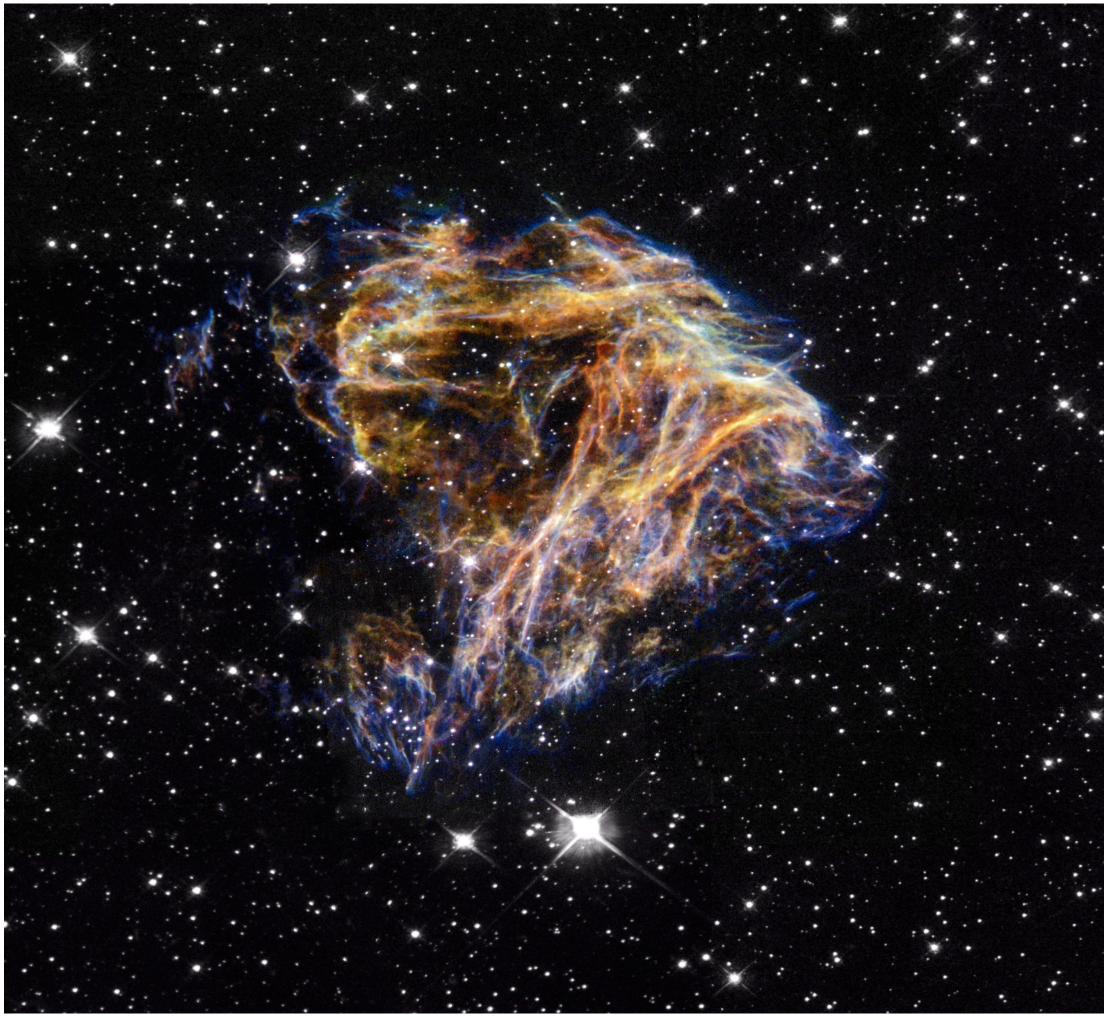
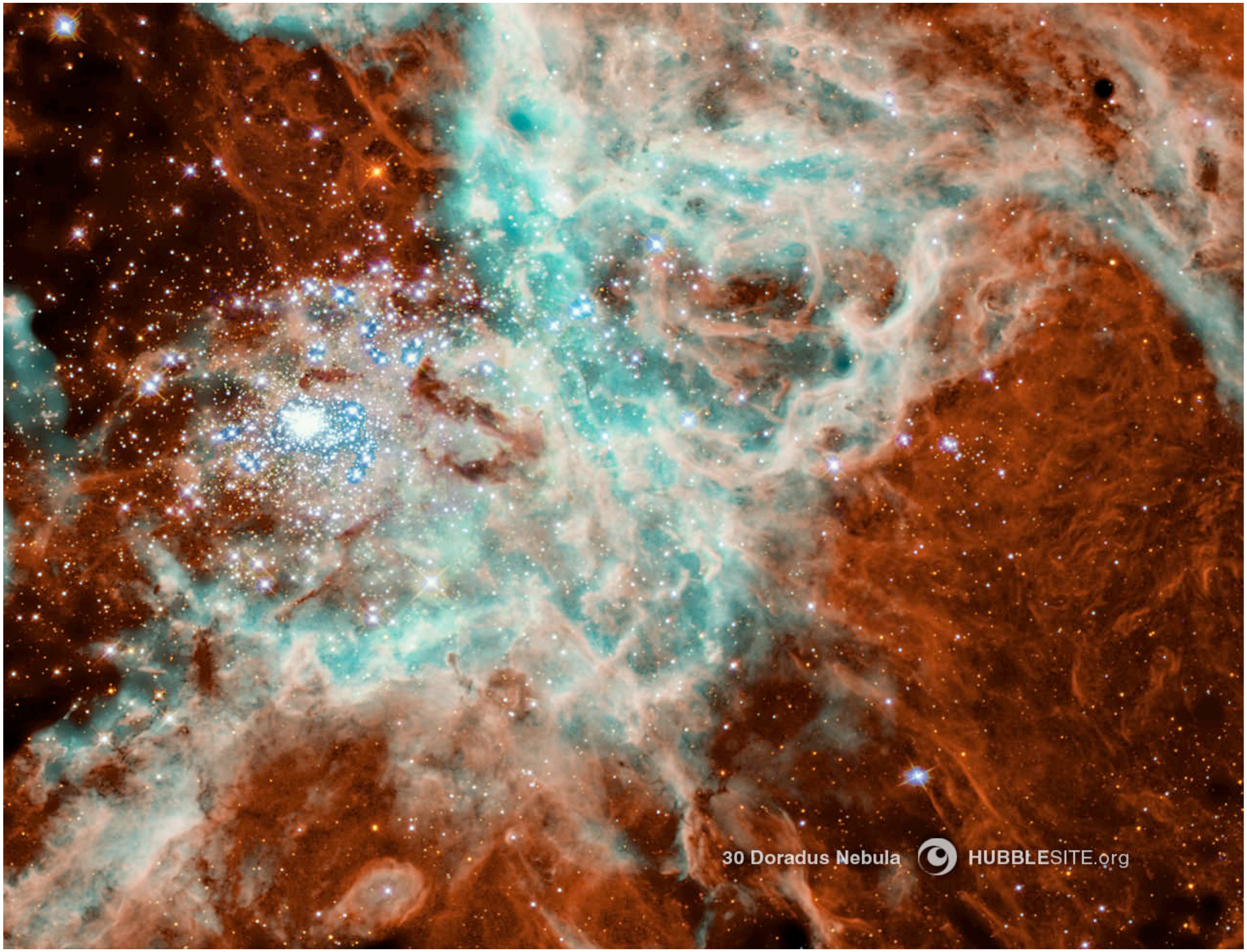
The Interstellar Medium

The space between stars is not a vacuum, it is filled with gas and dust that produces some of the most beautiful pictures in astronomy.



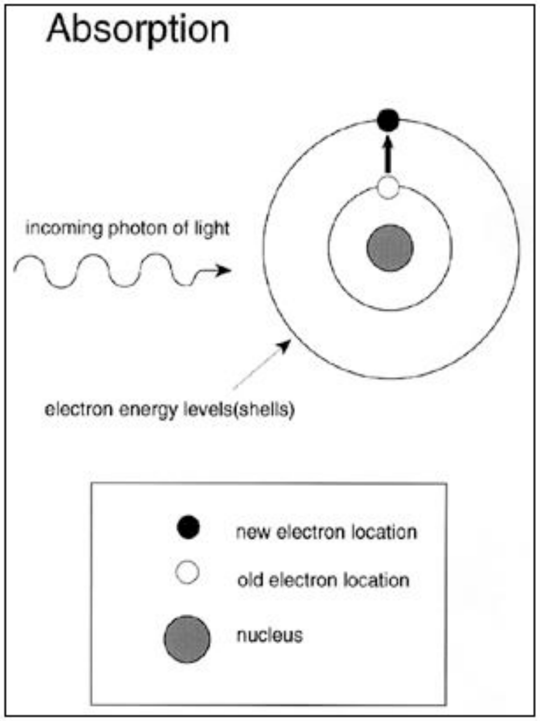
A supernova remant lights up the gas in the Large Magellanic Cloud.

The 30 Doradus star forming region embedded in its gaseous cradle



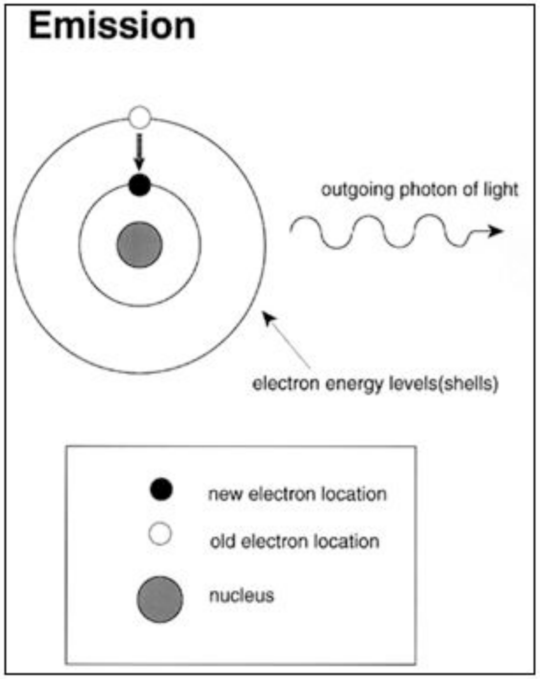
Dark clouds ('Thackery's Globules'), each measures 1.4 lightyears.

The Physics of Interstellar Gas Clouds (*NEBULAE)*



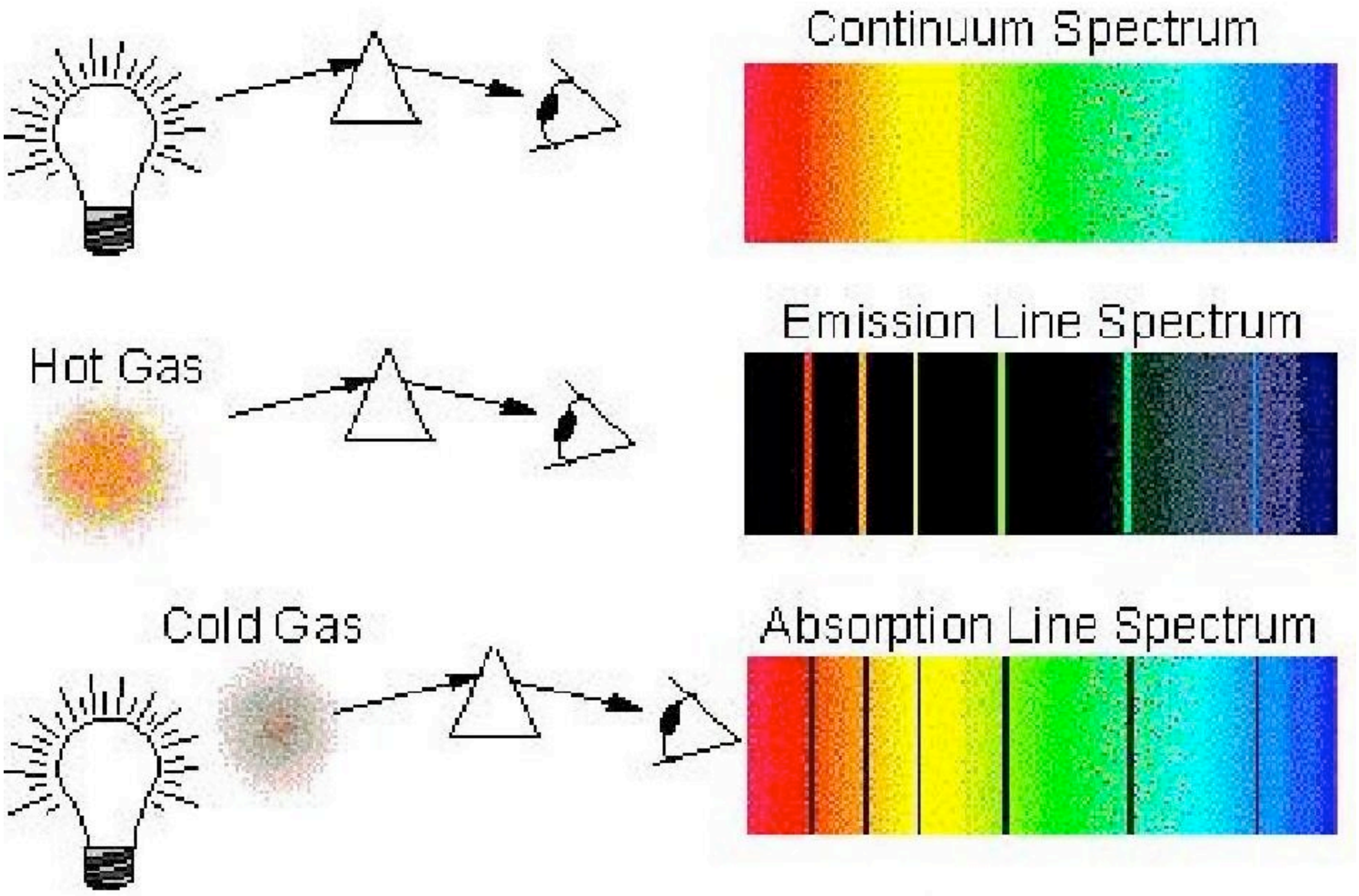
Two simple interactions between a photon and an atom.

A photon can be either absorbed ("used"), in which case an electron moves to higher energy, or emitted by an electron "falling" to a lower energy state.



A transition between any 2 given energy levels results in light being absorbed or emitted at a single wavelength.

3 different types of spectrum:



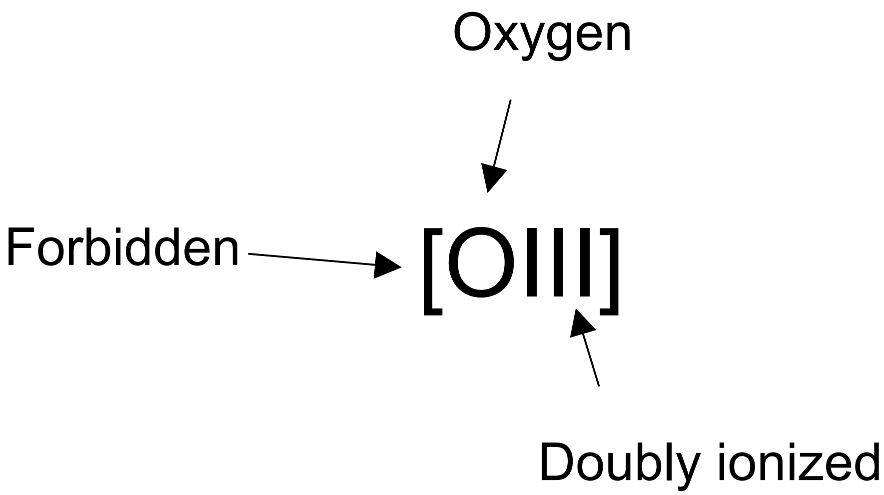
Emission Lines

Emission lines are sharp and occur as an electron “falls” between levels

In addition to these familiar “permitted” atomic transitions, in astrophysical environments we also find “forbidden” lines.

A forbidden line is a transition from a *metastable* state.

Astronomers write forbidden lines inside square brackets e.g:



Oxygen

Forbidden

[OIII]

Doubly ionized

These transitions are never seen on Earth because the time needed for the electron to spontaneously decay and emit a photon is very long compared with the timescale on which electrons get collisionally excited. Only in the low densities of the interstellar medium to these electrons ever get the chance to decay.

Different Flavours of Nebulae:

1) Emission nebulae (AKA HII regions because the hydrogen is mostly ionized). A very hot (> 25,000K) star excites the hydrogen gas around it to produce an emission spectrum. These nebulae usually look pink due to the blending of different Balmer emission lines.

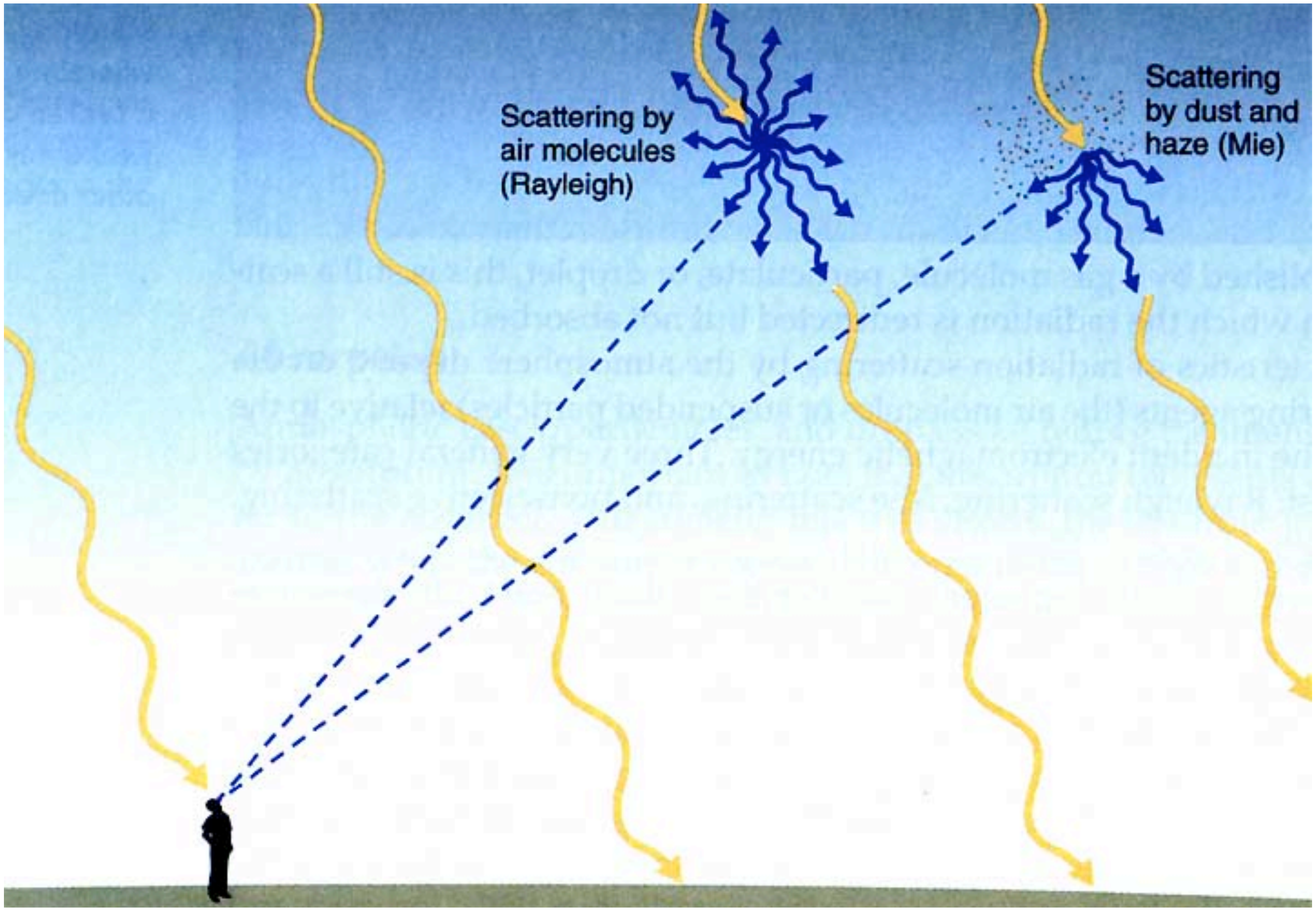
Star Cluster Hodge 301 in the Tarantula Nebula HUBBLESITE.org

Different Flavours of Nebulae:

2) Reflection nebulae. Seen when nearby starlight scatters from a nearby dust cloud. The light is therefore simply the reflected spectrum of the incident starlight. The colours of typical reflection nebulae are blue because short (blue) wavelengths scatter more easily than long (red) ones. This scattering is due to dust and is also part of the reason why the sky is blue.

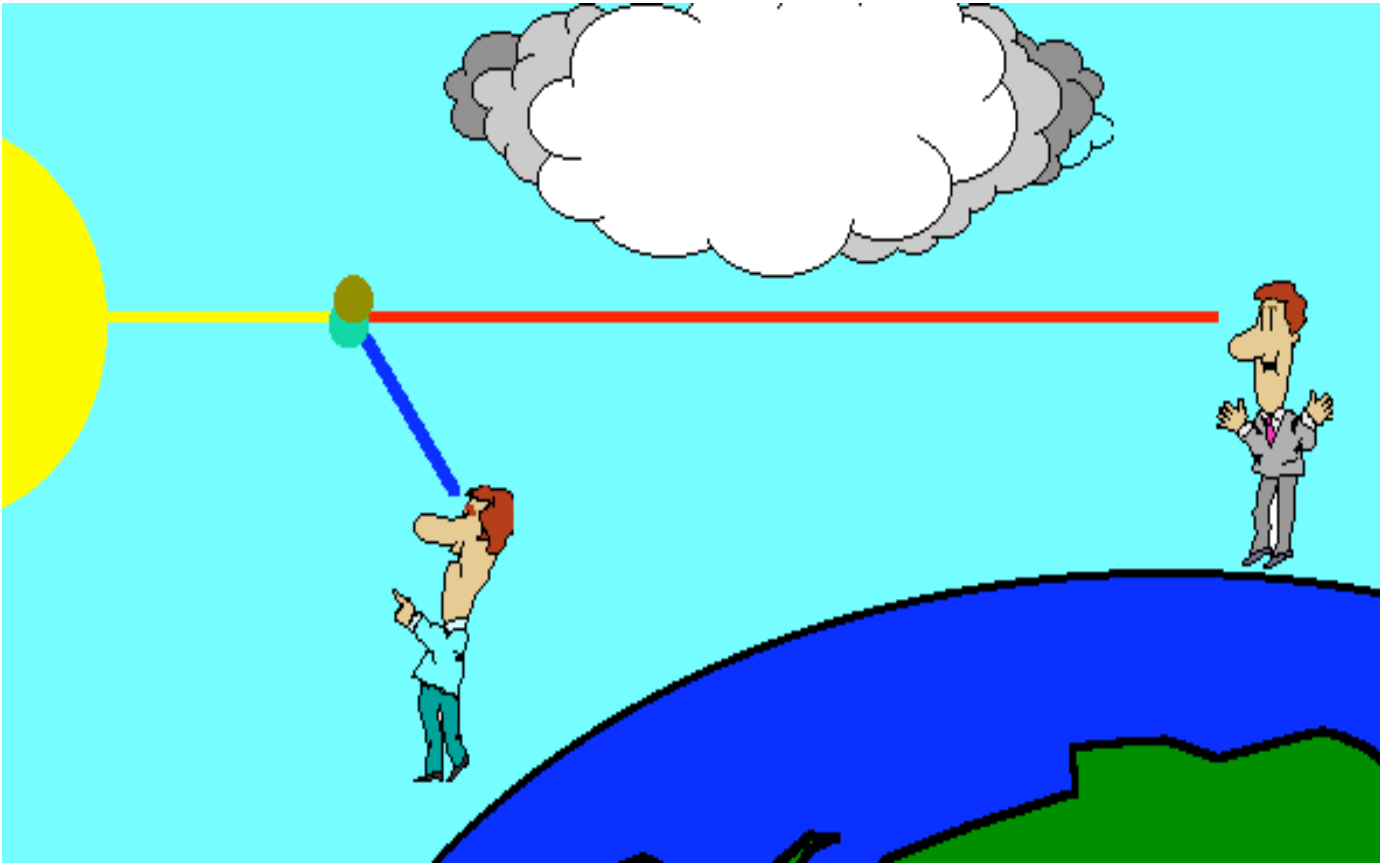
by Yuuji Kitahara

Scattering of light by dust (called Mie scattering) is part of the reason why the sky is blue. When dust grains are small, blue light gets scattered more efficiently than red light, so our eyes receive blue photons from all directions.

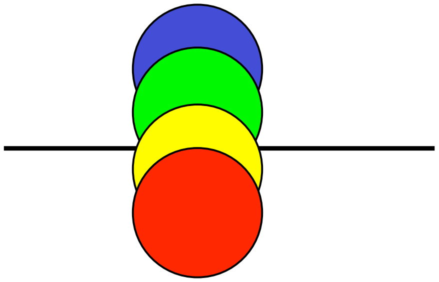


The sun looks redder at sunrise or sunset because the light travels through a thicker slice of the atmosphere, so scattering is more severe.

At sunset the angle towards the Sun takes our line of sight through more atmosphere, so the we receive mostly red light. Dust in the atmosphere can produce even more colourful sunsets



Another interesting effect at sunset is the green flash. Due to atmospheric diffraction, we actually see the sun below the horizon. The blue light is bent more, so we see the blue sun last. Since blue is mostly scattered, the last rays of sunlight appear green.

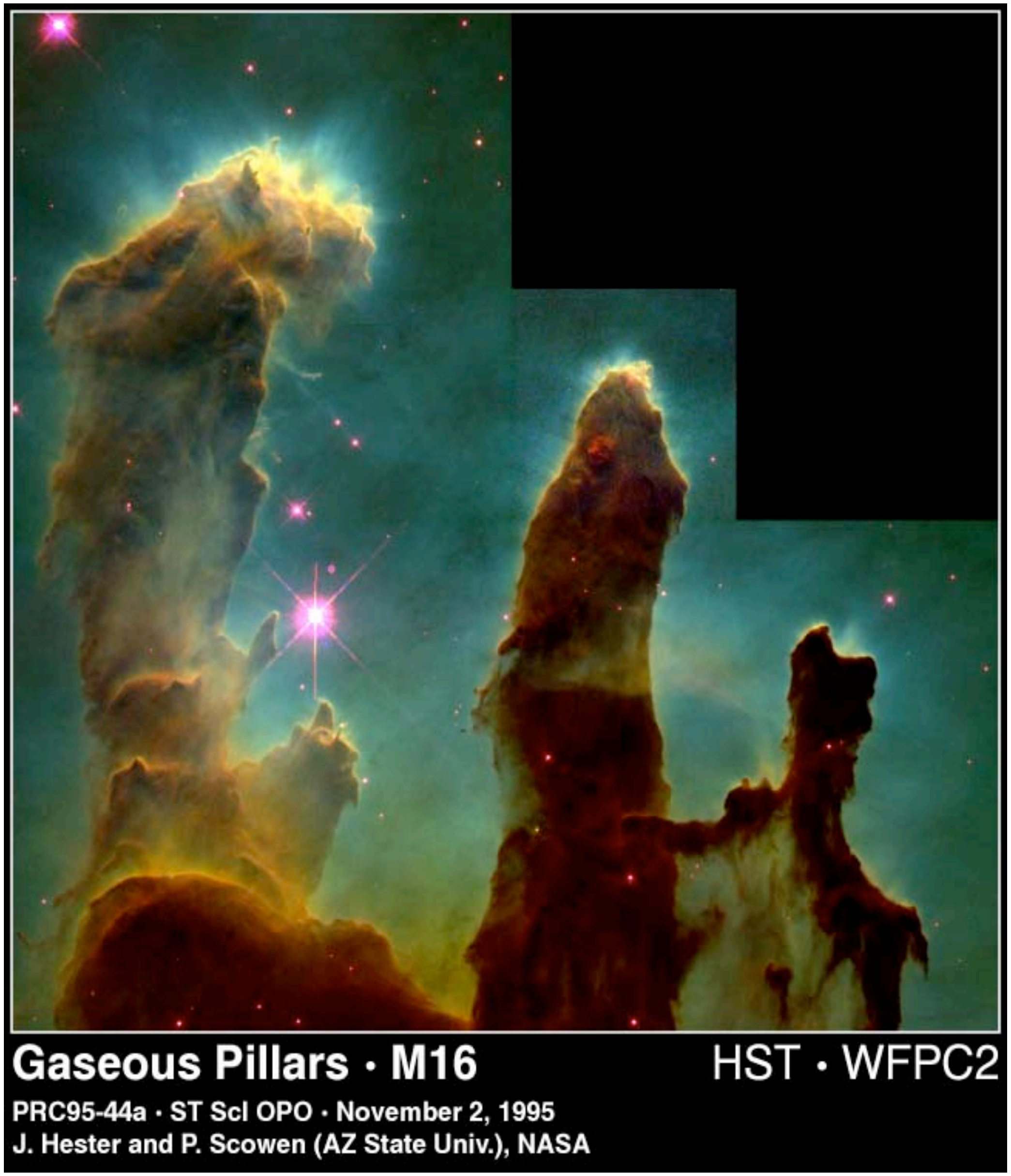


Different Flavours of Nebulae:

3) Dark nebulae.
These are observed when dark, dense clouds of dust obstruct our view of background stars.

The tallest pillars in the eagle nebula are 4 light years long.

These dark clouds are sometimes called 'Bok globules' after their discoverer.



Absorption Lines

Whereas emission lines typically originate in the hot, excited gas near stars, absorption lines occur in the cold gas of the remote interstellar medium.

The position (i.e. Wavelength) at which the absorption feature is observed depends on how far away the cloud is (recall the Doppler or redshift).

$$\frac{\text{change in wavelength}}{\text{original wavelength}} = \frac{\text{velocity}}{\text{lightspeed}} \longrightarrow \frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

Note that the change in wavelength is positive for objects moving away (redshift) and negative for objects moving towards us (blueshift)

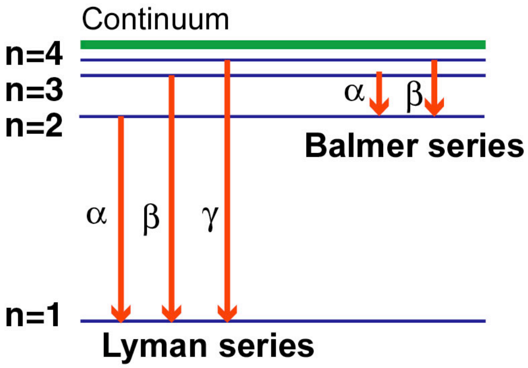
As we will see in future lectures, the size of the Doppler velocity shift tells us about how far away things are, because more distant objects are receding more quickly.

I.e. More distant clouds produce lines with longer (redder) wavelengths.

We can use bright continuum sources (like stars or distant quasars) as tools to study intervening gas clouds.

Example 1.

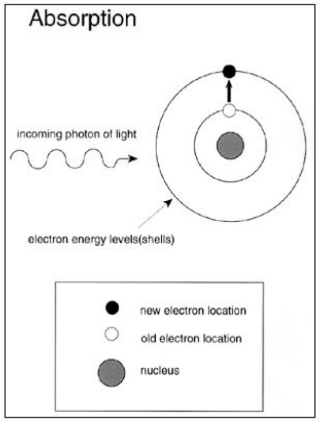
You take a spectrum of a star in a nearby galaxy and notice that there is an absorption line at 121.8 nm, which is close to what we'd expect for Lyman α. If this is Lyα, what is the Doppler velocity of the gas?



Lyman lines are simply transitions in hydrogen from the first energy level (cf Balmer from the 2nd).

$\lambda = 121.6$ nanometres = 121.6×10^{-9} m

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$



Here, the change in wavelength is 0.2 nm so:

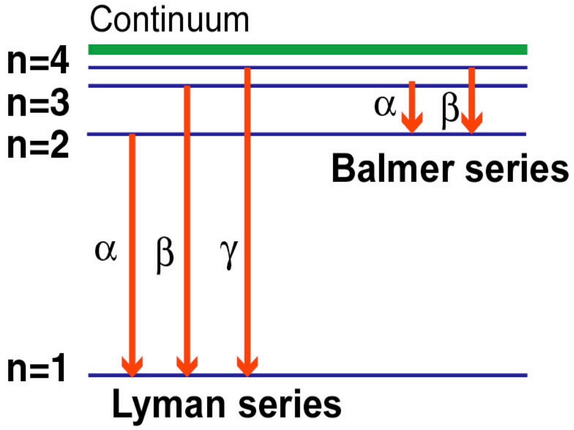
$v = 0.2/121.6 \times 300000$

$= 493$ km/s

Since the change in wavelength is positive, this is a redshift.

Example 2.

In the previous example, we found a gas cloud with velocity 493 km/s. This is very unlikely to be in the Milky Way because our Galaxy's rotation speed is only about 200 km/s. It looks like we are probing the gas in an external galaxy. What will be the wavelength of the Hα Balmer line?

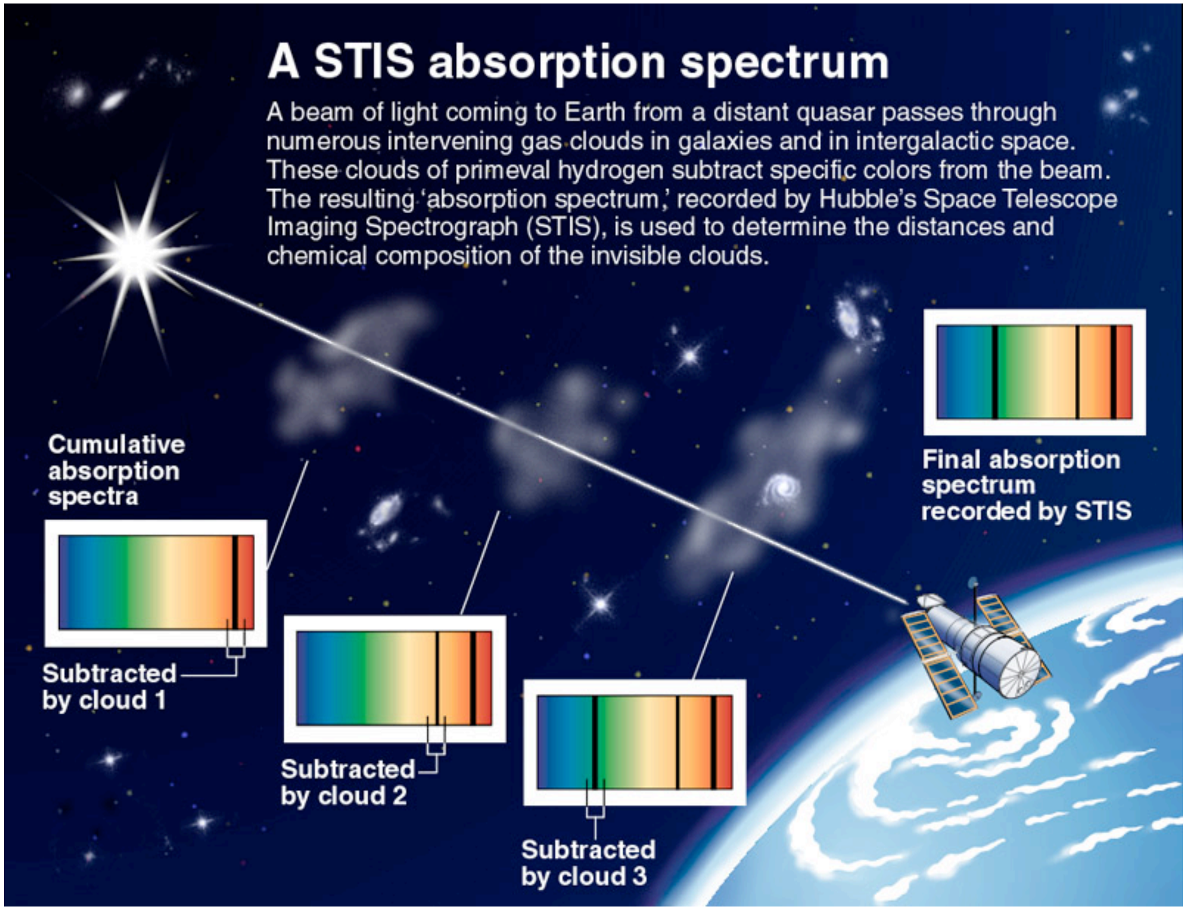


The normal (rest) wavelength of Hα is 656.3nm. We want to calculate the observed wavelength in a gas cloud with Doppler velocity of 493 km/s

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

Change in wavelength = 493/300000 x 656.3 = 1.1 nm. We will therefore observe the shifted Balmer line at 656.3 + 1.1 = 657.4 nm

This technique can be applied to other objects apart from stars. Very distant, bright sources such as quasars can be used to probe very distant galaxies. We'll re-visit this in future lectures.



A STIS absorption spectrum

A beam of light coming to Earth from a distant quasar passes through numerous intervening gas clouds in galaxies and in intergalactic space. These clouds of primeval hydrogen subtract specific colors from the beam. The resulting 'absorption spectrum,' recorded by Hubble's Space Telescope Imaging Spectrograph (STIS), is used to determine the distances and chemical composition of the invisible clouds.

The Hubble Space Telescope (HST) has been a very useful tool for astronomers studying gas in other galaxies. One reason is that being above the atmosphere means improved image quality (images no longer twinkle).

Another reason is that the atmosphere blocks UV radiation (luckily for us!) at wavelengths shorter than about 300nm. To observe light bluer than this, we must get above the atmosphere and use space telescopes.

Some characteristics of interstellar clouds and their absorption lines

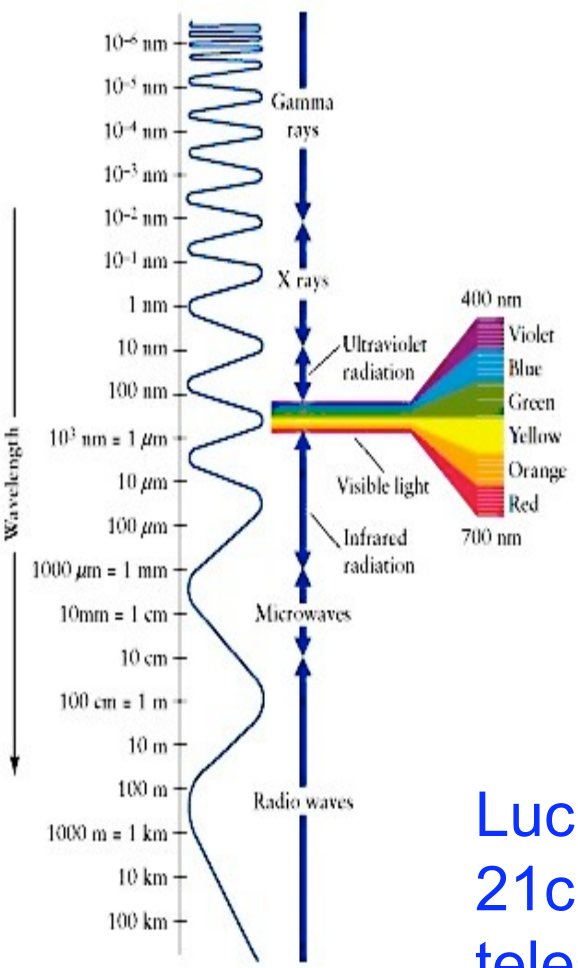
1) Interstellar absorption lines tend to be narrow compared with stellar absorption lines. This is because absorption in stellar atmospheres is blurred due to the fast motions (hot temperatures) and multiple collisions.

2) The sharpness of I.S. lines indicates that the absorbing gas cloud must
be cool and low density. Typically clouds have a few 10s – a few 100s of atoms per cm $^{-3}$ and have temperatures of about 100 K.

3) These clouds are mostly neutral, since they are not near a hot source (e.g. a star) that can ionize them. They are therefore often referred to as *HI clouds*.

4) HI clouds sit in an even lower density *intercloud medium* (0.1 atom per cm^3). This very low density means that photons from even distant stars can leak in an ionize the gas. The intercloud medium is therefore made of HII.

Radiation at 21cm – mapping the heavens with radio telescopes

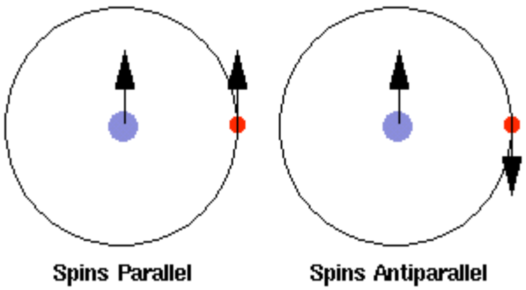


In order to “see” emission nebulae, light must be emitted in the optical regime that our eyes are sensitive to. However, this is only a tiny part of the full *electromagnetic spectrum.*

We have already had an example of how hydrogen in the ISM can be detected via Lyman alpha, but this line is in the UV at 121.6 nm. UV light is blocked by the atmosphere, so we don't see this line from the Milky Way.

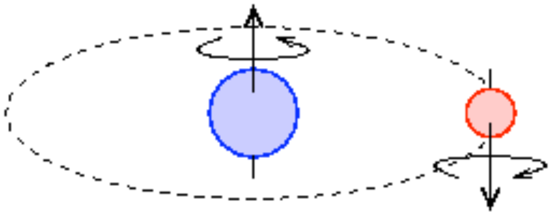
Luckily, hydrogen also has a transition at 21cm, which can be detected by radio telescopes. But this is no ordinary transition......

The lowest energy level of the hydrogen atom, is actually split into 2 closely levels. This is caused by the interactions of the magnetic fields around the proton (in the nucleus) and the orbiting electron.

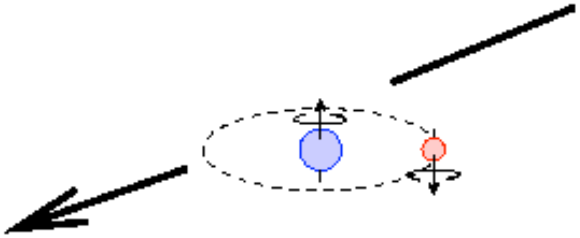


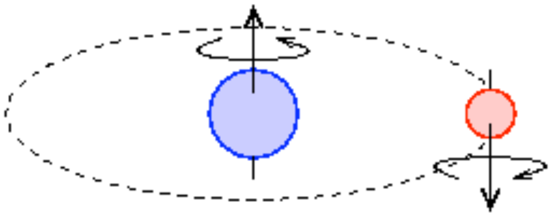
The electron's spin can either be parallel or anti-parallel compared with the proton. There is a small energy difference associated with these 2 states, which creates two closely spaced orbits in the atom.

The energy of a photon that drops between these levels corresponds to a wavelength of 21cm.

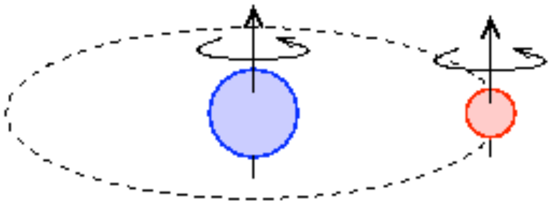


Start with a hydrogen atom in its very lowest energy state: spins of proton and electron are antiparallel.





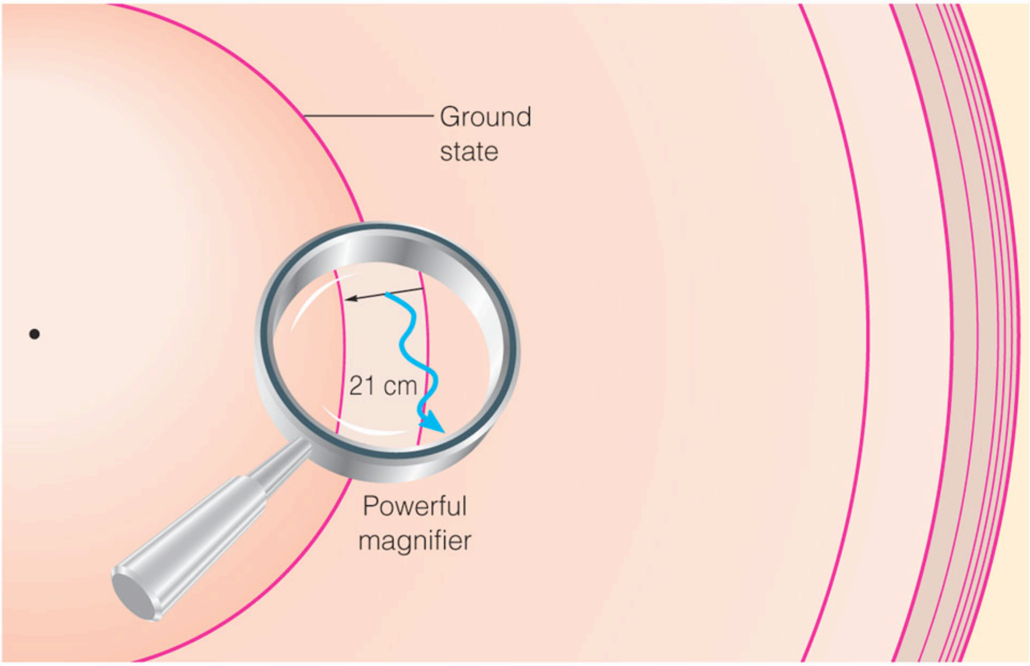
If this atom bumps into another, it may gain some energy ....

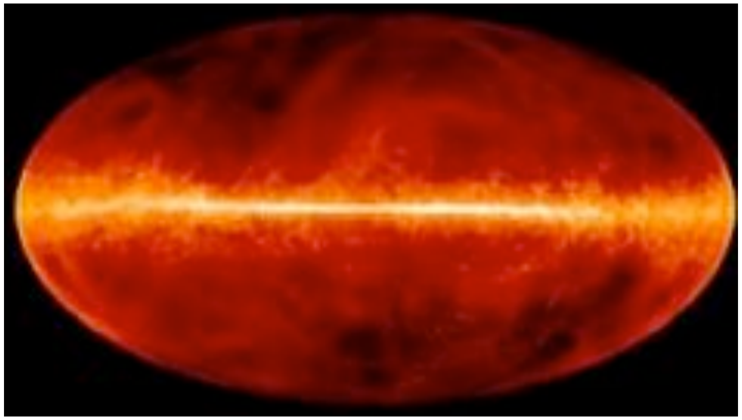


... enough to knock the spin of the electron parallel to the spin of the proton. It is now in an excited hyperfine state.

Because an electron has a slightly different energy if its spin is parallel or anti-parallel with the spin of the proton, we can imagine that the usual shells/energy levels are actually split by a very tiny amount. The split corresponds to a very small energy difference. If an electron changes its spin from parallel to anti-parallel with the proton, it is effectively dropping across this small energy difference.

As always, a change in energy means emission of a photon. Here, the photon has low energy because the energy change is small. The particular wavelength corresponding to this change is 21cm.





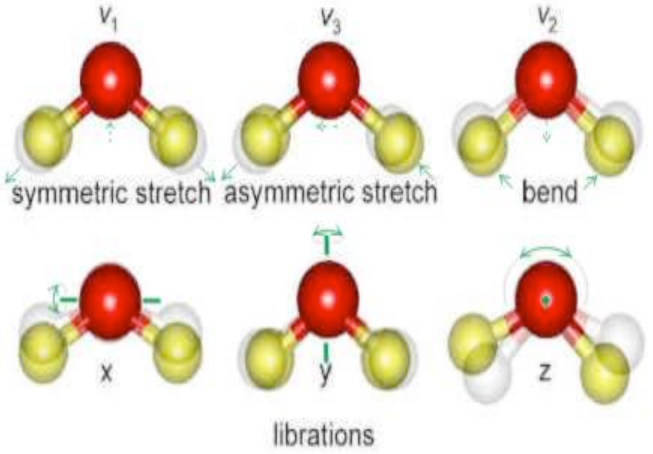
Using telescopes such as the Parkes dish in Australia (below) astronomers have mapped the neutral hydrogen in the Milky Way.

Note that at 21cm we only see neutral hydrogen because ionized hydrogen has no electron left to cause the atomic transition

The other advantage of 21cm emission is that it is unaffected by dust absorption, so we can 'see' through dust clouds to the far side of the galaxy and beyond.

Molecules in the ISM

Hydrogen is the most common ingredient in the ISM, so it is no surprising that H_2 is the most common molecule. However, many other molecules can be observed, usually containing a combination of C, O, H and N.

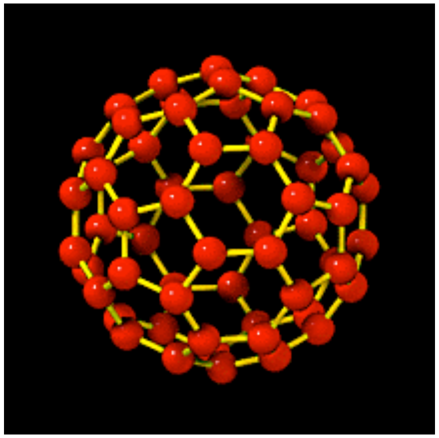


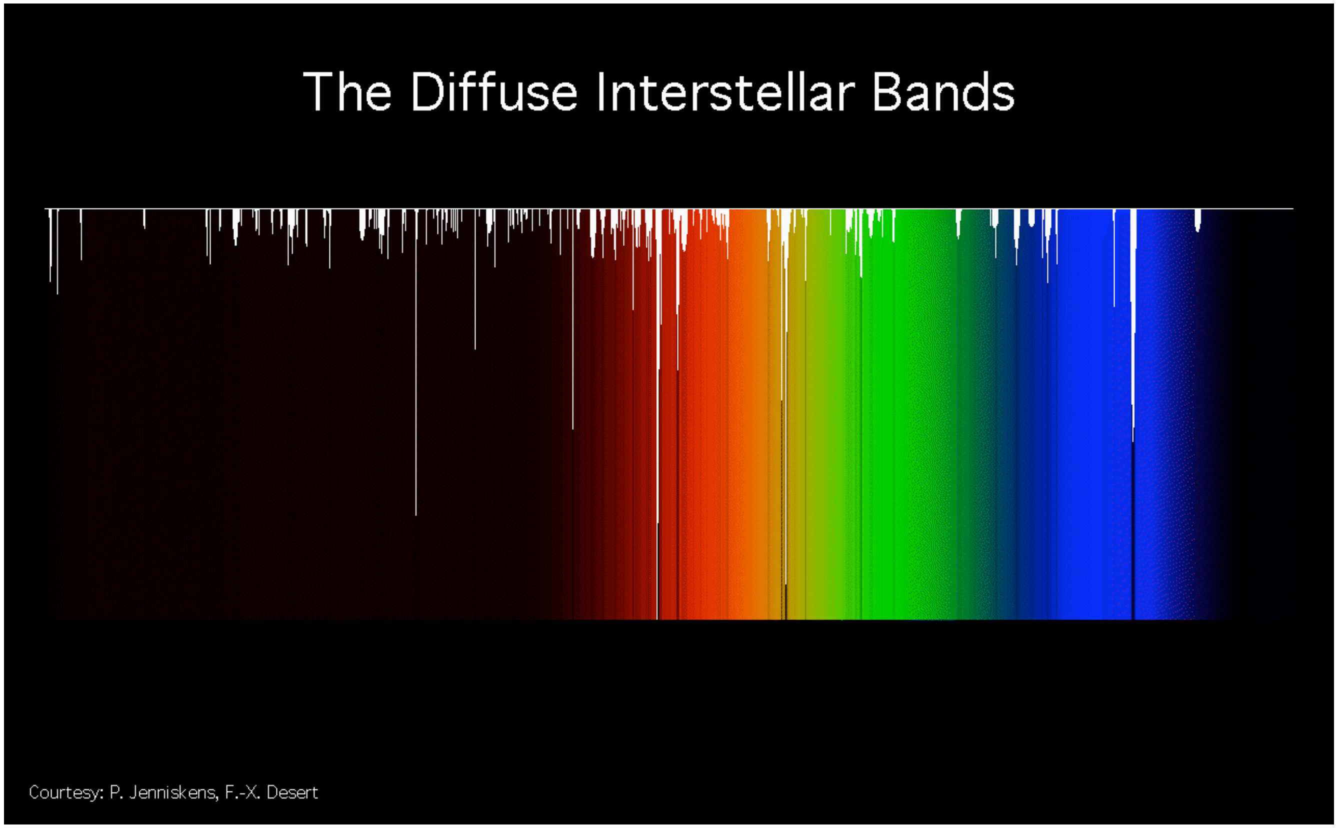
The complex structure of molecules means that it can resonate in many different ways, because the atoms act as if they were joined by springs. Different energy states are therefore caused by atoms vibrating and rotating.

One of the most important molecules is carbon monoxide (CO). Although CO is much rarer than H_2 it emits at radio wavelengths (as opposed to the UV).

Molecules are very fragile, i.e. they are easily destroyed (dissociated) by UV radiation. Therefore, they can only survive in dense clouds. Here the temperature is only ~10K because molecules efficiently emit radiation which cools the clouds.

There are about 300 absorption lines seen in the spectra of reddened stars which astronomers still can’t identify - the diffuse interstellar bands. We believe these are due to complex organic molecules, hydrocarbons. Buckyballs are one possibility.



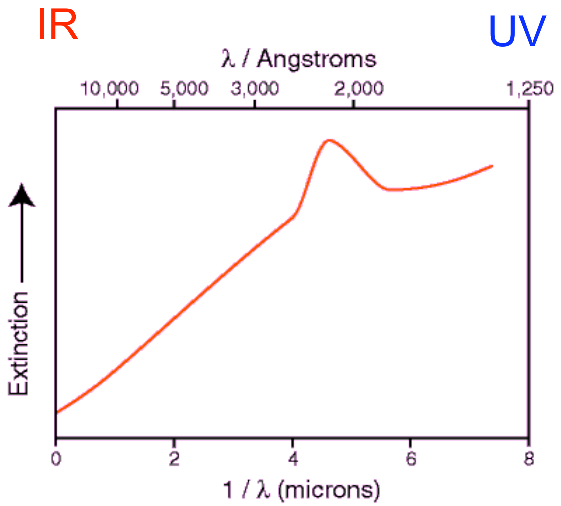


Dust in the ISM

Dust grains make up about 1% of the mass of the ISM, most of which is formed in the cool outer layers of stars. We already saw the effect of scattering by dust in reflection nebulae. We can infer the presence of dust in 3 other ways:

1) Emission in the infrared. Dust is quite cold (~30K) so emits at long wavelengths. The IRAS satellite mapped the dust in the Milky Way and found it is patchy, but mostly confined to the disk of the galaxy.

2) Extinction of background stars. Dust makes background stars look fainter. This is known as extinction. This can often fool is into thinking that stars are farther away.



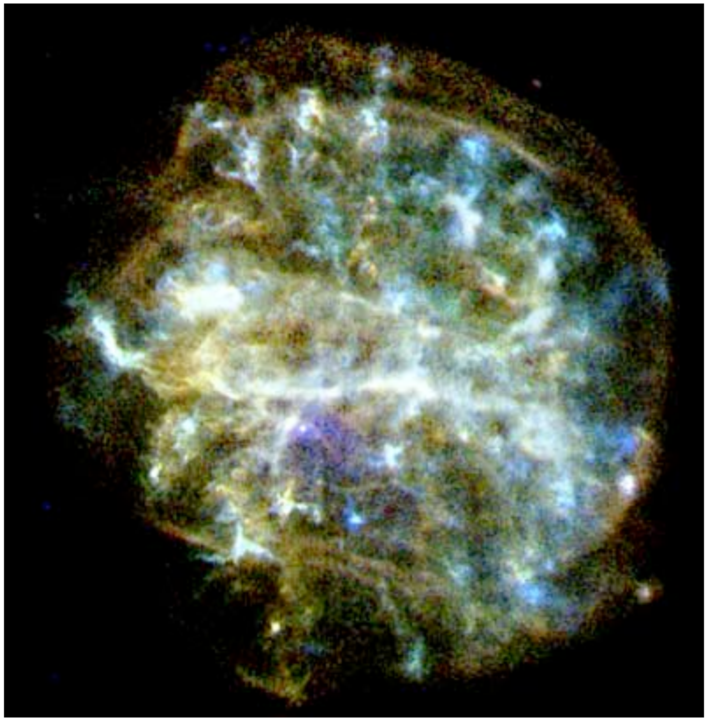
This is the extinction curve for the Milky Way. The bump at 220nm is due to graphite. Silicates and other compounds are also present in interstellar dust.

3) Reddening of background stars. Dust preferentially absorbs blue light, so a background star will look redder. The amount of reddening can be calculated by comparing 2 stars of the same spectral type.

The Coronal Gas Component of the ISM

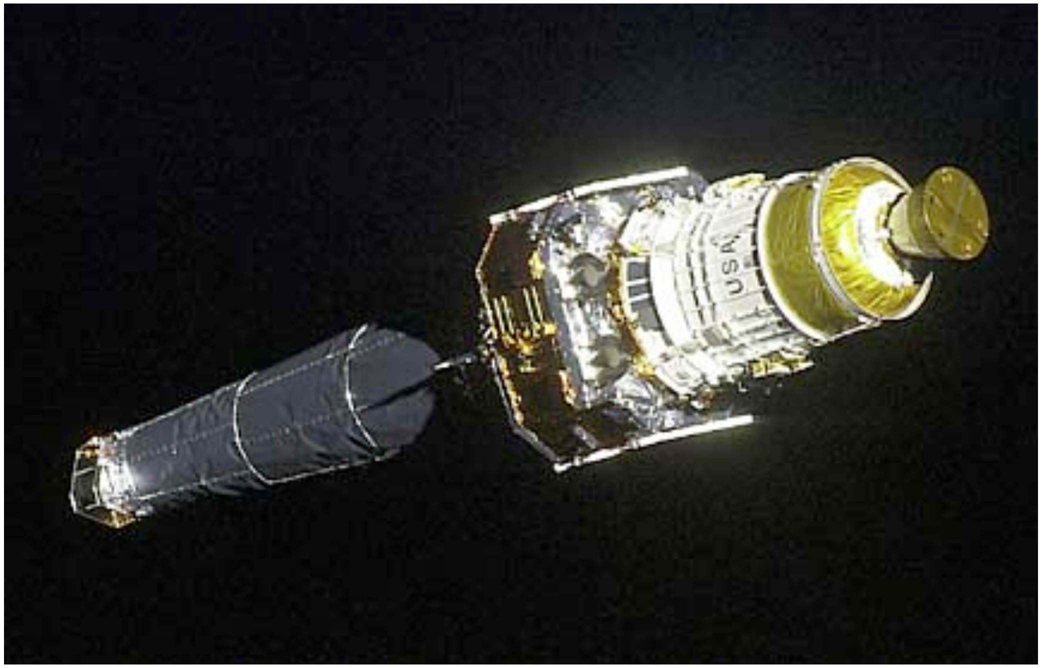
We have seen that most of the ISM (e.g. HI clouds, molecular clouds and dust) are quite cold. However, there is a hot coronal component at 1 million (10^6) K, just like the sun's corona.

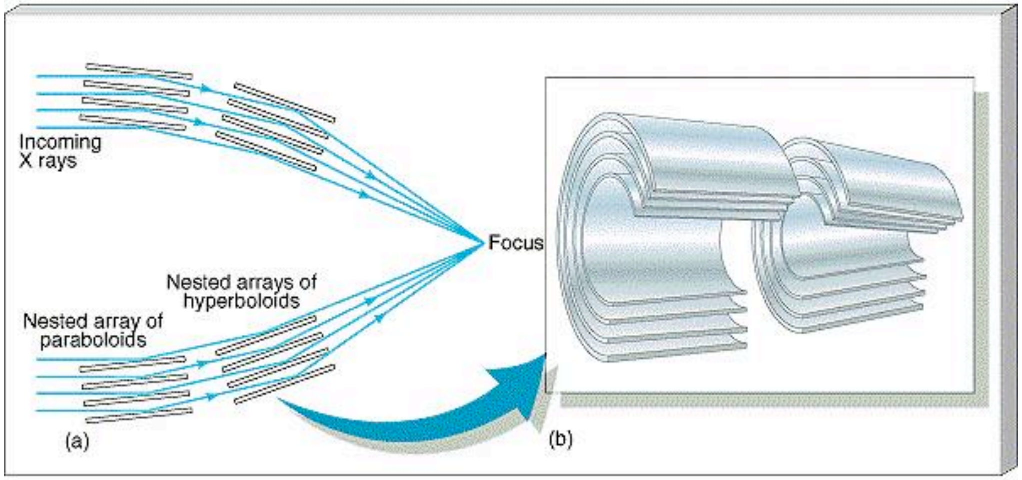
This gas is heated by supernova explosions. Due to its high temperature, the coronal gas emits energy at very short wavelengths, e.g. in the Xray. Note that this is the opposite of dust which is cold and therefore emits in the IR.



This supernova image was obtained by the Xray satellite Chandra and shows the complex filamentary structure in the hot gas than can result from a supernova blast.

X-ray telescopes like Chandra use nested parabolic mirrors because X-ray photons would go straight through the mirrors used in normal optical telescopes. X-ray photons needs to be focussed at very shallow angles.





The ISM – a summary.

Component	Temperature	Contents	Detected
HI clouds	50-150K	neutral hydrogen	Lyman alpha, 21cm
HII regions (intercloud)	1000-10000K	ionized hydrogen	nebulae/emission
Dust	20-50 K	carbon/silicon	IR emission
Molecular clouds	20-50 K	H_2, CO etc.	radio
Coronal gas	1 million K	ionized hydrogen	X-ray emission