Astrophysical Objects

Interstellar medium

An introduction to modern Astrophysics chapter 12

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Interstellar medium

What is the interstellar medium?

Why is it important?

Milky Way over Chimborazo

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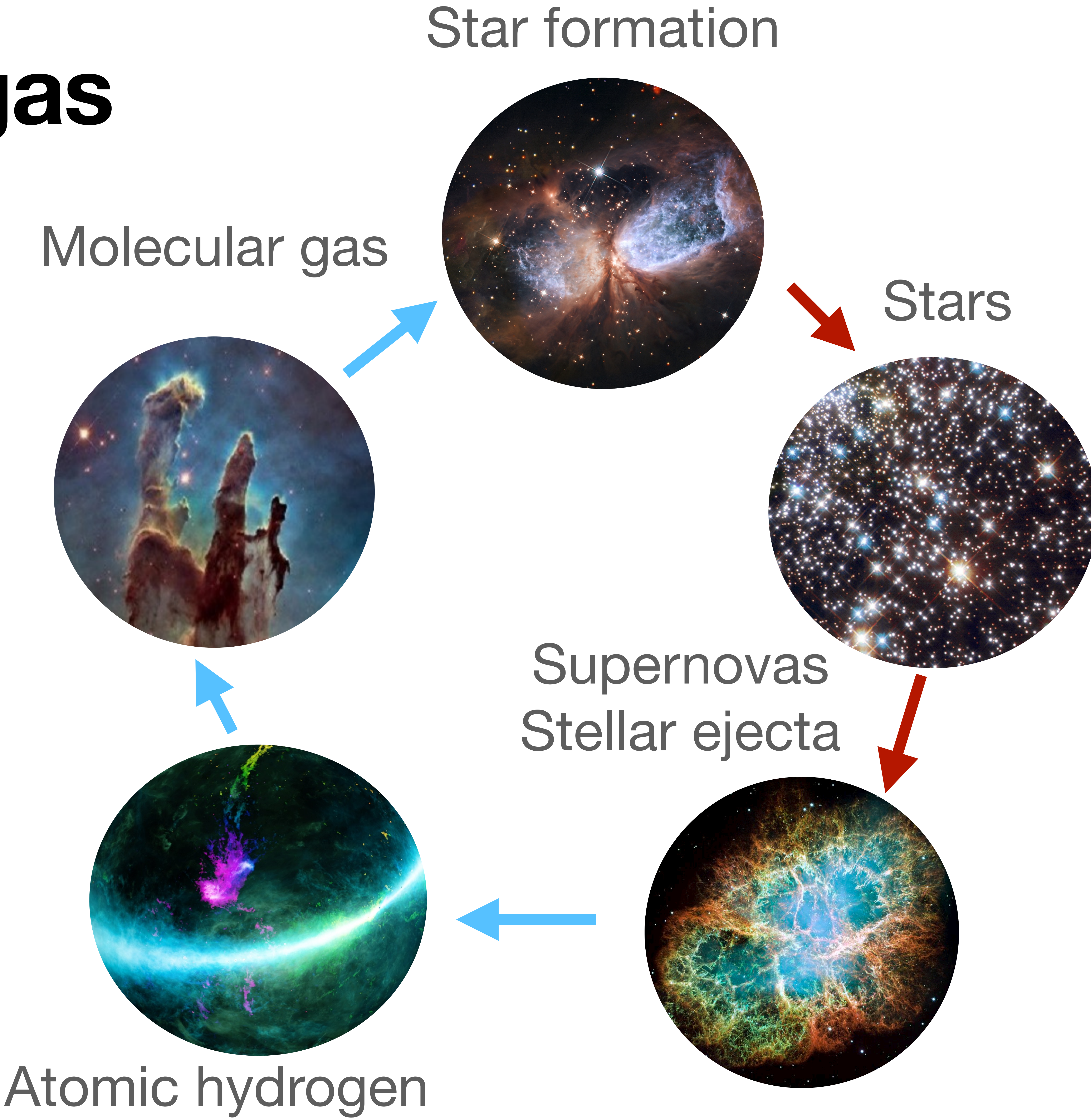
Interstellar dust and gas

In some sense the evolution of stars is a cyclic process. A star is born out of gas and dust that exists between the stars, known as the **interstellar medium** (ISM).

During its lifetime, depending on the star's total mass, much of that material may be returned to the ISM through stellar winds and explosive events. Subsequent generations of stars can then form from this processed material. As a result, to understand the evolution of a star, it is important to study the nature of the ISM.

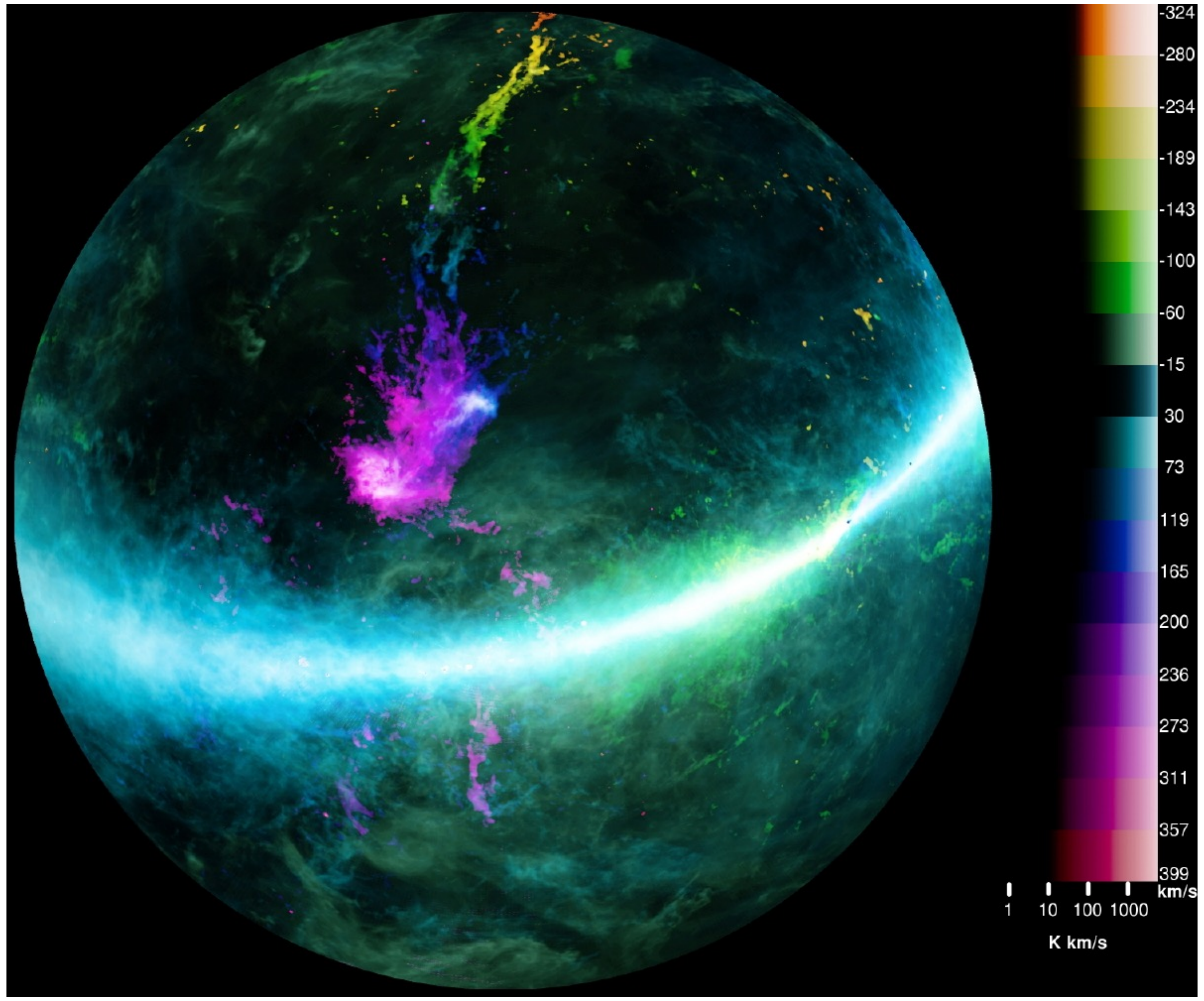


Interstellar dust and gas

- Understanding the interstellar medium is critical for more than its role in stellar evolution, however.
- The ISM is of profound importance in describing the structure, dynamics, and evolution of our Milky Way Galaxy, as well as galaxies throughout the universe.
- In addition, it impacts our observations of everything from relatively nearby stars to the most remote galaxies and quasars.

The ISM is an enormous and complex environment.

- The dynamics of the ISM involve turbulent gas motions, shocks, and galactic magnetic fields that lace through interstellar space. Thus, modeling the ISM ultimately requires detailed solutions to the equations of magnetohydrodynamics.
- The dust, molecules, atoms, ions, and free electrons that permeate the ISM challenge our understanding of radiative transfer, thermodynamics, and quantum mechanics.
- The production and destruction of dust grains and complex molecules requires a detailed understanding of chemistry in an environment not reproducible in a terrestrial laboratory.



Interstellar extinction - dust

On a dark night some of the **dust clouds** that populate our Milky Way Galaxy can be seen in the band of stars that is the disk of the Galaxy. It is not that these dark regions are devoid of stars, but rather that the stars located behind intervening dust clouds are obscured. This obscuration, referred to as **interstellar extinction**, is due to the summative effects of scattering and absorption of starlight.

Given the effect that extinction can have on the apparent magnitude of a star, the distance modulus equation must be modified appropriately. In a given wavelength band centered on λ, we now have:

$$m_\lambda = M_\lambda + 5\log_{10} d - 5 + A_\lambda$$

where d is the distance in pc

and $A_\lambda > 0$ represents the number of magnitudes of interstellar extinction present along the line of sight.

If A_λ is large enough, a star that would otherwise be visible to the naked eye or through a telescope could no longer be detected.

Interstellar extinction - dust

Clearly A_λ must be related to the optical depth of the material, measured back along the line of sight. The fractional change in the intensity of the light is given by

$$I_\lambda / I_{\lambda,0} = e^{-\tau_\lambda}$$

where $I_{\lambda,0}$ is the intensity in the absence of interstellar extinction.
We can now relate the optical depth to the **change in apparent magnitude due to extinction**, giving

$$m_\lambda - m_{\lambda,0} = -2.5 \log_{10} \left(e^{-\tau_\lambda}\right) = 2.5\tau_\lambda \log_{10} e = 1.086\tau_\lambda$$

The change in apparent magnitude is just A_λ, so $\quad A_\lambda = 1.086\tau_\lambda$

The change in magnitude due to extinction is approximately equal to the optical depth along the line of sight.

Interstellar extinction - dust

The optical depth through the cloud is given by

$$\tau_\lambda = \int_0^s n_d(s')\, \sigma_\lambda \, ds',$$

where $n_d(s')$ is the number density of scattering dust grains and σ_λ is the scattering cross section. If σ_λ is constant along the line of sight, then

$$\tau_\lambda = \sigma_\lambda \int_0^s n_d(s')\, ds' = \sigma_\lambda N_d$$

where N_d **, the dust grain *column density***, is the number of scattering dust particles in a thin cylinder with a cross section of 1 m^2 stretching from the observer to the star. Thus we see that **the amount of extinction depends on the amount of interstellar dust that the light passes through**, as one would expect.

The Mie Theory

An If we assume for simplicity, as was first done by Gustav Mie (1868–1957) in 1908, that dust particles are spherical and each has a radius a, then the geometrical cross section that a particle presents to a passing photon is just $\sigma_g = \pi a^2$.

We may now define the dimensionless **extinction coefficient** Q_λ to be

$$Q_\lambda \equiv \frac{\sigma_\lambda}{\sigma_g}$$

where Q_λ depends on the composition of the dust grains.

Mie was able to show that **when the wavelength of the light is on the order of the size of the dust grains**, then $Q_\lambda \sim a/\lambda$, implying that

$$\sigma_\lambda \propto \frac{a^3}{\lambda} \qquad (\lambda \gtrsim a)$$

The Mie Theory

In the limit that **λ becomes very large relative to a,** Q_λ goes to zero (**no extinction**).

On the other hand, if **λ becomes very small relative to a**, it can be shown that Q_λ approaches a constant, independent of λ so that

$$\sigma_\lambda \propto a^2 \qquad (\lambda \ll a)$$

These limiting behaviors can be understood by analogy to waves on the surface of a lake.

- If the wavelength of the waves is much larger than an object in their way, such as a grain of sand, the waves pass by almost completely unaffected ($\sigma_\lambda \sim 0$).
- On the other hand, if the waves are much smaller than the obstructing object—for instance, an island—they are simply blocked; the only waves that continue on are those that miss the island altogether.

Similarly, at sufficiently short wavelengths, the only light we detect passing through the dust cloud is the light that travels between the particles.

The Mie Theory

The Pleiades star cluster

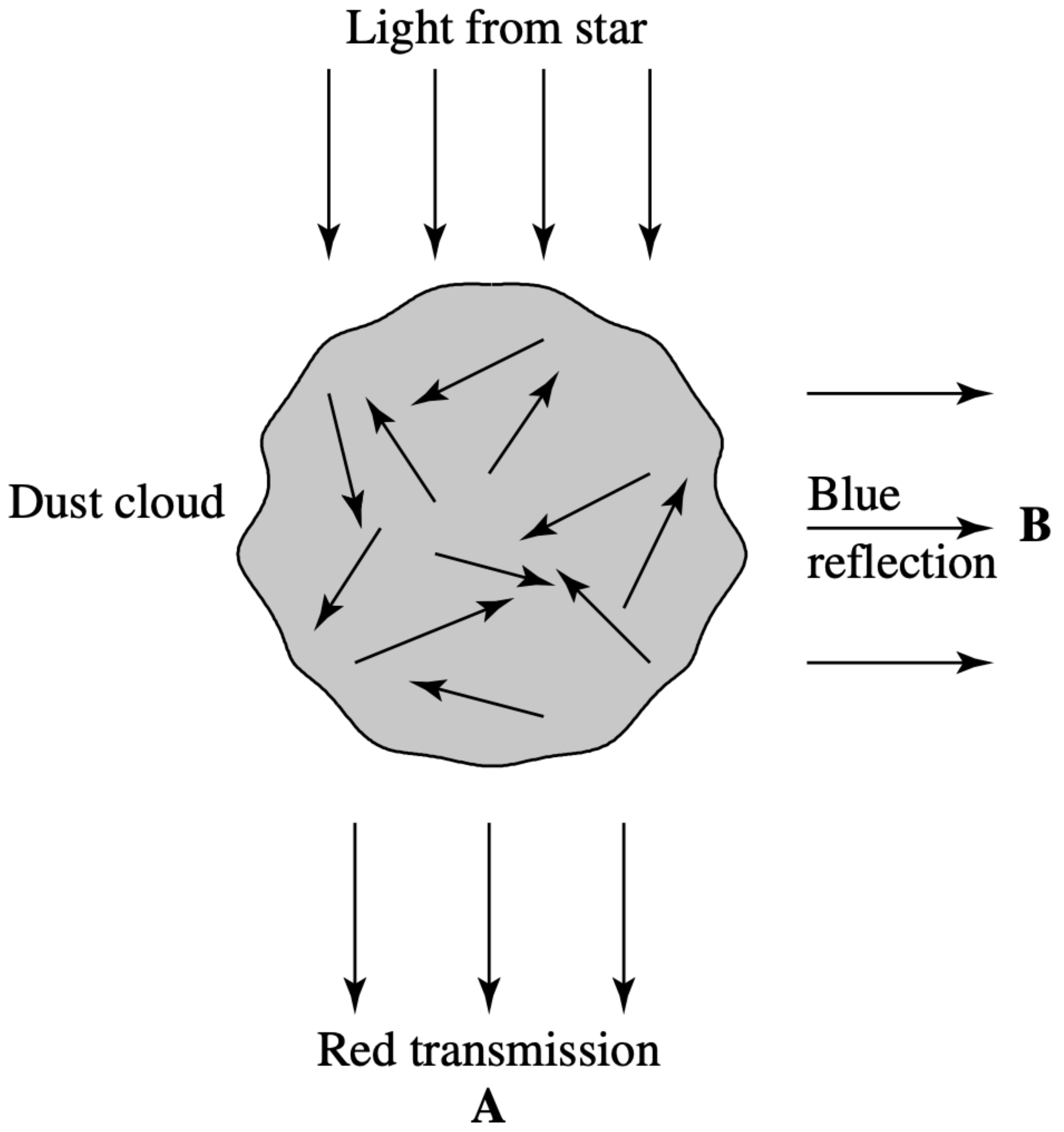
The amount of extinction, as measured by A_λ, must be wavelength-dependent.

Since the longer wavelengths of red light are not scattered as strongly as blue light, the starlight passing through intervening dust clouds becomes reddened as the blue light is removed. This **interstellar reddening** causes stars to appear redder than their effective temperatures would otherwise imply.

It is possible to detect this change by carefully analyzing the absorption and emission lines in the star's spectrum.

Much of the incident blue light is scattered out of its original path and can leave the cloud in virtually any direction. As a result, looking at the cloud in a direction other than along the line of sight to a bright star behind the cloud, an observer will see a blue **reflection nebula** such as the Pleiades.

This process is analogous to Rayleigh scattering, which produces a blue sky on Earth. The difference between Mie scattering and Rayleigh scattering is that the sizes of the scattering molecules associated with Rayleigh scattering are much smaller than the wavelength of visible light, leading to $\sigma_\lambda \propto \lambda^{-4}$.



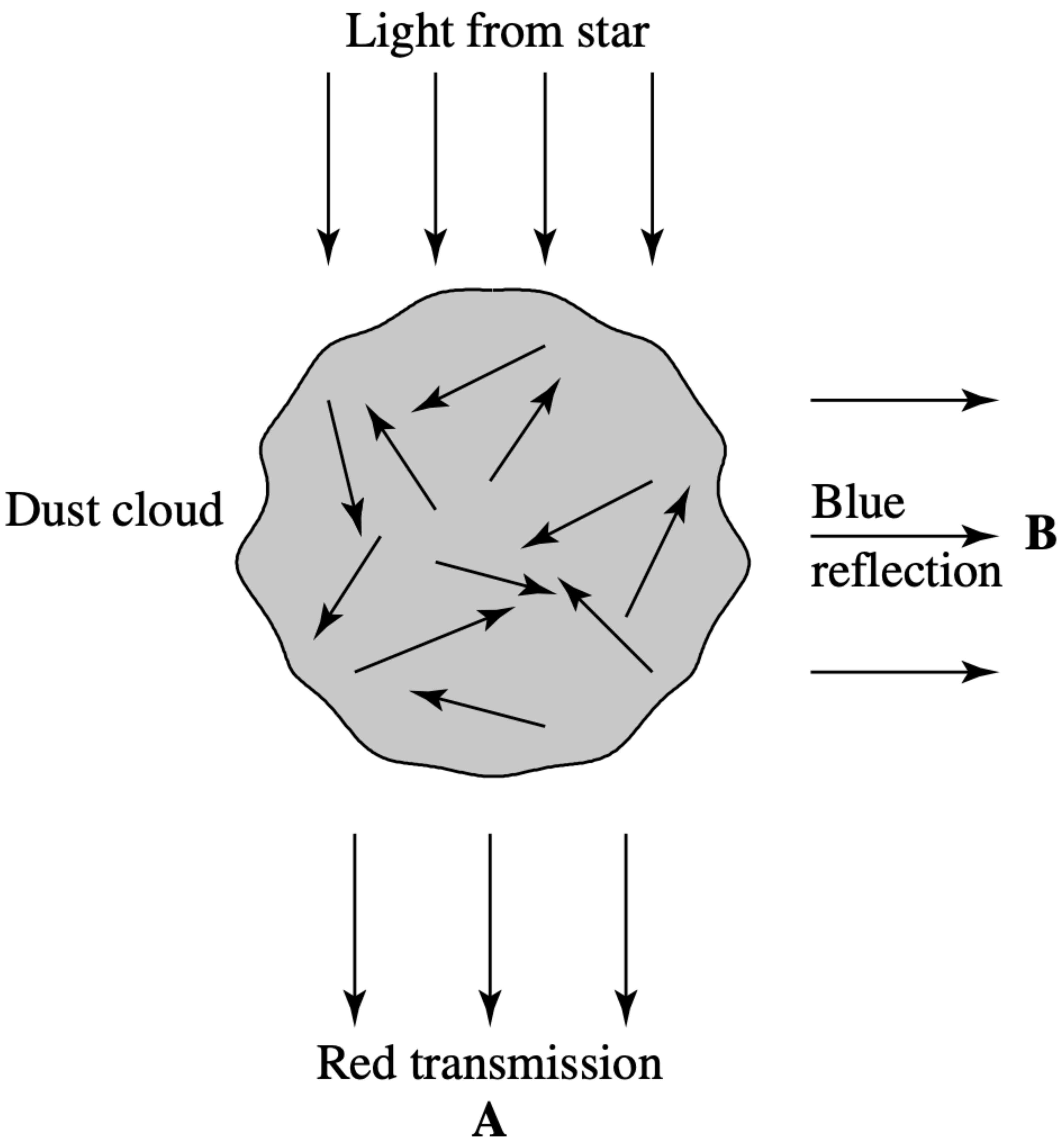
Interstellar extinction - dust

An interstellar cloud containing significant amounts of dust along with the gas (a dust cloud) can both scatter and absorb light that passes through it.

The amount of scattering and absorption depends on:

- the number density of dust grains,
- the wavelength of the light,
- and the thickness of the cloud.

Since shorter wavelengths are affected more significantly than longer ones, a star lying behind the cloud appears reddened to observer A. Observer B sees the scattered shorter wavelengths as a blue reflection nebula.



Interstellar extinction - dust

Example A certain star, located 0.8 kpc from Earth, is found to be dimmer than expected at 550 nm by $A_V = 1.1$ magnitudes, where A_V is the amount of extinction as measured through the *visual wavelength* filter.

If $Q_{550} = 1.5$ and the dust grains are assumed to be spherical with radii of 0.2 μm, estimate the average density ($\bar{n}$) of material between the star and Earth.

Interstellar extinction - dust

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The optical depth along the line of sight is nearly equal to the amount of extinction in magnitudes, or $\tau_{550} \simeq 1.1$ Also,

$$\sigma_{550} = \pi a^2 Q_{550} \simeq 2 \times 10^{-13}\ \mathrm{m}^2.$$

Now the column density of the dust along the line of sight is given by

$$N_d = \frac{\tau_{550}}{\sigma_{550}} \simeq 5 \times 10^{12}\ \mathrm{m}^{-2}.$$

Since

$$N_d = \int_0^s n(s')\, ds' = \bar{n} \times 0.8\ \mathrm{kpc},$$

$$\bar{n} = \frac{N_d}{0.8\ \mathrm{kpc}} = 2 \times 10^{-7}\ \mathrm{m}^{-3}.$$

Number densities of this magnitude are typical of the plane of the Milky Way Galaxy.

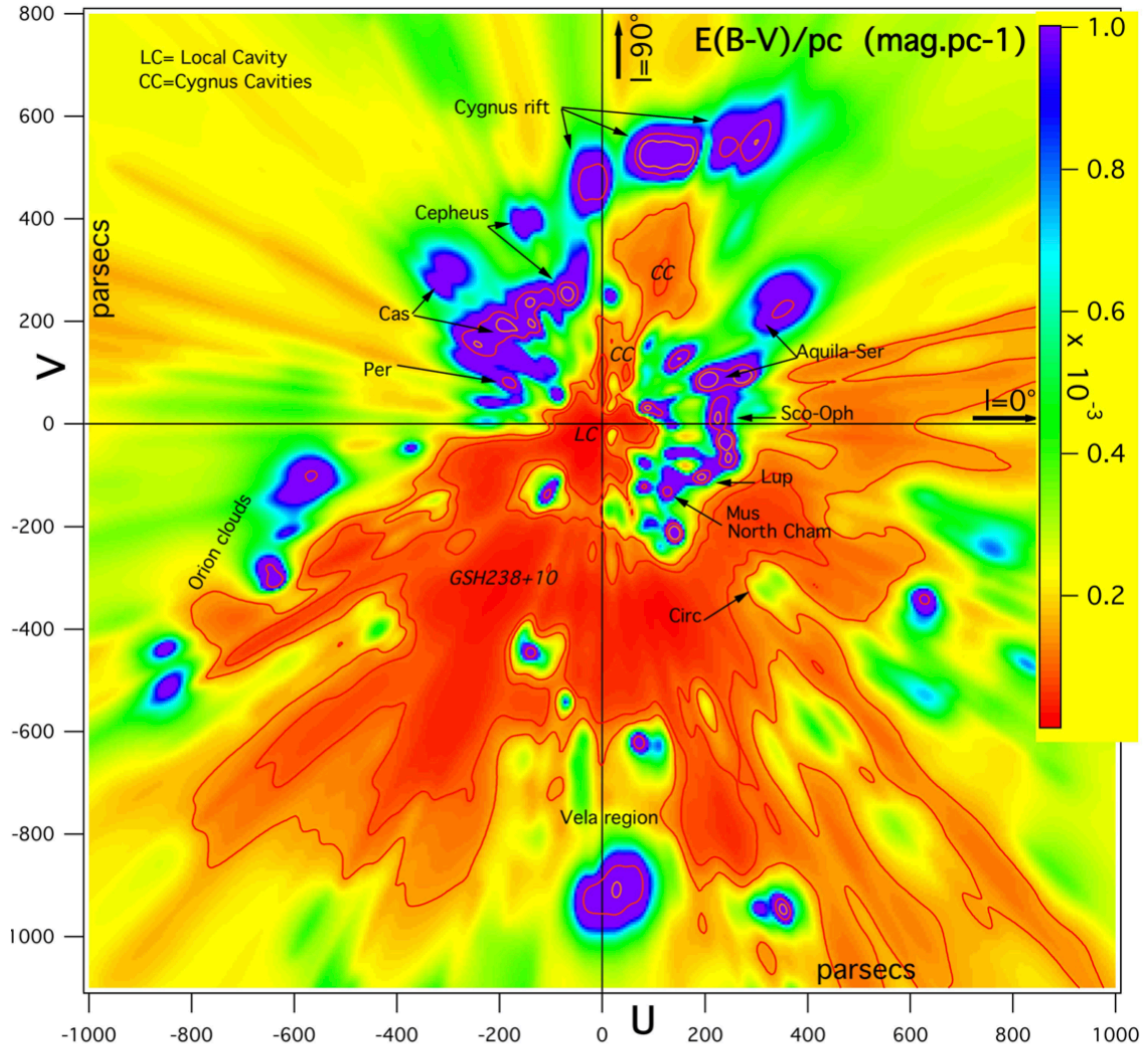
Interstellar extinction - dust

Why is it useful to know about the dust extinction?

Interstellar extinction - dust

Maps of interstellar reddening:

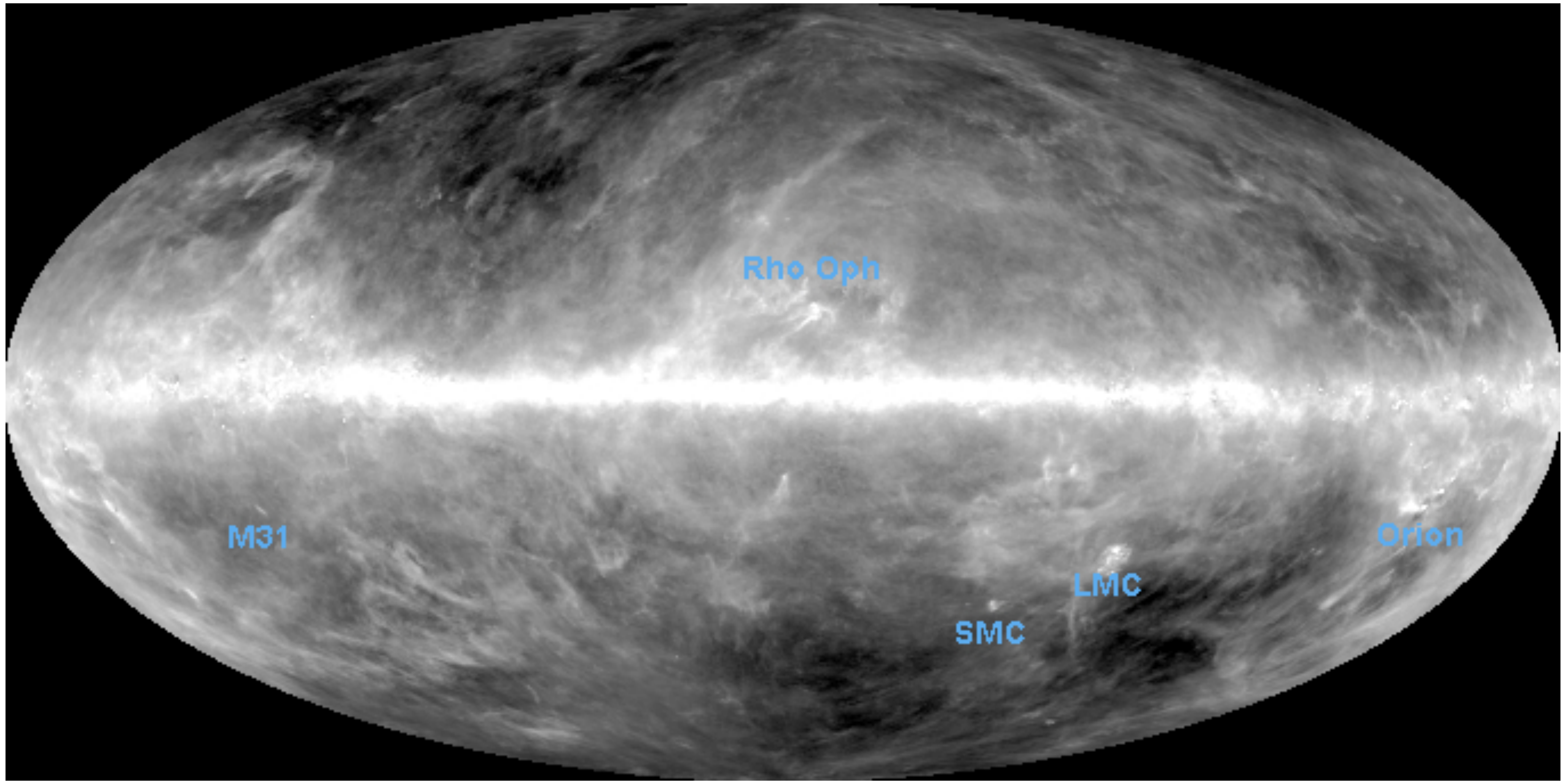
- Correcting the magnitude observations of all astrophysical objects.
- Learning about our closest environment: Local Bubble.



Lallement et al. 2014

Differential opacity distribution in the Galactic Plane

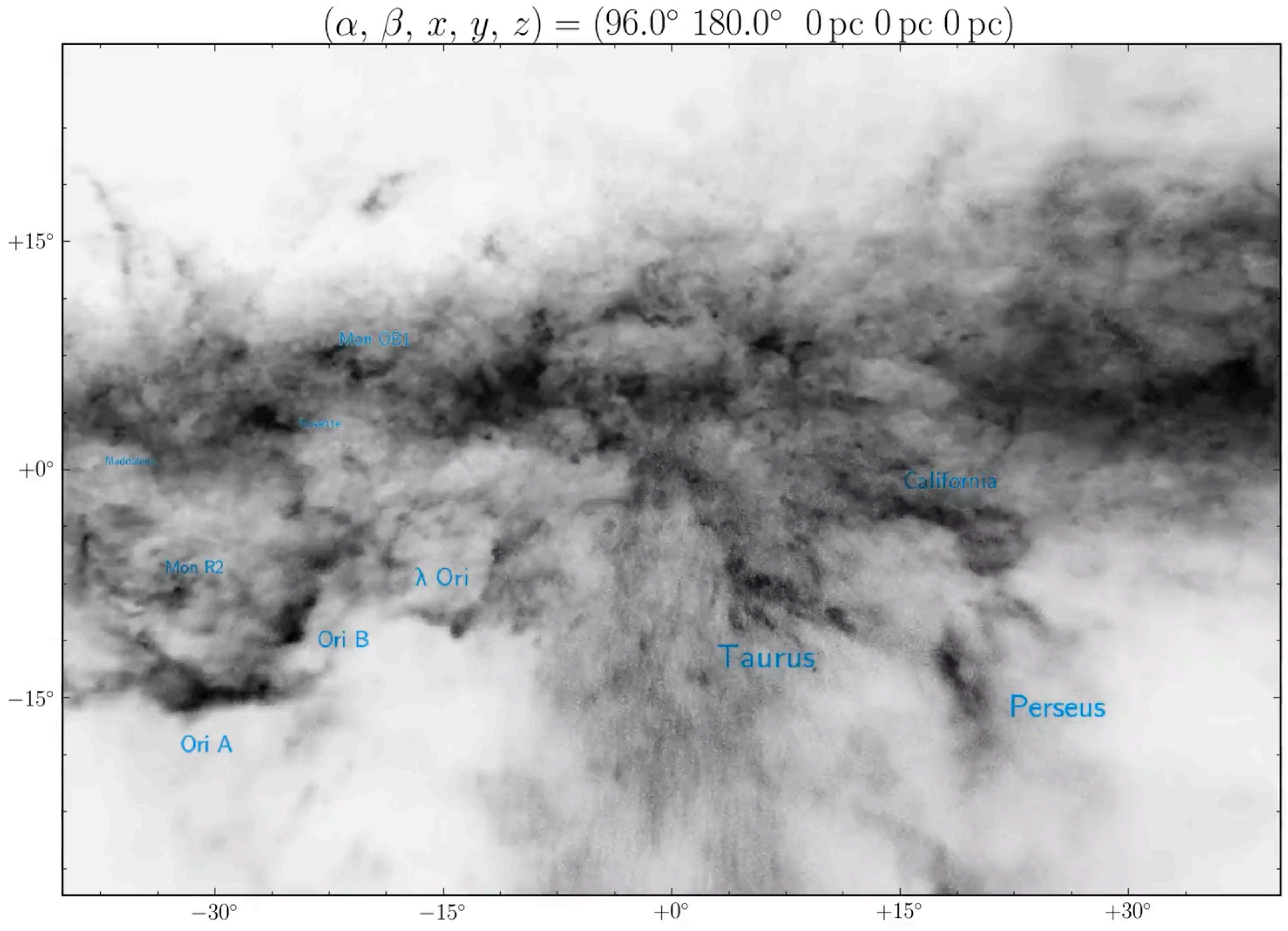
There is a cavity of material (red) around the Sun. This is often referred to as the Local Cavity or the Local Bubble.



Dust extinction map based on infrared IRAS 100 micron images

Interstellar extinction - dust

3D Dust Mapping
with Pan-STARRS 1, 2MASS and Gaia



http://argonaut.skymaps.info/

Interstellar extinction

What is the interstellar dust made of?

Interstellar extinction

Predictions of the Mie theory work well for longer wavelengths, typically from the infrared into the visible wavelength region.

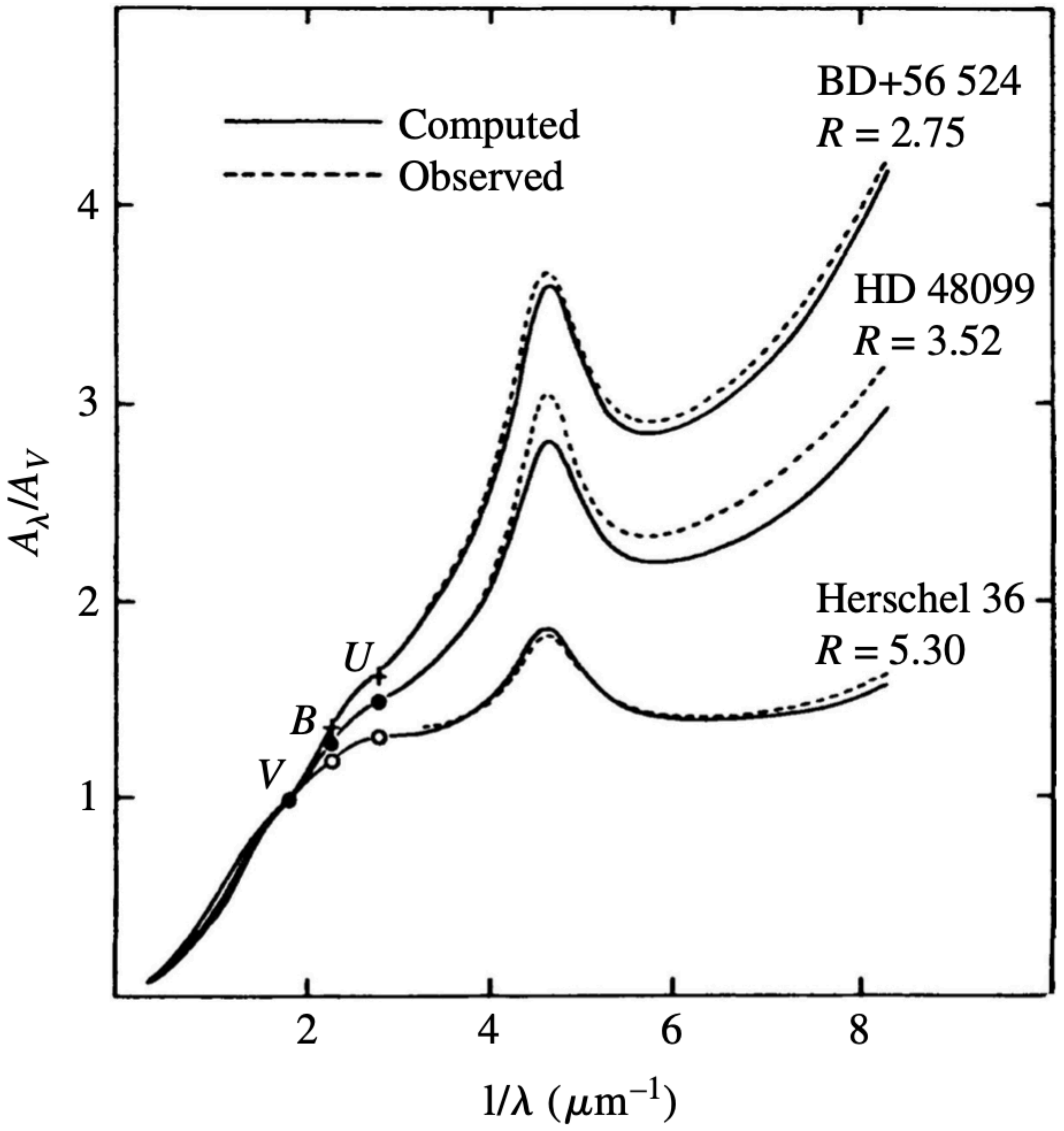
However, at **ultraviolet wavelengths significant deviations** become apparent, as can be seen by considering the ratio of A_λ, the extinction in a wavelength band centered at λ, to the extinction in some reference wavelength band, such as A_V.

This ratio is often plotted versus reciprocal wavelength λ^{-1}

Alternatively, **color excesses** are sometimes plotted instead, such as $(A_\lambda - A_V) / (A_B - A_V)$

or $E(B-V) \equiv (B-V)_{intrinsic} - (B-V)_{observed}$.

Dashed lines - observations
Solid lines - theoretical fits



Shorter wavelengths

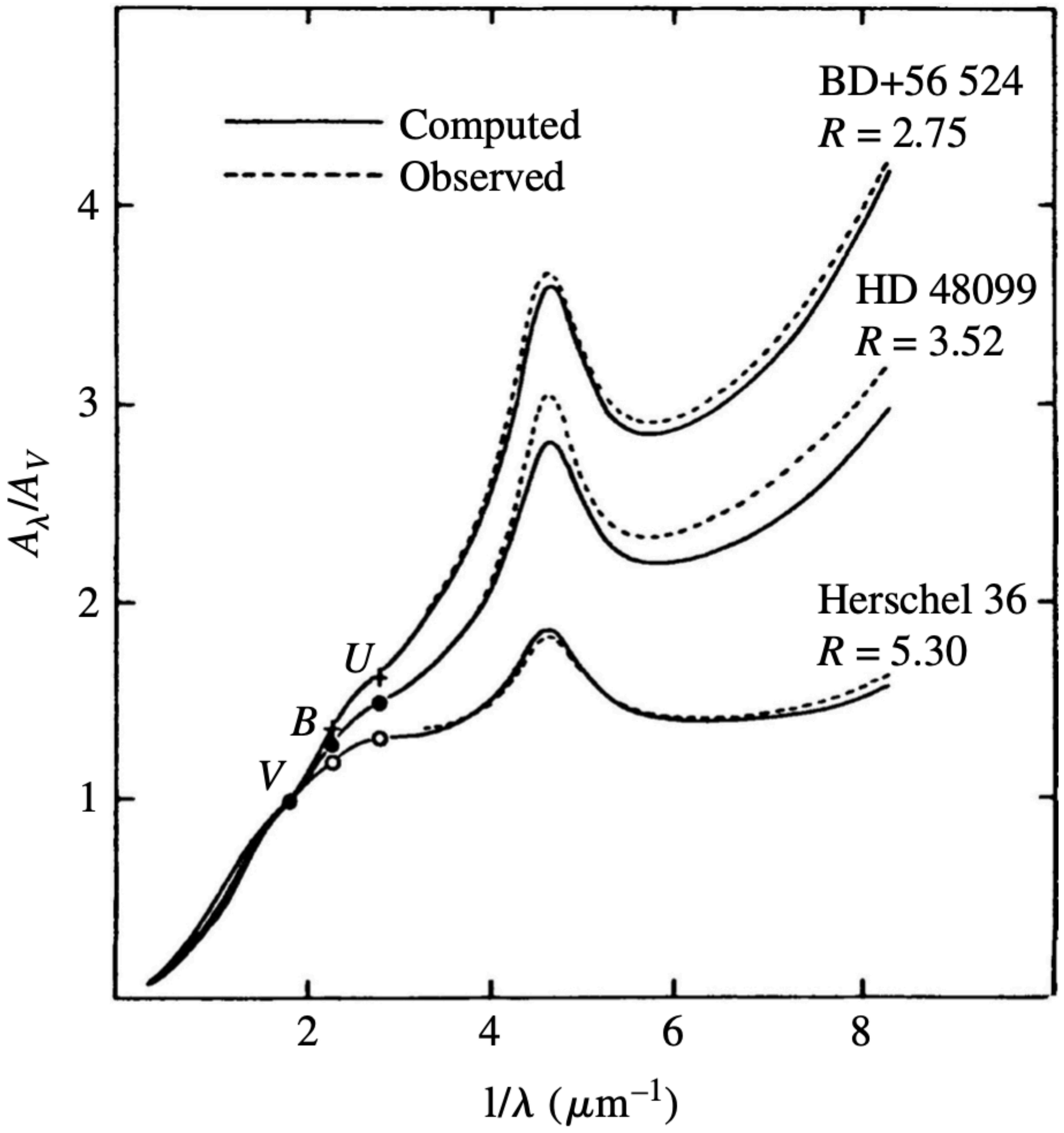
Interstellar extinction

Dashed lines - observations
Solid lines - theoretical fits

At longer wavelengths (the left side of the graph) the data agree well with the Mie theory. For wavelengths shorter than the blue wavelength band (B), however, the curves begin to diverge significantly, deviating from the expected relation, $A_\lambda/A_V \propto \lambda^{-1}$.

Particularly evident is the "bump" in the ultraviolet at 217.5 nm or 4.6 μm^{-1}.

At even shorter wavelengths, the extinction curve tends to rise sharply as the wavelength decreases.



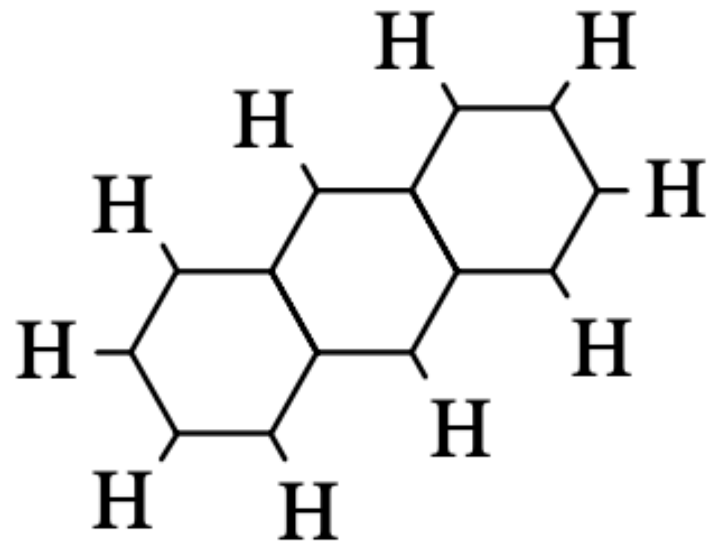
Shorter wavelengths

Interstellar extinction

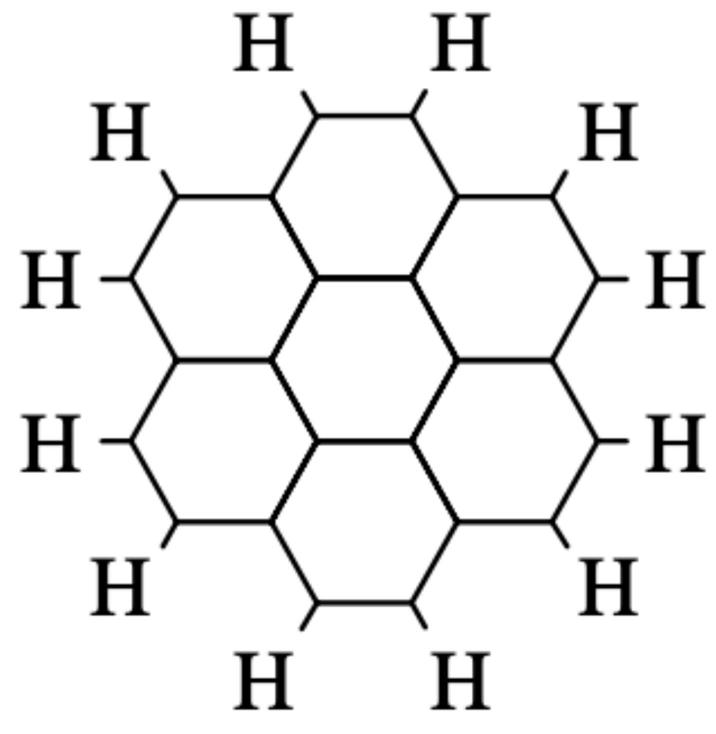
The existence of the “bump” gives us some hint of the composition of the dust.

Graphite, interacts strongly with light near 217.5 nm. Although it is uncertain how carbon can organize into large graphite particles in the interstellar medium, the strength of the “bump,” the abundance of carbon, and the existence of the 217.5-nm resonance have led most researchers to suggest that graphite may be a major component of interstellar dust.

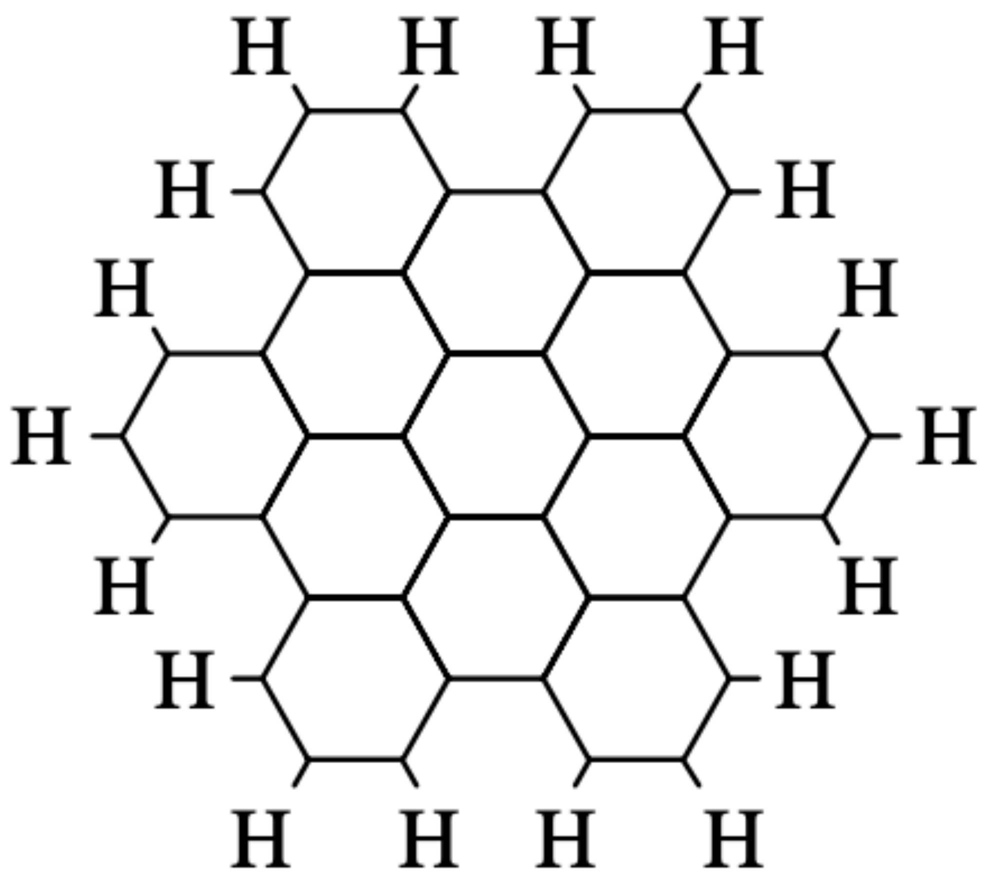
Another possible source of the 217.5-nm feature may be **polycyclic aromatic hydrocarbons** (PAHs). These are complex organic planar molecules with multiple benzene ring-like structures that are probably responsible for a series of molecular bands that have been observed in emission in the light from diffuse dust clouds.



$C_{14}H_{10}$



$C_{24}H_{12}$



$C_{42}H_{18}$

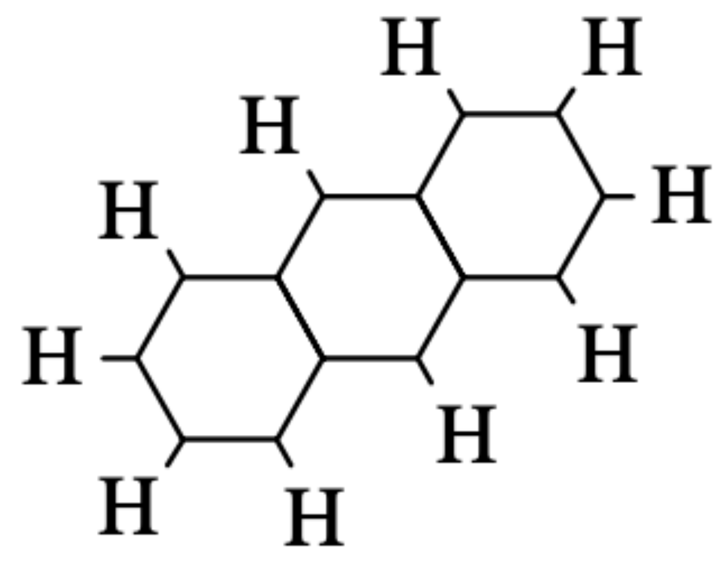
The structures of several polycyclic aromatic hydrocarbons: $C_{14}H_{10}$ (anthracene), $C_{24}H_{12}$ (coronene), $C_{42}H_{18}$ (hexabenzocoronene). The hexagonal structures indicate the presence of a carbon atom at each corner of the hexagon.

Interstellar extinction

The so-called *unidentified infrared emission bands* exist in the wavelength range between 3.3 μm and 12 μm; they appear to be due to vibrations in the C-C and C-H bonds common in PAHs.

Just as transitions between atomic energy levels are quantized, so are the energies associated with molecular bonds.

In the case of molecular bonds, the energy levels tend to be grouped in closely spaced bands, producing characteristic broad features in the spectrum of the light. **The vibration, rotation, and bending of molecular bonds are all quantized,** yielding complex spectra.



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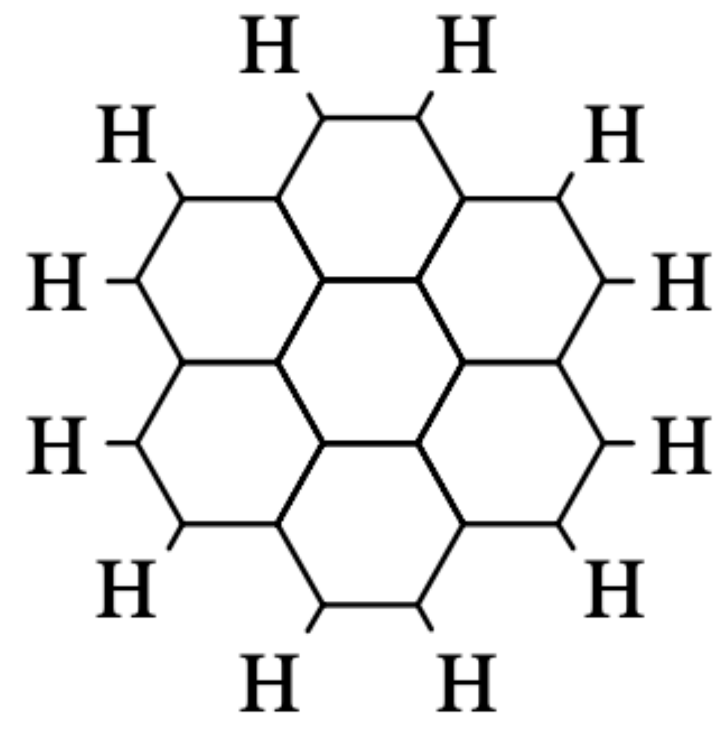

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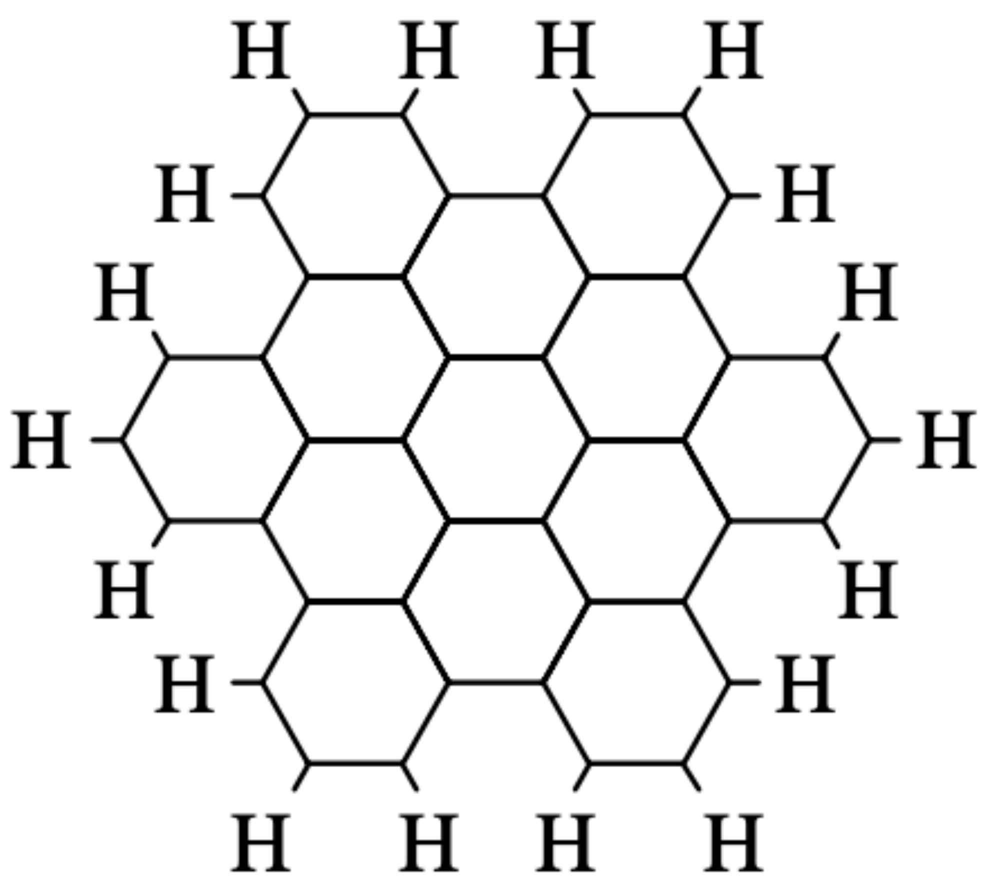

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Interstellar extinction

Interstellar dust is composed of other particles as well, as evidenced by the existence of dark absorption bands at wavelengths of 9.7 μm and 18 μm in the near-infrared. These features are believed to be the result of the stretching of the Si-O molecular bond and the bending of Si-O-Si bonds in **silicates**, respectively. The existence of these absorption bands involving silicon indicates that silicate grains are also present in the dust clouds and the diffuse dust of the ISM.

An important characteristic of the light scattered from interstellar dust is that it tends to be slightly **polarized**. The amount of polarization is typically a few percent and depends on wavelength. This necessarily **implies that the dust grains cannot be perfectly spherical**. Furthermore, they must be at least **somewhat aligned along a unique direction** since the electric field vectors of the radiation are preferentially oriented in a particular direction. The most likely way to establish such an alignment is for the **grains to interact with a weak magnetic field.** Because less energy is required, the particles tend to rotate with their long axes perpendicular to the direction of the magnetic field.

All of these observations give us some clues to the nature of the dust in the ISM. Apparently **the dust in the ISM is composed of both graphite and silicate grains ranging in size from several microns down to fractions of a nanometer, the characteristic size of the smaller PAHs.**

Interstellar extinction - gas

Although dust produces most of the obscuration that is readily noticeable, the dominant component of the ISM is hydrogen gas in its various forms:

- neutral hydrogen (H I),
- ionized hydrogen (H II),
- and molecular hydrogen (H_2).

Hydrogen comprises approximately 70% of the mass of matter in the ISM, and **helium** makes up most of the remaining mass; **metals,** such as carbon and silicon, **account for only a few percent of the total**.

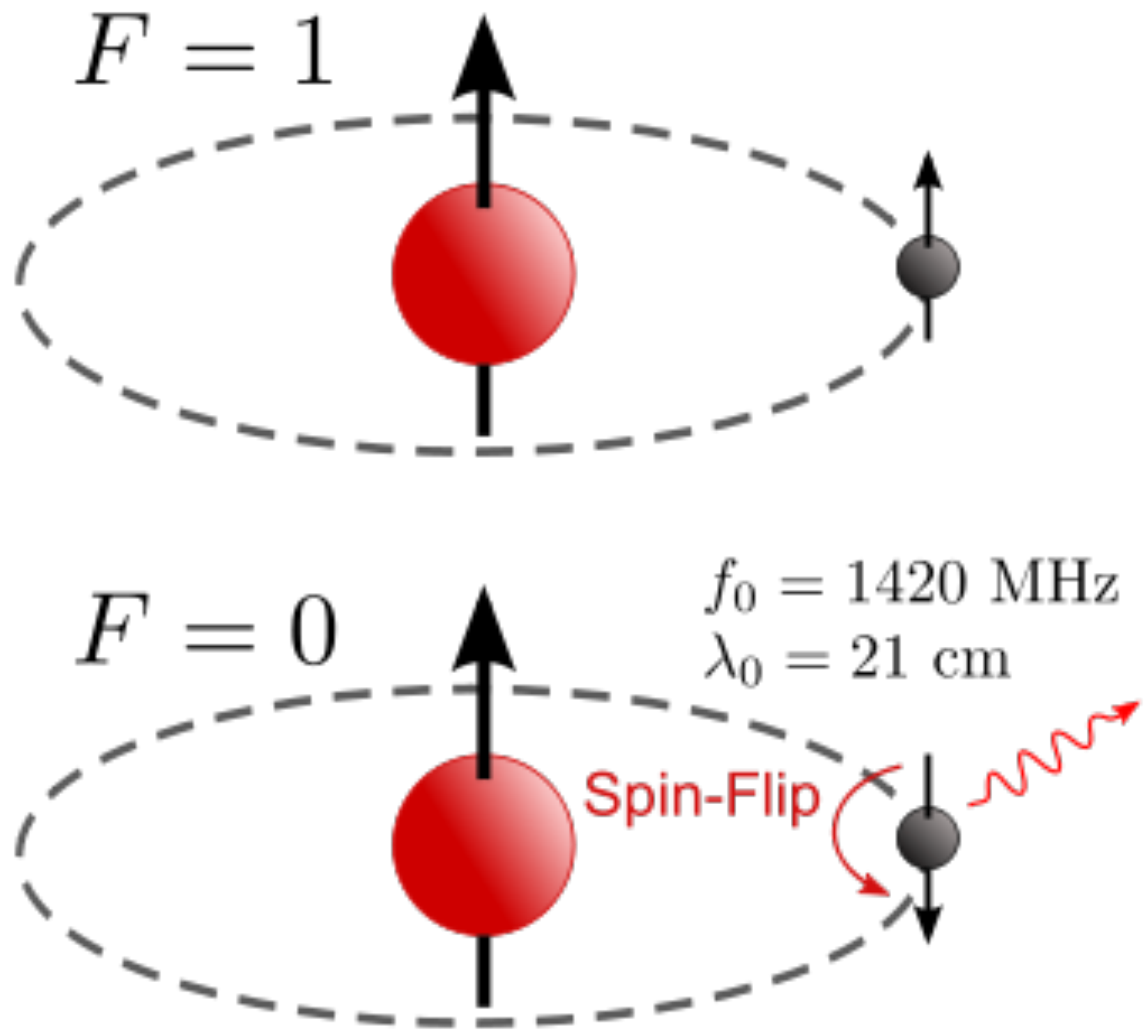
Most hydrogen in *diffuse* interstellar hydrogen clouds is in the form of H I in the ground state. As a result, the H I is generally incapable of producing emission lines by downward transitions of electrons from one orbit to another. It is also difficult to observe H I in absorption, since UV-wavelength photons are required to lift the electrons out of the ground state.

Interstellar extinction - gas

H I is detected in the unique radio-wavelength **21-cm line**. The 21-cm line is produced by the reversal of the spin of the electron relative to the proton in the atom's nucleus.

If the spins of the electron and proton are aligned (e.g., both spin axes are in the same direction), the atom has slightly more energy than if they are anti-aligned. As a result, if the electron's **spin "flips"** from being aligned with the proton to being anti-aligned, energy must be lost from the atom.

A photon can also be absorbed, exciting a hydrogen atom into aligning its electron and proton spins. The wavelength of the photon associated with the spin flip is **21.1 cm**, corresponding to a frequency of **1420 MHz.**



Interstellar extinction - gas

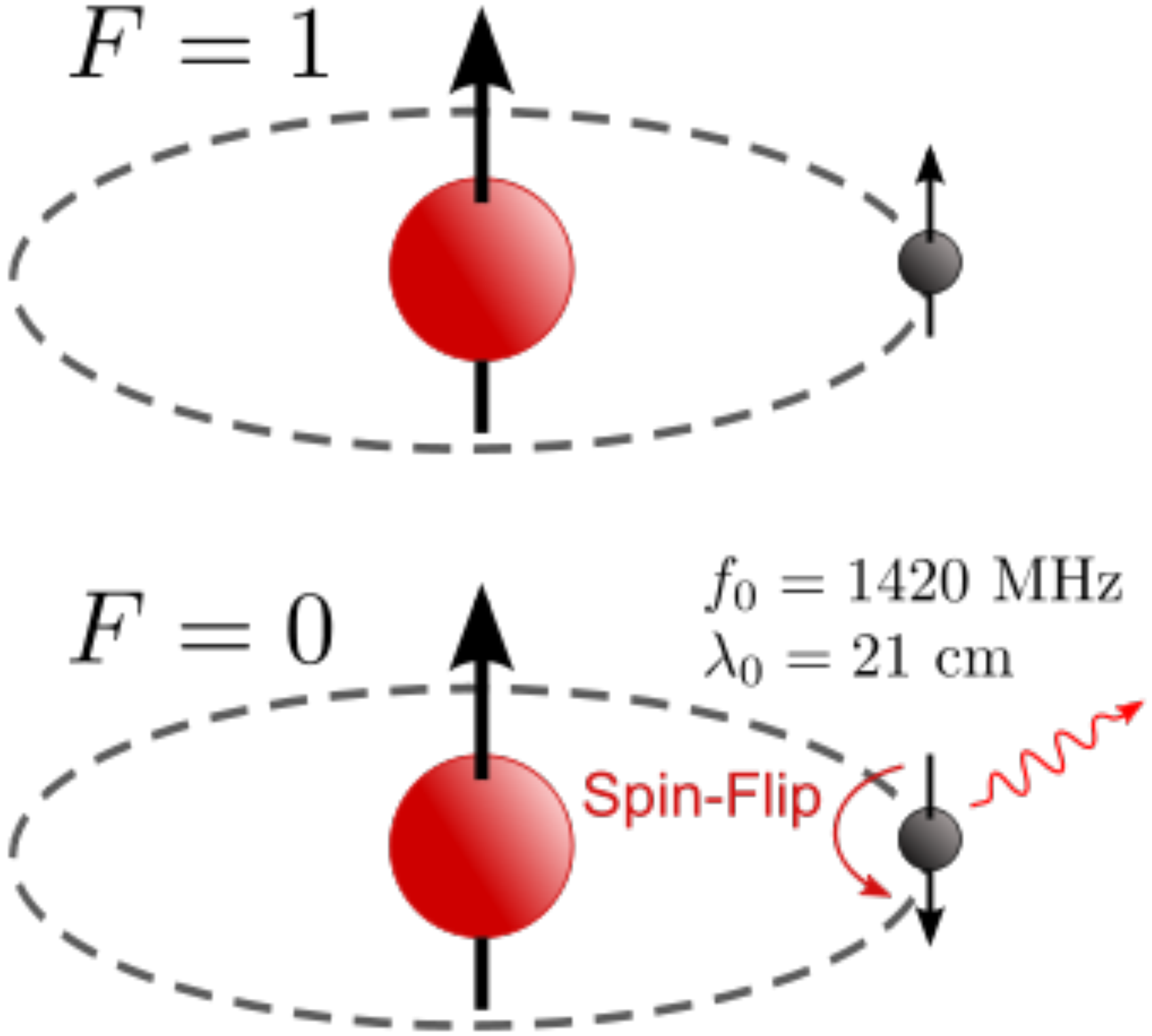
The emission of a 21-cm photon from an individual hydrogen atom is **extremely rare**. Several million years can pass on average before that atom will emit a photon. However, there is a lot of hydrogen in the universe.

The existence of 21-cm radiation was predicted in the early 1940s and first detected in 1951.

Since then it has become an important tool in:

- **mapping the location and density of H I,**
- **measuring radial velocities using the Doppler effect, and**
- **estimating magnetic fields using the Zeeman effect.**

21-cm radiation is particularly valuable in **determining the structure and kinematic properties of galaxies**, including our own.



Interstellar extinction - gas

Although H I is quite abundant, the rarity of 21-cm emission (or absorption) from individual atoms means that the center of this line can remain **optically thin over large interstellar distances**.

Assuming that the line profile is a Gaussian, like the shape of the Doppler line profile, the optical depth of the line center is given by

$$\tau_H = 5.2 \times 10^{-15} \frac{N_H}{T\,\Delta v}$$

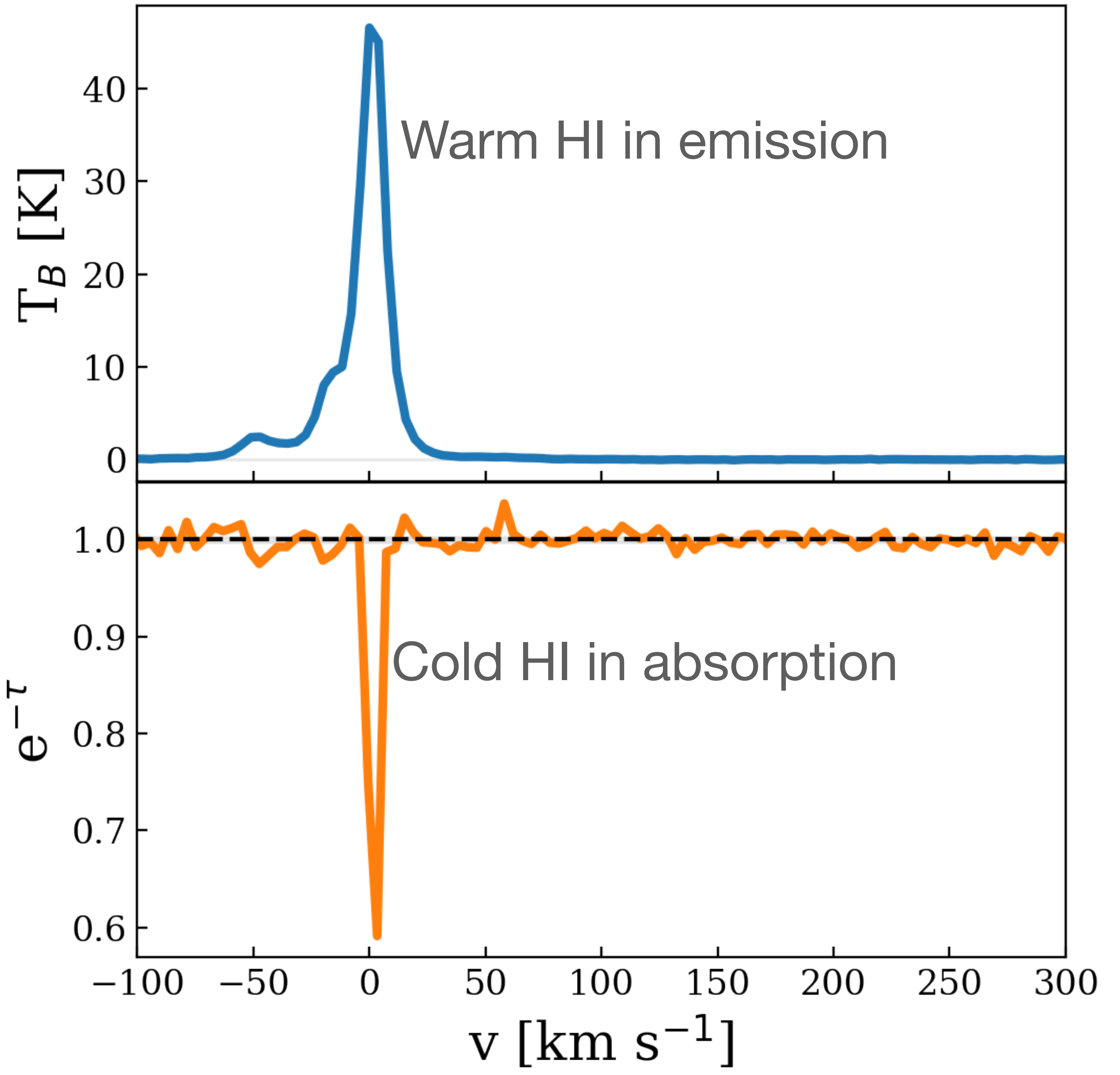
where N_H is the column density of H I (in units of m^{-2}), T is the temperature of the gas (in kelvins), and Δv is the full width of the line at half maximum (in km s^{-1}).

[Δv is expressed in units of velocity, rather than in wavelength units; typically $\Delta v \sim 10$ km s^{-1}.]

Filamentary HI in the Galaxy

Interstellar extinction - gas

- As long as the 21-cm hydrogen line is optically thin (i.e., on the linear part of the curve of growth), the optical depth is proportional to the neutral hydrogen column density.
- Studies of **diffuse H I clouds** indicate temperatures of 30 to 80 K, number densities in the range of $1 \times 10^8 m^{-3}$ to $8 \times 10^8 m^{-3}$, and masses on the order of 1–100 $M_\odot$.
- Comparing τ_H with A_V along the same line of sight shows that N_H is generally proportional to N_d (the column density of dust) when $A_V < 1$.
- **This observation suggests that dust and gas are distributed together throughout the ISM**.
- However, when $A_V > 1$, this correlation breaks down; the column density of H I no longer increases as rapidly as the column density of dust.



Molecular hydrogen

Optically thick dust clouds shield hydrogen from sources of ultraviolet radiation. One consequence of this is that molecular hydrogen can exist without the threat of undergoing **dissociation by UV photon** absorption.

Dust can also **enhance the H_2 formation rate** beyond what would be expected by random collisions of hydrogen atoms.

- A dust grain can provide a ***site*** on the surface of the grain where the hydrogen atoms can meet, rather than requiring chance encounters in the ISM, and
- the dust provides a ***sink*** for the binding energy that must be liberated if a stable molecule is to form. The liberated energy goes into heating the grain and ejecting the H_2 molecule from the formation site.

If the column density of **atomic hydrogen** is sufficiently large (N_H on the order of 10^{25} m^{-2}), it **can also shield H_2 from UV photodissociation**. Consequently, **molecular clouds are surrounded by shells of H I.**

Molecular hydrogen

The H_2 molecule does not emit 21-cm radiation. This explains why N_H and A_V are poorly correlated in molecular clouds when $A_V > 1$; the **number density of atomic hydrogen decreases significantly as the hydrogen becomes locked up in its molecular form.**

Unfortunately, **H_2 is very difficult to observe directly** because the molecule does not have any emission or absorption lines in the visible or radio portions of the electromagnetic spectrum at the cool temperatures typical of the ISM.

In special circumstances when $T > 2000$ K, it is possible to detect rotational and vibrational bands (known collectively as *rovibrational bands*) associated with the molecular bond.

However, in most cases it is necessary to use other molecules as ***tracers* of H_2** by making the assumption that their abundances are proportional to the abundance of H_2. Because of its relatively high abundance (approximately 10^{-4} that of H_2), the most commonly investigated tracer is **carbon monoxide, CO**.

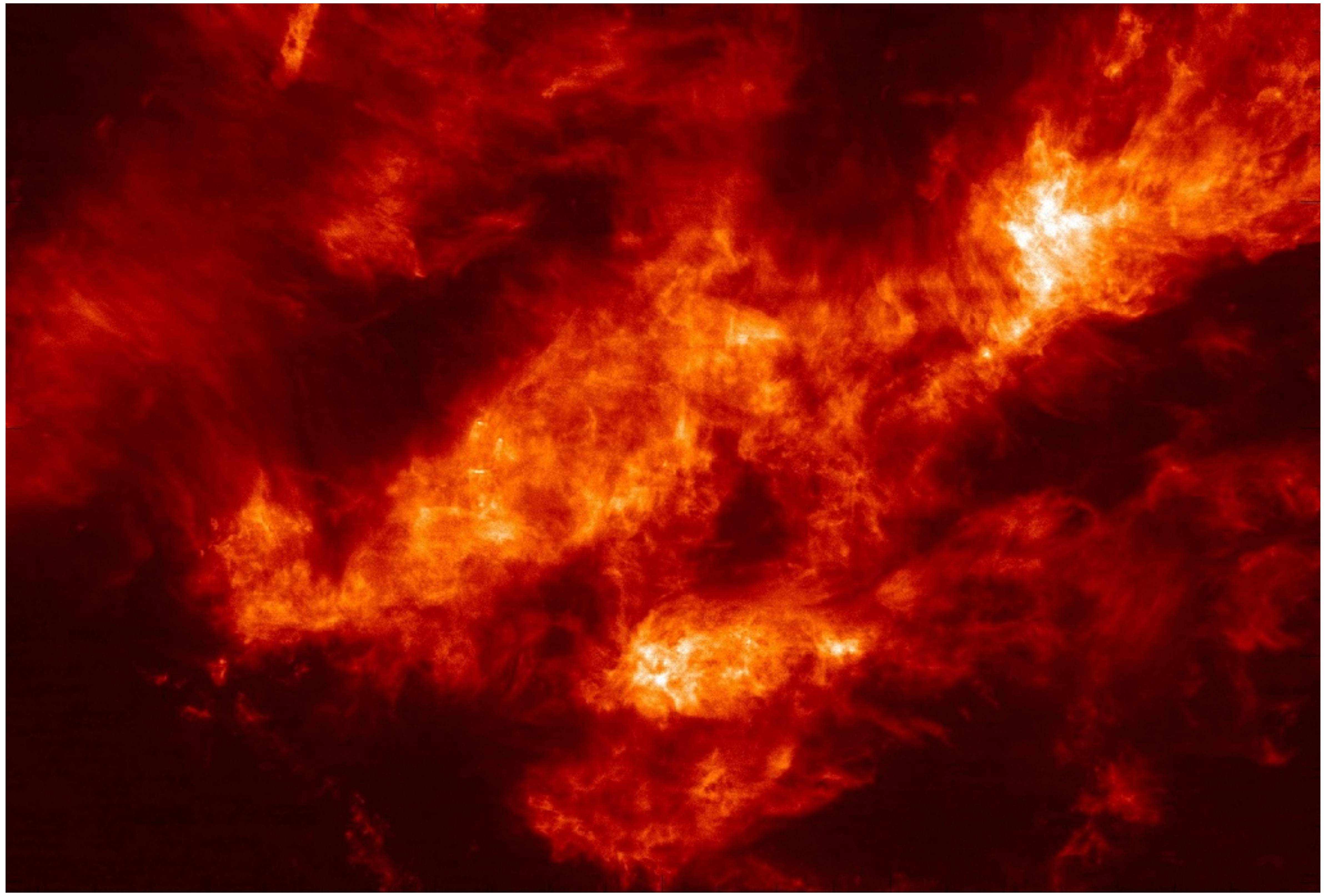
- other tracer molecules CH, OH, CS, C3H2, HCO+, and N2H+.
- It is also possible to use **isotopomers** of the molecules, such as ^{13}CO or $C^{18}O$.

Molecular hydrogen

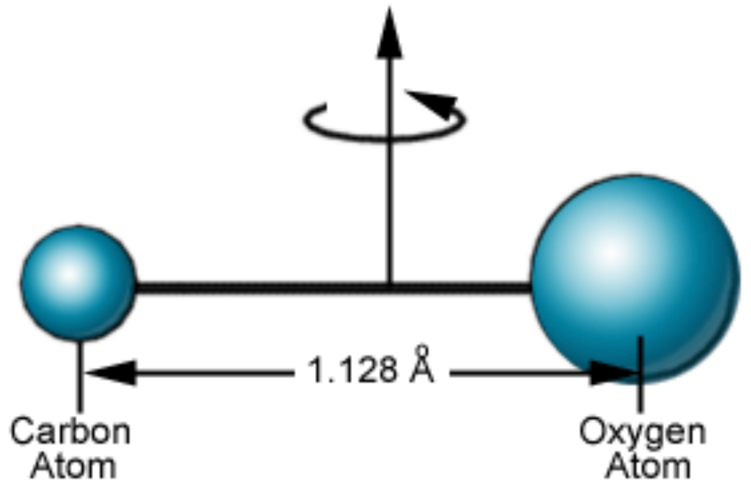
During collisions the tracer molecules become excited (or de-excited) and spontaneous transitions from excited states result in the emission of photons in wavelength regions that are more easily observed than those associated with H_2, such as the 2.6-mm transition of CO.

Since collision rates depend on both the gas temperature (or thermal kinetic energy) and the number densities of the species, **molecular tracers can provide information about the environment within a molecular cloud**.

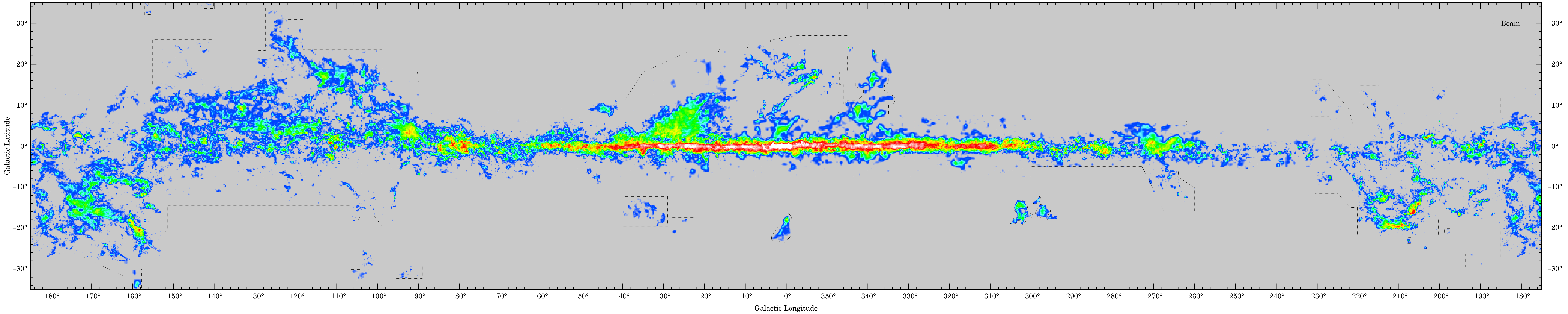
- The Taurus molecular cloud complex in CO
- Notice the filamentary and turbulent structure

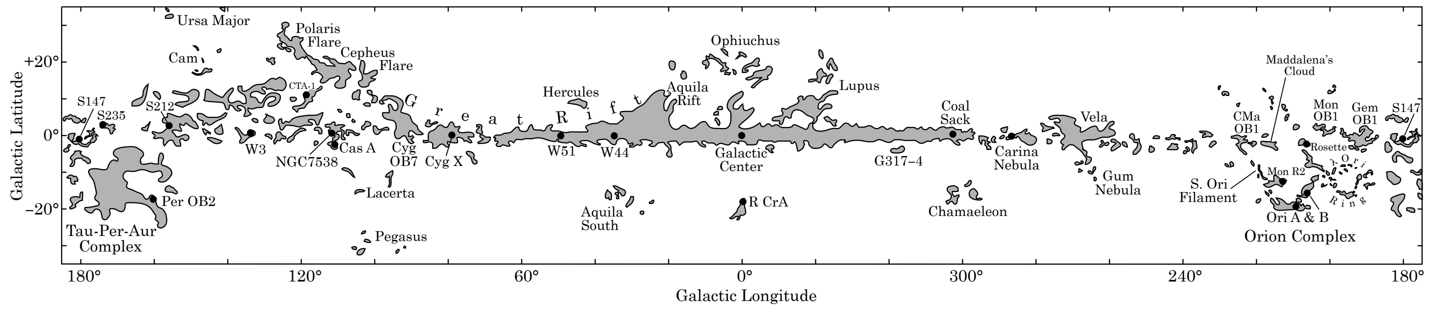


Molecular hydrogen



- The **distribution of CO in the Galaxy** has been studied quite extensively and is found to be somewhat different from the distribution of neutral hydrogen HI. Not much CO is found beyond 10 kpc from the galactic centre, whereas HI can be found at much greater distances.
  - Several **rotational lines:**
    - the fundamental frequency for CO is 115 GHz, corresponding to a wavelength of 2.6 mm.
    - The next higher frequencies are at 230 GHz, 345 GHz, and so on.





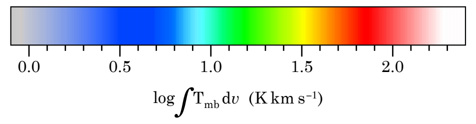


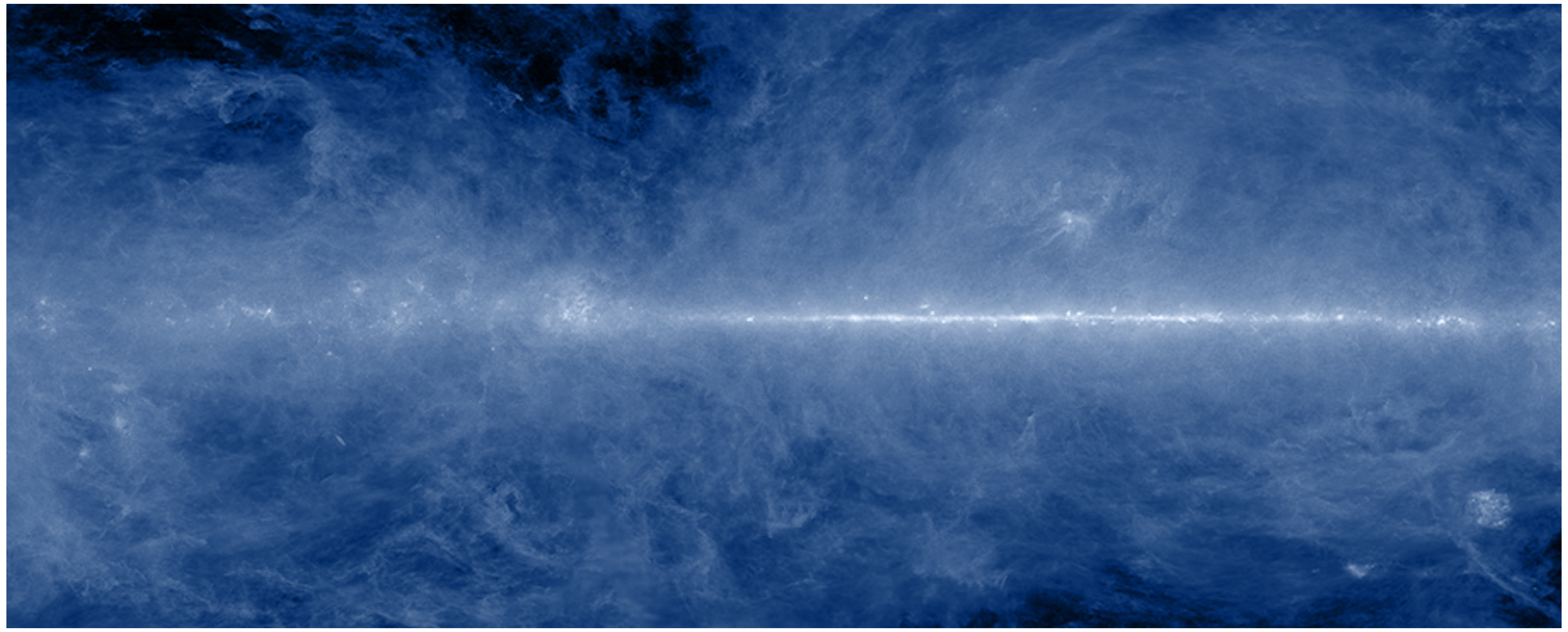
FIG. 2.–Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey was integrated individually using moment masking or clipping in order to display all statistically significant emission but little noise (see §2.2). A dotted line marks the sampling boundaries, given in more detail in Fig. 1.

Classification of Interstellar clouds

Conditions within molecular clouds can vary widely.

A **broad classification scheme** is still useful for distinguishing the general characteristics of specific environments.

In clouds where the hydrogen gas is primarily atomic and the interstellar extinction is roughly $1 < A_V < 5$, molecular hydrogen may be found in regions of higher column density. Such clouds are sometimes referred to as **diffuse molecular clouds**, or alternatively as **translucent molecular clouds**. Conditions in diffuse molecular clouds are typical of diffuse H I clouds but with somewhat higher masses; they have temperatures of 15 to 50 K, $n \sim 5\times10^8$ to $5\times10^9\ \mathrm{m}^{-3}$, $M \sim 3$ to $100\ M_\odot$, and they measure several parsecs across. Both H I clouds and diffuse molecular clouds tend to be irregularly shaped.



Infrared cirrus observed at 100 microns
Diffuse clouds at high Galactic latitude
Image: IRAS/COBE

Classification of Interstellar clouds

Giant molecular clouds (GMCs) are enormous complexes of dust and gas where temperatures are typically T ~ 15 K, number densities are in the range n ~ $1 \times 10^8 m^{-3}$ to $3 \times 10^8 m^{-3}$, masses are typically 10^5 $M_\odot$ but may reach 10^6 $M_\odot$, and typical sizes are on the order of 50 pc across. The famous Horsehead Nebula, also known as Barnard 33 (B33).

The Horsehead Nebula is a portion of the Orion giant molecular cloud complex. **Thousands of GMCs** are known to exist in our Galaxy, **mostly in its spiral arms.**

The overall, the structure of GMCs tend to be **clumpy with local regions of significantly greater density.**

The "horsehead" appearance is due to dust protruding into an H II (ionized hydrogen) environment.

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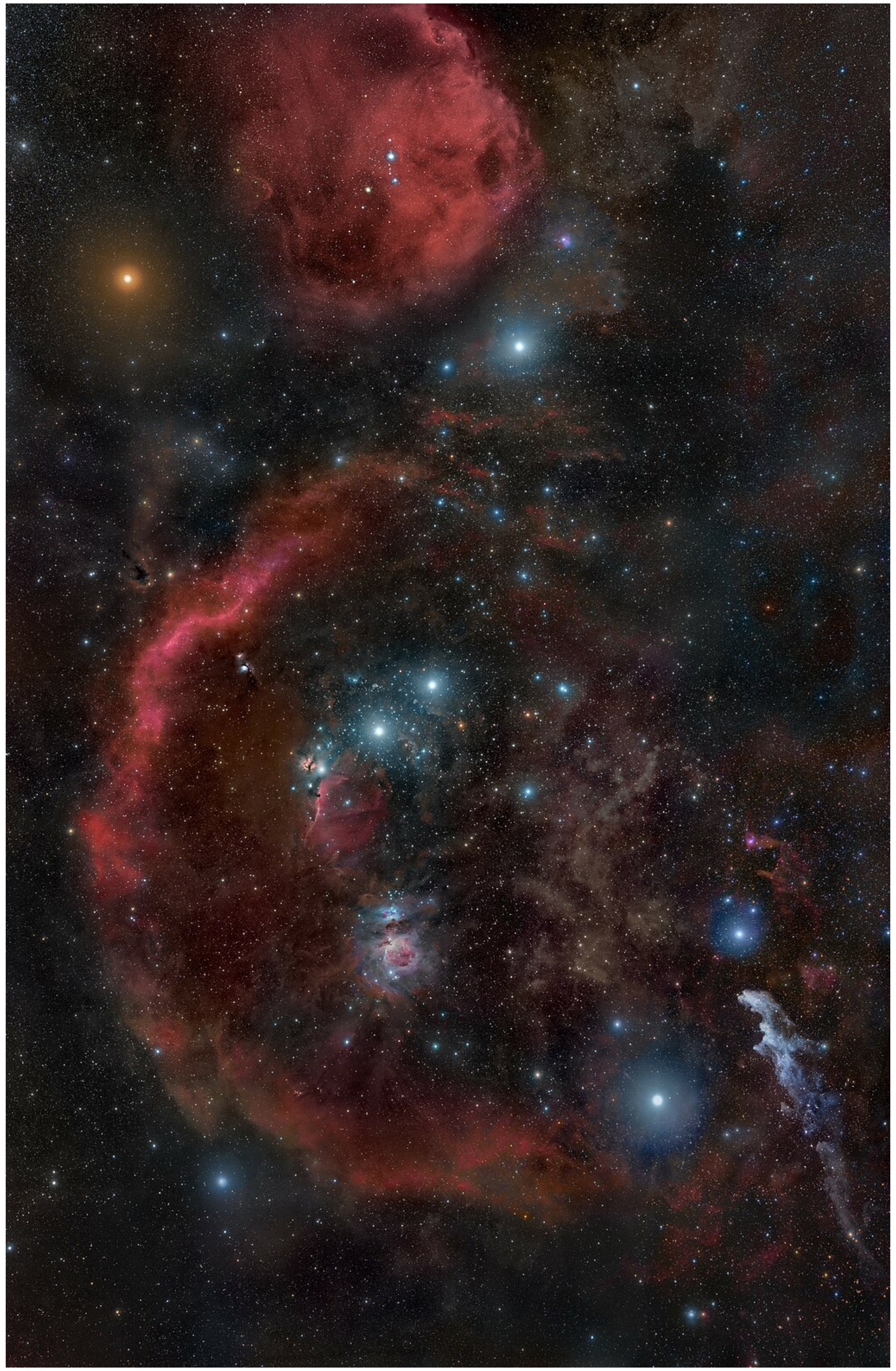


The Orion giant molecular cloud complex.

Classification of Interstellar clouds

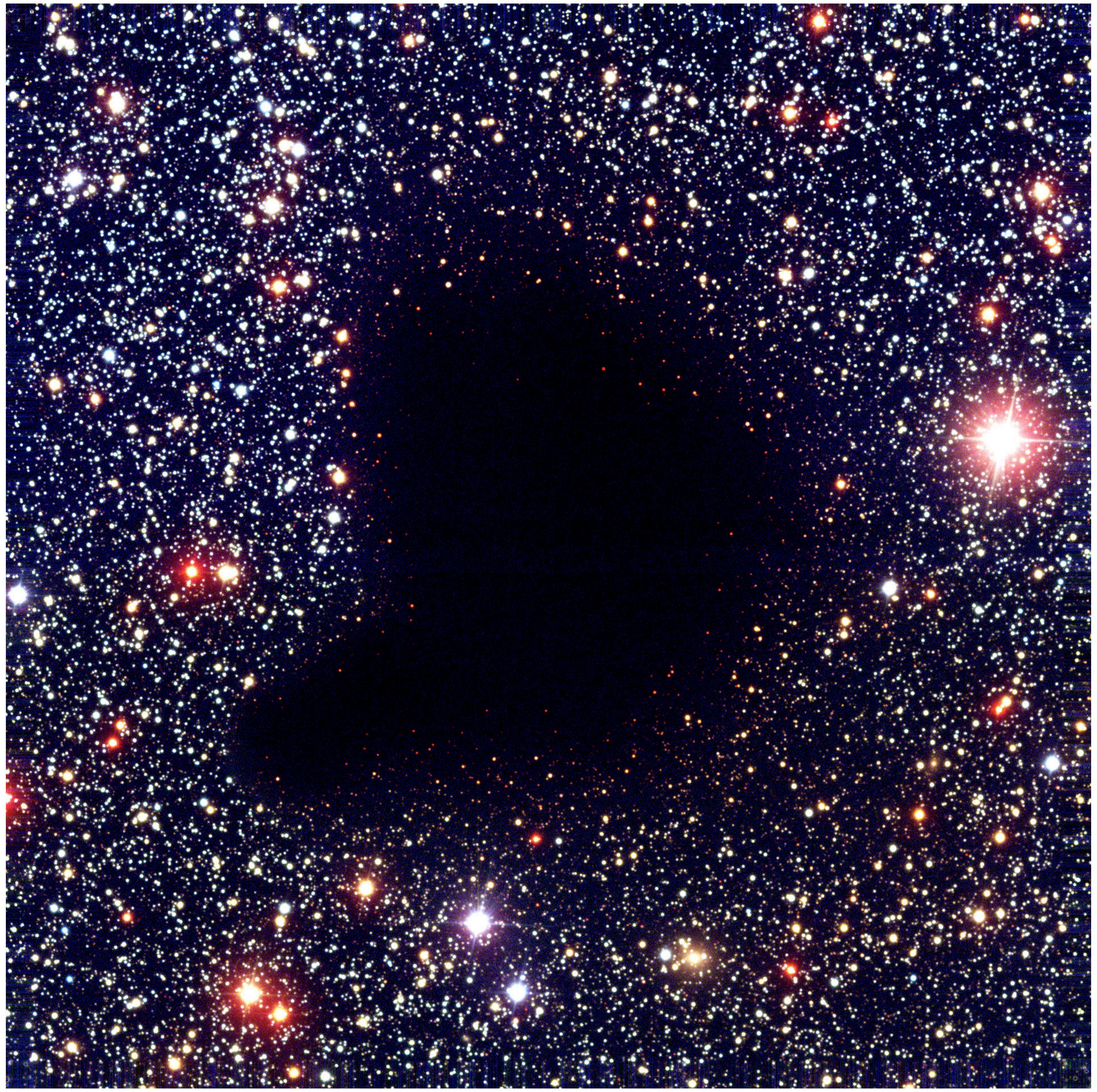
- **Dark cloud complexes** of roughly 10^4 $M_\odot$ have A_V~5, n ~ $5 \times 10^8 m^{-3}$, diameters on the order of 10 pc, and characteristic temperatures of 10 K.
- Smaller, individual **clumps** may be even more dense, with A_V~ 10, n ~ $10^9 m^{-3}$ diameters of a couple of parsecs, temperatures of 10 K or so, and masses of 30 $M_\odot$.
- At even smaller scales are **dense cores** with masses on the order of 10 $M_\odot$, $A_V > 10$, n ~ $10^{10} m^{-3}$, characteristic diameters of 0.1 pc, and temperatures of 10 K.
- Finally, in some localized regions of GMCs, observations reveal **hot cores** with characteristic sizes of 0.05 to 0.1 pc, where A_V ~ 50 to1000, T ~100 to 300K, n~10^{13} to $10^{15} m^{-3}$, and M~10 to 3000 $M_\odot$. Based on observations from infrared telescopes, hot cores appear to have massive, **young O and B stars** embedded within them, suggesting strongly that these are **regions of recent star formation.**

LDN 673, a dark cloud complex in Aquila
Image Credit & Copyright: Adam Block

Classification of Interstellar clouds

Located outside of larger molecular complexes are the almost spherical clouds known as **Bok globules.** These globules are characterized by **large visual extinctions** ($A_V \sim 10$), low temperatures ($T \sim 10$ K), relatively large number densities ($n > 10^{10} m^{-3}$), low masses ($M \sim 1$ to $1000\ M_\odot$), and small sizes of typically less than 1 pc.

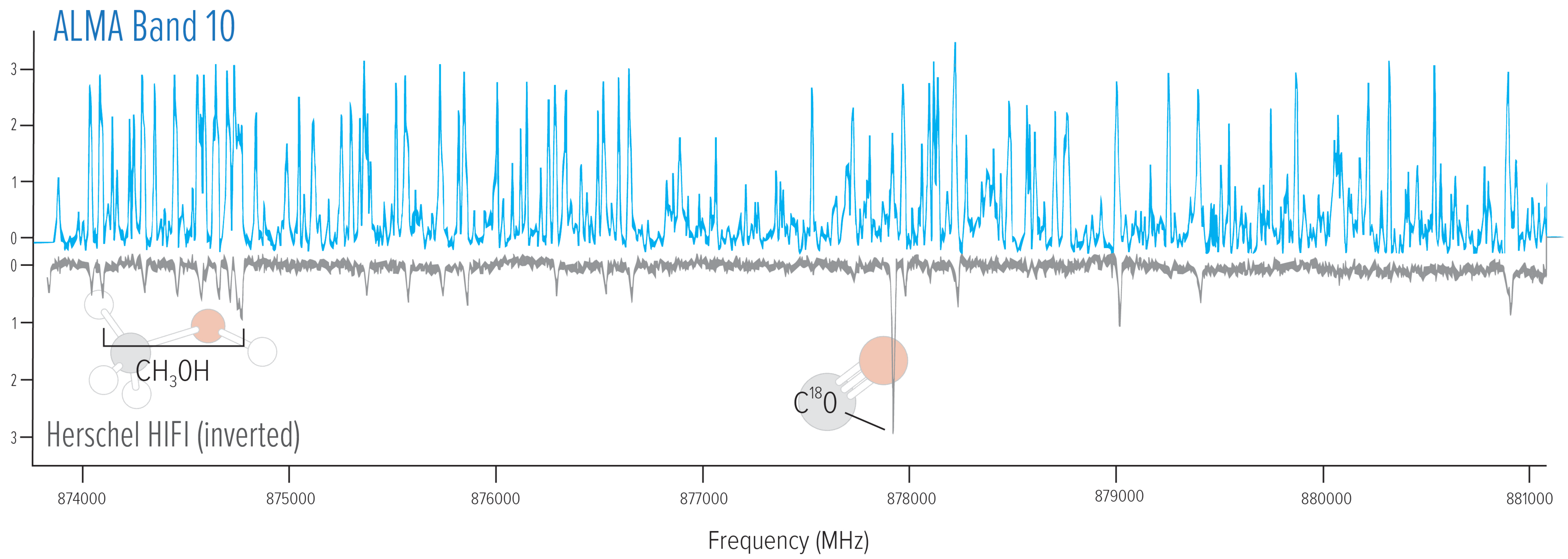
Infrared surveys of Bok globules have revealed that many, perhaps most, of these objects harbor **young low-luminosity stars** in their centers, implying that Bok globules are also **sites of active star formation.** In fact, Bok globules appear to be dense cores that have been stripped of their surrounding molecular gas by nearby hot, massive stars.



The Bok globule, Barnard 68 (B68)

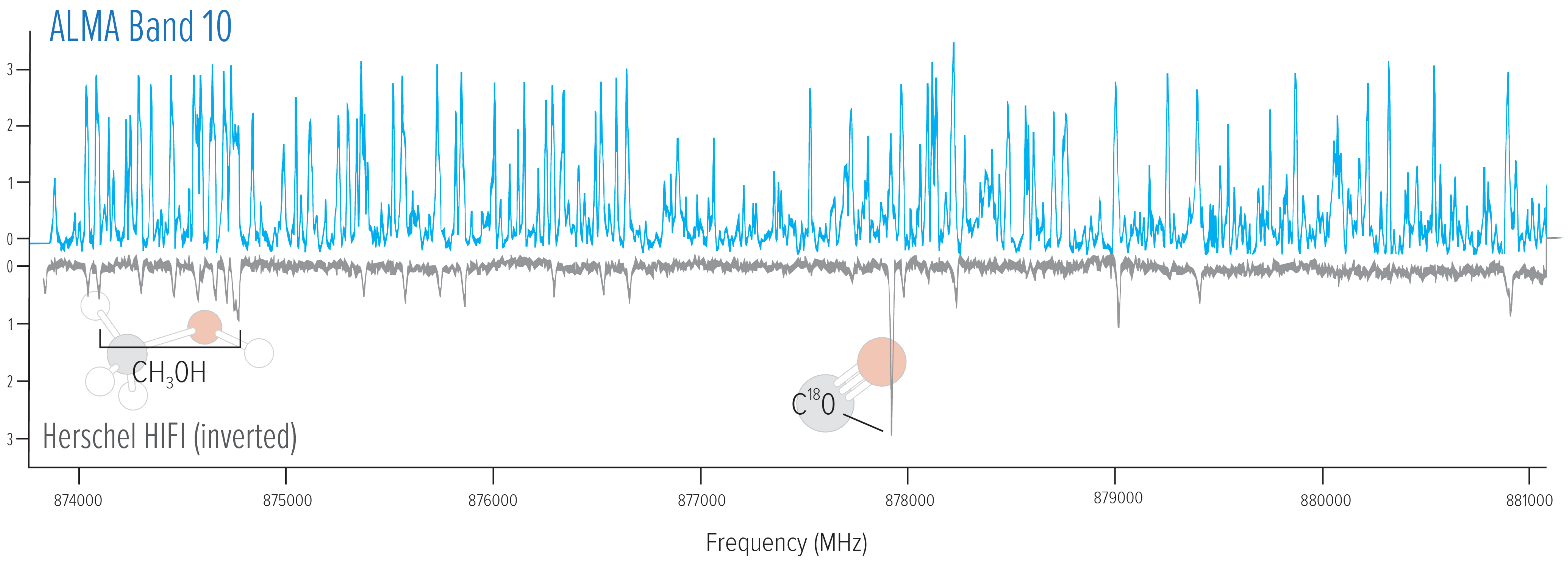
Interstellar Chemistry

Along with the molecules and dust grains already discussed, the **ISM is rich in other molecules** as well. **Radio observations** have resulted in the identification of **hundreds of molecules** (not including isotopomers), ranging in complexity from **diatomic molecules** such as H_2 and CO, and **triatomic molecules** such as H_2O and H_3^+, to fairly **long organic strings,** including $HC_{11}N$.



Interstellar Chemistry

- The upper blue portion of this graph shows the **spectral lines ALMA detected in a star-forming region** of the Cat's Paw Nebula.
- The lower black portion shows the lines detected by the European Space Agency's **Herschel** Space Observatory (infrared). The ALMA observations detected more than ten times as many spectral lines. Note that the Herschel data have been inverted for comparison. Two molecular lines are labeled for reference.



Interstellar Chemistry

The specific processes in operation in a given molecular cloud **depend on the density and temperature of the gas**, as well as **its composition and the presence of dust grains**.

- Dust grains must be **present for the formation of molecular hydrogen, H_2**, the dominant constituent in molecular clouds.
- It is also likely that dust grains can help **facilitate the formation of numerous other molecules** as well, including CH, NH, OH, CH_2, CO, CO_2, and H_2O.
- In sufficiently dense clouds, the formation of molecules on the surfaces of grains can actually lead to the development of **icy mantles on the grains.**
- **Absorption signatures of solid** CO, CO_2, H_2O, CH_4, CH_3OH, NH_3, and other **ices have been measured** in combination with the infrared spectra of silicate dust grains.

Interstellar Chemistry

In addition to the chemistry that can occur on grain surfaces, it is also possible for **molecules to form in the gas phase.**

For example, the hydroxyl molecule (OH) can form through a series of reactions involving atomic and molecular ions, including the ionic water molecule, H_2O^+

$$\mathrm{H^+ + O \rightarrow O^+ + H}$$

$$\mathrm{O^+ + H_2 \rightarrow OH^+ + H}$$

$$\mathrm{OH^+ + H_2 \rightarrow H_2O^+ + H}$$

$$\mathrm{H_2O^+} + e^- \rightarrow \mathrm{OH + H.}$$

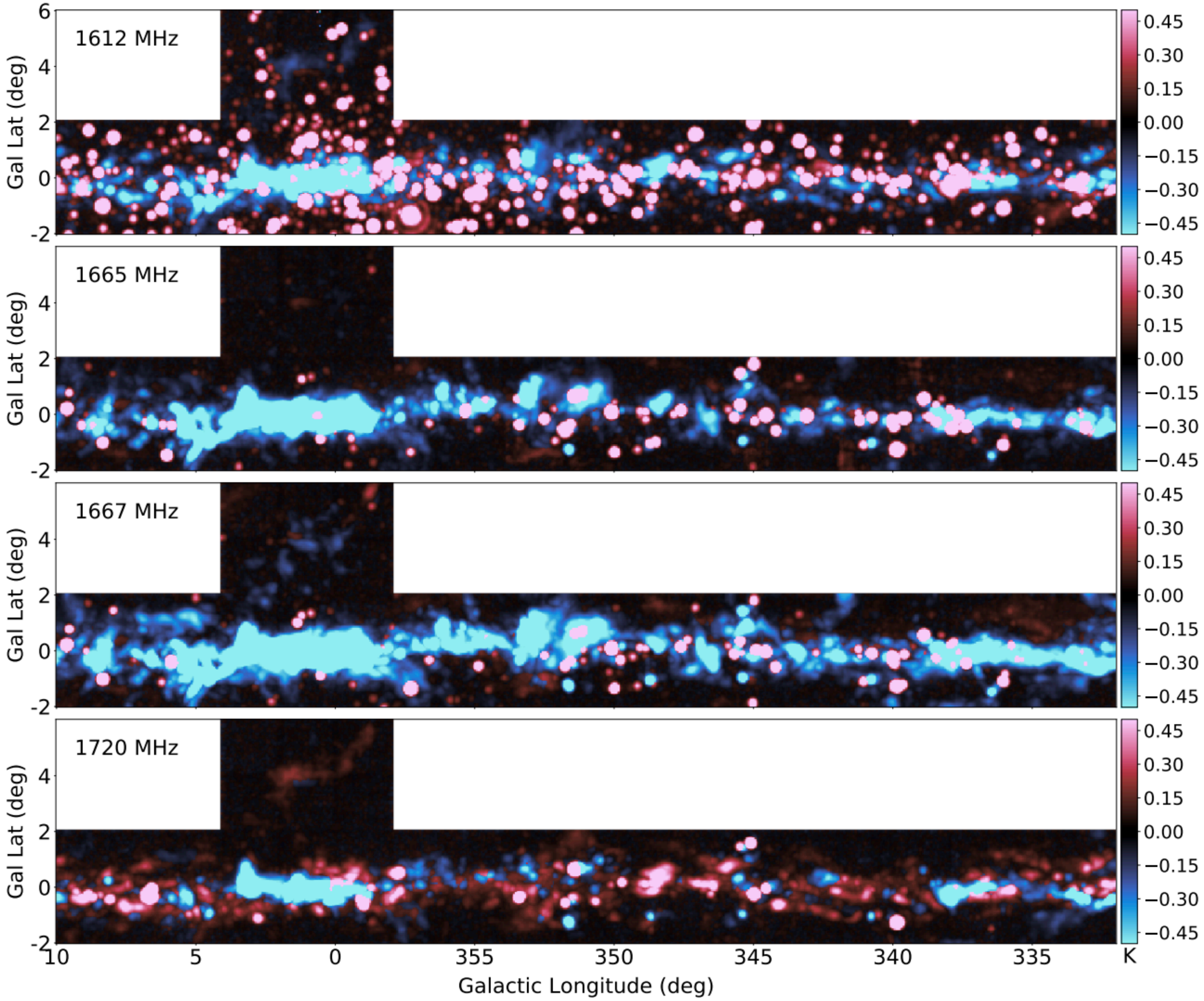
$$\mathrm{H_2O^+ + H_2 \rightarrow H_3O^+ + H,}$$

leading to the production of either a hydroxyl molecule (75% of the time) or a water molecule via

$$\mathrm{H_3O^+} + e^- \rightarrow \begin{cases} \mathrm{OH + H_2} \\ \mathrm{H_2O + H.} \end{cases}$$

Interstellar Chemistry

- **Peak emission/absorption maps of OH**
- Dawson et al 2022 - SPLASH survey
- OH has 4 lines at 1612, 1665, 1667 and 1720 MHZ
- masers in the 1612 MHz line (mostly evolved stellar sources),
- the tendency of the 1665, 1667 MHz lines to be seen in absorption (blue), and the 1720 MHz line to be seen in emission (red)
- OH: part of molecular clouds, masers around evolved stars



Heating and cooling of the ISM

Not only are molecules and dust grains critical in understanding the chemistry of the ISM, but they also play important roles in the heating and cooling of the material between the stars.

- Diffuse molecular clouds have higher gas temperatures than giant molecular clouds, and the dense cores of GMCs are even cooler yet.
- On the other hand, the hot cores of GMCs have significantly greater temperatures.
- What are the physical causes of these observational trends?

Much of the **heating of the interstellar medium** comes from **cosmic rays,** charged particles that travel through space with sometimes astonishing amounts of energy.

- A single proton may possess an energy ranging anywhere from 10 to 10^{14} MeV.
- The highest energy cosmic rays are extremely rare, but energies in the range 10^3 to 10^8 MeV are common.
- The sources of cosmic rays include stellar flares and supernova explosions.

Heating and cooling of the ISM

Heating by cosmic rays comes primarily through the **ionization of hydrogen atoms and molecules as a result of collisions with cosmic ray protons**:

$$p^+ + \mathrm{H} \rightarrow \mathrm{H}^+ + e^- + p^+$$

$$p^+ + \mathrm{H}_2 \rightarrow \mathrm{H}_2^+ + e^- + p^+.$$

When an atom or molecule is ionized, an electron is ejected that carries some of the original kinetic energy of the proton with it. It is this **ejected electron that interacts with the ISM to increase the average kinetic energy of the ISM's constituents via collisions with molecules.**

Those molecules then **collide with other molecules in the gas, distributing thermal kinetic energy** throughout the cloud, thereby raising the temperature of the cloud.

Heating and cooling of the ISM

Other sources of heating in molecular clouds include:

- the **ionization of carbon atoms by ultraviolet starlight resulting in ejected electrons**,
- the **photoelectric ejection of electrons from dust grains** by ultraviolet starlight,
- the **absorption of light** energy into the lattice of **dust grains**,
- and the **ionization of hydrogen by stellar X-rays**.
- **Shocks from supernovae or strong stellar winds** can also produce some heating of molecular clouds in special cases.

To balance the heating processes, **cooling mechanisms** must also be in operation. The primary mechanism for cooling is based on the **emission of infrared photons**. Recalling Mie scattering, when photon wavelengths are on the order of, or longer than, the size of dust grains, they are less likely to be scattered. **IR photons can pass more easily through the molecular cloud** than can shorter-wavelength photons, allowing the IR photons to **transport energy out of the cloud.**

Heating and cooling of the ISM

IR photons are produced in molecular clouds through collisions between ions, atoms, molecules, and dust grains. Typically a collision between ions, atoms, or molecules results in one of the species being left in an excited state; the energy of the excited state comes from the kinetic energy of the collision. The species in the excited state then decays back to the ground state through the emission of an IR photon. For example,

$$\mathrm{O} + \mathrm{H} \rightarrow \mathrm{O}^* + \mathrm{H}$$

$$\mathrm{O}^* \rightarrow \mathrm{O} + \gamma.$$

Here O* represents an excited state of the oxygen atom.

The collisional kinetic energy (thermal energy) is thus transformed into an IR photon that escapes the cloud. **Collisional excitations** of C^+ and CO by H and H_2, respectively, are also s**ignificant contributors to cooling of molecular clouds.**

Collisions involving dust grains can also result in cooling of molecular clouds. This process is similar to ionic, atomic, and molecular collisions in that the lattice of a dust grain can be left with excess thermal energy after the collision. The **grain then emits infrared energy that is able to escape from the cloud.**

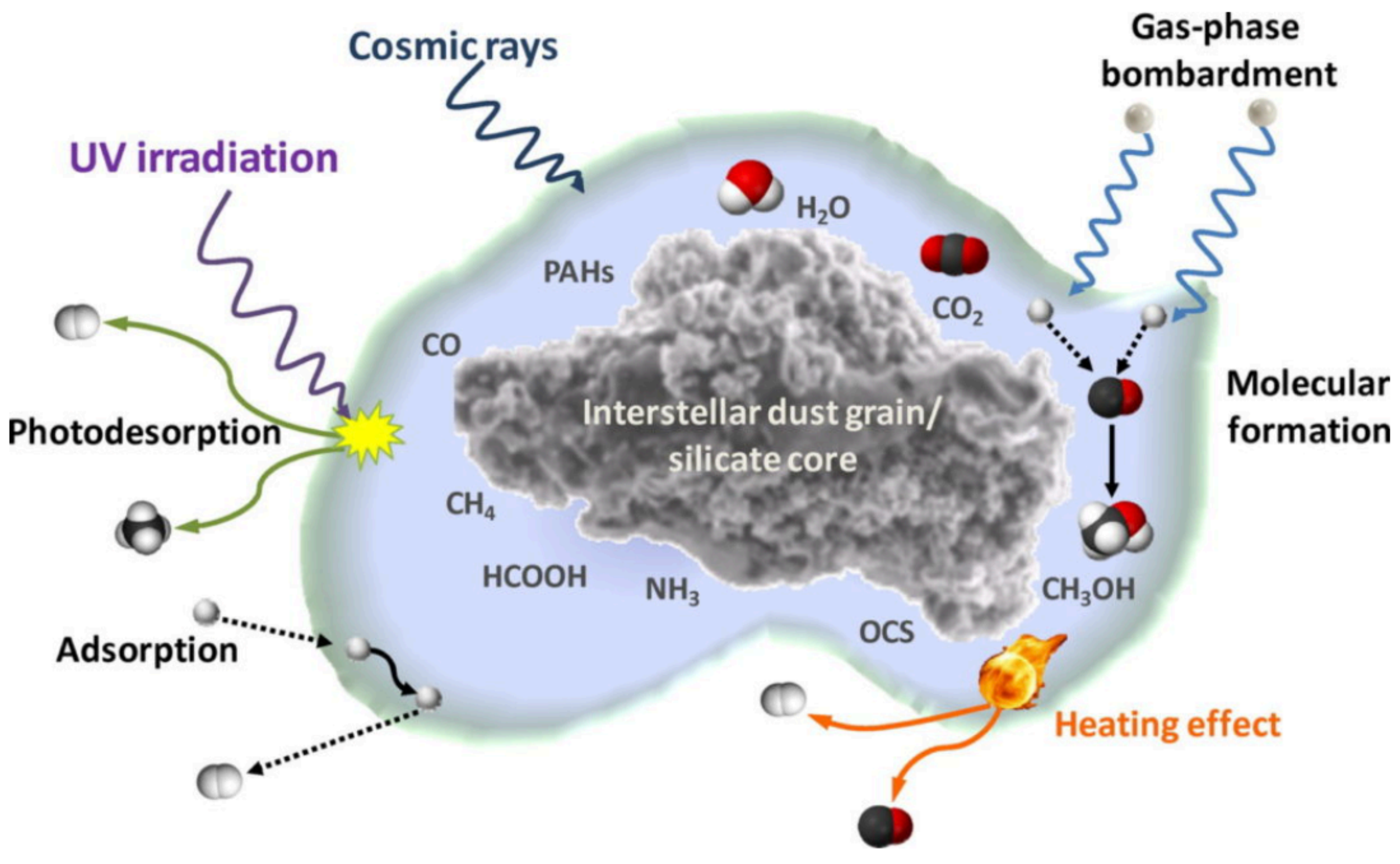
The source of dust grains

https://doi.org/10.1016/j.plrev.2011.08.005

It is apparent that even though **dust grains make up only about one percent of the mass of a molecular cloud**, they are important constituents in determining its chemistry and physics.

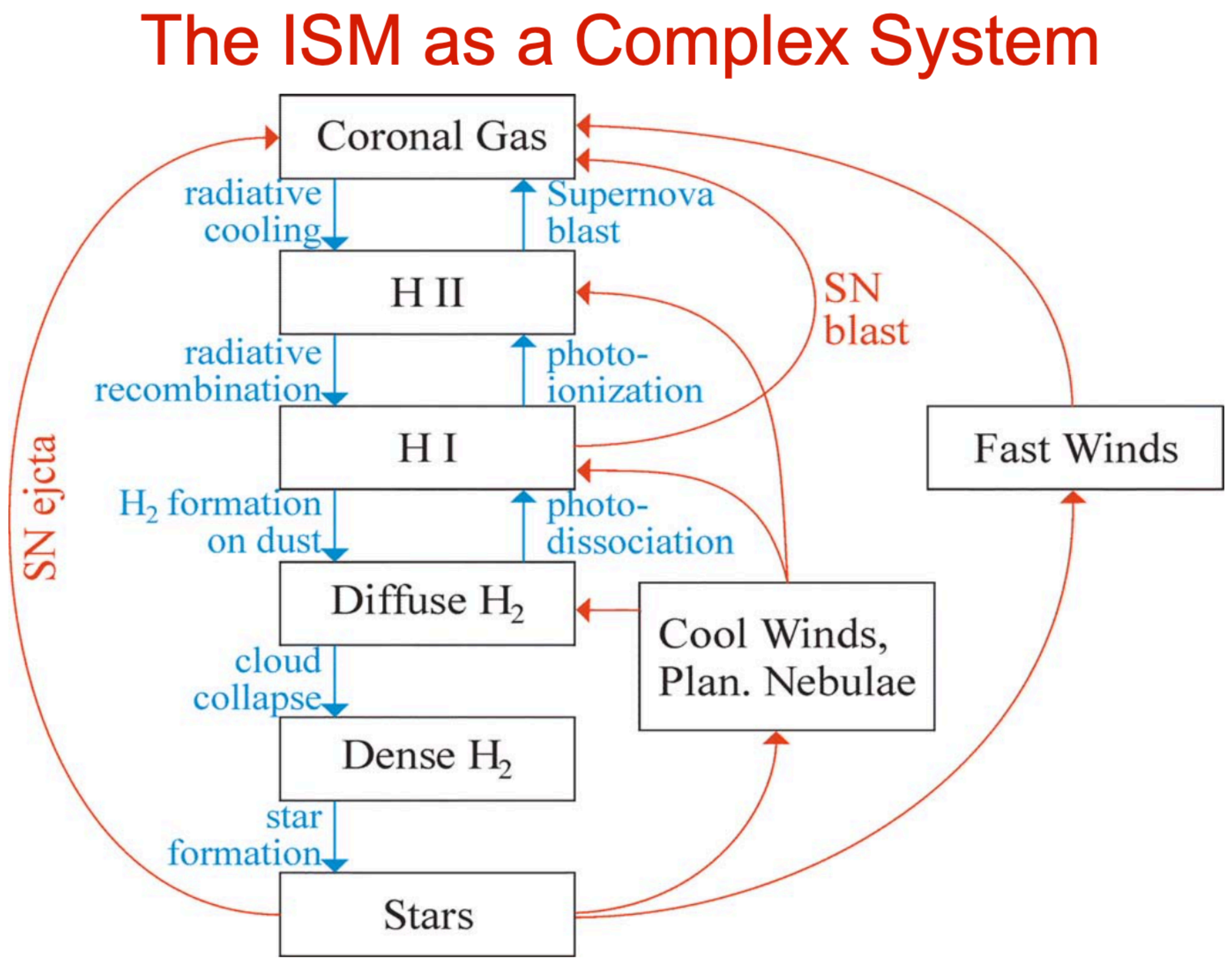
What is the **source of these grains**?

- Although observations indicate that **dust grains can be formed in the envelopes of very cool stars,** aided by the **enhanced density in those environments** relative to molecular clouds, **grains can also be easily destroyed by UV and X-ray photons**.
- **Dust grains are also formed as a product of supernova explosions and stellar winds.** However, none of these sources appear to be able to provide the abundance of massive grains found in molecular clouds.
- Rather, it appears that grains probably grow by a **process of coagulation within the molecular clouds** themselves.



This tiny interstellar dust grain is a chemical factory, where simple molecules can react to form bigger more complex molecules. Note that the ice layer is full of chemical diversity, and photons and cosmic rays help drive ice chemistry.

Heating and cooling of the ISM



Al Glassgold lecture notes