Lecture 3:
Imaging vs. Spectroscopy
at Radio Wavelengths

Rutgers Physics 346: Observational Astrophysics February 2, 2021

Quiz #2: Graded with solution available on Canvas.

Q: The center of the Milky Way is known to harbor a supermassive black hole. 50 years from now, will the (a) celestial and (b) Galactic coordinates of this black hole be different from their current values? Please explain your answers.

A: The Galactic coordinates will not change, since the center of the Milky Way is assigned longitude, latitude = 0,0. Celestial (a.k.a. equatorial) coordinates will change slightly due to precession of the North pole, which affects the intersection point of the celestial equator and ecliptic plane that defines the origin of the system. However, celestial coordinates in a fixed epoch such as J2000 will not change due to the precession. You might also worry about Galactic coordinates shifting due to the Sun's 220 million year orbit around the Galactic Center, but over 50 years that only amounts

to a 0.3" shift, which is negligible for most purposes.

Comments: Be precise and clear with your answers. I'm generous with partial credit; you'll get more credit for a well-explained-but-wrong answer than for a terse wrong answer.

What's different about radio astronomy?

Wavelengths are longer (λ = 0.35mm – 6m, vs. ~0.0005mm for visible light). This has several consequences:

Telescopes have larger diameters and lower surface accuracies.

Observations can often be done during day or night, and are less limited by the atmosphere (clouds, turbulence, etc.).

Detectors are often sensitive to the phase of incident radiation, not just its amplitude (in the sense of a complex number).

What do we study with radio telescopes?

Typically, we study interstellar matter:

+ dust grains that glow because they're warm
+ ionized plasmas that glow because they're warm, or because charged particles are accelerated in magnetic fields
+ clouds of atomic and molecular gas producing line emission

(Astronomy jargon that we'll see again: HI = neutral atomic hydrogen, HII = ionized hydrogen, H_2 = molecular hydrogen.)

We can also detect radio emission from planets and stars.

Line and continuum emission/absorption

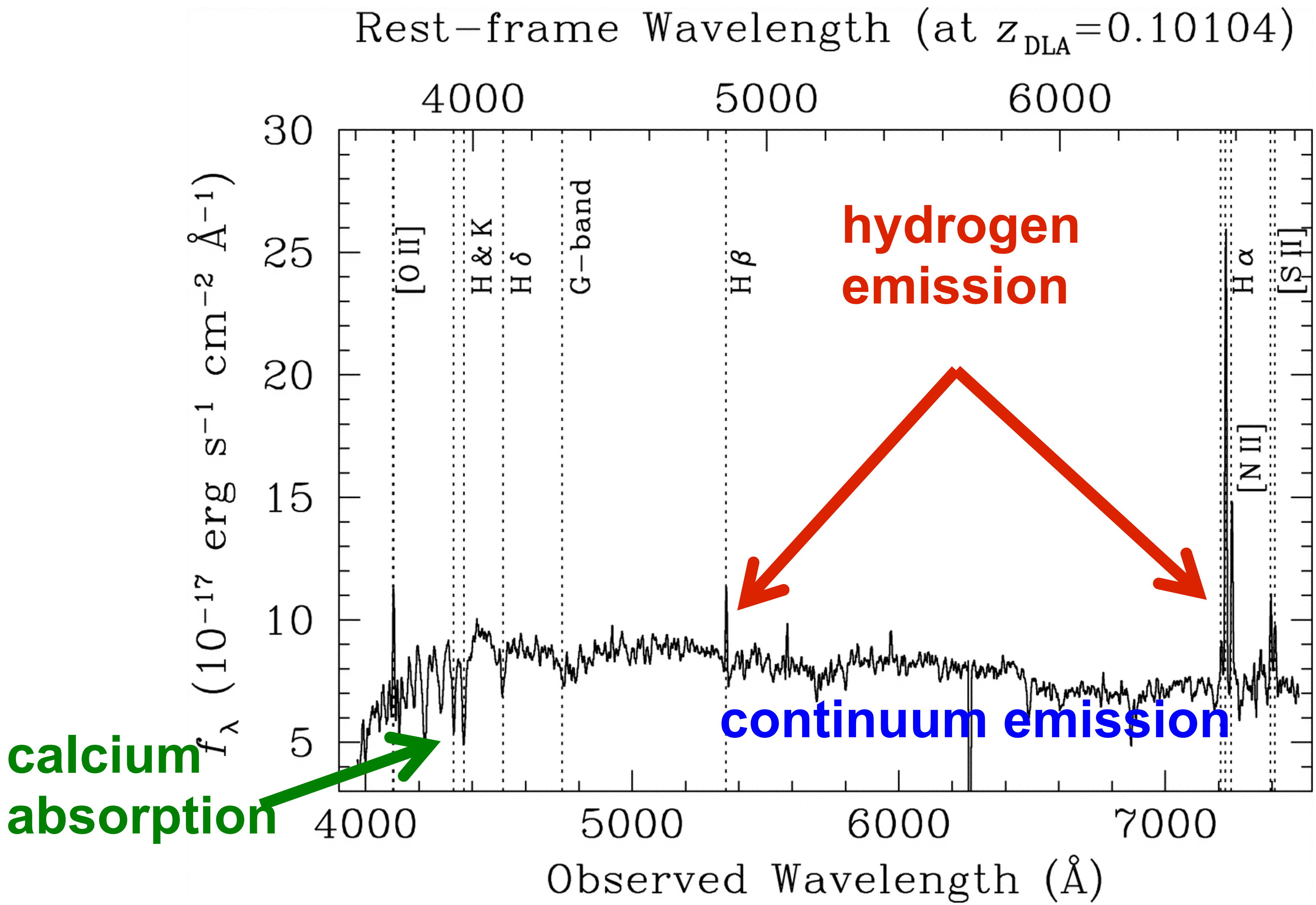
When we look at astronomical spectra (at all wavelengths), we classify features in two ways:

(1) line vs. continuum (roughly, narrow vs. broad)

(2) emission vs. absorption

Note: for an absorption line to be produced, there must be “background” continuum emission to be absorbed!

Example: optical spectrum of a galaxy



Radio continuum emission

Three principal mechanisms:

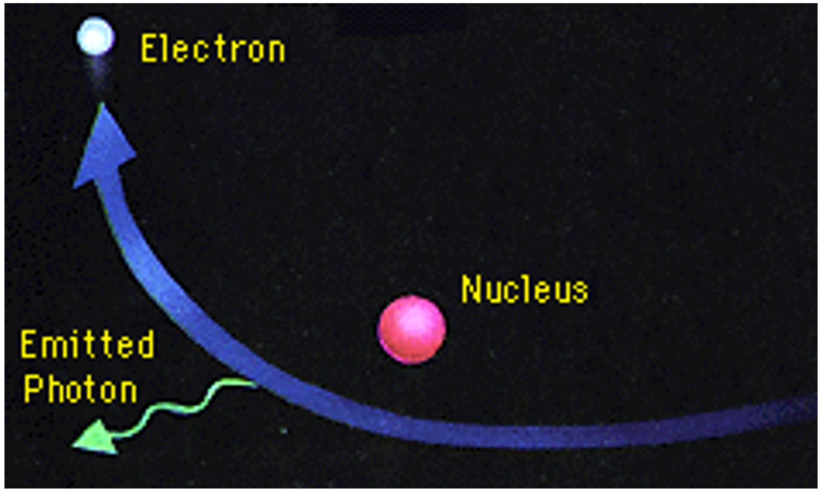
(1) free-free emission (a.k.a. "bremsstrahlung" = "braking radiation") from ionized gas

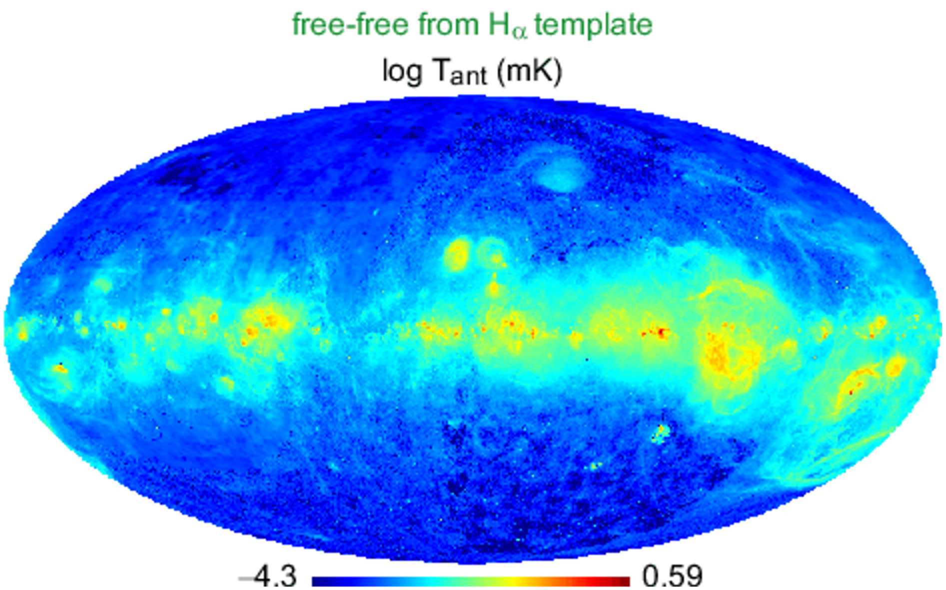
(2) synchrotron emission from electrons being accelerated in a strong magnetic field

(3) thermal emission (i.e., produced due to heat) by dust grains

Free-free emission

Mechanism: electrons are accelerated by the Coulomb potential of ions (higher temperature ⇔ faster motions ⇔ higher-energy photons).

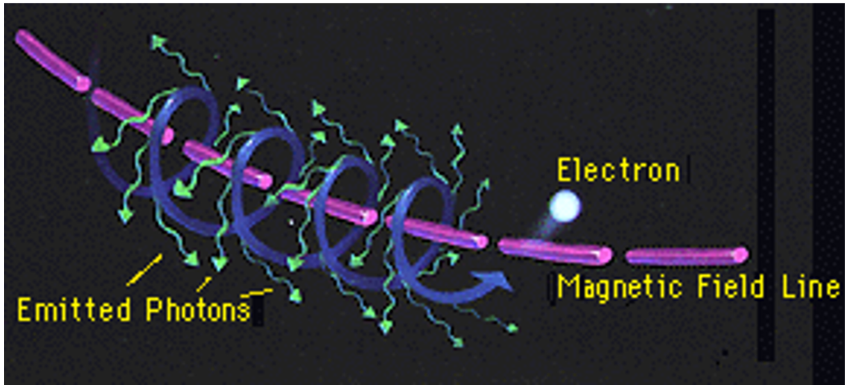


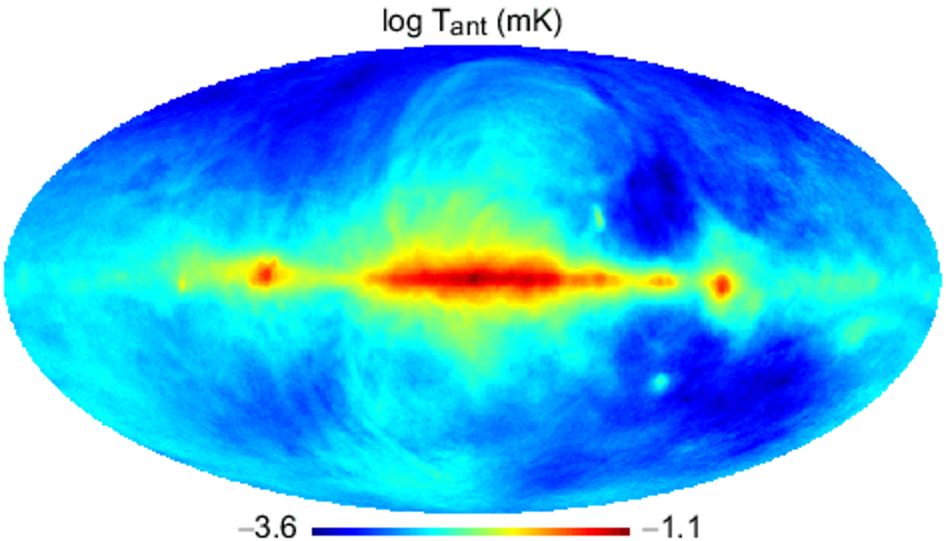


Burigana et al. (2004):
free-free emission from Milky Way at 100 GHz

Synchrotron emission

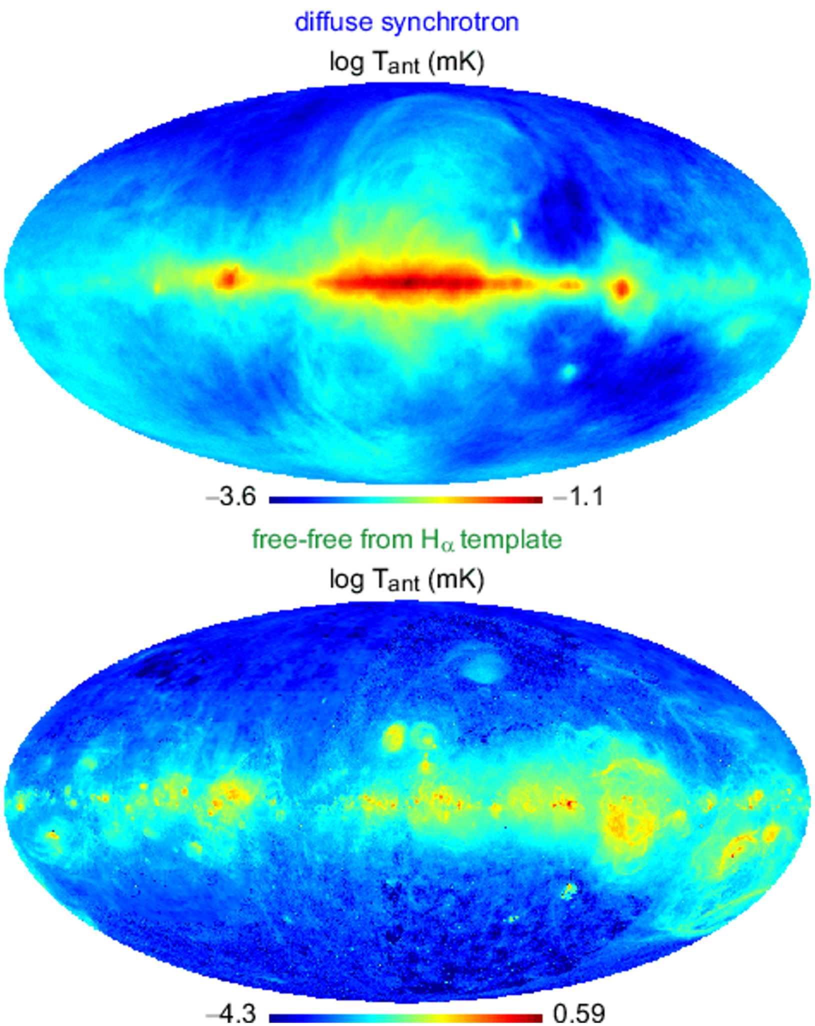
Mechanism: electrons are accelerated along helical trajectories in magnetic fields (stronger magnetic fields ⇔ higher-energy photons).



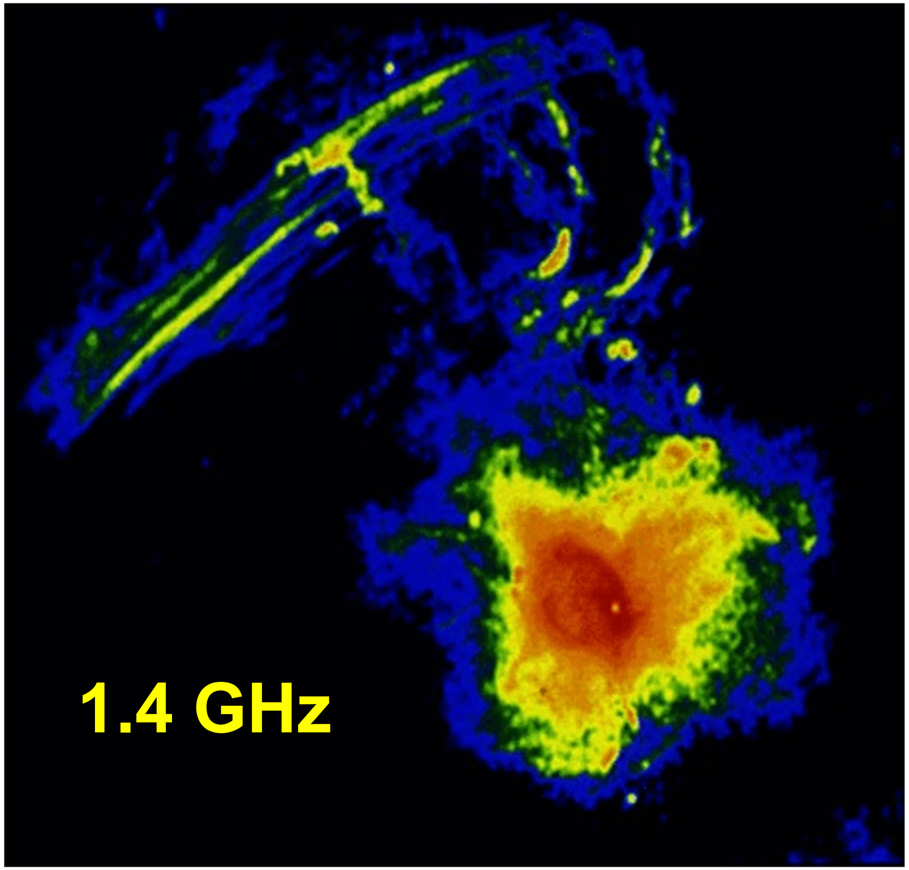


Burigana et al. (2004):
synchrotron emission from Milky Way at 100 GHz

Free-free vs. synchrotron emission



Galactic Center filaments:
which mechanism is responsible?



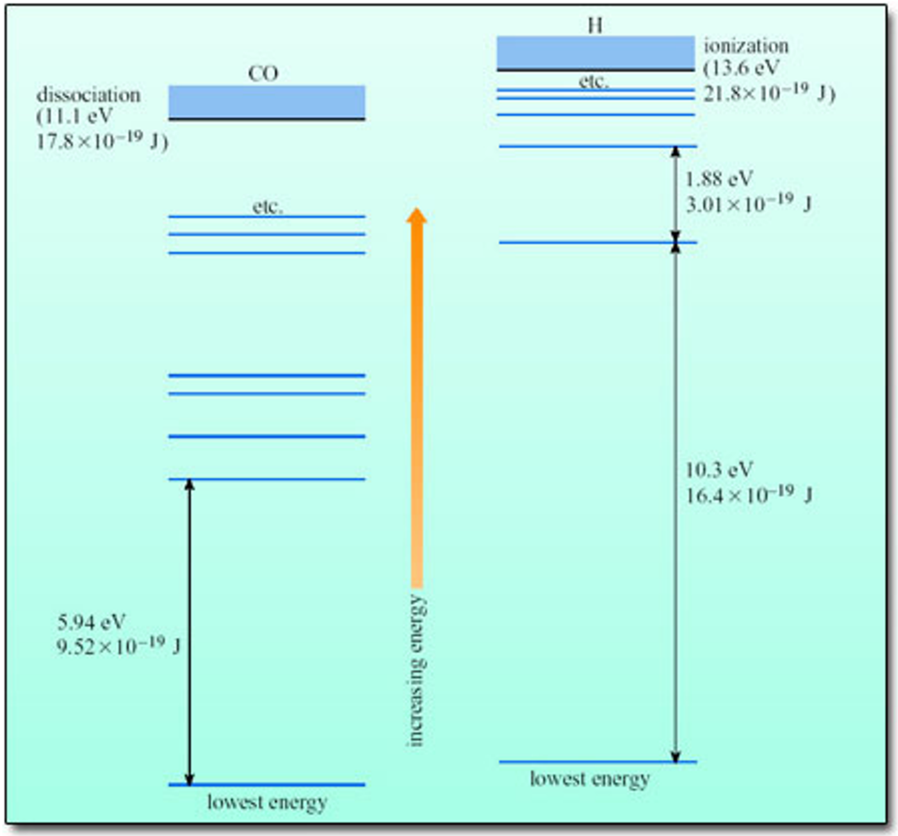
Why do these look different?

Line emission

A sharp line feature occurs when there is a transition in the electronic or spin state of an atom, or in the electronic, vibrational, or rotational state of a molecule.

This sharp feature is broadened by line-of-sight motions in the emitting/absorbing material (i.e., by the Doppler effect).

Electronic transitions

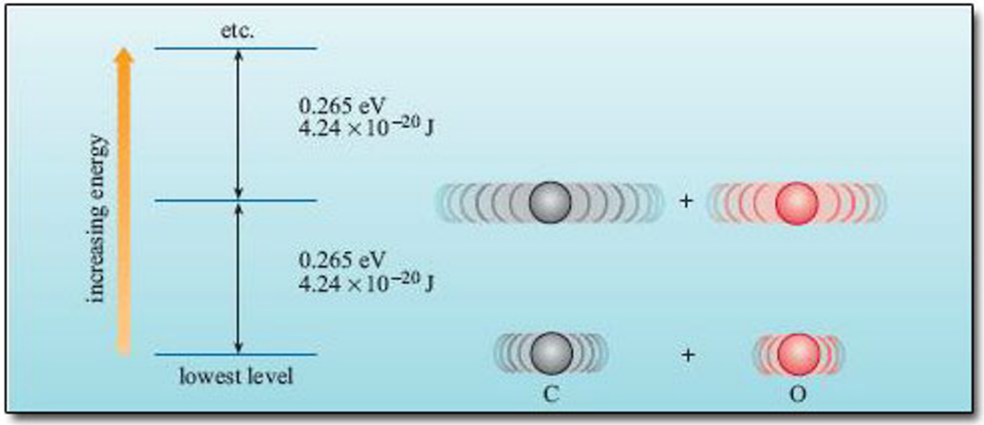


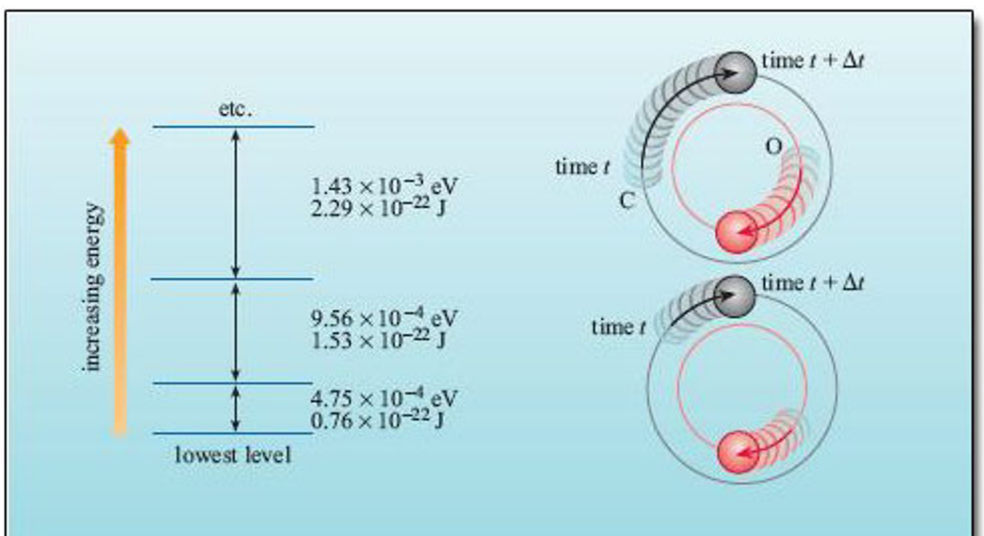
When an electron in an atom or molecule drops from a higher energy level to a lower energy level, a photon is emitted.

An incoming photon of the right wavelength/frequency can also be absorbed.

Courtesy of Open University.

Vibrational and rotational transitions





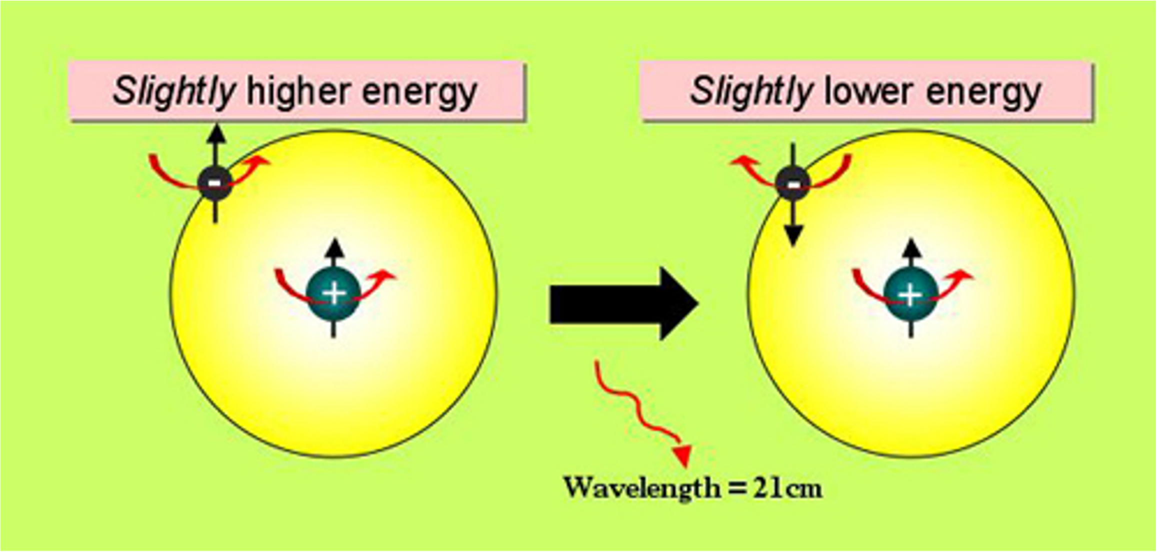
Courtesy of Open University.

Molecules also have quantized levels of vibrational and rotational energy (spacings are larger for the former).

Transitions are associated with absorption/emission of photons.

The key "spin flip" transition: 21cm H line

In a H atom, when the electron and the proton switch from having parallel spins to having antiparallel spins, a 21cm photon is emitted.



Doesn't trace ionized (HII) or molecular (H_2) gas – just neutral atomic (HI) gas!

Courtesy of Swinburne University.

Specific intensity

- define a small patch of area dA at x whose normal is $\hat{n}$ (note that $\hat{n}$ and $\hat{k}$ need not be the same);
- define a small solid angle $d\Omega$ centered on $\hat{k}$; and
- define a small range in frequency $d\nu$ about some particular frequency ν.

$$dE = I_\nu(x, \hat{k}, t)\, [\hat{k} \cdot \hat{n}]\, d\nu\, dA\, d\Omega\, dt$$

I_ν units are erg Hz^{-1} cm^{-2} ster^{-1} s^{-1}

In the absence of matter or changes in frequency, specific intensity is conserved along a ray. Define ***surface brightness*** by integrating over a fixed frequency range:

$$\mu \equiv \int I_\nu\, d\nu \sim \mathrm{erg\,cm^{-2}\,ster^{-1}\,s^{-1}}$$

Define ***flux density*** by (instead) integrating over solid angle:

$$f_\nu \equiv \int I_\nu\, [\hat{k} \cdot \hat{n}]\, d\Omega \sim \mathrm{erg\,Hz^{-1}\,cm^{-2}\,s^{-1}}$$

Flux density vs. flux

At far-IR and radio wavelengths, typically measure flux densities in ***Janskys***

$$1\,\mathrm{Jy} \equiv 10^{-23}\,\mathrm{erg\,Hz^{-1}\,cm^{-2}\,s^{-1}}$$

Integrate flux density over a frequency range or surface brightness over solid angle → ***flux***:

$$F = \int f_\nu \, d\nu = \int \mu\, [\hat{k} \cdot \hat{n}]\, d\Omega \sim \mathrm{erg\,cm^{-2}\,s^{-1}}$$

Flux obeys the inverse square law $F = L / (4\pi d^2)$

Brightness temperature

Brightness temperature is the approximate temperature that a thermal source would need to have to produce an observed radio flux density given its observed angular size

$$T_{\rm b} \equiv \frac{\lambda^2}{2k\Delta\Omega_{\rm src}} f_\nu$$

If the source is smaller than the telescope resolution element (beam), this changes to:

$$T_{\rm b} \rightarrow \frac{\lambda^2}{2k\Delta\Omega_{\rm beam}} f_\nu$$

Beam dilution refers to the reduced brightness temperature measured for a point source in a larger beam. ***Antenna temperature*** is the sum of brightness temperature and the ***system temperature*** reported when the telescope is looking at blank sky:

$$T_A = T_b + T_{\rm sys}$$

Imaging vs. Spectroscopy

A source is ***resolved*** (in an image) if it is larger than the angular resolution of an image.

The ***field of view*** of an observation is how much of the sky it covers.

photometry refers to measuring the total brightness of a source.

In spectroscopy, we disperse the light to enable brightness measurements as a function of wavelength, creating a tradeoff between the ***bandwidth*** and ***spectral resolution***

Imaging spectroscopy yields a spectrum for every resolution element; this is a standard operating mode for some radio and X-ray telescopes! For optical/IR telescopes, this requires specialized instruments known as ***integral field units*** (IFUs)

Coherent vs. Incoherent Detection

Coherent detectors measure phase and amplitude of incoming photons; sensitive to polarization of incident radiation. This is standard in radio astronomy.

Incoherent detectors measure only power of incoming radiation; not sensitive to phase or polarization. This is standard in optical/IR, although polarimeters can be built.

Coherent detection can deliver much higher spectral resolution and beats the strong but incoherent thermal noise.

However, it only detects one polarization, is strongly bandwidth-limited, and coherent detectors are highly complex electronically and can therefore only be fabricated as small arrays of receivers.

Homework for Thursday, Feb. 4

Due: Quiz #3 will appear on Canvas Assignments at 4:40pm, due at noon tomorrow (Feb. 3).

Do: Bring questions on your (graded) Worksheet #1. Be ready to work with your project group for most of the session – if that requires installing software or troubleshooting astrolab access, try to solve that ahead of time.