Astrophysical Objects

Interstellar medium

An introduction to modern Astrophysics chapter 12

Helga Dénes 2023 S2 Yachay Tech

hdenes@yachaytech.edu.ec

UNIVERSIDAD YACHAY TECH

SCHOOL OF PHYSICAL SCIENCES AND NANOTECHNOLOGY

Interstellar medium

What is the interstellar medium?

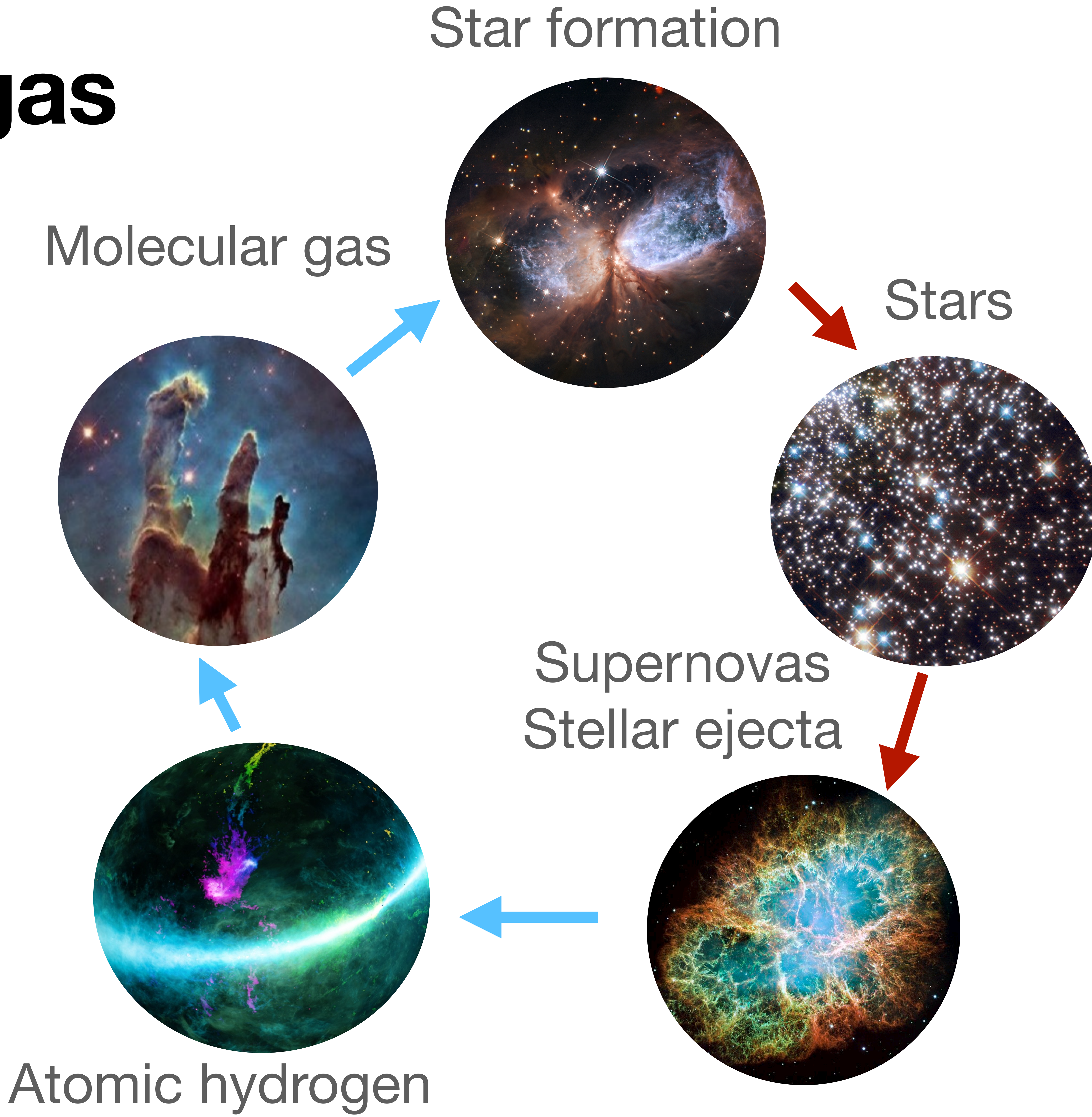
Why is it important?

Milky Way over Chimborazo

Interstellar dust and gas

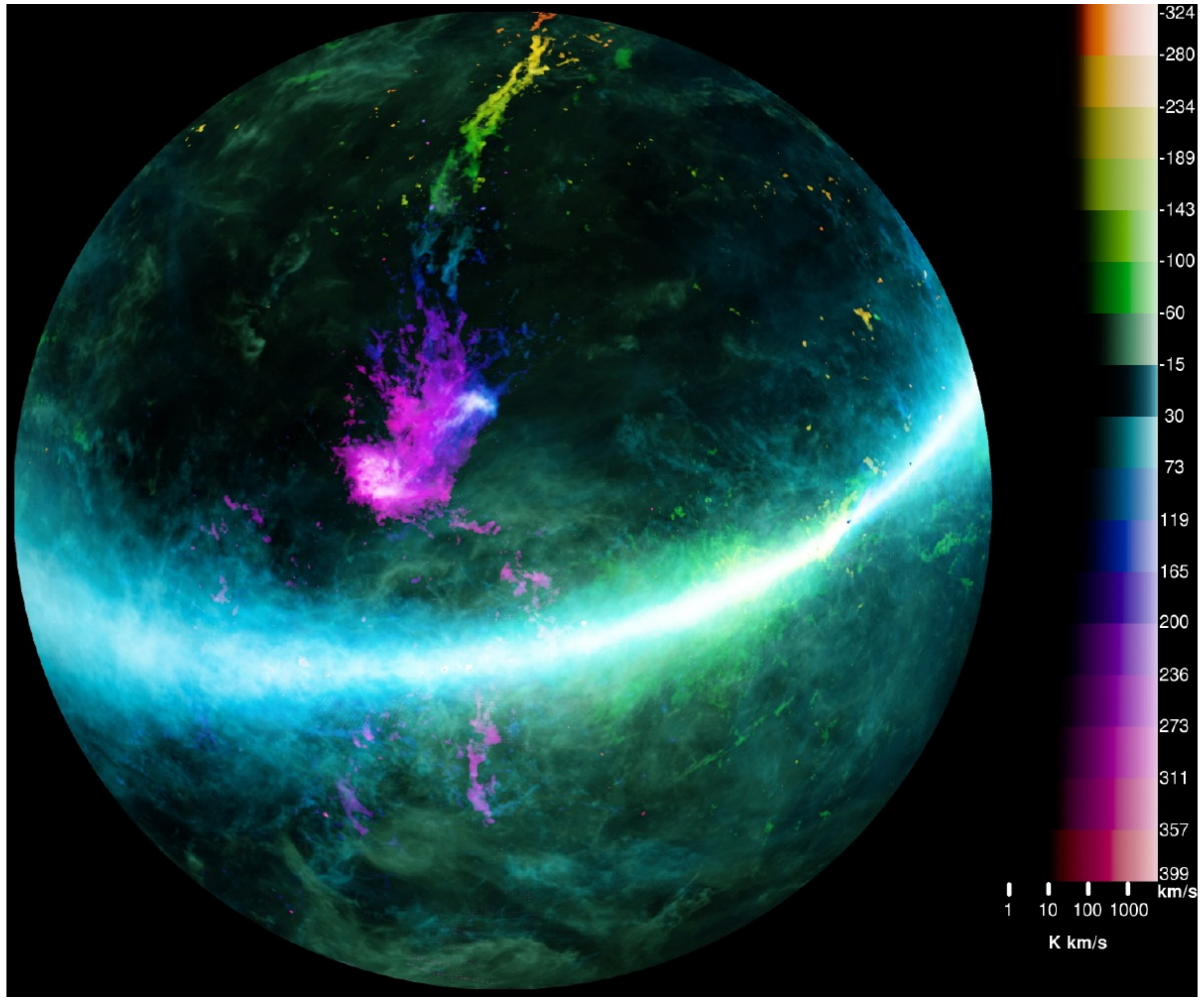
In some sense the evolution of stars is a cyclic process. A star is born out of gas and dust that exists between the stars, known as the **interstellar medium** (ISM).

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 $A_\lambda = 1.086 \tau_\lambda$

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

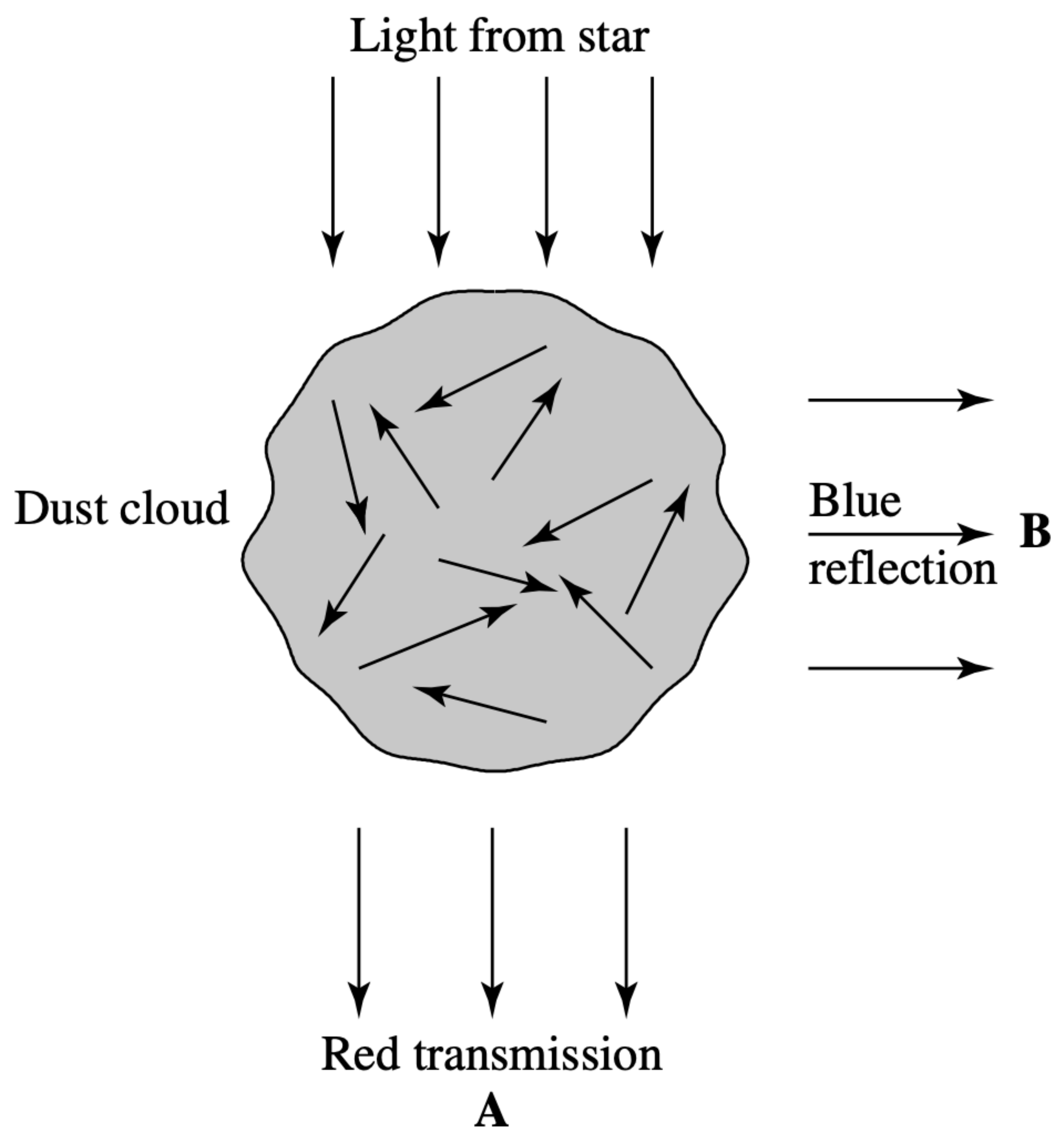
Since the longer wavelengths of red light are not scattered as strongly as blue light, the starlight passing through intervening dust clouds becomes reddened as the blue light is removed. This **interstellar reddening** causes stars to appear redder than their effective temperatures would otherwise imply.

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 $\sigma_\lambda \propto \lambda^{-4}$.

The Pleiades star cluster



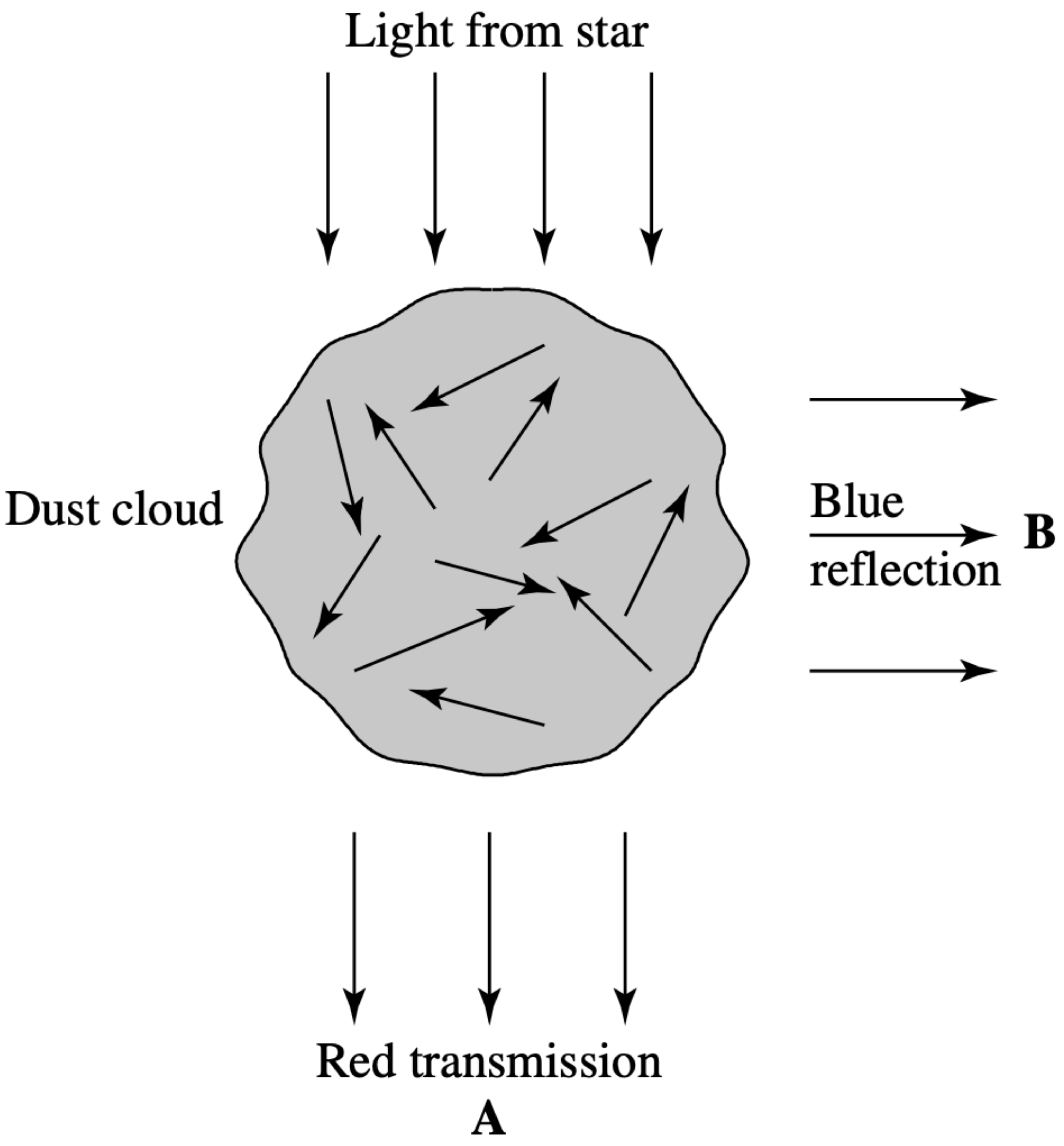
Interstellar extinction - dust

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 (n) of material between the star and Earth.

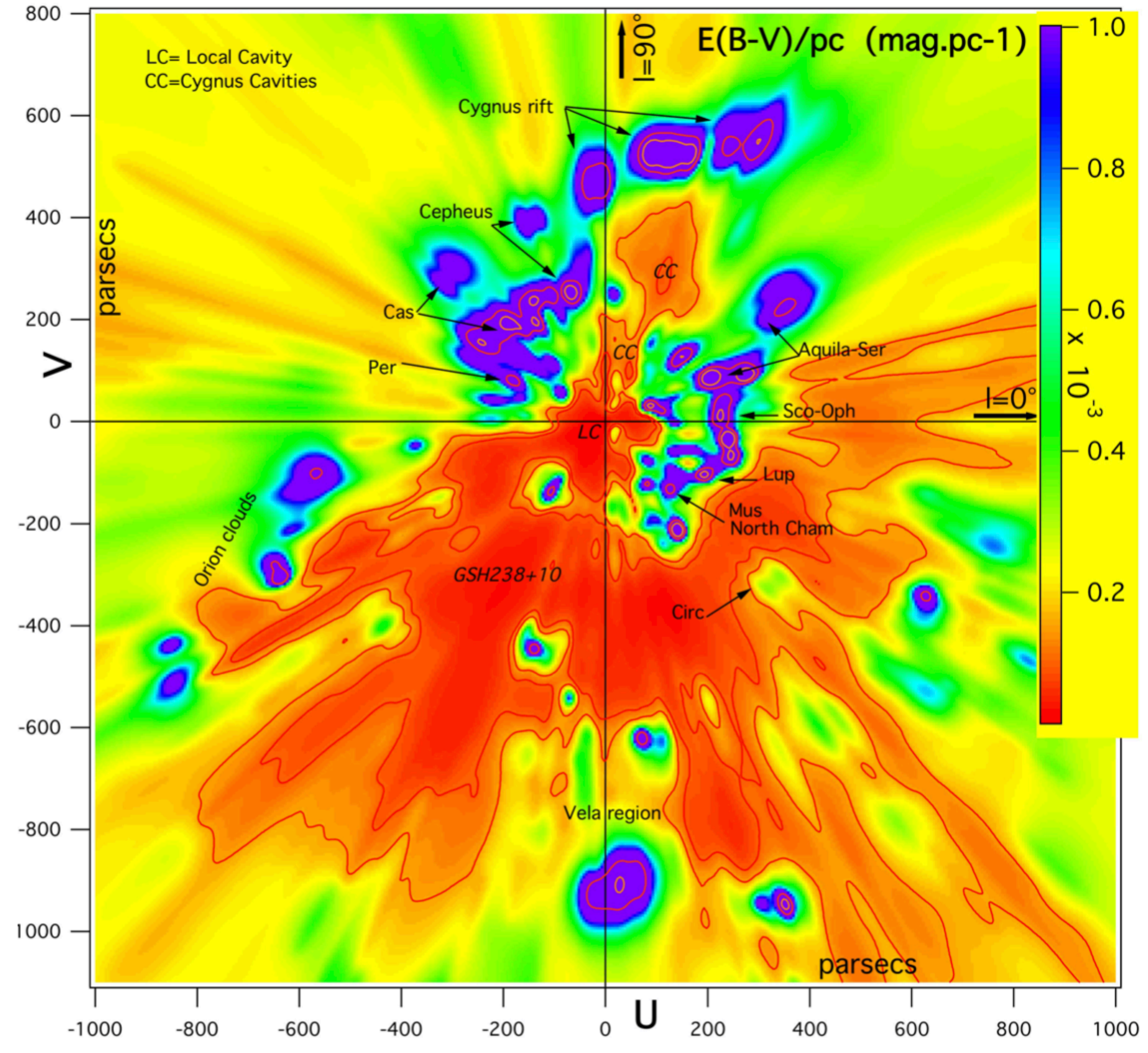
Interstellar extinction - dust

Why is it useful to know about the dust extinction?

Interstellar extinction - dust

Maps of interstellar reddening:

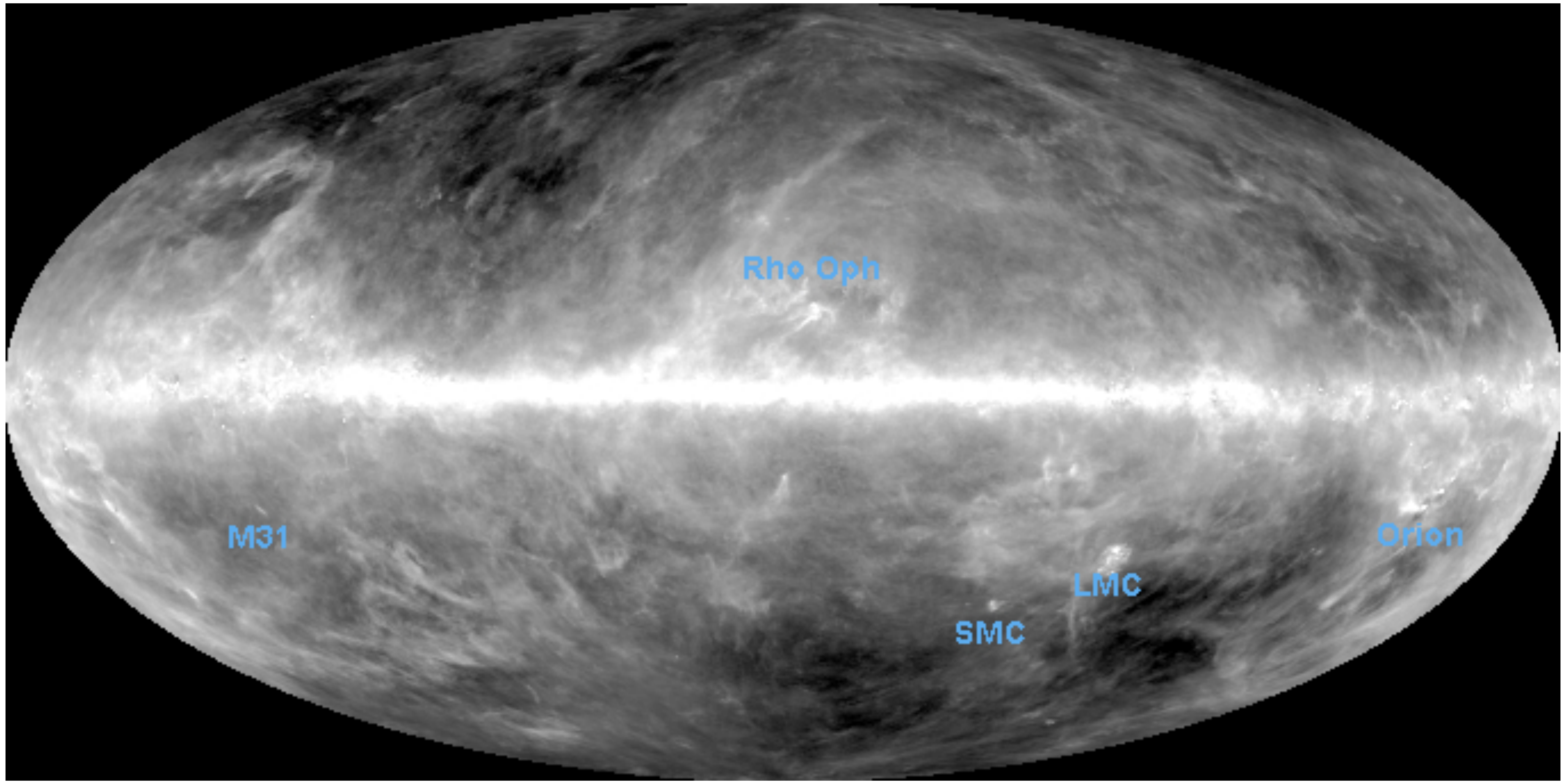
- Correcting the magnitude observations of all astrophysical objects.
- Learning about our closest environment: Local Bubble.



Lallement et al. 2014

Differential opacity distribution in the Galactic Plane

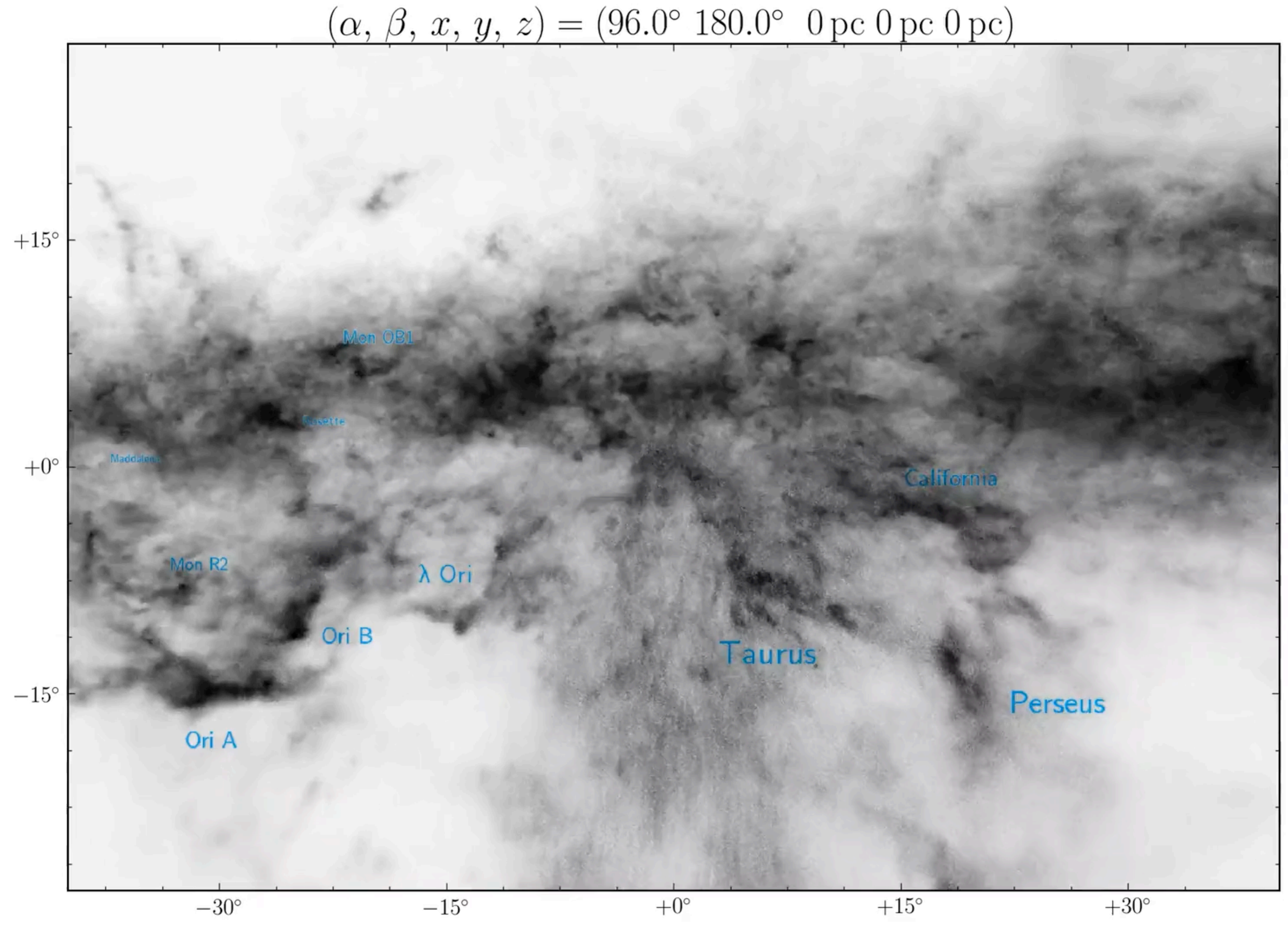
There is a cavity of material (red) around the Sun. This is often referred to as the Local Cavity or the Local Bubble.



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/