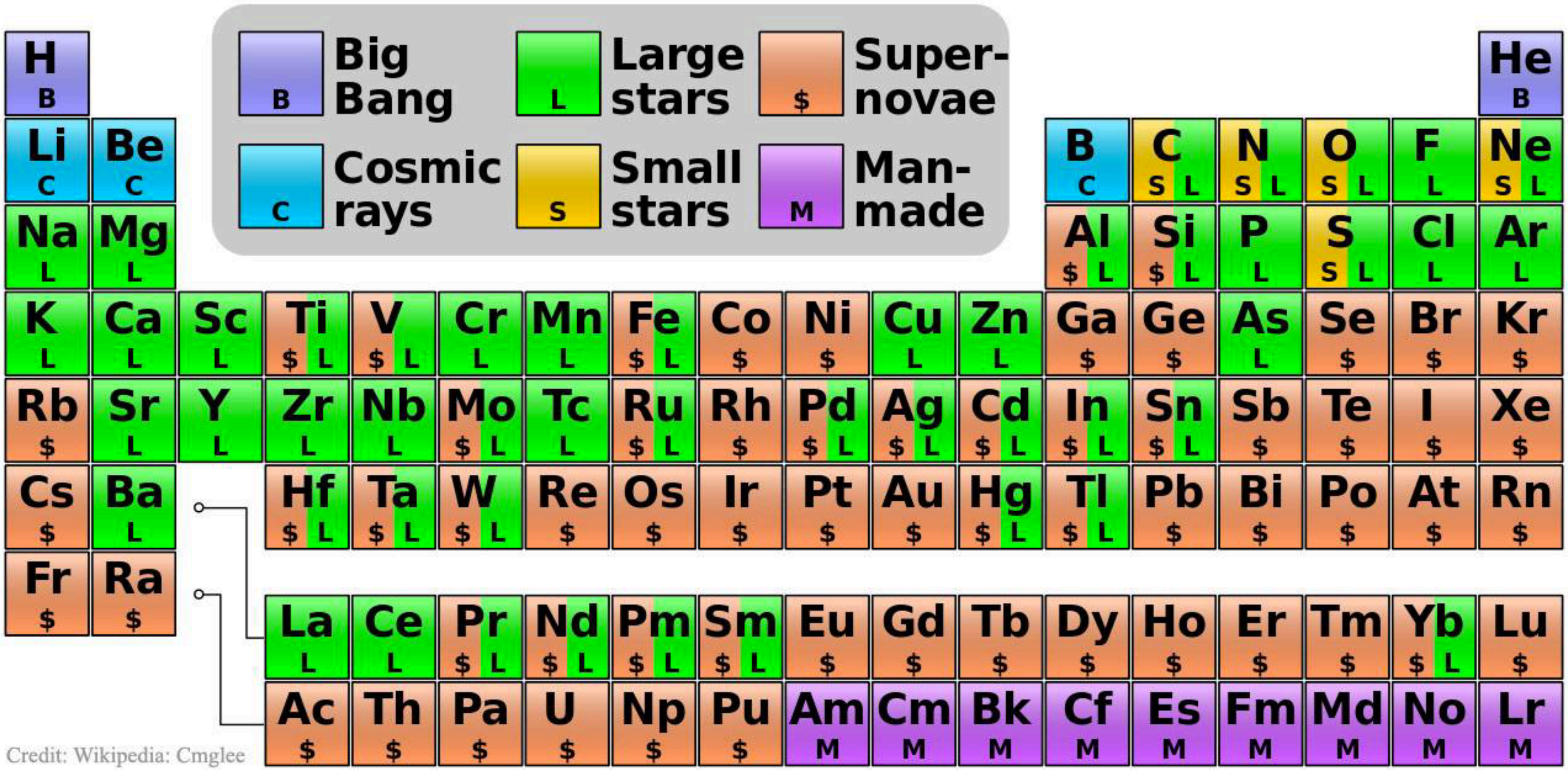
Existence of Interstellar Dust

Properties of the Interstellar Medium

Abundances, Depletion, Composition

Dusty astrophysical objects

Abundances of elements

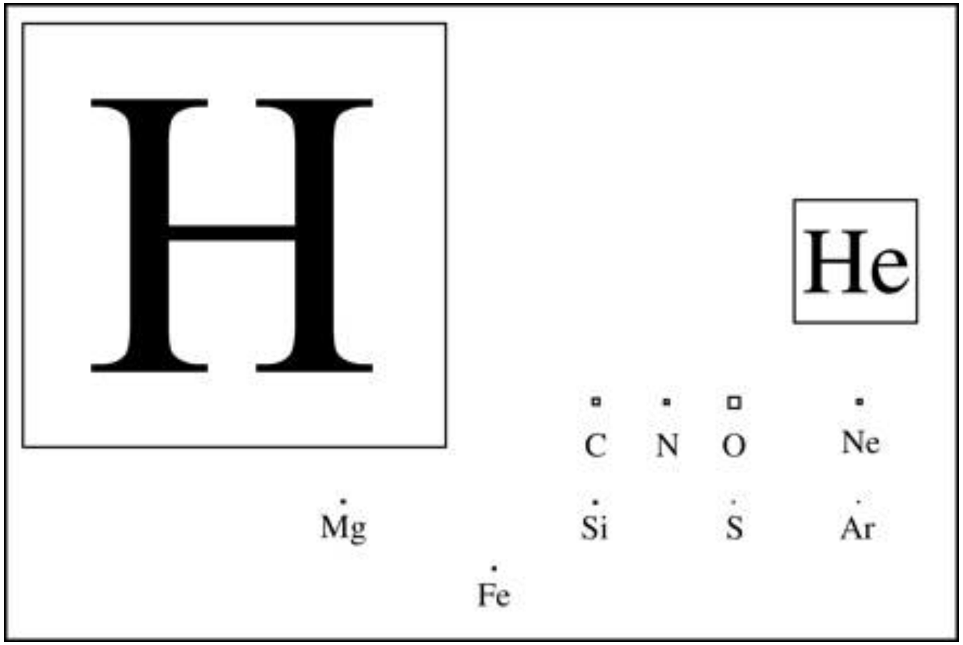


Elements of the periodic table colored based on its origin

Abundances of elements

Elements of the periodic table according to their abundance in the Universe

Astronomer's periodic table



Hydrogen is the most abundant element (about 70% in mass), followed by **helium** (about 25% in mass) and then other elements (**carbon**, **oxygen**, **nitrogen**)

Abundances of elements

Big Bang nucleogenesis

Production of nuclei during the early phases of the Universe

It probably took place during the first ≈ 10 minutes after the Big Bang

Element	Symbol	Comp.	% in num.		% in mass
Hydrogen	^{1}H	1 p	92 %		75 % in mass
Helium	^{4}He	2 p , 2 n	8 %		25 % in mass
Deuterium	^{2}H (or D)	1 p , 1 n	0.01 %	(or ≈ 10^{-4} - 10^{-5})	---
Helium-3	^{3}He	2 p , 1 n	0.01 %	(or ≈ 10^{-4} - 10^{-5})	---
Lithium	^{7}Li	3 p , 4 n	10^{-8} %	(or ≈ 10^{-10})	---
Tritium	^{3}H (or T)	1 p , 2 n	→ decayed fast into ^{3}He		
Beryllium	^{7}Be	4 p , 7 n	→ decayed fast into ^{7}Li		

Abundances of elements

Stellar nucleosynthesis

The rest of the elements (essentially all except H and He) are produced inside stars

… at T ≈ 10^6 K The little amounts of Li, Be and B are quickly converted to ^{4}He

… at T > 10^7 K H-burning begins at the inner hot core

$$4\,^1\mathrm{H} \rightarrow \,^4\mathrm{He} + 2\mathrm{e}^+ + 2\nu$$

pp-chain

no heavier element than Hydrogen is required

CNO cycle

$$\begin{aligned}
^{12}\mathrm{C} + \mathrm{p} &\rightarrow \,^{13}\mathrm{N} + \gamma \\
^{13}\mathrm{N} &\rightarrow \,^{13}\mathrm{C} + \mathrm{e}^+ + \nu \\
^{13}\mathrm{C} + \mathrm{p} &\rightarrow \,^{14}\mathrm{N} + \gamma \\
^{14}\mathrm{N} + \mathrm{p} &\rightarrow \,^{15}\mathrm{O} + \gamma \\
^{15}\mathrm{O} &\rightarrow \,^{15}\mathrm{N} + \mathrm{e}^+ + \nu \\
^{15}\mathrm{N} + \mathrm{p} &\rightarrow \,^{4}\mathrm{He} + \,^{12}\mathrm{C}.
\end{aligned}$$

Abundances of elements

Stellar nucleosynthesis

The rest of the elements (essentially all except H and He) are produced inside stars

… at $T \approx 10^6$ K The little amounts of Li, Be and B are quickly converted to ^{4}He

… at $T > 10^7$ K H-burning begins at the inner hot core

… at $T > 10^8$ K He-burning begins at the inner core where H is exhausted inner core (10 % of the mass) collapses and becomes hotter, while the envelope expands and cools down

$$^4\mathrm{He} + {}^4\mathrm{He} \rightleftharpoons {}^8\mathrm{Be} + \gamma$$

^{8}Be dissociates rapidly back to ^{4}He

$$3\,{}^4\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

$$^{12}\mathrm{C} + {}^4\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \gamma$$

Abundances of elements

Stellar nucleosynthesis

The rest of the elements (essentially all except H and He) are produced inside stars

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… at T > 10^7 K H-burning begins at the inner hot core

… at T > 10^8 K He-burning begins at the inner core where H is exhausted

… at T > 5x10^8 K C-burning begins at the inner core

… at T > 10^9 K O-burning begins at the inner core

$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{12}\mathrm{C} &\rightarrow {}^{24}\mathrm{Mg} + \gamma \\
&\rightarrow {}^{23}\mathrm{Na} + \mathrm{p} \\
&\rightarrow {}^{20}\mathrm{Ne} + {}^{4}\mathrm{He}
\end{aligned}
$$

$$
\begin{aligned}
{}^{20}\mathrm{Ne} + {}^{4}\mathrm{He} &\rightarrow {}^{24}\mathrm{Mg} + \gamma \\
{}^{24}\mathrm{Mg} + {}^{4}\mathrm{He} &\rightarrow {}^{28}\mathrm{Si} + \gamma
\end{aligned}
$$

$$
\begin{aligned}
{}^{16}\mathrm{O} + {}^{16}\mathrm{O} &\rightarrow {}^{32}\mathrm{S} + \gamma \\
&\rightarrow {}^{31}\mathrm{P} + \mathrm{p} \\
&\rightarrow {}^{31}\mathrm{S} + \mathrm{n} \\
&\rightarrow {}^{28}\mathrm{Si} + {}^{4}\mathrm{He}
\end{aligned}
$$

Abundances of elements

Stellar nucleosynthesis

The rest of the elements (essentially all except H and He) are produced inside stars

... at $T \approx 10^6$ K The little amounts of Li, Be and B are quickly converted to ^{4}He

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... at $T > 10^8$ K He-burning begins at the inner core where H is exhausted

... at $T > 5 \times 10^8$ K C-burning begins at the inner core

... at $T > 10^9$ K O-burning begins at the inner core

... at $T > 2 \times 10^9$ K we reach the limit by forming Fe and Ni at the core of the star

Abundances of elements

Stellar nucleosynthesis

The rest of the elements (essentially all except H and He) are produced inside stars

... at $T \approx 10^6$ K The little amounts He

... at $T > 10^7$ K H-burning begins a

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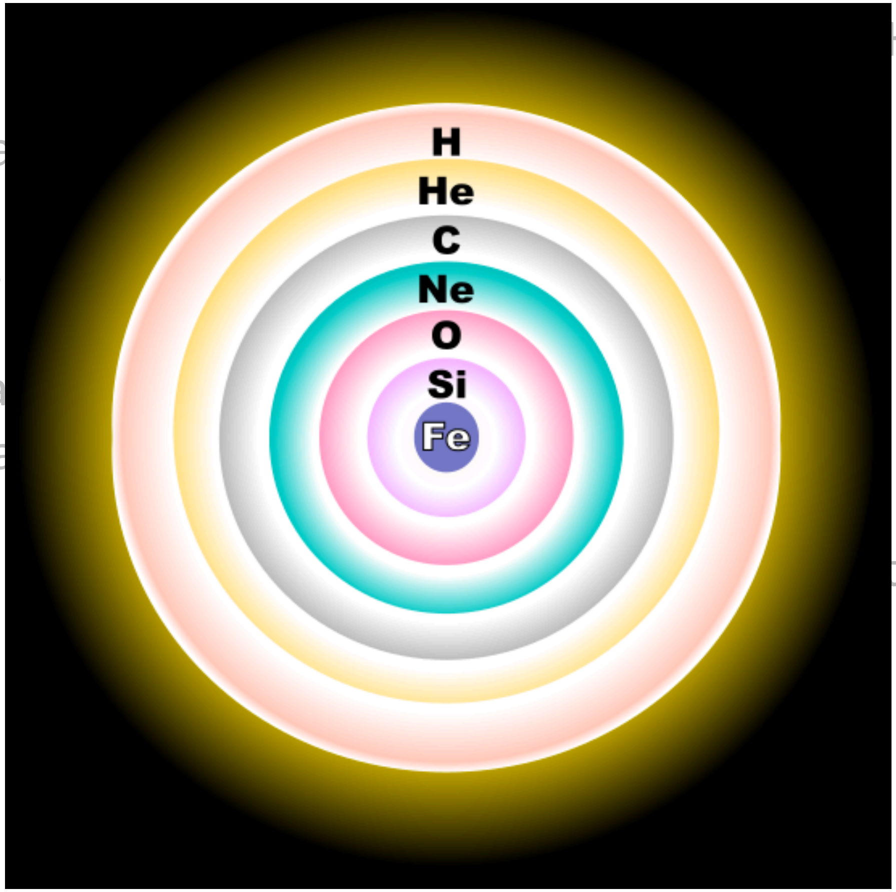
... at $T > 5x10^8$ K C-burning begins a

... at $T > 10^9$ K O-burning begins a

... at $T > 2x10^9$ K we reach the limit tar

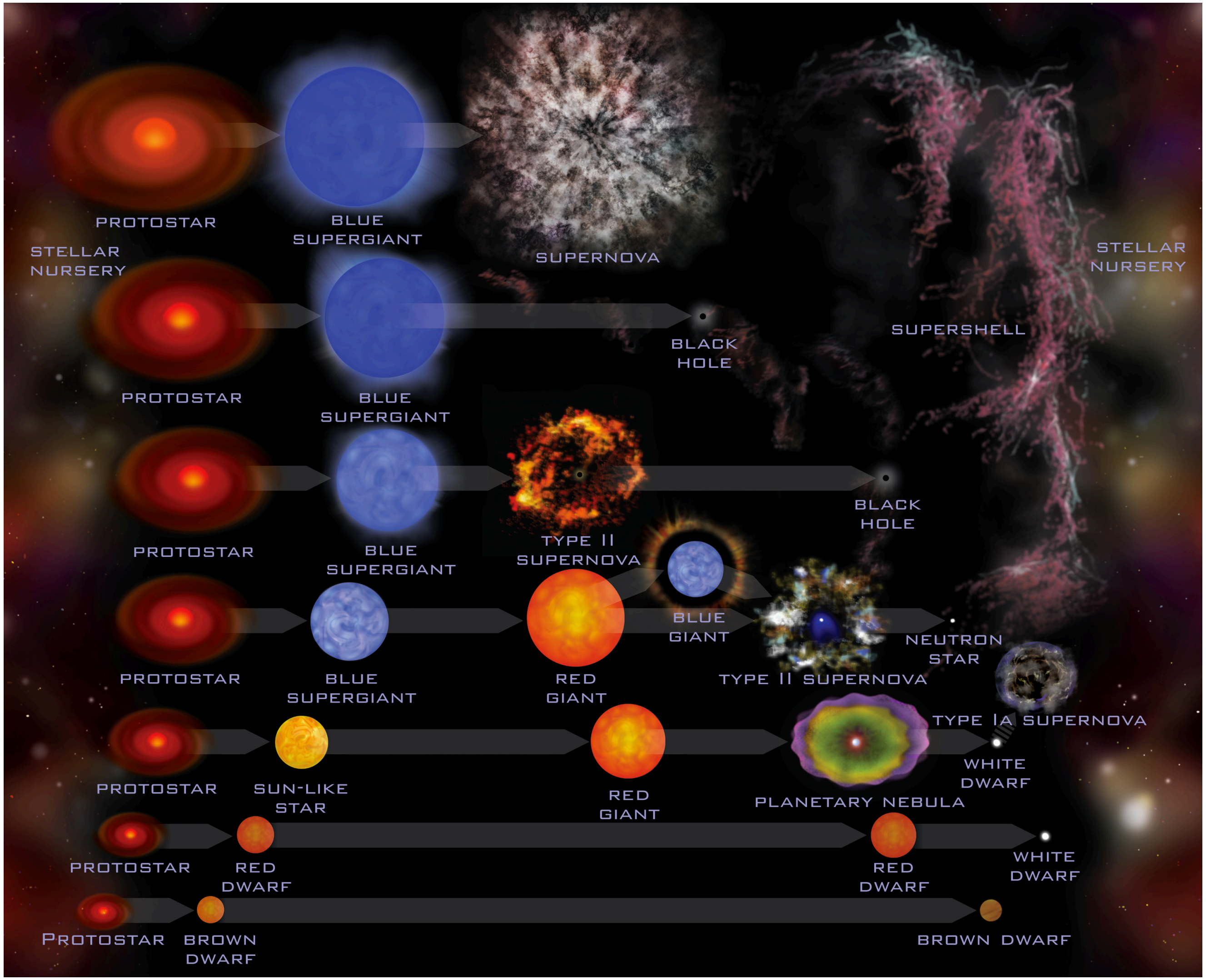


Stars are onion-like structures with heavier elements in their centers

Abundances, depletion, composition

Abundances of elements

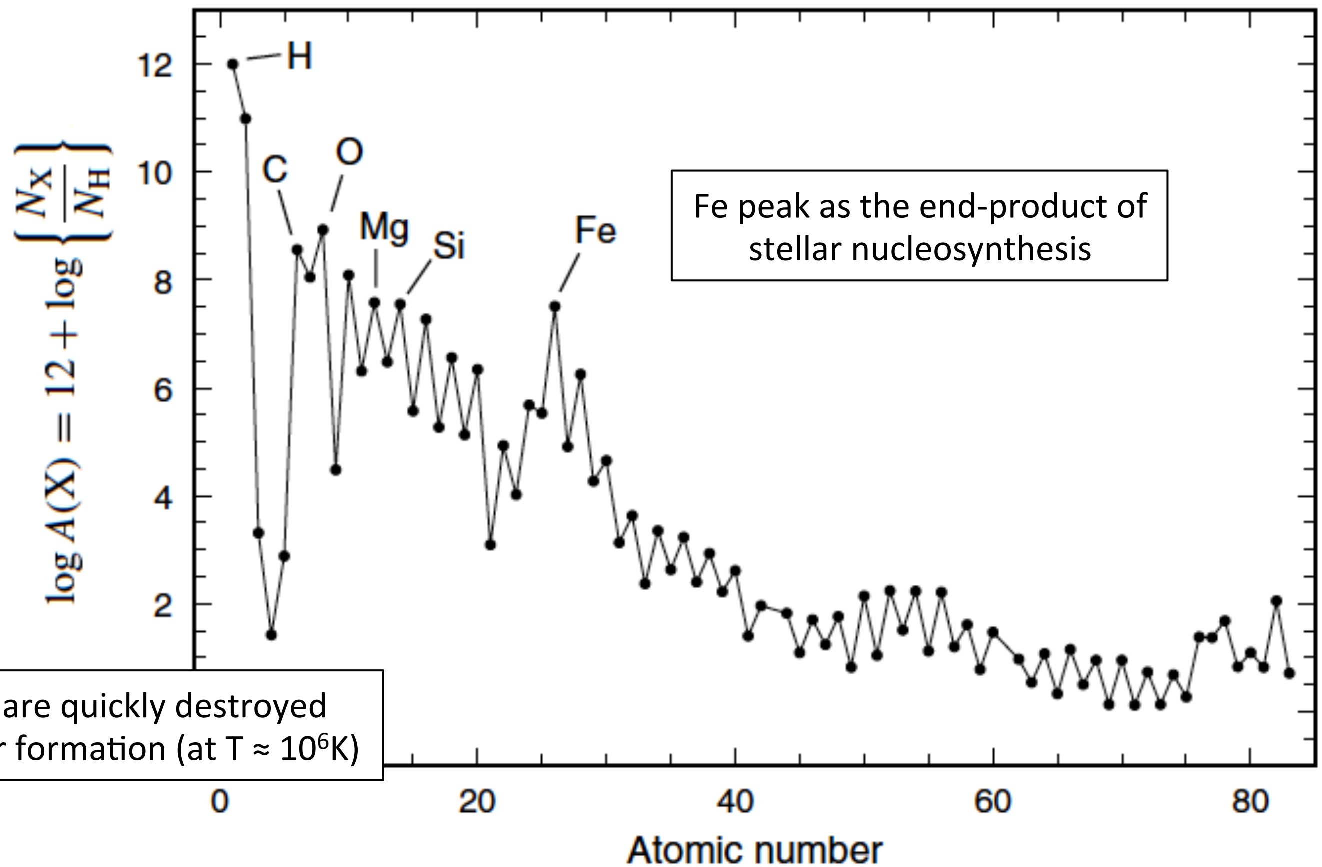
Enrichment of the Interstellar Medium (via winds, AGBs and SNe)



Credit Jet Propulsion Laboratory

Typical abundances in the interstellar medium

The element abundances in the Solar System provide a general reference set

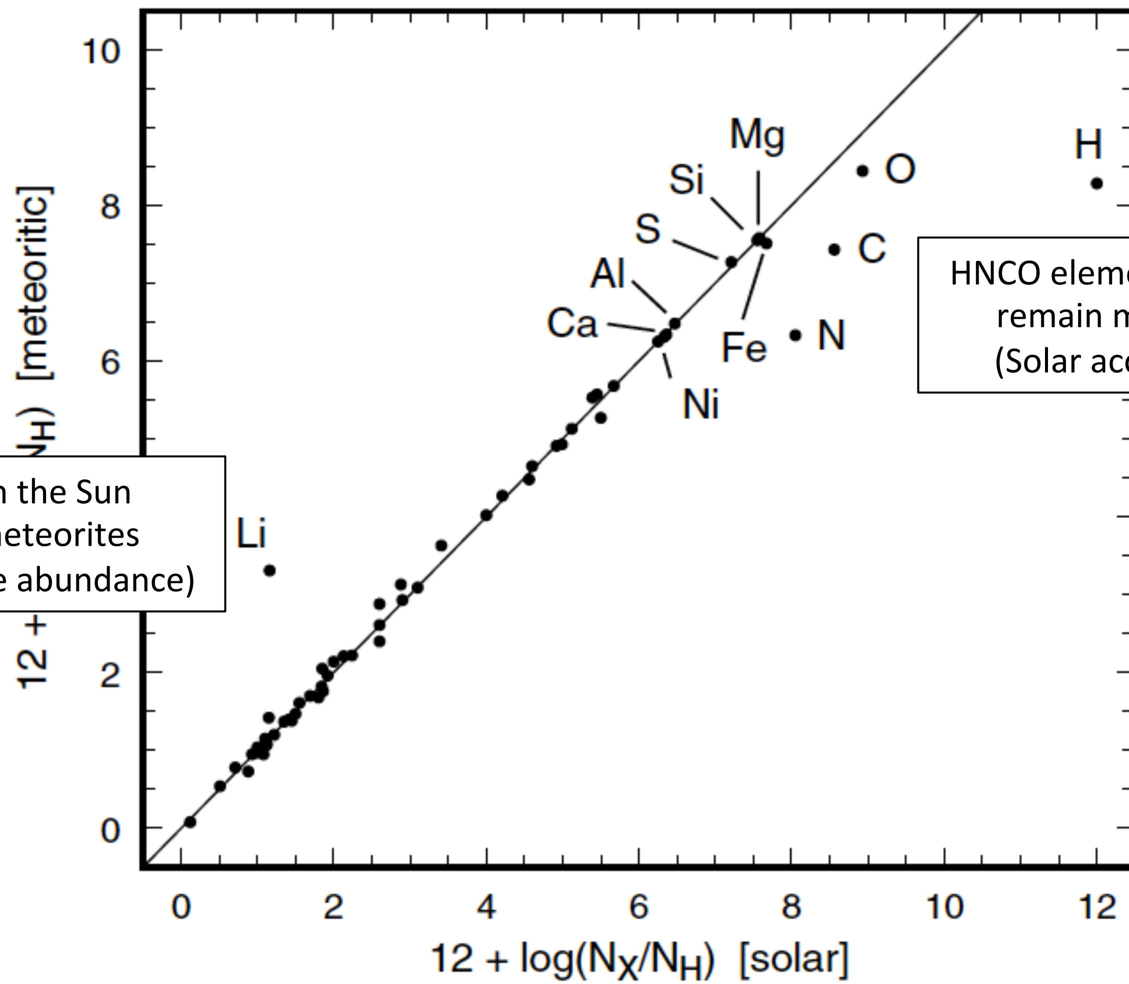


Li, Be, B are quickly destroyed during star formation (at T ≈ 10^6K)

Note.- Elements in Sun's photosphere are all in gas phase (i.e. detectable)
Not processed by nuclear reactions (not connected to the stellar core)
→ trace abundances of the interstellar gas when the Sun formed

Typical abundances in the interstellar medium

Solar System abundances from Sun's photosphere and abundances in meteorites



HNCO elements are volatiles that remain mainly in gas phase (Solar accurate abundance)

Li is destroyed in the Sun but remains in meteorites (meteorites accurate abundance)

Abundances, depletion, composition

Typical abundances in the interstellar medium

Element	z	m ($\mathrm{g\,mol^{-1}}$)	$\log A_\odot$ ($N_H = 10^{12}$)	$A_\odot$ (ppm)
H	1	1.01	12.00	10^6
C	6	12.01	8.56	360
N	7	14.01	7.97	93
O	8	16.00	8.83	676
Na	11	22.99	6.31	2
Mg	12	24.31	7.59	39
Al	13	26.98	6.48	3
Si	14	28.09	7.55	35
P	15	30.97	5.57	0.4
S	16	32.06	7.27	19
Ca	20	40.08	6.34	2
Cr	24	52.00	5.68	0.5
Fe	26	55.85	7.51	32
Ni	28	58.71	6.25	2

Solar System abundances of the 14 most abundant elements likely to be present in the interstellar matter (dust)

$$A(X) = 10^6 \left\{ \frac{N_X}{N_H} \right\}$$

ppm: parts per million

$$\log A(X) = 12 + \log \left\{ \frac{N_X}{N_H} \right\}$$

Abundances, depletion, composition

Typical abundances in the interstellar medium

Element	z	m ($\mathrm{g\,mol^{-1}}$)	$\log A_\odot$ ($N_H = 10^{12}$)	$A_\odot$ (ppm)
H	1	1.01	12.00	10^6
C	6	12.01	8.56	360
N	7	14.01	7.97	93
O	8	16.00	8.83	676
Na	11	22.99	6.31	2
Mg	12	24.31	7.59	39
Al	13	26.98	6.48	3
Si	14	28.09	7.55	35
P	15	30.97	5.57	0.4
S	16	32.06	7.27	19
Ca	20	40.08	6.34	2
Cr	24	52.00	5.68	0.5
Fe	26	55.85	7.51	32
Ni	28	58.71	6.25	2

Interstellar dust is expected to be made of these elements

Thus, the mass fraction available to make dust is:

$$Z_\odot = 0.71 \sum \left\{ \frac{m_X N_X}{m_H N_H} \right\}_\odot \simeq 0.016$$

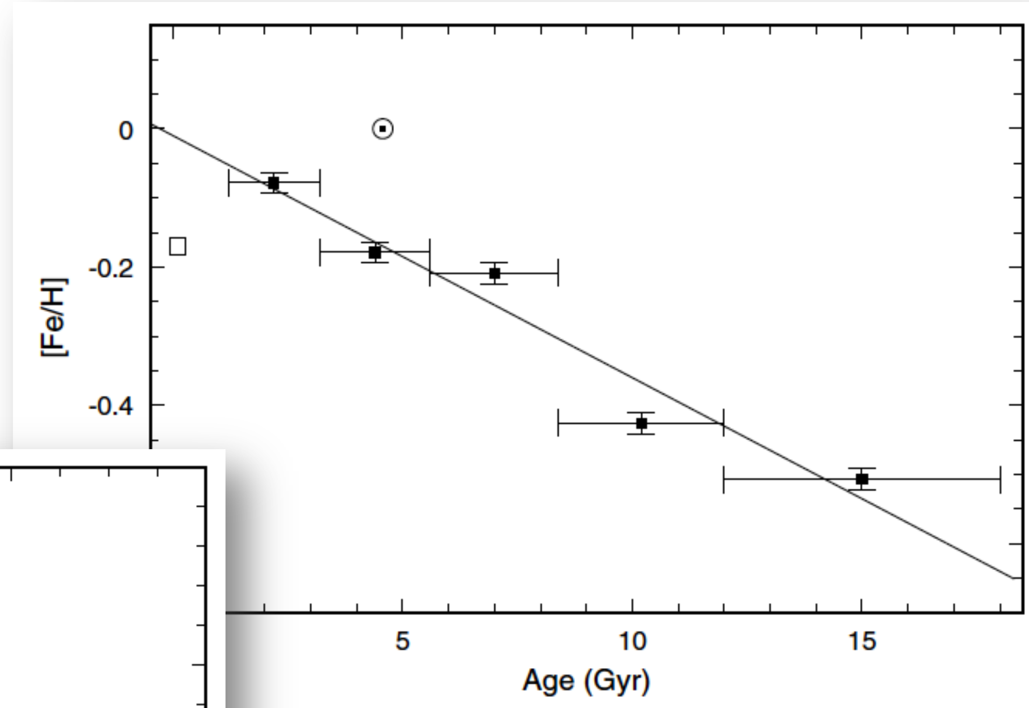
Note.- 0.71 is a factor to discount noble gases

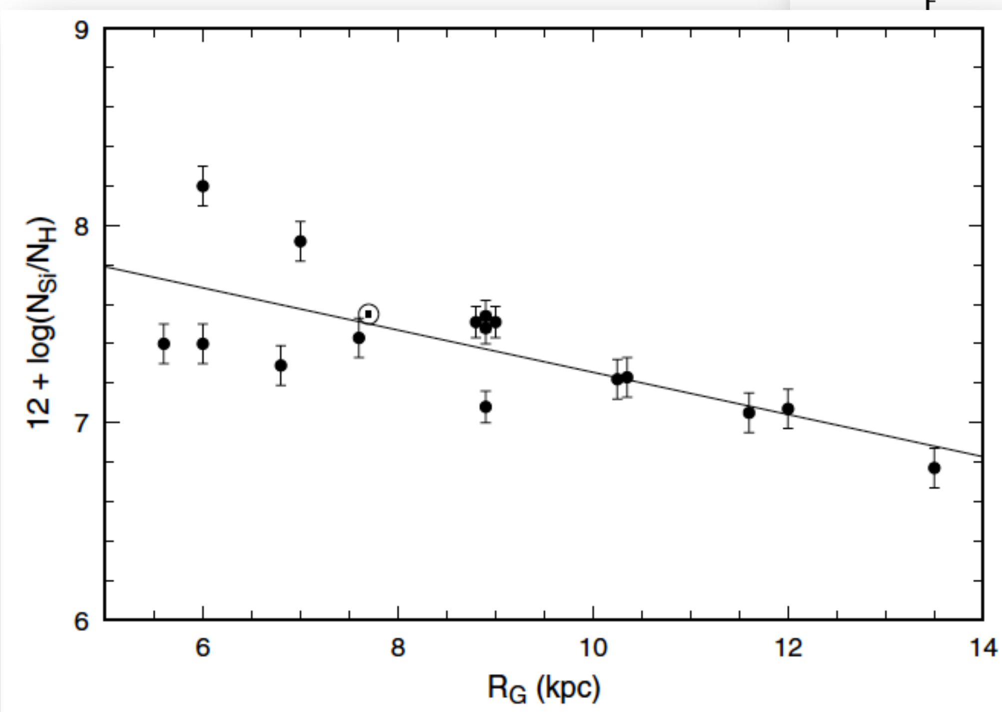
This is effectively an upper limit on the dust-to-gas ratio
(for solar abundances)

Abundances, depletion, composition

Abundances trends in the Galaxy

Temporal variation
of heavy-element enrichment of the interstellar medium





Spatial variation
of heavy-element enrichment of the interstellar medium

Depletions of elemental abundances

Depletion

Under-abundance of a gas-phase element with respect to its standard reference

Element	A_{gas} (ppm)	(Standard ≡ Solar) D	δ	A_{dust}
C	140	−0.41	0.61	220
N	75	−0.09	0.19	17
O	320	−0.32	0.52	356
Na	0.6	−0.50	0.68	1
Mg	3.1	−1.10	0.92	36
Al	0.01	−2.50	1.00	3
Si	0.9	−1.60	0.97	34
P	0.07	−0.74	0.82	0.3
S	19	0.00	0.00	0
Ca	0.0005	−3.60	1.00	2
Cr	0.04	−2.10	0.99	0.5
Fe	0.32	−2.00	0.99	32
Ni	0.01	−2.30	1.00	2

Depletion of element X is defined as:

$$D(X) = \log\left\{\frac{N_X}{N_H}\right\} - \log\left\{\frac{N_X}{N_H}\right\}_{ISM}$$

ISM refers to solar abundance

Fractional depletion:

$$\delta(X) = 1 - 10^{D(X)}$$

Abundance of element X in the dust relative to total hydrogen:

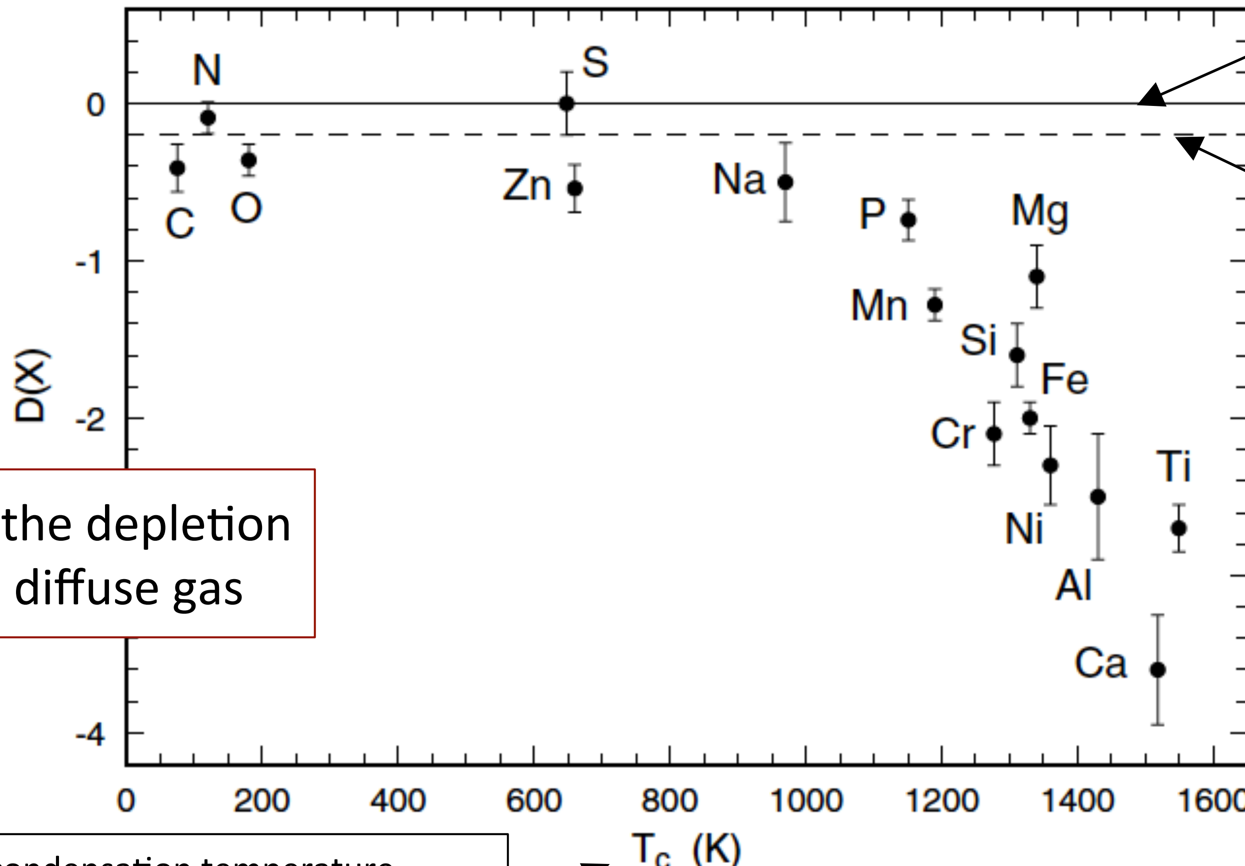
$$A_{dust} = \delta(X) A_{ISM}$$

$$A_{ISM} = A_{gas} + A_{dust}.$$

Depletions of elemental abundances

Depletion

Under-abundance of a gas-phase element with respect to its standard reference



Solar abundance

D(x) = -0.2 dex

These are the depletion levels in diffuse gas

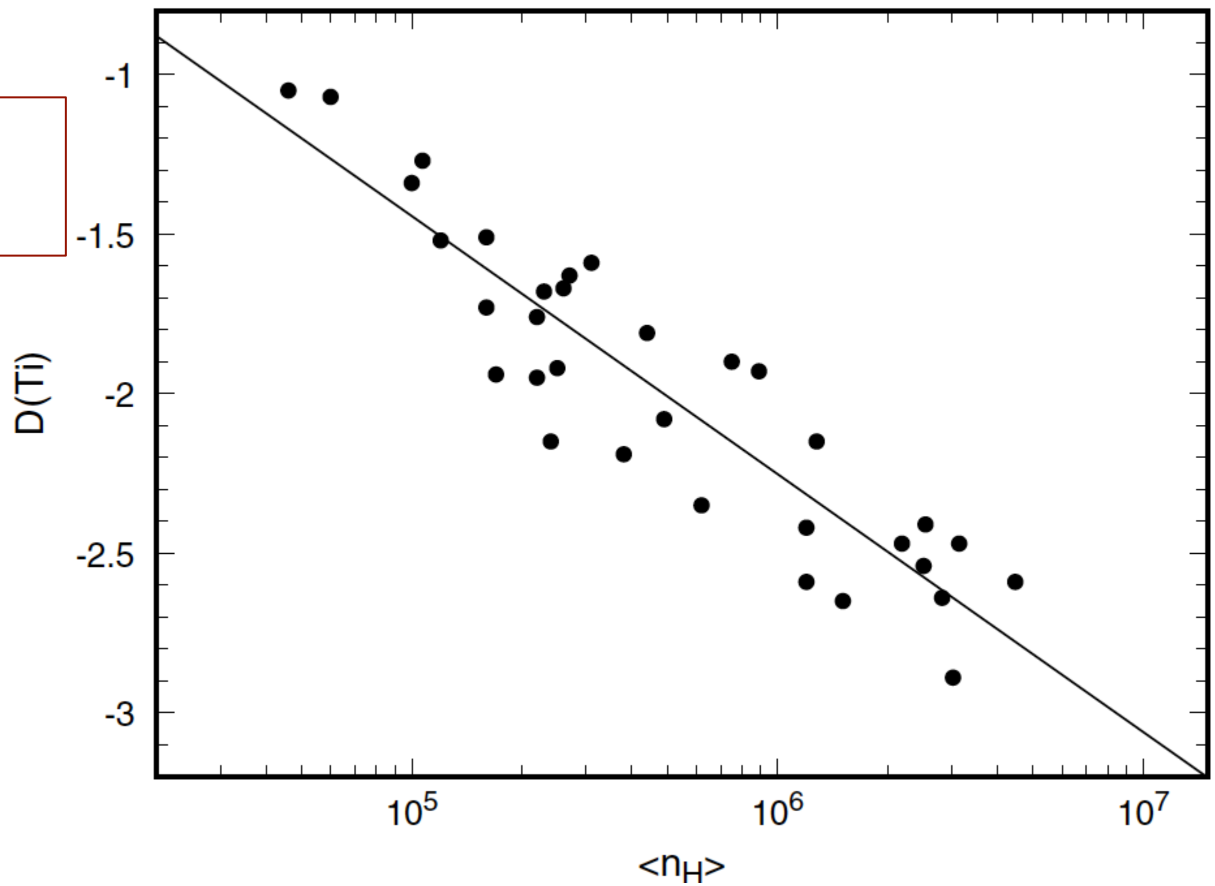
Tc – condensation temperature
Defined as the temperature at which 50% of the atoms condense into the solid phase

Depletions of elemental abundances

Depletion

Under-abundance of a gas-phase element with respect to its standard reference

Depletion increases with gas density



Example of increase of depletion for Ti as function of ISM gas density

Depletions of elemental abundances

Depletion

Under-abundance of a gas-phase element with respect to its standard reference

Grouping the elements contained in dust

Group I C, N, O, S, Zn

Elements with low to moderate depletions (0-60%) that do not correlate strongly with physical conditions (e.g., density)

Group II Mg, Si, P

Elements with varying depletion according to density: low in intercloud medium, but high in diffuse clouds (80-100%)

Group III Fe, Ti, Ca, Cr, Mn, Ni

Elements with varying depletion according to density, but always high (80-100%). Seems to represent an almost indestructible component of interstellar dust

Depletions of elemental abundances

Depletion

Under-abundance of a gas-phase element with respect to its standard reference

Element	A_{gas} (ppm)	(Standard ≡ Solar) D	δ	A_{dust}
C	140	−0.41	0.61	220
N	75	−0.09	0.19	17
O	320	−0.32	0.52	356
Na	0.6	−0.50	0.68	1
Mg	3.1	−1.10	0.92	36
Al	0.01	−2.50	1.00	3
Si	0.9	−1.60	0.97	34
P	0.07	−0.74	0.82	0.3
S	19	0.00	0.00	0
Ca	0.0005	−3.60	1.00	2
Cr	0.04	−2.10	0.99	0.5
Fe	0.32	−2.00	0.99	32
Ni	0.01	−2.30	1.00	2

Mass density of the dust components

$$\rho_d(X) = 10^{-6} A_{dust} \left(\frac{m_X}{m_H} \right) \rho_H$$

$$\rho_d = \sum \rho_d(X)$$

$$\approx 2.3 \times 10^{-23} \text{ kg m}^{-3}$$

Dust-to-gas mass fraction is:

$$Z_d = 0.71 \frac{\rho_d}{\rho_H} \approx 0.009$$

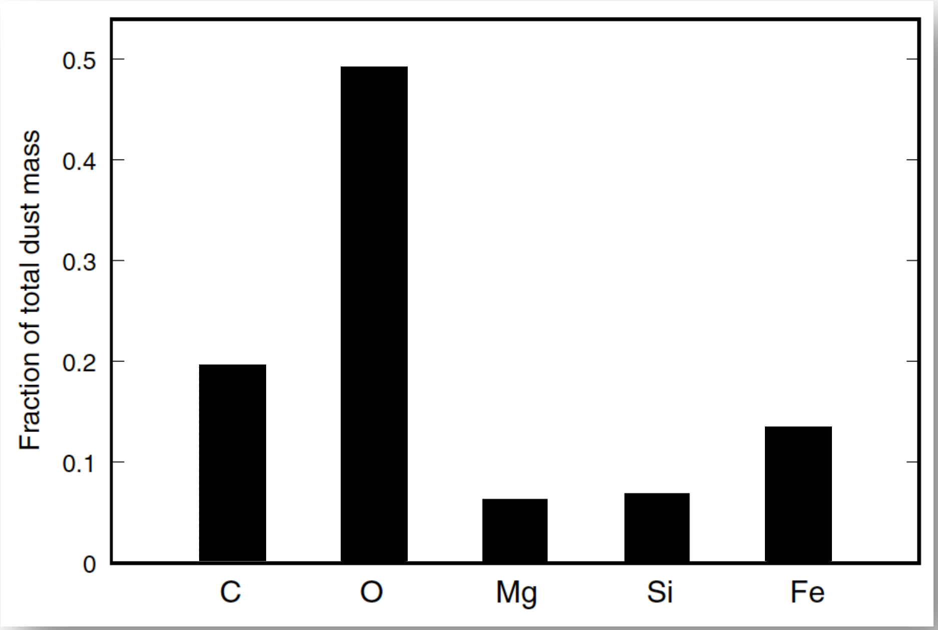
Note.- 0.71 is a factor to discount noble gases

Depletions of elemental abundances

Depletion

Under-abundance of a gas-phase element with respect to its standard reference

Mass fraction of the total dust mass



Mass density of the dust components

$$\rho_{\rm d}(X) = 10^{-6} A_{\rm dust} \left(\frac{m_X}{m_H}\right) \rho_H$$

$$\rho_{\rm d} = \sum \rho_{\rm d}(X)$$

$$\approx 2.3 \times 10^{-23}\ {\rm kg\ m^{-3}}$$

Dust-to-gas mass fraction is:

$$Z_{\rm d} = 0.71 \frac{\rho_{\rm d}}{\rho_H} \approx 0.009$$

Note.- 0.71 is a factor to discount noble gases

Models of dust grains

Grain models

Descriptions of the **composition** of dust grains that reproduce all observables

- **Ices such as H_2O, CO, NH_3, CH_4, …** (e.g. Lindblad 1935):
  Favored by the high cosmic abundance of the constituent atoms
- **Metals such as iron** (e.g. Schalen 1936):
  Metals alone not sufficient abundant to account for the interstellar extinction
- **Dirty ices** (e.g. Oort and van de Hulst 1946):
  Model for ice nucleation and growth, including metals.
  Extinction calculations for such particles give a good fit to the extinction curve from infrared to near ultraviolet (e.g., Greenberg 1968)
- **Platt particles** (e.g. Platt 1956, Donn 1968):
  Unsaturated molecules (rather than classical ice grains),
  with radii no more than ≈ 1 nm
  This macromolecules are indeed polycyclic aromatic hydrocarbons (PAHs),
  which account for ≈ 15% of C in the grain

Models of dust grains

Grain models

Descriptions of the **composition** of dust grains that reproduce all observables

- **Graphites and Silicates**:
  New observations, expanding the observable electromagnetic range (IR, UV) revealed that previous models were not enough

diamond graphite fullerene (C_{60})

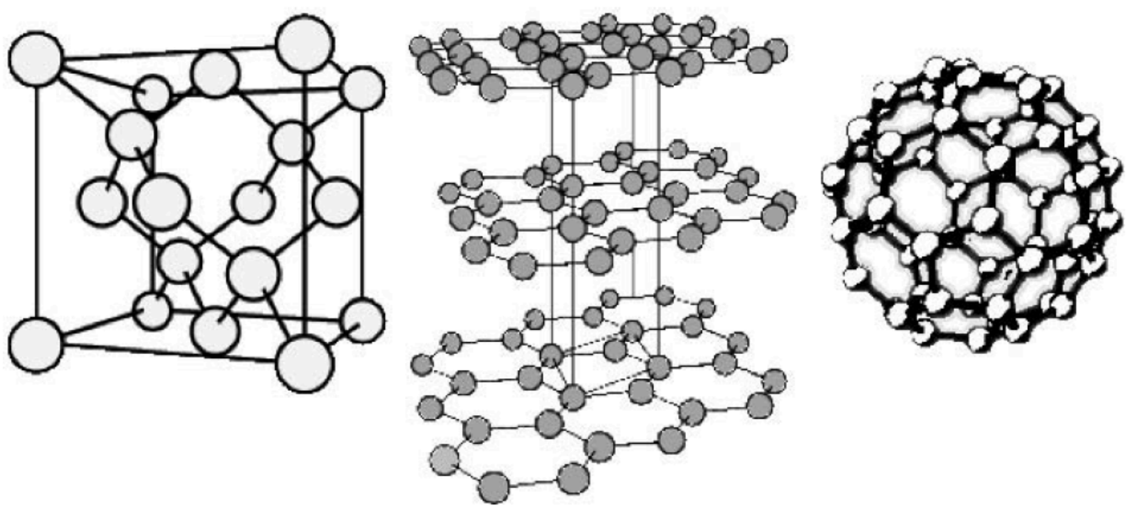


Figure credit: Mark Raylings

Models of dust grains

Grain models

Descriptions of the **composition** of dust grains that reproduce all observables

- **Graphites and Silicates**:
  New observations, expanding the observable electromagnetic range (IR, UV) revealed that previous models were not enough

2-d representation of amorphous silicate

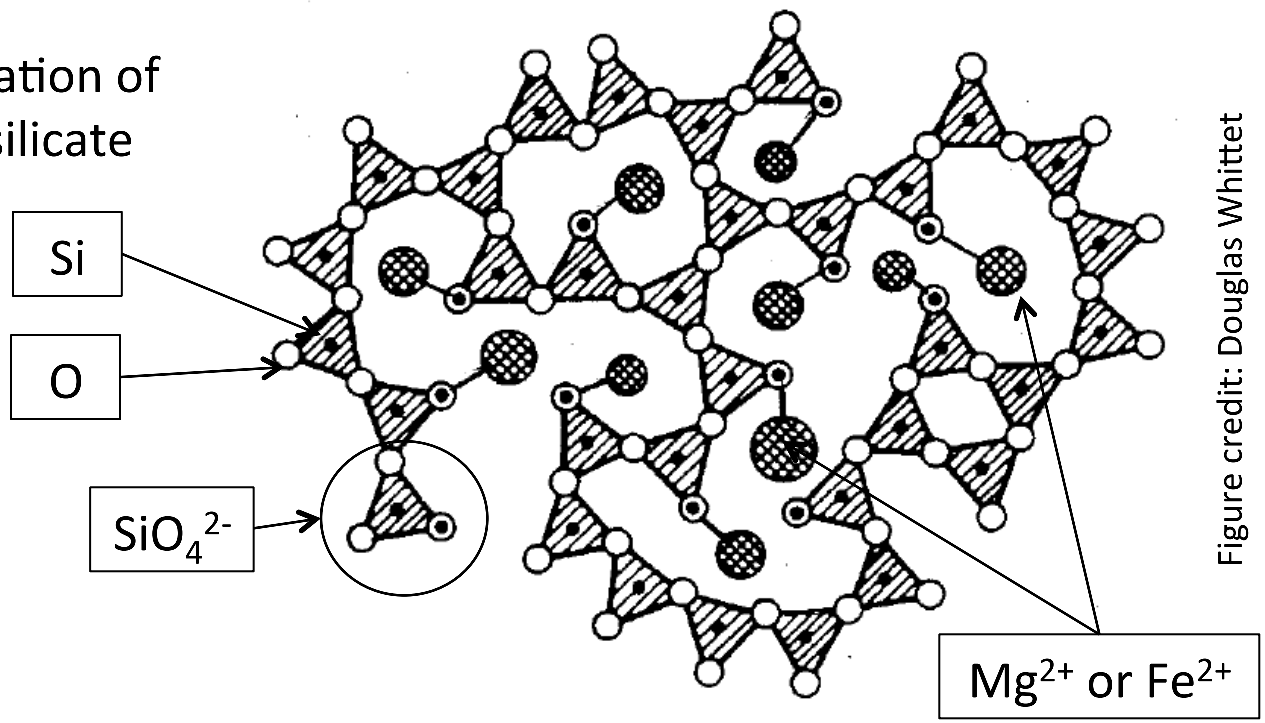


Figure credit: Douglas Whittet

Models of dust grains

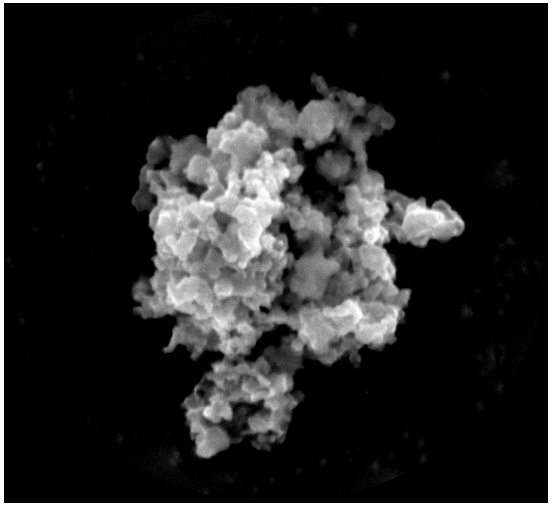
Grain models

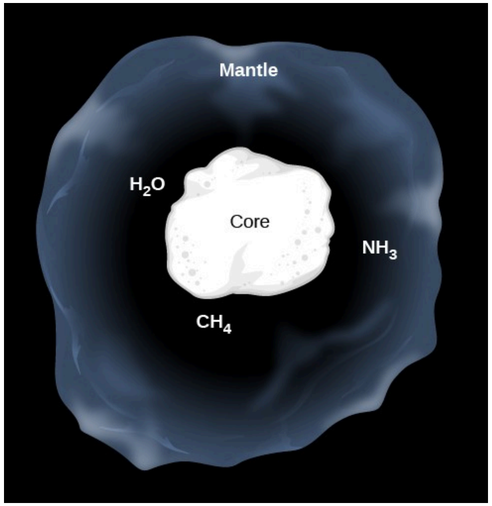
Descriptions of the **composition** of dust grains that reproduce all observables

- **Refractory mantle models**:
  The so-called MRN model (e.g. Mathis et al 1977) explains the extinction curve from infrared to far ultraviolet by separate populations of graphite and silicates

  Defines a power-law size distribution: $n(a) \propto a^{-3.5}$

  Effects of porosity are also included in the models





Models of dust grains

Grain models

Descriptions of the **composition** of dust grains that reproduce all observables

Grain models have to fit all observables (see Draine et al 2003, ARA&A)

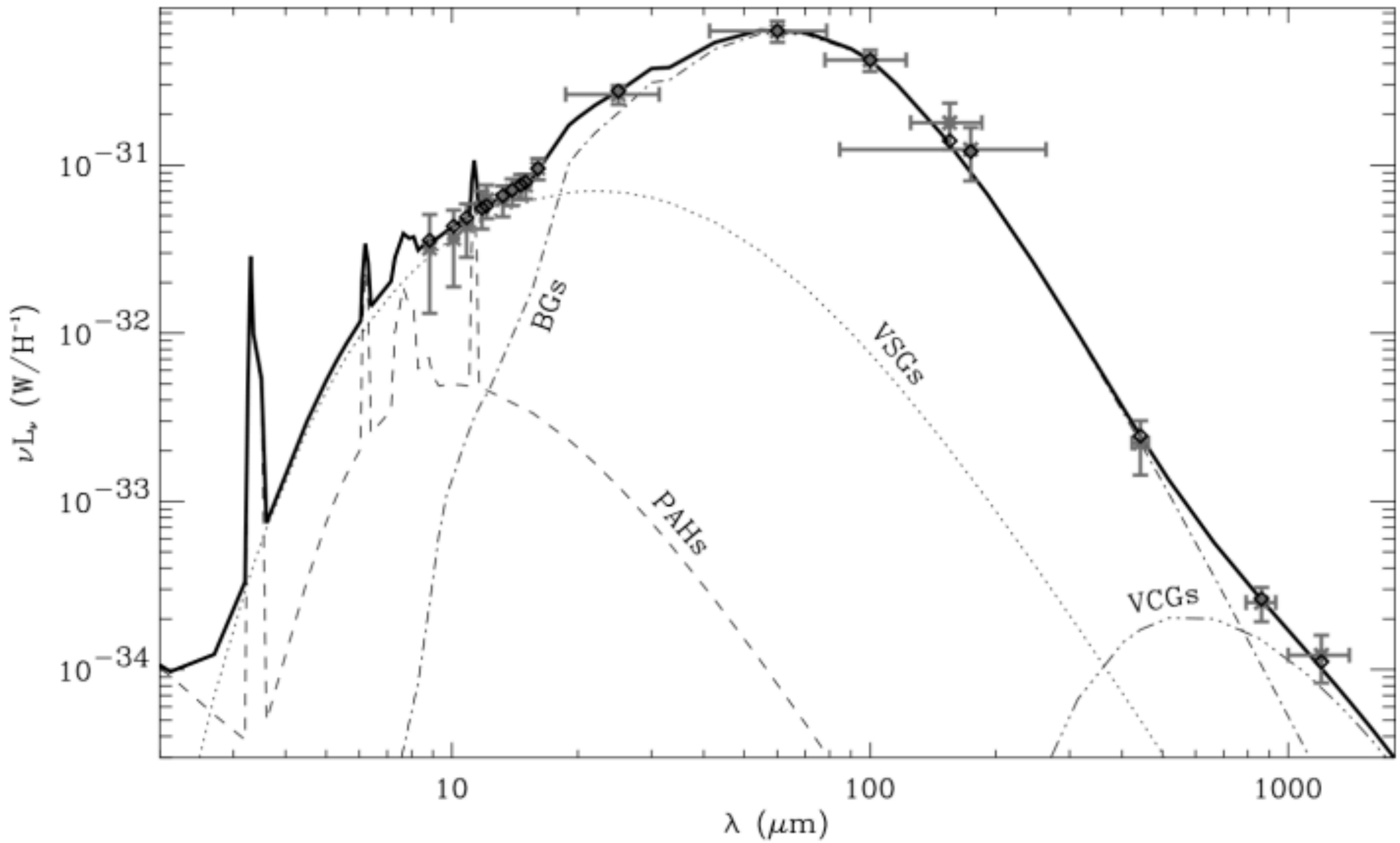
- absorption and scattering in the UV and optical (extinction curves)
- emission in the infrared (and sub-mm), both continuum and spectral features
- polarization properties
- abundances and depletion constraints

Models of dust grains

Grain models

Descriptions of the **composition** of dust grains that reproduce all observables

Grain models have to fit all observables (see Draine et al 2003, ARA&A)



Composition of grains via infrared spectroscopy

Vibrational modes in solids

Dust composition is investigated via spectroscopic observations in the infrared

Molecular vibrational modes in some refractory solids

Material	Mode	λ (μm)	κ ($m^2\ kg^{-1}$)
HAC	C–H stretch	3.4	30–690
Organic residue	C–H stretch	3.4	40–80
$MgSiO_3$ (enstatite)	Si–O stretch	9.7	315
	O–Si–O bend	19.0	88
$(Mg, Fe)SiO_3$ (bronzite)	Si–O stretch	9.5	300
	O–Si–O bend	18.5	165
$FeSiO_3$ (ferrosilite)	Si–O stretch	9.5	210
	O–Si–O bend	20.0	82
Mg_2SiO_4 (fosterite)	Si–O stretch	10.0	240
	O–Si–O bend	19.5	86
Silicon carbide	Si–C stretch	11.2	660

Abundances, depleti

Composition of grains via

Vibrational modes in solids

Dust composition is investigated via spectro

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Silicon carbide	Si–C stretch	11.2	660

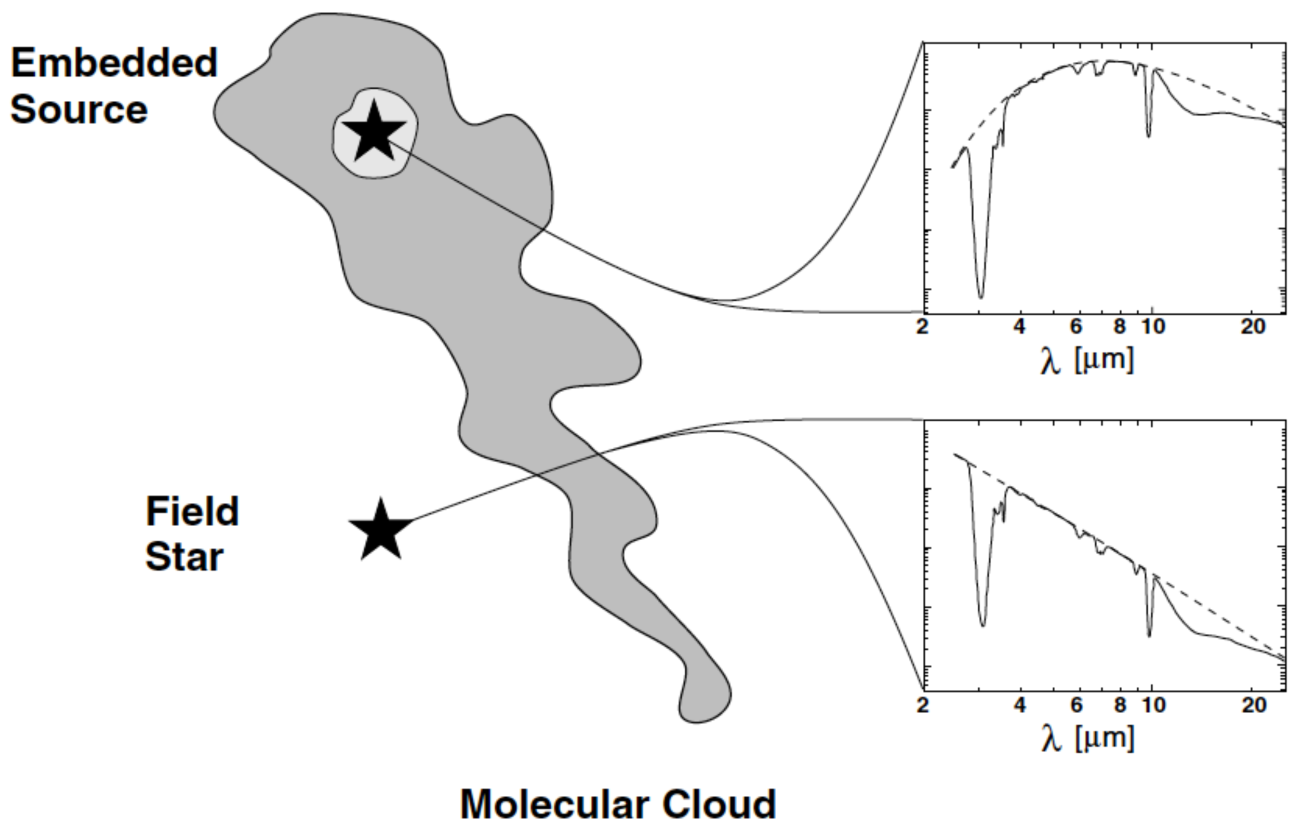
Molecular vibrational modes in some ices

Molecule	Mode	λ (μm)	$\mathcal{A}$ (m/molecule)
H_2O	O–H stretch	3.05	2.0×10^{-18}
	H–O–H bend	6.0	8.4×10^{-20}
	libration	12	3.1×10^{-19}
NH_3	N–H stretch	2.96	2.2×10^{-19}
	deformation	6.16	4.7×10^{-20}
	inversion	9.35	1.7×10^{-19}
CH_4	C–H stretch	3.32	7.7×10^{-20}
	deformation	7.69	7.3×10^{-20}
CO	C=O stretch	4.67	1.1×10^{-19}
CO_2	C=O stretch	4.27	7.6×10^{-19}
	O=C=O bend	15.3	1.5×10^{-19}
CH_3OH	O–H stretch	3.08	1.3×10^{-18}
	C–H stretch	3.53	5.3×10^{-20}
	CH_3 deformation	6.85	1.2×10^{-19}
	CH_3 rock	8.85	1.8×10^{-20}
	C–O stretch	9.75	1.8×10^{-19}
H_2CO	C–H stretch (asym.)	3.47	2.7×10^{-20}
	C–H stretch (sym.)	3.54	3.7×10^{-20}
	C=O stretch	5.81	9.6×10^{-20}
	CH_2 scissor	6.69	3.9×10^{-20}
HCOOH	C=O stretch	5.85	6.7×10^{-19}
	CH deformation	7.25	2.6×10^{-20}
C_2H_6	C–H stretch	3.36	1.6×10^{-19}
	CH_3 deformation	6.85	6.0×10^{-20}
CH_3CN	C≡N stretch	4.41	3.0×10^{-20}
OCN^-	C≡N stretch	4.62	1.0×10^{-18}
H_2S	S–H stretch	3.93	2.9×10^{-19}
OCS	O=C=S stretch	4.93	1.5×10^{-18}
SO_2	S=O stretch	7.55	3.4×10^{-19}

Composition of grains via infrared spectroscopy

Vibrational modes in solids

Dust composition is investigated via spectroscopic observations in the infrared

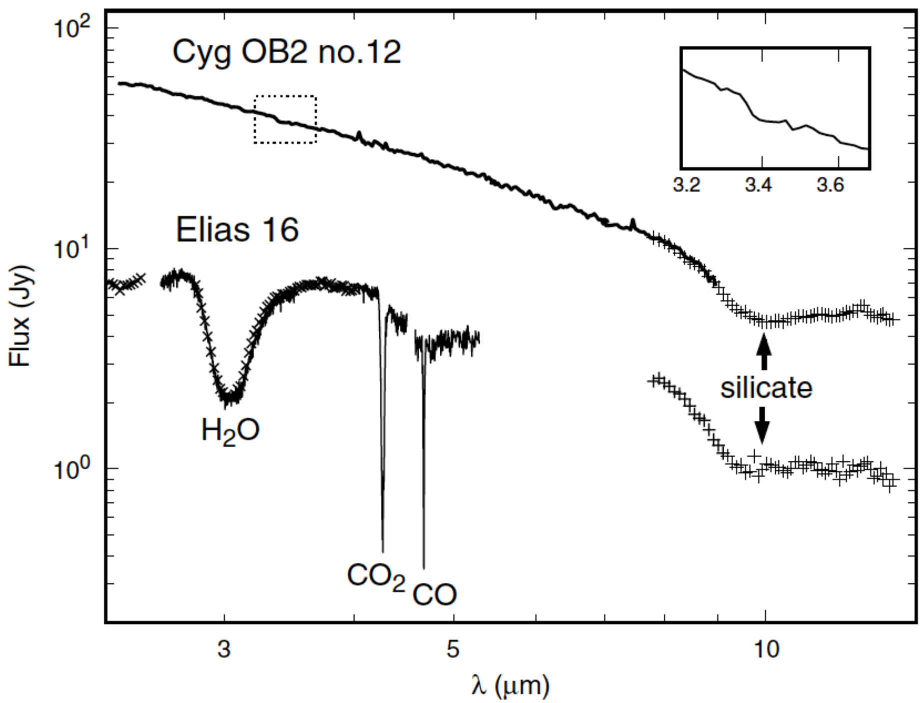


Sketch showing different continuum levels depending on the location of the star
Figure credit: Perry Gerakines, Douglas Whittet

Composition of grains via infrared spectroscopy

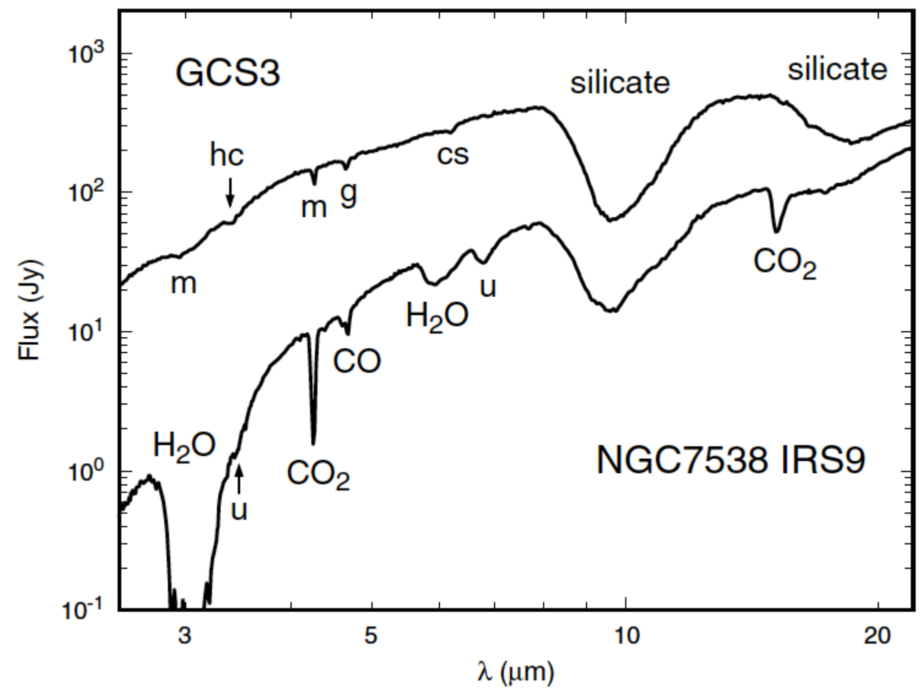
Vibrational modes in solids

Dust composition is investigated via spectroscopic observations in the infrared



IR spectra from 2 to 15 μm of two field stars

CygOB2 n.12.- blue hyper-giant reddened by diffuse-cloud material (with no ice)
Elias 16.- red giant behind a dense clump in Taurus



IR spectra from 2.5 to 20 μm of embedded sources

GCS3.- galactic center source
NGC7538-IRS9.- embedded protostar
Feature ‘g’ is CO gas-phase, all others are solid-phase
‘m’: ices; ‘hc’: hydrocarbons in diffuse ISM;
‘cs’ circumstellar shell of GCS3

Abundances, depletion, composition

Composition of grains via infrared spectroscopy

Infrared spectroscopy of **silicates**

Olivine

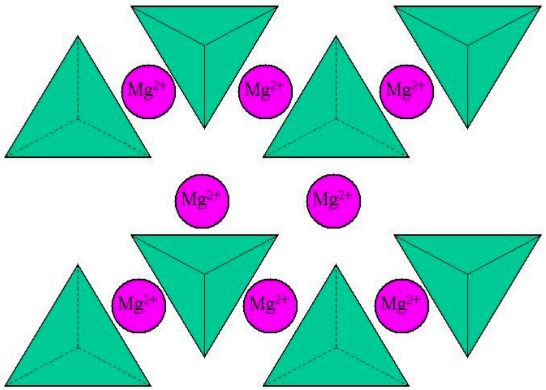
$Fe_{2x}Mg_{2(1-x)}SiO_4$

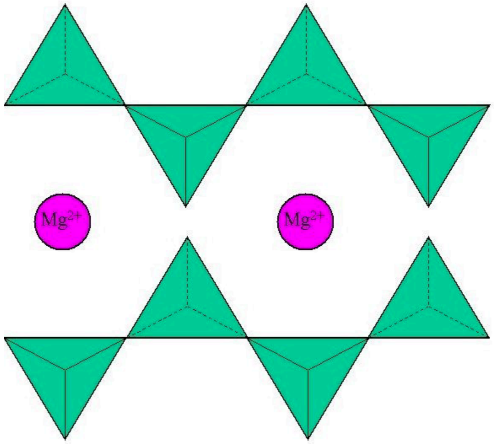
x=0 → Mg_2SiO_4 (*fosterite*)

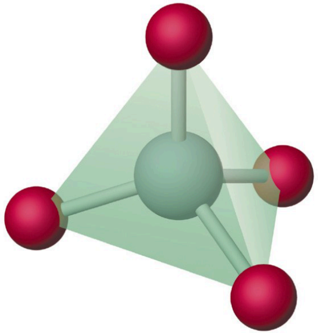
Pyroxene

$Fe_xMg_{1-x}SiO_3$

x=0 → $MgSiO_3$ (*enstatite*)





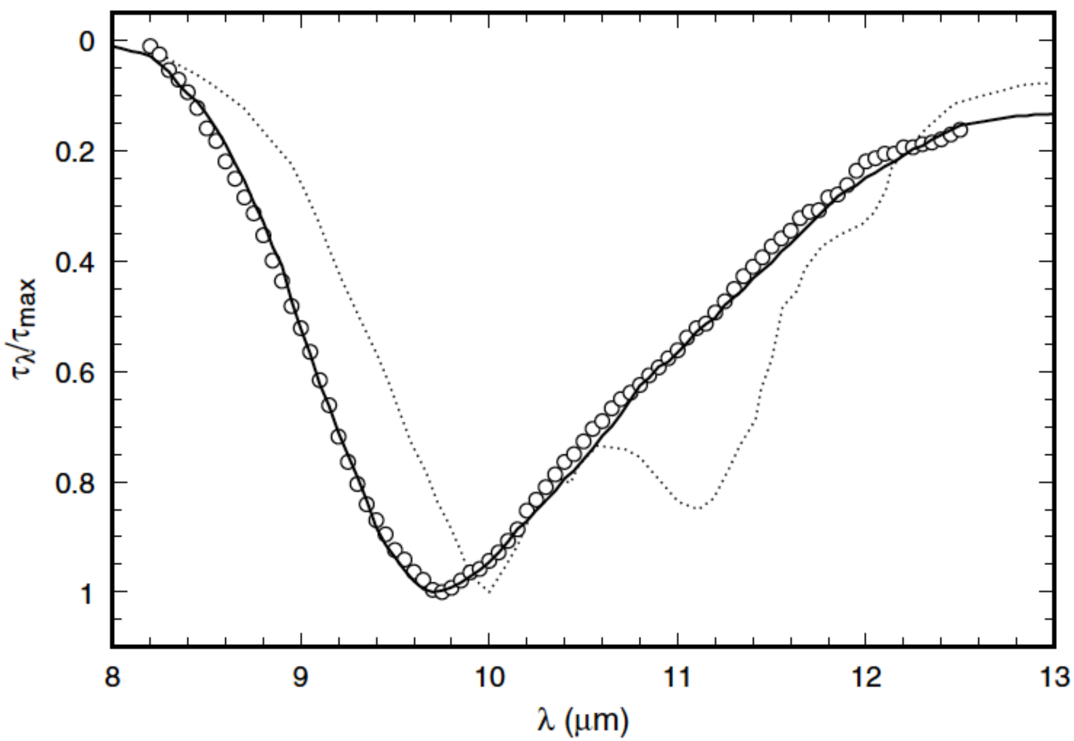


Composition of grains via infrared spectroscopy

Infrared spectroscopy of **silicates**

Assigning features to compounds

9.7 µm silicate profile towards the Galactic Center source SgrA



○○○ observational data

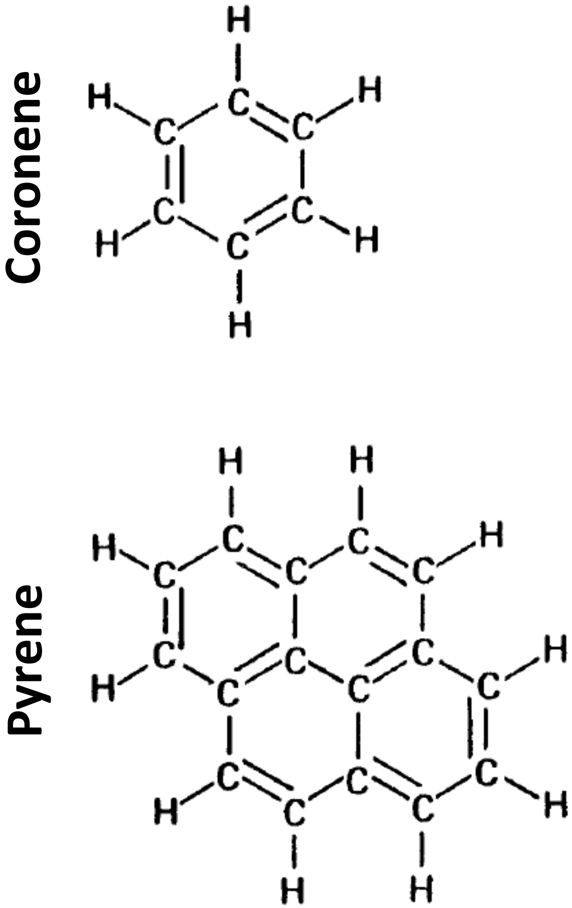
—— laboratory spectrum of amorphous olivine $MgFeSiO_4$

------ laboratory spectrum of annealed fosterite Mg_2SiO_4

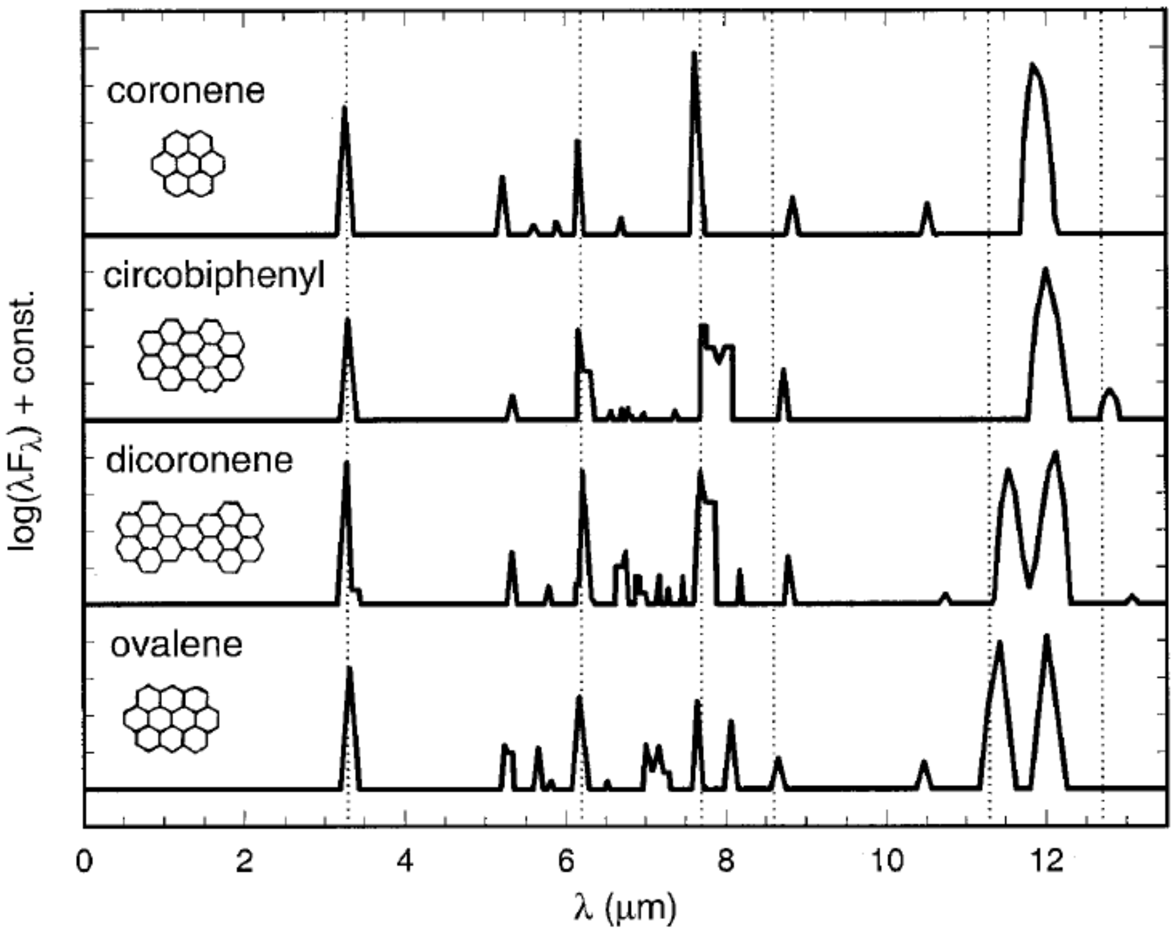
Abundances, depletion, composition

Composition of grains via infrared spectroscopy

Infrared spectroscopy of **polycyclic aromatic hydrocarbons (PAHs)**



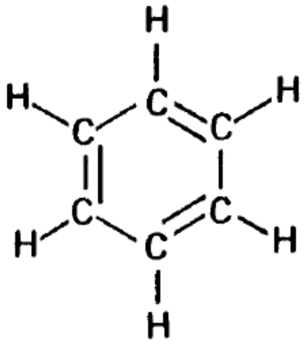
Main observable features marked at 3.3, 6.2, 7.7, 8.6, 11.3, 12.7 μm



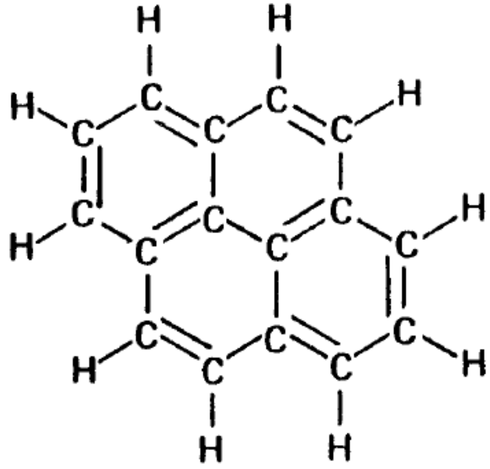
Composition of grains via infrared spectroscopy

Infrared spectroscopy of **polycyclic aromatic hydrocarbons (PAHs)**

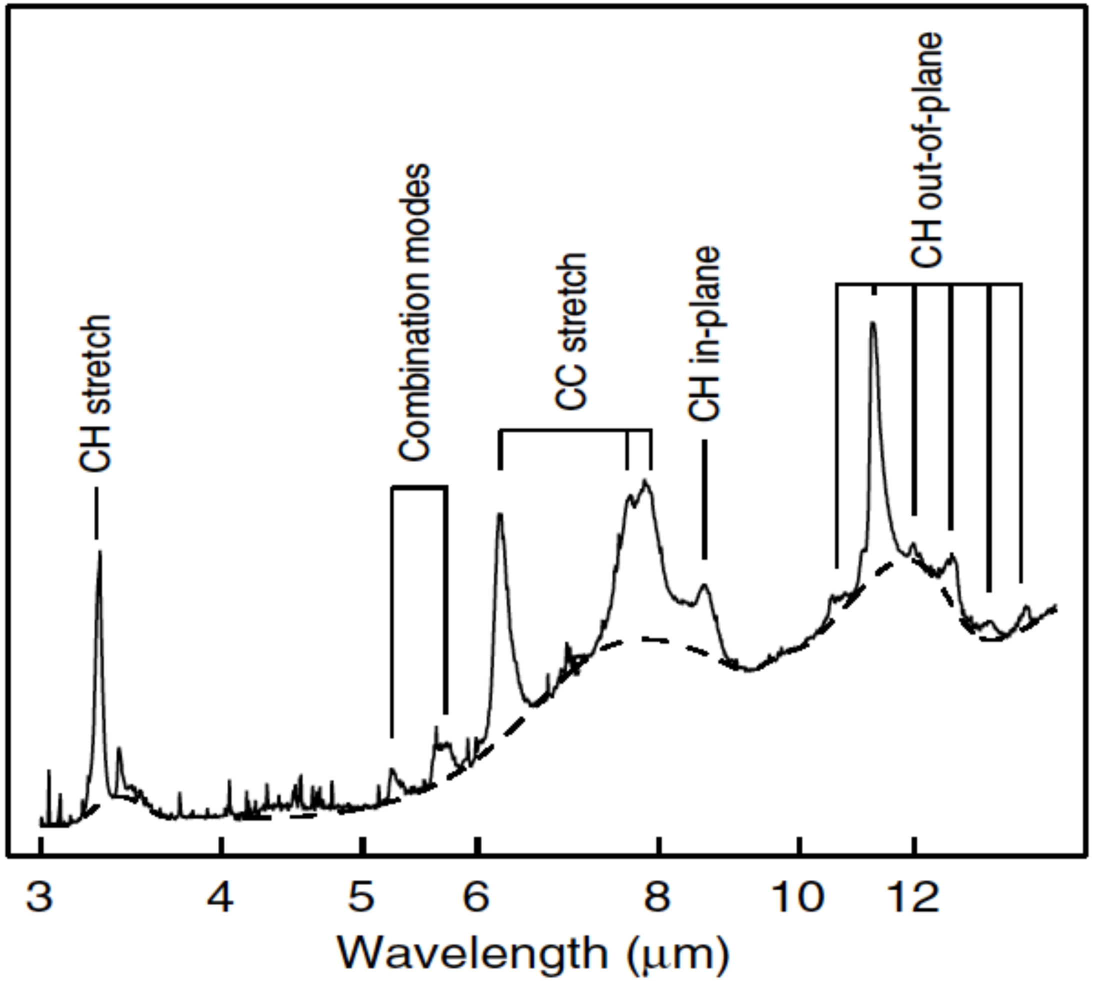
Coronene



Pyrene

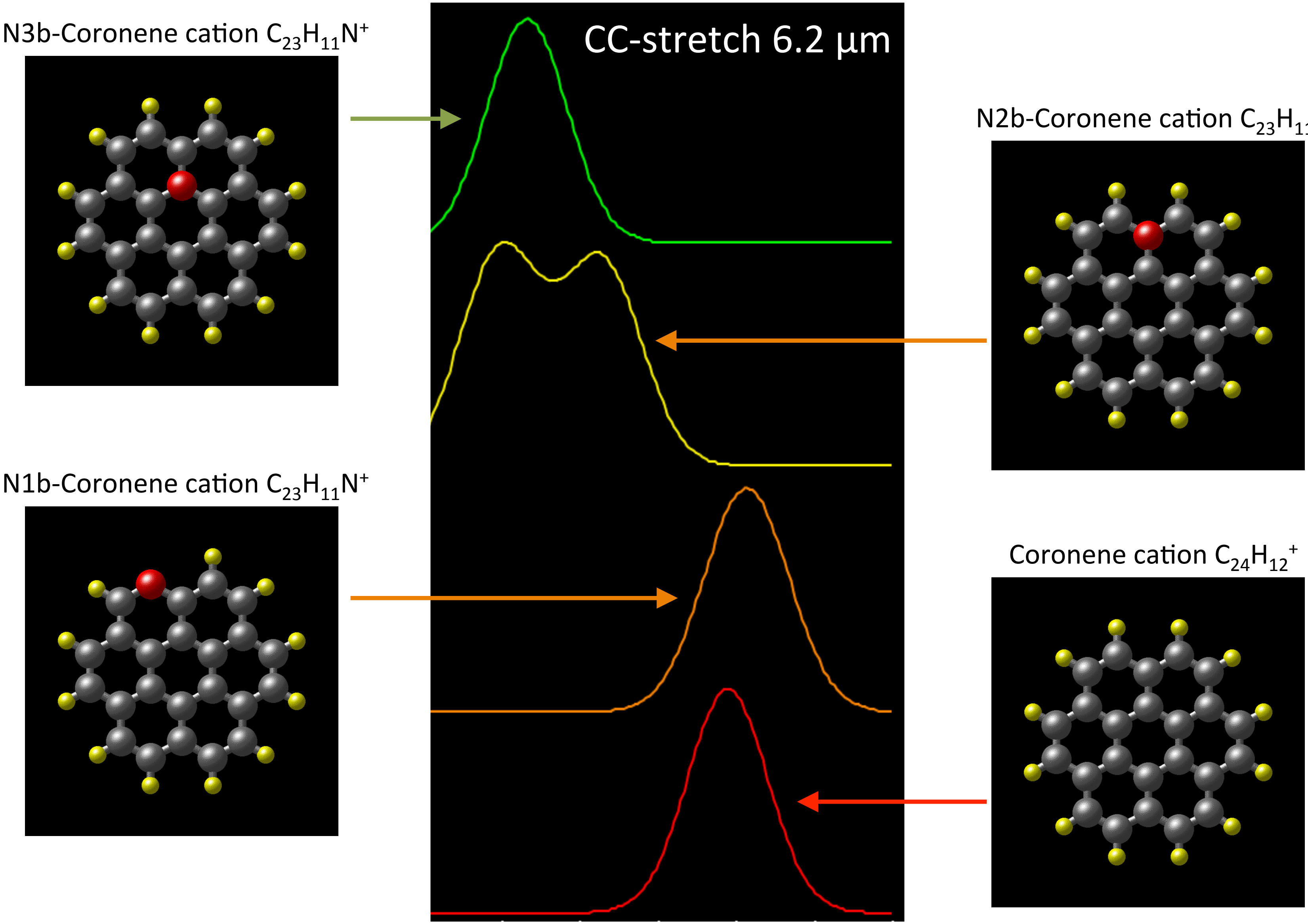


Aromatic features towards the planetary nebula NGC7027



Abundances, depletion, composition

Composition of grains via infrared spectroscopy



Credit: Ciska Kemper's Dust tutorial 2016 / Origin: Hudgins/Baushlicher

Dust components in the ISM

Amorphous olivine:	$(Fe,Mg)_2SiO_4$	Iron-Mangesium oxide:	$Mg_{(0,1)}Fe_{(0,9)}O$
Amorphous pyroxene:	$(Fe,Mg)SiO_3$	Periclase:	MgO
Metallic iron:	Fe	Corundum:	Al_2O_3
Enstatite:	$MgSiO_3$	Pyrite:	FeS_2
Forsterite:	Mg_2SiO_4	Pyrrhotite:	$Fe_{1-X}S$
Diopside:	$(Ca,Mg)SiO_3$	Troilite:	FeS
Hydrous silicates:	silicate + H_2O	Silicon carbide:	SiC
Carbonates:	$(Ca,Mg)CO_3$	Amorphous carbon:	C
Silica:	SiO_2	Graphite:	C
Spinel:	$MgAl_2O_4$	Magnesium sulfide:	MgS

\+ Polycyclic Aromatic Hydrocarbons

\+ various ices: H_2O, CO_2, CO, CH_4, CH_3OH, …

Take home messages

Abundances, Depletion, Composition

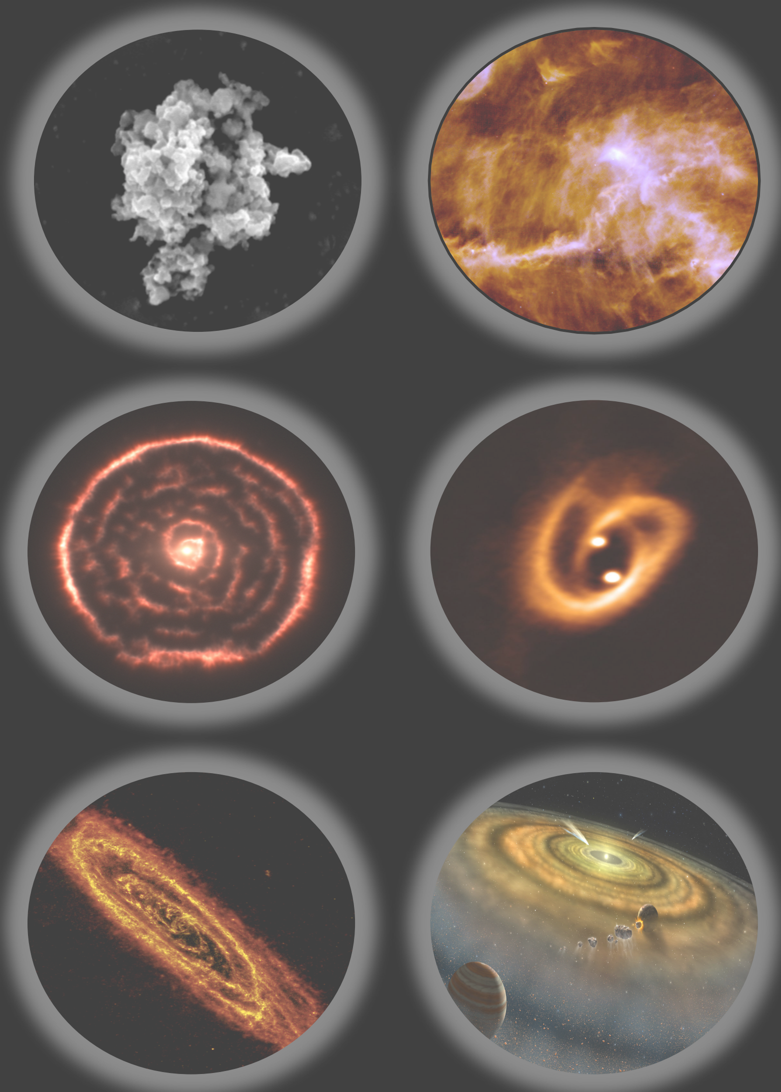
Abundances *of elements in the ISM (from stellar photospheres, e.g. Sun)*
Spatial and temporal variation: e.g. heavy-elements increase in new generations

Depletion*: under-abundance of a gas-phase element*
High depletion levels for heavy elements such as: Ti, Fe, Si, Mg, …
Mass fraction of depleted elements ≈ 0.01 → dust-to-gas mass ratio

Dust grain models*: (porous) refractory cores surrounded by ices*

Composition *of dust grains via infrared spectroscopy (obsverations vs laboratory)*
Main constituents: silicates, graphites, PAHs and ices

Life Cycle of Dust



Outline

Existence of Interstellar Dust

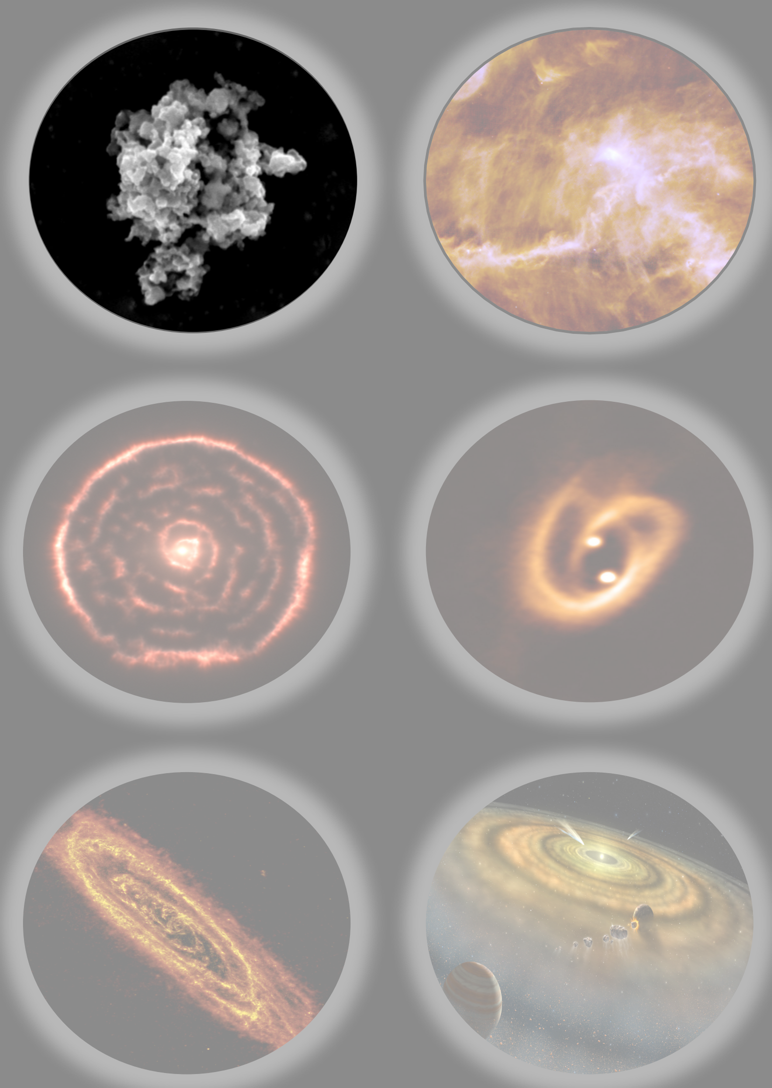
Properties of the Interstellar Medium

Abundances, Depletion, Composition

Dusty astrophysical objects

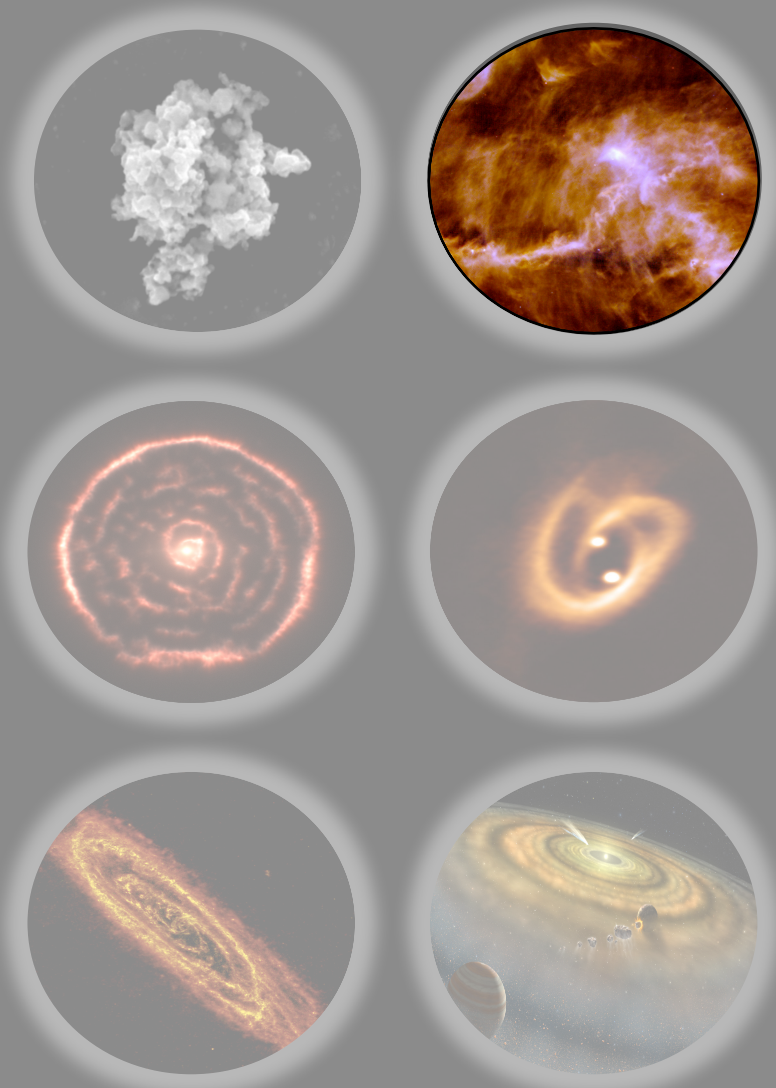
Outline

Life Cycle of Dust



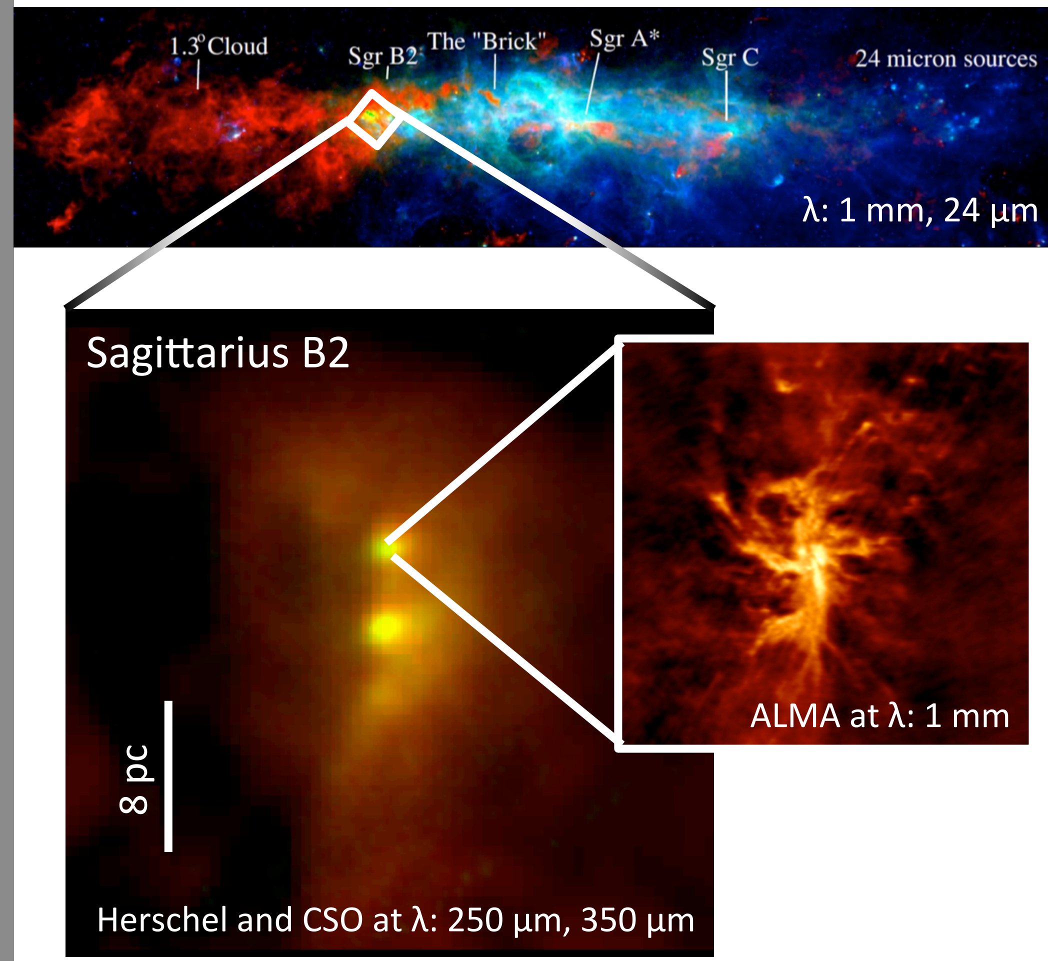
interstellar dust

Life Cycle of Dust



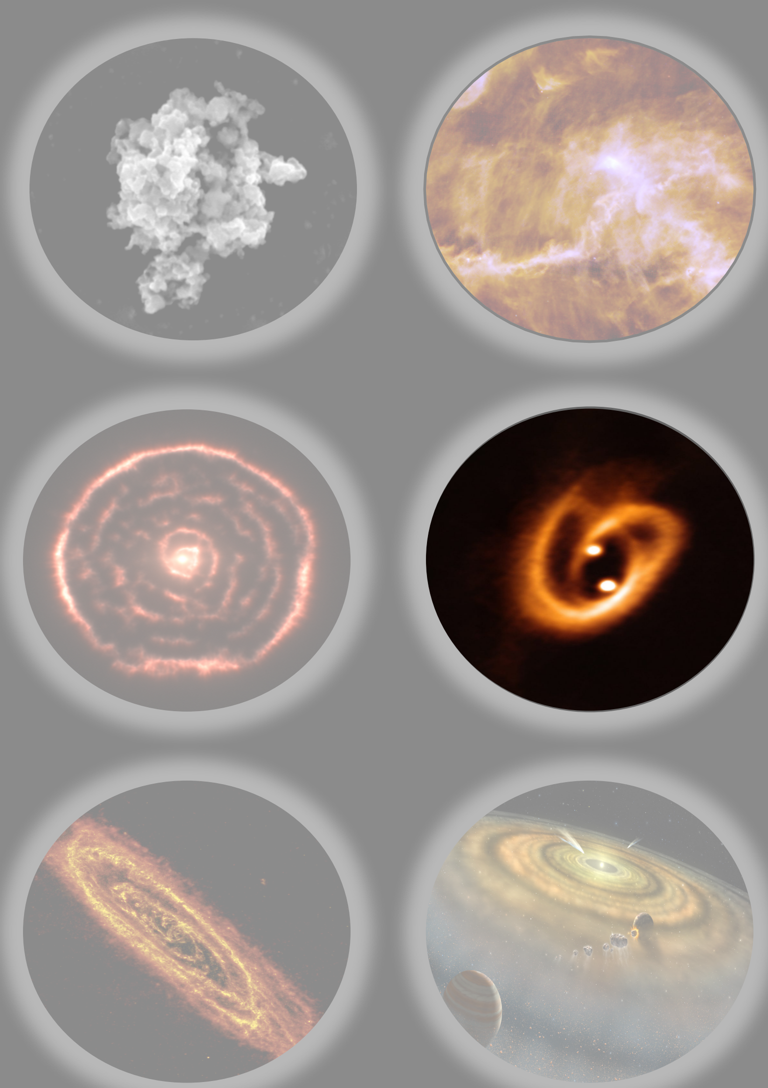
Outline

interstellar medium



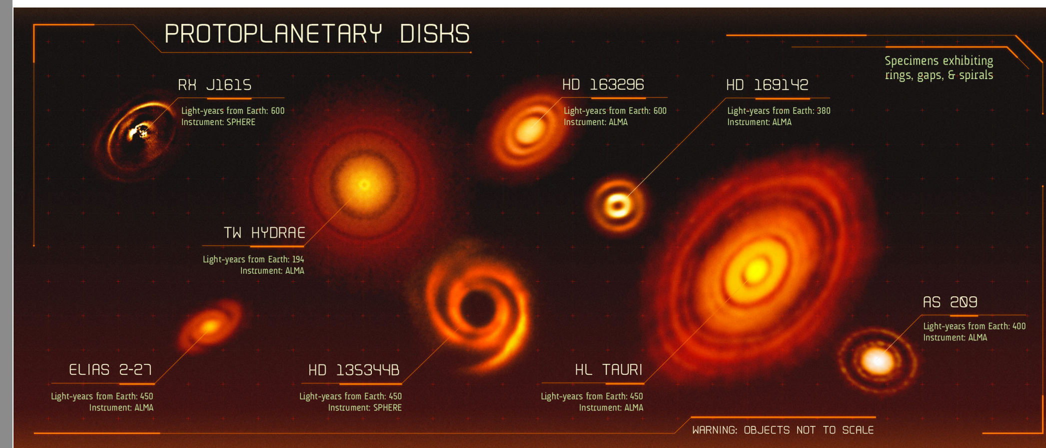
clouds, clumps, cores and filaments

Life Cycle of Dust



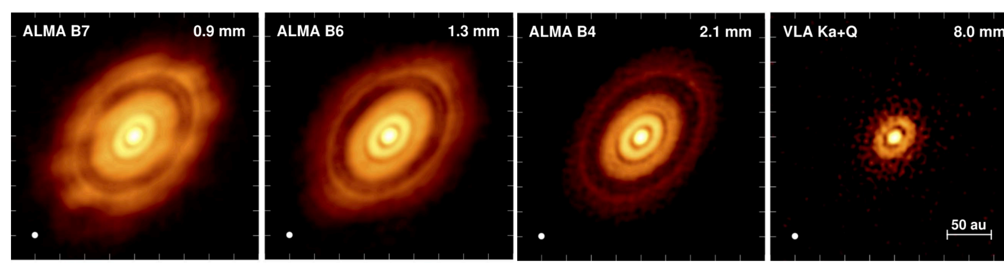
Outline

protostellar disks



disks: morphology, rings, gaps, spirals

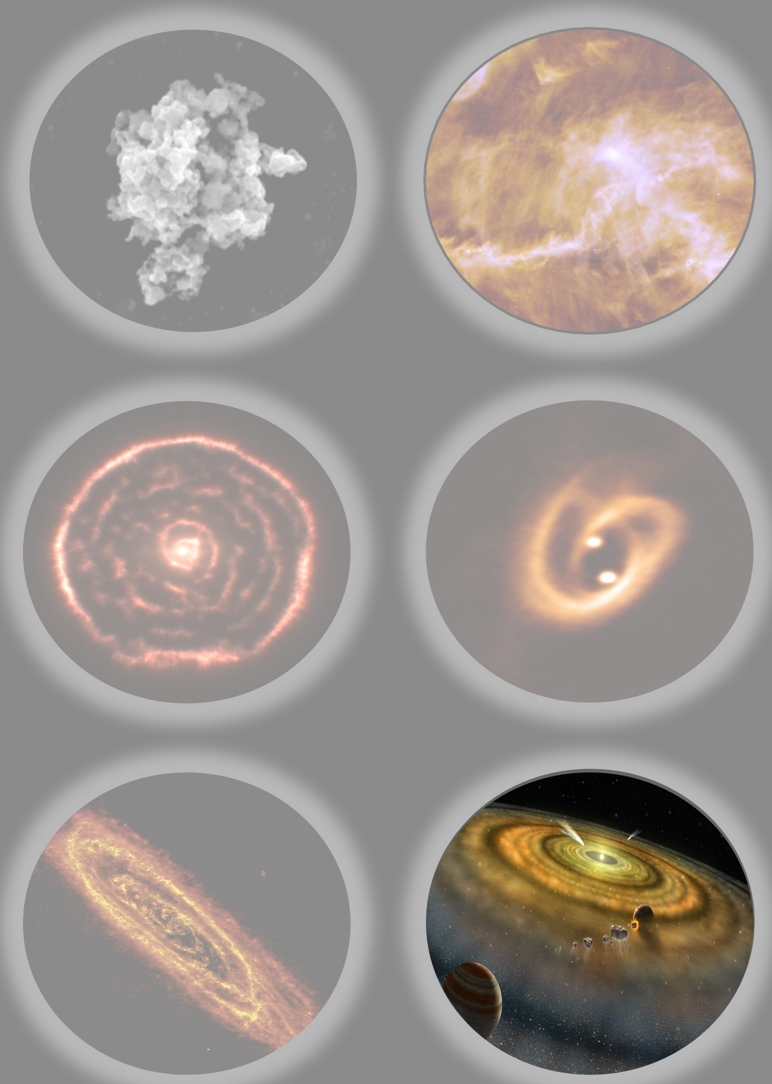
λ: 0.9 mm λ: 1.3 mm λ: 2.1 mm λ: 8.0 mm



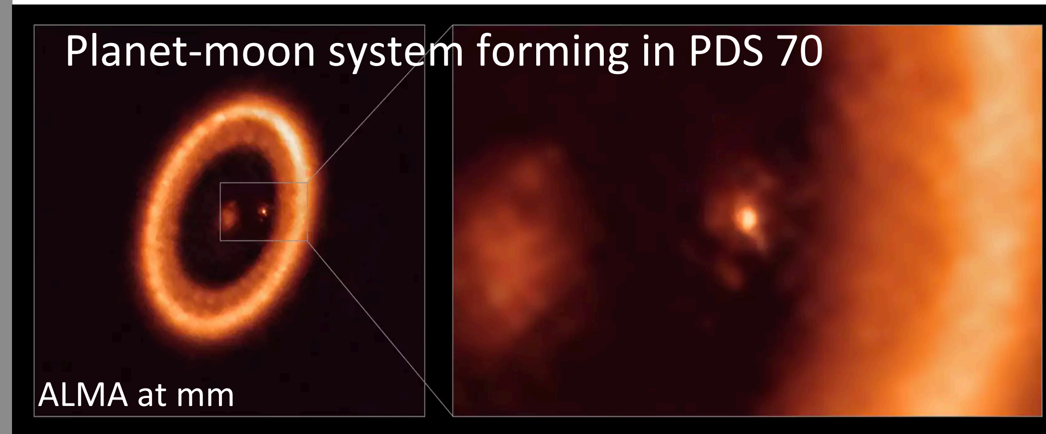
disks: grain growth

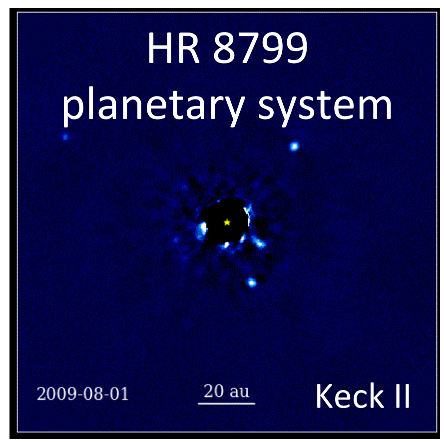
Outline

Life Cycle of Dust



stellar (planetary) systems

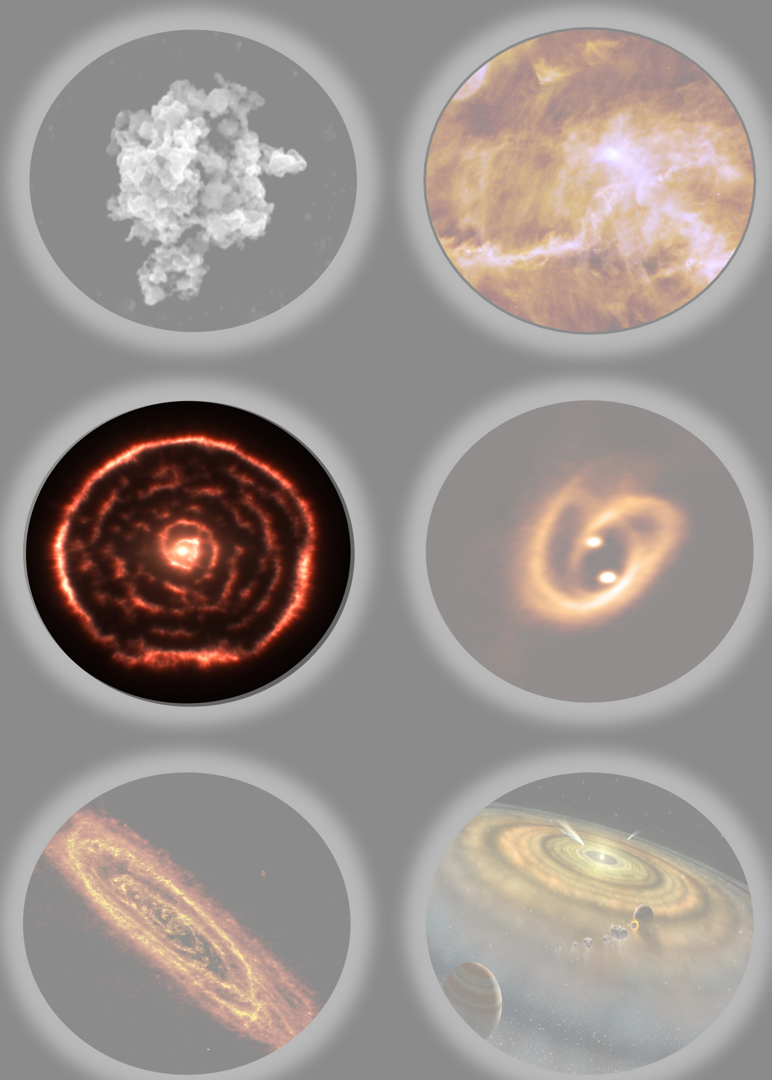




NWA 869 meteorite

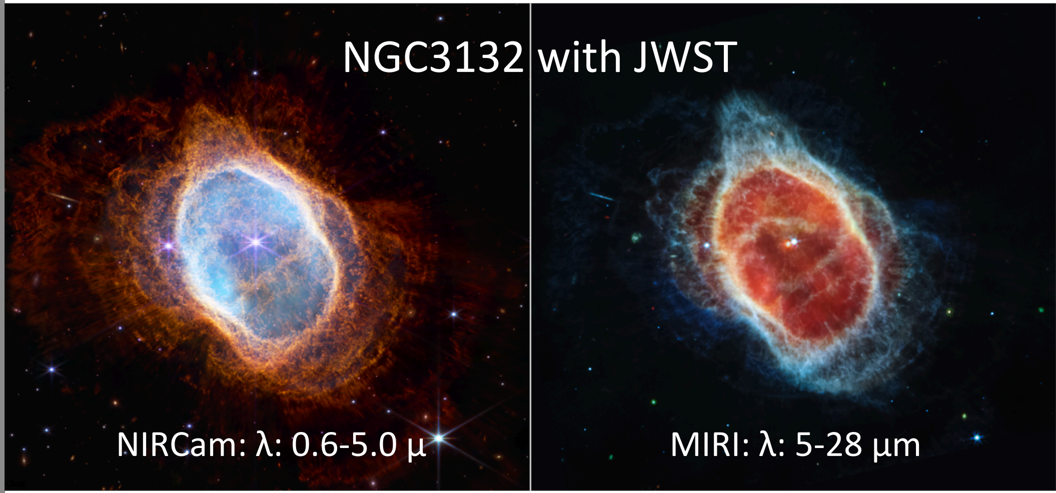
planets, satellites, meteorites, asteroides

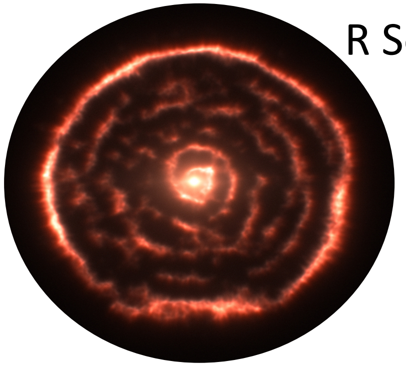
Life Cycle of Dust



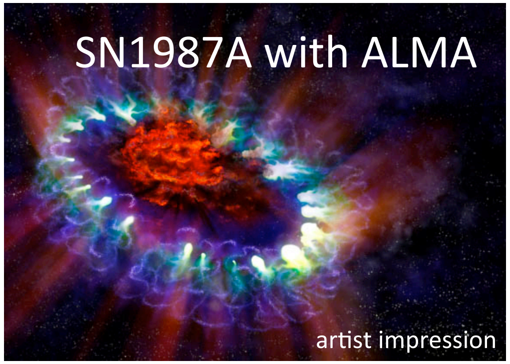
Outline

evolved stars



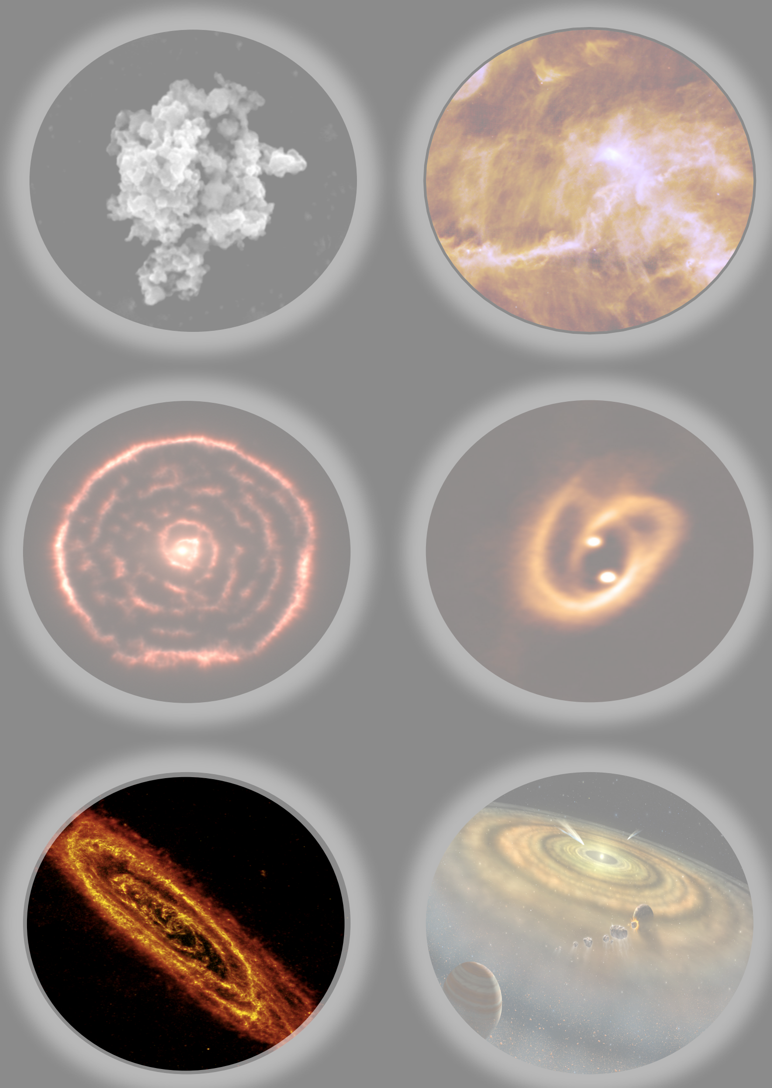


R Sculptoris with ALMA



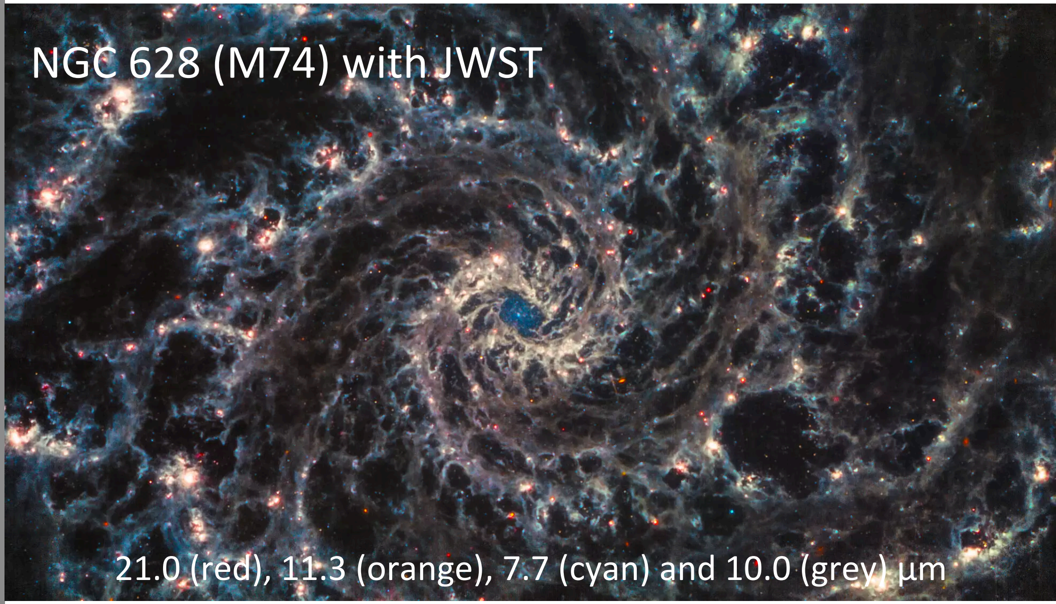
dust formation in PNe, AGBs, SNe

Life Cycle of Dust

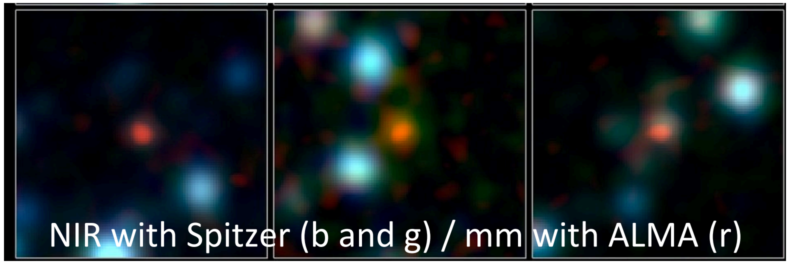


Outline

galaxies across cosmic time

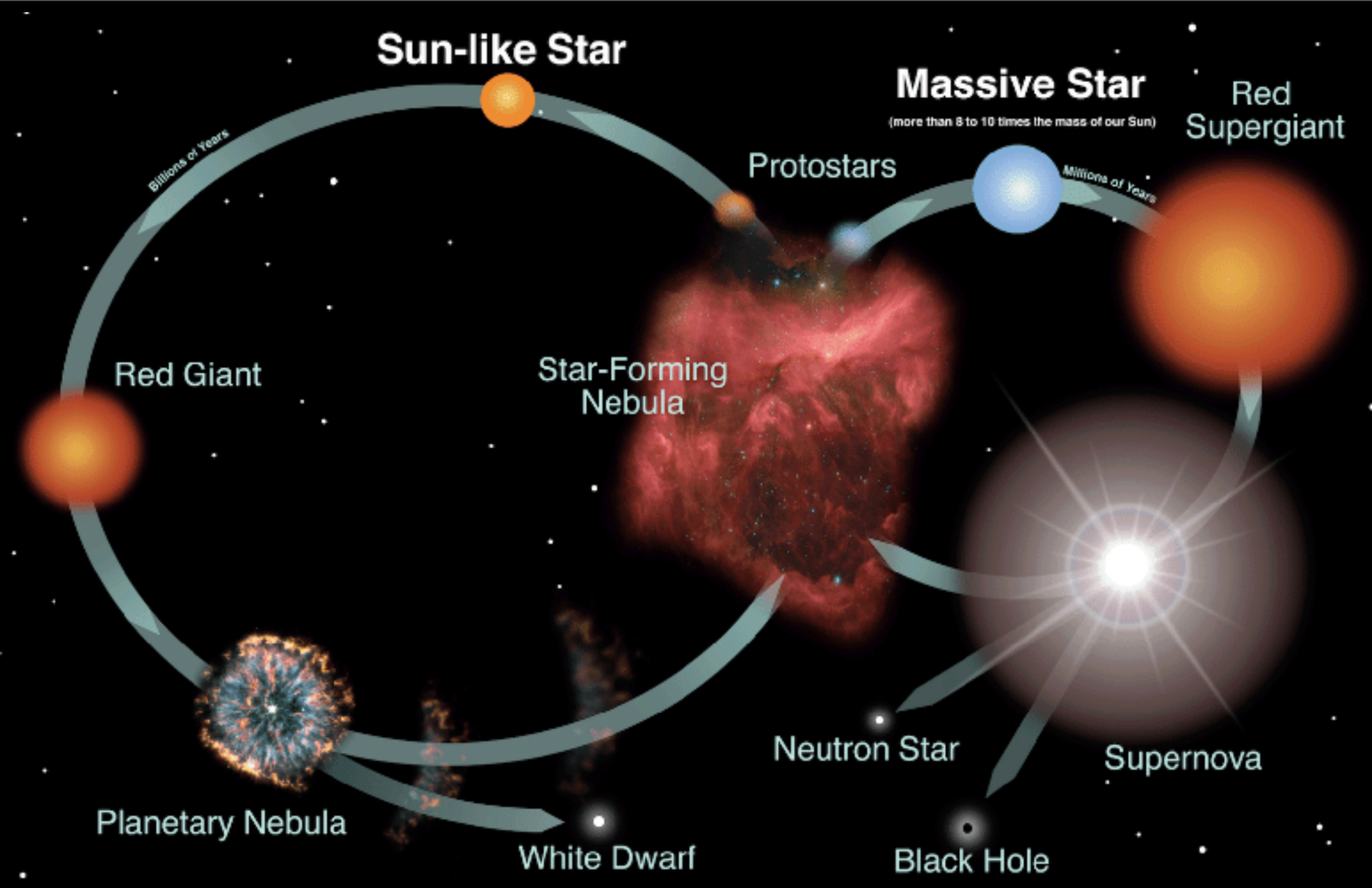


Galaxies at redshifts $z > 3$



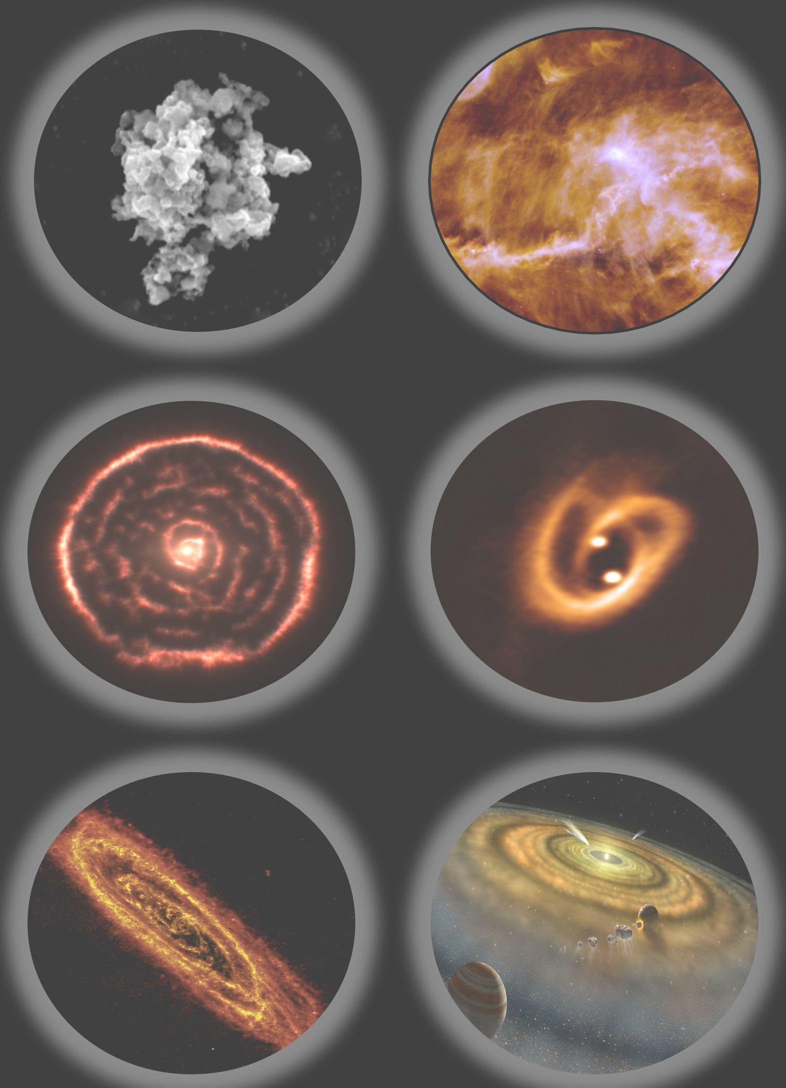
dust in galaxies / galaxy formation

The life cycle of dust



Astro2020: Decadal Survey on Astronomy and Astrophysics, no. 241; Rau et al 2019

Life Cycle of Dust



Thank you

Álvaro Sánchez-Monge

Institute of Space Sciences (ICE-CSIC / IEEC)

Institute of Space Sciences

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