ISYA 2024 – THE INTERSTELLAR MEDIUM (ISM): LECTURE 1.
An Overview of the ISM & the Way We Study It

Frédéric GALLIANO

CEA Paris-Saclay, France

September 23, 2024

Outline of the Lecture

1. **OVERVIEW: WHAT IS THE ISM?**
   - Composition, physical properties, characteristic regions
   - The Milky Way and the diversity of external galaxies
   - Recommended bibliography and outline of the course

Outline of the Lecture

Outline of the Lecture

Outline of the Lecture

Outline of the Lecture

1. **OVERVIEW: WHAT IS THE ISM?**
   - Composition, physical properties, characteristic regions
   - The Milky Way and the diversity of external galaxies
   - Recommended bibliography and outline of the course
2. **A BRIEF HISTORY OF STUDIES OF THE ISM**
   - Before the XXth Century
   - From astronomy to astrophysics
   - The modern era
3. **METHODOLOGY: HOW DO WE STUDY INTERSTELLAR MEDIA?**
   - The microphysical components of the ISM
   - The challenges of studying macroscopic regions
   - The Sociology of ISMology
4. **CONCLUSION**
   - Take-away points
   - References

ISM: Medium filling the space between the stars in a galaxy.

ISM: Medium filling the space between the stars in a galaxy.

⇒ Mostly *baryonic* matter, that is not in stars, compact objects & their immediate surroundings.

ISM: Medium filling the space between the stars in a galaxy.

⇒ Mostly *baryonic* matter, that is not in stars, compact objects & their immediate surroundings.

PARSEC SCALE (*e.g.* Horsehead nebula)

Observatory: Euclid (visible range).

Credit: ESA/Euclid/Euclid Consortium/NASA.

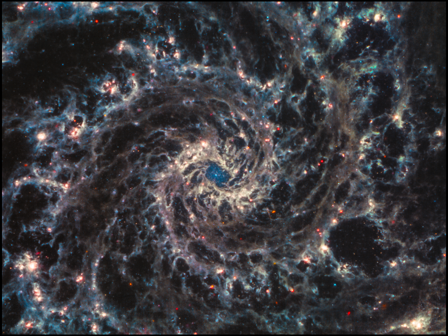
ISM: Medium filling the space between the stars in a galaxy.

⇒ Mostly *baryonic* matter, that is not in stars, compact objects & their immediate surroundings.

PARSEC SCALE (*e.g.* Horsehead nebula)

Observatory: Euclid (visible range).
Credit: ESA/Euclid/Euclid Consortium/NASA.

KILOPARSEC SCALE (*e.g.* NGC 628)

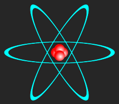


Observatory: JWST (mid-infrared range).
Credit: Williams et al. 2022.

BARYONIC MATTER

BARYONIC MATTER

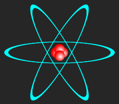
Atoms



Including fully ionized nuclei & free e^-.

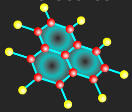
BARYONIC MATTER

Atoms



Including fully ionized nuclei & free e^-.

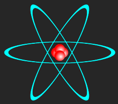
Molecules



Free-flying or frozen on grains.

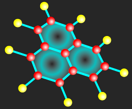
BARYONIC MATTER

Atoms



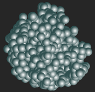
Including fully ionized nuclei & free e^-.

Molecules



Free-flying or frozen on grains.

Dust grains

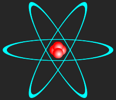


Small solids with radii $\gtrsim 3$ Å and $\lesssim 0.3\ \mu$m.

Overview | Inventory of ISM's Microphysical Constituents

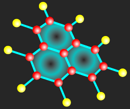
BARYONIC MATTER

Atoms



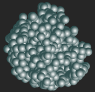
Including fully ionized nuclei & free e^-.

Molecules



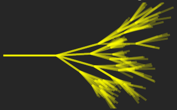
Free-flying or frozen on grains.

Dust grains



Small solids with radii $\gtrsim 3$ Å and $\lesssim 0.3\ \mu$m.

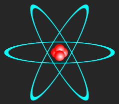
Cosmic rays



Relativistic nuclei & e^- ($10^6 - 10^{20}$ eV).

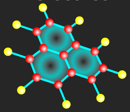
BARYONIC MATTER

Atoms



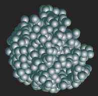
Including fully ionized nuclei & free e^-.

Molecules



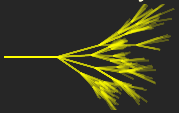
Free-flying or frozen on grains.

Dust grains



Small solids with radii $\gtrsim 3$ Å and $\lesssim 0.3\ \mu$m.

Cosmic rays



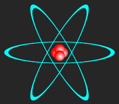
Relativistic nuclei & e^- ($10^6 - 10^{20}$ eV).

PERMEATED BY FIELDS

Overview | Inventory of ISM's Microphysical Constituents

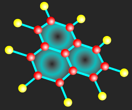
BARYONIC MATTER

Atoms



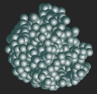
Including fully ionized nuclei & free e^-.

Molecules



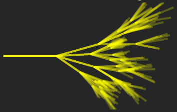
Free-flying or frozen on grains.

Dust grains



Small solids with radii $\gtrsim 3$ Å and $\lesssim 0.3\ \mu$m.

Cosmic rays



Relativistic nuclei & e^- ($10^6 - 10^{20}$ eV).

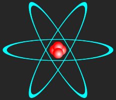
PERMEATED BY FIELDS

Electromagnetic

From γ-rays to decametric.

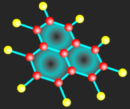
BARYONIC MATTER

Atoms



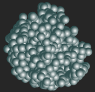
Including fully ionized nuclei & free e^-.

Molecules



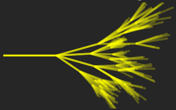
Free-flying or frozen on grains.

Dust grains



Small solids with radii $\gtrsim 3$ Å and $\lesssim 0.3\ \mu$m.

Cosmic rays



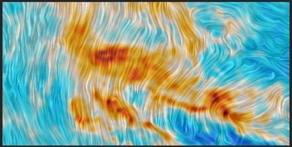
Relativistic nuclei & e^- ($10^6 - 10^{20}$ eV).

PERMEATED BY FIELDS

Electromagnetic

From γ-rays to decametric.

Magnetic

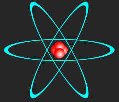


$\Rightarrow$ MHD required.

Overview | Inventory of ISM's Microphysical Constituents

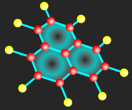
BARYONIC MATTER

Atoms



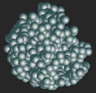
Including fully ionized nuclei & free e^-.

Molecules



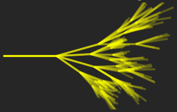
Free-flying or frozen on grains.

Dust grains



Small solids with radii $\gtrsim 3$ Å and $\lesssim 0.3\ \mu$m.

Cosmic rays



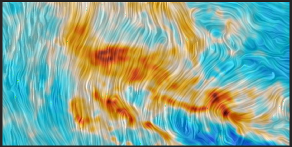
Relativistic nuclei & e^- ($10^6 - 10^{20}$ eV).

PERMEATED BY FIELDS

Electromagnetic

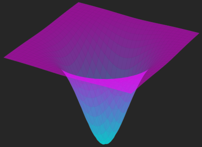
From γ-rays to decametric.

Magnetic



$\Rightarrow$ MHD required.

Gravitational



Including dark matter particles.

TYPICAL INTERSTELLAR REGIONS

TYPICAL INTERSTELLAR REGIONS

Cirrus clouds

Credit: J.-C. Cuillandre.
Observatory: CFHT / Megacam.

TYPICAL INTERSTELLAR REGIONS

Cirrus clouds

Credit: J.-C. Cuillandre.
Observatory: CFHT / Megacam.

Reflection nebulae

Credit: G. Duchene & G. Kober.
Observatory: HST.

TYPICAL INTERSTELLAR REGIONS

Cirrus clouds

Credit: J.-C. Cuillandre.

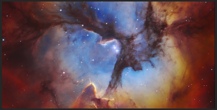
Observatory: CFHT / Megacam.

Reflection nebulae

Credit: G. Duchene & G. Kober.

Observatory: HST.

H II regions



Credit: M. Pugh & R. Gendler.

Observatory: HST & Subaru.

TYPICAL INTERSTELLAR REGIONS

Cirrus clouds

Credit: J.-C. Cuillandre.

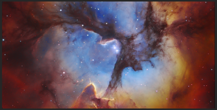
Observatory: CFHT / Megacam.

Reflection nebulae

Credit: G. Duchene & G. Kober.

Observatory: HST.

H II regions



Credit: M. Pugh & R. Gendler.

Observatory: HST & Subaru.

Molecular clouds

Credit: NASA, ESA.

Observatory: HST.

TYPICAL INTERSTELLAR REGIONS

Cirrus clouds

Credit: J.-C. Cuillandre.

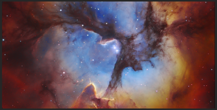
Observatory: CFHT / Megacam.

Reflection nebulae

Credit: G. Duchene & G. Kober.

Observatory: HST.

H II regions



Credit: M. Pugh & R. Gendler.

Observatory: HST & Subaru.

Molecular clouds

Credit: NASA, ESA.

Observatory: HST.

CIRCUMSTELLAR REGIONS

TYPICAL INTERSTELLAR REGIONS

Cirrus clouds

Credit: J.-C. Cuillandre.

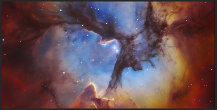
Observatory: CFHT / Megacam.

Reflection nebulae

Credit: G. Duchene & G. Kober.

Observatory: HST.

H II regions



Credit: M. Pugh & R. Gendler.

Observatory: HST & Subaru.

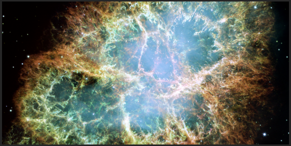
Molecular clouds

Credit: NASA, ESA.

Observatory: HST.

CIRCUMSTELLAR REGIONS

Supernova remnants



Credit: NASA, ESA.

Observatory: HST.

TYPICAL INTERSTELLAR REGIONS

Cirrus clouds

Credit: J.-C. Cuillandre.

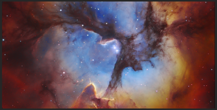
Observatory: CFHT / Megacam.

Reflection nebulae

Credit: G. Duchene & G. Kober.

Observatory: HST.

H II regions



Credit: M. Pugh & R. Gendler.

Observatory: HST & Subaru.

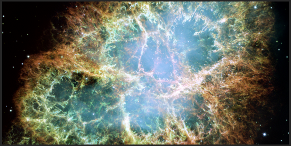
Molecular clouds

Credit: NASA, ESA.

Observatory: HST.

CIRCUMSTELLAR REGIONS

Supernova remnants



Credit: NASA, ESA.

Observatory: HST.

Planetary nebulae

Credit: NASA, ESA.

Observatory: HST.

TYPICAL INTERSTELLAR REGIONS

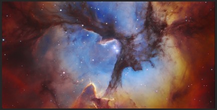
Cirrus clouds

Credit: J.-C. Cuillandre.
Observatory: CFHT / Megacam.

Reflection nebulae

Credit: G. Duchene & G. Kober.
Observatory: HST.

H II regions



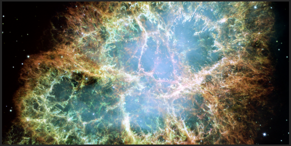
Credit: M. Pugh & R. Gendler.
Observatory: HST & Subaru.

Molecular clouds

Credit: NASA, ESA.
Observatory: HST.

CIRCUMSTELLAR REGIONS

Supernova remnants

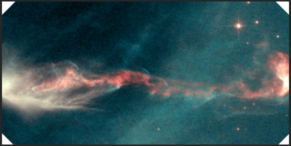


Credit: NASA, ESA.
Observatory: HST.

Planetary nebulae

Credit: NASA, ESA.
Observatory: HST.

Protostellar objects



Credit: NASA, ESA.
Observatory: HST.

TYPICAL INTERSTELLAR REGIONS

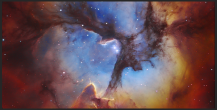
Cirrus clouds

Credit: J.-C. Cuillandre.
Observatory: CFHT / Megacam.

Reflection nebulae

Credit: G. Duchene & G. Kober.
Observatory: HST.

H II regions



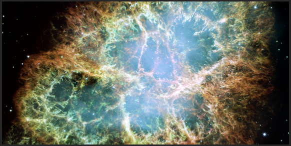
Credit: M. Pugh & R. Gendler.
Observatory: HST & Subaru.

Molecular clouds

Credit: NASA, ESA.
Observatory: HST.

CIRCUMSTELLAR REGIONS

Supernova remnants

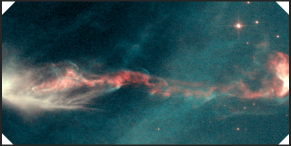


Credit: NASA, ESA.
Observatory: HST.

Planetary nebulae

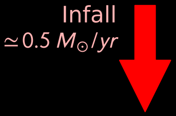
Credit: NASA, ESA.
Observatory: HST.

Protostellar objects

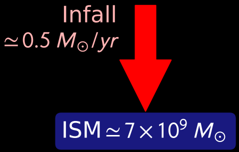


Credit: NASA, ESA.
Observatory: HST.

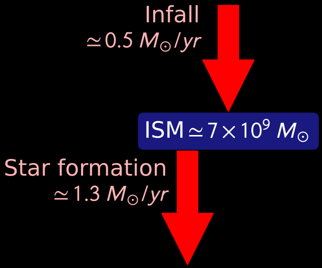
$\Rightarrow$ at the interface with the ISM.



(Adapted from Draine 2011, Chap. 1)

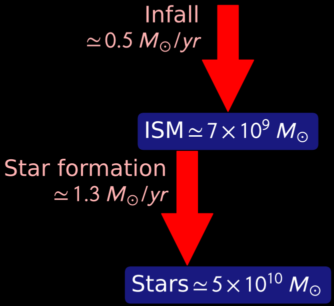


(Adapted from Draine 2011, Chap. 1)



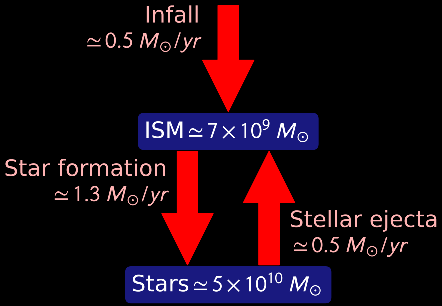
(Adapted from Draine 2011, Chap. 1)

Overview | Composition of the ISM of the Milky Way

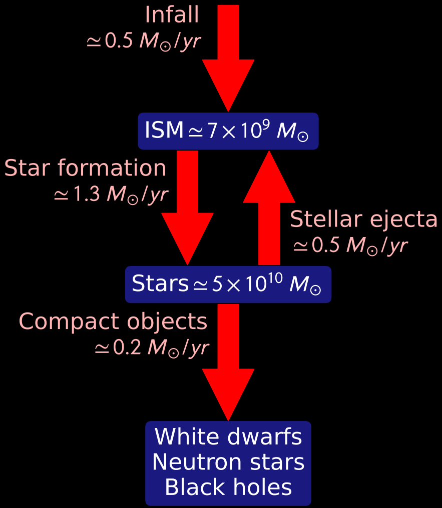


(Adapted from Draine 2011, Chap. 1)

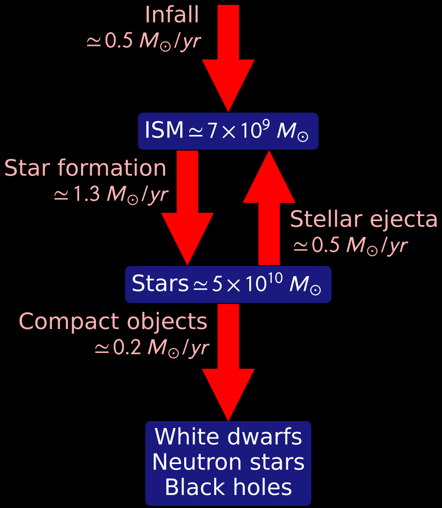
Overview | Composition of the ISM of the Milky Way



(Adapted from Draine 2011, Chap. 1)



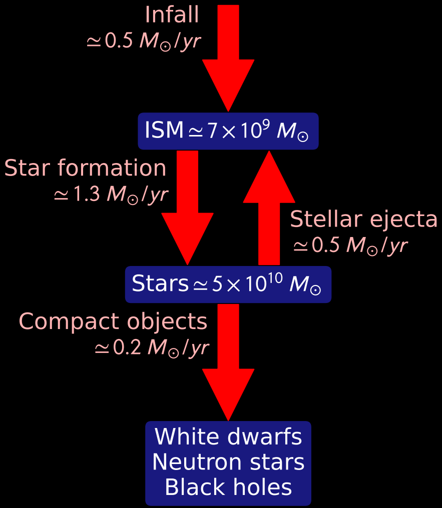
(Adapted from Draine 2011, Chap. 1)



$\Rightarrow$ ISM-to-star mass ratio $\simeq 14\,\%$.

(Adapted from Draine 2011, Chap. 1)

Overview | Composition of the ISM of the Milky Way

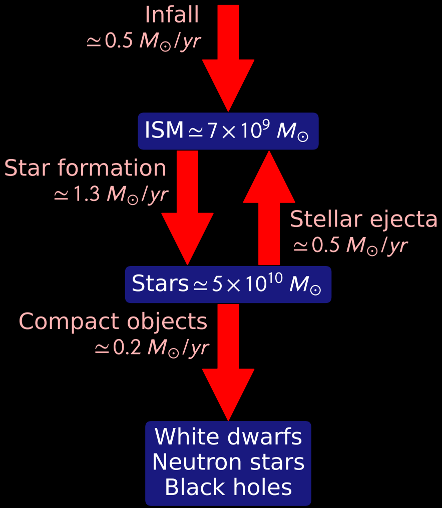


$\Rightarrow$ ISM-to-star mass ratio $\simeq$ 14 %.

(Adapted from Draine 2011, Chap. 1)

Gas associated with different states of H

Overview | Composition of the ISM of the Milky Way



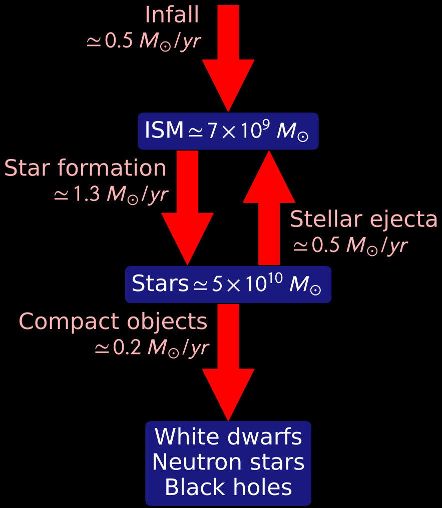
$\Rightarrow$ ISM-to-star mass ratio $\simeq$ 14 %.

(Adapted from Draine 2011, Chap. 1)

Gas associated with different states of H

H^+	$1.5 \times 10^9\ M_\odot$	23 %

Overview | Composition of the ISM of the Milky Way



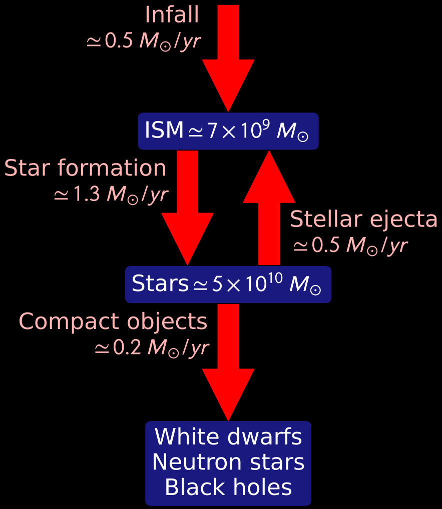
Gas associated with different states of H

H^+	1.5×10^9 $M_\odot$	23 %
H^0	4×10^9 $M_\odot$	60 %

⇒ ISM-to-star mass ratio ≃ 14 %.

(Adapted from Draine 2011, Chap. 1)

Composition of the ISM of the Milky Way

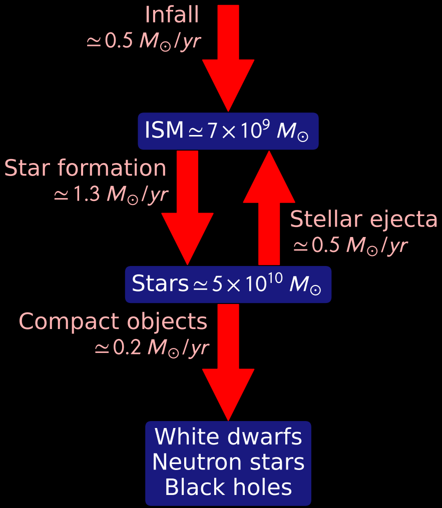


Gas associated with different states of H

H^+	$1.5 \times 10^9\ M_\odot$	23 %
H^0	$4 \times 10^9\ M_\odot$	60 %
H_2	$1.2 \times 10^9\ M_\odot$	17 %

$\Rightarrow$ ISM-to-star mass ratio $\simeq$ 14 %.

(Adapted from Draine 2011, Chap. 1)



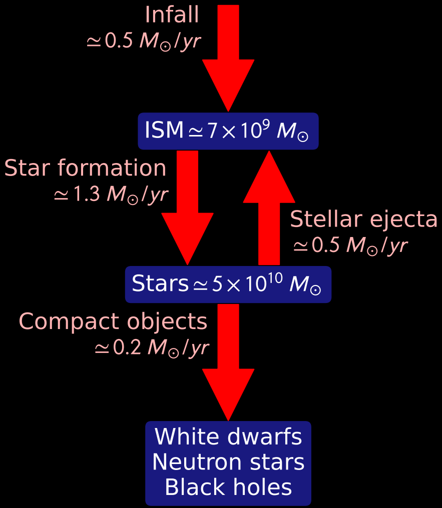
Gas associated with different states of H

H^+	$1.5\times10^9\ M_\odot$	23 %
H^0	$4\times10^9\ M_\odot$	60 %
H_2	$1.2\times10^9\ M_\odot$	17 %
Total gas	$6.7\times10^9\ M_\odot$	100 %

$\Rightarrow$ ISM-to-star mass ratio $\simeq$ 14 %.

(Adapted from Draine 2011, Chap. 1)

Overview | Composition of the ISM of the Milky Way



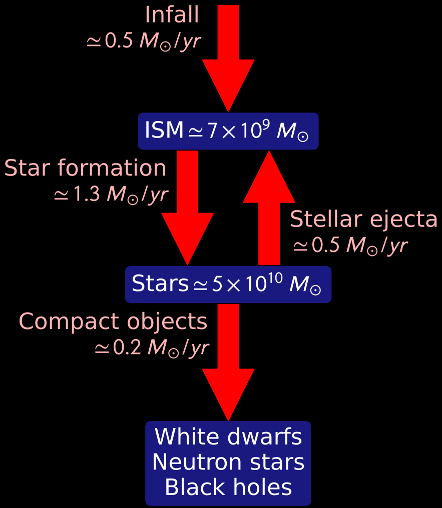
$\Rightarrow$ ISM-to-star mass ratio $\simeq 14\,\%$.

(Adapted from Draine 2011, Chap. 1)

Gas associated with different states of H

H^+	$1.5 \times 10^9\ M_\odot$	23 %
H^0	$4 \times 10^9\ M_\odot$	60 %
H_2	$1.2 \times 10^9\ M_\odot$	17 %
Total gas	$6.7 \times 10^9\ M_\odot$	100 %

Element mass fractions (Asplund et al. 2009)



⇒ ISM-to-star mass ratio $\simeq$ 14 %.

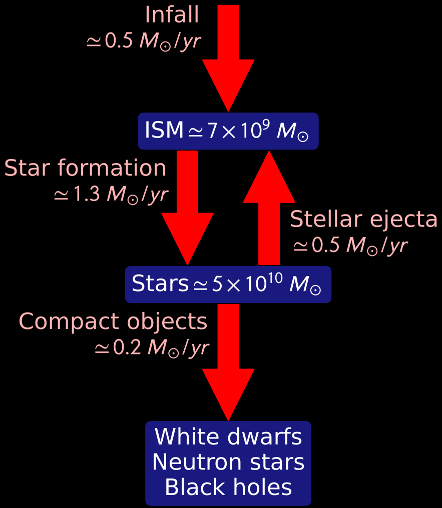
(Adapted from Draine 2011, Chap. 1)

Gas associated with different states of H

H^+	1.5×10^9 $M_\odot$	23 %
H^0	4×10^9 $M_\odot$	60 %
H_2	1.2×10^9 $M_\odot$	17 %
Total gas	6.7×10^9 $M_\odot$	100 %

Element mass fractions (Asplund et al. 2009)

$$X_\odot \equiv \frac{M_\text{H}}{M_\text{gas}} \simeq 73.8\,\%$$



$\Rightarrow$ ISM-to-star mass ratio $\simeq 14\,\%$.

(Adapted from Draine 2011, Chap. 1)

Gas associated with different states of H

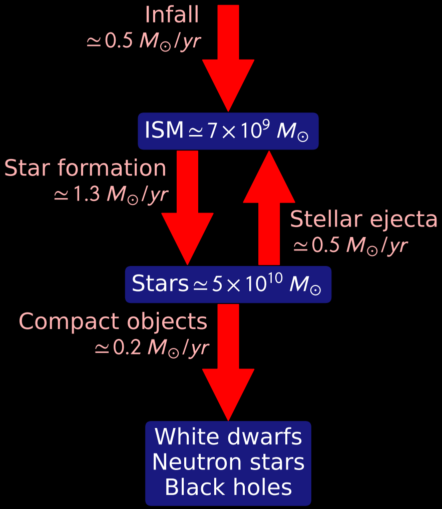
H^+	$1.5\times10^9\ M_\odot$	23 %
H^0	$4\times10^9\ M_\odot$	60 %
H_2	$1.2\times10^9\ M_\odot$	17 %
Total gas	$6.7\times10^9\ M_\odot$	100 %

Element mass fractions (Asplund et al. 2009)

$$X_\odot \equiv \frac{M_\mathrm{H}}{M_\mathrm{gas}} \simeq 73.8\,\%$$

$$Y_\odot \equiv \frac{M_\mathrm{He}}{M_\mathrm{gas}} \simeq 24.9\,\%$$

Overview | Composition of the ISM of the Milky Way



$\Rightarrow$ ISM-to-star mass ratio $\simeq 14\,\%$.

(Adapted from Draine 2011, Chap. 1)

Gas associated with different states of H

H^+	$1.5 \times 10^9\ M_\odot$	23 %
H^0	$4 \times 10^9\ M_\odot$	60 %
H_2	$1.2 \times 10^9\ M_\odot$	17 %
Total gas	$6.7 \times 10^9\ M_\odot$	100 %

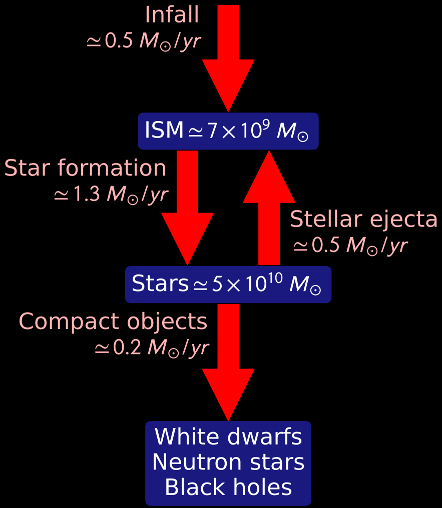
Element mass fractions (Asplund et al. 2009)

$$X_\odot \equiv \frac{M_\mathrm{H}}{M_\mathrm{gas}} \simeq 73.8\,\%$$

$$Y_\odot \equiv \frac{M_\mathrm{He}}{M_\mathrm{gas}} \simeq 24.9\,\%$$

$\rightarrow$ Most He formed during primordial nucleosynthesis.

Overview | Composition of the ISM of the Milky Way



$\Rightarrow$ ISM-to-star mass ratio $\simeq$ 14 %.

(Adapted from Draine 2011, Chap. 1)

Gas associated with different states of H

H^+	$1.5\times10^9\ M_\odot$	23 %
H^0	$4\times10^9\ M_\odot$	60 %
H_2	$1.2\times10^9\ M_\odot$	17 %
Total gas	$6.7\times10^9\ M_\odot$	100 %

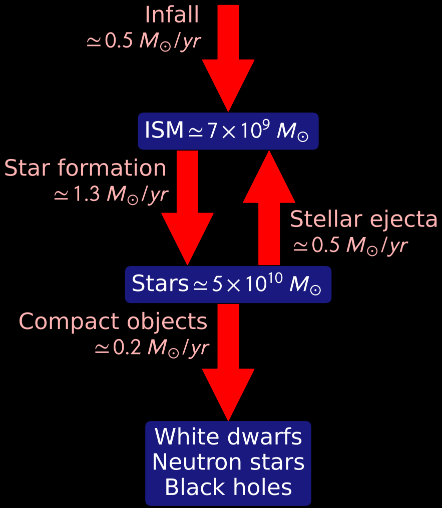
Element mass fractions (Asplund et al. 2009)

$$X_\odot \equiv \frac{M_{\rm H}}{M_{\rm gas}} \simeq 73.8\,\%$$

$$Y_\odot \equiv \frac{M_{\rm He}}{M_{\rm gas}} \simeq 24.9\,\%$$

$\rightarrow$ Most He formed during primordial nucleosynthesis.

$$Z_\odot \equiv \frac{M_{>\rm He}}{M_{\rm gas}} \simeq 1.3\,\%$$



$\Rightarrow$ ISM-to-star mass ratio $\simeq 14\,\%$.

(Adapted from Draine 2011, Chap. 1)

Gas associated with different states of H

H^+	$1.5\times10^9\ M_\odot$	23 %
H^0	$4\times10^9\ M_\odot$	60 %
H_2	$1.2\times10^9\ M_\odot$	17 %
Total gas	$6.7\times10^9\ M_\odot$	100 %

Element mass fractions (Asplund et al. 2009)

$$X_\odot \equiv \frac{M_{\rm H}}{M_{\rm gas}} \simeq 73.8\,\%$$

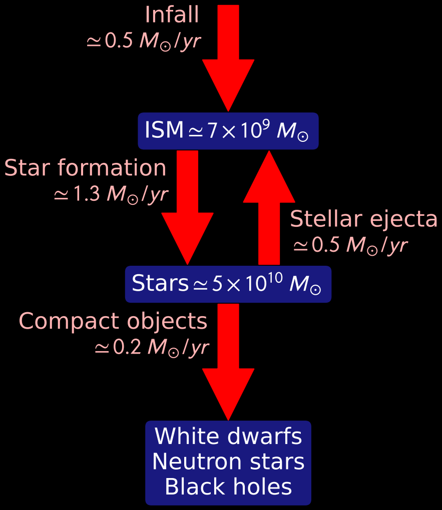
$$Y_\odot \equiv \frac{M_{\rm He}}{M_{\rm gas}} \simeq 24.9\,\%$$

$\rightarrow$ Most He formed during primordial nucleosynthesis.

$$Z_\odot \equiv \frac{M_{>\rm He}}{M_{\rm gas}} \simeq 1.3\,\%$$

(*metallicity*) $\rightarrow$ large variations among galaxy types.

Composition of the ISM of the Milky Way



⇒ ISM-to-star mass ratio $\simeq 14\,\%$.

(Adapted from Draine 2011, Chap. 1)

Gas associated with different states of H

H^+	$1.5\times10^9\ M_\odot$	$23\,\%$
H^0	$4\times10^9\ M_\odot$	$60\,\%$
H_2	$1.2\times10^9\ M_\odot$	$17\,\%$
Total gas	$6.7\times10^9\ M_\odot$	$100\,\%$

Element mass fractions (Asplund et al. 2009)

$$X_\odot \equiv \frac{M_\mathrm{H}}{M_\mathrm{gas}} \simeq 73.8\,\%$$

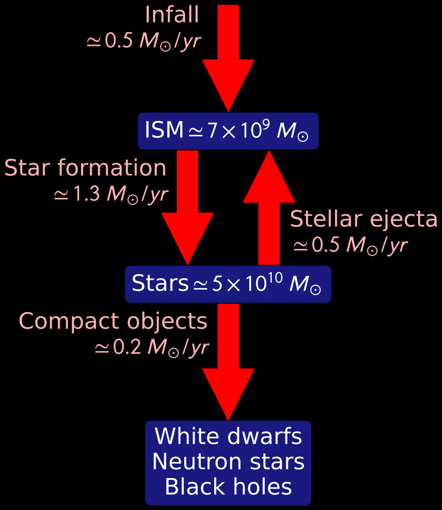
$$Y_\odot \equiv \frac{M_\mathrm{He}}{M_\mathrm{gas}} \simeq 24.9\,\%$$

$$Z_\odot \equiv \frac{M_{>\mathrm{He}}}{M_\mathrm{gas}} \simeq 1.3\,\%$$

$$X_\odot + Y_\odot + Z_\odot = 1$$

→ Most He formed during primordial nucleosynthesis.

(*metallicity*) → large variations among galaxy types.



$\Rightarrow$ ISM-to-star mass ratio $\simeq 14\,\%$.

(Adapted from Draine 2011, Chap. 1)

Gas associated with different states of H

H^+	1.5×10^9 $M_\odot$	23 %
H^0	4×10^9 $M_\odot$	60 %
H_2	1.2×10^9 $M_\odot$	17 %
Total gas	6.7×10^9 $M_\odot$	100 %

Element mass fractions (Asplund et al. 2009)

$$X_\odot \equiv \frac{M_{\rm H}}{M_{\rm gas}} \simeq 73.8\,\%$$

$$Y_\odot \equiv \frac{M_{\rm He}}{M_{\rm gas}} \simeq 24.9\,\%$$

$$Z_\odot \equiv \frac{M_{>\rm He}}{M_{\rm gas}} \simeq 1.3\,\%$$

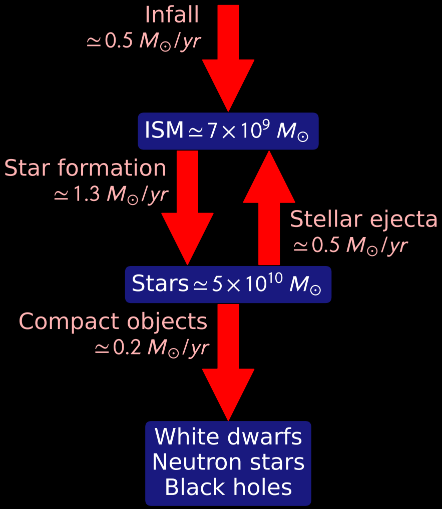
$$X_\odot + Y_\odot + Z_\odot = 1$$

$\rightarrow$ Most He formed during primordial nucleosynthesis.

(*metallicity*) $\rightarrow$ large variations among galaxy types.

Dust mass fractions (Galliano 2022)

Overview | Composition of the ISM of the Milky Way



$\Rightarrow$ ISM-to-star mass ratio $\simeq$ 14 %.

(Adapted from Draine 2011, Chap. 1)

Gas associated with different states of H

H^+	1.5×10^9 M$_\odot$	23 %
H^0	4×10^9 M$_\odot$	60 %
H_2	1.2×10^9 M$_\odot$	17 %
Total gas	6.7×10^9 M$_\odot$	100 %

Element mass fractions (Asplund et al. 2009)

$$X_\odot \equiv \frac{M_{\rm H}}{M_{\rm gas}} \simeq 73.8\,\%$$

$$X_\odot + Y_\odot + Z_\odot = 1$$

$$Y_\odot \equiv \frac{M_{\rm He}}{M_{\rm gas}} \simeq 24.9\,\%$$

$\rightarrow$ Most He formed during primordial nucleosynthesis.

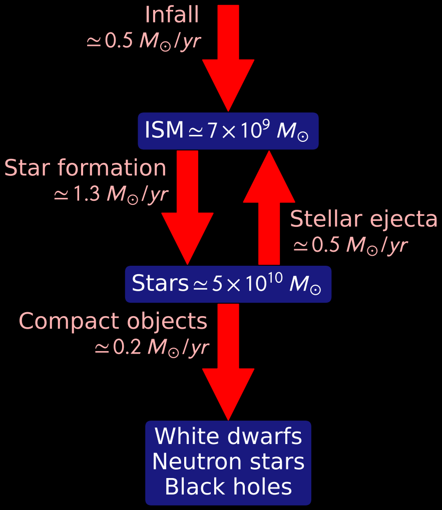
$$Z_\odot \equiv \frac{M_{>\rm He}}{M_{\rm gas}} \simeq 1.3\,\%$$

(*metallicity*) $\rightarrow$ large variations among galaxy types.

Dust mass fractions (Galliano 2022)

$$Z_{\rm dust} \equiv \frac{M_{\rm dust}}{M_{\rm gas}} \simeq 1/150$$

Composition of the ISM of the Milky Way



⇒ ISM-to-star mass ratio ≃ 14 %.

(Adapted from Draine 2011, Chap. 1)

Gas associated with different states of H

H^+	1.5×10^9 M$_\odot$	23 %
H^0	4×10^9 M$_\odot$	60 %
H_2	1.2×10^9 M$_\odot$	17 %
Total gas	6.7×10^9 M$_\odot$	100 %

Element mass fractions (Asplund et al. 2009)

$$X_\odot \equiv \frac{M_\text{H}}{M_\text{gas}} \simeq 73.8\,\%$$

$$X_\odot + Y_\odot + Z_\odot = 1$$

$$Y_\odot \equiv \frac{M_\text{He}}{M_\text{gas}} \simeq 24.9\,\%$$

→ Most He formed during primordial nucleosynthesis.

$$Z_\odot \equiv \frac{M_{>\text{He}}}{M_\text{gas}} \simeq 1.3\,\%$$

(*metallicity*) → large variations among galaxy types.

Dust mass fractions (Galliano 2022)

$$Z_\text{dust} \equiv \frac{M_\text{dust}}{M_\text{gas}} \simeq 1/150 \qquad DM \equiv \frac{M_\text{dust}}{M_{>\text{He}}} \simeq 1/2$$

Dust extinction

Credit: Barnard 68 (dark nebula); FORS Team, 8.2-meter VLT Antu, ESO.

Dust extinction

Credit: Barnard 68 (dark nebula); FORS Team, 8.2-meter VLT Antu, ESO.

⇒ Dust extincts starlight, mainly from the UV to the mid-IR.

Dust extinction

Credit: Barnard 68 (dark nebula); FORS Team, 8.2-meter VLT Antu, ESO.

⇒ Dust extincts starlight, mainly from the UV to the mid-IR.

Extinction in magnitude

Dust extinction

Credit: Barnard 68 (dark nebula); FORS Team, 8.2-meter VLT Antu, ESO.

⇒ Dust extincts starlight, mainly from the UV to the mid-IR.

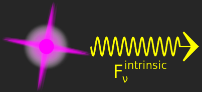
Extinction in magnitude

Dust extinction

Credit: Barnard 68 (dark nebula); FORS Team, 8.2-meter VLT Antu, ESO.

⇒ Dust extincts starlight, mainly from the UV to the mid-IR.

Extinction in magnitude

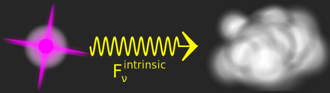


Dust extinction

Credit: Barnard 68 (dark nebula); FORS Team, 8.2-meter VLT Antu, ESO.

⇒ Dust extincts starlight, mainly from the UV to the mid-IR.

Extinction in magnitude

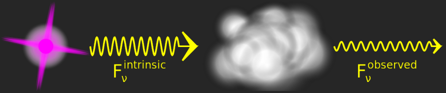


Dust extinction

Credit: Barnard 68 (dark nebula); FORS Team, 8.2-meter VLT Antu, ESO.

⇒ Dust extincts starlight, mainly from the UV to the mid-IR.

Extinction in magnitude

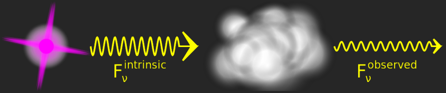


Dust extinction

Credit: Barnard 68 (dark nebula); FORS Team, 8.2-meter VLT Antu, ESO.

⇒ Dust extincts starlight, mainly from the UV to the mid-IR.

Extinction in magnitude



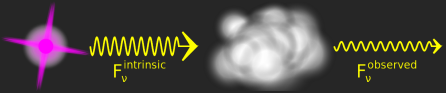
$$A(\lambda) \equiv m_{\text{observed}}(\lambda) - m_{\text{intrinsic}}(\lambda)$$

Dust extinction

Credit: Barnard 68 (dark nebula); FORS Team, 8.2-meter VLT Antu, ESO.

⇒ Dust extincts starlight, mainly from the UV to the mid-IR.

Extinction in magnitude



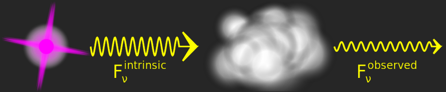
$$A(\lambda) \equiv m_{\text{observed}}(\lambda) - m_{\text{intrinsic}}(\lambda)$$
$$= 2.5\log\left(\frac{F_\nu^{\text{intrinsic}}(\lambda)}{F_\nu^{\text{observed}}(\lambda)}\right)$$

Dust extinction

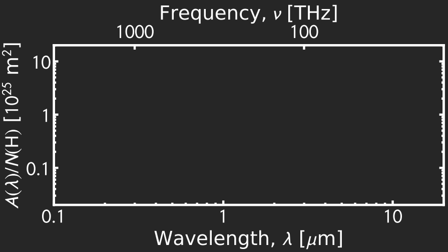
Credit: Barnard 68 (dark nebula); FORS Team, 8.2-meter VLT Antu, ESO.

⇒ Dust extincts starlight, mainly from the UV to the mid-IR.

Extinction in magnitude



$$A(\lambda) \equiv m_{\text{observed}}(\lambda) - m_{\text{intrinsic}}(\lambda) = 2.5 \log \left(\frac{F_\nu^{\text{intrinsic}}(\lambda)}{F_\nu^{\text{observed}}(\lambda)} \right)$$

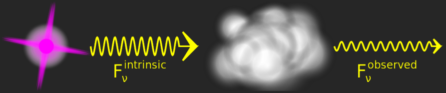


Dust extinction

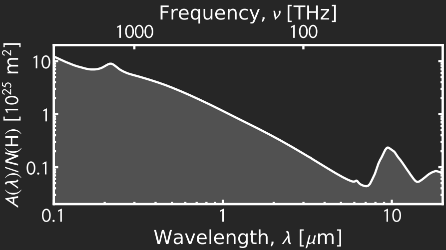
Credit: Barnard 68 (dark nebula); FORS Team, 8.2-meter VLT Antu, ESO.

⇒ Dust extincts starlight, mainly from the UV to the mid-IR.

Extinction in magnitude



$$A(\lambda) \equiv m_{\text{observed}}(\lambda) - m_{\text{intrinsic}}(\lambda) = 2.5 \log\left(\frac{F_\nu^{\text{intrinsic}}(\lambda)}{F_\nu^{\text{observed}}(\lambda)}\right)$$

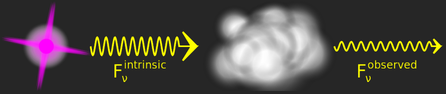


Dust extinction

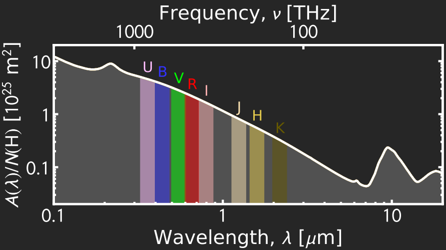
Credit: Barnard 68 (dark nebula); FORS Team, 8.2-meter VLT Antu, ESO.

⇒ Dust extincts starlight, mainly from the UV to the mid-IR.

Extinction in magnitude



$$A(\lambda) \equiv m_{\text{observed}}(\lambda) - m_{\text{intrinsic}}(\lambda) = 2.5 \log \left(\frac{F_\nu^{\text{intrinsic}}(\lambda)}{F_\nu^{\text{observed}}(\lambda)} \right)$$

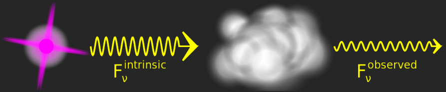


Dust extinction

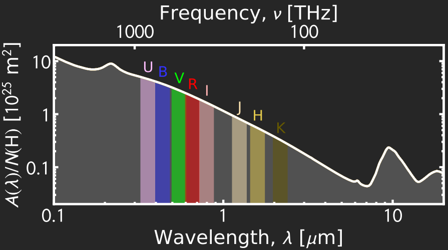
Credit: Barnard 68 (dark nebula); FORS Team, 8.2-meter VLT Antu, ESO.

$\Rightarrow$ Dust extincts starlight, mainly from the UV to the mid-IR.

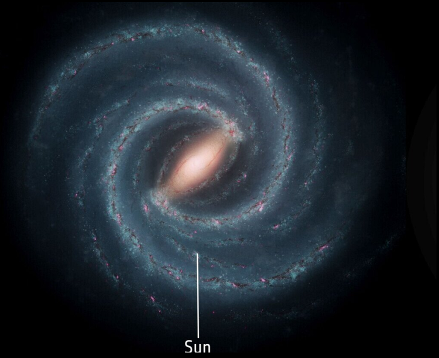
Extinction in magnitude



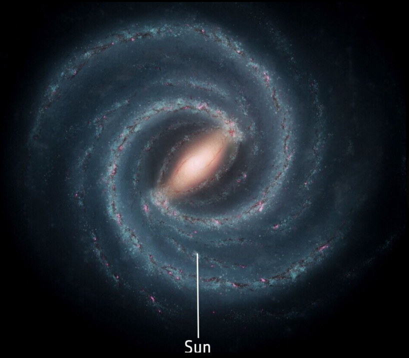
$$A(\lambda) \equiv m_{\text{observed}}(\lambda) - m_{\text{intrinsic}}(\lambda) = 2.5 \log\left(\frac{F_\nu^{\text{intrinsic}}(\lambda)}{F_\nu^{\text{observed}}(\lambda)}\right)$$

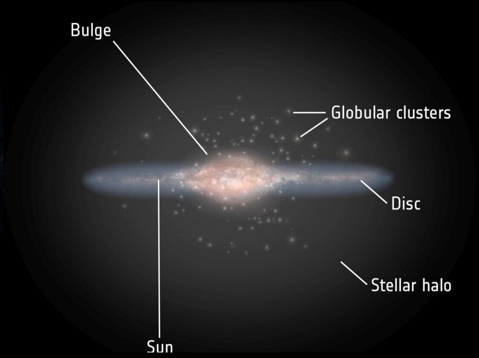


$$\frac{N(\text{H I})}{A(V)} \simeq 2.8 \times 10^{25}\ \text{m}^{-2}\text{mag}^{-1}$$



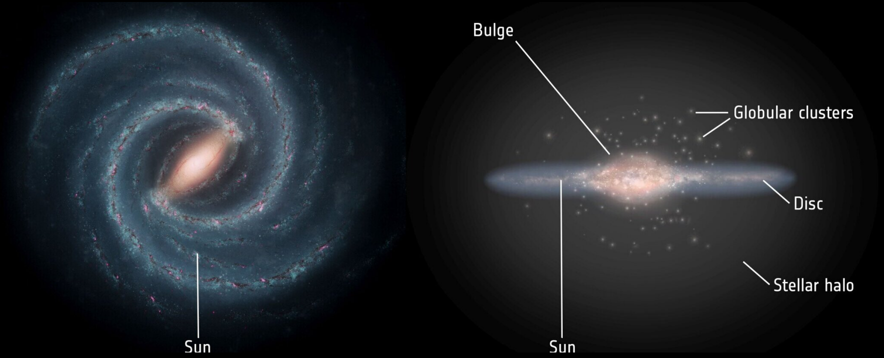
Credit: artist view; NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab.





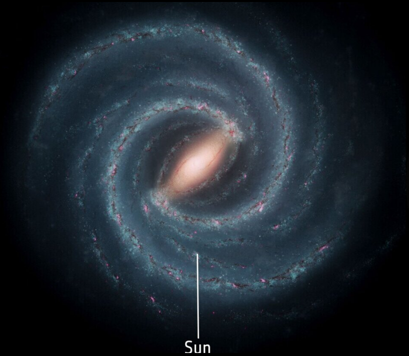
Credit: artist view; NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab.

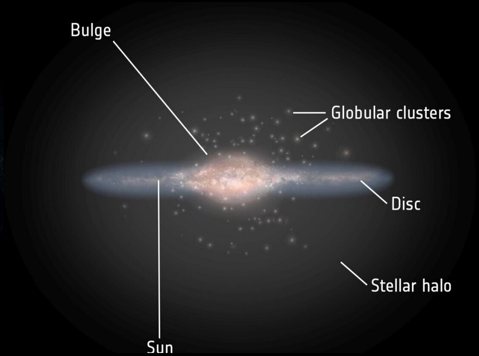
Overview | Morphology of the Milky Way



Credit: artist view; NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab.

Quantitative information

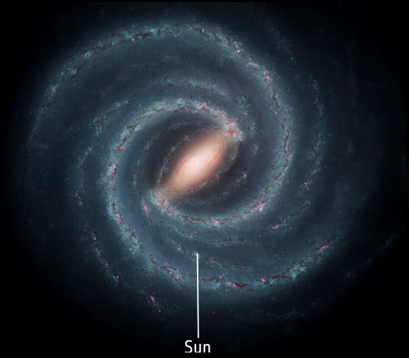


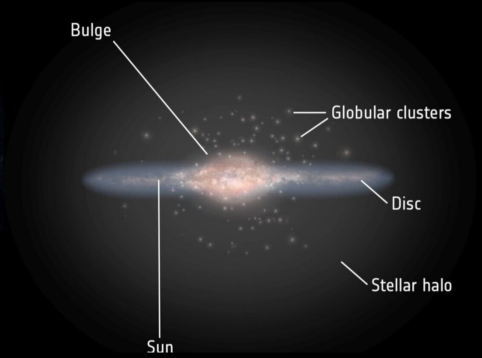


Credit: artist view; NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab.

Quantitative information

Full diameter: $D_{25} \simeq 27$ kpc.

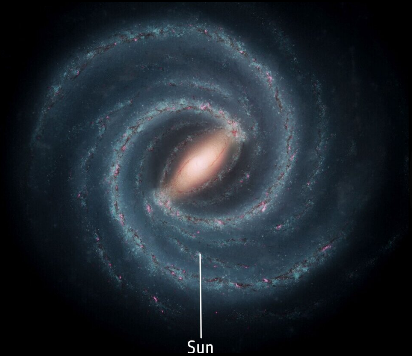


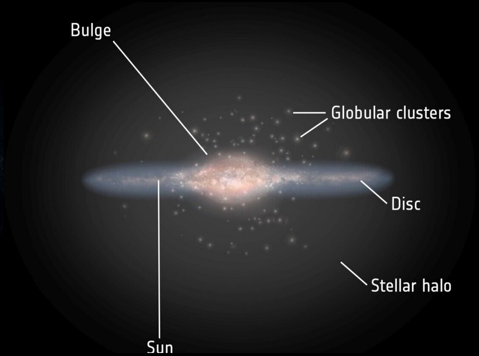


Credit: artist view; NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab.

Quantitative information

Full diameter: $D_{25} \simeq 27$ kpc.
Position of the Sun: $R_\odot \simeq 8.5$ kpc.

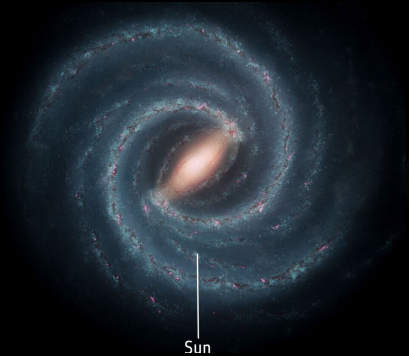


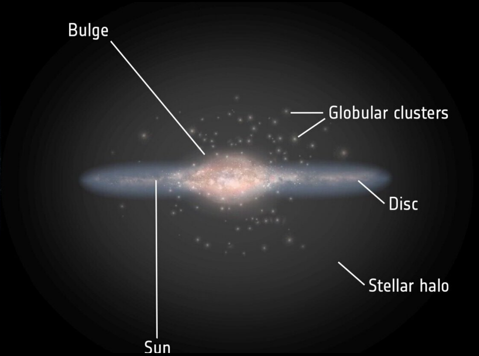


Credit: artist view; NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab.

Quantitative information

Full diameter: $D_{25} \simeq 27$ kpc.
Position of the Sun: $R_\odot \simeq 8.5$ kpc.
Disk thickness: $h \simeq 500$ pc (at 1/2 radius).

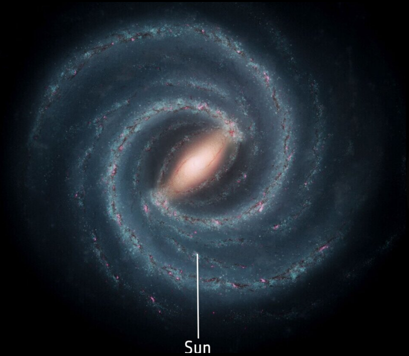


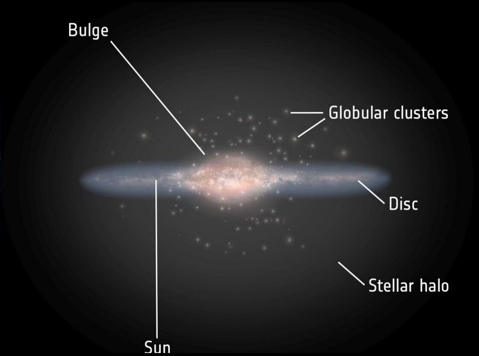


Credit: artist view; NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab.

Quantitative information

Full diameter: $D_{25} \simeq 27$ kpc.
Position of the Sun: $R_\odot \simeq 8.5$ kpc.
Disk thickness: $h \simeq 500$ pc (at 1/2 radius).
$\rightarrow$ most of the ISM is in the disk.

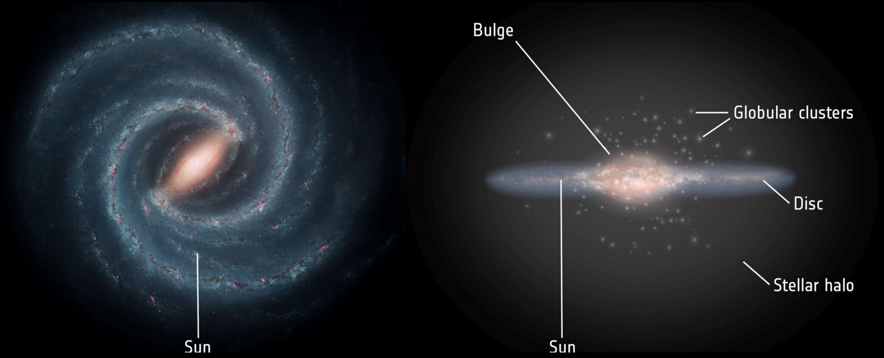




Credit: artist view; NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab.

Quantitative information

Full diameter: $D_{25} \simeq 27$ kpc.
Position of the Sun: $R_\odot \simeq 8.5$ kpc.
Disk thickness: $h \simeq 500$ pc (at 1/2 radius).
$\rightarrow$ most of the ISM is in the disk.
Mean distance between stars: $d_\star \simeq 1$ pc.

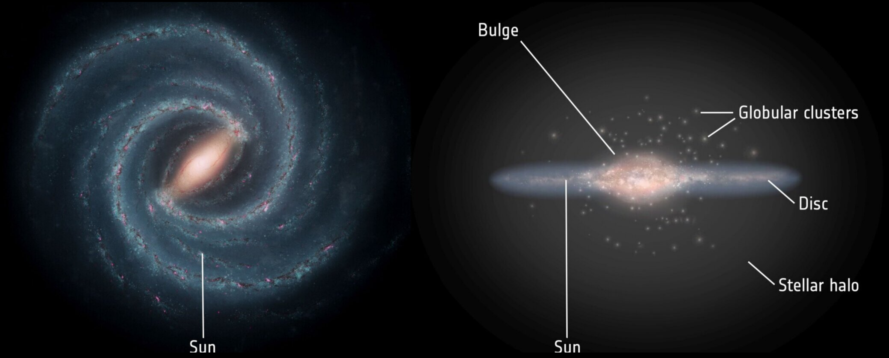


Credit: artist view; NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab.

Quantitative information

Full diameter: $D_{25} \simeq 27$ kpc.
Position of the Sun: $R_\odot \simeq 8.5$ kpc.
Disk thickness: $h \simeq 500$ pc (at 1/2 radius).
$\rightarrow$ most of the ISM is in the disk.
Mean distance between stars: $d_\star \simeq 1$ pc.

Mean ISM density: $n_{\text{H}} \simeq 0.3$ H/cm^3



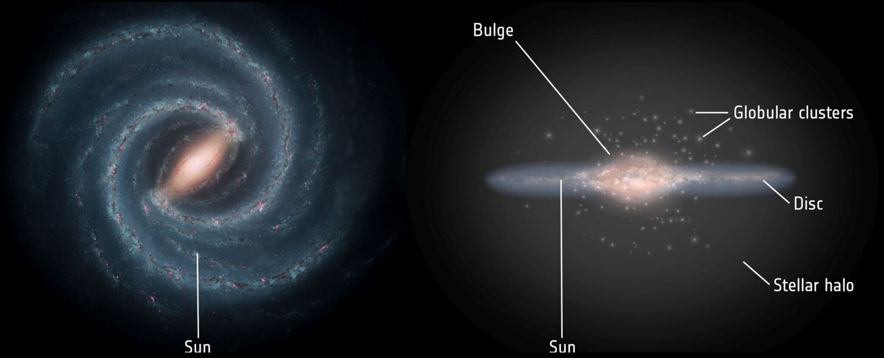
Credit: artist view; NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab.

Quantitative information

Full diameter: $D_{25} \simeq 27$ kpc.
Position of the Sun: $R_{\odot} \simeq 8.5$ kpc.
Disk thickness: $h \simeq 500$ pc (at 1/2 radius).
$\rightarrow$ most of the ISM is in the disk.
Mean distance between stars: $d_{\star} \simeq 1$ pc.

Mean ISM density: $n_{\text{H}} \simeq 0.3\ \text{H/cm}^3$

- Man-made ultra-high vacuum $\simeq 100\ \text{cm}^{-3}$.



Credit: artist view; NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab.

Quantitative information

Full diameter: $D_{25} \simeq 27$ kpc.
Position of the Sun: $R_{\odot} \simeq 8.5$ kpc.
Disk thickness: $h \simeq 500$ pc (at 1/2 radius).
$\rightarrow$ most of the ISM is in the disk.
Mean distance between stars: $d_{\star} \simeq 1$ pc.

Mean ISM density: $n_{\mathrm{H}} \simeq 0.3\ \mathrm{H/cm^3}$

- Man-made ultra-high vacuum $\simeq 100\ \mathrm{cm^{-3}}$.
- Air density $\simeq 10^{20}\ \mathrm{cm^{-3}}$.

Mean collision time between two H atoms

Mean collision time between two H atoms

Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Mean collision time between two H atoms

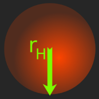
Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å:

Mean collision time between two H atoms

Let's assume that the ISM is only made of H atoms, with $n_{\mathrm{H}} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

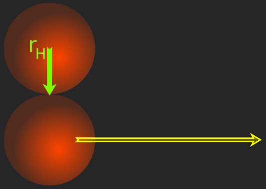
Collision cross-section between two H atoms, with $r_{\mathrm{H}} = 0.5$ Å:



Mean collision time between two H atoms

Let's assume that the ISM is only made of H atoms, with $n_{\rm H} = 0.3\ {\rm cm}^{-3}$ & $T = 1000$ K.

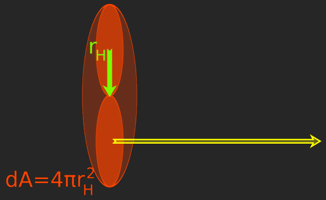
Collision cross-section between two H atoms, with $r_{\rm H} = 0.5$ Å:



Mean collision time between two H atoms

Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

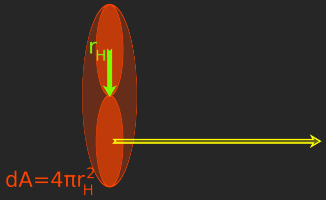
Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å:



Mean collision time between two H atoms

Let's assume that the ISM is only made of H atoms, with $n_{\mathrm{H}} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

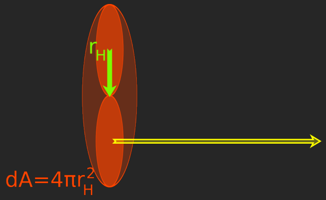
Collision cross-section between two H atoms, with $r_{\mathrm{H}} = 0.5$ Å: $\sigma_{\mathrm{H}} \equiv \pi(2r_{\mathrm{H}})^2$.



Mean collision time between two H atoms

Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å: $\sigma_\mathrm{H} \equiv \pi(2r_\mathrm{H})^2$.



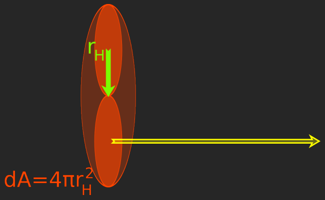
Mean free-path:

Mean collision time between two H atoms

Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å: $\sigma_\mathrm{H} \equiv \pi(2r_\mathrm{H})^2$.

Mean free-path: $\lambda_\mathrm{H} \equiv \dfrac{1}{n_\mathrm{H}\sigma_\mathrm{H}}$

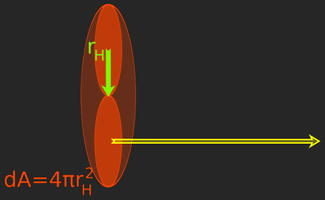


Mean collision time between two H atoms

Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å: $\sigma_\mathrm{H} \equiv \pi(2r_\mathrm{H})^2$.

Mean free-path: $\lambda_\mathrm{H} \equiv \dfrac{1}{n_\mathrm{H}\sigma_\mathrm{H}} \simeq 10^{13}$ m

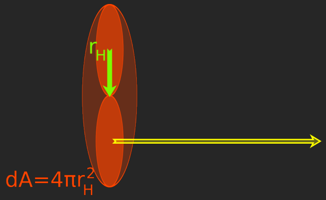


Mean collision time between two H atoms

Let's assume that the ISM is only made of H atoms, with $n_\text{H} = 0.3\ \text{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\text{H} = 0.5$ Å: $\sigma_\text{H} \equiv \pi(2r_\text{H})^2$.

Mean free-path: $\lambda_\text{H} \equiv \dfrac{1}{n_\text{H}\sigma_\text{H}} \simeq 10^{13}\ \text{m} \simeq 700$ a.u.



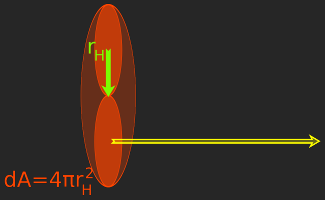
Mean collision time between two H atoms

Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å: $\sigma_\mathrm{H} \equiv \pi(2r_\mathrm{H})^2$.

Mean free-path: $\lambda_\mathrm{H} \equiv \dfrac{1}{n_\mathrm{H}\sigma_\mathrm{H}} \simeq 10^{13}\ \mathrm{m} \simeq 700$ a.u.

Mean velocity:



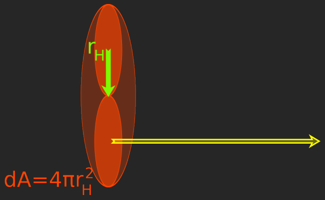
Mean collision time between two H atoms

Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å: $\sigma_\mathrm{H} \equiv \pi(2r_\mathrm{H})^2$.

Mean free-path: $\lambda_\mathrm{H} \equiv \dfrac{1}{n_\mathrm{H}\sigma_\mathrm{H}} \simeq 10^{13}\ \mathrm{m} \simeq 700$ a.u.

Mean velocity: $\dfrac{1}{2} m_\mathrm{H} v_\mathrm{H}^2 = \dfrac{3}{2} kT$



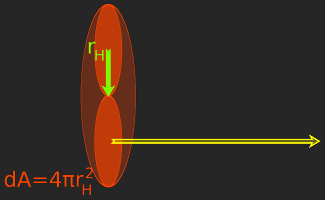
Mean collision time between two H atoms

Let's assume that the ISM is only made of H atoms, with $n_{\mathrm{H}} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_{\mathrm{H}} = 0.5$ Å: $\sigma_{\mathrm{H}} \equiv \pi(2r_{\mathrm{H}})^2$.

Mean free-path: $\lambda_{\mathrm{H}} \equiv \dfrac{1}{n_{\mathrm{H}}\sigma_{\mathrm{H}}} \simeq 10^{13}\ \mathrm{m} \simeq 700$ a.u.

Mean velocity: $\dfrac{1}{2}m_{\mathrm{H}}v_{\mathrm{H}}^2 = \dfrac{3}{2}kT \Rightarrow v_{\mathrm{H}} = \sqrt{\dfrac{3kT}{m_{\mathrm{H}}}}$.



Mean collision time between two H atoms

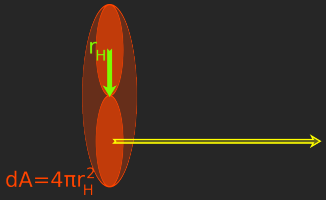
Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å: $\sigma_\mathrm{H} \equiv \pi(2r_\mathrm{H})^2$.

Mean free-path: $\lambda_\mathrm{H} \equiv \dfrac{1}{n_\mathrm{H}\sigma_\mathrm{H}} \simeq 10^{13}$ m $\simeq 700$ a.u.

Mean velocity: $\dfrac{1}{2}m_\mathrm{H}v_\mathrm{H}^2 = \dfrac{3}{2}kT \Rightarrow v_\mathrm{H} = \sqrt{\dfrac{3kT}{m_\mathrm{H}}}$.

Collision time:



Mean collision time between two H atoms

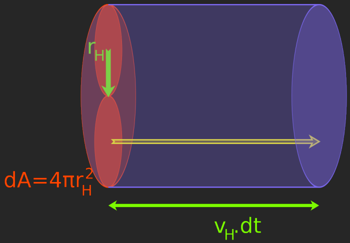
Let's assume that the ISM is only made of H atoms, with $n_{\mathrm{H}} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_{\mathrm{H}} = 0.5$ Å: $\sigma_{\mathrm{H}} \equiv \pi(2r_{\mathrm{H}})^2$.

Mean free-path: $\lambda_{\mathrm{H}} \equiv \frac{1}{n_{\mathrm{H}}\sigma_{\mathrm{H}}} \simeq 10^{13}\ \mathrm{m} \simeq 700$ a.u.

Mean velocity: $\frac{1}{2}m_{\mathrm{H}}v_{\mathrm{H}}^2 = \frac{3}{2}kT \Rightarrow v_{\mathrm{H}} = \sqrt{\frac{3kT}{m_{\mathrm{H}}}}$.

Collision time:



Mean collision time between two H atoms

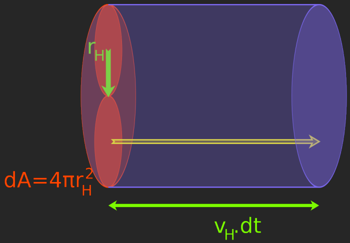
Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å: $\sigma_\mathrm{H} \equiv \pi(2r_\mathrm{H})^2$.

Mean free-path: $\lambda_\mathrm{H} \equiv \dfrac{1}{n_\mathrm{H}\sigma_\mathrm{H}} \simeq 10^{13}\ \mathrm{m} \simeq 700$ a.u.

Mean velocity: $\dfrac{1}{2} m_\mathrm{H} v_\mathrm{H}^2 = \dfrac{3}{2} kT \Rightarrow v_\mathrm{H} = \sqrt{\dfrac{3kT}{m_\mathrm{H}}}$.

Collision time: $\tau_\mathrm{coll} \equiv \dfrac{\lambda_\mathrm{H}}{v_\mathrm{H}}$



Mean collision time between two H atoms

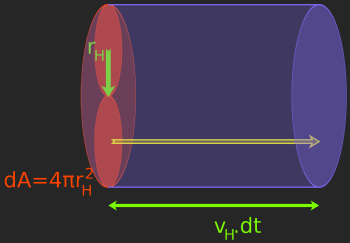
Let's assume that the ISM is only made of H atoms, with $n_{\rm H} = 0.3\ {\rm cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_{\rm H} = 0.5$ Å: $\sigma_{\rm H} \equiv \pi(2r_{\rm H})^2$.

Mean free-path: $\lambda_{\rm H} \equiv \frac{1}{n_{\rm H}\sigma_{\rm H}} \simeq 10^{13}\ {\rm m} \simeq 700$ a.u.

Mean velocity: $\frac{1}{2}m_{\rm H}v_{\rm H}^2 = \frac{3}{2}kT \Rightarrow v_{\rm H} = \sqrt{\frac{3kT}{m_{\rm H}}}$.

Collision time: $\tau_{\rm coll} \equiv \frac{\lambda_{\rm H}}{v_{\rm H}} = \frac{\lambda_{\rm H}}{\sqrt{3kT/m_{\rm H}}}$



Mean collision time between two H atoms

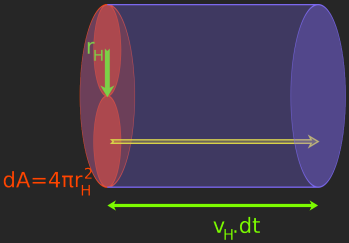
Let's assume that the ISM is only made of H atoms, with $n_{\rm H} = 0.3\ {\rm cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_{\rm H} = 0.5$ Å: $\sigma_{\rm H} \equiv \pi(2r_{\rm H})^2$.

Mean free-path: $\lambda_{\rm H} \equiv \dfrac{1}{n_{\rm H}\sigma_{\rm H}} \simeq 10^{13}\ {\rm m} \simeq 700$ a.u.

Mean velocity: $\dfrac{1}{2}m_{\rm H}v_{\rm H}^2 = \dfrac{3}{2}kT \Rightarrow v_{\rm H} = \sqrt{\dfrac{3kT}{m_{\rm H}}}$.

Collision time: $\tau_{\rm coll} \equiv \dfrac{\lambda_{\rm H}}{v_{\rm H}} = \dfrac{\lambda_{\rm H}}{\sqrt{3kT/m_{\rm H}}} \simeq 2 \times 10^{10}$ s



Mean collision time between two H atoms

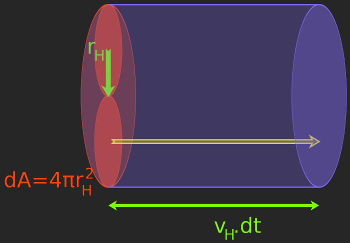
Let's assume that the ISM is only made of H atoms, with $n_{\rm H} = 0.3\ {\rm cm^{-3}}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_{\rm H} = 0.5$ Å: $\sigma_{\rm H} \equiv \pi(2r_{\rm H})^2$.

Mean free-path: $\lambda_{\rm H} \equiv \dfrac{1}{n_{\rm H}\sigma_{\rm H}} \simeq 10^{13}\ {\rm m} \simeq 700$ a.u.

Mean velocity: $\dfrac{1}{2}m_{\rm H}v_{\rm H}^2 = \dfrac{3}{2}kT \Rightarrow v_{\rm H} = \sqrt{\dfrac{3kT}{m_{\rm H}}}$.

Collision time: $\tau_{\rm coll} \equiv \dfrac{\lambda_{\rm H}}{v_{\rm H}} = \dfrac{\lambda_{\rm H}}{\sqrt{3kT/m_{\rm H}}} \simeq 2\times 10^{10}$ s $\simeq 700$ yr.



Mean collision time between two H atoms

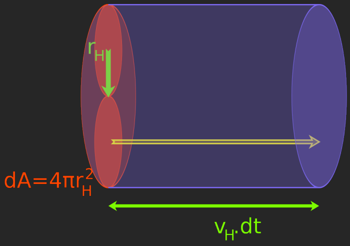
Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å: $\sigma_\mathrm{H} \equiv \pi(2r_\mathrm{H})^2$.

Mean free-path: $\lambda_\mathrm{H} \equiv \frac{1}{n_\mathrm{H}\sigma_\mathrm{H}} \simeq 10^{13}\ \mathrm{m} \simeq 700$ a.u.

Mean velocity: $\frac{1}{2}m_\mathrm{H}v_\mathrm{H}^2 = \frac{3}{2}kT \Rightarrow v_\mathrm{H} = \sqrt{\frac{3kT}{m_\mathrm{H}}}$.

Collision time: $\tau_\mathrm{coll} \equiv \frac{\lambda_\mathrm{H}}{v_\mathrm{H}} = \frac{\lambda_\mathrm{H}}{\sqrt{3kT/m_\mathrm{H}}} \simeq 2 \times 10^{10}\ \mathrm{s}$ $\simeq 700$ yr.



Conditions for Local Thermal Equilibirum (LTE)

Mean collision time between two H atoms

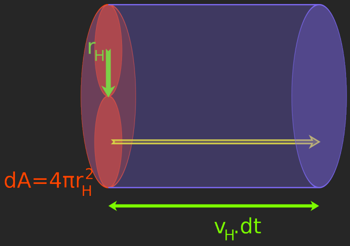
Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å: $\sigma_\mathrm{H} \equiv \pi(2r_\mathrm{H})^2$.

Mean free-path: $\lambda_\mathrm{H} \equiv \dfrac{1}{n_\mathrm{H}\sigma_\mathrm{H}} \simeq 10^{13}\ \mathrm{m} \simeq 700$ a.u.

Mean velocity: $\dfrac{1}{2} m_\mathrm{H} v_\mathrm{H}^2 = \dfrac{3}{2} kT \Rightarrow v_\mathrm{H} = \sqrt{\dfrac{3kT}{m_\mathrm{H}}}$.

Collision time: $\tau_\mathrm{coll} \equiv \dfrac{\lambda_\mathrm{H}}{v_\mathrm{H}} = \dfrac{\lambda_\mathrm{H}}{\sqrt{3kT/m_\mathrm{H}}} \simeq 2 \times 10^{10}$ s $\simeq 700$ yr.



Conditions for Local Thermal Equilibirum (LTE)

Spontaneous transition rate for the first levels of H:

Mean collision time between two H atoms

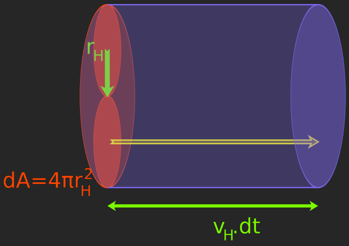
Let's assume that the ISM is only made of H atoms, with $n_\text{H} = 0.3\ \text{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\text{H} = 0.5$ Å: $\sigma_\text{H} \equiv \pi(2r_\text{H})^2$.

Mean free-path: $\lambda_\text{H} \equiv \frac{1}{n_\text{H}\sigma_\text{H}} \simeq 10^{13}\ \text{m} \simeq 700$ a.u.

Mean velocity: $\frac{1}{2}m_\text{H}v_\text{H}^2 = \frac{3}{2}kT \Rightarrow v_\text{H} = \sqrt{\frac{3kT}{m_\text{H}}}$.

Collision time: $\tau_\text{coll} \equiv \frac{\lambda_\text{H}}{v_\text{H}} = \frac{\lambda_\text{H}}{\sqrt{3kT/m_\text{H}}} \simeq 2\times10^{10}$ s $\simeq 700$ yr.



Conditions for Local Thermal Equilibirum (LTE)

Spontaneous transition rate for the first levels of H:

$$\tau_\text{cool} = \frac{1}{A\ (\text{Einstein coefficient})}$$

Mean collision time between two H atoms

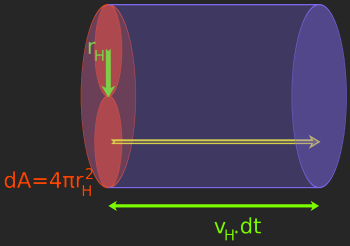
Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å: $\sigma_\mathrm{H} \equiv \pi(2r_\mathrm{H})^2$.

Mean free-path: $\lambda_\mathrm{H} \equiv \dfrac{1}{n_\mathrm{H}\sigma_\mathrm{H}} \simeq 10^{13}$ m $\simeq 700$ a.u.

Mean velocity: $\dfrac{1}{2} m_\mathrm{H} v_\mathrm{H}^2 = \dfrac{3}{2} kT \Rightarrow v_\mathrm{H} = \sqrt{\dfrac{3kT}{m_\mathrm{H}}}$.

Collision time: $\tau_\mathrm{coll} \equiv \dfrac{\lambda_\mathrm{H}}{v_\mathrm{H}} = \dfrac{\lambda_\mathrm{H}}{\sqrt{3kT/m_\mathrm{H}}} \simeq 2 \times 10^{10}$ s $\simeq 700$ yr.



Conditions for Local Thermal Equilibirum (LTE)

Spontaneous transition rate for the first levels of H:

$$\tau_\mathrm{cool} = \frac{1}{A\ (\text{Einstein coefficient})} \simeq 10^{-8} - 10^{-5}\ \mathrm{s}$$

Mean collision time between two H atoms

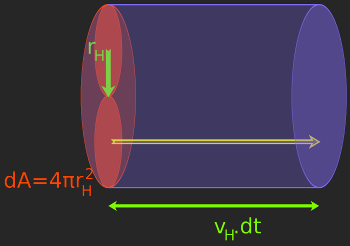
Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å: $\sigma_\mathrm{H} \equiv \pi(2r_\mathrm{H})^2$.

Mean free-path: $\lambda_\mathrm{H} \equiv \dfrac{1}{n_\mathrm{H}\sigma_\mathrm{H}} \simeq 10^{13}$ m $\simeq 700$ a.u.

Mean velocity: $\dfrac{1}{2} m_\mathrm{H} v_\mathrm{H}^2 = \dfrac{3}{2} kT \Rightarrow v_\mathrm{H} = \sqrt{\dfrac{3kT}{m_\mathrm{H}}}$.

Collision time: $\tau_\mathrm{coll} \equiv \dfrac{\lambda_\mathrm{H}}{v_\mathrm{H}} = \dfrac{\lambda_\mathrm{H}}{\sqrt{3kT/m_\mathrm{H}}} \simeq 2 \times 10^{10}$ s $\simeq 700$ yr.



Conditions for Local Thermal Equilibirum (LTE)

Spontaneous transition rate for the first levels of H:

$$\tau_\mathrm{cool} = \frac{1}{A\ \text{(Einstein coefficient)}} \simeq 10^{-8} - 10^{-5}\ \mathrm{s}$$

$$\Rightarrow \tau_\mathrm{cool} \ll \tau_\mathrm{coll}$$

Mean collision time between two H atoms

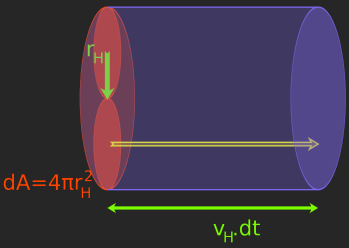
Let's assume that the ISM is only made of H atoms, with $n_\mathrm{H} = 0.3\ \mathrm{cm}^{-3}$ & $T = 1000$ K.

Collision cross-section between two H atoms, with $r_\mathrm{H} = 0.5$ Å: $\sigma_\mathrm{H} \equiv \pi(2r_\mathrm{H})^2$.

Mean free-path: $\lambda_\mathrm{H} \equiv \dfrac{1}{n_\mathrm{H}\sigma_\mathrm{H}} \simeq 10^{13}\ \mathrm{m} \simeq 700$ a.u.

Mean velocity: $\dfrac{1}{2} m_\mathrm{H} v_\mathrm{H}^2 = \dfrac{3}{2} kT \Rightarrow v_\mathrm{H} = \sqrt{\dfrac{3kT}{m_\mathrm{H}}}$.

Collision time: $\tau_\mathrm{coll} \equiv \dfrac{\lambda_\mathrm{H}}{v_\mathrm{H}} = \dfrac{\lambda_\mathrm{H}}{\sqrt{3kT/m_\mathrm{H}}} \simeq 2 \times 10^{10}$ s $\simeq 700$ yr.



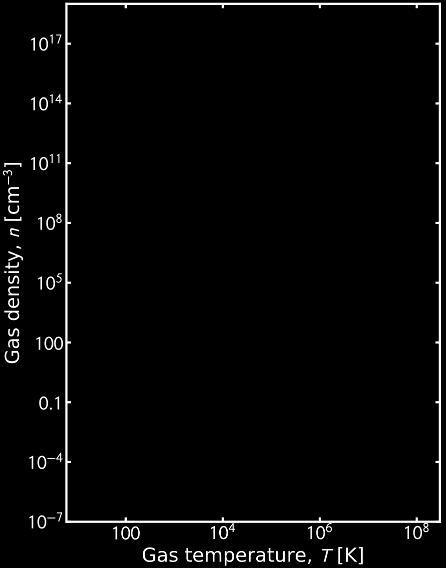
Conditions for Local Thermal Equilibirum (LTE)

Spontaneous transition rate for the first levels of H:

$$\tau_\mathrm{cool} = \frac{1}{A\ (\text{Einstein coefficient})} \simeq 10^{-8} - 10^{-5}\ \mathrm{s}$$

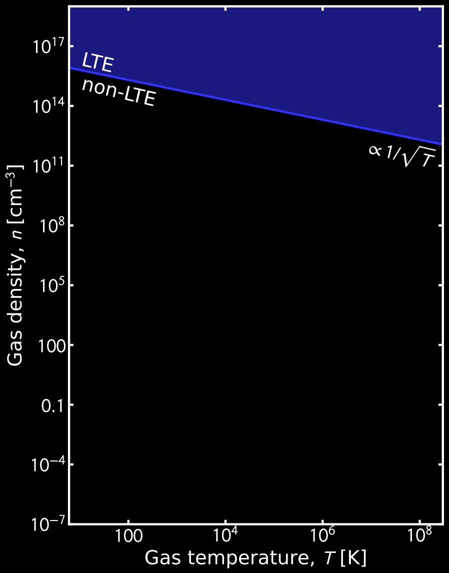
$\Rightarrow$ $\tau_\mathrm{cool} \ll \tau_\mathrm{coll}$

$\Rightarrow$ T is not sufficient to describe the physical state of the ISM (species are usually in their ground state).

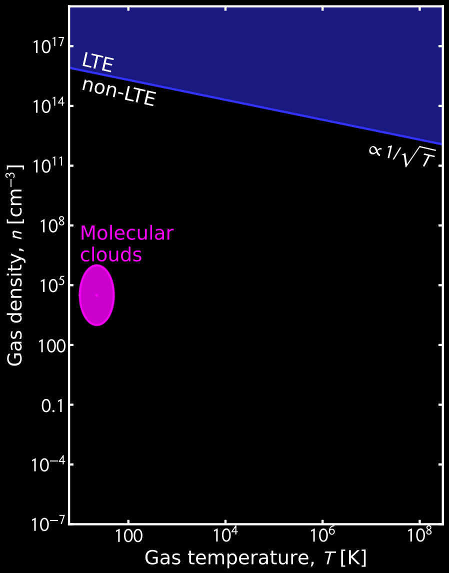


(Adapted from Dopita & Sutherland 2003)

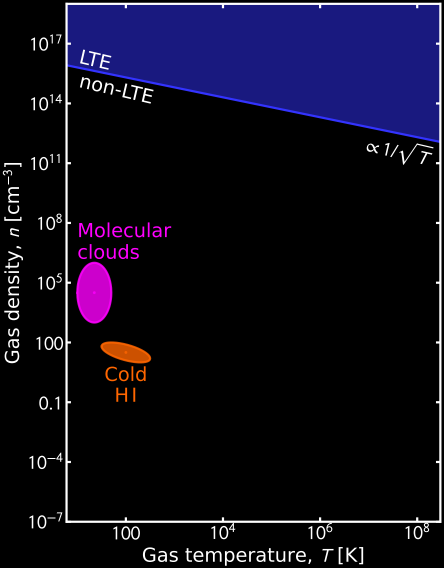
Overview | Density & Temperature Range of the ISM



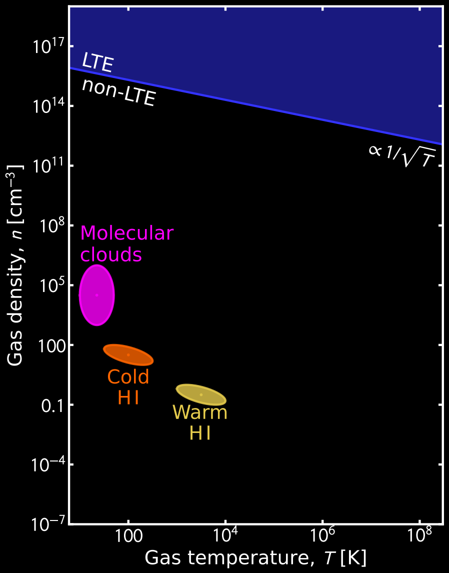
(Adapted from Dopita & Sutherland 2003)



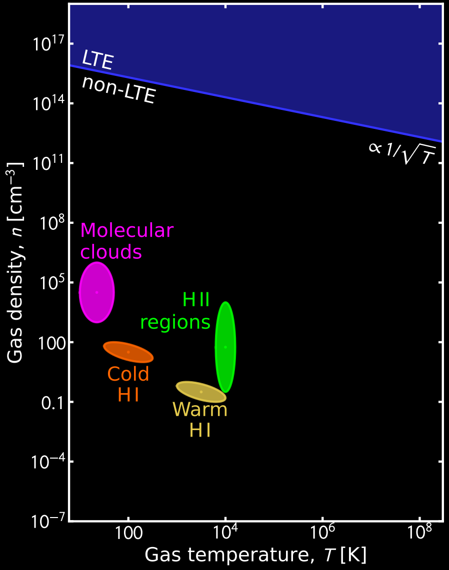
(Adapted from Dopita & Sutherland 2003)



(Adapted from Dopita & Sutherland 2003)

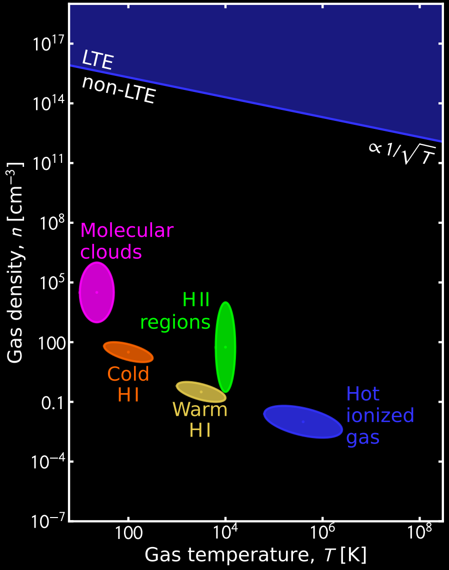


(Adapted from Dopita & Sutherland 2003)



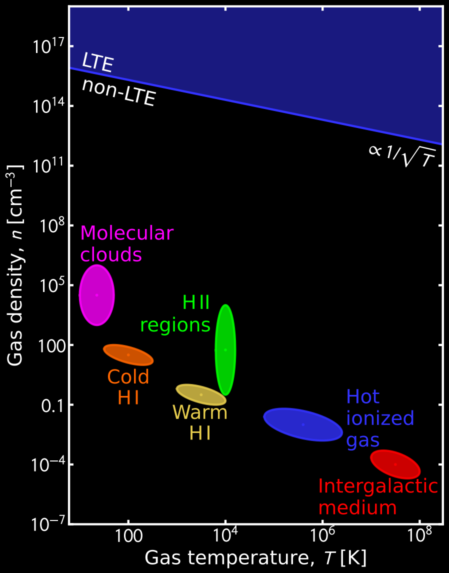
(Adapted from Dopita & Sutherland 2003)

Overview | Density & Temperature Range of the ISM

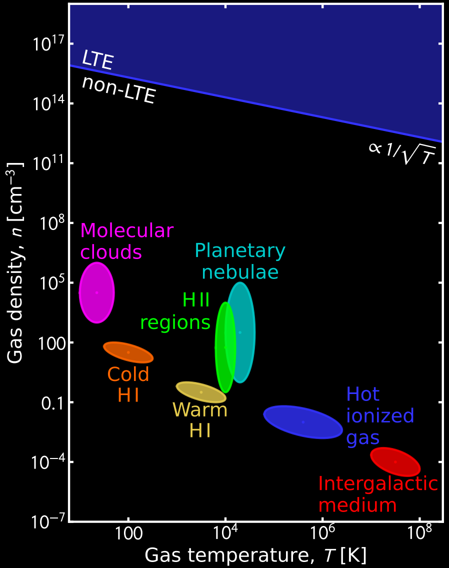


(Adapted from Dopita & Sutherland 2003)

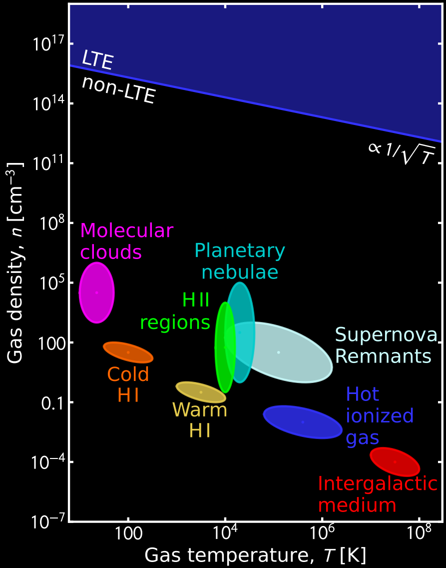
Overview | Density & Temperature Range of the ISM



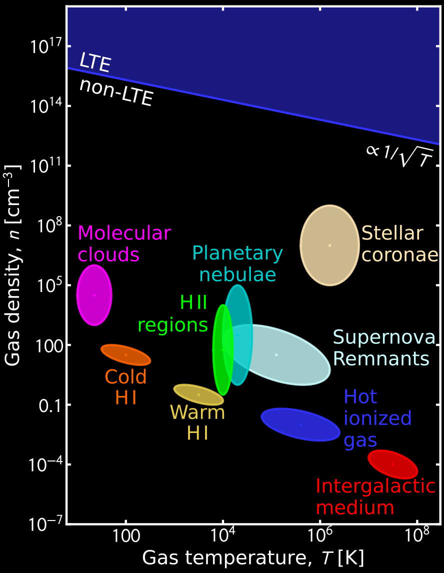
(Adapted from Dopita & Sutherland 2003)



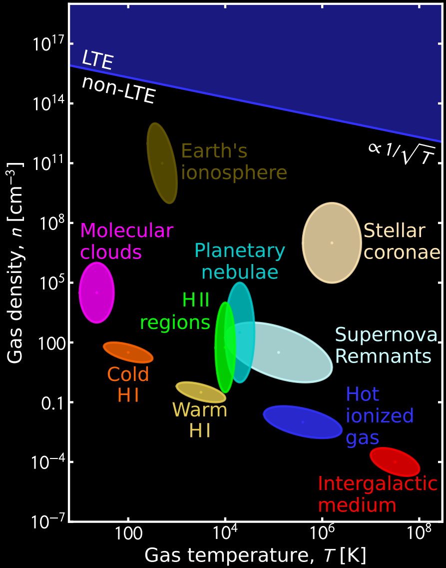
(Adapted from Dopita & Sutherland 2003)



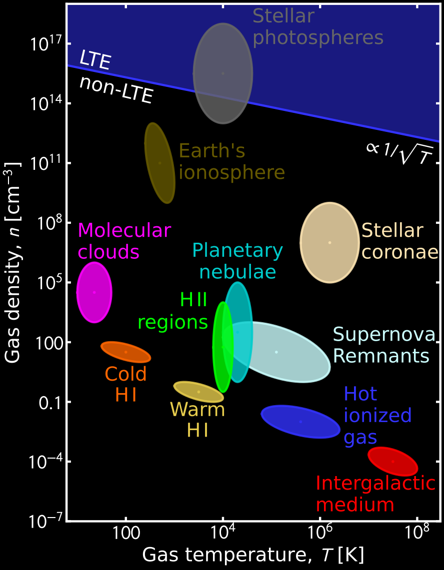
(Adapted from Dopita & Sutherland 2003)



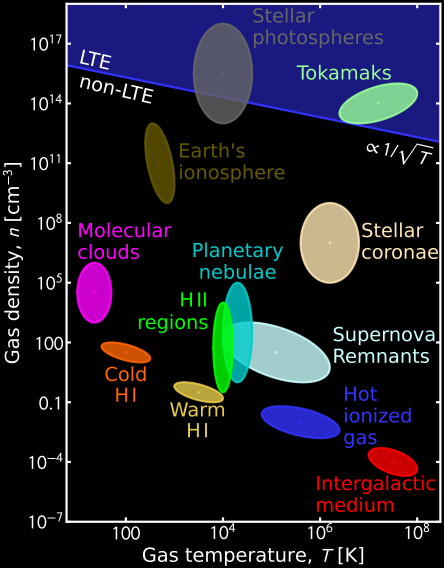
(Adapted from Dopita & Sutherland 2003)



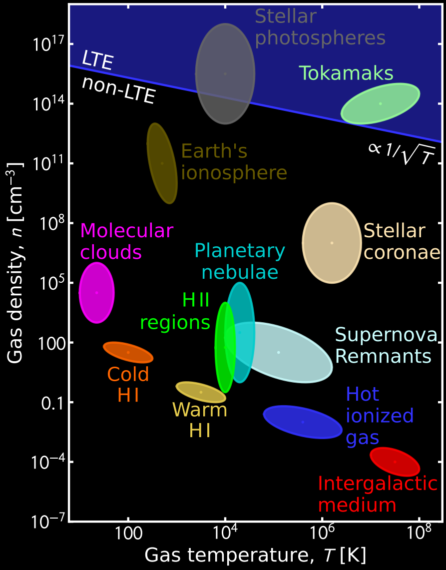
(Adapted from Dopita & Sutherland 2003)



(Adapted from Dopita & Sutherland 2003)

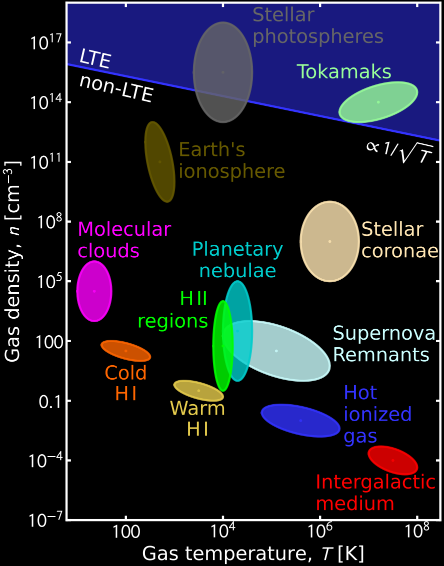


(Adapted from Dopita & Sutherland 2003)



(Adapted from Dopita & Sutherland 2003)

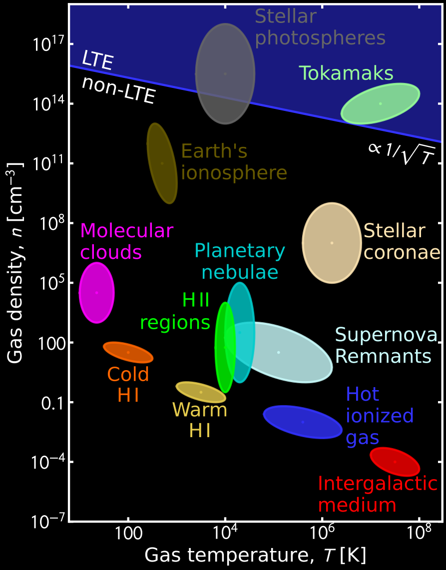
Velocity distribution in the ISM



(Adapted from Dopita & Sutherland 2003)

Velocity distribution in the ISM

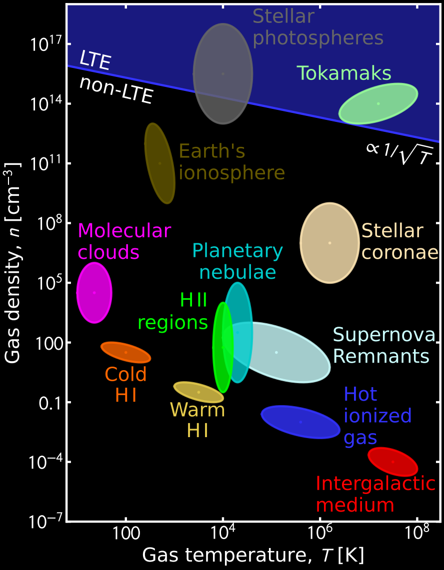
1. Typical scale of interstellar clouds: $L_{\rm ISM} \simeq 1$ pc



(Adapted from Dopita & Sutherland 2003)

Velocity distribution in the ISM

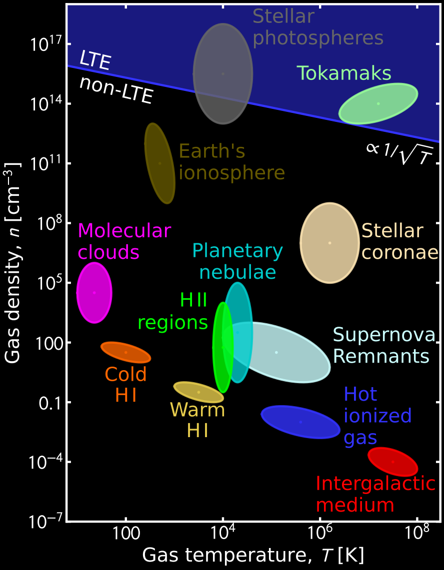
1. Typical scale of interstellar clouds: $L_{\rm ISM} \simeq 1$ pc $\gg \lambda_{\rm H}$.



(Adapted from Dopita & Sutherland 2003)

Velocity distribution in the ISM

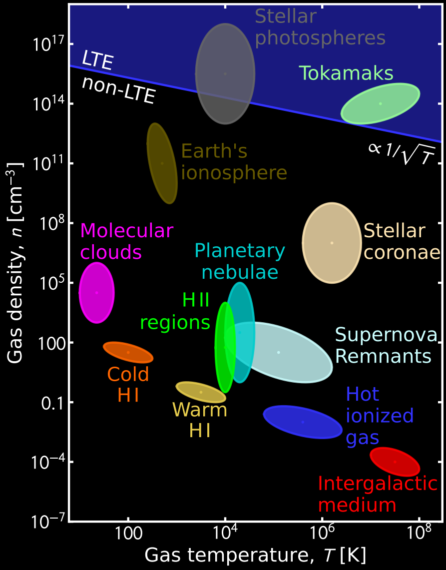
1. Typical scale of interstellar clouds: $L_{\rm ISM} \simeq 1$ pc $\gg \lambda_{\rm H}$.
2. Typical cloud lifetimes: $\tau_{\rm cl} \gtrsim 1$ Myr



(Adapted from Dopita & Sutherland 2003)

Velocity distribution in the ISM

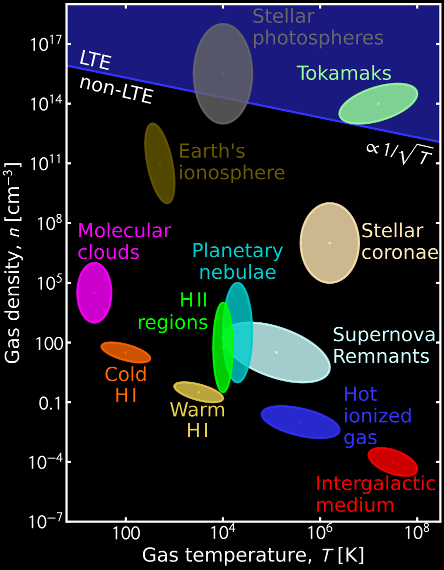
1. Typical scale of interstellar clouds: $L_{\rm ISM} \simeq 1$ pc $\gg \lambda_{\rm H}$.
2. Typical cloud lifetimes: $\tau_{\rm cl} \gtrsim 1$ Myr $\gg \tau_{\rm coll}$.



(Adapted from Dopita & Sutherland 2003)

Velocity distribution in the ISM

1. Typical scale of interstellar clouds: $L_{\rm ISM} \simeq 1$ pc $\gg \lambda_{\rm H}$.
2. Typical cloud lifetimes: $\tau_{\rm cl} \gtrsim 1$ Myr $\gg \tau_{\rm coll}$.
3. Collisions are essentially elastic $\Rightarrow$ good thermalization.

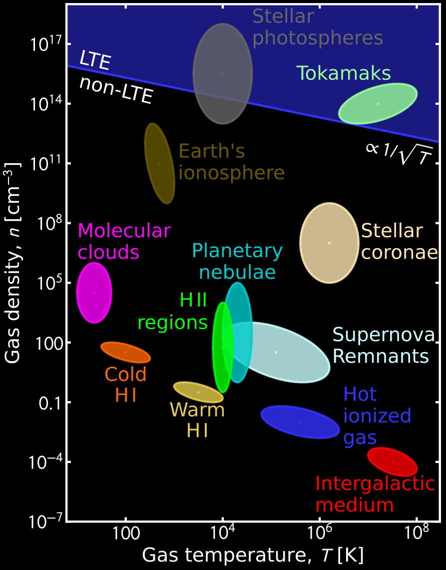


(Adapted from Dopita & Sutherland 2003)

Velocity distribution in the ISM

1. Typical scale of interstellar clouds: $L_{\rm ISM} \simeq 1\ {\rm pc} \gg \lambda_{\rm H}$.
2. Typical cloud lifetimes: $\tau_{\rm cl} \gtrsim 1\ {\rm Myr} \gg \tau_{\rm coll}$.
3. Collisions are essentially elastic $\Rightarrow$ good thermalization.

$\Rightarrow$ interstellar atoms mostly follow a *Maxwell-Boltzmann distribution*:



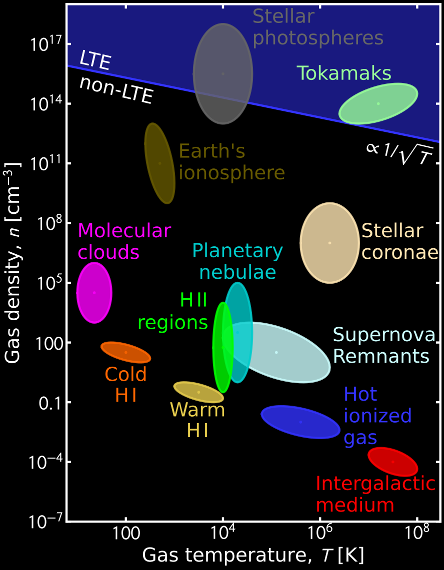
(Adapted from Dopita & Sutherland 2003)

Velocity distribution in the ISM

1. Typical scale of interstellar clouds: $L_{\rm ISM} \simeq 1$ pc $\gg \lambda_{\rm H}$.
2. Typical cloud lifetimes: $\tau_{\rm cl} \gtrsim 1$ Myr $\gg \tau_{\rm coll}$.
3. Collisions are essentially elastic $\Rightarrow$ good thermalization.

$\Rightarrow$ interstellar atoms mostly follow a *Maxwell-Boltzmann distribution*:

$$f(v) \equiv \left(\frac{m}{2\pi kT}\right)^{3/2} 4\pi v^2 \exp\left(-\frac{mv^2}{2kT}\right).$$



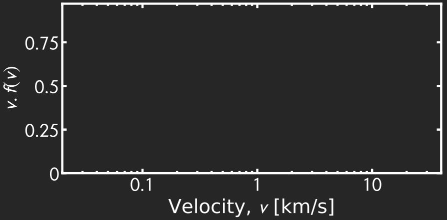
(Adapted from Dopita & Sutherland 2003)

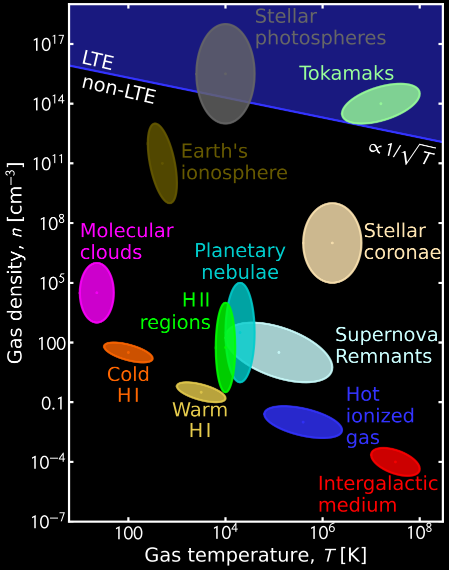
Velocity distribution in the ISM

1. Typical scale of interstellar clouds: $L_{\rm ISM} \simeq 1$ pc $\gg \lambda_{\rm H}$.
2. Typical cloud lifetimes: $\tau_{\rm cl} \gtrsim 1$ Myr $\gg \tau_{\rm coll}$.
3. Collisions are essentially elastic $\Rightarrow$ good thermalization.

$\Rightarrow$ interstellar atoms mostly follow a *Maxwell-Boltzmann distribution*:

$$f(v) \equiv \left(\frac{m}{2\pi kT}\right)^{3/2} 4\pi v^2 \exp\left(-\frac{mv^2}{2kT}\right).$$





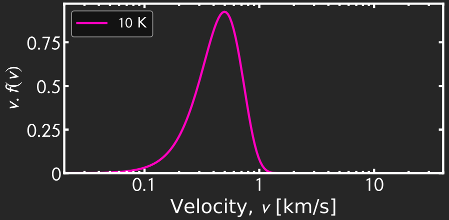
(Adapted from Dopita & Sutherland 2003)

Velocity distribution in the ISM

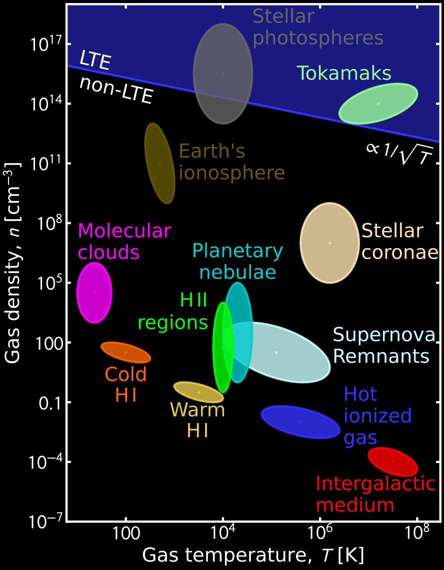
1. Typical scale of interstellar clouds: $L_{\rm ISM} \simeq 1$ pc $\gg \lambda_{\rm H}$.
2. Typical cloud lifetimes: $\tau_{\rm cl} \gtrsim 1$ Myr $\gg \tau_{\rm coll}$.
3. Collisions are essentially elastic $\Rightarrow$ good thermalization.

$\Rightarrow$ interstellar atoms mostly follow a *Maxwell-Boltzmann distribution*:

$$f(v) \equiv \left(\frac{m}{2\pi kT}\right)^{3/2} 4\pi v^2 \exp\left(-\frac{mv^2}{2kT}\right).$$



Overview | Density & Temperature Range of the ISM



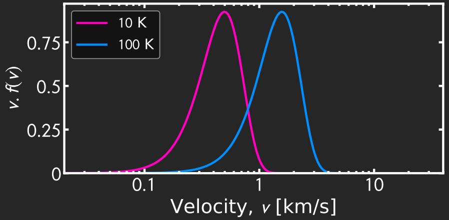
(Adapted from Dopita & Sutherland 2003)

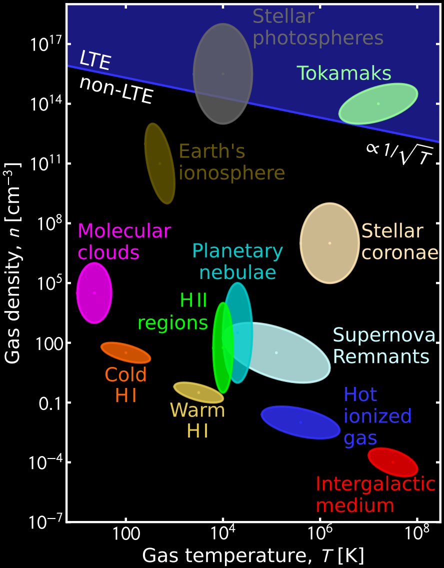
Velocity distribution in the ISM

1. Typical scale of interstellar clouds: $L_{\rm ISM} \simeq 1\ \text{pc} \gg \lambda_{\rm H}$.
2. Typical cloud lifetimes: $\tau_{\rm cl} \gtrsim 1\ \text{Myr} \gg \tau_{\rm coll}$.
3. Collisions are essentially elastic $\Rightarrow$ good thermalization.

$\Rightarrow$ interstellar atoms mostly follow a *Maxwell-Boltzmann distribution*:

$$f(v) \equiv \left(\frac{m}{2\pi kT}\right)^{3/2} 4\pi v^2 \exp\left(-\frac{mv^2}{2kT}\right).$$





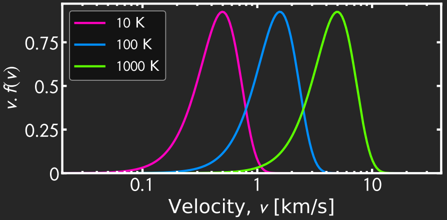
(Adapted from Dopita & Sutherland 2003)

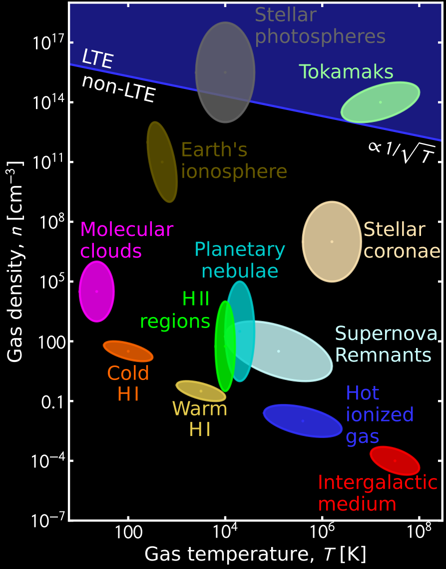
Velocity distribution in the ISM

1. Typical scale of interstellar clouds: $L_{\rm ISM} \simeq 1\ {\rm pc} \gg \lambda_{\rm H}$.
2. Typical cloud lifetimes: $\tau_{\rm cl} \gtrsim 1\ {\rm Myr} \gg \tau_{\rm coll}$.
3. Collisions are essentially elastic $\Rightarrow$ good thermalization.

$\Rightarrow$ interstellar atoms mostly follow a *Maxwell-Boltzmann distribution*:

$$f(v) \equiv \left(\frac{m}{2\pi kT}\right)^{3/2} 4\pi v^2 \exp\left(-\frac{mv^2}{2kT}\right).$$





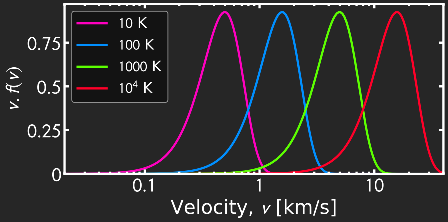
(Adapted from Dopita & Sutherland 2003)

Velocity distribution in the ISM

1. Typical scale of interstellar clouds: $L_{\rm ISM} \simeq 1\ \text{pc} \gg \lambda_{\rm H}$.
2. Typical cloud lifetimes: $\tau_{\rm cl} \gtrsim 1\ \text{Myr} \gg \tau_{\rm coll}$.
3. Collisions are essentially elastic $\Rightarrow$ good thermalization.

$\Rightarrow$ interstellar atoms mostly follow a *Maxwell-Boltzmann distribution*:

$$f(v) \equiv \left(\frac{m}{2\pi kT}\right)^{3/2} 4\pi v^2 \exp\left(-\frac{mv^2}{2kT}\right).$$



Power injection in the ISM

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		

(Tielens 2005, Chap. 1)

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection			
All stars	$4 \times 10^{10}\ L_\odot$		

(Tielens 2005, Chap. 1)

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection			
All stars	$4 \times 10^{10}\ L_\odot$		
O, B, A stars	$8 \times 10^{9}\ L_\odot$		

(Tielens 2005, Chap. 1)

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection	
All stars	$4 \times 10^{10}\ L_\odot$		
O, B, A stars	$8 \times 10^{9}\ L_\odot$		

(Tielens 2005, Chap. 1)

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	
O, B, A stars	$8 \times 10^9\ L_\odot$			

(Tielens 2005, Chap. 1)

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	

(Tielens 2005, Chap. 1)

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^{8}\ L_\odot$	
O, B, A stars	$8 \times 10^{9}\ L_\odot$	Wolf-Rayet	$2 \times 10^{7}\ L_\odot$	
		O, B, A stars	$1 \times 10^{7}\ L_\odot$	

(Tielens 2005, Chap. 1)

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	
		O, B, A stars	$1 \times 10^7\ L_\odot$	
		AGB stars	$1 \times 10^4\ L_\odot$	

(Tielens 2005, Chap. 1)

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	
		O, B, A stars	$1 \times 10^7\ L_\odot$	
		AGB stars	$1 \times 10^4\ L_\odot$	

(Tielens 2005, Chap. 1)

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$		
		O, B, A stars	$1 \times 10^7\ L_\odot$		
		AGB stars	$1 \times 10^4\ L_\odot$		

(Tielens 2005, Chap. 1)

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$		
		AGB stars	$1 \times 10^4\ L_\odot$		

(Tielens 2005, Chap. 1)

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	[C II]$_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$		

(Tielens 2005, Chap. 1)

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	[C II]$_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	[C II]$_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	[C II]$_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{th} =$

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	[C II]$_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{th} = \frac{3}{2}P =$

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	[C II]$_{158\mu m}$	$5 \times 10^7\ L_\odot$
(Tielens 2005, Chap. 1)		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\text{th}} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ \text{K.cm}^{-3}}\right)$ eV/cm^3

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	$[\mathrm{C\,II}]_{158\mu\mathrm{m}}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ \mathrm{K.cm^{-3}}}\right)$ eV/cm$^3 \simeq 0.39$ eV/cm^3.

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	$[\mathrm{C\,II}]_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ \mathrm{K.cm^{-3}}}\right)$ eV/cm^3 $\simeq 0.39$ eV/cm^3.

Turbulent energy: $U_{\rm turb} =$

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^{8}\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^{9}\ L_\odot$	Wolf-Rayet	$2 \times 10^{7}\ L_\odot$	Radio	$1.5 \times 10^{8}\ L_\odot$
		O, B, A stars	$1 \times 10^{7}\ L_\odot$	[C II]$_{158\mu m}$	$5 \times 10^{7}\ L_\odot$
		AGB stars	$1 \times 10^{4}\ L_\odot$	γ-rays	$3 \times 10^{5}\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ \rm K.cm^{-3}}\right)$ eV/cm^3 $\simeq 0.39$ eV/cm^3.

Turbulent energy: $U_{\rm turb} = \frac{1}{2}\rho\langle v^2\rangle =$

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^{8}\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^{9}\ L_\odot$	Wolf-Rayet	$2 \times 10^{7}\ L_\odot$	Radio	$1.5 \times 10^{8}\ L_\odot$
		O, B, A stars	$1 \times 10^{7}\ L_\odot$	$[\mathrm{C\,II}]_{158\mu m}$	$5 \times 10^{7}\ L_\odot$
		AGB stars	$1 \times 10^{4}\ L_\odot$	γ-rays	$3 \times 10^{5}\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ \mathrm{K.cm^{-3}}}\right)$ eV/cm^3 $\simeq 0.39$ eV/cm^3.

Turbulent energy: $U_{\rm turb} = \frac{1}{2}\rho\langle v^2\rangle = 0.13 \times \left(\frac{n_{\rm H}}{1\ \mathrm{cm^{-3}}}\right)\left(\frac{\sigma(v)}{5\ \mathrm{km/s}}\right)^2$ eV/cm^3

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^{8}\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^{9}\ L_\odot$	Wolf-Rayet	$2 \times 10^{7}\ L_\odot$	Radio	$1.5 \times 10^{8}\ L_\odot$
		O, B, A stars	$1 \times 10^{7}\ L_\odot$	[C II]$_{158\mu m}$	$5 \times 10^{7}\ L_\odot$
		AGB stars	$1 \times 10^{4}\ L_\odot$	γ-rays	$3 \times 10^{5}\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ {\rm K.cm^{-3}}}\right)\ {\rm eV/cm^3} \simeq 0.39\ {\rm eV/cm^3}$.

Turbulent energy: $U_{\rm turb} = \frac{1}{2}\rho\langle v^2\rangle = 0.13 \times \left(\frac{n_{\rm H}}{1\ {\rm cm^{-3}}}\right)\left(\frac{\sigma(v)}{5\ {\rm km/s}}\right)^2 {\rm eV/cm^3} \simeq 0.13\ {\rm eV/cm^3}$.

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	[C II]$_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\text{th}} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ \text{K.cm}^{-3}}\right)\ \text{eV/cm}^3 \simeq 0.39\ \text{eV/cm}^3$.

Turbulent energy: $U_{\text{turb}} = \frac{1}{2}\rho\langle v^2\rangle = 0.13 \times \left(\frac{n_{\text{H}}}{1\ \text{cm}^{-3}}\right)\left(\frac{\sigma(v)}{5\ \text{km/s}}\right)^2 \text{eV/cm}^3 \simeq 0.13\ \text{eV/cm}^3$.

Magnetic energy: $U_{\text{magn}} =$

Overview | Energetics of the ISM of the Milky Way

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^{8}\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^{9}\ L_\odot$	Wolf-Rayet	$2 \times 10^{7}\ L_\odot$	Radio	$1.5 \times 10^{8}\ L_\odot$
		O, B, A stars	$1 \times 10^{7}\ L_\odot$	$[\mathrm{C\,II}]_{158\mu m}$	$5 \times 10^{7}\ L_\odot$
(Tielens 2005, Chap. 1)		AGB stars	$1 \times 10^{4}\ L_\odot$	γ-rays	$3 \times 10^{5}\ L_\odot$

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2} P = 0.39 \times \left(\frac{P/k}{3000\ \mathrm{K.cm^{-3}}}\right)\ \mathrm{eV/cm^3} \simeq 0.39\ \mathrm{eV/cm^3}$.

Turbulent energy: $U_{\rm turb} = \frac{1}{2}\rho\langle v^2\rangle = 0.13 \times \left(\frac{n_{\rm H}}{1\ \mathrm{cm^{-3}}}\right)\left(\frac{\sigma(v)}{5\ \mathrm{km/s}}\right)^2 \mathrm{eV/cm^3} \simeq 0.13\ \mathrm{eV/cm^3}$.

Magnetic energy: $U_{\rm magn} = \frac{B^2}{2\mu_0} =$

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4\times10^{10}\ L_\odot$	SNe	$2\times10^{8}\ L_\odot$	Dust	$1.7\times10^{10}\ L_\odot$
O, B, A stars	$8\times10^{9}\ L_\odot$	Wolf-Rayet	$2\times10^{7}\ L_\odot$	Radio	$1.5\times10^{8}\ L_\odot$
		O, B, A stars	$1\times10^{7}\ L_\odot$	[C II]$_{158\mu m}$	$5\times10^{7}\ L_\odot$
		AGB stars	$1\times10^{4}\ L_\odot$	γ-rays	$3\times10^{5}\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39\times\left(\frac{P/k}{3000\ {\rm K.cm^{-3}}}\right)\ {\rm eV/cm^3} \simeq 0.39\ {\rm eV/cm^3}$.

Turbulent energy: $U_{\rm turb} = \frac{1}{2}\rho\langle v^2\rangle = 0.13\times\left(\frac{n_{\rm H}}{1\ {\rm cm^{-3}}}\right)\left(\frac{\sigma(v)}{5\ {\rm km/s}}\right)^2 {\rm eV/cm^3} \simeq 0.13\ {\rm eV/cm^3}$.

Magnetic energy: $U_{\rm magn} = \frac{B^2}{2\mu_0} = 0.88\times\left(\frac{B}{0.6\ {\rm nT}}\right)^2\ {\rm eV/cm^3}$

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	[C II]$_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ {\rm K.cm^{-3}}}\right)$ eV/cm$^3 \simeq 0.39$ eV/cm^3.

Turbulent energy: $U_{\rm turb} = \frac{1}{2}\rho\langle v^2\rangle = 0.13 \times \left(\frac{n_{\rm H}}{1\ {\rm cm^{-3}}}\right)\left(\frac{\sigma(v)}{5\ {\rm km/s}}\right)^2$ eV/cm$^3 \simeq 0.13$ eV/cm^3.

Magnetic energy: $U_{\rm magn} = \frac{B^2}{2\mu_0} = 0.88 \times \left(\frac{B}{0.6\ {\rm nT}}\right)^2$ eV/cm$^3 \simeq 0.88$ eV/cm^3.

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	$[\mathrm{C\,II}]_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ \mathrm{K.cm^{-3}}}\right)$ eV/cm^3 $\simeq 0.39$ eV/cm^3.

Turbulent energy: $U_{\rm turb} = \frac{1}{2}\rho\langle v^2\rangle = 0.13 \times \left(\frac{n_{\rm H}}{1\ \mathrm{cm^{-3}}}\right)\left(\frac{\sigma(v)}{5\ \mathrm{km/s}}\right)^2$ eV/cm^3 $\simeq 0.13$ eV/cm^3.

Magnetic energy: $U_{\rm magn} = \frac{B^2}{2\mu_0} = 0.88 \times \left(\frac{B}{0.6\ \mathrm{nT}}\right)^2$ eV/cm^3 $\simeq 0.88$ eV/cm^3.

Cosmic microwave background: $U_{\rm CMB} =$

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	$[\mathrm{C\,II}]_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ \mathrm{K.cm^{-3}}}\right)$ eV/cm^3 $\simeq 0.39$ eV/cm^3.

Turbulent energy: $U_{\rm turb} = \frac{1}{2}\rho\langle v^2\rangle = 0.13 \times \left(\frac{n_{\rm H}}{1\ \mathrm{cm^{-3}}}\right)\left(\frac{\sigma(v)}{5\ \mathrm{km/s}}\right)^2$ eV/cm^3 $\simeq 0.13$ eV/cm^3.

Magnetic energy: $U_{\rm magn} = \frac{B^2}{2\mu_0} = 0.88 \times \left(\frac{B}{0.6\ \mathrm{nT}}\right)^2$ eV/cm^3 $\simeq 0.88$ eV/cm^3.

Cosmic microwave background: $U_{\rm CMB} = \frac{c}{4}\sigma T_{\rm CMB}^4 =$

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4\ \mathrm{K/cm^3}$.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	$[\mathrm{C\,II}]_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ \mathrm{K.cm^{-3}}}\right)\ \mathrm{eV/cm^3} \simeq 0.39\ \mathrm{eV/cm^3}$.

Turbulent energy: $U_{\rm turb} = \frac{1}{2}\rho\langle v^2\rangle = 0.13 \times \left(\frac{n_{\rm H}}{1\ \mathrm{cm^{-3}}}\right)\left(\frac{\sigma(v)}{5\ \mathrm{km/s}}\right)^2 \mathrm{eV/cm^3} \simeq 0.13\ \mathrm{eV/cm^3}$.

Magnetic energy: $U_{\rm magn} = \frac{B^2}{2\mu_0} = 0.88 \times \left(\frac{B}{0.6\ \mathrm{nT}}\right)^2\ \mathrm{eV/cm^3} \simeq 0.88\ \mathrm{eV/cm^3}$.

Cosmic microwave background: $U_{\rm CMB} = \frac{c}{4}\sigma T_{\rm CMB}^4 = 0.26 \times \left(\frac{T_{\rm CMB}}{2.725\ \mathrm{K}}\right)^4\ \mathrm{eV/cm^3}$

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	$[\mathrm{C\,II}]_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ \mathrm{K.cm^{-3}}}\right)$ eV/cm^3 $\simeq 0.39$ eV/cm^3.

Turbulent energy: $U_{\rm turb} = \frac{1}{2}\rho\langle v^2\rangle = 0.13 \times \left(\frac{n_{\rm H}}{1\ \mathrm{cm^{-3}}}\right)\left(\frac{\sigma(v)}{5\ \mathrm{km/s}}\right)^2$ eV/cm^3 $\simeq 0.13$ eV/cm^3.

Magnetic energy: $U_{\rm magn} = \frac{B^2}{2\mu_0} = 0.88 \times \left(\frac{B}{0.6\ \mathrm{nT}}\right)^2$ eV/cm^3 $\simeq 0.88$ eV/cm^3.

Cosmic microwave background: $U_{\rm CMB} = \frac{c}{4}\sigma T_{\rm CMB}^4 = 0.26 \times \left(\frac{T_{\rm CMB}}{2.725\ \mathrm{K}}\right)^4$ eV/cm^3 $\simeq 0.26$ eV/cm^3.

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	$[\mathrm{C\,II}]_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ \mathrm{K.cm^{-3}}}\right)$ eV/cm^3 $\simeq 0.39$ eV/cm^3.

Turbulent energy: $U_{\rm turb} = \frac{1}{2}\rho\langle v^2\rangle = 0.13 \times \left(\frac{n_{\rm H}}{1\ \mathrm{cm^{-3}}}\right)\left(\frac{\sigma(v)}{5\ \mathrm{km/s}}\right)^2$ eV/cm^3 $\simeq 0.13$ eV/cm^3.

Magnetic energy: $U_{\rm magn} = \frac{B^2}{2\mu_0} = 0.88 \times \left(\frac{B}{0.6\ \mathrm{nT}}\right)^2$ eV/cm^3 $\simeq 0.88$ eV/cm^3.

Cosmic microwave background: $U_{\rm CMB} = \frac{c}{4}\sigma T_{\rm CMB}^4 = 0.26 \times \left(\frac{T_{\rm CMB}}{2.725\ \mathrm{K}}\right)^4$ eV/cm^3 $\simeq 0.26$ eV/cm^3.

Starlight: $U_\star \simeq 0.5$ eV/cm^3.

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4\times10^{10}\ L_\odot$	SNe	$2\times10^{8}\ L_\odot$	Dust	$1.7\times10^{10}\ L_\odot$
O, B, A stars	$8\times10^{9}\ L_\odot$	Wolf-Rayet	$2\times10^{7}\ L_\odot$	Radio	$1.5\times10^{8}\ L_\odot$
		O, B, A stars	$1\times10^{7}\ L_\odot$	$[\mathrm{C\,II}]_{158\mu m}$	$5\times10^{7}\ L_\odot$
		AGB stars	$1\times10^{4}\ L_\odot$	γ-rays	$3\times10^{5}\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39\times\left(\frac{P/k}{3000\ \mathrm{K.cm^{-3}}}\right)\ \mathrm{eV/cm^3} \simeq 0.39\ \mathrm{eV/cm^3}$.

Turbulent energy: $U_{\rm turb} = \frac{1}{2}\rho\langle v^2\rangle = 0.13\times\left(\frac{n_{\rm H}}{1\ \mathrm{cm^{-3}}}\right)\left(\frac{\sigma(v)}{5\ \mathrm{km/s}}\right)^2\ \mathrm{eV/cm^3} \simeq 0.13\ \mathrm{eV/cm^3}$.

Magnetic energy: $U_{\rm magn} = \frac{B^2}{2\mu_0} = 0.88\times\left(\frac{B}{0.6\ \mathrm{nT}}\right)^2\ \mathrm{eV/cm^3} \simeq 0.88\ \mathrm{eV/cm^3}$.

Cosmic microwave background: $U_{\rm CMB} = \frac{c}{4}\sigma T_{\rm CMB}^4 = 0.26\times\left(\frac{T_{\rm CMB}}{2.725\ \mathrm{K}}\right)^4\ \mathrm{eV/cm^3} \simeq 0.26\ \mathrm{eV/cm^3}$.

Starlight: $U_\star \simeq 0.5\ \mathrm{eV/cm^3}$.

Cosmic rays: $U_{\rm CR} \simeq 0.8\ \mathrm{eV/cm^3}$.

Power injection in the ISM

Most ISM phases are at thermal pressure equilibrium: $P/k = n.T \simeq 10^3 - 10^4$ K/cm^3.

Radiative power injection		Mechanical power injection		Radiative cooling	
All stars	$4 \times 10^{10}\ L_\odot$	SNe	$2 \times 10^8\ L_\odot$	Dust	$1.7 \times 10^{10}\ L_\odot$
O, B, A stars	$8 \times 10^9\ L_\odot$	Wolf-Rayet	$2 \times 10^7\ L_\odot$	Radio	$1.5 \times 10^8\ L_\odot$
		O, B, A stars	$1 \times 10^7\ L_\odot$	[C II]$_{158\mu m}$	$5 \times 10^7\ L_\odot$
		AGB stars	$1 \times 10^4\ L_\odot$	γ-rays	$3 \times 10^5\ L_\odot$

(Tielens 2005, Chap. 1)

Rough equipartition of all energy densities

Thermal kinetic energy: $U_{\rm th} = \frac{3}{2}P = 0.39 \times \left(\frac{P/k}{3000\ {\rm K.cm^{-3}}}\right)$ eV/cm$^3 \simeq 0.39$ eV/cm^3.

Turbulent energy: $U_{\rm turb} = \frac{1}{2}\rho\langle v^2\rangle = 0.13 \times \left(\frac{n_{\rm H}}{1\ {\rm cm^{-3}}}\right)\left(\frac{\sigma(v)}{5\ {\rm km/s}}\right)^2$ eV/cm$^3 \simeq 0.13$ eV/cm^3.

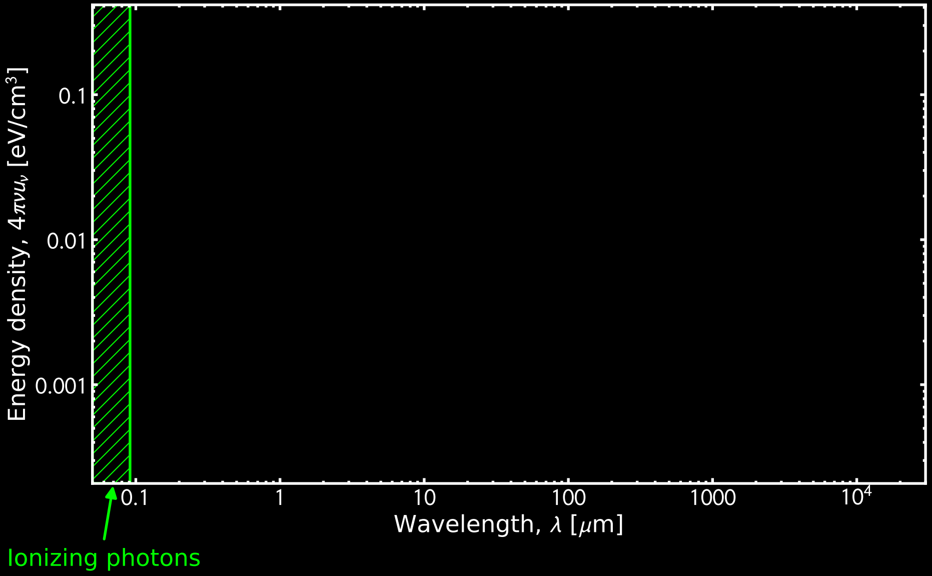
Magnetic energy: $U_{\rm magn} = \frac{B^2}{2\mu_0} = 0.88 \times \left(\frac{B}{0.6\ {\rm nT}}\right)^2$ eV/cm$^3 \simeq 0.88$ eV/cm^3.

Cosmic microwave background: $U_{\rm CMB} = \frac{c}{4}\sigma T_{\rm CMB}^4 = 0.26 \times \left(\frac{T_{\rm CMB}}{2.725\ {\rm K}}\right)^4$ eV/cm$^3 \simeq 0.26$ eV/cm^3.

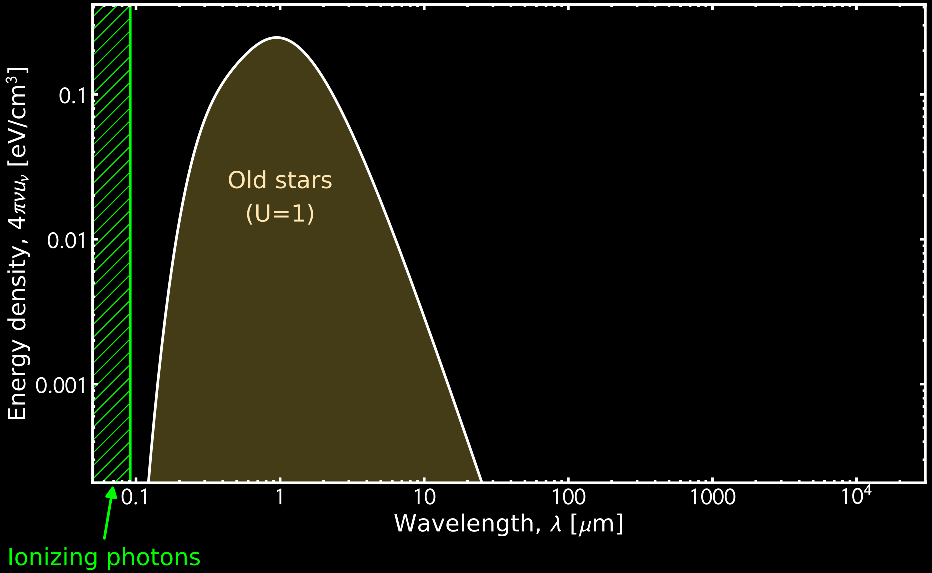
Starlight: $U_\star \simeq 0.5$ eV/cm^3.

Cosmic rays: $U_{\rm CR} \simeq 0.8$ eV/cm^3.

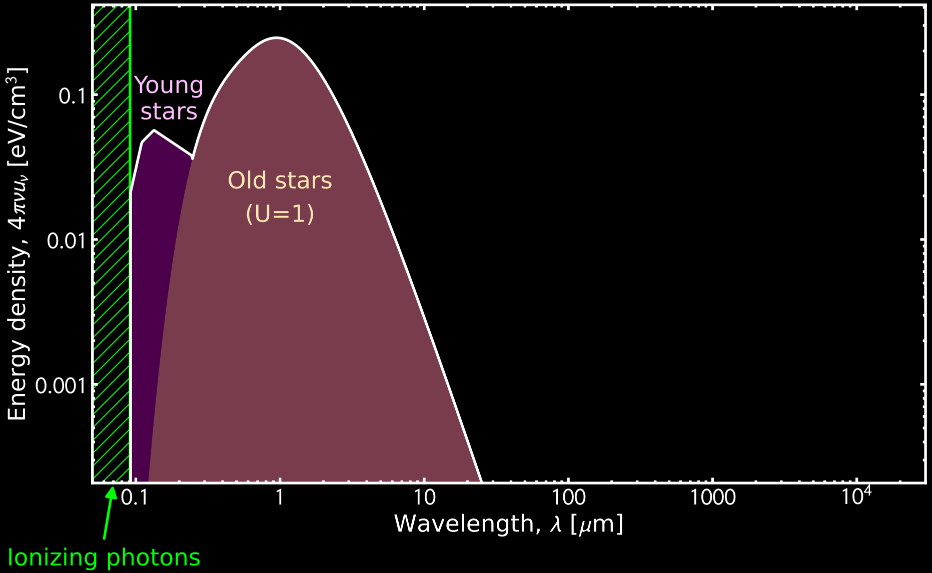
$$U_{\rm th} \simeq U_{\rm turb} \simeq U_{\rm magn} \simeq U_{\rm CMB} \simeq U_\star \simeq U_{\rm CR} \simeq 0.3\ {\rm eV/cm^3}$$



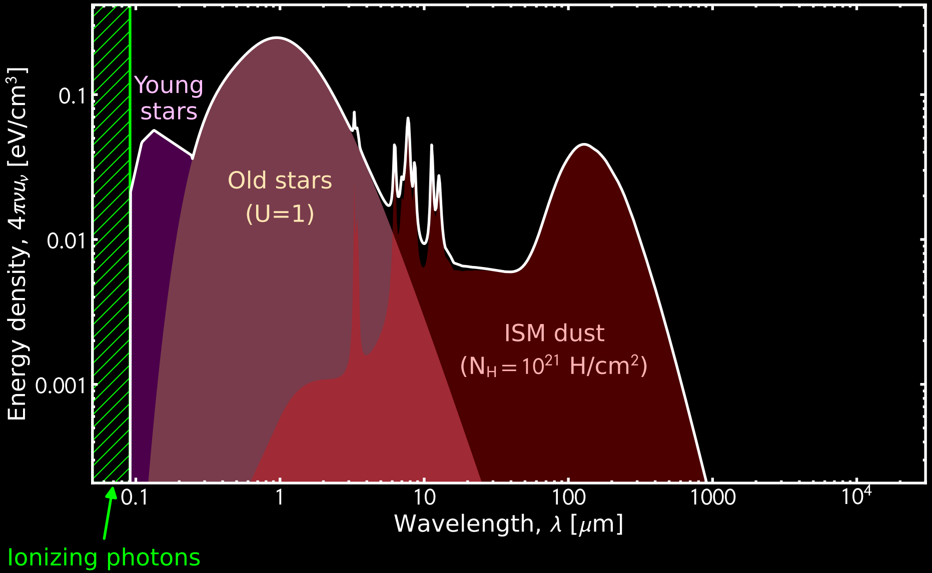
(Mathis et al. 1983)



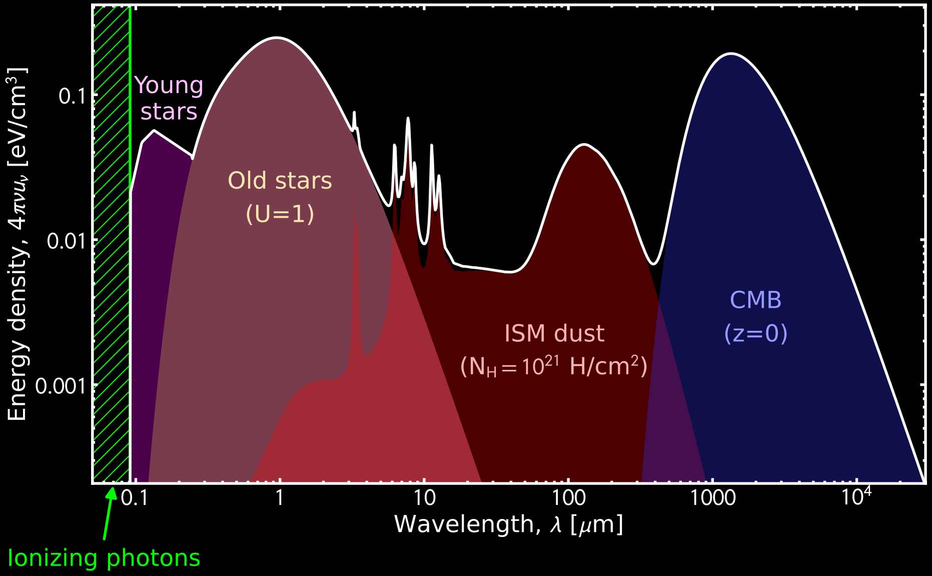
(Mathis et al. 1983)



(Mathis et al. 1983)



(Mathis et al. 1983)



(Mathis et al. 1983)

Terminology

Terminology

"The Galaxy" = the Milky Way.

Terminology

"The Galaxy" = the Milky Way.
"Galactic" = relative to the Milky Way.

Terminology

"The Galaxy" = the Milky Way.

"Galactic" = relative to the Milky Way.

"galaxies" = that are not the Milky Way.

Terminology

"The Galaxy" = the Milky Way.

"Galactic" = relative to the Milky Way.

"galaxies" = that are not the Milky Way.

Dwarf / Irregular

Credit: I Zw 18 (Aloisi et al., 2007).

Terminology

"The Galaxy" = the Milky Way. **"galaxies"** = that are not the Milky Way.
"Galactic" = relative to the Milky Way.

Dwarf / Irregular

Credit: I Zw 18 (Aloisi et al., 2007).

Metallicity: low ($\lesssim 1/50\ Z_\odot$).

Terminology

"The Galaxy" = the Milky Way.
"Galactic" = relative to the Milky Way.
"galaxies" = that are not the Milky Way.

Dwarf / Irregular

Credit: I Zw 18 (Aloisi et al., 2007).

Metallicity: low ($\lesssim 1/50\ Z_\odot$).
Gas fraction: high ($\gtrsim 95\,\%$).

Terminology

"The Galaxy" = the Milky Way.
"Galactic" = relative to the Milky Way.
"galaxies" = that are not the Milky Way.

Dwarf / Irregular

Credit: I Zw 18 (Aloisi et al., 2007).

Metallicity: low ($\lesssim 1/50\ Z_\odot$).
Gas fraction: high ($\gtrsim 95\,\%$).
SFR/$M_\star$: high ($\gtrsim 10\ \text{Gyr}^{-1}$).

Terminology

"The Galaxy" = the Milky Way.

"galaxies" = that are not the Milky Way.

"Galactic" = relative to the Milky Way.

Dwarf / Irregular

Credit: I Zw 18 (Aloisi et al., 2007).

Metallicity: low ($\lesssim 1/50\ Z_\odot$).
Gas fraction: high ($\gtrsim 95\,\%$).
SFR/$M_\star$: high ($\gtrsim 10\ \mathrm{Gyr}^{-1}$).

Spiral / Late-Type

Credit: M 33 (Subaru / HST).

Terminology

"The Galaxy" = the Milky Way.

"Galactic" = relative to the Milky Way.

"galaxies" = that are not the Milky Way.

Dwarf / Irregular

Credit: I Zw 18 (Aloisi et al., 2007).

Metallicity: low ($\lesssim 1/50\ Z_\odot$).
Gas fraction: high ($\gtrsim 95\,\%$).
SFR/$M_\star$: high ($\gtrsim 10\ \mathrm{Gyr}^{-1}$).

Spiral / Late-Type

Credit: M 33 (Subaru / HST).

Metallicity: av. ($\simeq Z_\odot$).

Terminology

"The Galaxy" = the Milky Way.
"Galactic" = relative to the Milky Way.
"galaxies" = that are not the Milky Way.

Dwarf / Irregular

Credit: I Zw 18 (Aloisi et al., 2007).

Metallicity: low ($\lesssim 1/50\ Z_\odot$).
Gas fraction: high ($\gtrsim 95\,\%$).
SFR/$M_\star$: high ($\gtrsim 10$ Gyr^{-1}).

Spiral / Late-Type

Credit: M 33 (Subaru / HST).

Metallicity: av. ($\simeq Z_\odot$).
Gas fraction: av. ($\simeq 30\,\%$).

Terminology

"The Galaxy" = the Milky Way.
"Galactic" = relative to the Milky Way.
"galaxies" = that are not the Milky Way.

Dwarf / Irregular

Credit: I Zw 18 (Aloisi et al., 2007).

Metallicity: low ($\lesssim 1/50\ Z_\odot$).
Gas fraction: high ($\gtrsim 95\,\%$).
SFR/$M_\star$: high ($\gtrsim 10$ Gyr^{-1}).

Spiral / Late-Type

Credit: M 33 (Subaru / HST).

Metallicity: av. ($\simeq Z_\odot$).
Gas fraction: av. ($\simeq 30\,\%$).
SFR/$M_\star$: av. ($\simeq 0.1$ Gyr^{-1}).

Terminology

"The Galaxy" = the Milky Way.

"Galactic" = relative to the Milky Way.

"galaxies" = that are not the Milky Way.

Dwarf / Irregular

Credit: I Zw 18 (Aloisi et al., 2007).

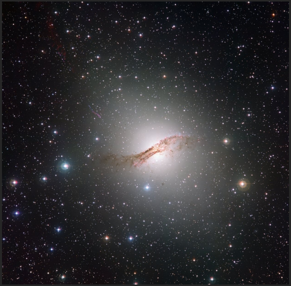
Metallicity: low ($\lesssim 1/50\ Z_\odot$).
Gas fraction: high ($\gtrsim 95\,\%$).
$\mathrm{SFR}/M_\star$: high ($\gtrsim 10\ \mathrm{Gyr}^{-1}$).

Spiral / Late-Type

Credit: M 33 (Subaru / HST).

Metallicity: av. ($\simeq Z_\odot$).
Gas fraction: av. ($\simeq 30\,\%$).
$\mathrm{SFR}/M_\star$: av. ($\simeq 0.1\ \mathrm{Gyr}^{-1}$).

Elliptical / Early-Type



Credit: Centaurus A (D. Alemazkour).

Terminology

"The Galaxy" = the Milky Way.

"Galactic" = relative to the Milky Way.

"galaxies" = that are not the Milky Way.

Dwarf / Irregular

Credit: I Zw 18 (Aloisi et al., 2007).

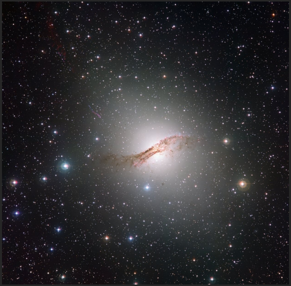
Metallicity: low ($\lesssim 1/50\ Z_\odot$).
Gas fraction: high ($\gtrsim 95\,\%$).
$\mathrm{SFR}/M_\star$: high ($\gtrsim 10\ \mathrm{Gyr}^{-1}$).

Spiral / Late-Type

Credit: M 33 (Subaru / HST).

Metallicity: av. ($\simeq Z_\odot$).
Gas fraction: av. ($\simeq 30\,\%$).
$\mathrm{SFR}/M_\star$: av. ($\simeq 0.1\ \mathrm{Gyr}^{-1}$).

Elliptical / Early-Type



Credit: Centaurus A (D. Alemazkour).

Metallicity: high ($\gtrsim Z_\odot$).

Terminology

"The Galaxy" = the Milky Way.

"Galactic" = relative to the Milky Way.

"galaxies" = that are not the Milky Way.

Dwarf / Irregular

Credit: I Zw 18 (Aloisi et al., 2007).

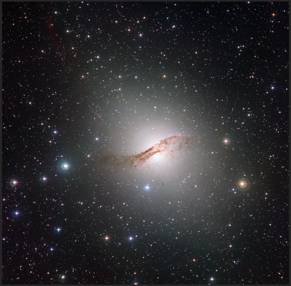
Metallicity: low ($\lesssim 1/50\,Z_\odot$).
Gas fraction: high ($\gtrsim 95\,\%$).
$\mathrm{SFR}/M_\star$: high ($\gtrsim 10\ \mathrm{Gyr}^{-1}$).

Spiral / Late-Type

Credit: M 33 (Subaru / HST).

Metallicity: av. ($\simeq Z_\odot$).
Gas fraction: av. ($\simeq 30\,\%$).
$\mathrm{SFR}/M_\star$: av. ($\simeq 0.1\ \mathrm{Gyr}^{-1}$).

Elliptical / Early-Type



Credit: Centaurus A (D. Alemazkour).

Metallicity: high ($\gtrsim Z_\odot$).
Gas fraction: low ($\lesssim 20\,\%$).

Terminology

"The Galaxy" = the Milky Way.

"Galactic" = relative to the Milky Way.

"galaxies" = that are not the Milky Way.

Dwarf / Irregular

Credit: I Zw 18 (Aloisi et al., 2007).

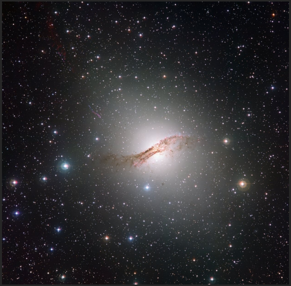
Metallicity: low ($\lesssim 1/50\ Z_\odot$).
Gas fraction: high ($\gtrsim 95\,\%$).
SFR/$M_\star$: high ($\gtrsim 10\ \mathrm{Gyr}^{-1}$).

Spiral / Late-Type

Credit: M 33 (Subaru / HST).

Metallicity: av. ($\simeq Z_\odot$).
Gas fraction: av. ($\simeq 30\,\%$).
SFR/$M_\star$: av. ($\simeq 0.1\ \mathrm{Gyr}^{-1}$).

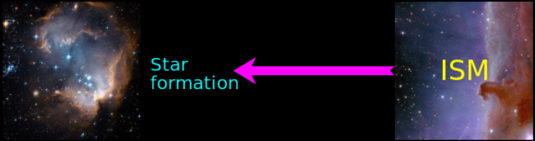
Elliptical / Early-Type



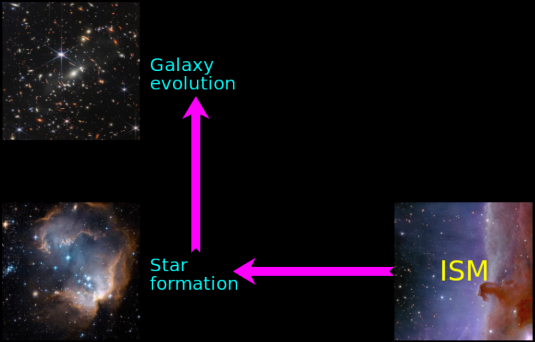
Credit: Centaurus A (D. Alemazkour).

Metallicity: high ($\gtrsim Z_\odot$).
Gas fraction: low ($\lesssim 20\,\%$).
SFR/$M_\star$: low ($\lesssim 0.01\ \mathrm{Gyr}^{-1}$).

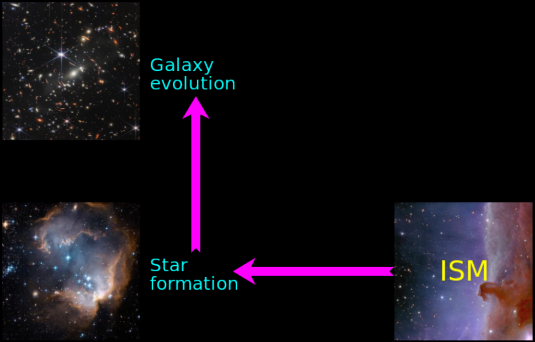

ISM


Star
formation
ISM

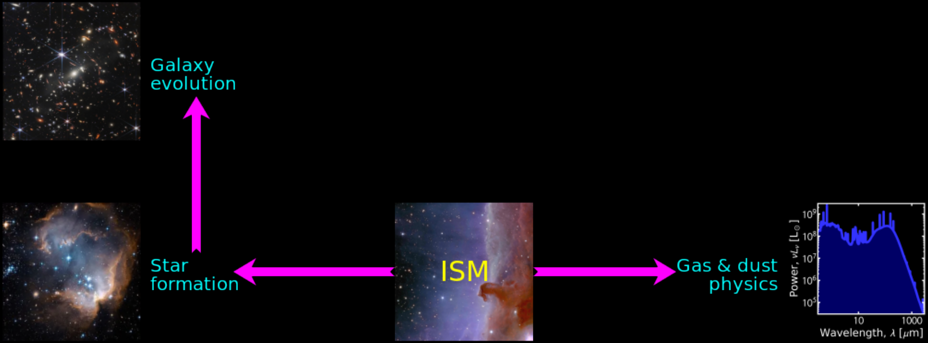
Overview | Why Is It Important to Understand the ISM?



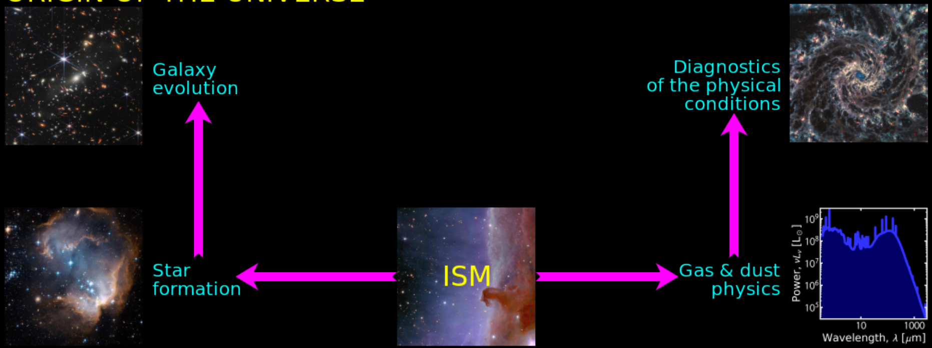
ORIGIN OF THE UNIVERSE



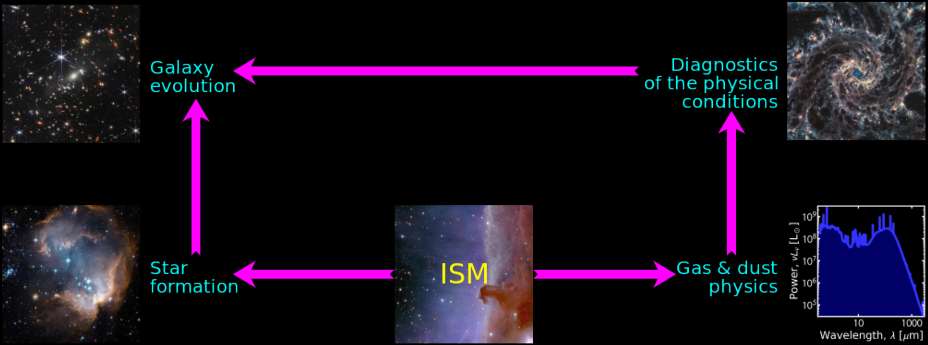
ORIGIN OF THE UNIVERSE



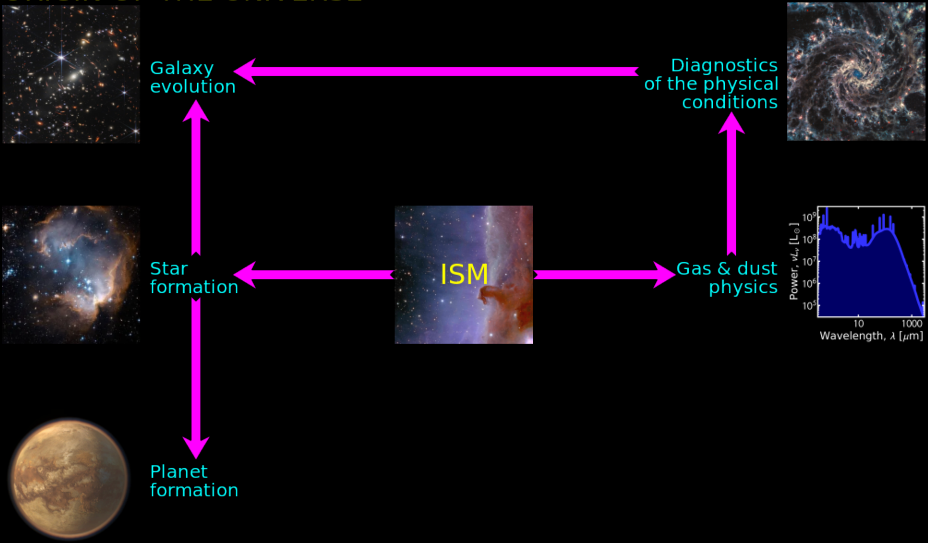
ORIGIN OF THE UNIVERSE



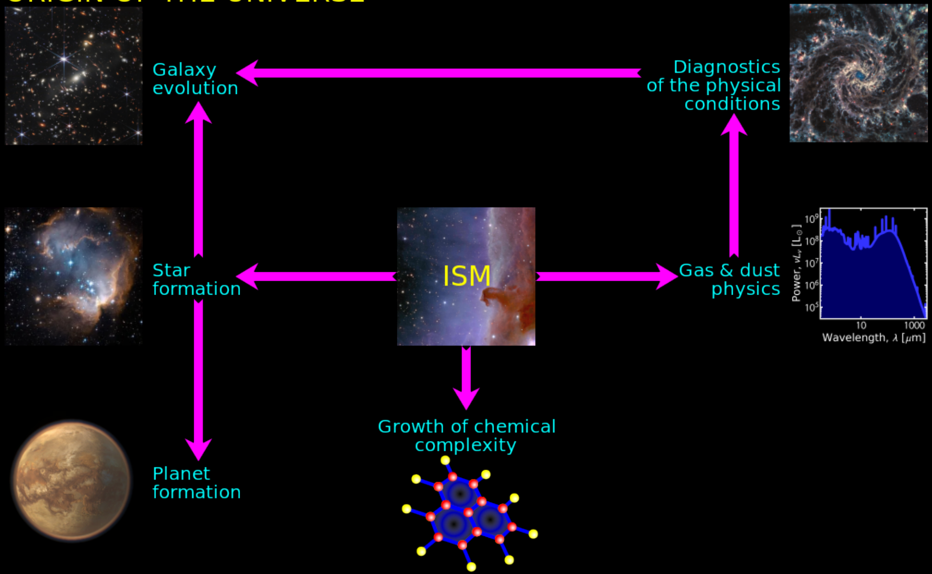
ORIGIN OF THE UNIVERSE



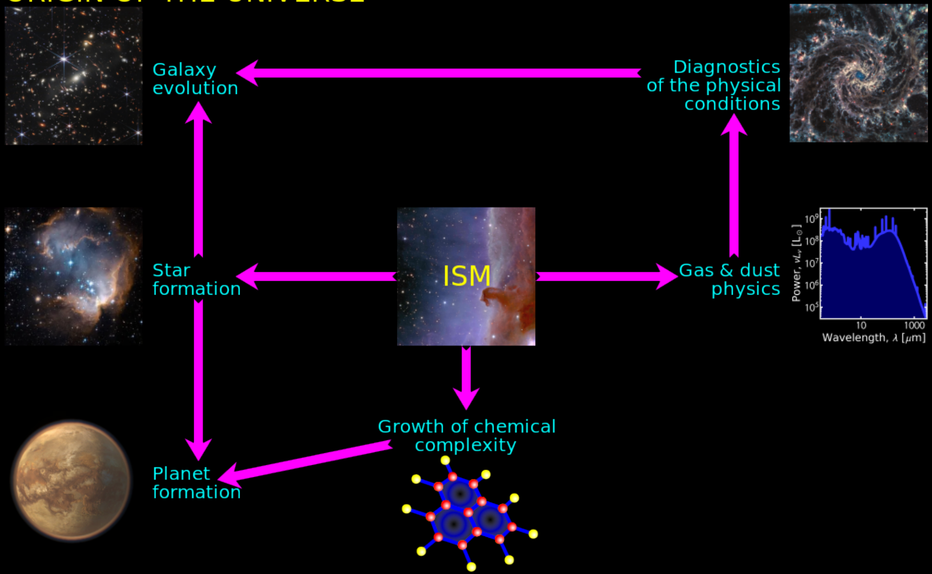
ORIGIN OF THE UNIVERSE



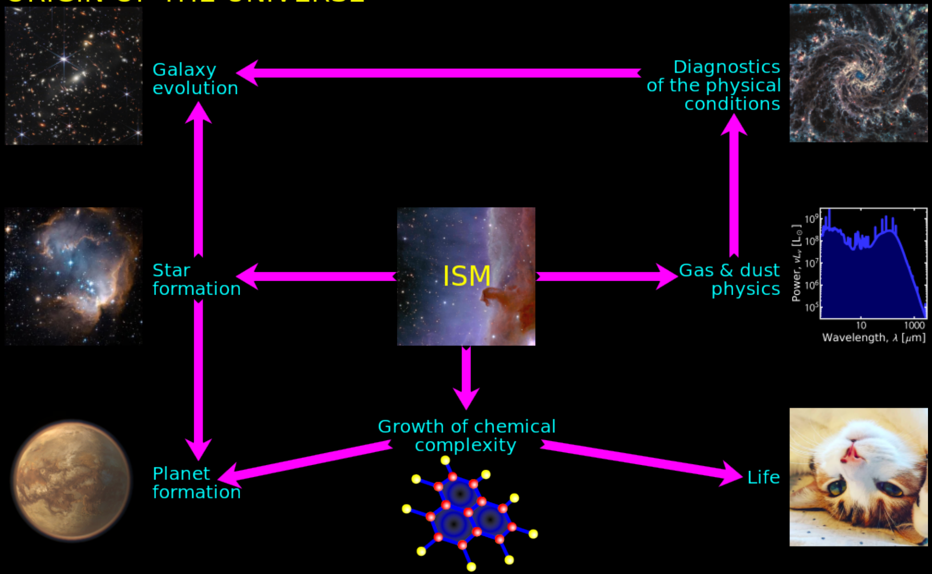
ORIGIN OF THE UNIVERSE

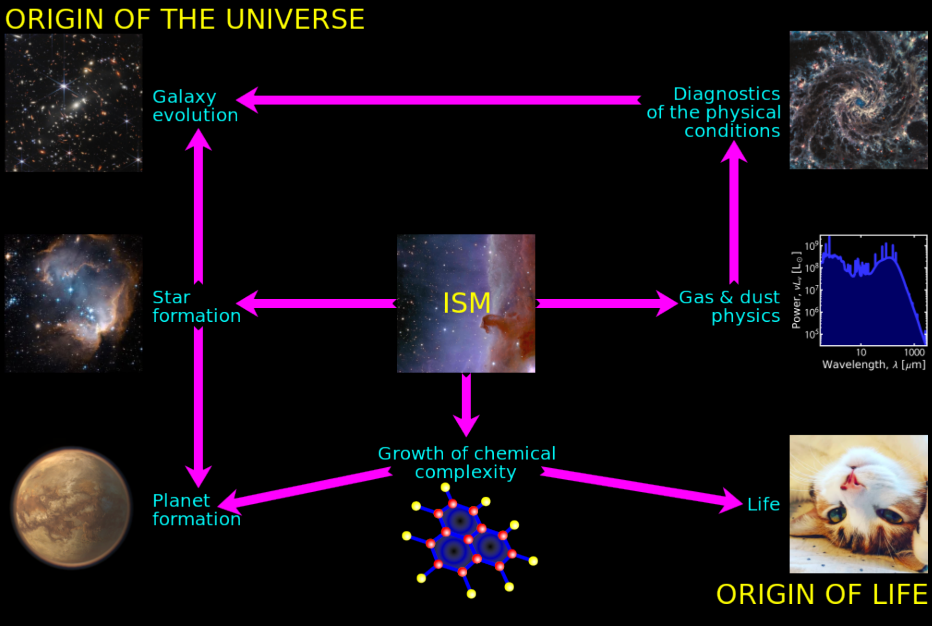


ORIGIN OF THE UNIVERSE



ORIGIN OF THE UNIVERSE




ORIGIN OF THE UNIVERSE
Galaxy evolution
Diagnostics of the physical conditions
Star formation
ISM
Gas & dust physics
Power, νLν [L⊙]
Wavelength, λ [μm]
Growth of chemical complexity
Planet formation
Life
ORIGIN OF LIFE

Scientific Perspective

Scientific Perspective

ISMology:
- Dust properties in different environments.

Scientific Perspective

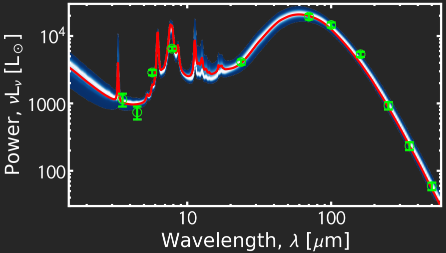
ISMology:

- Dust properties in different environments.
- Polycyclic Aromatic Hydrocarbons (PAH), photoelectric heating, dark gas, *etc.*

Scientific Perspective

ISMology:

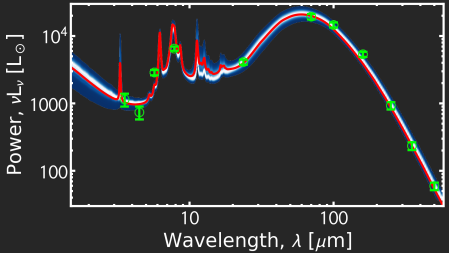
- Dust properties in different environments.
- Polycyclic Aromatic Hydrocarbons (PAH), photoelectric heating, dark gas, *etc.*



Scientific Perspective

ISMology:
- Dust properties in different environments.
- Polycyclic Aromatic Hydrocarbons (PAH), photoelectric heating, dark gas, *etc.*

Galaxies:
- Focus on nearby galaxies ⇒ understand galaxy evolution.



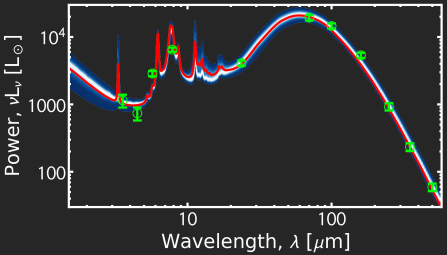
Scientific Perspective

ISMology:

- Dust properties in different environments.
- Polycyclic Aromatic Hydrocarbons (PAH), photoelectric heating, dark gas, *etc.*

Galaxies:

- Focus on nearby galaxies ⇒ understand galaxy evolution.
- Cosmic dust evolution.



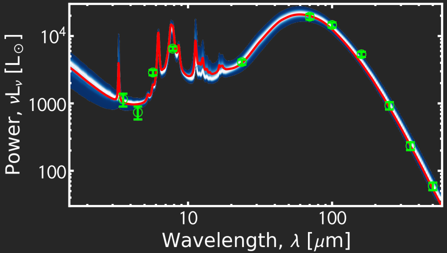
Scientific Perspective

ISMology:

- Dust properties in different environments.
- Polycyclic Aromatic Hydrocarbons (PAH), photoelectric heating, dark gas, *etc.*

Galaxies:

- Focus on nearby galaxies ⇒ understand galaxy evolution.
- Cosmic dust evolution.

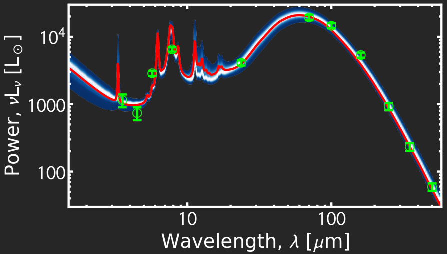


Methodological Approach

Scientific Perspective

ISMology:
- Dust properties in different environments.
- Polycyclic Aromatic Hydrocarbons (PAH), photoelectric heating, dark gas, *etc.*

Galaxies:
- Focus on nearby galaxies ⇒ understand galaxy evolution.
- Cosmic dust evolution.



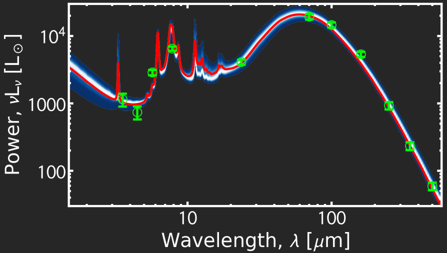
Methodological Approach

Modelling:
- Spectral Energy Distribution (SED) modelling.

Scientific Perspective

ISMology:
- Dust properties in different environments.
- Polycyclic Aromatic Hydrocarbons (PAH), photoelectric heating, dark gas, *etc.*

Galaxies:
- Focus on nearby galaxies ⇒ understand galaxy evolution.
- Cosmic dust evolution.



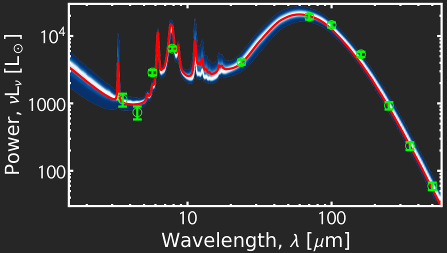
Methodological Approach

Modelling:
- Spectral Energy Distribution (SED) modelling.
- Spectral decomposition.

Scientific Perspective

ISMology:
- Dust properties in different environments.
- Polycyclic Aromatic Hydrocarbons (PAH), photoelectric heating, dark gas, *etc.*

Galaxies:
- Focus on nearby galaxies ⇒ understand galaxy evolution.
- Cosmic dust evolution.



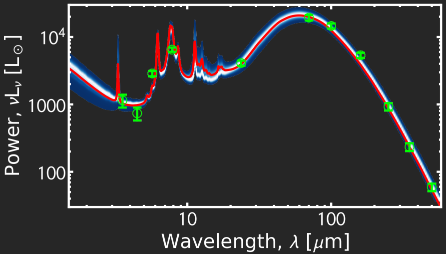
Methodological Approach

Modelling:
- Spectral Energy Distribution (SED) modelling.
- Spectral decomposition.
- Bayesian statistics.

Scientific Perspective

ISMology:
- Dust properties in different environments.
- Polycyclic Aromatic Hydrocarbons (PAH), photoelectric heating, dark gas, *etc.*

Galaxies:
- Focus on nearby galaxies ⇒ understand galaxy evolution.
- Cosmic dust evolution.



Methodological Approach

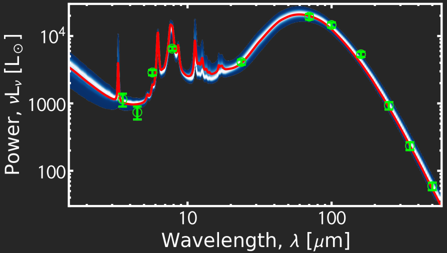
Modelling:
- Spectral Energy Distribution (SED) modelling.
- Spectral decomposition.
- Bayesian statistics.

Observations:
- Infrared expertise (*ISO*, *Spitzer*, *Herschel*).

Scientific Perspective

ISMology:
- Dust properties in different environments.
- Polycyclic Aromatic Hydrocarbons (PAH), photoelectric heating, dark gas, *etc.*

Galaxies:
- Focus on nearby galaxies ⇒ understand galaxy evolution.
- Cosmic dust evolution.



Methodological Approach

Modelling:
- Spectral Energy Distribution (SED) modelling.
- Spectral decomposition.
- Bayesian statistics.

Observations:
- Infrared expertise (*ISO*, *Spitzer*, *Herschel*).
- Currently : mm observations @ IRAM-30m.

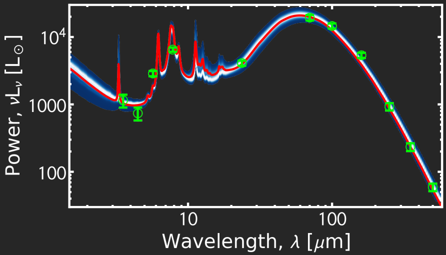
Scientific Perspective

ISMology:

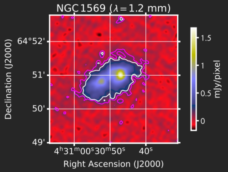
- Dust properties in different environments.
- Polycyclic Aromatic Hydrocarbons (PAH), photoelectric heating, dark gas, *etc.*

Galaxies:

- Focus on nearby galaxies ⇒ understand galaxy evolution.
- Cosmic dust evolution.



Methodological Approach



Modelling:

- Spectral Energy Distribution (SED) modelling.
- Spectral decomposition.
- Bayesian statistics.

Observations:

- Infrared expertise (*ISO*, *Spitzer*, *Herschel*).
- Currently : mm observations @ IRAM-30m.

LECTURE 1: AN OVERVIEW OF THE ISM AND THE WAY WE STUDY IT

1. Overview: What is the ISM?
2. A Brief History of ISM studies.
3. Methodology: how do we study interstellar media?

LECTURE 1: AN OVERVIEW OF THE ISM AND THE WAY WE STUDY IT

1. Overview: What is the ISM?
2. A Brief History of ISM studies.
3. Methodology: how do we study interstellar media?

LECTURE 2: ATOMS, MOLECULES AND DUST

1. Atoms and ions.
2. Molecules in space.
3. Interstellar dust grains.

LECTURE 3: HEATING AND COOLING - THE PHASES OF THE ISM

1. Cooling and heating of the gas.
2. Radiative transfer.
3. Star-forming regions.

LECTURE 1: AN OVERVIEW OF THE ISM AND THE WAY WE STUDY IT

1. Overview: What is the ISM?
2. A Brief History of ISM studies.
3. Methodology: how do we study interstellar media?

LECTURE 2: ATOMS, MOLECULES AND DUST

1. Atoms and ions.
2. Molecules in space.
3. Interstellar dust grains.

LECTURE 3: HEATING AND COOLING - THE PHASES OF THE ISM

1. Cooling and heating of the gas.
2. Radiative transfer.
3. Star-forming regions.

LECTURE 4: THE INTERSTELLAR LIFECYCLE

1. Molecular clouds.
2. The star formation process.
3. Elemental & dust evolution.

Overview | Recommended Bibliography (1/2)

Textbooks about the ISM

- *"The Physics and Chemistry of the Interstellar Medium"*, by A. G. G. M. Tielens, 2005, Cambridge University Press.
- *"Physics of the Interstellar and Intergalactic Medium"*, by B. T. Draine, 2011, Princeton University Press.
- *"Astrophysics of the diffuse Universe"*, by M. A. Dopita & R. S. Sutherland, 2003, Springer, open text.

Textbooks about the ISM

- *"The Physics and Chemistry of the Interstellar Medium"*, by A. G. G. M. Tielens, 2005, Cambridge University Press.
- *"Physics of the Interstellar and Intergalactic Medium"*, by B. T. Draine, 2011, Princeton University Press.
- *"Astrophysics of the diffuse Universe"*, by M. A. Dopita & R. S. Sutherland, 2003, Springer, open text.

Textbooks about an ISM-related Topic

- **"Astrophysics of gaseous nebulae and active galactic nuclei"** by D. E. Osterbrock & G. J. Ferland, 2006, University Science Books.
- **"Radiative processes in astrophysics"**, by G. B. Rybicky & A. P. Lightman, 1979, Wiley.
- **"The physics of interstellar dust"**, by E. Krügel, 2003, IoP.

Textbooks about the ISM

- *"The Physics and Chemistry of the Interstellar Medium"*, by A. G. G. M. Tielens, 2005, Cambridge University Press.
- *"Physics of the Interstellar and Intergalactic Medium"*, by B. T. Draine, 2011, Princeton University Press.
- *"Astrophysics of the diffuse Universe"*, by M. A. Dopita & R. S. Sutherland, 2003, Springer, open text.

Textbooks about an ISM-related Topic

- **"Astrophysics of gaseous nebulae and active galactic nuclei"** by D. E. Osterbrock & G. J. Ferland, 2006, University Science Books.
- **"Radiative processes in astrophysics"**, by G. B. Rybicky & A. P. Lightman, 1979, Wiley.
- **"The physics of interstellar dust"**, by E. Krügel, 2003, IoP.

Open Reviews about the Phases of the ISM

- *"The Three-Phase Interstellar Medium Revisited"*, by D. P. Cox, 2005, ARA&A.
- *"The HI distribution of the Milky Way"*, by P. M. W. Kalberla & K. Jürgen, 2009, ARA&A.
- *"Molecular clouds in the Milky Way"*, by M. Heyer & T. M. Dame, 2015, ARA&A.
- *"Physical processes in the interstellar medium"*, by R. S. Klessen & S. C. O. Glover, 2016, Saas-Fee Advanced Course.

Open Reviews about Dust

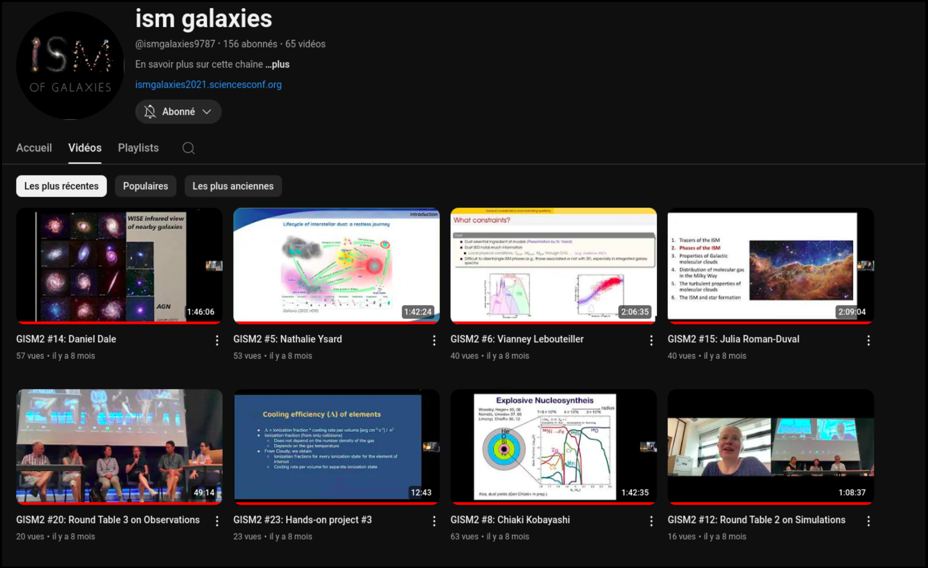
- *"Interstellar dust grains"*, by B. T. Draine, 2003, ARA&A.
- *"The interstellar dust properties of nearby galaxies"*, by F. Galliano, M. Galametz & A. P. Jones, 2018, ARA&A.
- *"A nearby galaxy perspective on interstellar dust properties and their evolution"*, by F. Galliano, Habilitation thesis, 2022, Université Paris-Saclay.

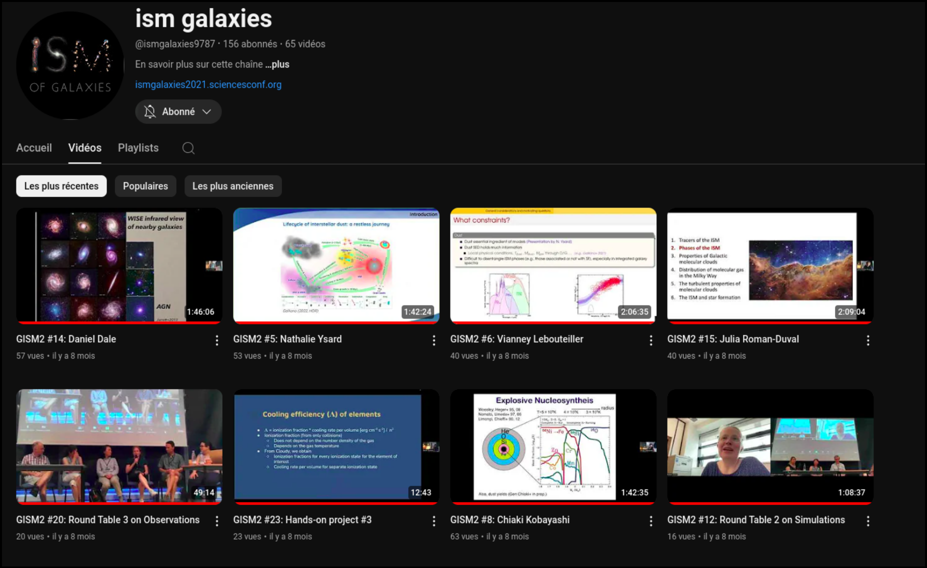
Open Reviews about Dust

- *"Interstellar dust grains"*, by B. T. Draine, 2003, ARA&A.
- *"The interstellar dust properties of nearby galaxies"*, by F. Galliano, M. Galametz & A. P. Jones, 2018, ARA&A.
- *"A nearby galaxy perspective on interstellar dust properties and their evolution"*, by F. Galliano, Habilitation thesis, 2022, Université Paris-Saclay.

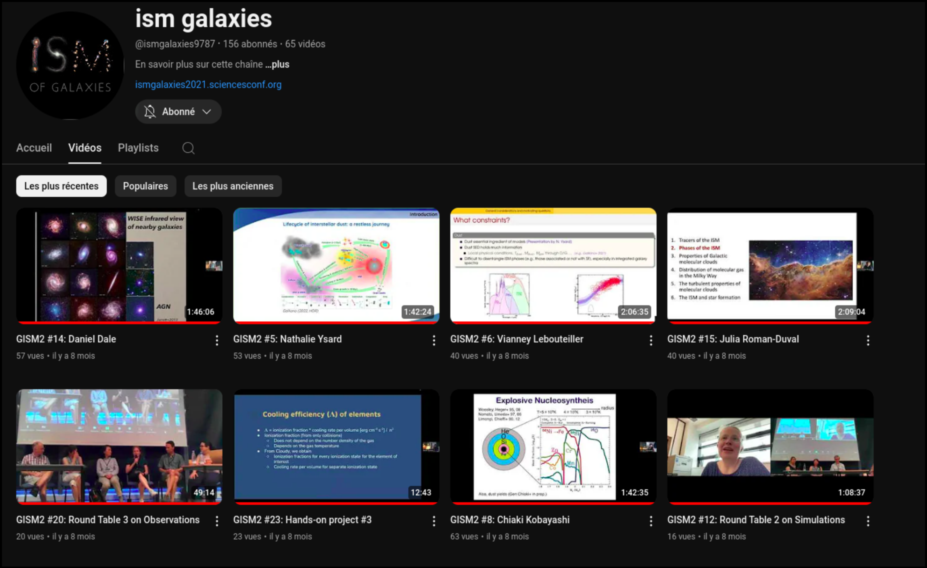
Open Reviews about PDRs

- *"Dense photodissociation regions (PDRs)"*, by A. G. G. M. Tielens & D. J. Hollenbach, 1997, ARA&A.
- *"Photodissociation and X-Ray-Dominated Regions"*, by M. Wolfire, L. Vallini & M. Chevance, 2022, ARA&A.


ISM OF GALAXIES
ism galaxies
@ismgalaxies9787 · 156 abonnés · 65 vidéos
En savoir plus sur cette chaîne ...plus
ismgalaxies2021.sciencesconf.org
Abonné
Accueil
Vidéos
Playlists
Les plus récentes
Populaires
Les plus anciennes
WISE infrared view of nearby galaxies
AGN
1:46:06
GISM2 #14: Daniel Dale
57 vues • il y a 8 mois
Lifecycle of interstellar dust: a restless journey
Introduction
1:42:24
GISM2 #5: Nathalie Ysard
53 vues • il y a 8 mois
What constraints?
2:06:35
GISM2 #6: Vianney Lebouteiller
40 vues • il y a 8 mois
1. Tracers of the ISM
2. Phases of the ISM
3. Properties of Galactic molecular clouds
4. Distribution of molecular gas in the Milky Way
5. The turbulent properties of molecular clouds
6. The ISM and star formation
2:09:04
GISM2 #15: Julia Roman-Duval
40 vues • il y a 8 mois
49:14
GISM2 #20: Round Table 3 on Observations
20 vues • il y a 8 mois
Cooling efficiency (Λ) of elements
12:43
GISM2 #23: Hands-on project #3
23 vues • il y a 8 mois
Explosive Nucleosyntheis
1:42:35
GISM2 #8: Chiaki Kobayashi
63 vues • il y a 8 mois
1:08:37
GISM2 #12: Round Table 2 on Simulations
16 vues • il y a 8 mois



2021 International summer school on the ISM of galaxies: videos & slides.



2021 International summer school on the ISM of galaxies: videos & slides.

2023 International summer school on the ISM of galaxies: videos & slides.

Next Galaxies' ISM Summer School: July 21 – August 1, 2025 – Banyuls-sur-mer France

Next Galaxies' ISM Summer School: July 21 – August 1, 2025 – Banyuls-sur-mer France

Next Galaxies' ISM Summer School: July 21 – August 1, 2025 – Banyuls-sur-mer France

Scope: theory and observations of the ISM of nearby galaxies, with an emphasis on modern data analysis methods.

Next Galaxies' ISM Summer School: July 21 – August 1, 2025 – Banyuls-sur-mer France

Scope: theory and observations of the ISM of nearby galaxies, with an emphasis on modern data analysis methods.

Confirmed speakers: Dalya BARON, Danielle BERG, Pierre CHAINAIS, Emmanuel DARTOIS, Simon GLOVER, Javier GOICOECHEA, Anna MCLEOD, Adeline PAIEMENT, Kate PATTLE, Donatella ROMANO, Antoine ROUEFF, Serena VITI.

Overview | International Summer School on the ISM of Galaxies

Next Galaxies' ISM Summer School: July 21 – August 1, 2025 – Banyuls-sur-mer France

Scope: theory and observations of the ISM of nearby galaxies, with an emphasis on modern data analysis methods.

Confirmed speakers: Dalya BARON, Danielle BERG, Pierre CHAINAIS, Emmanuel DARTOIS, Simon GLOVER, Javier GOICOECHEA, Anna MCLEOD, Adeline PAIEMENT, Kate PATTLE, Donatella ROMANO, Antoine ROUEFF, Serena VITI.

Registration: January 27 – April 18, 2025.

Overview | International Summer School on the ISM of Galaxies

Next Galaxies' ISM Summer School: July 21 – August 1, 2025 – Banyuls-sur-mer France

Scope: theory and observations of the ISM of nearby galaxies, with an emphasis on modern data analysis methods.

Confirmed speakers: Dalya BARON, Danielle BERG, Pierre CHAINAIS, Emmanuel DARTOIS, Simon GLOVER, Javier GOICOECHEA, Anna MCLEOD, Adeline PAIEMENT, Kate PATTLE, Donatella ROMANO, Antoine ROUEFF, Serena VITI.

Registration: January 27 – April 18, 2025.

More info: https://ismgalaxies2025.sciencesconf.org/?lang=en.

Outline of the Lecture

Naked eye observations (Antiquity – Middle Age)

Naked eye observations (Antiquity – Middle Age)

A few *fixed clouds* were noted by various authors during Antiquity & Middle Age. Among others:

Naked eye observations (Antiquity – Middle Age)

A few *fixed clouds* were noted by various authors during Antiquity & Middle Age. Among others:

- The Milky Way (dark clouds);

Credit: The Milky Way, as seen with a naked eye, © 2013 Alan DYER.

Naked eye observations (Antiquity – Middle Age)

A few *fixed clouds* were noted by various authors during Antiquity & Middle Age. Among others:

- The Milky Way (dark clouds);
- M 42 (the Orion nebula, a H II region);

Credit: The Milky Way, as seen with a naked eye, © 2013 Alan DYER.

Naked eye observations (Antiquity – Middle Age)

A few *fixed clouds* were noted by various authors during Antiquity & Middle Age. Among others:

- The Milky Way (dark clouds);
- M 42 (the Orion nebula, a H II region);
- M 17 (the Omega nebulae, a H II region);

Credit: The Milky Way, as seen with a naked eye, © 2013 Alan DYER.

Naked eye observations (Antiquity – Middle Age)

A few *fixed clouds* were noted by various authors during Antiquity & Middle Age. Among others:

- The Milky Way (dark clouds);
- M 42 (the Orion nebula, a H II region);
- M 17 (the Omega nebulae, a H II region);
- The Pleiades (reflection nebula);

Credit: The Milky Way, as seen with a naked eye, © 2013 Alan DYER.

Naked eye observations (Antiquity – Middle Age)

A few *fixed clouds* were noted by various authors during Antiquity & Middle Age. Among others:

- The Milky Way (dark clouds);
- M 42 (the Orion nebula, a H II region);
- M 17 (the Omega nebulae, a H II region);
- The Pleiades (reflection nebula);
- M 31 (Andromeda galaxy);

Credit: The Milky Way, as seen with a naked eye, © 2013 Alan DYER.

Naked eye observations (Antiquity – Middle Age)

A few *fixed clouds* were noted by various authors during Antiquity & Middle Age. Among others:

- The Milky Way (dark clouds);
- M 42 (the Orion nebula, a H II region);
- M 17 (the Omega nebulae, a H II region);
- The Pleiades (reflection nebula);
- M 31 (Andromeda galaxy);
- The Magellanic Clouds (dwarf galaxies).

Credit: The Milky Way, as seen with a naked eye, © 2013 Alan DYER.

First studies of the Orion nebula

(Harrison, 1984)

First studies of the Orion nebula

1609: first telescope pointed toward the sky by Galileo.

Galileo GALILEI

 (1564–1642)

(Harrison, 1984)

First studies of the Orion nebula

1609: first telescope pointed toward the sky by Galileo.

1610: first detailed observation of M 42 by Nicolas Claude FABRI DE PEREISC, as a *"small illuminated cloud"*.

(Harrison, 1984)

Galileo GALILEI

 (1564–1642)

First studies of the Orion nebula

1609: first telescope pointed toward the sky by Galileo.

1610: first detailed observation of M 42 by Nicolas Claude FABRI DE PEREISC, as a *"small illuminated cloud"*.

1659: observations by Christian HUYGENS → reports variability.

(Harrison, 1984)

Galileo GALILEI (1564–1642)

First studies of the Orion nebula

1609: first telescope pointed toward the sky by Galileo.

1610: first detailed observation of M 42 by Nicolas Claude FABRI DE PEREISC, as a *"small illuminated cloud"*.

1659: observations by Christian HUYGENS → reports variability.

1774-1811: observations by William HERSCHEL → refine its structure and discusses its variability.

(Harrison, 1984)

Galileo GALILEI
(1564–1642)

First studies of the Orion nebula

1609: first telescope pointed toward the sky by Galileo.

1610: first detailed observation of M 42 by Nicolas Claude FABRI DE PEREISC, as a *"small illuminated cloud"*.

1659: observations by Christian HUYGENS → reports variability.

1774-1811: observations by William HERSCHEL → refine its structure and discusses its variability.

(Harrison, 1984)

Galileo GALILEI
(1564–1642)

The Messier catalog (1774–1784)

Charles MESSIER
(1730–1817)

(Messier, 1781)

First studies of the Orion nebula

1609: first telescope pointed toward the sky by Galileo.

1610: first detailed observation of M 42 by Nicolas Claude FABRI DE PEREISC, as a *"small illuminated cloud"*.

1659: observations by Christian HUYGENS → reports variability.

1774-1811: observations by William HERSCHEL → refine its structure and discusses its variability.

(Harrison, 1984)

Galileo GALILEI
(1564–1642)

The Messier catalog (1774–1784)

Charles MESSIER
(1730–1817)

- Catalog identifying 110 *"nebulae"* (*i.e.* permanent diffuse objects)

(Messier, 1781)

First studies of the Orion nebula

1609: first telescope pointed toward the sky by Galileo.

1610: first detailed observation of M 42 by Nicolas Claude FABRI DE PEREISC, as a *"small illuminated cloud"*.

1659: observations by Christian HUYGENS → reports variability.

1774-1811: observations by William HERSCHEL → refine its structure and discusses its variability.

(Harrison, 1984)

Galileo GALILEI
(1564–1642)

The Messier catalog (1774–1784)

Charles MESSIER
(1730–1817)

- Catalog identifying 110 *"nebulae"* (*i.e.* permanent diffuse objects)

⇒ allow identifying comets (*i.e.* moving diffuse objects).

(Messier, 1781)

First studies of the Orion nebula

1609: first telescope pointed toward the sky by Galileo.

1610: first detailed observation of M 42 by Nicolas Claude FABRI DE PEREISC, as a *"small illuminated cloud"*.

1659: observations by Christian HUYGENS → reports variability.

1774-1811: observations by William HERSCHEL → refine its structure and discusses its variability.

(Harrison, 1984)

Galileo GALILEI (1564–1642)

The Messier catalog (1774–1784)

Charles MESSIER (1730–1817)

- Catalog identifying 110 *"nebulae"* (*i.e.* permanent diffuse objects)

⇒ allow identifying comets (*i.e.* moving diffuse objects).

- Restricted to the northern hemisphere.

(Messier, 1781)

First studies of the Orion nebula

1609: first telescope pointed toward the sky by Galileo.

1610: first detailed observation of M 42 by Nicolas Claude FABRI DE PEREISC, as a *"small illuminated cloud"*.

1659: observations by Christian HUYGENS → reports variability.

1774-1811: observations by William HERSCHEL → refine its structure and discusses its variability.

(Harrison, 1984)

Galileo GALILEI
(1564–1642)

The Messier catalog (1774–1784)

Charles MESSIER
(1730–1817)

- Catalog identifying 110 *"nebulae"* (*i.e.* permanent diffuse objects)

⇒ allow identifying comets (*i.e.* moving diffuse objects).

- Restricted to the northern hemisphere.
- Mixes indifferently: reflection nebulae, planetary nebulae, H II regions, stellar clusters & galaxies.

(Messier, 1781)

William HERSCHEL
(1738–1822)

William HERSCHEL
(1738–1822)

Pioneering observational techniques

History | The Contributions of William HERSCHEL

William HERSCHEL
(1738–1822)

Pioneering observational techniques

1785: construction of the first large reflecting telescope ($\varnothing = 1.26$ m), with a *speculum* ($2/3\,\mathrm{Cu} + 1/3\,\mathrm{Sn}$) mirror.

William HERSCHEL

  (1738–1822)

Pioneering observational techniques

1785: construction of the first large reflecting telescope ($\varnothing = 1.26$ m), with a *speculum* ($2/3\,Cu + 1/3\,Sn$) mirror.

1800: discovery of *infrared radiation*, from the Sun, using thermometers

William HERSCHEL
(1738–1822)

Pioneering observational techniques

1785: construction of the first large reflecting telescope ($\varnothing = 1.26$ m), with a *speculum* ($2/3\,\mathrm{Cu} + 1/3\,\mathrm{Sn}$) mirror.

1800: discovery of *infrared radiation*, from the Sun, using thermometers

$\Rightarrow$ significant development of astronomical spectrophotometry.

William HERSCHEL
(1738–1822)

Pioneering observational techniques

1785: construction of the first large reflecting telescope ($\varnothing = 1.26$ m), with a *speculum* ($2/3\,\mathrm{Cu} + 1/3\,\mathrm{Sn}$) mirror.

1800: discovery of *infrared radiation*, from the Sun, using thermometers

$\Rightarrow$ significant development of astronomical spectrophotometry.

Progressing on nebulae

William HERSCHEL

 (1738–1822)

Pioneering observational techniques

1785: construction of the first large reflecting telescope ($\varnothing = 1.26$ m), with a *speculum* ($2/3\,\mathrm{Cu} + 1/3\,\mathrm{Sn}$) mirror.

1800: discovery of *infrared radiation*, from the Sun, using thermometers

$\Rightarrow$ significant development of astronomical spectrophotometry.

Progressing on nebulae

1785: *"a hole in the Heavens"* $\rightarrow$ actually a dark cloud in front of a rich stellar field (Herschel, 1785).

William HERSCHEL
(1738–1822)

Pioneering observational techniques

1785: construction of the first large reflecting telescope ($\varnothing = 1.26$ m), with a *speculum* ($2/3\,\mathrm{Cu} + 1/3\,\mathrm{Sn}$) mirror.

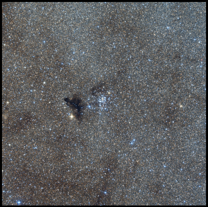
1800: discovery of *infrared radiation*, from the Sun, using thermometers

$\Rightarrow$ significant development of astronomical spectrophotometry.

Progressing on nebulae

1785: *"a hole in the Heavens"* $\rightarrow$ actually a dark cloud in front of a rich stellar field (Herschel, 1785).

The Inkspot nebula



Credit: Gábor Tóth.

William HERSCHEL (1738–1822)

Pioneering observational techniques

1785: construction of the first large reflecting telescope ($\varnothing = 1.26$ m), with a *speculum* ($2/3\,\mathrm{Cu} + 1/3\,\mathrm{Sn}$) mirror.

1800: discovery of *infrared radiation*, from the Sun, using thermometers

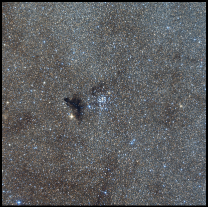
$\Rightarrow$ significant development of astronomical spectrophotometry.

Progressing on nebulae

1785: *"a hole in the Heavens"* $\rightarrow$ actually a dark cloud in front of a rich stellar field (Herschel, 1785).

1791: hypothesize that some nebulae can not be resolved into individual stars $\rightarrow$ *"a shining fluid, of a nature totally unknown to us"* (Herschel, 1791).

The Inkspot nebula



Credit: Gábor Tóth.

History | The Contributions of William HERSCHEL

William HERSCHEL (1738–1822)

Pioneering observational techniques

1785: construction of the first large reflecting telescope ($\varnothing = 1.26$ m), with a *speculum* ($2/3\,\mathrm{Cu} + 1/3\,\mathrm{Sn}$) mirror.

1800: discovery of *infrared radiation*, from the Sun, using thermometers

$\Rightarrow$ significant development of astronomical spectrophotometry.

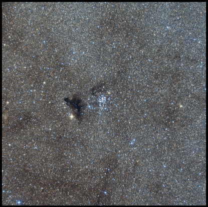
Progressing on nebulae

1785: *"a hole in the Heavens"* $\rightarrow$ actually a dark cloud in front of a rich stellar field (Herschel, 1785).

1791: hypothesize that some nebulae can not be resolved into individual stars $\rightarrow$ *"a shining fluid, of a nature totally unknown to us"* (Herschel, 1791).

1821: extended catalog of 5000 objects

The Inkspot nebula



Credit: Gábor Tóth.

History | The Contributions of William HERSCHEL

William HERSCHEL

 (1738–1822)

Pioneering observational techniques

1785: construction of the first large reflecting telescope ($\varnothing = 1.26$ m), with a *speculum* ($2/3\,\mathrm{Cu} + 1/3\,\mathrm{Sn}$) mirror.

1800: discovery of *infrared radiation*, from the Sun, using thermometers

$\Rightarrow$ significant development of astronomical spectrophotometry.

Progressing on nebulae

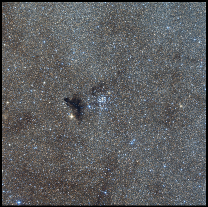
1785: *"a hole in the Heavens"* $\rightarrow$ actually a dark cloud in front of a rich stellar field (Herschel, 1785).

1791: hypothesize that some nebulae can not be resolved into individual stars $\rightarrow$ *"a shining fluid, of a nature totally unknown to us"* (Herschel, 1791).

1821: extended catalog of 5000 objects

$\Rightarrow$ distinguish star clusters & nebulae / galaxies

The Inkspot nebula



Credit: Gábor Tóth.

History | The Contributions of William HERSCHEL

William HERSCHEL
(1738–1822)

Pioneering observational techniques

1785: construction of the first large reflecting telescope ($\varnothing = 1.26$ m), with a *speculum* ($2/3\,\mathrm{Cu} + 1/3\,\mathrm{Sn}$) mirror.

1800: discovery of *infrared radiation*, from the Sun, using thermometers

$\Rightarrow$ significant development of astronomical spectrophotometry.

Progressing on nebulae

1785: *"a hole in the Heavens"* $\rightarrow$ actually a dark cloud in front of a rich stellar field (Herschel, 1785).

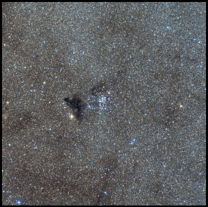
1791: hypothesize that some nebulae can not be resolved into individual stars $\rightarrow$ *"a shining fluid, of a nature totally unknown to us"* (Herschel, 1791).

1821: extended catalog of 5000 objects

$\Rightarrow$ distinguish star clusters & nebulae / galaxies

$\rightarrow$ basis for the *New General Catalog* (NGC), compiled by John DREYER (Dreyer, 1888).

The Inkspot nebula



Credit: Gábor Tóth.

Astrophotography: turning astronomy into a reproducible science

Astrophotography: turning astronomy into a reproducible science

1860: first silvered-glass mirrors (by Léon FOUCAULT) better than speculum mirrors $\rightarrow$ implemented on large telescopes.

Astrophotography: turning astronomy into a reproducible science

1860: first silvered-glass mirrors (by Léon FOUCAULT) better than speculum mirrors → implemented on large telescopes.

1880: first deep-sky photograph (the Orion nebula) by Henry DRAPER (Barker, 1888).

Astrophotography: turning astronomy into a reproducible science

1860: first silvered-glass mirrors (by Léon FOUCAULT) better than speculum mirrors → implemented on large telescopes.

1880: first deep-sky photograph (the Orion nebula) by Henry DRAPER (Barker, 1888).

Photograph of Orion by Henry DRAPER.

Astrophotography: turning astronomy into a reproducible science

1860: first silvered-glass mirrors (by Léon FOUCAULT) better than speculum mirrors → implemented on large telescopes.

1880: first deep-sky photograph (the Orion nebula) by Henry DRAPER (Barker, 1888).

1899: Edward BARNARD's photographs of Ophiucus showed dark lanes through the nebula (Barnard, 1899).

Photograph of Orion by Henry DRAPER.

Astrophotography: turning astronomy into a reproducible science

1860: first silvered-glass mirrors (by Léon FOUCAULT) better than speculum mirrors → implemented on large telescopes.

1880: first deep-sky photograph (the Orion nebula) by Henry DRAPER (Barker, 1888).

1899: Edward BARNARD's photographs of Ophiucus showed dark lanes through the nebula (Barnard, 1899).

1903: They were interpreted by Agnes CLERKE, as *"glades and clearing"* in the stellar distribution (Clerke, 1903).

Photograph of Orion by Henry DRAPER.

Astrophotography: turning astronomy into a reproducible science

1860: first silvered-glass mirrors (by Léon FOUCAULT) better than speculum mirrors → implemented on large telescopes.

1880: first deep-sky photograph (the Orion nebula) by Henry DRAPER (Barker, 1888).

1899: Edward BARNARD's photographs of Ophiucus showed dark lanes through the nebula (Barnard, 1899).

1903: They were interpreted by Agnes CLERKE, as *"glades and clearing"* in the stellar distribution (Clerke, 1903).

1919: Edward BARNARD realized these were *"real, obscuring masses, most probably dark nebulae"* (Barnard, 1919).

Photograph of Orion by Henry DRAPER.

Astrophotography: turning astronomy into a reproducible science

1860: first silvered-glass mirrors (by Léon FOUCAULT) better than speculum mirrors → implemented on large telescopes.

1880: first deep-sky photograph (the Orion nebula) by Henry DRAPER (Barker, 1888).

1899: Edward BARNARD's photographs of Ophiucus showed dark lanes through the nebula (Barnard, 1899).

1903: They were interpreted by Agnes CLERKE, as *"glades and clearing"* in the stellar distribution (Clerke, 1903).

1919: Edward BARNARD realized these were *"real, obscuring masses, most probably dark nebulae"* (Barnard, 1919).

Photograph of Orion by Henry DRAPER.

The development of spectrophotometry

Astrophotography: turning astronomy into a reproducible science

1860: first silvered-glass mirrors (by Léon FOUCAULT) better than speculum mirrors → implemented on large telescopes.

1880: first deep-sky photograph (the Orion nebula) by Henry DRAPER (Barker, 1888).

1899: Edward BARNARD's photographs of Ophiucus showed dark lanes through the nebula (Barnard, 1899).

1903: They were interpreted by Agnes CLERKE, as *"glades and clearing"* in the stellar distribution (Clerke, 1903).

1919: Edward BARNARD realized these were *"real, obscuring masses, most probably dark nebulae"* (Barnard, 1919).

Photograph of Orion by Henry DRAPER.

The development of spectrophotometry

- Photography allowed recording spectra of faint objects.

Astrophotography: turning astronomy into a reproducible science

1860: first silvered-glass mirrors (by Léon FOUCAULT) better than speculum mirrors → implemented on large telescopes.

1880: first deep-sky photograph (the Orion nebula) by Henry DRAPER (Barker, 1888).

1899: Edward BARNARD's photographs of Ophiucus showed dark lanes through the nebula (Barnard, 1899).

1903: They were interpreted by Agnes CLERKE, as *"glades and clearing"* in the stellar distribution (Clerke, 1903).

1919: Edward BARNARD realized these were *"real, obscuring masses, most probably dark nebulae"* (Barnard, 1919).

Photograph of Orion by Henry DRAPER.

The development of spectrophotometry

- Photography allowed recording spectra of faint objects.
- William HUGGINS took the spectra of $\simeq 70$ nebulae (Huggins & Miller, 1864). Distinguish:

Astrophotography: turning astronomy into a reproducible science

1860: first silvered-glass mirrors (by Léon FOUCAULT) better than speculum mirrors → implemented on large telescopes.

1880: first deep-sky photograph (the Orion nebula) by Henry DRAPER (Barker, 1888).

1899: Edward BARNARD's photographs of Ophiucus showed dark lanes through the nebula (Barnard, 1899).

1903: They were interpreted by Agnes CLERKE, as *"glades and clearing"* in the stellar distribution (Clerke, 1903).

1919: Edward BARNARD realized these were *"real, obscuring masses, most probably dark nebulae"* (Barnard, 1919).

Photograph of Orion by Henry DRAPER.

The development of spectrophotometry

- Photography allowed recording spectra of faint objects.
- William HUGGINS took the spectra of $\simeq$ 70 nebulae (Huggins & Miller, 1864). Distinguish:
  H II regions: bright emission lines;

Astrophotography: turning astronomy into a reproducible science

1860: first silvered-glass mirrors (by Léon FOUCAULT) better than speculum mirrors → implemented on large telescopes.

1880: first deep-sky photograph (the Orion nebula) by Henry DRAPER (Barker, 1888).

1899: Edward BARNARD's photographs of Ophiucus showed dark lanes through the nebula (Barnard, 1899).

1903: They were interpreted by Agnes CLERKE, as *"glades and clearing"* in the stellar distribution (Clerke, 1903).

1919: Edward BARNARD realized these were *"real, obscuring masses, most probably dark nebulae"* (Barnard, 1919).

Photograph of Orion by Henry DRAPER.

The development of spectrophotometry

- Photography allowed recording spectra of faint objects.
- William HUGGINS took the spectra of $\simeq$ 70 nebulae (Huggins & Miller, 1864). Distinguish:

  H II regions: bright emission lines;

  Reflection nebulae: continuous spectrum (reflected starlight).

Cepheid stars, a standard candle to estimate large distances

Cepheid stars, a standard candle to estimate large distances

Cepheid stars: pulsating stars with a period-luminosity relation.

Cepheid stars, a standard candle to estimate large distances

Cepheid stars: pulsating stars with a period-luminosity relation.

Discovery of the relation: by Leavitt & Pickering (1912) using 25 Cepheids in the *Small Magellanic Cloud* (SMC).

Cepheid stars, a standard candle to estimate large distances

Henrietta SWAN LEAVITT
(1868–1921)

Cepheid stars: pulsating stars with a period-luminosity relation.

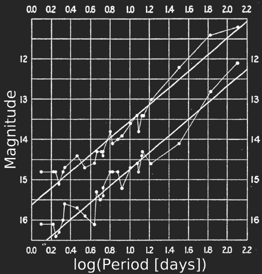
Discovery of the relation: by Leavitt & Pickering (1912) using 25 Cepheids in the *Small Magellanic Cloud* (SMC).

Cepheid stars, a standard candle to estimate large distances

Henrietta SWAN LEAVITT (1868–1921)

Cepheid stars: pulsating stars with a period-luminosity relation.

Discovery of the relation: by Leavitt & Pickering (1912) using 25 Cepheids in the *Small Magellanic Cloud* (SMC).



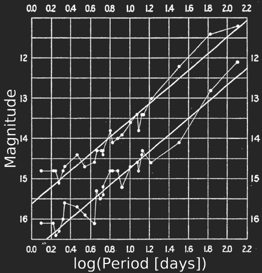
Cepheid stars, a standard candle to estimate large distances

Henrietta SWAN LEAVITT (1868–1921)

Cepheid stars: pulsating stars with a period-luminosity relation.

Discovery of the relation: by Leavitt & Pickering (1912) using 25 Cepheids in the *Small Magellanic Cloud* (SMC).

Distance estimator: period + apparent magnitude → distance.



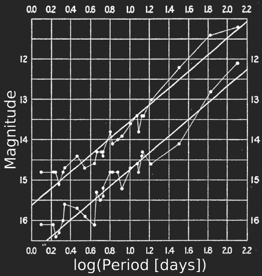
Cepheid stars, a standard candle to estimate large distances

Henrietta SWAN LEAVITT (1868–1921)

Cepheid stars: pulsating stars with a period-luminosity relation.

Discovery of the relation: by Leavitt & Pickering (1912) using 25 Cepheids in the *Small Magellanic Cloud* (SMC).

Distance estimator: period + apparent magnitude → distance.



First evidence of extragalactic nebulae: M 31 & M 33 are outside the Milky Way

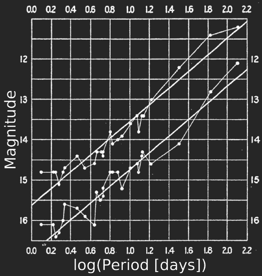
Cepheid stars, a standard candle to estimate large distances

Henrietta SWAN LEAVITT (1868–1921)

Cepheid stars: pulsating stars with a period-luminosity relation.

Discovery of the relation: by Leavitt & Pickering (1912) using 25 Cepheids in the *Small Magellanic Cloud* (SMC).

Distance estimator: period + apparent magnitude → distance.



First evidence of extragalactic nebulae: M 31 & M 33 are outside the Milky Way

- Hubble (1925) resolved Cepheids in M 31 & M 33, with long pauses, at Mount Wilson Observatory.

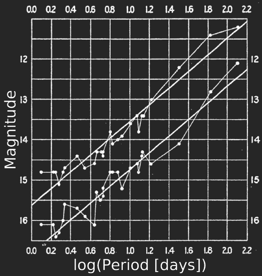
Cepheid stars, a standard candle to estimate large distances

Henrietta SWAN LEAVITT
(1868–1921)

Cepheid stars: pulsating stars with a period-luminosity relation.

Discovery of the relation: by Leavitt & Pickering (1912) using 25 Cepheids in the *Small Magellanic Cloud* (SMC).

Distance estimator: period + apparent magnitude → distance.



First evidence of extragalactic nebulae: M 31 & M 33 are outside the Milky Way

Edwin HUBBLE
(1889–1953)

- Hubble (1925) resolved Cepheids in M 31 & M 33, with long pauses, at Mount Wilson Observatory.

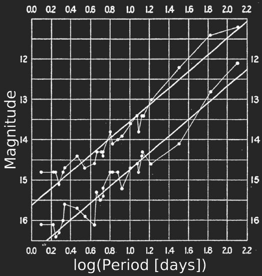
Cepheid stars, a standard candle to estimate large distances

Henrietta SWAN LEAVITT (1868–1921)

Cepheid stars: pulsating stars with a period-luminosity relation.

Discovery of the relation: by Leavitt & Pickering (1912) using 25 Cepheids in the *Small Magellanic Cloud* (SMC).

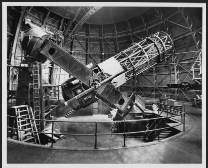
Distance estimator: period + apparent magnitude → distance.



First evidence of extragalactic nebulae: M 31 & M 33 are outside the Milky Way

Edwin HUBBLE (1889–1953)

- Hubble (1925) resolved Cepheids in M 31 & M 33, with long pauses, at Mount Wilson Observatory.



Mount Wilson's 100-inch reflector.

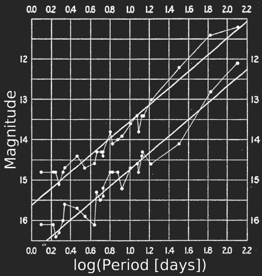
Cepheid stars, a standard candle to estimate large distances

Henrietta SWAN LEAVITT (1868–1921)

Cepheid stars: pulsating stars with a period-luminosity relation.

Discovery of the relation: by Leavitt & Pickering (1912) using 25 Cepheids in the *Small Magellanic Cloud* (SMC).

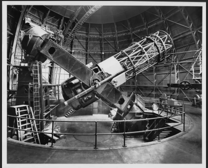
Distance estimator: period + apparent magnitude → distance.



First evidence of extragalactic nebulae: M 31 & M 33 are outside the Milky Way

Edwin HUBBLE (1889–1953)

- Hubble (1925) resolved Cepheids in M 31 & M 33, with long pauses, at Mount Wilson Observatory.
- Derived their distance, equal to ≃ 285 kpc (actually 765 & 970 kpc)



Mount Wilson's 100-inch reflector.

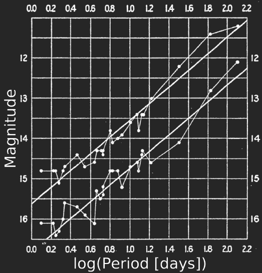
Cepheid stars, a standard candle to estimate large distances

Henrietta SWAN LEAVITT
(1868–1921)

Cepheid stars: pulsating stars with a period-luminosity relation.

Discovery of the relation: by Leavitt & Pickering (1912) using 25 Cepheids in the *Small Magellanic Cloud* (SMC).

Distance estimator: period + apparent magnitude → distance.

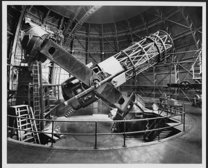


First evidence of extragalactic nebulae: M 31 & M 33 are outside the Milky Way

Edwin HUBBLE
(1889–1953)

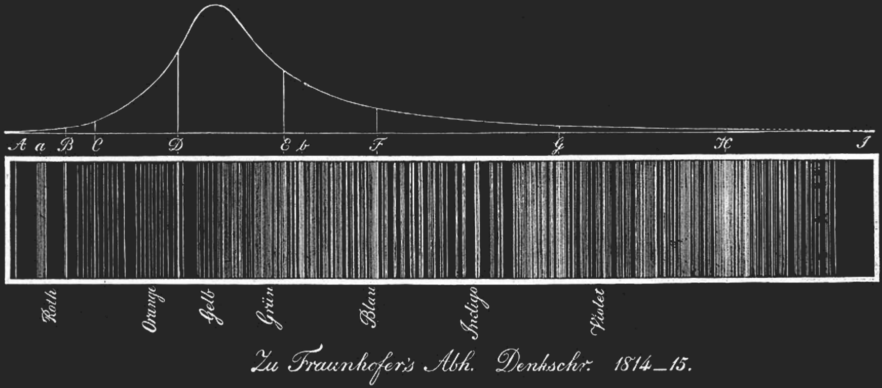
- Hubble (1925) resolved Cepheids in M 31 & M 33, with long pauses, at Mount Wilson Observatory.
- Derived their distance, equal to ≃ 285 kpc (actually 765 & 970 kpc)

⇒ they are outside the Milky Way.

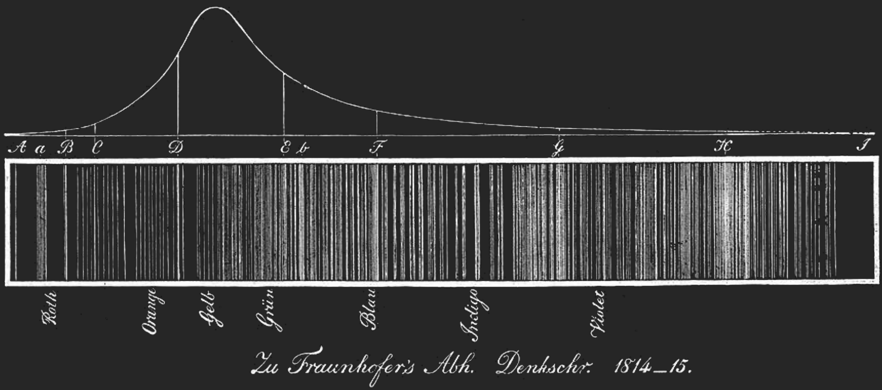


Mount Wilson's 100-inch reflector.

The first astrophysical spectrum: the Sun, by Joseph VON FRAUNHOFER (1814)

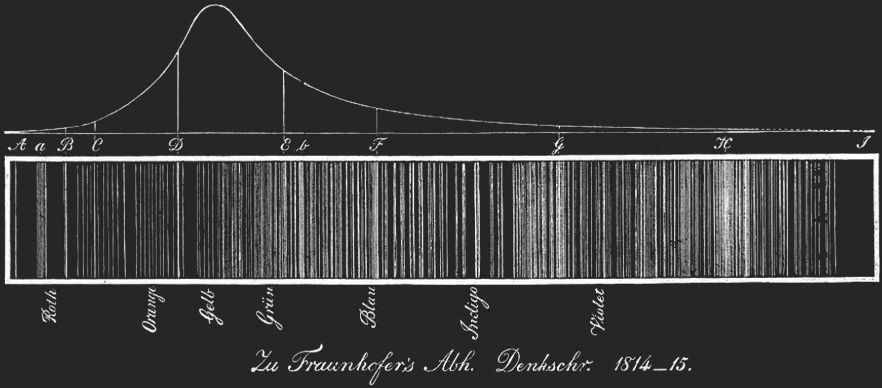


The first astrophysical spectrum: the Sun, by Joseph VON FRAUNHOFER (1814)



Quantum Physics: the possibility to study distant matter

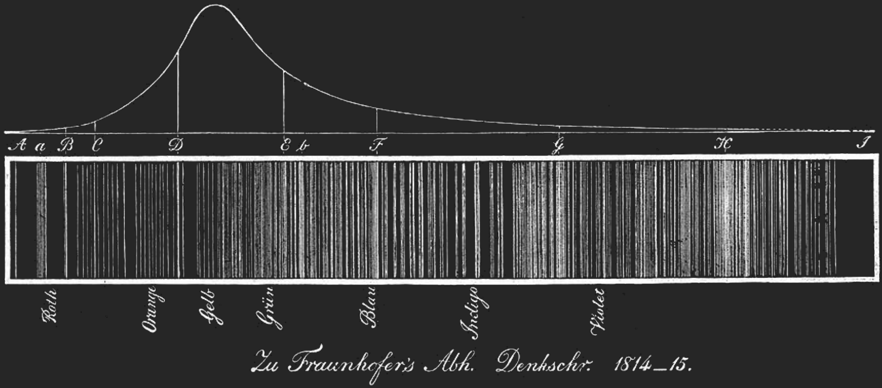
The first astrophysical spectrum: the Sun, by Joseph VON FRAUNHOFER (1814)



Quantum Physics: the possibility to study distant matter

- Quantum physics → identifying atoms & molecules in distant objects

The first astrophysical spectrum: the Sun, by Joseph VON FRAUNHOFER (1814)



Quantum Physics: the possibility to study distant matter

- Quantum physics → identifying atoms & molecules in distant objects

⇒ measuring their abundance (Payne, 1925), temperature, density, charge + kinematics, magnetic field.

1930 – First evidence of interstellar dust

1930 – First evidence of interstellar dust

1922: Russell (1922) noted the reddening of starlight ⇒ produced mainly by dust particles of $\simeq 0.03 - 0.1\ \mu$m in diameter.

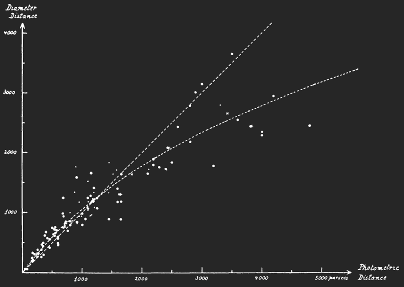
1930 – First evidence of interstellar dust

1922: Russell (1922) noted the reddening of starlight ⇒ produced mainly by dust particles of $\simeq 0.03 - 0.1~\mu$m in diameter.

1930: Trumpler (1930) studied 100 open clusters ⇒ diameter distance $<$ photometric distance

1930 – First evidence of interstellar dust

- **1922:** Russell (1922) noted the reddening of starlight ⇒ produced mainly by dust particles of $\simeq 0.03 - 0.1\ \mu$m in diameter.
- **1930:** Trumpler (1930) studied 100 open clusters ⇒ diameter distance < photometric distance

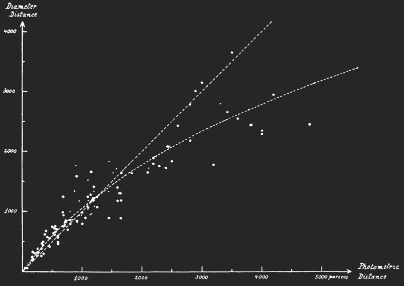


1930 – First evidence of interstellar dust

1922: Russell (1922) noted the reddening of starlight ⇒ produced mainly by dust particles of $\simeq 0.03 - 0.1\ \mu$m in diameter.

1930: Trumpler (1930) studied 100 open clusters ⇒ diameter distance < photometric distance

→ effect increases with distance



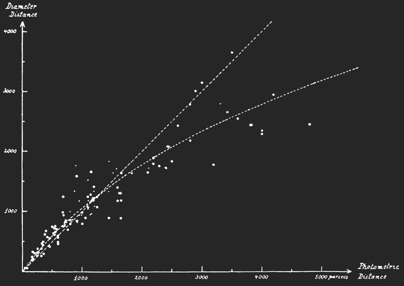
1930 – First evidence of interstellar dust

1922: Russell (1922) noted the reddening of starlight ⇒ produced mainly by dust particles of $\simeq 0.03 - 0.1\ \mu$m in diameter.

1930: Trumpler (1930) studied 100 open clusters ⇒ diameter distance < photometric distance

→ effect increases with distance

⇒ selective extinction by fine dust particles (larger than 2 nm).



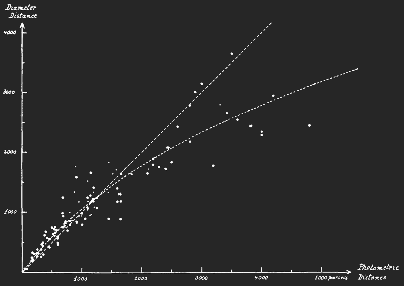
1930 – First evidence of interstellar dust

1922: Russell (1922) noted the reddening of starlight ⇒ produced mainly by dust particles of $\simeq 0.03 - 0.1\ \mu$m in diameter.

1930: Trumpler (1930) studied 100 open clusters ⇒ diameter distance < photometric distance

→ effect increases with distance

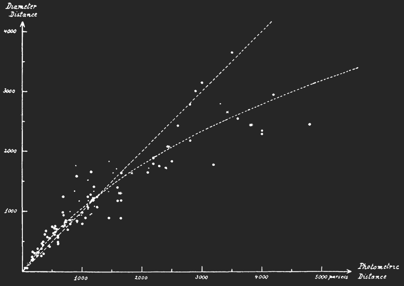
⇒ selective extinction by fine dust particles (larger than 2 nm).



1937 – Detection of the first interstellar molecule

1930 – First evidence of interstellar dust

- **1922:** Russell (1922) noted the reddening of starlight ⇒ produced mainly by dust particles of $\simeq 0.03 - 0.1\ \mu$m in diameter.
- **1930:** Trumpler (1930) studied 100 open clusters ⇒ diameter distance < photometric distance
  - → effect increases with distance
  - ⇒ selective extinction by fine dust particles (larger than 2 nm).



1937 – Detection of the first interstellar molecule

1937: identification of a line of CH at $\lambda = 4300$ Å by Swings & Rosenfeld (1937).

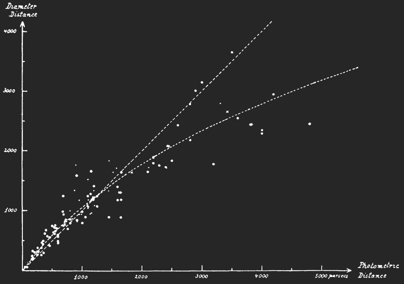
1930 – First evidence of interstellar dust

1922: Russell (1922) noted the reddening of starlight ⇒ produced mainly by dust particles of $\simeq 0.03 - 0.1\ \mu$m in diameter.

1930: Trumpler (1930) studied 100 open clusters ⇒ diameter distance < photometric distance

→ effect increases with distance

⇒ selective extinction by fine dust particles (larger than 2 nm).



1937 – Detection of the first interstellar molecule

1937: identification of a line of CH at $\lambda = 4300$ Å by Swings & Rosenfeld (1937).

1963: first detection of a molecular radio line (OH_{18cm}) by Weinreb et al. (1963).

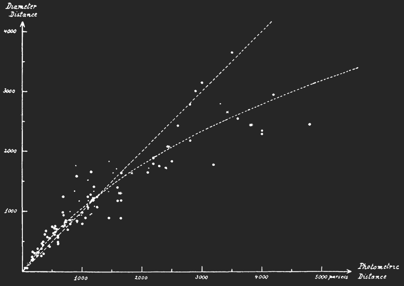
1930 – First evidence of interstellar dust

1922: Russell (1922) noted the reddening of starlight ⇒ produced mainly by dust particles of $\simeq 0.03 - 0.1\ \mu$m in diameter.

1930: Trumpler (1930) studied 100 open clusters ⇒ diameter distance < photometric distance

→ effect increases with distance

⇒ selective extinction by fine dust particles (larger than 2 nm).



1937 – Detection of the first interstellar molecule

1937: identification of a line of CH at $\lambda = 4300$ Å by Swings & Rosenfeld (1937).

1963: first detection of a molecular radio line (OH_{18cm}) by Weinreb et al. (1963).

1951 – Detection of interstellar atomic Hydrogen

History | 1930–1950: Unveiling the Constituents of the ISM

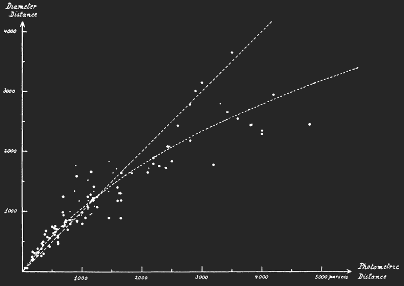
1930 – First evidence of interstellar dust

1922: Russell (1922) noted the reddening of starlight ⇒ produced mainly by dust particles of $\simeq 0.03 - 0.1\ \mu$m in diameter.

1930: Trumpler (1930) studied 100 open clusters ⇒ diameter distance < photometric distance

→ effect increases with distance

⇒ selective extinction by fine dust particles (larger than 2 nm).



1937 – Detection of the first interstellar molecule

1937: identification of a line of CH at $\lambda = 4300$ Å by Swings & Rosenfeld (1937).

1963: first detection of a molecular radio line (OH_{18cm}) by Weinreb et al. (1963).

1951 – Detection of interstellar atomic Hydrogen

1945: prediction of the $[\mathrm{H\,I}]_{21\,\mathrm{cm}}$ line by van de Hulst (1945).

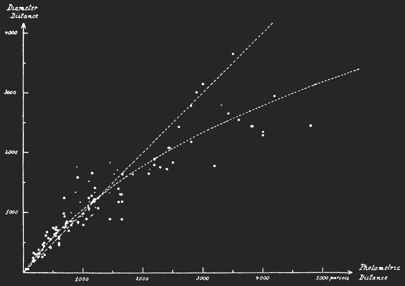
1930 – First evidence of interstellar dust

1922: Russell (1922) noted the reddening of starlight ⇒ produced mainly by dust particles of $\simeq 0.03 - 0.1\ \mu$m in diameter.

1930: Trumpler (1930) studied 100 open clusters ⇒ diameter distance < photometric distance

→ effect increases with distance

⇒ selective extinction by fine dust particles (larger than 2 nm).



1937 – Detection of the first interstellar molecule

1937: identification of a line of CH at $\lambda = 4300$ Å by Swings & Rosenfeld (1937).

1963: first detection of a molecular radio line (OH_{18cm}) by Weinreb et al. (1963).

1951 – Detection of interstellar atomic Hydrogen

1945: prediction of the $[\mathrm{H\,I}]_{21\,\mathrm{cm}}$ line by van de Hulst (1945).

1951: detection of the $[\mathrm{H\,I}]_{21\,\mathrm{cm}}$ line by Ewen & Purcell (1951).

Solid-state physics

Solid-state physics

After World War II: strong impulse $\rightarrow$ prospective development of electronics (Martin, 2013).

Solid-state physics

After World War II: strong impulse $\rightarrow$ prospective development of electronics (Martin, 2013).

1947: invention of the transistor, at Bell laboratories in New Jersey.

Solid-state physics

After World War II: strong impulse → prospective development of electronics (Martin, 2013).

1947: invention of the transistor, at Bell laboratories in New Jersey.

The introduction of computers

Solid-state physics

After World War II: strong impulse → prospective development of electronics (Martin, 2013).

1947: invention of the transistor, at Bell laboratories in New Jersey.

The introduction of computers

1937: principle of the computer laid out by Alan TURING (Turing, 1937).

Solid-state physics

After World War II: strong impulse → prospective development of electronics (Martin, 2013).

1947: invention of the transistor, at Bell laboratories in New Jersey.

The introduction of computers

1937: principle of the computer laid out by Alan TURING (Turing, 1937).

World War II: first computers developed to break the German encryption codes (*e.g.* McGrayne 2011).

Solid-state physics

After World War II: strong impulse → prospective development of electronics (Martin, 2013).

1947: invention of the transistor, at Bell laboratories in New Jersey.

The introduction of computers

1937: principle of the computer laid out by Alan TURING (Turing, 1937).

World War II: first computers developed to break the German encryption codes (*e.g.* McGrayne 2011).

1950s: first numerical models of stellar structures.

Solid-state physics

After World War II: strong impulse → prospective development of electronics (Martin, 2013).

1947: invention of the transistor, at Bell laboratories in New Jersey.

The introduction of computers

1937: principle of the computer laid out by Alan TURING (Turing, 1937).

World War II: first computers developed to break the German encryption codes (*e.g.* McGrayne 2011).

1950s: first numerical models of stellar structures.

1970: first dust radiative transfer numerical computations, using iterative methods (Mathis, 1970) & Monte-Carlo methods (Mattila, 1970).

Solid-state physics

After World War II: strong impulse → prospective development of electronics (Martin, 2013).

1947: invention of the transistor, at Bell laboratories in New Jersey.

The introduction of computers

1937: principle of the computer laid out by Alan TURING (Turing, 1937).

World War II: first computers developed to break the German encryption codes (*e.g.* McGrayne 2011).

1950s: first numerical models of stellar structures.

1970: first dust radiative transfer numerical computations, using iterative methods (Mathis, 1970) & Monte-Carlo methods (Mattila, 1970).

The development of modern detectors

Solid-state physics

After World War II: strong impulse → prospective development of electronics (Martin, 2013).

1947: invention of the transistor, at Bell laboratories in New Jersey.

The introduction of computers

1937: principle of the computer laid out by Alan TURING (Turing, 1937).

World War II: first computers developed to break the German encryption codes (*e.g.* McGrayne 2011).

1950s: first numerical models of stellar structures.

1970: first dust radiative transfer numerical computations, using iterative methods (Mathis, 1970) & Monte-Carlo methods (Mattila, 1970).

The development of modern detectors

They solved the issues of photography: *(i)* non-linear response; *(ii)* restricted dynamic range; *(iii)* low detection efficiency; *(iv)* reciprocity failure; and *(v)* adjacency effects (Boksenberg, 1982).

Solid-state physics

After World War II: strong impulse → prospective development of electronics (Martin, 2013).

1947: invention of the transistor, at Bell laboratories in New Jersey.

The introduction of computers

1937: principle of the computer laid out by Alan TURING (Turing, 1937).

World War II: first computers developed to break the German encryption codes (*e.g.* McGrayne 2011).

1950s: first numerical models of stellar structures.

1970: first dust radiative transfer numerical computations, using iterative methods (Mathis, 1970) & Monte-Carlo methods (Mattila, 1970).

The development of modern detectors

They solved the issues of photography: *(i)* non-linear response; *(ii)* restricted dynamic range; *(iii)* low detection efficiency; *(iv)* reciprocity failure; and *(v)* adjacency effects (Boksenberg, 1982).

1930s: first IR photomultipliers & bolometers → important military applications: night vision & guiding rockets (Rogalski, 2012).

Solid-state physics

After World War II: strong impulse → prospective development of electronics (Martin, 2013).

1947: invention of the transistor, at Bell laboratories in New Jersey.

The introduction of computers

1937: principle of the computer laid out by Alan TURING (Turing, 1937).

World War II: first computers developed to break the German encryption codes (*e.g.* McGrayne 2011).

1950s: first numerical models of stellar structures.

1970: first dust radiative transfer numerical computations, using iterative methods (Mathis, 1970) & Monte-Carlo methods (Mattila, 1970).

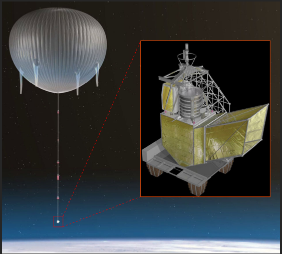
The development of modern detectors

They solved the issues of photography: *(i)* non-linear response; *(ii)* restricted dynamic range; *(iii)* low detection efficiency; *(iv)* reciprocity failure; and *(v)* adjacency effects (Boksenberg, 1982).

1930s: first IR photomultipliers & bolometers → important military applications: night vision & guiding rockets (Rogalski, 2012).

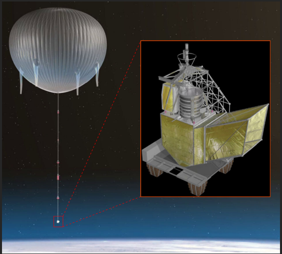
1969: first *Charge-Coupled Device* (CCD) invented at Bell laboratories (Amelio et al., 1970).

Balloons & rockets



Credit: PILOT (Bernard et al., 2016).

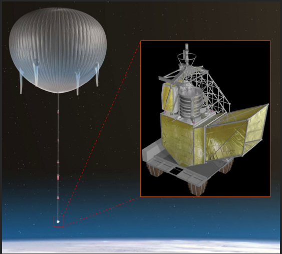
Balloons & rockets



Credit: PILOT (Bernard et al., 2016).

1. Stratospheric balloons can reach altitudes of $\simeq 40$ km, above most water vapor absorption.

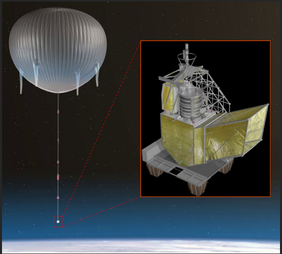
Balloons & rockets



Credit: PILOT (Bernard et al., 2016).

1. Stratospheric balloons can reach altitudes of $\simeq$ 40 km, above most water vapor absorption.
2. observe for several days continuously, but landing is hazardous $\longrightarrow$ only a few flights during their lifetime.

Balloons & rockets

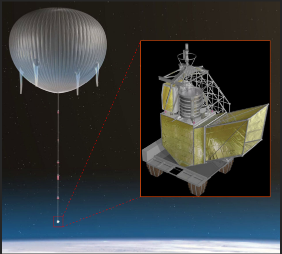


Credit: PILOT (Bernard et al., 2016).

1. Stratospheric balloons can reach altitudes of $\simeq$ 40 km, above most water vapor absorption.
2. observe for several days continuously, but landing is hazardous $\rightarrow$ only a few flights during their lifetime.

1959: first IR balloon launched from Johns Hopkins.

Balloons & rockets



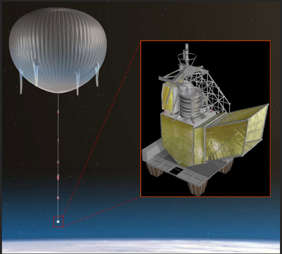
Credit: PILOT (Bernard et al., 2016).

1. Stratospheric balloons can reach altitudes of $\simeq 40$ km, above most water vapor absorption.
2. observe for several days continuously, but landing is hazardous $\rightarrow$ only a few flights during their lifetime.

1959: first IR balloon launched from Johns Hopkins.

1966: a balloon sent by the Goddard Institute mapped the sky at $\lambda = 100\ \mu$m (Walker, 2000).

Balloons & rockets



Credit: PILOT (Bernard et al., 2016).

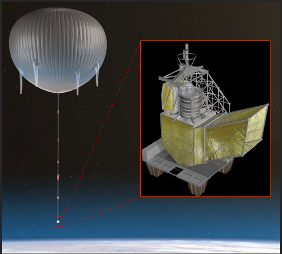
1. Stratospheric balloons can reach altitudes of $\simeq$ 40 km, above most water vapor absorption.
2. observe for several days continuously, but landing is hazardous $\rightarrow$ only a few flights during their lifetime.

1959: first IR balloon launched from Johns Hopkins.

1966: a balloon sent by the Goddard Institute mapped the sky at $\lambda = 100\ \mu$m (Walker, 2000).

Airborne observatories

Balloons & rockets



Credit: PILOT (Bernard et al., 2016).

1. Stratospheric balloons can reach altitudes of $\simeq 40$ km, above most water vapor absorption.
2. observe for several days continuously, but landing is hazardous $\rightarrow$ only a few flights during their lifetime.

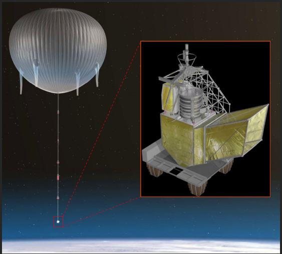
1959: first IR balloon launched from Johns Hopkins.

1966: a balloon sent by the Goddard Institute mapped the sky at $\lambda = 100\ \mu$m (Walker, 2000).

Airborne observatories

1. Airplanes can fly up to $\simeq 15$ km, operate during $\simeq 10$ hours.

Balloons & rockets



Credit: PILOT (Bernard et al., 2016).

1. Stratospheric balloons can reach altitudes of $\simeq 40$ km, above most water vapor absorption.
2. observe for several days continuously, but landing is hazardous $\rightarrow$ only a few flights during their lifetime.

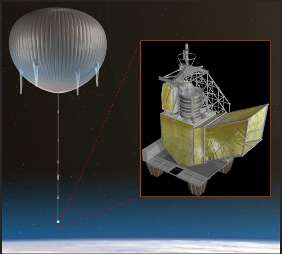
1959: first IR balloon launched from Johns Hopkins.

1966: a balloon sent by the Goddard Institute mapped the sky at $\lambda = 100\ \mu$m (Walker, 2000).

Airborne observatories

1. Airplanes can fly up to $\simeq 15$ km, operate during $\simeq 10$ hours.
2. perform numerous flights, but telescope motion must be perpendicular to the plane

Balloons & rockets



Credit: PILOT (Bernard et al., 2016).

1. Stratospheric balloons can reach altitudes of $\simeq 40$ km, above most water vapor absorption.
2. observe for several days continuously, but landing is hazardous $\rightarrow$ only a few flights during their lifetime.

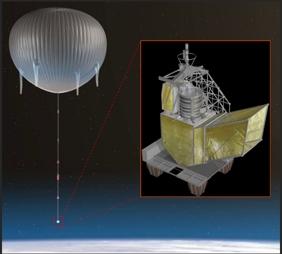
1959: first IR balloon launched from Johns Hopkins.

1966: a balloon sent by the Goddard Institute mapped the sky at $\lambda = 100\ \mu$m (Walker, 2000).

Airborne observatories

1. Airplanes can fly up to $\simeq 15$ km, operate during $\simeq 10$ hours.
2. perform numerous flights, but telescope motion must be perpendicular to the plane $\Rightarrow$ flight path has to be adapted.

Balloons & rockets



Credit: PILOT (Bernard et al., 2016).

1. Stratospheric balloons can reach altitudes of $\simeq 40$ km, above most water vapor absorption.
2. observe for several days continuously, but landing is hazardous $\rightarrow$ only a few flights during their lifetime.

1959: first IR balloon launched from Johns Hopkins.

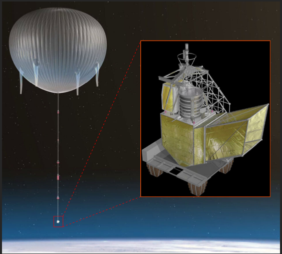
1966: a balloon sent by the Goddard Institute mapped the sky at $\lambda = 100\ \mu$m (Walker, 2000).

Airborne observatories

1. Airplanes can fly up to $\simeq 15$ km, operate during $\simeq 10$ hours.
2. perform numerous flights, but telescope motion must be perpendicular to the plane $\Rightarrow$ flight path has to be adapted.

1974–1995: the *Kuiper Airborne Observatory* (KAO; $\varnothing = 0.9$ m; Erickson & Meyer 2013).

Balloons & rockets



Credit: PILOT (Bernard et al., 2016).

1. Stratospheric balloons can reach altitudes of $\simeq$ 40 km, above most water vapor absorption.
2. observe for several days continuously, but landing is hazardous $\rightarrow$ only a few flights during their lifetime.

1959: first IR balloon launched from Johns Hopkins.

1966: a balloon sent by the Goddard Institute mapped the sky at $\lambda = 100\ \mu$m (Walker, 2000).

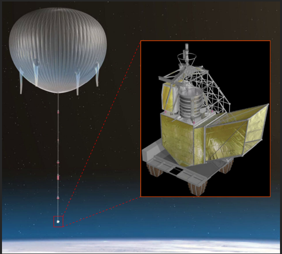
Airborne observatories

1. Airplanes can fly up to $\simeq$ 15 km, operate during $\simeq$ 10 hours.
2. perform numerous flights, but telescope motion must be perpendicular to the plane $\Rightarrow$ flight path has to be adapted.

1974–1995: the *Kuiper Airborne Observatory* (KAO; $\varnothing = 0.9$ m; Erickson & Meyer 2013).

2010–2022: the *Stratospheric Observatory for Infrared Astronomy* (SOFIA; $\varnothing = 2.5$ m; Young et al. 2012).

Balloons & rockets



Credit: PILOT (Bernard et al., 2016).

1. Stratospheric balloons can reach altitudes of $\simeq 40$ km, above most water vapor absorption.
2. observe for several days continuously, but landing is hazardous $\rightarrow$ only a few flights during their lifetime.

1959: first IR balloon launched from Johns Hopkins.

1966: a balloon sent by the Goddard Institute mapped the sky at $\lambda = 100\ \mu$m (Walker, 2000).

Airborne observatories

1. Airplanes can fly up to $\simeq 15$ km, operate during $\simeq 10$ hours.
2. perform numerous flights, but telescope motion must be perpendicular to the plane $\Rightarrow$ flight path has to be adapted.

1974–1995: the *Kuiper Airborne Observatory* (KAO; $\varnothing = 0.9$ m; Erickson & Meyer 2013).

2010–2022: the *Stratospheric Observatory for Infrared Astronomy* (SOFIA; $\varnothing = 2.5$ m; Young et al. 2012).

Credit: SOFIA; NASA.

1983 – The *InfraRed Astronomical Satellite* (IRAS; $\varnothing = 0.57$ m; Neugebauer et al. 1984)

1983 – The *InfraRed Astronomical Satellite* (IRAS; $\varnothing = 0.57$ m; Neugebauer et al. 1984)

- First IR observatory to perform an all-sky survey, at $\lambda = 12$, 25, 60 and 100 μm (angular resolution $\simeq 0.5' - 2'$).

1983 – The *InfraRed Astronomical Satellite* (IRAS; $\varnothing = 0.57$ m; Neugebauer et al. 1984)

- First IR observatory to perform an all-sky survey, at $\lambda = 12$, 25, 60 and 100 μm (angular resolution $\simeq 0.5' - 2'$).
- Discovered more than 300 000 point sources $\rightarrow$ many were the unexpected starburst galaxies (Soifer et al., 1987).

1983 – The *InfraRed Astronomical Satellite* (IRAS; $\varnothing = 0.57$ m; Neugebauer et al. 1984)

- First IR observatory to perform an all-sky survey, at $\lambda = 12$, 25, 60 and 100 μm (angular resolution $\simeq 0.5' - 2'$).
- Discovered more than 300 000 point sources → many were the unexpected starburst galaxies (Soifer et al., 1987). New categories: *Luminous InfraRed Galaxies* (LIRG; $10^{11}\ L_\odot < L_{\rm IR} < 10^{12}\ L_\odot$) and *UltraLuminous InfraRed Galaxies* (ULIRG; $L_{\rm IR} > 10^{12}\ L_\odot$).

1983 – The *InfraRed Astronomical Satellite* (IRAS; $\varnothing = 0.57$ m; Neugebauer et al. 1984)

- First IR observatory to perform an all-sky survey, at $\lambda = 12$, 25, 60 and 100 μm (angular resolution $\simeq 0.5' - 2'$).
- Discovered more than 300 000 point sources → many were the unexpected starburst galaxies (Soifer et al., 1987). New categories: *Luminous InfraRed Galaxies* (LIRG; $10^{11}\ L_\odot < L_{\rm IR} < 10^{12}\ L_\odot$) and *UltraLuminous InfraRed Galaxies* (ULIRG; $L_{\rm IR} > 10^{12}\ L_\odot$).
- Dusty disks around stars were also discovered (Beichman, 1987).

1983 – The *InfraRed Astronomical Satellite* (IRAS; $\varnothing = 0.57$ m; Neugebauer et al. 1984)

- First IR observatory to perform an all-sky survey, at $\lambda = 12$, 25, 60 and 100 μm (angular resolution $\simeq 0.5' - 2'$).
- Discovered more than 300 000 point sources → many were the unexpected starburst galaxies (Soifer et al., 1987). New categories: *Luminous InfraRed Galaxies* (LIRG; $10^{11}\ L_\odot < L_{\rm IR} < 10^{12}\ L_\odot$) and *UltraLuminous InfraRed Galaxies* (ULIRG; $L_{\rm IR} > 10^{12}\ L_\odot$).
- Dusty disks around stars were also discovered (Beichman, 1987).
- Access to cold grain emission ⇒ first reliable dust masses of galaxies & Galactic clouds.

1983 – The *InfraRed Astronomical Satellite* (IRAS; $\varnothing = 0.57$ m; Neugebauer et al. 1984)

- First IR observatory to perform an all-sky survey, at $\lambda = 12$, 25, 60 and 100 μm (angular resolution $\simeq 0.5' - 2'$).
- Discovered more than 300 000 point sources $\rightarrow$ many were the unexpected starburst galaxies (Soifer et al., 1987). New categories: *Luminous InfraRed Galaxies* (LIRG; $10^{11}\ L_\odot < L_{\rm IR} < 10^{12}\ L_\odot$) and *UltraLuminous InfraRed Galaxies* (ULIRG; $L_{\rm IR} > 10^{12}\ L_\odot$).
- Dusty disks around stars were also discovered (Beichman, 1987).
- Access to cold grain emission $\Rightarrow$ first reliable dust masses of galaxies & Galactic clouds.
- IRAS data shaped modern dust models (Désert et al., 1990) $\rightarrow$ still used nowadays.

1983 – The *InfraRed Astronomical Satellite* (IRAS; $\varnothing = 0.57$ m; Neugebauer et al. 1984)

- First IR observatory to perform an all-sky survey, at $\lambda = 12$, 25, 60 and 100 μm (angular resolution $\simeq 0.5' - 2'$).
- Discovered more than 300 000 point sources → many were the unexpected starburst galaxies (Soifer et al., 1987). New categories: *Luminous InfraRed Galaxies* (LIRG; $10^{11}\ L_\odot < L_{\rm IR} < 10^{12}\ L_\odot$) and *UltraLuminous InfraRed Galaxies* (ULIRG; $L_{\rm IR} > 10^{12}\ L_\odot$).
- Dusty disks around stars were also discovered (Beichman, 1987).
- Access to cold grain emission ⇒ first reliable dust masses of galaxies & Galactic clouds.
- IRAS data shaped modern dust models (Désert et al., 1990) → still used nowadays.

Prominent space observatories aimed at the ISM

1983 – The *InfraRed Astronomical Satellite* (IRAS; $\varnothing = 0.57$ m; Neugebauer et al. 1984)

- First IR observatory to perform an all-sky survey, at $\lambda = 12$, 25, 60 and 100 μm (angular resolution $\simeq 0.5' - 2'$).
- Discovered more than 300 000 point sources → many were the unexpected starburst galaxies (Soifer et al., 1987). New categories: *Luminous InfraRed Galaxies* (LIRG; $10^{11}\ L_\odot < L_{\rm IR} < 10^{12}\ L_\odot$) and *UltraLuminous InfraRed Galaxies* (ULIRG; $L_{\rm IR} > 10^{12}\ L_\odot$).
- Dusty disks around stars were also discovered (Beichman, 1987).
- Access to cold grain emission ⇒ first reliable dust masses of galaxies & Galactic clouds.
- IRAS data shaped modern dust models (Désert et al., 1990) → still used nowadays.

Prominent space observatories aimed at the ISM

In the IR: COBE (1989–1993; Boggess et al. 1992); ISO (1995–1998; Kessler et al. 1996); *Spitzer* (2003–2009; Werner et al. 2004); *Herschel* (2009–2013; Pilbratt et al. 2010); *Planck* (2009–2013; Tauber et al. 2010); the JWST (2021–; McElwain et al. 2020).

1983 – The *InfraRed Astronomical Satellite* (IRAS; $\varnothing = 0.57$ m; Neugebauer et al. 1984)

- First IR observatory to perform an all-sky survey, at $\lambda = 12$, 25, 60 and 100 μm (angular resolution $\simeq 0.5' - 2'$).
- Discovered more than 300 000 point sources $\rightarrow$ many were the unexpected starburst galaxies (Soifer et al., 1987). New categories: *Luminous InfraRed Galaxies* (LIRG; $10^{11}\ L_\odot < L_{\rm IR} < 10^{12}\ L_\odot$) and *UltraLuminous InfraRed Galaxies* (ULIRG; $L_{\rm IR} > 10^{12}\ L_\odot$).
- Dusty disks around stars were also discovered (Beichman, 1987).
- Access to cold grain emission $\Rightarrow$ first reliable dust masses of galaxies & Galactic clouds.
- IRAS data shaped modern dust models (Désert et al., 1990) $\rightarrow$ still used nowadays.

Prominent space observatories aimed at the ISM

In the IR: COBE (1989–1993; Boggess et al. 1992); ISO (1995–1998; Kessler et al. 1996); *Spitzer* (2003–2009; Werner et al. 2004); *Herschel* (2009–2013; Pilbratt et al. 2010); *Planck* (2009–2013; Tauber et al. 2010); the JWST (2021–; McElwain et al. 2020).

Credit: Launch of JWST; artist view; ESA.

1983 – The *InfraRed Astronomical Satellite* (IRAS; $\varnothing = 0.57$ m; Neugebauer et al. 1984)

- First IR observatory to perform an all-sky survey, at $\lambda = 12$, 25, 60 and 100 μm (angular resolution $\simeq 0.5' - 2'$).
- Discovered more than 300 000 point sources → many were the unexpected starburst galaxies (Soifer et al., 1987). New categories: *Luminous InfraRed Galaxies* (LIRG; 10^{11} $L_\odot < L_{\rm IR} < 10^{12}$ $L_\odot$) and *UltraLuminous InfraRed Galaxies* (ULIRG; $L_{\rm IR} > 10^{12}$ $L_\odot$).
- Dusty disks around stars were also discovered (Beichman, 1987).
- Access to cold grain emission ⇒ first reliable dust masses of galaxies & Galactic clouds.
- IRAS data shaped modern dust models (Désert et al., 1990) → still used nowadays.

Prominent space observatories aimed at the ISM

In the IR: COBE (1989–1993; Boggess et al. 1992); ISO (1995–1998; Kessler et al. 1996); *Spitzer* (2003–2009; Werner et al. 2004); *Herschel* (2009–2013; Pilbratt et al. 2010); *Planck* (2009–2013; Tauber et al. 2010); the JWST (2021–; McElwain et al. 2020).

In the UV: IUE (1978–1996; Boggess et al. 1978); HST (1990–; Burrows et al. 1991); FUSE (1999–2007; Moos et al. 2000).

Credit: Launch of JWST; artist view; ESA.

Observations – A panchromatic view of the ISM

Observations – A panchromatic view of the ISM

- The ISM of the Milky Way & nearby galaxies have been observed in all spectral windows.

Observations – A panchromatic view of the ISM

- The ISM of the Milky Way & nearby galaxies have been observed in all spectral windows.
- High angular resolution ($\simeq 1''$) in the visible, near- & mid-IR, & submm-to-cm regimes.

Observations – A panchromatic view of the ISM

- The ISM of the Milky Way & nearby galaxies have been observed in all spectral windows.
- High angular resolution ($\simeq 1''$) in the visible, near- & mid-IR, & submm-to-cm regimes.
- Detection of spectral features in the X-ray (Milky Way).

Observations – A panchromatic view of the ISM

- The ISM of the Milky Way & nearby galaxies have been observed in all spectral windows.
- High angular resolution ($\simeq 1''$) in the visible, near- & mid-IR, & submm-to-cm regimes.
- Detection of spectral features in the X-ray (Milky Way).
- Probing the ISM content with γ-rays.

Observations – A panchromatic view of the ISM

- The ISM of the Milky Way & nearby galaxies have been observed in all spectral windows.
- High angular resolution ($\simeq 1''$) in the visible, near- & mid-IR, & submm-to-cm regimes.
- Detection of spectral features in the X-ray (Milky Way).
- Probing the ISM content with γ-rays.

Simulations – Intensive computations with detailed microphysics

Observations – A panchromatic view of the ISM

- The ISM of the Milky Way & nearby galaxies have been observed in all spectral windows.
- High angular resolution ($\simeq 1''$) in the visible, near- & mid-IR, & submm-to-cm regimes.
- Detection of spectral features in the X-ray (Milky Way).
- Probing the ISM content with γ-rays.

Simulations – Intensive computations with detailed microphysics

- 3D simulations of the ISM down to A.U. scales, implementing: MHD, gravity, turbulence, realistic heating & cooling, & complex chemistry networks ($\simeq$ 1000s of reactions).

Observations – A panchromatic view of the ISM

- The ISM of the Milky Way & nearby galaxies have been observed in all spectral windows.
- High angular resolution ($\simeq 1''$) in the visible, near- & mid-IR, & submm-to-cm regimes.
- Detection of spectral features in the X-ray (Milky Way).
- Probing the ISM content with γ-rays.

Simulations – Intensive computations with detailed microphysics

- 3D simulations of the ISM down to A.U. scales, implementing: MHD, gravity, turbulence, realistic heating & cooling, & complex chemistry networks ($\simeq$ 1000s of reactions).
- 3D radiative transfer (lines & dust continuum) with high resolution $\Rightarrow$ produce realistic synthetic observables.

Observations – A panchromatic view of the ISM

- The ISM of the Milky Way & nearby galaxies have been observed in all spectral windows.
- High angular resolution ($\simeq 1''$) in the visible, near- & mid-IR, & submm-to-cm regimes.
- Detection of spectral features in the X-ray (Milky Way).
- Probing the ISM content with γ-rays.

Simulations – Intensive computations with detailed microphysics

- 3D simulations of the ISM down to A.U. scales, implementing: MHD, gravity, turbulence, realistic heating & cooling, & complex chemistry networks ($\simeq$ 1000s of reactions).
- 3D radiative transfer (lines & dust continuum) with high resolution $\Rightarrow$ produce realistic synthetic observables.

Laboratory experiments – Reproducing the conditions in the ISM

Observations – A panchromatic view of the ISM

- The ISM of the Milky Way & nearby galaxies have been observed in all spectral windows.
- High angular resolution ($\simeq 1''$) in the visible, near- & mid-IR, & submm-to-cm regimes.
- Detection of spectral features in the X-ray (Milky Way).
- Probing the ISM content with γ-rays.

Simulations – Intensive computations with detailed microphysics

- 3D simulations of the ISM down to A.U. scales, implementing: MHD, gravity, turbulence, realistic heating & cooling, & complex chemistry networks ($\simeq$ 1000s of reactions).
- 3D radiative transfer (lines & dust continuum) with high resolution $\Rightarrow$ produce realistic synthetic observables.

Laboratory experiments – Reproducing the conditions in the ISM

- Possibility to constrain microphysical properties in the lab (reaction rates, cross-sections, molecular lines, *etc.*).

Observations – A panchromatic view of the ISM

- The ISM of the Milky Way & nearby galaxies have been observed in all spectral windows.
- High angular resolution ($\simeq 1''$) in the visible, near- & mid-IR, & submm-to-cm regimes.
- Detection of spectral features in the X-ray (Milky Way).
- Probing the ISM content with γ-rays.

Simulations – Intensive computations with detailed microphysics

- 3D simulations of the ISM down to A.U. scales, implementing: MHD, gravity, turbulence, realistic heating & cooling, & complex chemistry networks ($\simeq$ 1000s of reactions).
- 3D radiative transfer (lines & dust continuum) with high resolution $\Rightarrow$ produce realistic synthetic observables.

Laboratory experiments – Reproducing the conditions in the ISM

- Possibility to constrain microphysical properties in the lab (reaction rates, cross-sections, molecular lines, *etc.*).
- Identification of complex molecules in the ISM: $\simeq$ 300 *Complex Organic Molecules* (COMs) & fullerenes.

Observations – A panchromatic view of the ISM

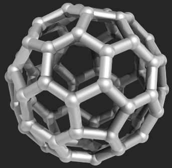
- The ISM of the Milky Way & nearby galaxies have been observed in all spectral windows.
- High angular resolution ($\simeq 1''$) in the visible, near- & mid-IR, & submm-to-cm regimes.
- Detection of spectral features in the X-ray (Milky Way).
- Probing the ISM content with γ-rays.

Simulations – Intensive computations with detailed microphysics

- 3D simulations of the ISM down to A.U. scales, implementing: MHD, gravity, turbulence, realistic heating & cooling, & complex chemistry networks ($\simeq$ 1000s of reactions).
- 3D radiative transfer (lines & dust continuum) with high resolution $\Rightarrow$ produce realistic synthetic observables.

Laboratory experiments – Reproducing the conditions in the ISM

- Possibility to constrain microphysical properties in the lab (reaction rates, cross-sections, molecular lines, *etc.*).
- Identification of complex molecules in the ISM: $\simeq$ 300 *Complex Organic Molecules* (COMs) & fullerenes.



Fullerene (C_{60}).

Observations – A panchromatic view of the ISM

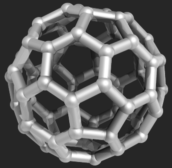
- The ISM of the Milky Way & nearby galaxies have been observed in all spectral windows.
- High angular resolution ($\simeq 1''$) in the visible, near- & mid-IR, & submm-to-cm regimes.
- Detection of spectral features in the X-ray (Milky Way).
- Probing the ISM content with γ-rays.

Simulations – Intensive computations with detailed microphysics

- 3D simulations of the ISM down to A.U. scales, implementing: MHD, gravity, turbulence, realistic heating & cooling, & complex chemistry networks ($\simeq$ 1000s of reactions).
- 3D radiative transfer (lines & dust continuum) with high resolution $\Rightarrow$ produce realistic synthetic observables.

Laboratory experiments – Reproducing the conditions in the ISM

- Possibility to constrain microphysical properties in the lab (reaction rates, cross-sections, molecular lines, *etc.*).
- Identification of complex molecules in the ISM: $\simeq$ 300 *Complex Organic Molecules* (COMs) & fullerenes.
- Analysis of returned samples (spacecraft or meteorites).



Fullerene (C_{60}).

History | Man-Made Artefacts in the ISM

Voyager 1 & 2

Voyager 1 & 2

1977: launch.

Voyager 1 & 2

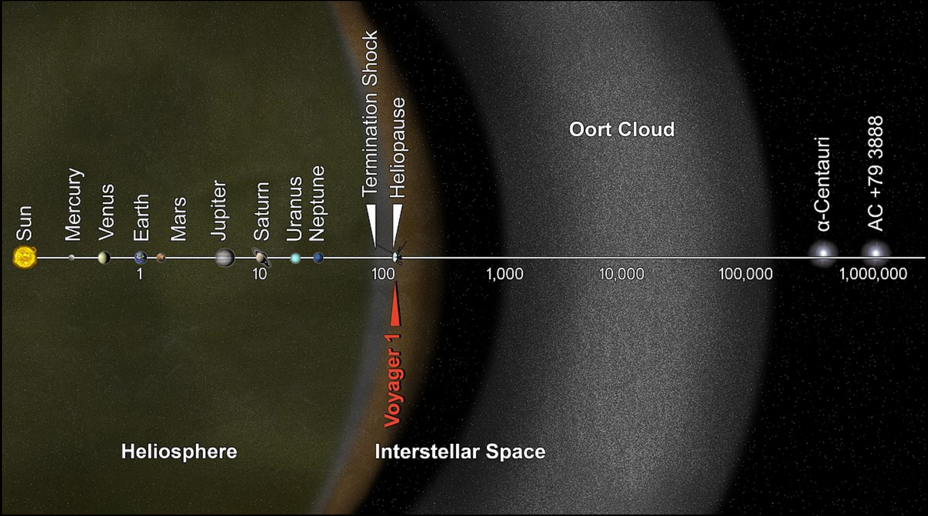
1977: launch.

2012: leaving heliosphere.

Voyager 1 & 2

1977: launch.

2012: leaving heliosphere.



Credit: artist concept, NASA / JPL – Caltech

Outline of the Lecture

How to collect information on the ISM?

How to collect information on the ISM?

We can not study the ISM *in situ* $\Rightarrow$ we need to rely on vectors of information.

How to collect information on the ISM?

We can not study the ISM *in situ* $\Rightarrow$ we need to rely on vectors of information.

Photons, observed first by eye, lately with detectors:

How to collect information on the ISM?

We can not study the ISM *in situ* $\Rightarrow$ we need to rely on vectors of information.

- **Photons,** observed first by eye, lately with detectors:
  - ***Visible,*** since Antiquity;

How to collect information on the ISM?

We can not study the ISM *in situ* $\Rightarrow$ we need to rely on vectors of information.

Photons, observed first by eye, lately with detectors:

- ***Visible,*** since Antiquity;
- ***Infrared,*** since 1800;

How to collect information on the ISM?

We can not study the ISM *in situ* $\Rightarrow$ we need to rely on vectors of information.

Photons, observed first by eye, lately with detectors:

- ***Visible,*** since Antiquity;
- ***Infrared,*** since 1800;
- ***X-rays,*** since 1920;

How to collect information on the ISM?

We can not study the ISM *in situ* $\Rightarrow$ we need to rely on vectors of information.

Photons, observed first by eye, lately with detectors:

- ***Visible,*** since Antiquity;
- ***Infrared,*** since 1800;
- ***X-rays,*** since 1920;
- ***Radio,*** since 1933.

How to collect information on the ISM?

We can not study the ISM *in situ* $\Rightarrow$ we need to rely on vectors of information.

Photons, observed first by eye, lately with detectors:

- ***Visible,*** since Antiquity;
- ***Infrared,*** since 1800;
- ***X-rays,*** since 1920;
- ***Radio,*** since 1933.

Cosmic rays: energetic particles (*i.e.* relativistic protons & nuclei), since 1912.

How to collect information on the ISM?

We can not study the ISM *in situ* ⇒ we need to rely on vectors of information.

Photons, observed first by eye, lately with detectors:

- ***Visible,*** since Antiquity;
- ***Infrared,*** since 1800;
- ***X-rays,*** since 1920;
- ***Radio,*** since 1933.

Cosmic rays: energetic particles (*i.e.* relativistic protons & nuclei), since 1912.

Neutrinos, since 1967, from the Sun & supernovae

How to collect information on the ISM?

We can not study the ISM *in situ* $\Rightarrow$ we need to rely on vectors of information.

Photons, observed first by eye, lately with detectors:

- ***Visible,*** since Antiquity;
- ***Infrared,*** since 1800;
- ***X-rays,*** since 1920;
- ***Radio,*** since 1933.

Cosmic rays: energetic particles (*i.e.* relativistic protons & nuclei), since 1912.

~~**Neutrinos:**~~ since 1967, from the Sun & supernovae $\rightarrow$ no relevant application for the ISM.

How to collect information on the ISM?

We can not study the ISM *in situ* ⇒ we need to rely on vectors of information.

Photons, observed first by eye, lately with detectors:

- ***Visible,*** since Antiquity;
- ***Infrared,*** since 1800;
- ***X-rays,*** since 1920;
- ***Radio,*** since 1933.

Cosmic rays: energetic particles (*i.e.* relativistic protons & nuclei), since 1912.

~~**Neutrinos:**~~ since 1967, from the Sun & supernovae → no relevant application for the ISM.

Interstellar grains, found in the Solar system:

How to collect information on the ISM?

We can not study the ISM *in situ* ⇒ we need to rely on vectors of information.

Photons, observed first by eye, lately with detectors:

- ***Visible,*** since Antiquity;
- ***Infrared,*** since 1800;
- ***X-rays,*** since 1920;
- ***Radio,*** since 1933.

Cosmic rays: energetic particles (*i.e.* relativistic protons & nuclei), since 1912.

~~**Neutrinos:**~~ since 1967, from the Sun & supernovae → no relevant application for the ISM.

Interstellar grains, found in the Solar system:

- ***Inclusion in meteorites,*** since 1987;

How to collect information on the ISM?

We can not study the ISM *in situ* ⇒ we need to rely on vectors of information.

Photons, observed first by eye, lately with detectors:

- ***Visible,*** since Antiquity;
- ***Infrared,*** since 1800;
- ***X-rays,*** since 1920;
- ***Radio,*** since 1933.

Cosmic rays: energetic particles (*i.e.* relativistic protons & nuclei), since 1912.

~~**Neutrinos:**~~ since 1967, from the Sun & supernovae → no relevant application for the ISM.

Interstellar grains, found in the Solar system:

- ***Inclusion in meteorites,*** since 1987;
- ***Collected in the Solar system,*** by spacecrafts, since 2003.

How to collect information on the ISM?

We can not study the ISM *in situ* $\Rightarrow$ we need to rely on vectors of information.

Photons, observed first by eye, lately with detectors:

- ***Visible,*** since Antiquity;
- ***Infrared,*** since 1800;
- ***X-rays,*** since 1920;
- ***Radio,*** since 1933.

Cosmic rays: energetic particles (*i.e.* relativistic protons & nuclei), since 1912.

~~**Neutrinos:**~~ since 1967, from the Sun & supernovae $\rightarrow$ no relevant application for the ISM.

Interstellar grains, found in the Solar system:

- ***Inclusion in meteorites,*** since 1987;
- ***Collected in the Solar system,*** by spacecrafts, since 2003.

Gravitational waves: space-time perturbations originating in cataclysmic events, detected since 2015

How to collect information on the ISM?

We can not study the ISM *in situ* ⇒ we need to rely on vectors of information.

Photons, observed first by eye, lately with detectors:

- ***Visible,*** since Antiquity;
- ***Infrared,*** since 1800;
- ***X-rays,*** since 1920;
- ***Radio,*** since 1933.

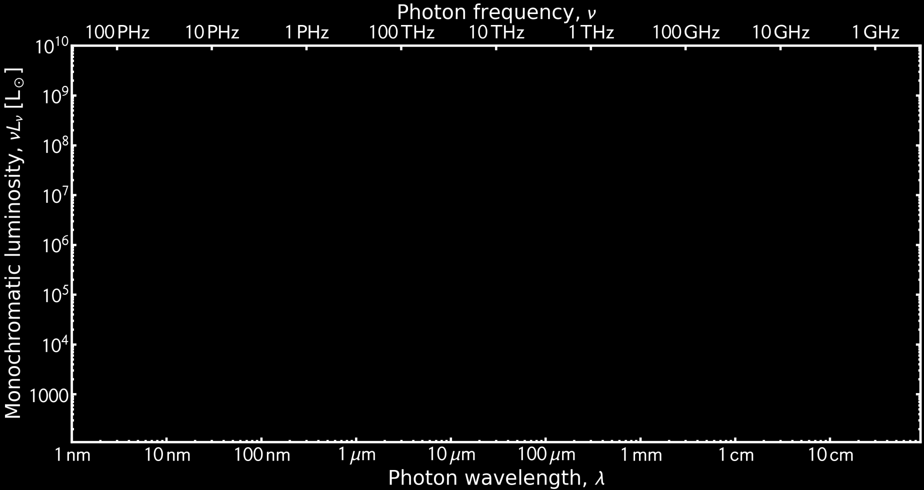
Cosmic rays: energetic particles (*i.e.* relativistic protons & nuclei), since 1912.

~~**Neutrinos:**~~ since 1967, from the Sun & supernovae → no relevant application for the ISM.

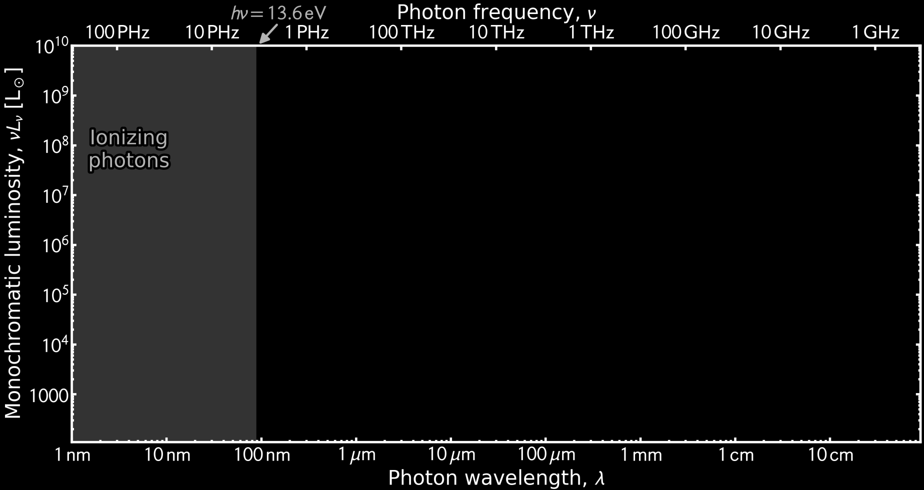
Interstellar grains, found in the Solar system:

- ***Inclusion in meteorites,*** since 1987;
- ***Collected in the Solar system,*** by spacecrafts, since 2003.

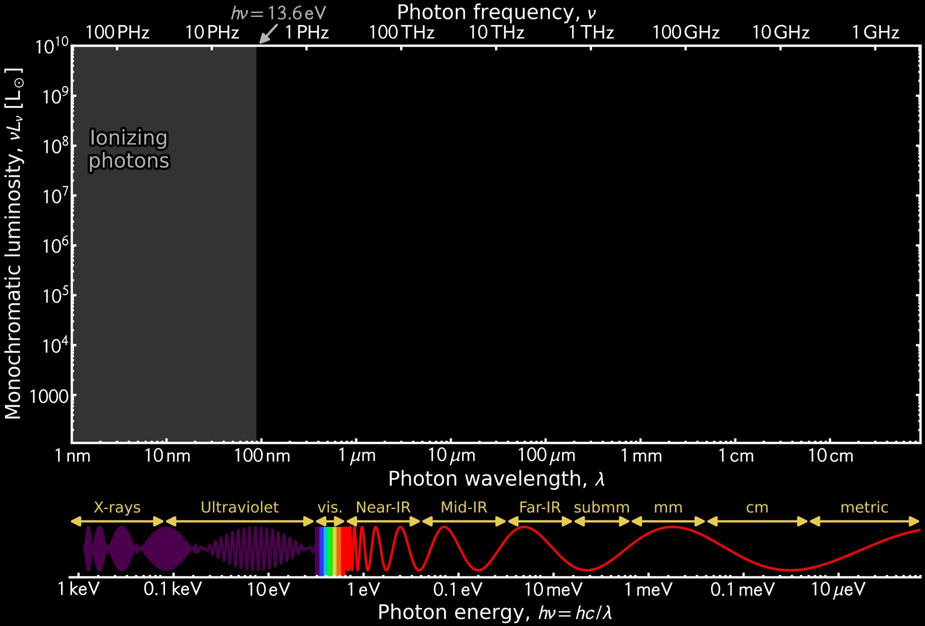
~~**Gravitational waves:**~~ space-time perturbations originating in cataclysmic events, detected since 2015 → no relevant application for the ISM.



Photon frequency, ν
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Monochromatic luminosity, νL_ν [$L_\odot$]
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
1000
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ

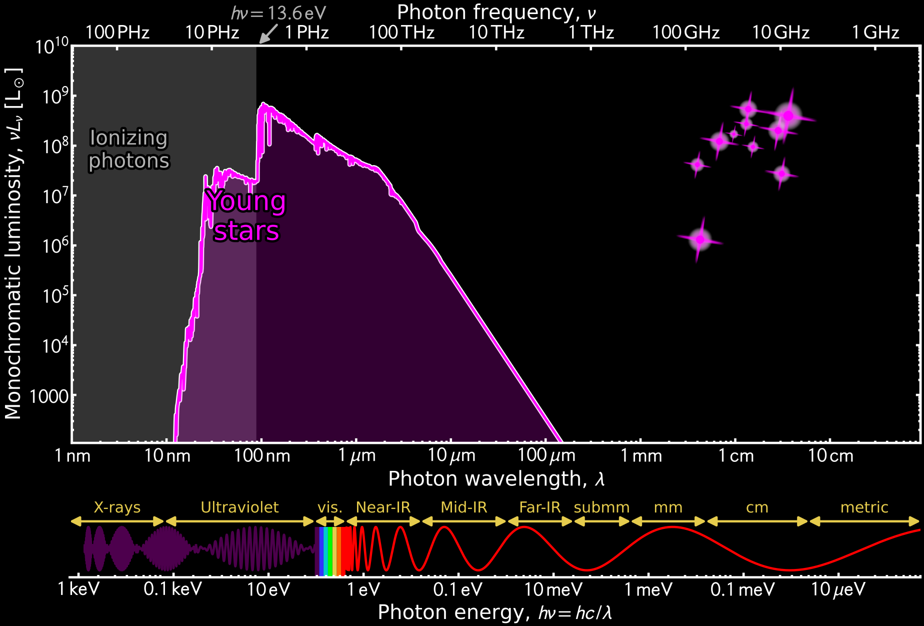


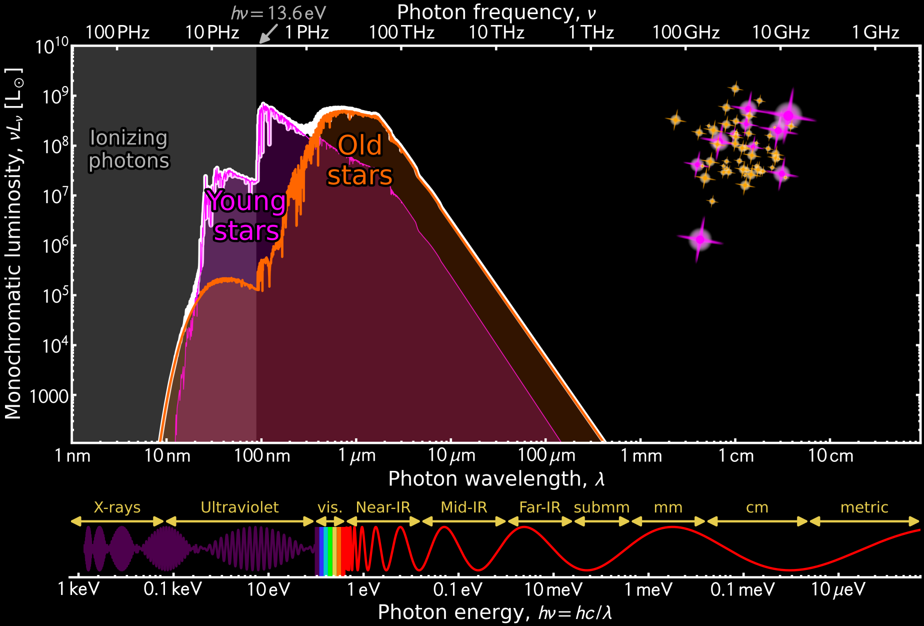
$h\nu = 13.6\,\text{eV}$
Photon frequency, ν
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
1000
Monochromatic luminosity, νL_ν [$L_\odot$]
Ionizing photons
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ



hν = 13.6 eV
Photon frequency, ν
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Monochromatic luminosity, νLν [L⊙]
10^10
10^9
10^8
10^7
10^6
10^5
10^4
1000
Ionizing photons
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ
X-rays
Ultraviolet
vis.
Near-IR
Mid-IR
Far-IR
submm
mm
cm
metric
1 keV
0.1 keV
10 eV
1 eV
0.1 eV
10 meV
1 meV
0.1 meV
10 μeV
Photon energy, hν = hc/λ

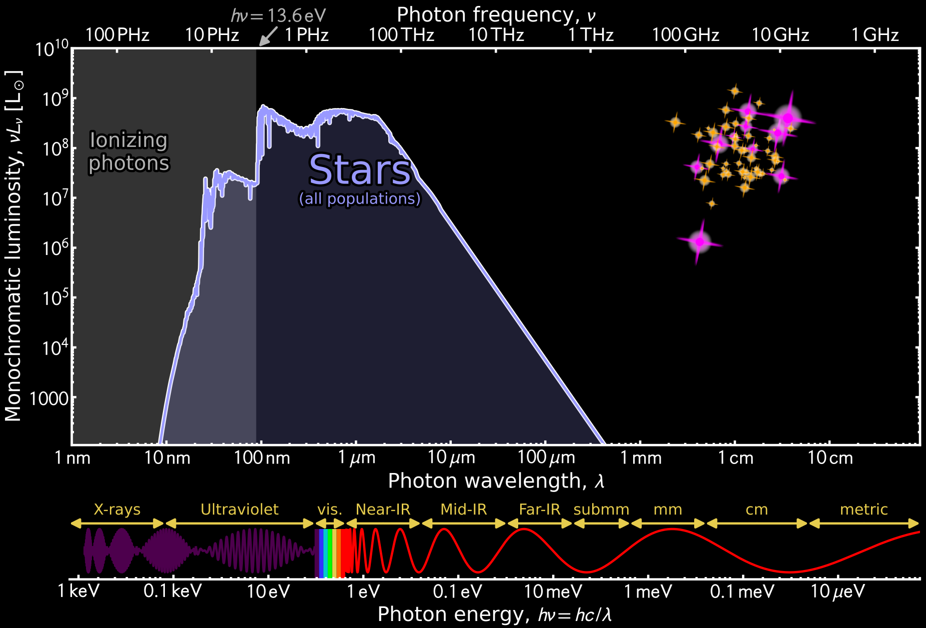
Methods | The Electromagnetic Spectrum of a Gas-Rich Galaxy

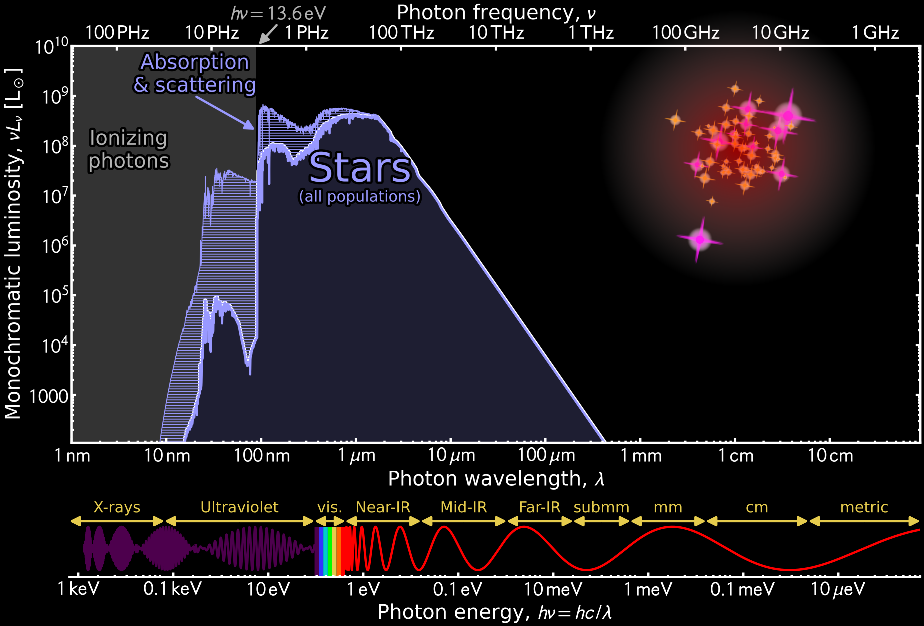




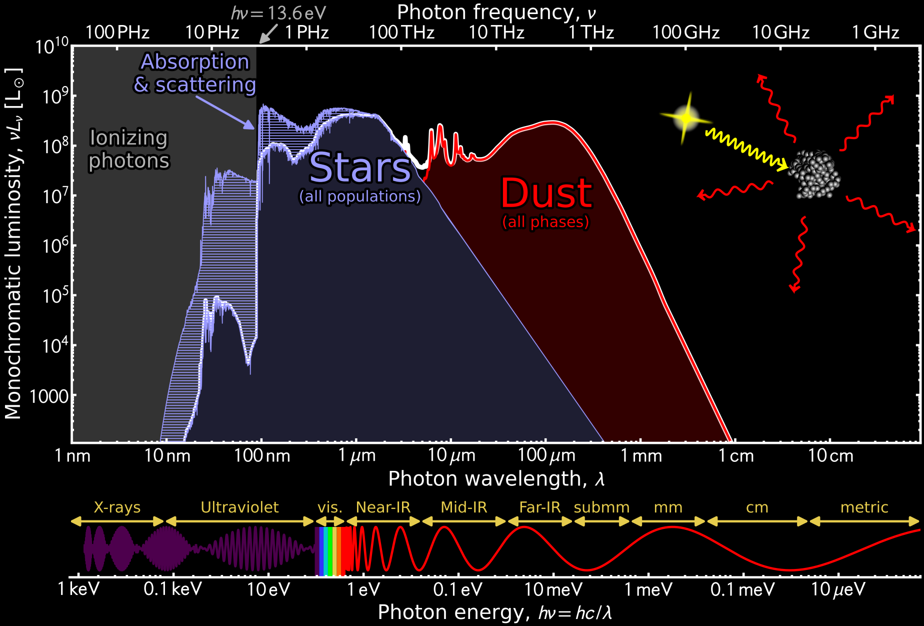
Photon frequency, ν
hν = 13.6 eV
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Monochromatic luminosity, νLν [L⊙]
10^10
10^9
10^8
10^7
10^6
10^5
10^4
1000
Ionizing photons
Young stars
Old stars
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ
X-rays
Ultraviolet
vis.
Near-IR
Mid-IR
Far-IR
submm
mm
cm
metric
1 keV
0.1 keV
10 eV
1 eV
0.1 eV
10 meV
1 meV
0.1 meV
10 μeV
Photon energy, hν = hc/λ

Methods | The Electromagnetic Spectrum of a Gas-Rich Galaxy

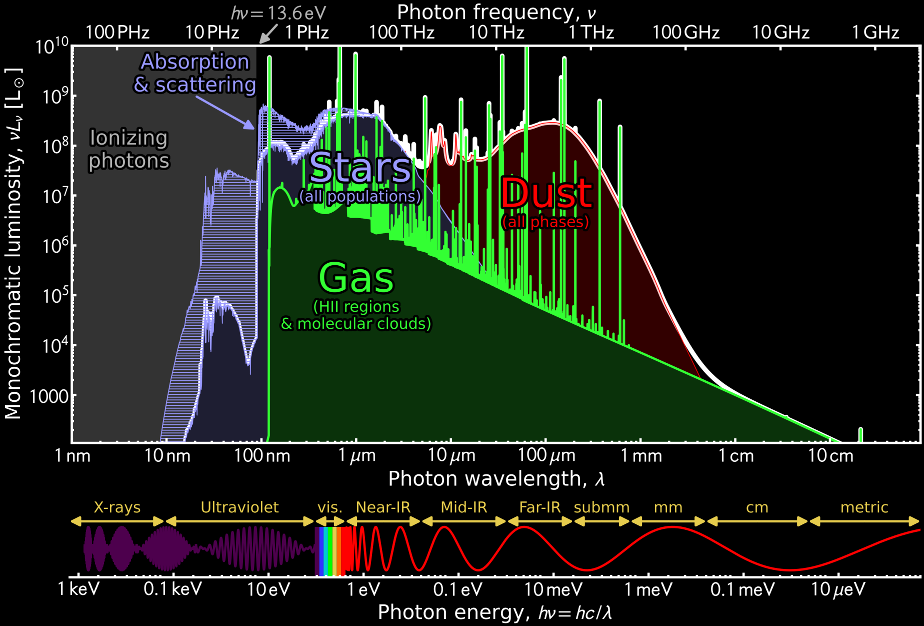


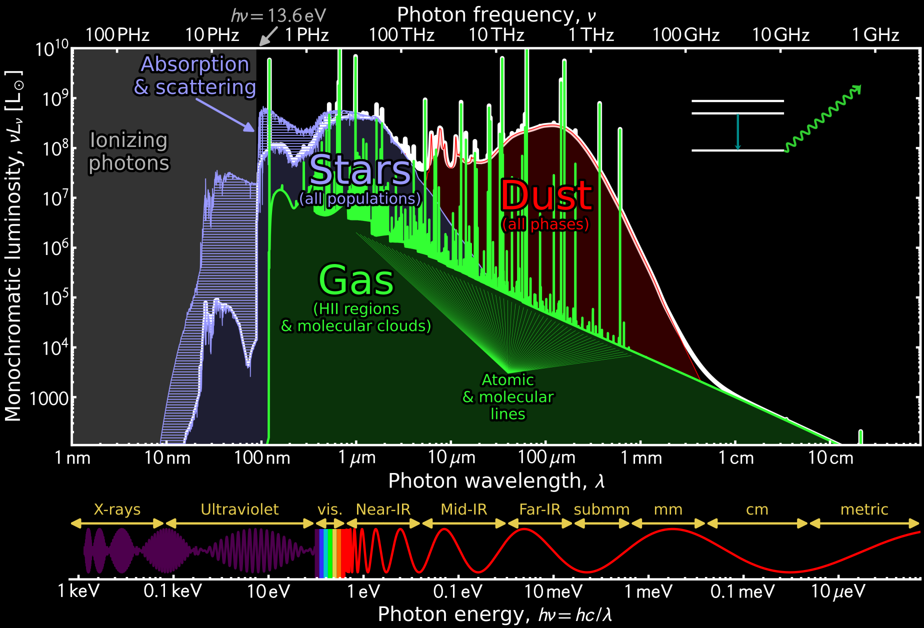


Photon frequency, ν
$h\nu = 13.6\,\mathrm{eV}$
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Monochromatic luminosity, νL_ν [$L_\odot$]
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
1000
Absorption
& scattering
Ionizing
photons
Stars
(all populations)
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ
X-rays
Ultraviolet
vis.
Near-IR
Mid-IR
Far-IR
submm
mm
cm
metric
1 keV
0.1 keV
10 eV
1 eV
0.1 eV
10 meV
1 meV
0.1 meV
10 μeV
Photon energy, $h\nu = hc/\lambda$

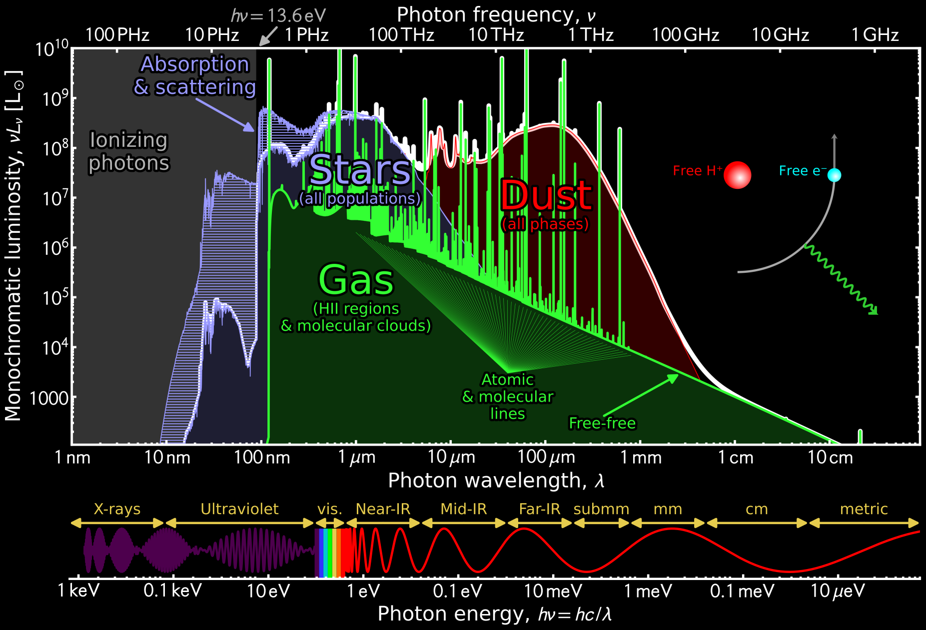


$h\nu = 13.6\,\text{eV}$
Photon frequency, ν
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
1000
Monochromatic luminosity, νL_ν [$L_\odot$]
Absorption & scattering
Ionizing photons
Stars
(all populations)
Dust
(all phases)
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ
X-rays
Ultraviolet
vis.
Near-IR
Mid-IR
Far-IR
submm
mm
cm
metric
1 keV
0.1 keV
10 eV
1 eV
0.1 eV
10 meV
1 meV
0.1 meV
10 μeV
Photon energy, $h\nu = hc/\lambda$

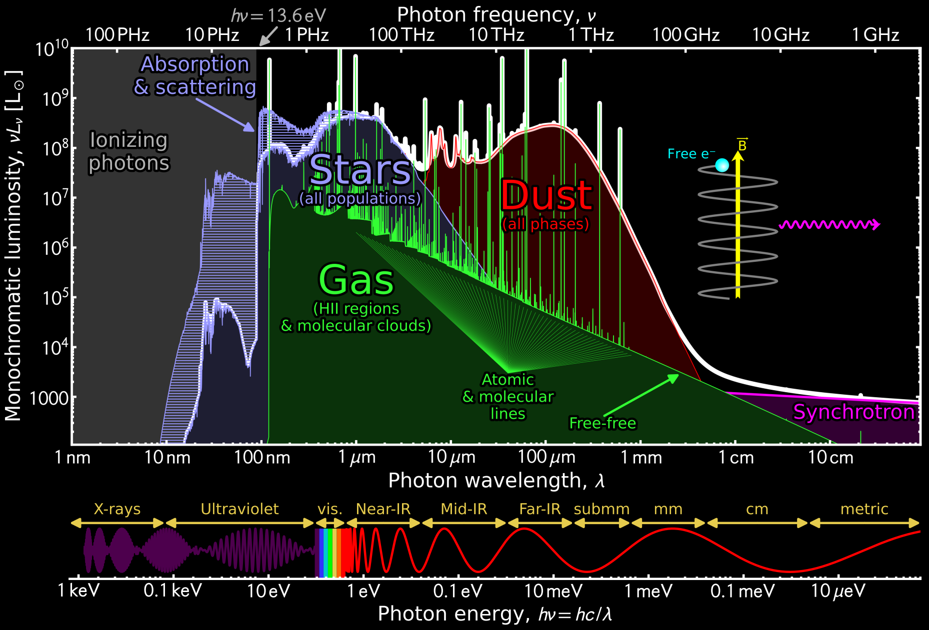

$h\nu = 13.6\,\mathrm{eV}$
Photon frequency, ν
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Monochromatic luminosity, νL_ν [$L_\odot$]
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
1000
Absorption
& scattering
Ionizing
photons
Stars
(all populations)
Dust
(all phases)
Gas
(HII regions
& molecular clouds)
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ
X-rays
Ultraviolet
vis.
Near-IR
Mid-IR
Far-IR
submm
mm
cm
metric
1 keV
0.1 keV
10 eV
1 eV
0.1 eV
10 meV
1 meV
0.1 meV
10 μeV
Photon energy, $h\nu = hc/\lambda$



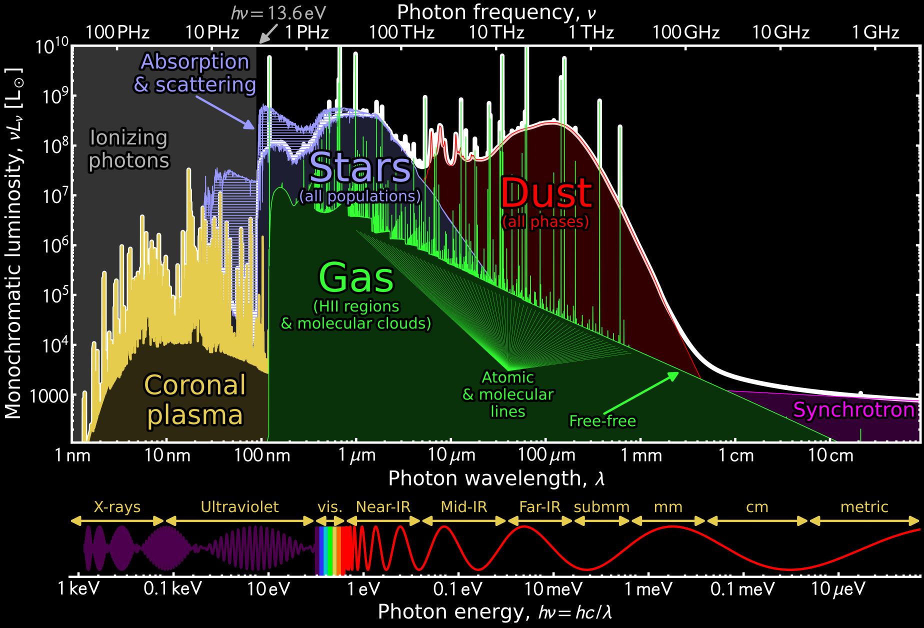
$h\nu = 13.6\,eV$
Photon frequency, ν
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Monochromatic luminosity, νL_ν [$L_\odot$]
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
1000
Absorption & scattering
Ionizing photons
Stars (all populations)
Dust (all phases)
Gas (HII regions & molecular clouds)
Atomic & molecular lines
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ
X-rays
Ultraviolet
vis.
Near-IR
Mid-IR
Far-IR
submm
mm
cm
metric
1 keV
0.1 keV
10 eV
1 eV
0.1 eV
10 meV
1 meV
0.1 meV
10 μeV
Photon energy, $h\nu = hc/\lambda$

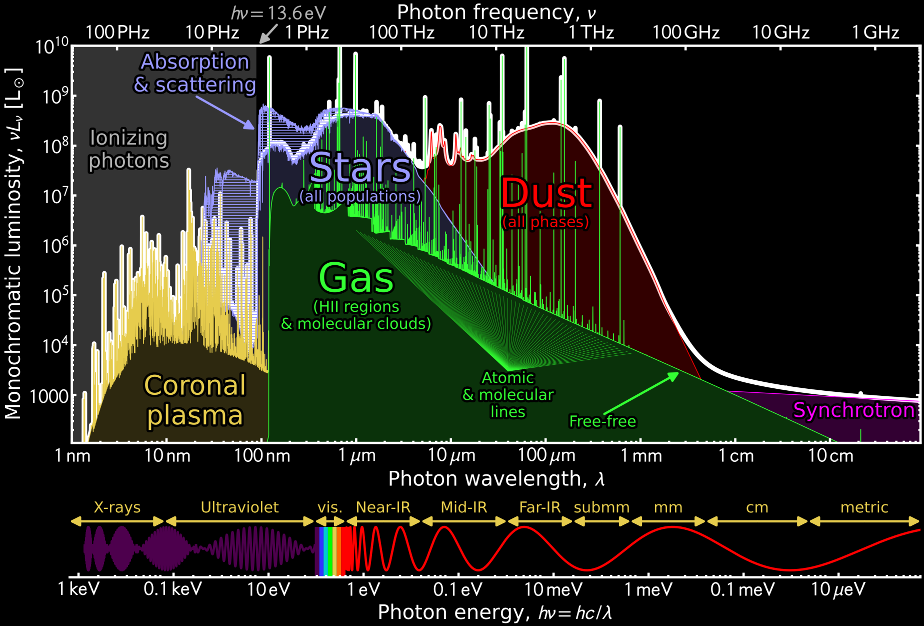

Photon frequency, ν
$h\nu = 13.6\,\mathrm{eV}$
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Monochromatic luminosity, νL_ν [$L_\odot$]
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
1000
Absorption & scattering
Ionizing photons
Stars (all populations)
Dust (all phases)
Gas (HII regions & molecular clouds)
Atomic & molecular lines
Free-free
Free H^+
Free e^-
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ
X-rays
Ultraviolet
vis.
Near-IR
Mid-IR
Far-IR
submm
mm
cm
metric
1 keV
0.1 keV
10 eV
1 eV
0.1 eV
10 meV
1 meV
0.1 meV
10 μeV
Photon energy, $h\nu = hc/\lambda$

Methods | The Electromagnetic Spectrum of a Gas-Rich Galaxy

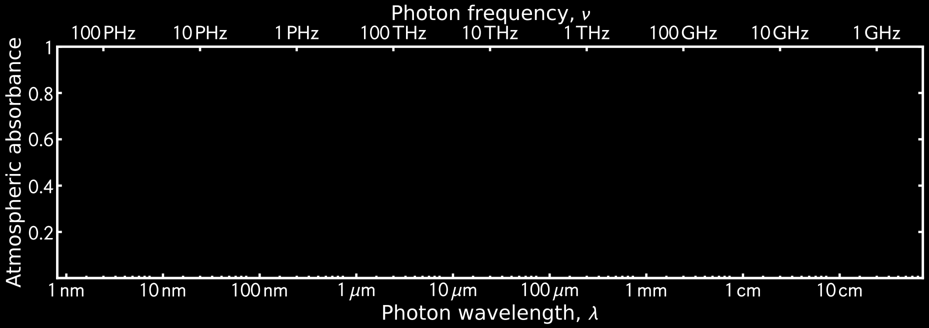


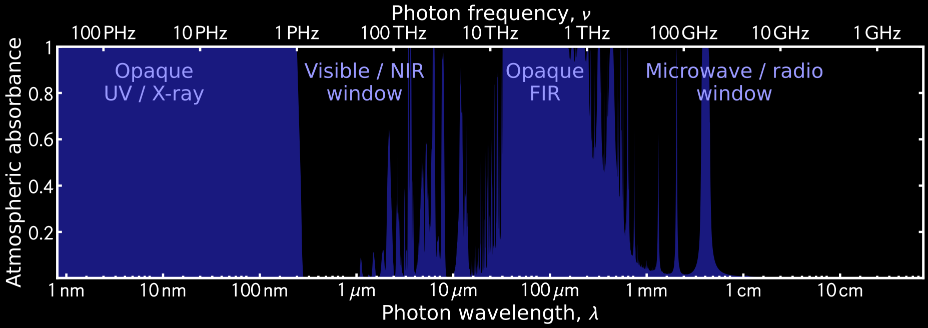
Methods | The Electromagnetic Spectrum of a Gas-Rich Galaxy

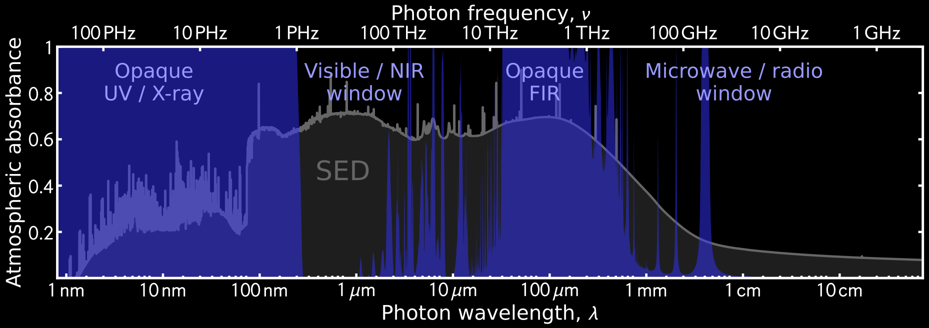




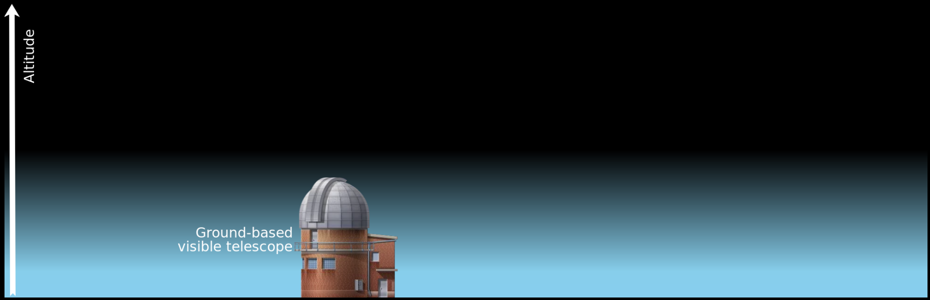
Photon frequency, ν
$h\nu = 13.6\,\mathrm{eV}$
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Monochromatic luminosity, νL_ν [$L_\odot$]
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
1000
Absorption & scattering
Ionizing photons
Stars (all populations)
Dust (all phases)
Gas (HII regions & molecular clouds)
Coronal plasma
Atomic & molecular lines
Free-free
Synchrotron
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ
X-rays
Ultraviolet
vis.
Near-IR
Mid-IR
Far-IR
submm
mm
cm
metric
1 keV
0.1 keV
10 eV
1 eV
0.1 eV
10 meV
1 meV
0.1 meV
10 μeV
Photon energy, $h\nu = hc/\lambda$

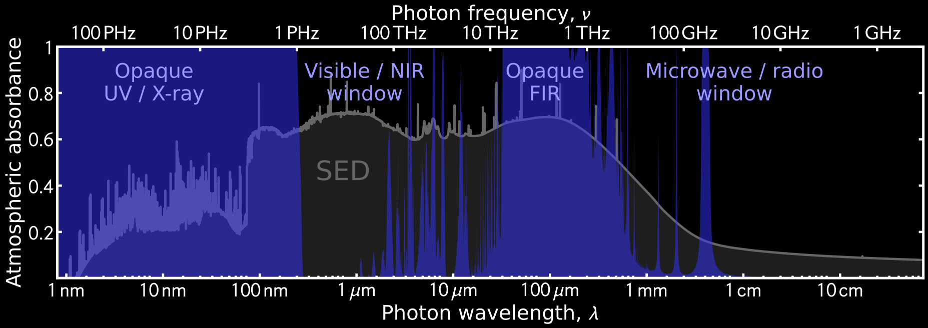

Photon frequency, ν
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Atmospheric absorbance
1
0.8
0.6
0.4
0.2
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ


Photon frequency, ν
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Atmospheric absorbance
1
0.8
0.6
0.4
0.2
Opaque
UV / X-ray
Visible / NIR
window
Opaque
FIR
Microwave / radio
window
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ

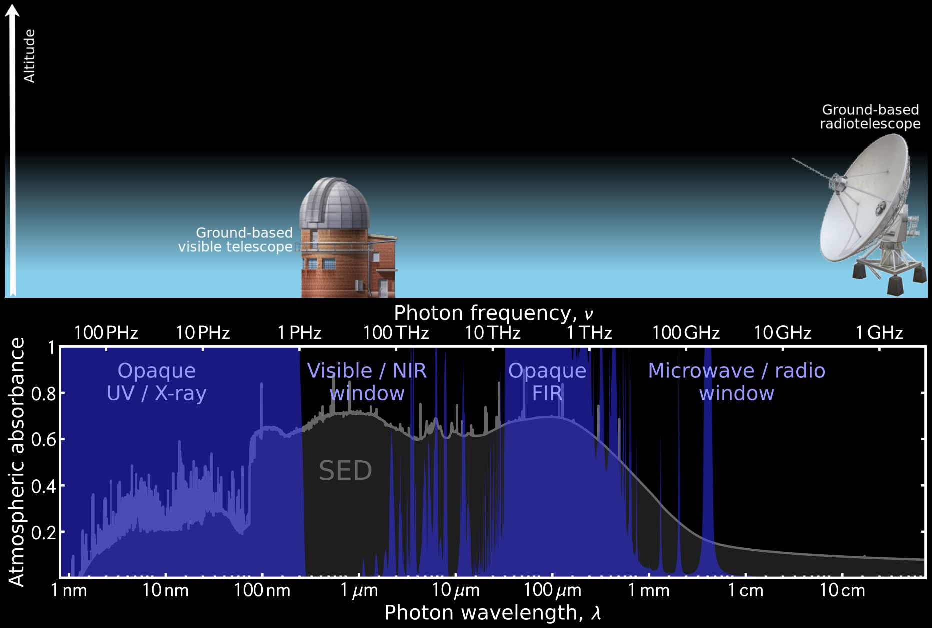

Photon frequency, ν
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Opaque
UV / X-ray
Visible / NIR
window
Opaque
FIR
Microwave / radio
window
SED
Atmospheric absorbance
1
0.8
0.6
0.4
0.2
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ

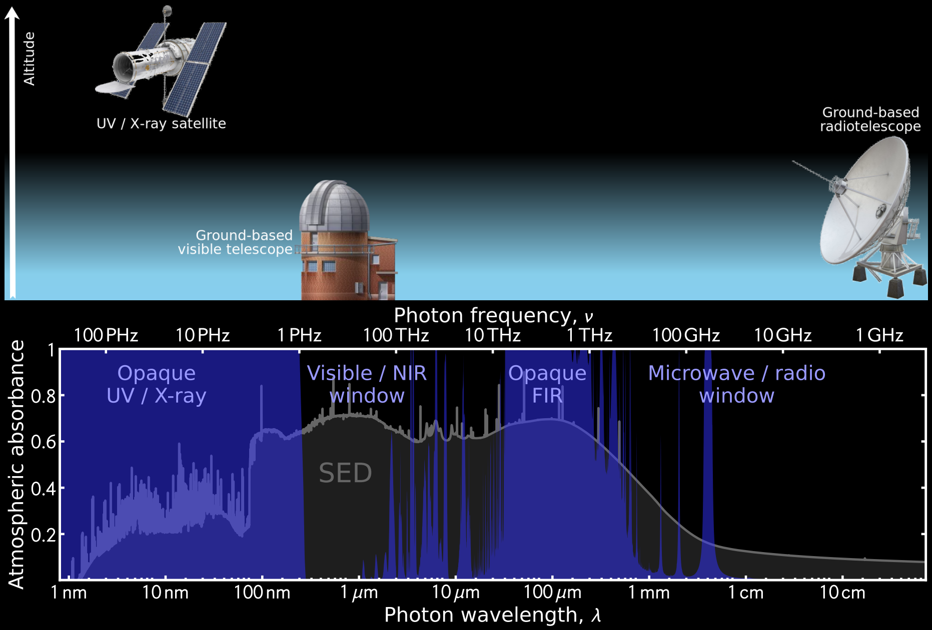
Methods | The Limitations due to the Atmosphere of Earth

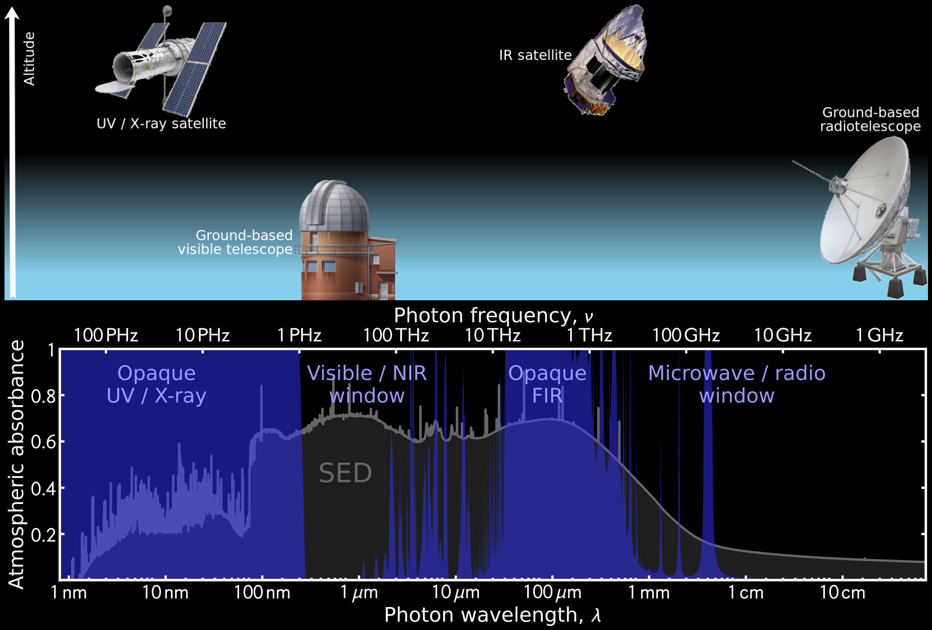




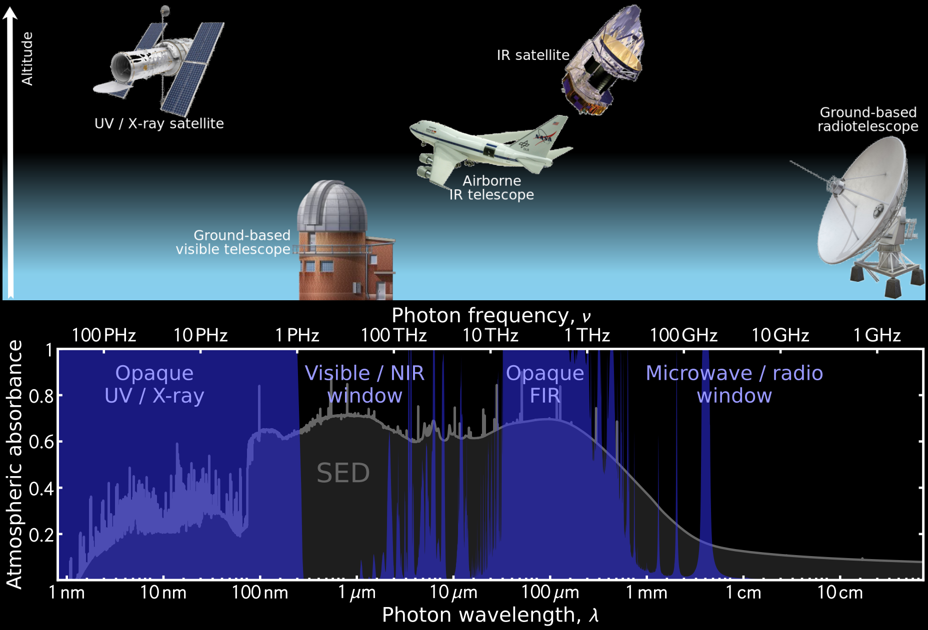
Methods | The Limitations due to the Atmosphere of Earth

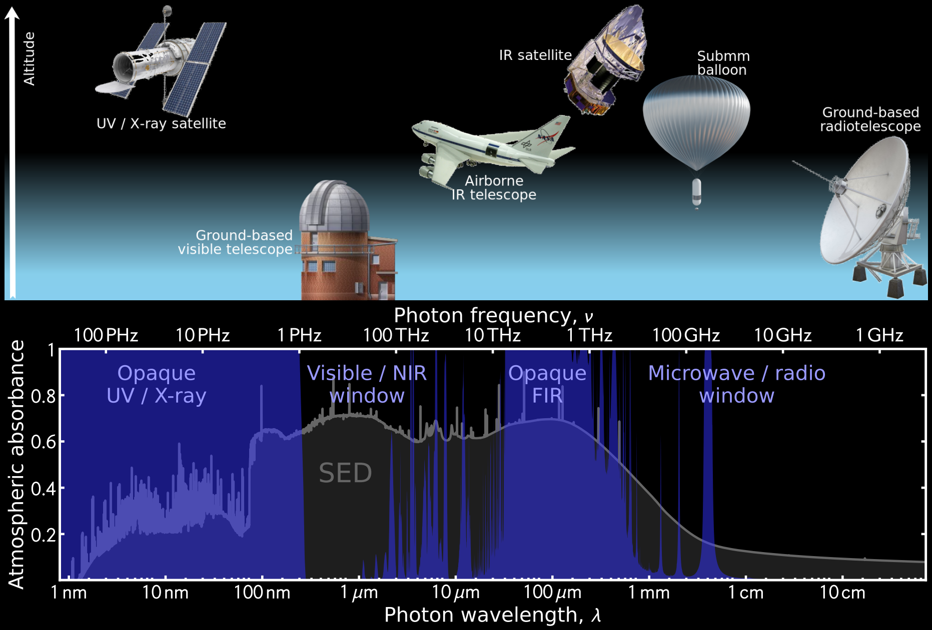


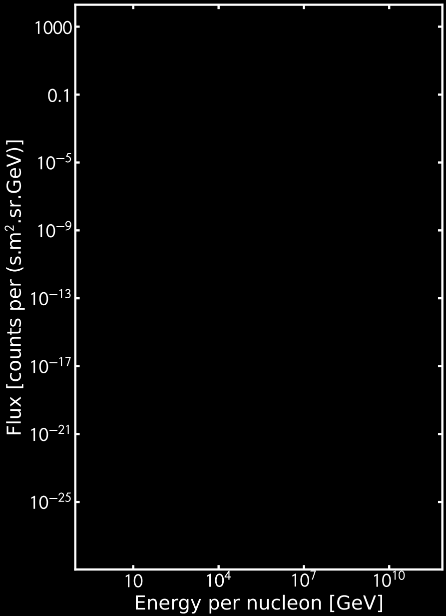

Altitude
UV / X-ray satellite
Ground-based radiotelescope
Ground-based visible telescope
Photon frequency, ν
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Atmospheric absorbance
Opaque UV / X-ray
Visible / NIR window
Opaque FIR
Microwave / radio window
SED
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ


Altitude
UV / X-ray satellite
IR satellite
Ground-based radiotelescope
Ground-based visible telescope
Photon frequency, ν
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Atmospheric absorbance
1
0.8
0.6
0.4
0.2
Opaque UV / X-ray
Visible / NIR window
Opaque FIR
Microwave / radio window
SED
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ

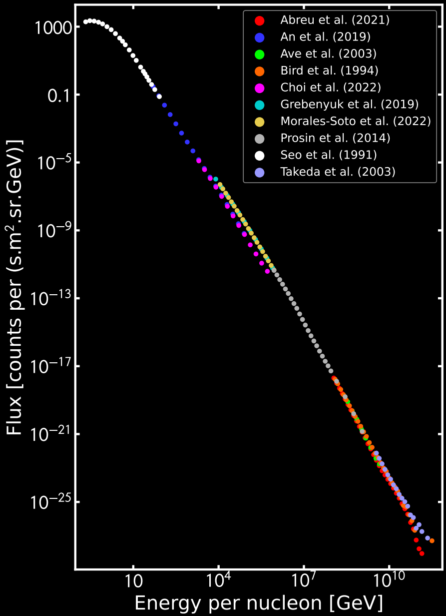
Methods | The Limitations due to the Atmosphere of Earth



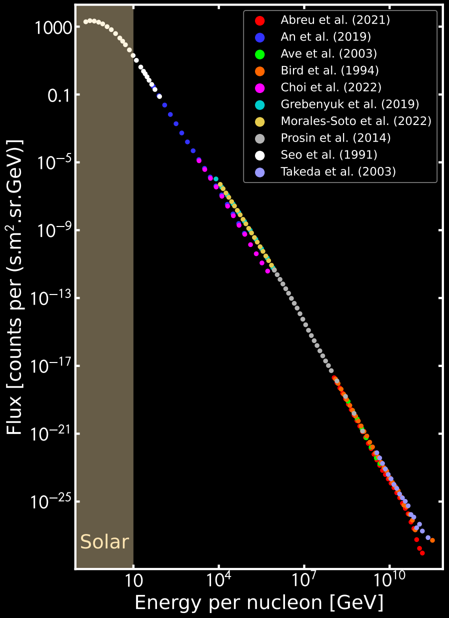

Altitude
UV / X-ray satellite
IR satellite
Submm balloon
Airborne IR telescope
Ground-based visible telescope
Ground-based radiotelescope
Photon frequency, ν
100 PHz
10 PHz
1 PHz
100 THz
10 THz
1 THz
100 GHz
10 GHz
1 GHz
Atmospheric absorbance
1
0.8
0.6
0.4
0.2
Opaque UV / X-ray
Visible / NIR window
Opaque FIR
Microwave / radio window
SED
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
Photon wavelength, λ



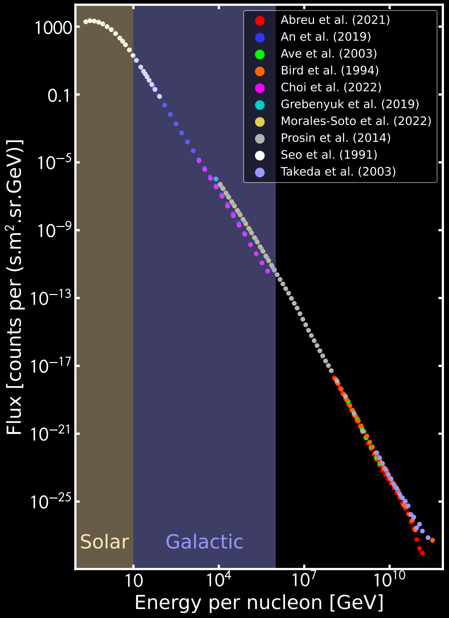
1000
0.1
10^{-5}
10^{-9}
10^{-13}
10^{-17}
10^{-21}
10^{-25}
Flux [counts per (s.m^2.sr.GeV)]
10
10^4
10^7
10^{10}
Energy per nucleon [GeV]

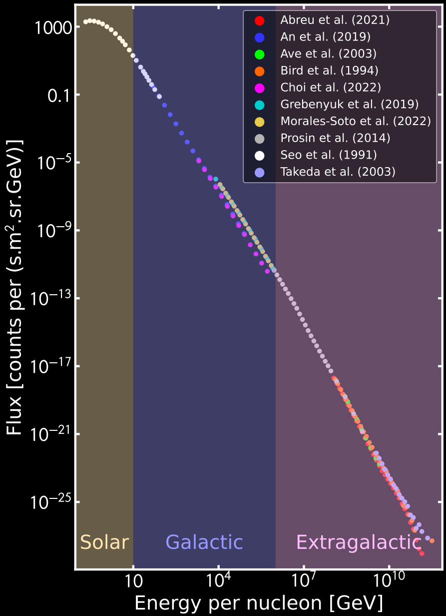


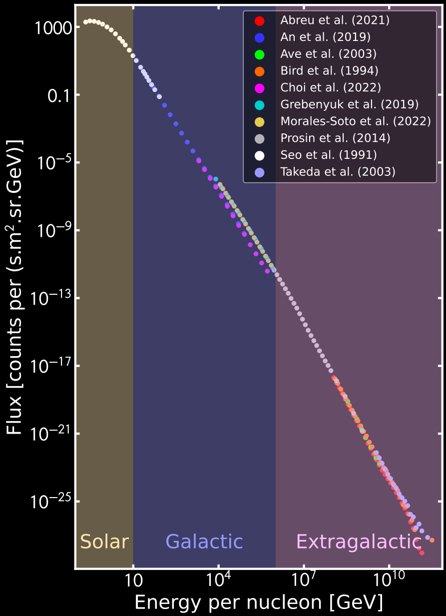
Abreu et al. (2021)
An et al. (2019)
Ave et al. (2003)
Bird et al. (1994)
Choi et al. (2022)
Grebenyuk et al. (2019)
Morales-Soto et al. (2022)
Prosin et al. (2014)
Seo et al. (1991)
Takeda et al. (2003)
1000
0.1
10^{-5}
10^{-9}
10^{-13}
10^{-17}
10^{-21}
10^{-25}
Flux [counts per (s.m^2.sr.GeV)]
10
10^4
10^7
10^{10}
Energy per nucleon [GeV]



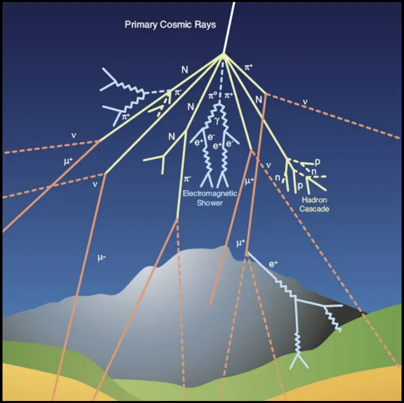
Abreu et al. (2021)
An et al. (2019)
Ave et al. (2003)
Bird et al. (1994)
Choi et al. (2022)
Grebenyuk et al. (2019)
Morales-Soto et al. (2022)
Prosin et al. (2014)
Seo et al. (1991)
Takeda et al. (2003)
Solar
1000
0.1
10^{-5}
10^{-9}
10^{-13}
10^{-17}
10^{-21}
10^{-25}
10
10^{4}
10^{7}
10^{10}
Flux [counts per (s.m^2.sr.GeV)]
Energy per nucleon [GeV]


Abreu et al. (2021)
An et al. (2019)
Ave et al. (2003)
Bird et al. (1994)
Choi et al. (2022)
Grebenyuk et al. (2019)
Morales-Soto et al. (2022)
Prosin et al. (2014)
Seo et al. (1991)
Takeda et al. (2003)
Solar
Galactic
Flux [counts per (s.m^2.sr.GeV)]
1000
0.1
10^{-5}
10^{-9}
10^{-13}
10^{-17}
10^{-21}
10^{-25}
10
10^4
10^7
10^{10}
Energy per nucleon [GeV]

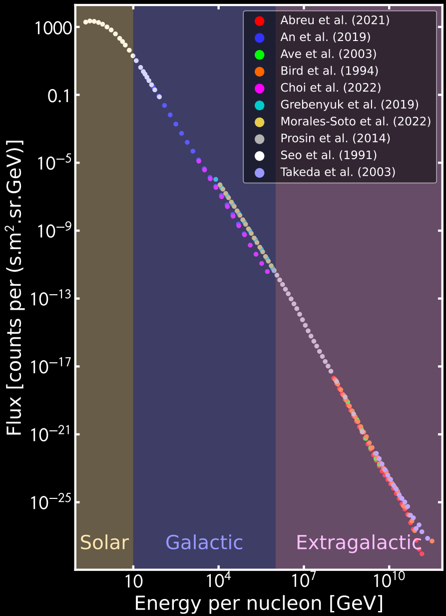

Abreu et al. (2021)
An et al. (2019)
Ave et al. (2003)
Bird et al. (1994)
Choi et al. (2022)
Grebenyuk et al. (2019)
Morales-Soto et al. (2022)
Prosin et al. (2014)
Seo et al. (1991)
Takeda et al. (2003)
Solar
Galactic
Extragalactic
Flux [counts per (s.m^2.sr.GeV)]
1000
0.1
10^{-5}
10^{-9}
10^{-13}
10^{-17}
10^{-21}
10^{-25}
10
10^4
10^7
10^{10}
Energy per nucleon [GeV]

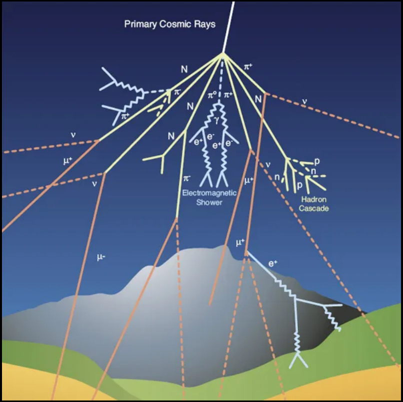


Abreu et al. (2021)
An et al. (2019)
Ave et al. (2003)
Bird et al. (1994)
Choi et al. (2022)
Grebenyuk et al. (2019)
Morales-Soto et al. (2022)
Prosin et al. (2014)
Seo et al. (1991)
Takeda et al. (2003)
1000
0.1
10^{-5}
10^{-9}
10^{-13}
10^{-17}
10^{-21}
10^{-25}
Flux [counts per (s.m^2.sr.GeV)]
Solar
Galactic
Extragalactic
10
10^4
10^7
10^{10}
Energy per nucleon [GeV]

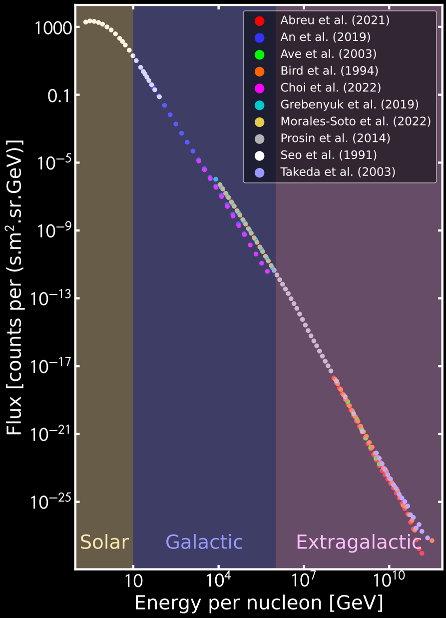


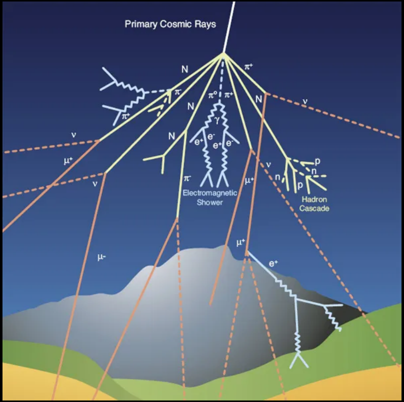
Primary Cosmic Rays
Electromagnetic Shower
Hadron Cascade





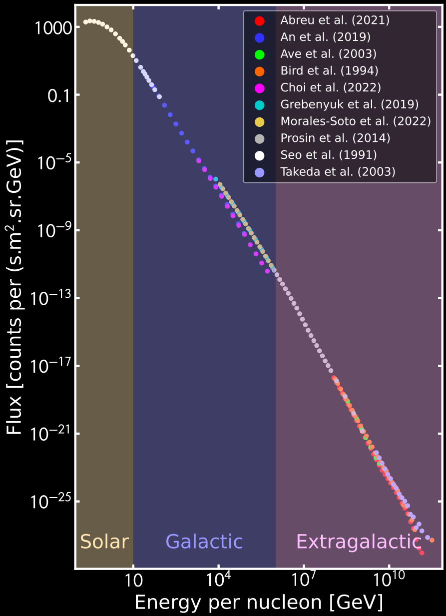
The Relevance of Cosmic Rays for the ISM

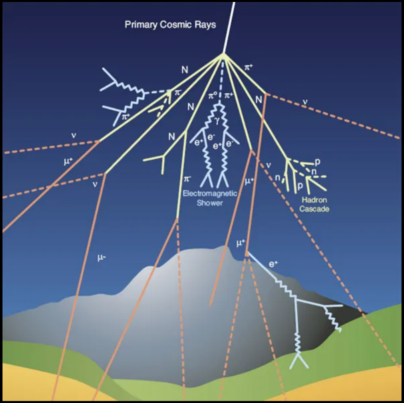




The Relevance of Cosmic Rays for the ISM

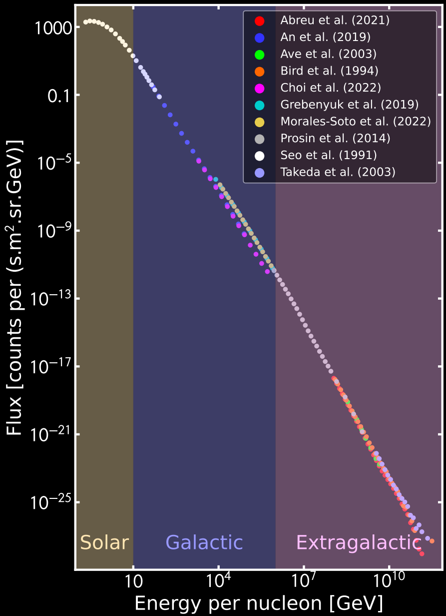
Pressure:

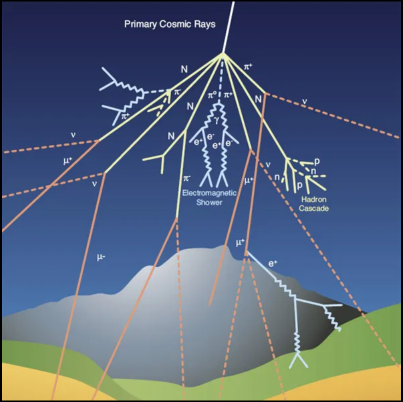




The Relevance of Cosmic Rays for the ISM

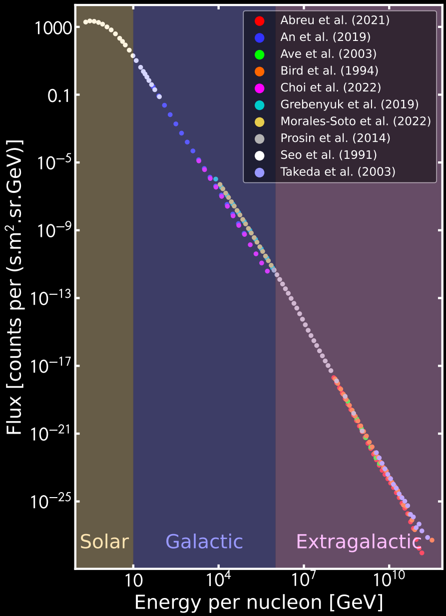
Pressure: $\underbrace{n_{\rm CR}}_{\simeq 10^{-10}\,\rm cm^{-3}}$

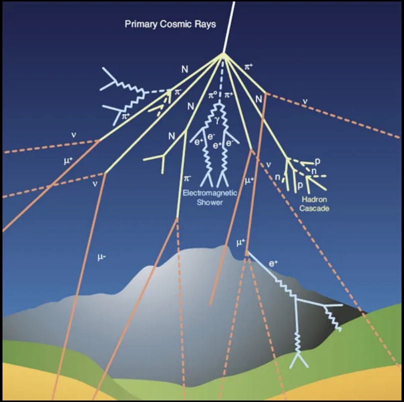




The Relevance of Cosmic Rays for the ISM

Pressure: $\underbrace{n_{CR}}_{\simeq 10^{-10}\ \mathrm{cm}^{-3}} \times \underbrace{T_{CR}}_{\text{large, non-thermal}}$.

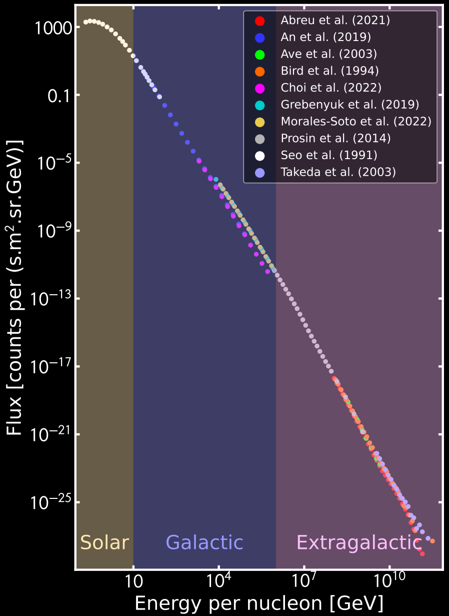


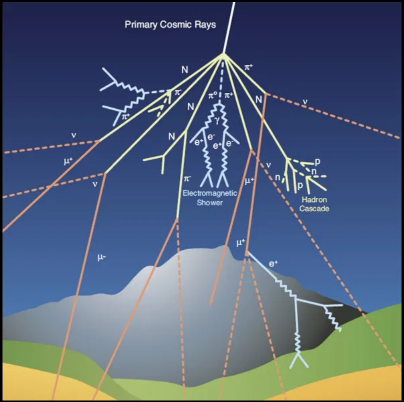


The Relevance of Cosmic Rays for the ISM

Pressure: $\underbrace{n_{CR}}_{\simeq 10^{-10}\ \mathrm{cm}^{-3}} \times \underbrace{T_{CR}}_{\text{large, non-thermal}}$.

Heating: dominant in dense cores.





The Relevance of Cosmic Rays for the ISM

Pressure: $\underbrace{n_{CR}}_{\simeq 10^{-10}\,\text{cm}^{-3}} \times \underbrace{T_{CR}}_{\text{large, non-thermal}}$.

Heating: dominant in dense cores.

Chemistry: ionizing molecules, processing grains.

Methods | Collecting Interstellar Grains in the Solar System

Grain-collecting spacecrafts

Grain-collecting spacecrafts

- Heliosphere moves at $\simeq 26$ km/s

Grain-collecting spacecrafts

- Heliosphere moves at $\simeq 26$ km/s $\Rightarrow$ flow of interstellar grains in the Solar system.

Grain-collecting spacecrafts

- Heliosphere moves at $\simeq$ 26 km/s $\Rightarrow$ flow of interstellar grains in the Solar system.
- Since the 2000s $\rightarrow$ several grain collecting spacecrafts (Ulysses, Galileo, Cassini, Startdust)

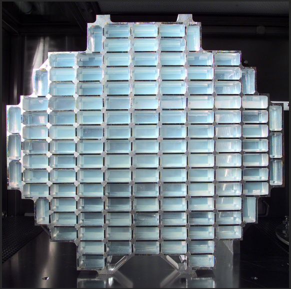
Grain-collecting spacecrafts

- Heliosphere moves at $\simeq$ 26 km/s $\Rightarrow$ flow of interstellar grains in the Solar system.
- Since the 2000s $\rightarrow$ several grain collecting spacecrafts (Ulysses, Galileo, Cassini, Startdust) $\Rightarrow$ possibility to identify interstellar grains.

Grain-collecting spacecrafts

- Heliosphere moves at $\simeq 26$ km/s $\Rightarrow$ flow of interstellar grains in the Solar system.
- Since the 2000s $\rightarrow$ several grain collecting spacecrafts (Ulysses, Galileo, Cassini, Startdust) $\Rightarrow$ possibility to identify interstellar grains.

Aerogel honeycomb matrix

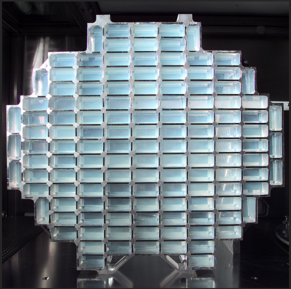


Credit: Stardust, NASA / JPL.

Grain-collecting spacecrafts

- Heliosphere moves at $\simeq 26$ km/s $\Rightarrow$ flow of interstellar grains in the Solar system.
- Since the 2000s $\rightarrow$ several grain collecting spacecrafts (Ulysses, Galileo, Cassini, Startdust) $\Rightarrow$ possibility to identify interstellar grains.

Aerogel honeycomb matrix



Credit: Stardust, NASA / JPL.

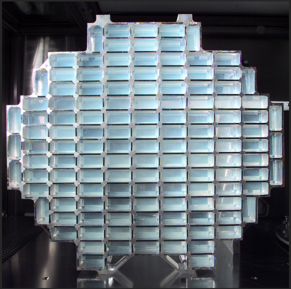
Aerogel dust track

Credit: Stardust, NASA / JPL.

Grain-collecting spacecrafts

- Heliosphere moves at $\simeq 26$ km/s $\Rightarrow$ flow of interstellar grains in the Solar system.
- Since the 2000s $\rightarrow$ several grain collecting spacecrafts (Ulysses, Galileo, Cassini, Startdust) $\Rightarrow$ possibility to identify interstellar grains.

Aerogel honeycomb matrix

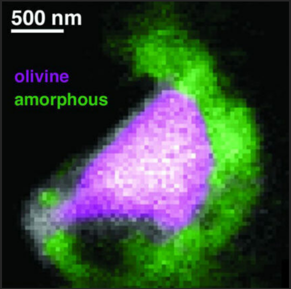


Credit: Stardust, NASA / JPL.

Aerogel dust track

Credit: Stardust, NASA / JPL.

X-ray imaging of a grain

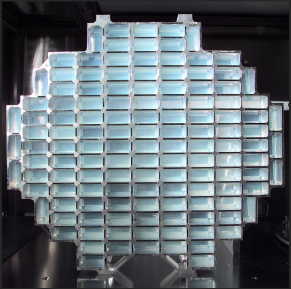


Credit: A. Butterworth.

Grain-collecting spacecrafts

- Heliosphere moves at $\simeq 26$ km/s $\Rightarrow$ flow of interstellar grains in the Solar system.
- Since the 2000s $\rightarrow$ several grain collecting spacecrafts (Ulysses, Galileo, Cassini, Startdust) $\Rightarrow$ possibility to identify interstellar grains.

Aerogel honeycomb matrix

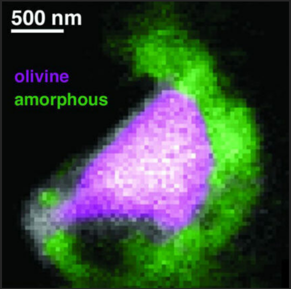


Credit: Stardust, NASA / JPL.

Aerogel dust track

Credit: Stardust, NASA / JPL.

X-ray imaging of a grain



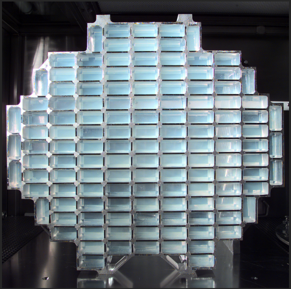
Credit: A. Butterworth.

Interstellar grains locked in meteorites

Grain-collecting spacecrafts

- Heliosphere moves at $\simeq 26$ km/s $\Rightarrow$ flow of interstellar grains in the Solar system.
- Since the 2000s $\rightarrow$ several grain collecting spacecrafts (Ulysses, Galileo, Cassini, Startdust) $\Rightarrow$ possibility to identify interstellar grains.

Aerogel honeycomb matrix

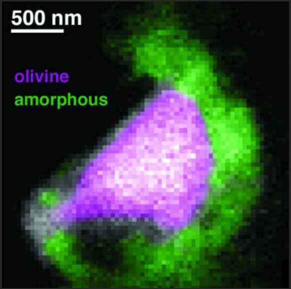


Credit: Stardust, NASA / JPL.

Aerogel dust track

Credit: Stardust, NASA / JPL.

X-ray imaging of a grain



Credit: A. Butterworth.

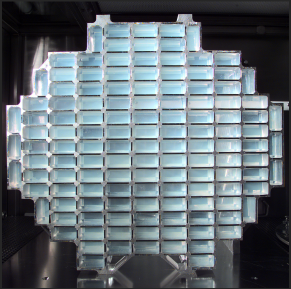
Interstellar grains locked in meteorites

- Primitive meteorites contain pre-Solar grains $\Rightarrow$ of interstellar origin.

Grain-collecting spacecrafts

- Heliosphere moves at $\simeq 26$ km/s $\Rightarrow$ flow of interstellar grains in the Solar system.
- Since the 2000s $\rightarrow$ several grain collecting spacecrafts (Ulysses, Galileo, Cassini, Startdust) $\Rightarrow$ possibility to identify interstellar grains.

Aerogel honeycomb matrix

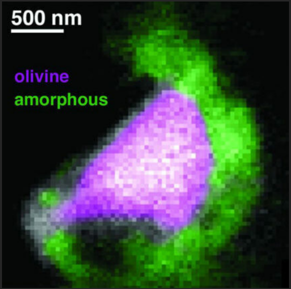


Credit: Stardust, NASA / JPL.

Aerogel dust track

Credit: Stardust, NASA / JPL.

X-ray imaging of a grain



Credit: A. Butterworth.

Interstellar grains locked in meteorites

- Primitive meteorites contain pre-Solar grains $\Rightarrow$ of interstellar origin.

$\Rightarrow$ Possibility to identify and study them (*e.g.* Hoppe & Zinner 2000).

Methods | Collecting Interstellar Grains on Earth

Credit: collecting micrometeorites in Antartica (Dome C, 2002; CNRS).

Methods | The Challenges of Studying Extended Regions

ISM targets are usually diffuse & extended

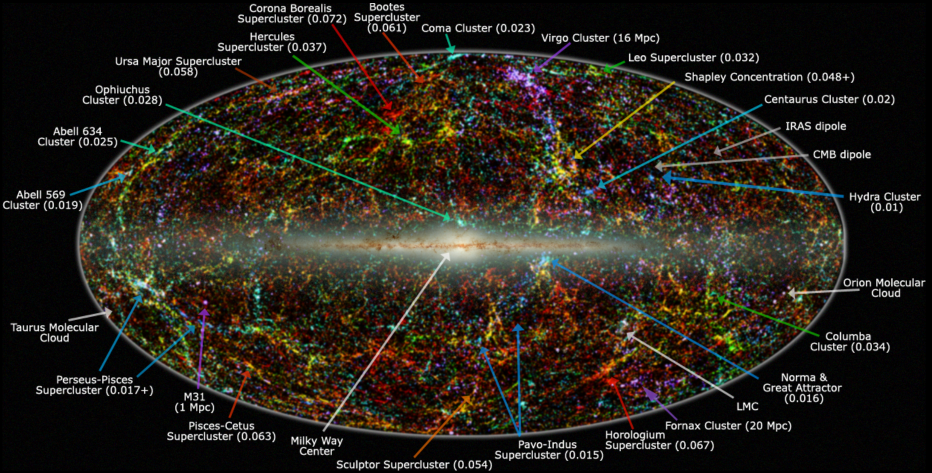
ISM targets are usually diffuse & extended

- ISM pervades everything $\Rightarrow$ large fraction of the sky & low-surface brightness.

Methods | The Challenges of Studying Extended Regions

ISM targets are usually diffuse & extended

- ISM pervades everything ⇒ large fraction of the sky & low-surface brightness.

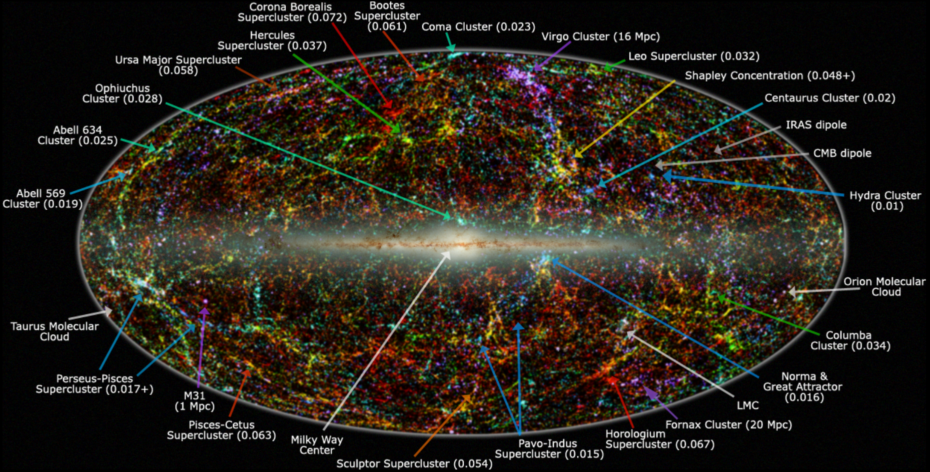


Credit: 2MASS extended source catalog (Jarrett, 2004).

ISM targets are usually diffuse & extended

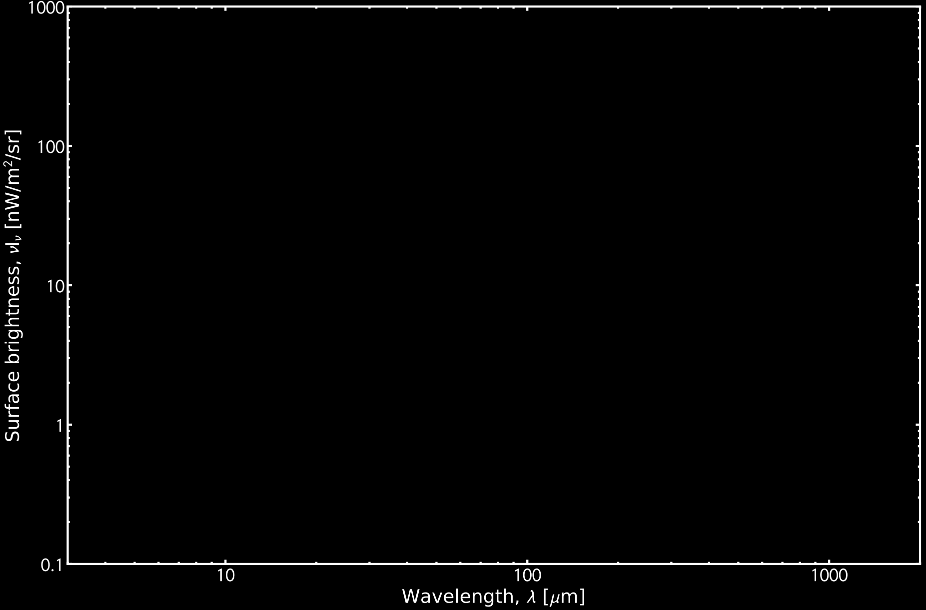
- ISM pervades everything ⇒ large fraction of the sky & low-surface brightness.

⇒ need sophisticated methods to isolate it from the rest.

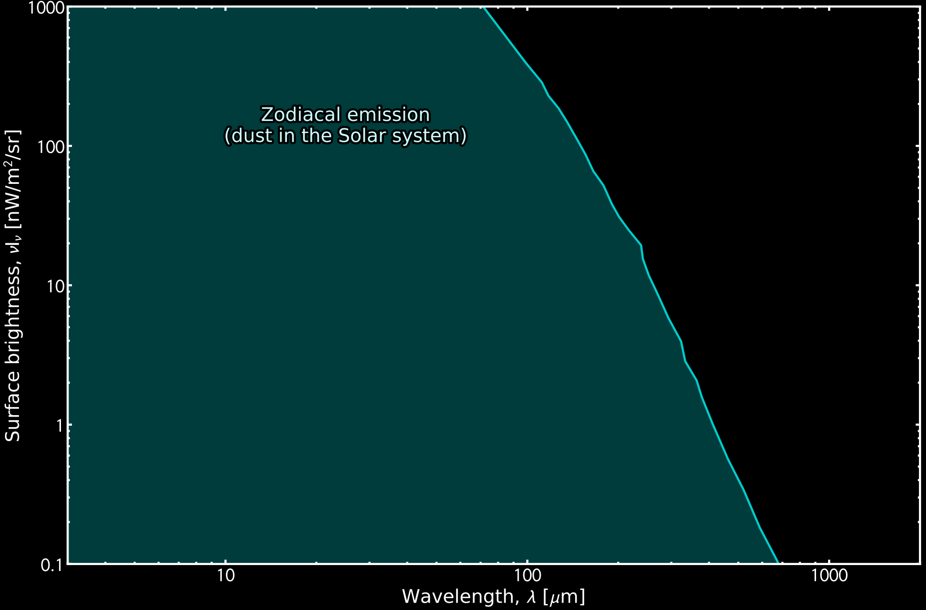


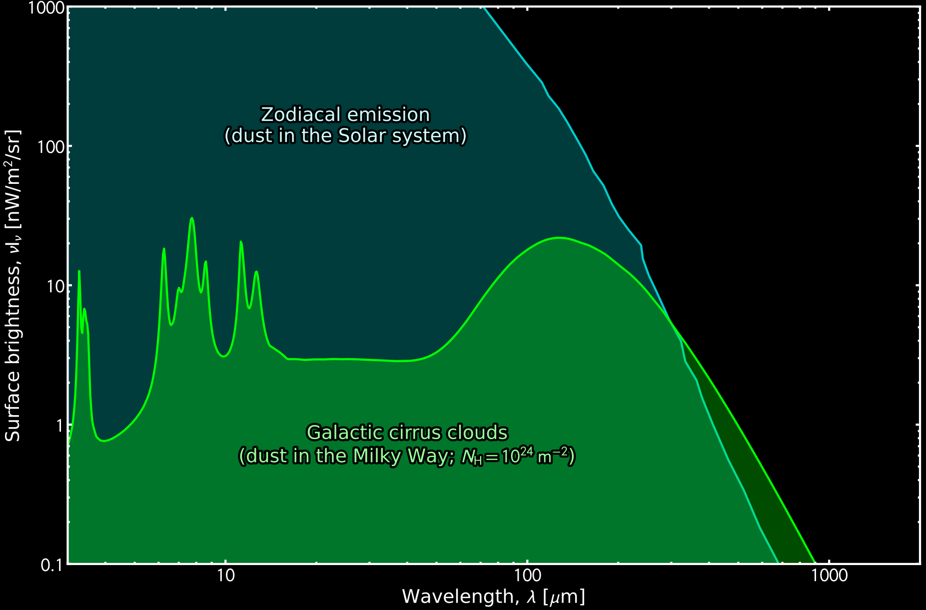
Credit: 2MASS extended source catalog (Jarrett, 2004).

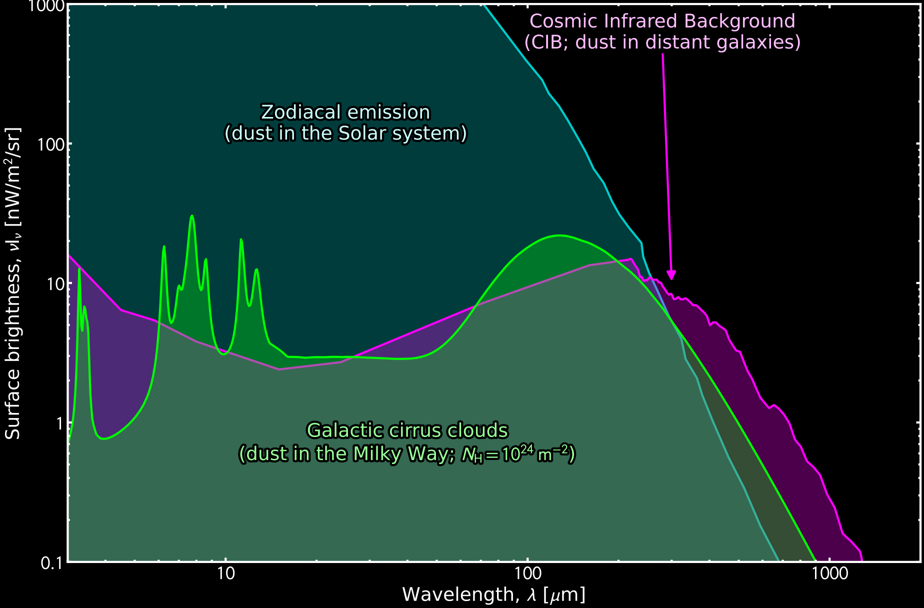
Methods | Spectral Confusion with Backgrounds & Foregrounds

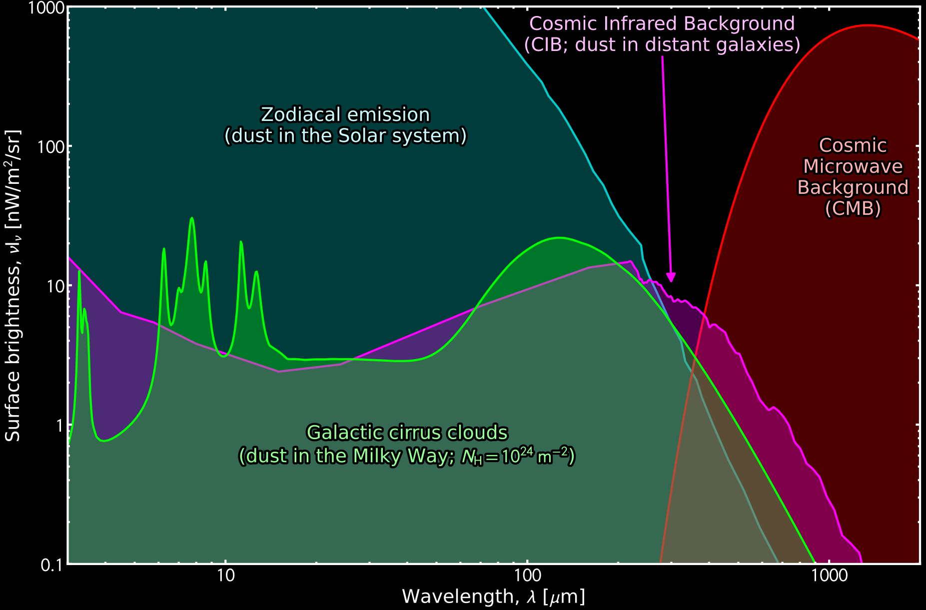


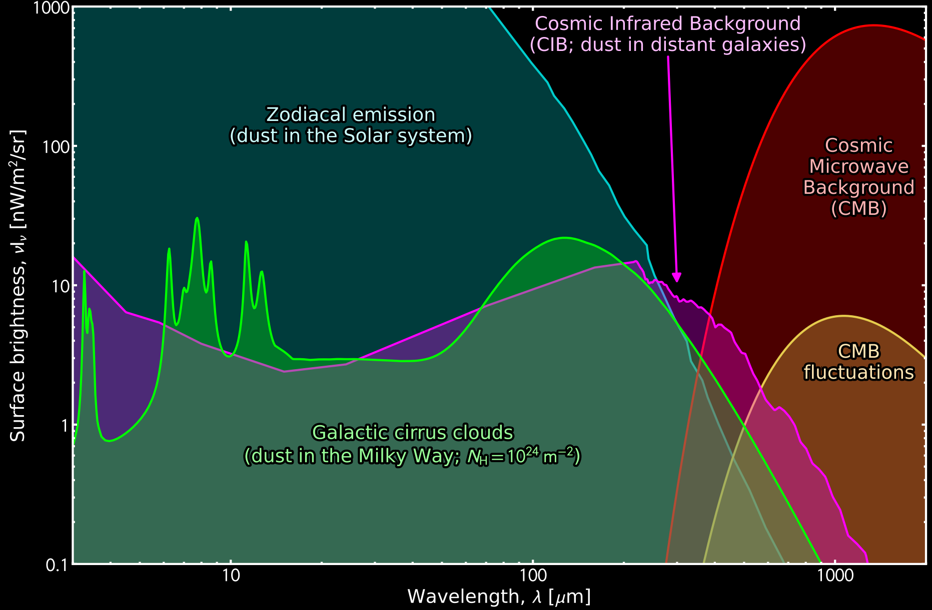
Methods | Spectral Confusion with Backgrounds & Foregrounds




Zodiacal emission
(dust in the Solar system)
Galactic cirrus clouds
(dust in the Milky Way; $N_H = 10^{24}\ m^{-2}$)
Surface brightness, νI_ν [nW/m^2/sr]
Wavelength, λ [μm]
1000
100
10
1
0.1
10
100
1000


Cosmic Infrared Background
(CIB; dust in distant galaxies)
Zodiacal emission
(dust in the Solar system)
Galactic cirrus clouds
(dust in the Milky Way; $N_H = 10^{24}\,m^{-2}$)
Surface brightness, νI_ν [$nW/m^2/sr$]
Wavelength, λ [μm]
1000
100
10
1
0.1
10
100
1000


Cosmic Infrared Background
(CIB; dust in distant galaxies)
Zodiacal emission
(dust in the Solar system)
Cosmic
Microwave
Background
(CMB)
Galactic cirrus clouds
(dust in the Milky Way; $N_H = 10^{24}$ m^{-2})
Surface brightness, νI_ν [nW/m^2/sr]
1000
100
10
1
0.1
10
100
1000
Wavelength, λ [μm]


Zodiacal emission
(dust in the Solar system)
Cosmic Infrared Background
(CIB; dust in distant galaxies)
Cosmic Microwave Background (CMB)
CMB fluctuations
Galactic cirrus clouds
(dust in the Milky Way; $N_H = 10^{24}$ m^{-2})
Surface brightness, νI_ν [nW/m^2/sr]
Wavelength, λ [μm]
1000
100
10
1
0.1
10
100
1000

Necessity to develop methods to extract ISM observables

Necessity to develop methods to extract ISM observables

Spectral decomposition, using SED fitting, with ancillary data, *etc.*

Necessity to develop methods to extract ISM observables

Spectral decomposition, using SED fitting, with ancillary data, *etc.*

Machine-learning methods: new development, but robustness difficult to assess.

Necessity to develop methods to extract ISM observables

Spectral decomposition, using SED fitting, with ancillary data, *etc.*

Machine-learning methods: new development, but robustness difficult to assess.

Statistically-motivated methods: most popular approaches.

Necessity to develop methods to extract ISM observables

Spectral decomposition, using SED fitting, with ancillary data, *etc.*

Machine-learning methods: new development, but robustness difficult to assess.

Statistically-motivated methods: most popular approaches.

$\Rightarrow$ no Universal method $\Rightarrow$ very dependent on the type of data.

Necessity to develop methods to extract ISM observables

Spectral decomposition, using SED fitting, with ancillary data, *etc.*

Machine-learning methods: new development, but robustness difficult to assess.

Statistically-motivated methods: most popular approaches.

$\Rightarrow$ no Universal method $\Rightarrow$ very dependent on the type of data.

Example: Separating Milky Way dust & the Cosmic Infrared Background

Necessity to develop methods to extract ISM observables

Spectral decomposition, using SED fitting, with ancillary data, *etc.*

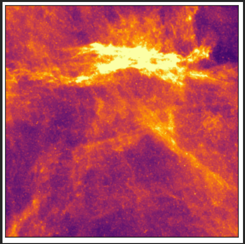
Machine-learning methods: new development, but robustness difficult to assess.

Statistically-motivated methods: most popular approaches.

$\Rightarrow$ no Universal method $\Rightarrow$ very dependent on the type of data.

Example: Separating Milky Way dust & the Cosmic Infrared Background

***Herschel* 250 μm image**



Credit: separation of a high-Galactic-latitude field using *wavelet phase harmonics* (Auclair et al., 2024).

Methods | The Delicate Decomposition of Diffuse Data

Necessity to develop methods to extract ISM observables

Spectral decomposition, using SED fitting, with ancillary data, *etc.*

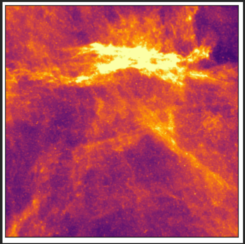
Machine-learning methods: new development, but robustness difficult to assess.

Statistically-motivated methods: most popular approaches.

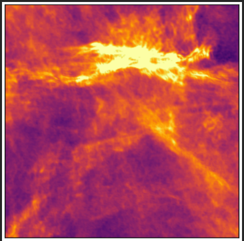
$\Rightarrow$ no Universal method $\Rightarrow$ very dependent on the type of data.

Example: Separating Milky Way dust & the Cosmic Infrared Background

Herschel **250 μm image**



Extracted dust



Credit: separation of a high-Galactic-latitude field using *wavelet phase harmonics* (Auclair et al., 2024).

Necessity to develop methods to extract ISM observables

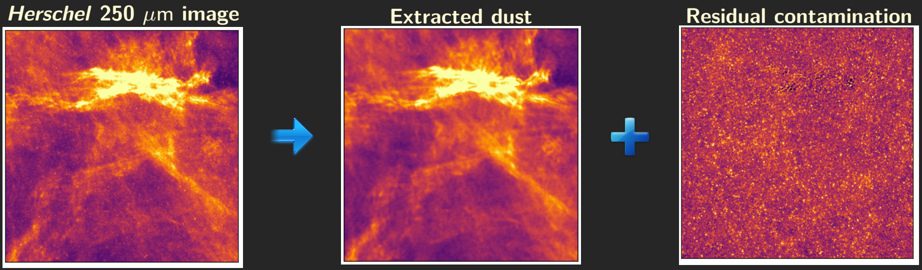
Spectral decomposition, using SED fitting, with ancillary data, *etc.*

Machine-learning methods: new development, but robustness difficult to assess.

Statistically-motivated methods: most popular approaches.

$\Rightarrow$ no Universal method $\Rightarrow$ very dependent on the type of data.

Example: Separating Milky Way dust & the Cosmic Infrared Background



Credit: separation of a high-Galactic-latitude field using *wavelet phase harmonics* (Auclair et al., 2024).

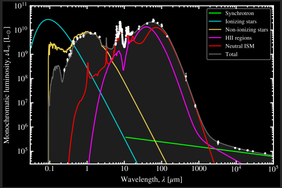
Theory & Simulations

Analytical theory & numerical simulations.

Theory & Simulations

Analytical theory & numerical simulations.

Models



Accurate comparison of theory & observations.

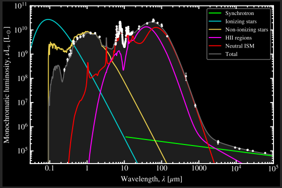
Theory & Simulations

Analytical theory & numerical simulations.

Observations

Planning, performing & analyzing observations.

Models



Accurate comparison of theory & observations.

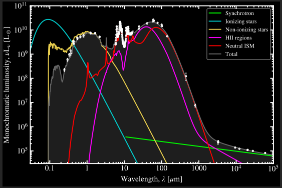
Theory & Simulations

Analytical theory & numerical simulations.

Observations

Planning, performing & analyzing observations.

Models



Accurate comparison of theory & observations.

Laboratory Experiments

Isolating & measuring astrophysical processes.

Theory & Simulations

Analytical theory & numerical simulations.

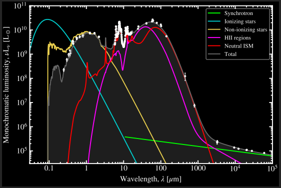
Observations

Planning, performing & analyzing observations.

Instrumentation

Designing, building & commissioning instruments.

Models



Accurate comparison of theory & observations.

Laboratory Experiments

Isolating & measuring astrophysical processes.

Theory & Simulations

Analytical theory & numerical simulations.

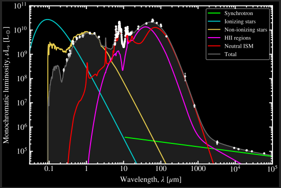
Observations

Planning, performing & analyzing observations.

Instrumentation

Designing, building & commissioning instruments.

Models



Accurate comparison of theory & observations.

Laboratory Experiments

Isolating & measuring astrophysical processes.

Bibliometry

Theory & Simulations

Analytical theory & numerical simulations.

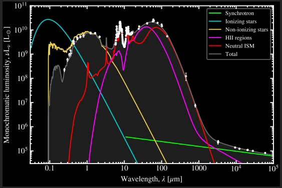
Observations

Planning, performing & analyzing observations.

Instrumentation

Designing, building & commissioning instruments.

Models



Accurate comparison of theory & observations.

Laboratory Experiments

Isolating & measuring astrophysical processes.

Bibliometry

- past 10 years → 15 % of *Annual Review of Astronomy & Astrophysics* (ARA&A) papers about ISM.

Theory & Simulations

Analytical theory & numerical simulations.

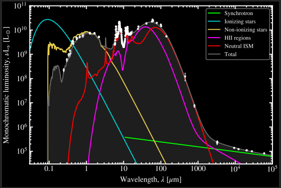
Observations

Planning, performing & analyzing observations.

Instrumentation

Designing, building & commissioning instruments.

Models



Accurate comparison of theory & observations.

Laboratory Experiments

Isolating & measuring astrophysical processes.

Bibliometry

- past 10 years $\rightarrow$ 15 % of *Annual Review of Astronomy & Astrophysics* (ARA&A) papers about ISM.
- $\simeq$ 10 new publications per week day.

Project scaling

Project scaling

- Possibility to work in small teams $\Rightarrow$ control the whole process (observations, models, *etc.*).

Project scaling

- Possibility to work in small teams $\Rightarrow$ control the whole process (observations, models, *etc.*).
- Possibility to participate to large collaborations (large surveys, mission design, *etc.*).

Project scaling

- Possibility to work in small teams ⇒ control the whole process (observations, models, *etc.*).
- Possibility to participate to large collaborations (large surveys, mission design, *etc.*).

Interdisciplinarity

Project scaling

- Possibility to work in small teams ⇒ control the whole process (observations, models, *etc.*).
- Possibility to participate to large collaborations (large surveys, mission design, *etc.*).

Interdisciplinarity

ISM permeates everything ⇒ interface with:

Project scaling

- Possibility to work in small teams ⇒ control the whole process (observations, models, *etc.*).
- Possibility to participate to large collaborations (large surveys, mission design, *etc.*).

Interdisciplinarity

ISM permeates everything ⇒ interface with:

- planetary system, galaxy evolution, compact objects, stellar physics;

Methods | The Uniqueness of Working on the ISM

Project scaling

- Possibility to work in small teams ⇒ control the whole process (observations, models, *etc.*).
- Possibility to participate to large collaborations (large surveys, mission design, *etc.*).

Interdisciplinarity

ISM permeates everything ⇒ interface with:

- planetary system, galaxy evolution, compact objects, stellar physics;
- chemistry, material science, *etc.*

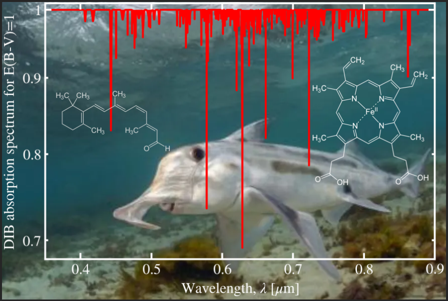
Project scaling

- Possibility to work in small teams ⇒ control the whole process (observations, models, *etc.*).
- Possibility to participate to large collaborations (large surveys, mission design, *etc.*).

Interdisciplinarity

ISM permeates everything ⇒ interface with:

- planetary system, galaxy evolution, compact objects, stellar physics;
- chemistry, material science, *etc.*



(van den Broek d'Obrenan et al., 2023)

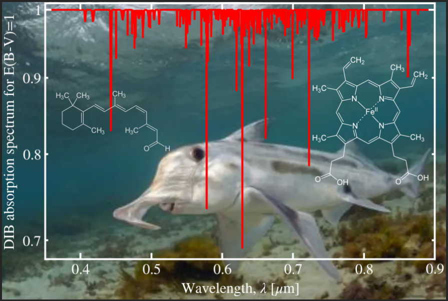
Project scaling

- Possibility to work in small teams ⇒ control the whole process (observations, models, *etc.*).
- Possibility to participate to large collaborations (large surveys, mission design, *etc.*).

Interdisciplinarity

ISM permeates everything ⇒ interface with:

- planetary system, galaxy evolution, compact objects, stellar physics;
- chemistry, material science, *etc.*



Aesthetics

(van den Broek d'Obrenan et al., 2023)

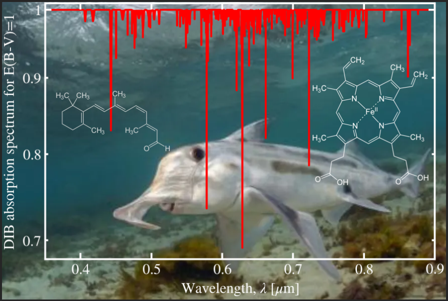
Project scaling

- Possibility to work in small teams ⇒ control the whole process (observations, models, *etc.*).
- Possibility to participate to large collaborations (large surveys, mission design, *etc.*).

Interdisciplinarity

ISM permeates everything ⇒ interface with:

- planetary system, galaxy evolution, compact objects, stellar physics;
- chemistry, material science, *etc.*



Aesthetics

Credit: JWST, NASA, ESA, CSA, STScI.

(van den Broek d'Obrenan et al., 2023)

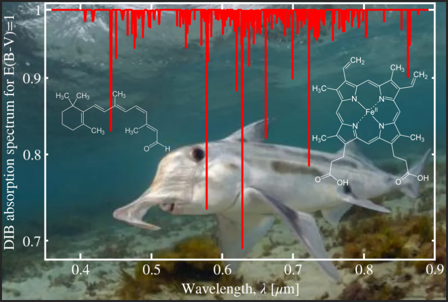
Project scaling

- Possibility to work in small teams ⇒ control the whole process (observations, models, *etc.*).
- Possibility to participate to large collaborations (large surveys, mission design, *etc.*).

Interdisciplinarity

ISM permeates everything ⇒ interface with:

- planetary system, galaxy evolution, compact objects, stellar physics;
- chemistry, material science, *etc.*



(van den Broek d'Obrenan et al., 2023)

Aesthetics

Credit: JWST, NASA, ESA, CSA, STScI.

ISM ⇒ the most beautiful images.

Outline of the Lecture

1. OVERVIEW: WHAT IS THE ISM?
   - Composition, physical properties, characteristic regions
   - The Milky Way and the diversity of external galaxies
   - Recommended bibliography and outline of the course
2. A BRIEF HISTORY OF STUDIES OF THE ISM
   - Before the XXth Century
   - From astronomy to astrophysics
   - The modern era
3. METHODOLOGY: HOW DO WE STUDY INTERSTELLAR MEDIA?
   - The microphysical components of the ISM
   - The challenges of studying macroscopic regions
   - The Sociology of ISMology
4. CONCLUSION
   - Take-away points
   - References

Overview of the physical components of the ISM

Overview of the physical components of the ISM

1. The ISM is the medium filling the space between stars in a galaxy, made of atoms, molecules, dust grains & cosmic rays, bathed with photons, and magnetic & gravitational fields.

Overview of the physical components of the ISM

1. The ISM is the medium filling the space between stars in a galaxy, made of atoms, molecules, dust grains & cosmic rays, bathed with photons, and magnetic & gravitational fields.
2. Most of its mass is in atomic Hydrogen, with $\simeq 25\,\%$ of Helium, and traces of other elements & dust. The ionized & molecular phases account for $\simeq 20\,\%$ of the mass each.

Overview of the physical components of the ISM

1. The ISM is the medium filling the space between stars in a galaxy, made of atoms, molecules, dust grains & cosmic rays, bathed with photons, and magnetic & gravitational fields.
2. Most of its mass is in atomic Hydrogen, with $\simeq 25\,\%$ of Helium, and traces of other elements & dust. The ionized & molecular phases account for $\simeq 20\,\%$ of the mass each.
3. There is a wide diversity of phases with $\langle n_{\rm H}\rangle \simeq 0.3\ {\rm cm^{-3}}$, with $10^{-3}\ {\rm cm^{-3}} \lesssim n_{\rm H} \lesssim 10^{6}\ {\rm cm^{-3}}$ & $10\ {\rm K} \lesssim T_{\rm gas} \lesssim 10^{6}\ {\rm K}$. These phases are far from thermal equilibrium.

Conclusion | Take-Away Points

Overview of the physical components of the ISM

1. The ISM is the medium filling the space between stars in a galaxy, made of atoms, molecules, dust grains & cosmic rays, bathed with photons, and magnetic & gravitational fields.
2. Most of its mass is in atomic Hydrogen, with $\simeq 25\,\%$ of Helium, and traces of other elements & dust. The ionized & molecular phases account for $\simeq 20\,\%$ of the mass each.
3. There is a wide diversity of phases with $\langle n_{\rm H}\rangle \simeq 0.3\ {\rm cm}^{-3}$, with $10^{-3}\ {\rm cm}^{-3} \lesssim n_{\rm H} \lesssim 10^6\ {\rm cm}^{-3}$ & $10\ {\rm K} \lesssim T_{\rm gas} \lesssim 10^6\ {\rm K}$. These phases are far from thermal equilibrium.

Chronology of the main breakthroughs

Overview of the physical components of the ISM

1. The ISM is the medium filling the space between stars in a galaxy, made of atoms, molecules, dust grains & cosmic rays, bathed with photons, and magnetic & gravitational fields.
2. Most of its mass is in atomic Hydrogen, with $\simeq 25\,\%$ of Helium, and traces of other elements & dust. The ionized & molecular phases account for $\simeq 20\,\%$ of the mass each.
3. There is a wide diversity of phases with $\langle n_{\rm H} \rangle \simeq 0.3\ {\rm cm}^{-3}$, with $10^{-3}\ {\rm cm}^{-3} \lesssim n_{\rm H} \lesssim 10^{6}\ {\rm cm}^{-3}$ & $10\ {\rm K} \lesssim T_{\rm gas} \lesssim 10^{6}\ {\rm K}$. These phases are far from thermal equilibrium.

Chronology of the main breakthroughs

1. Scientific studies of the ISM started about a Century ago, with the first evidence of dust extinction & the first detections of atoms & molecules.

Conclusion | Take-Away Points

Overview of the physical components of the ISM

1. The ISM is the medium filling the space between stars in a galaxy, made of atoms, molecules, dust grains & cosmic rays, bathed with photons, and magnetic & gravitational fields.
2. Most of its mass is in atomic Hydrogen, with $\simeq 25\,\%$ of Helium, and traces of other elements & dust. The ionized & molecular phases account for $\simeq 20\,\%$ of the mass each.
3. There is a wide diversity of phases with $\langle n_{\rm H}\rangle \simeq 0.3$ cm^{-3}, with 10^{-3} cm$^{-3} \lesssim n_{\rm H} \lesssim 10^6$ cm^{-3} & 10 K $\lesssim T_{\rm gas} \lesssim 10^6$ K. These phases are far from thermal equilibrium.

Chronology of the main breakthroughs

1. Scientific studies of the ISM started about a Century ago, with the first evidence of dust extinction & the first detections of atoms & molecules.
2. The development of detectors over the whole electromagnetic spectrum was instrumental. *Spectroscopy* is a key technique to remotely probe the physical conditions in the ISM.

Overview of the physical components of the ISM

1. The ISM is the medium filling the space between stars in a galaxy, made of atoms, molecules, dust grains & cosmic rays, bathed with photons, and magnetic & gravitational fields.
2. Most of its mass is in atomic Hydrogen, with $\simeq 25\,\%$ of Helium, and traces of other elements & dust. The ionized & molecular phases account for $\simeq 20\,\%$ of the mass each.
3. There is a wide diversity of phases with $\langle n_\text{H} \rangle \simeq 0.3$ cm^{-3}, with 10^{-3} cm$^{-3} \lesssim n_\text{H} \lesssim 10^6$ cm^{-3} & 10 K $\lesssim T_\text{gas} \lesssim 10^6$ K. These phases are far from thermal equilibrium.

Chronology of the main breakthroughs

1. Scientific studies of the ISM started about a Century ago, with the first evidence of dust extinction & the first detections of atoms & molecules.
2. The development of detectors over the whole electromagnetic spectrum was instrumental. *Spectroscopy* is a key technique to remotely probe the physical conditions in the ISM.
3. Modern ISMology heavily relies on the data from space missions to circumvent the atmosphere.

Overview of the physical components of the ISM

1. The ISM is the medium filling the space between stars in a galaxy, made of atoms, molecules, dust grains & cosmic rays, bathed with photons, and magnetic & gravitational fields.
2. Most of its mass is in atomic Hydrogen, with $\simeq 25\,\%$ of Helium, and traces of other elements & dust. The ionized & molecular phases account for $\simeq 20\,\%$ of the mass each.
3. There is a wide diversity of phases with $\langle n_\mathrm{H}\rangle \simeq 0.3\ \mathrm{cm}^{-3}$, with $10^{-3}\ \mathrm{cm}^{-3} \lesssim n_\mathrm{H} \lesssim 10^{6}\ \mathrm{cm}^{-3}$ & $10\ \mathrm{K} \lesssim T_\mathrm{gas} \lesssim 10^{6}\ \mathrm{K}$. These phases are far from thermal equilibrium.

Chronology of the main breakthroughs

1. Scientific studies of the ISM started about a Century ago, with the first evidence of dust extinction & the first detections of atoms & molecules.
2. The development of detectors over the whole electromagnetic spectrum was instrumental. *Spectroscopy* is a key technique to remotely probe the physical conditions in the ISM.
3. Modern ISMology heavily relies on the data from space missions to circumvent the atmosphere.

The methodological approach of ISMology

Overview of the physical components of the ISM

1. The ISM is the medium filling the space between stars in a galaxy, made of atoms, molecules, dust grains & cosmic rays, bathed with photons, and magnetic & gravitational fields.
2. Most of its mass is in atomic Hydrogen, with $\simeq 25\,\%$ of Helium, and traces of other elements & dust. The ionized & molecular phases account for $\simeq 20\,\%$ of the mass each.
3. There is a wide diversity of phases with $\langle n_\text{H} \rangle \simeq 0.3$ cm^{-3}, with 10^{-3} cm$^{-3} \lesssim n_\text{H} \lesssim 10^6$ cm^{-3} & 10 K $\lesssim T_\text{gas} \lesssim 10^6$ K. These phases are far from thermal equilibrium.

Chronology of the main breakthroughs

1. Scientific studies of the ISM started about a Century ago, with the first evidence of dust extinction & the first detections of atoms & molecules.
2. The development of detectors over the whole electromagnetic spectrum was instrumental. *Spectroscopy* is a key technique to remotely probe the physical conditions in the ISM.
3. Modern ISMology heavily relies on the data from space missions to circumvent the atmosphere.

The methodological approach of ISMology

1. The microphysics of the ISM can be studied over the whole electromagnetic spectrum.

Conclusion | Take-Away Points

Overview of the physical components of the ISM

1. The ISM is the medium filling the space between stars in a galaxy, made of atoms, molecules, dust grains & cosmic rays, bathed with photons, and magnetic & gravitational fields.
2. Most of its mass is in atomic Hydrogen, with $\simeq 25\,\%$ of Helium, and traces of other elements & dust. The ionized & molecular phases account for $\simeq 20\,\%$ of the mass each.
3. There is a wide diversity of phases with $\langle n_\mathrm{H} \rangle \simeq 0.3\ \mathrm{cm}^{-3}$, with $10^{-3}\ \mathrm{cm}^{-3} \lesssim n_\mathrm{H} \lesssim 10^{6}\ \mathrm{cm}^{-3}$ & $10\ \mathrm{K} \lesssim T_\mathrm{gas} \lesssim 10^{6}\ \mathrm{K}$. These phases are far from thermal equilibrium.

Chronology of the main breakthroughs

1. Scientific studies of the ISM started about a Century ago, with the first evidence of dust extinction & the first detections of atoms & molecules.
2. The development of detectors over the whole electromagnetic spectrum was instrumental. *Spectroscopy* is a key technique to remotely probe the physical conditions in the ISM.
3. Modern ISMology heavily relies on the data from space missions to circumvent the atmosphere.

The methodological approach of ISMology

1. The microphysics of the ISM can be studied over the whole electromagnetic spectrum.
2. Due to the diffuse nature of the ISM's emission, confusion is a major limitation.

Conclusion | Take-Away Points

Overview of the physical components of the ISM

1. The ISM is the medium filling the space between stars in a galaxy, made of atoms, molecules, dust grains & cosmic rays, bathed with photons, and magnetic & gravitational fields.
2. Most of its mass is in atomic Hydrogen, with $\simeq 25\,\%$ of Helium, and traces of other elements & dust. The ionized & molecular phases account for $\simeq 20\,\%$ of the mass each.
3. There is a wide diversity of phases with $\langle n_\mathrm{H} \rangle \simeq 0.3~\mathrm{cm^{-3}}$, with $10^{-3}~\mathrm{cm^{-3}} \lesssim n_\mathrm{H} \lesssim 10^{6}~\mathrm{cm^{-3}}$ & $10~\mathrm{K} \lesssim T_\mathrm{gas} \lesssim 10^{6}~\mathrm{K}$. These phases are far from thermal equilibrium.

Chronology of the main breakthroughs

1. Scientific studies of the ISM started about a Century ago, with the first evidence of dust extinction & the first detections of atoms & molecules.
2. The development of detectors over the whole electromagnetic spectrum was instrumental. *Spectroscopy* is a key technique to remotely probe the physical conditions in the ISM.
3. Modern ISMology heavily relies on the data from space missions to circumvent the atmosphere.

The methodological approach of ISMology

1. The microphysics of the ISM can be studied over the whole electromagnetic spectrum.
2. Due to the diffuse nature of the ISM's emission, confusion is a major limitation.
3. Working on the ISM can imply a wide range of approaches & some inter-disciplinarity.

Abreu, P., Aglietta, M., Albury, J. M., et al. 2021, European Physical Journal C, 81, 966

Aloisi, A., Clementini, G., Tosi, M., et al. 2007, ApJ, 667, L151

Amelio, G. F., Tompsett, M. F., & Smith, G. E. 1970, The Bell System Technical Journal, 49, 593

An, Q., Asfandiyarov, R., Azzarello, P., et al. 2019, Science Advances, 5, eaax3793

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481

Auclair, C., Allys, E., Boulanger, F., et al. 2024, A&A, 681, A1

Ave, M., Knapp, J., Lloyd-Evans, J., Marchesini, M., & Watson, A. A. 2003, Astroparticle Physics, 19, 47

Barker, G. F. 1888, Bibliographical memoir of Heny Draper (Report of the National Academy of Sciences)

Barnard, E. E. 1899, ApJ, 9, 157

Barnard, E. E. 1919, ApJ, 49, 1

Beichman, C. A. 1987, ARA&A, 25, 521

Bernard, J. P., Ade, P., André, Y., et al. 2016, Experimental Astronomy, 42, 199

Bird, D. J., Corbato, S. C., Dai, H. Y., et al. 1994, ApJ, 424, 491

Boggess, A., Carr, F. A., Evans, D. C., et al. 1978, Nature, 275, 372

Boggess, N. W., Mather, J. C., Weiss, R., et al. 1992, ApJ, 397, 420

Boksenberg, A. 1982, Nature, 298, 795

Burrows, C. J., Holtzman, J. A., Faber, S. M., et al. 1991, ApJ, 369, L21

Choi, G. H., Seo, E. S., Aggarwal, S., et al. 2022, ApJ, 940, 107

Clerke, A. M. 1903, Problems in Astrophysics (London: A. & C. Black)

Cox, D. P. 2005, ARA&A, 43, 337

Désert, F.-X., Boulanger, F., & Puget, J. L. 1990, A&A, 237, 215

Dopita, M. A. & Sutherland, R. S. 2003, Astrophysics of the diffuse universe (Springer)

Draine, B. T. 2003, ApJ, 598, 1017

Draine, B. T. 2011, Physics of the Interstellar and Intergalactic Medium (Princeton University Press)

Dreyer, J. L. E. 1888, MmRAS, 49, 1

Erickson, E. F. & Meyer, A. W. 2013, in NASA's Kuiper Airborne Observatory, 1971–1995: An Operations Retrospective With a View to SOFIA (NASA)

Ewen, H. I. & Purcell, E. M. 1951, Nature, 168, 356

Galliano, F. 2022, HDR, Université Paris-Saclay

Galliano, F., Galametz, M., & Jones, A. P. 2018, ARA&A, 56, 673

Grebenyuk, V., Karmanov, D., Kovalev, I., et al. 2019, Advances in Space Research, 64, 2546

Harrison, T. G. 1984, QJRAS, 25, 65

Herschel, W. 1785, Phil. Trans. R. Soc., 75, 213–266

Herschel, W. 1791, Philosophical Transactions of the Royal Society of London Series I, 81, 71

Heyer, M. & Dame, T. M. 2015, ARA&A, 53, 583

Hollenbach, D. J. & Tielens, A. G. G. M. 1997, ARA&A, 35, 179

Hoppe, P. & Zinner, E. 2000, J. Geophys. Res., 105, 10371

Hubble, E. P. 1925, The Observatory, 48, 139

Huggins, W. & Miller, W. A. 1864, Philosophical Transactions of the Royal Society of London Series I, 154, 437

Jarrett, T. 2004, PASA, 21, 396

Kalberla, P. M. W. & Kerp, J. 2009, ARA&A, 47, 27

Kessler, M. F., Steinz, J. A., Anderegg, M. E., et al. 1996, A&A, 315, L27

Klessen, R. S. & Glover, S. C. O. 2016, Saas-Fee Advanced Course, 43, 85

Krügel, E. 2003, The physics of interstellar dust (IoP)

Leavitt, H. S. & Pickering, E. C. 1912, Harvard College Observatory Circular, 173, 1

Martin, J. D. 2013, PhD thesis, University of Minnesota

Mathis, J. S. 1970, ApJ, 159, 263

Mathis, J. S., Mezger, P. G., & Panagia, N. 1983, A&A, 128, 212

Mattila, K. 1970, A&A, 9, 53

McElwain, M. W., Feinberg, L. D., Kimble, R. A., et al. 2020, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 11443, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 114430T

McGrayne, S. 2011, The Theory That Would Not Die: How Bayes' Rule Cracked the Enigma Code, Hunted Down Russian Submarines, and Emerged Triumphant from Two Centuries of Controversy (Yale University Press)

Messier, C. 1781, Catalogue des Nébuleuses et des Amas d'Étoiles (Catalog of Nebulae and Star Clusters), Connoissance des Temps ou des Mouvements Célestes, for 1784, p. 227-267

Moos, H. W., Cash, W. C., Cowie, L. L., et al. 2000, ApJ, 538, L1

Morales-Soto, J. A., Arteaga-Velázquez, J. C., Hawc, et al. 2022, in 37th International Cosmic Ray Conference, 330

Neugebauer, G., Habing, H. J., van Duinen, R., et al. 1984, ApJ, 278, L1

Osterbrock, D. E. & Ferland, G. J. 2006, Astrophysics of gaseous nebulae and active galactic nuclei (University Science Books)

Payne, C. H. 1925, Proceedings of the National Academy of Science, 11, 192

Pilbratt, G. L., Riedinger, J. R., Passvogel, T., et al. 2010, A&A, 518, L1

Prosin, V. V., Berezhnev, S. F., Budnev, N. M., et al. 2014, Nuclear Instruments and Methods in Physics Research A, 756, 94

Rogalski, A. 2012, Opto-Electronics Review, 20

Russell, H. N. 1922, Proceedings of the National Academy of Science, 8, 115

Rybicky, G. B. & Lightman, A. P. 1979, Radiative processes in astrophysics (Wiley)

Seo, E. S., Ormes, J. F., Streitmatter, R. E., et al. 1991, ApJ, 378, 763

Soifer, B. T., Neugebauer, G., & Houck, J. R. 1987, ARA&A, 25, 187

Swings, P. & Rosenfeld, L. 1937, ApJ, 86, 483

Takeda, M., Sakaki, N., Honda, K., et al. 2003, Astroparticle Physics, 19, 447

Tauber, J. A., Mandolesi, N., Puget, J. L., et al. 2010, A&A, 520, A1

Tielens, A. G. G. M. 2005, The Physics and Chemistry of the Interstellar Medium (Cambridge University Press)

Trumpler, R. J. 1930, PASP, 42, 214

Turing, A. M. 1937, Proceedings of the London Mathematical Society, s2-42, 230

van de Hulst, H. C. 1945, Nederlandsch Tijdschrift voor Natuurkunde, 11, 210

van den Broek d'Obrenan, C., Galliano, F., Minton, J., Botev, V., & Wu, R. 2023, Journal of Interdisciplinary Methodologies and Issues in Science (JIMIS, 11, 9388

Walker, H. J. 2000, Astronomy and Geophysics, 41, 10

Weinreb, S., Barrett, A. H., Meeks, M. L., & Henry, J. C. 1963, Nature, 200, 829

Werner, M. W., Roellig, T. L., Low, F. J., et al. 2004, ApJS, 154, 1

Williams, T. G., Sun, J., Barnes, A. T., et al. 2022, ApJ, 941, L27

Wolfire, M. G., Vallini, L., & Chevance, M. 2022, ARA&A, 60, 247

Young, E. T., Becklin, E. E., Marcum, P. M., et al. 2012, ApJ, 749, L17