NCTS-TCA Summer Student Program 2025
Mini-Workshop

Radiative Processes and Transport

Sheng-Yuan Liu (ASIAA)


Astronomy and Astrophysics
an Observational Science
https://cdn.shopify.com/s/files/1/0742/7719/1954/files/famous_astronomers_1024x1024.jpg?v=1682805109

Astronomy and Astrophysics
an Observational Science

Observation | Theory | Computation

Astronomy and Astrophysics
an Observational Science

Observation Theory Computation

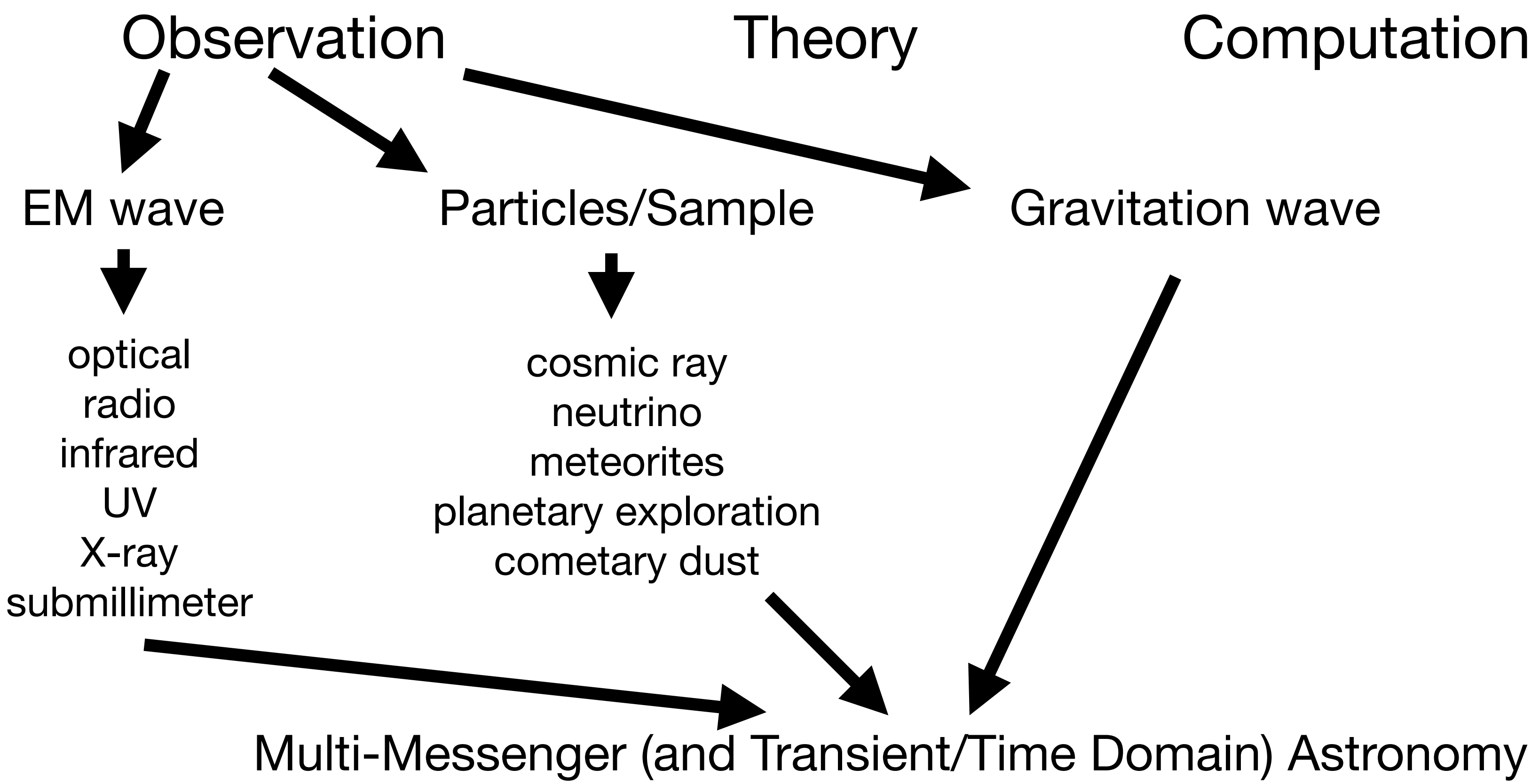
- Observation → EM wave
- Observation → Particles/Sample
- Observation → Gravitation wave

Astronomy and Astrophysics
an Observational Science

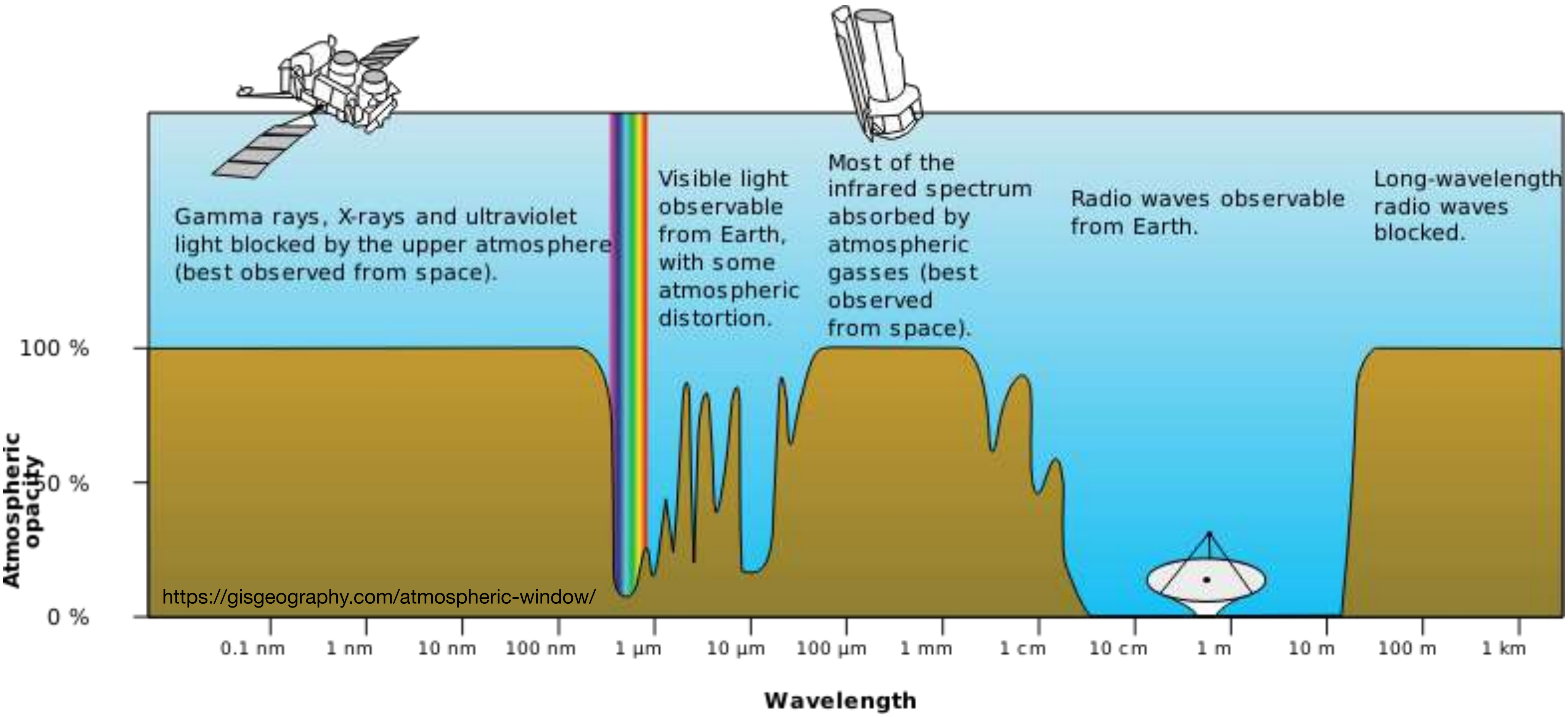
Observation   Theory   Computation

- Observation
  - EM wave
    - optical
    - radio
    - infrared
    - UV
    - X-ray
    - submillimeter
  - Particles/Sample
    - cosmic ray
    - neutrino
    - meteorites
    - planetary exploration
    - cometary dust
  - Gravitation wave

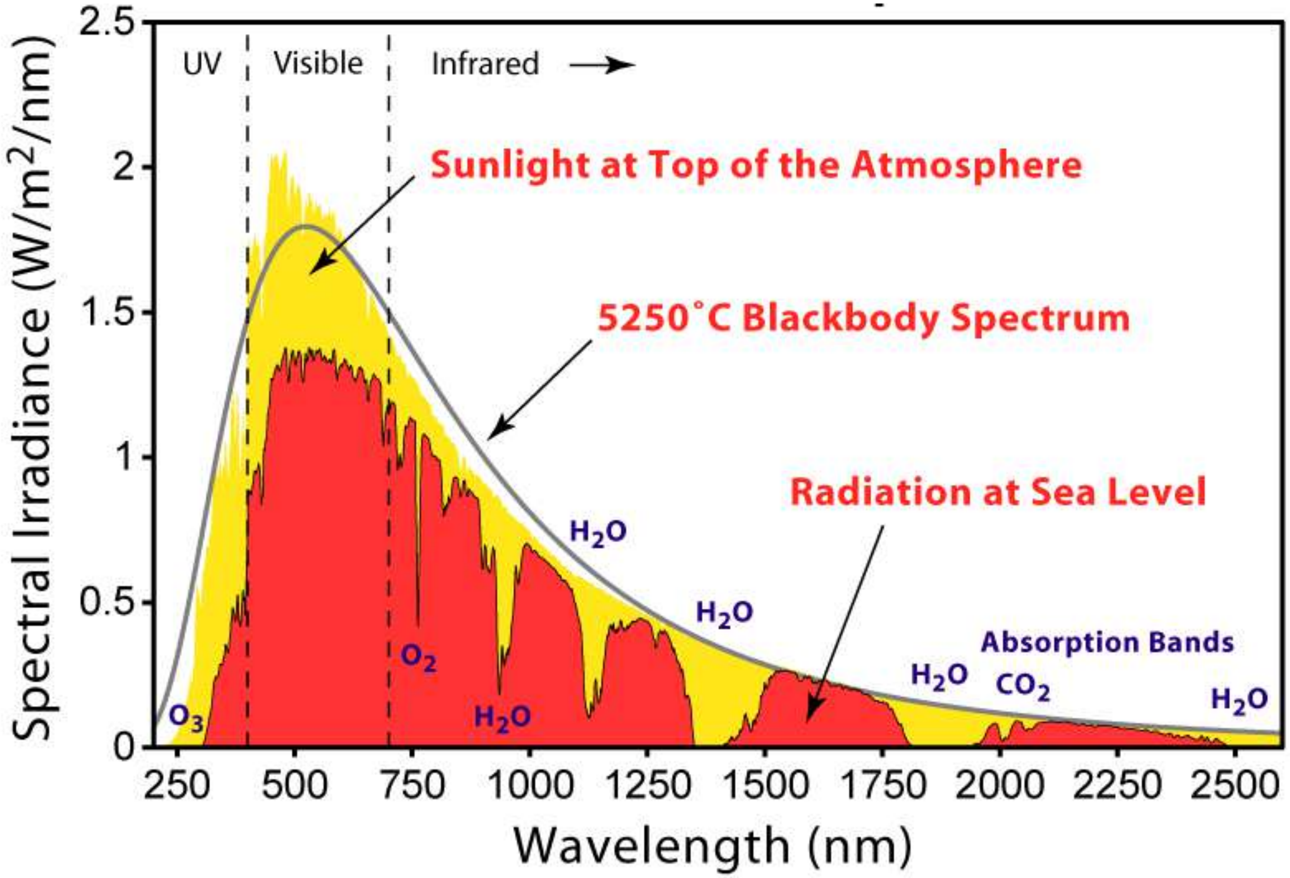
Astronomy and Astrophysics
an Observational Science



Electromagnetic Wave and Atmospheric Window



Solar Radiation Spectrum as a Blackbody



https://physics.stackexchange.com/questions/130209/how-can-it-be-that-the-sun-emits-more-than-a-black-body

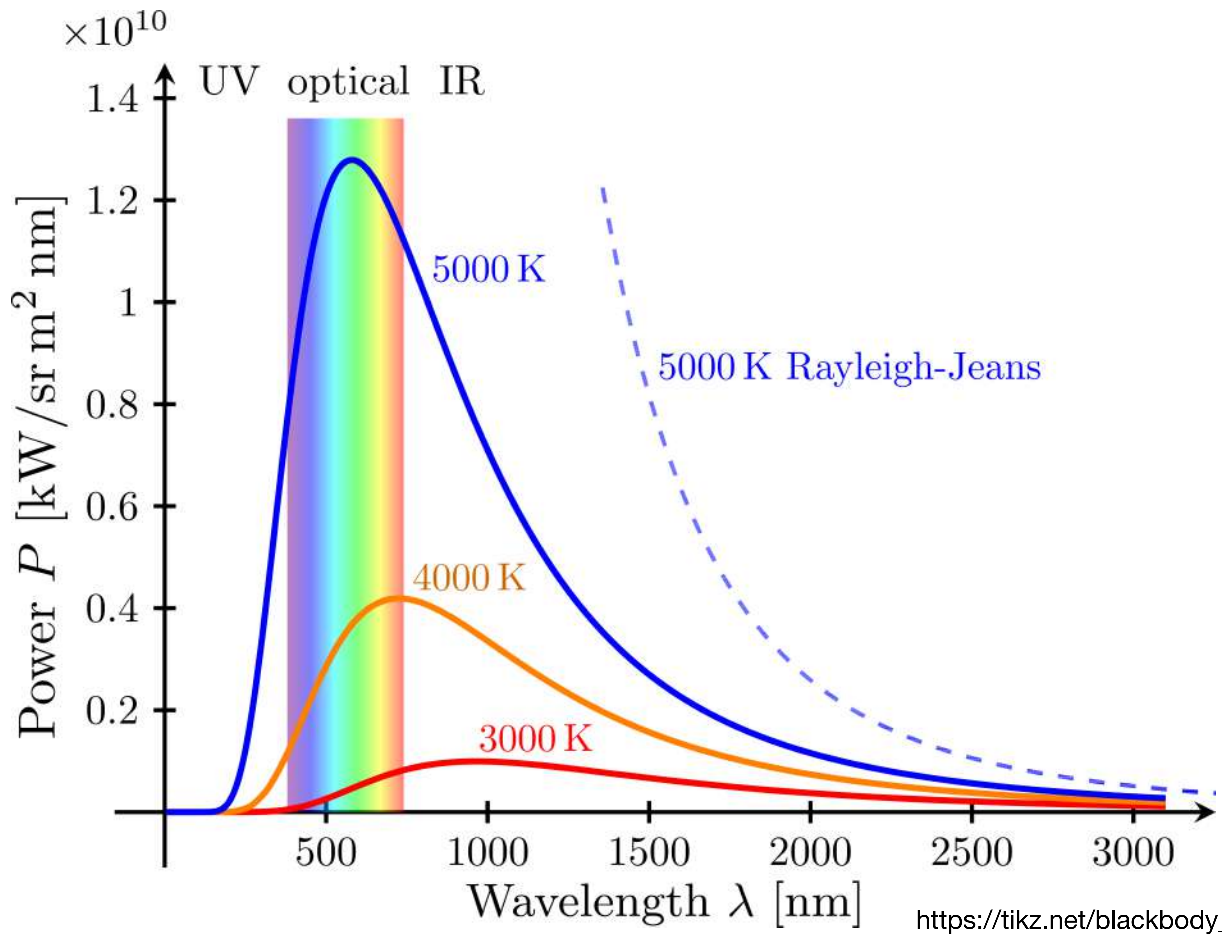
Radiation at multiple wavelengths - Blackbody Radiation

$$B_\nu(T) = \frac{2h\nu^3/c^2}{\exp(h\nu/kT) - 1}$$

$$B_\lambda(T) = \frac{2hc^2/\lambda^5}{\exp(hc/k\lambda T) - 1}$$

Wien's Displacement Law

$$\lambda_{peak} = 0.002898\ (\frac{T}{K})\ m$$

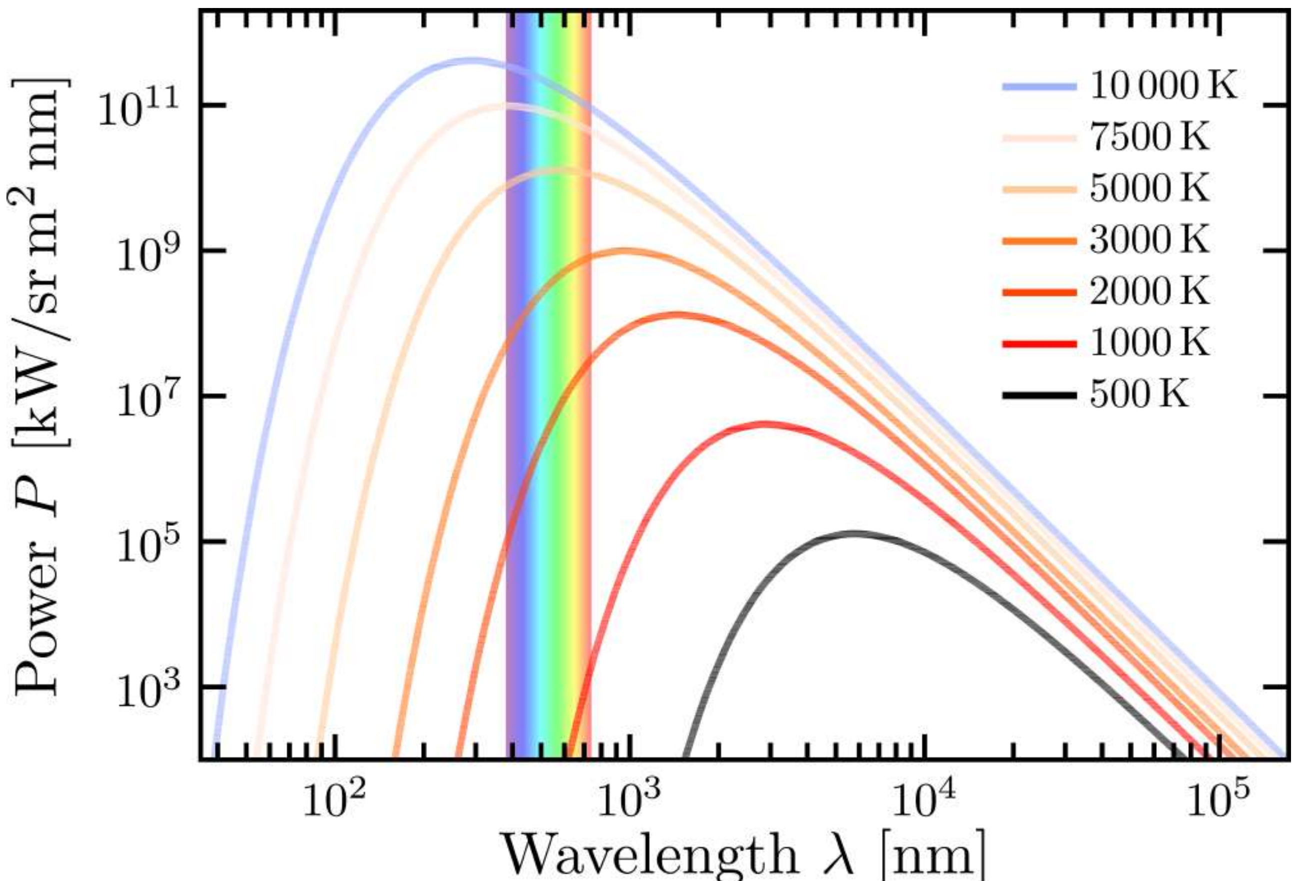


https://tikz.net/blackbody_plots/

Blackbody Radiation

$$B_\nu(T) = \frac{2h\nu^3 / c^2}{\exp(h\nu / kT) - 1}$$

$$B_\lambda(T) = \frac{2hc^2 / \lambda^5}{\exp(hc / k\lambda T) - 1}$$



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Blackbody Radiation

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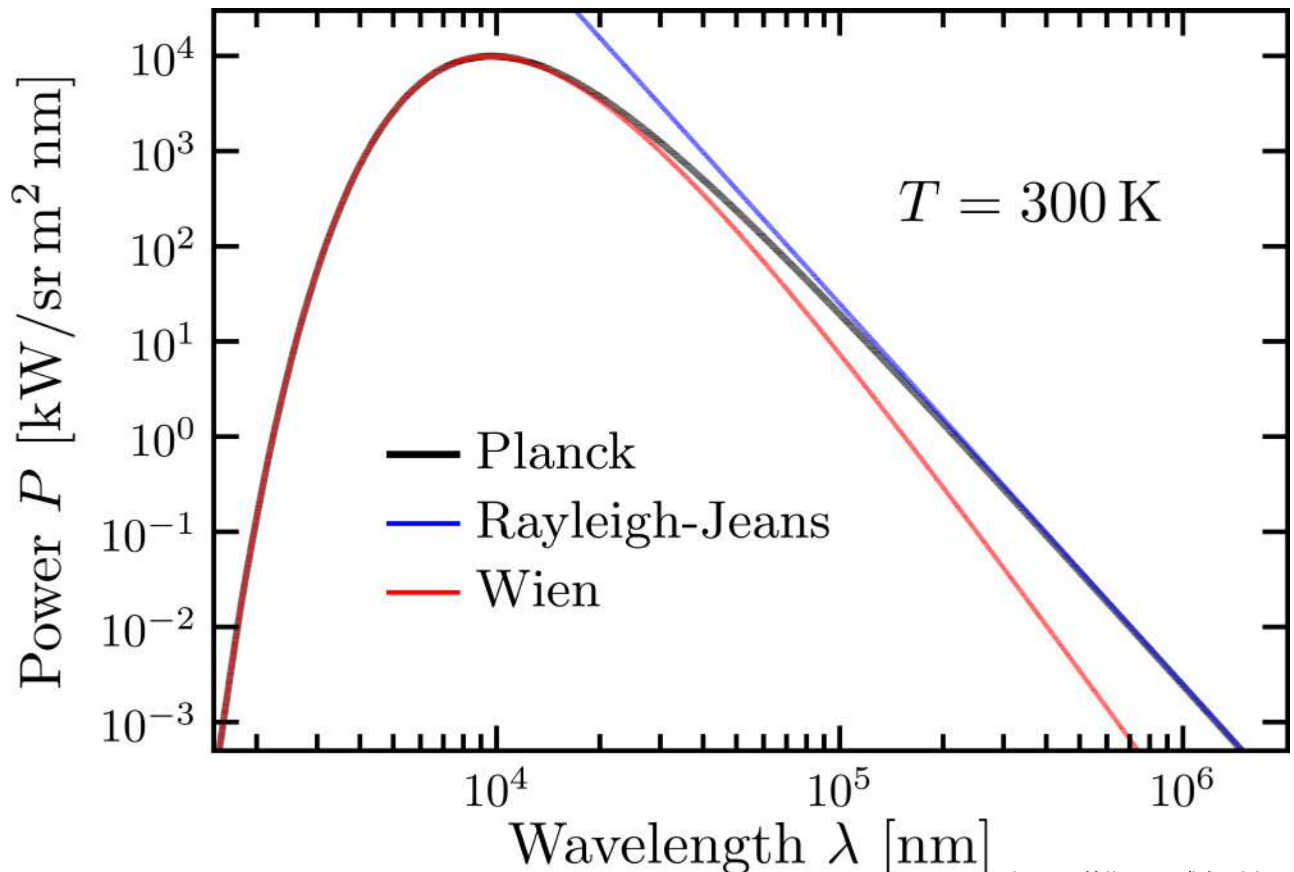
$$B_\lambda(T) = \frac{2hc^2/\lambda^5}{\exp(hc/k\lambda T)-1}$$

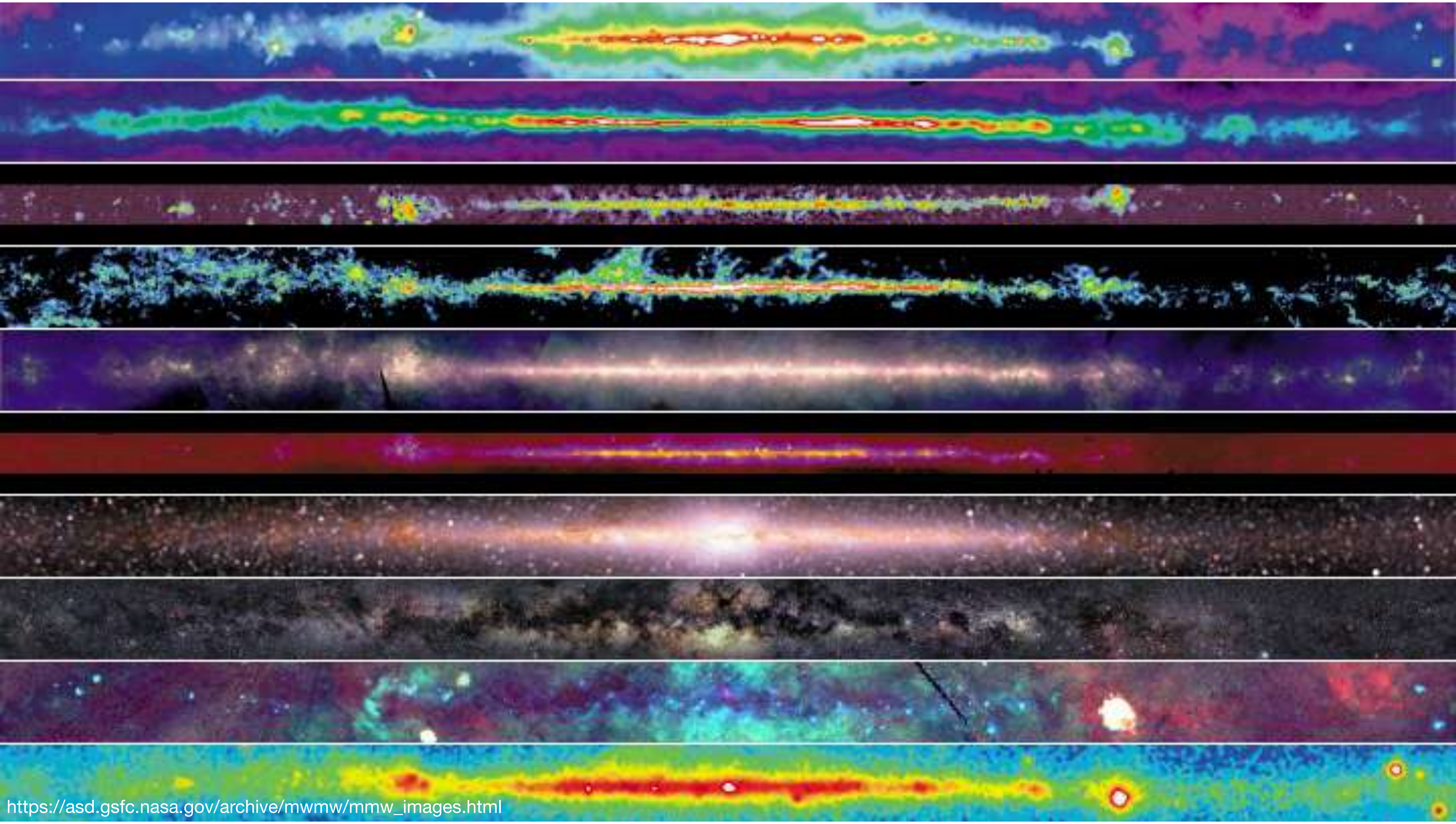
Approximations

$$B_\nu(T) = \frac{2h\nu^3}{c^2}e^{-\frac{h\nu}{k_BT}}$$ Wien ($\nu \gg 1$)

$$B_\nu(T) = \frac{2\nu^2 k_B T}{c^2}$$ Rayleigh-Jeans ($\nu \ll 1$)

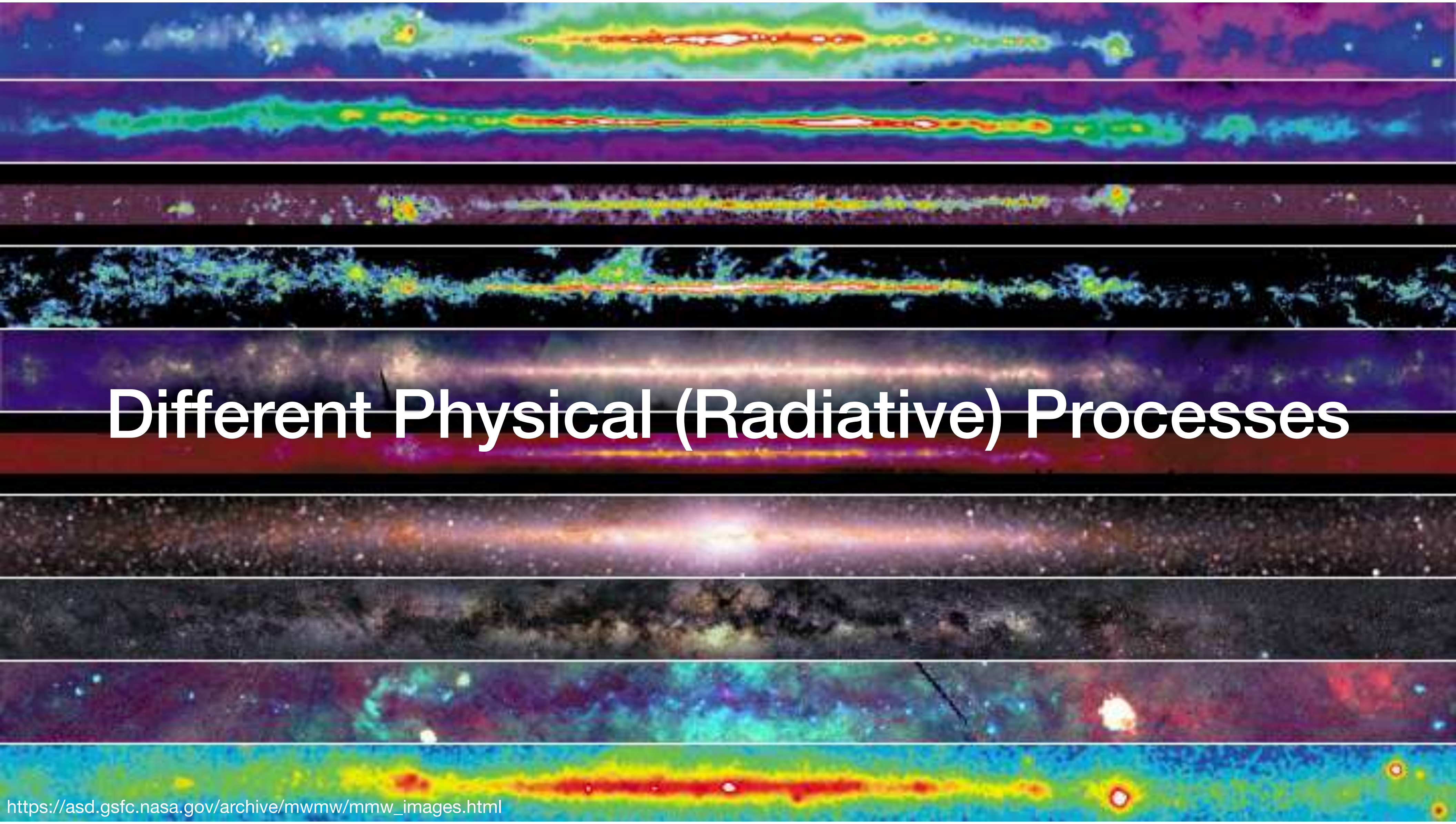


https://tikz.net/blackbody_plots/



https://asd.gsfc.nasa.gov/archive/mwmw/mmw_images.html

Different Physical (Radiative) Processes



https://asd.gsfc.nasa.gov/archive/mwmw/mmw_images.html

Transport (of EM Waves) = Radiative Transfer

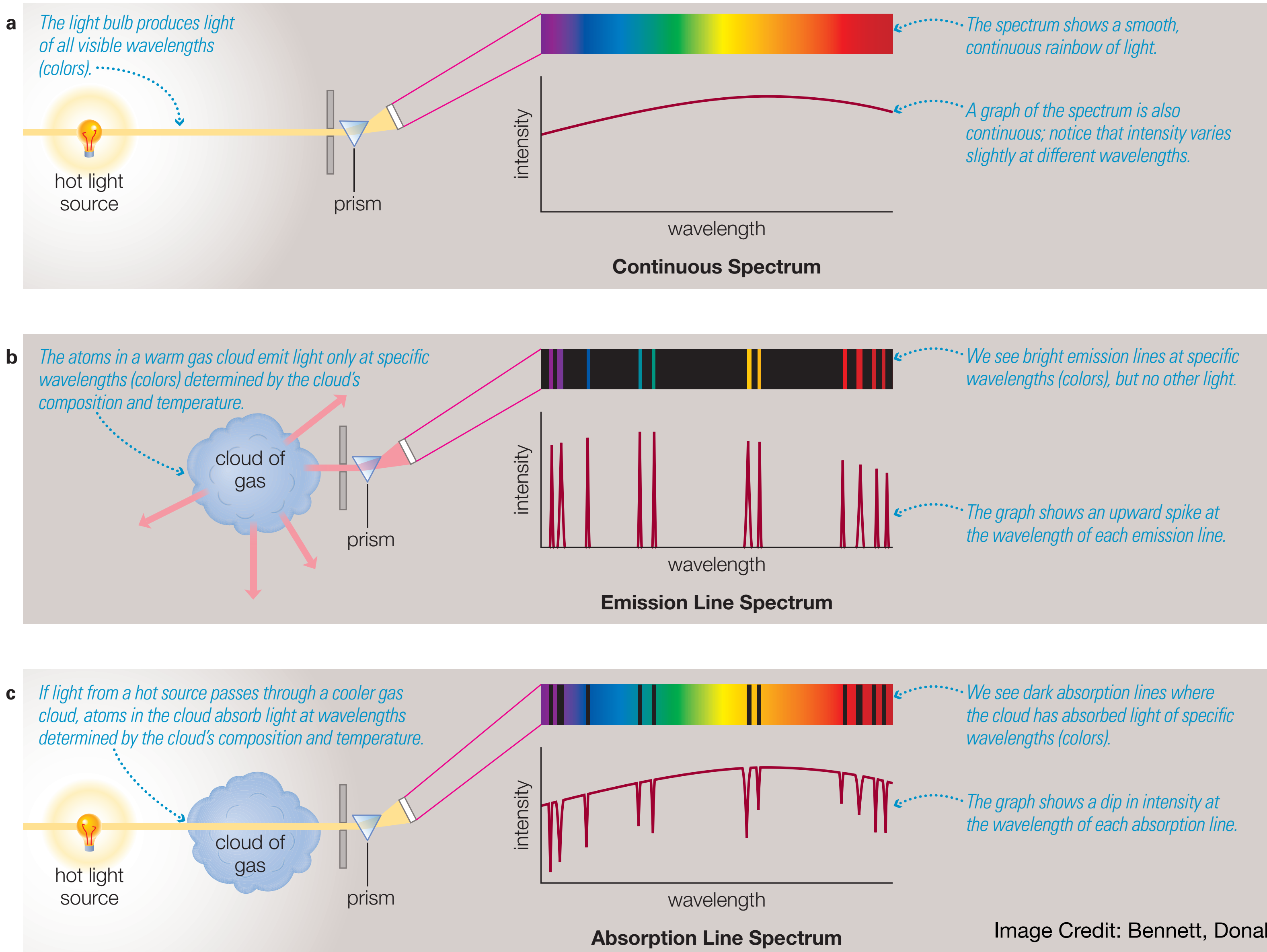


Image Credit: Bennett, Donahue, Schneider, Voit

hot vs. cold

continuum vs. line

foreground vs. background

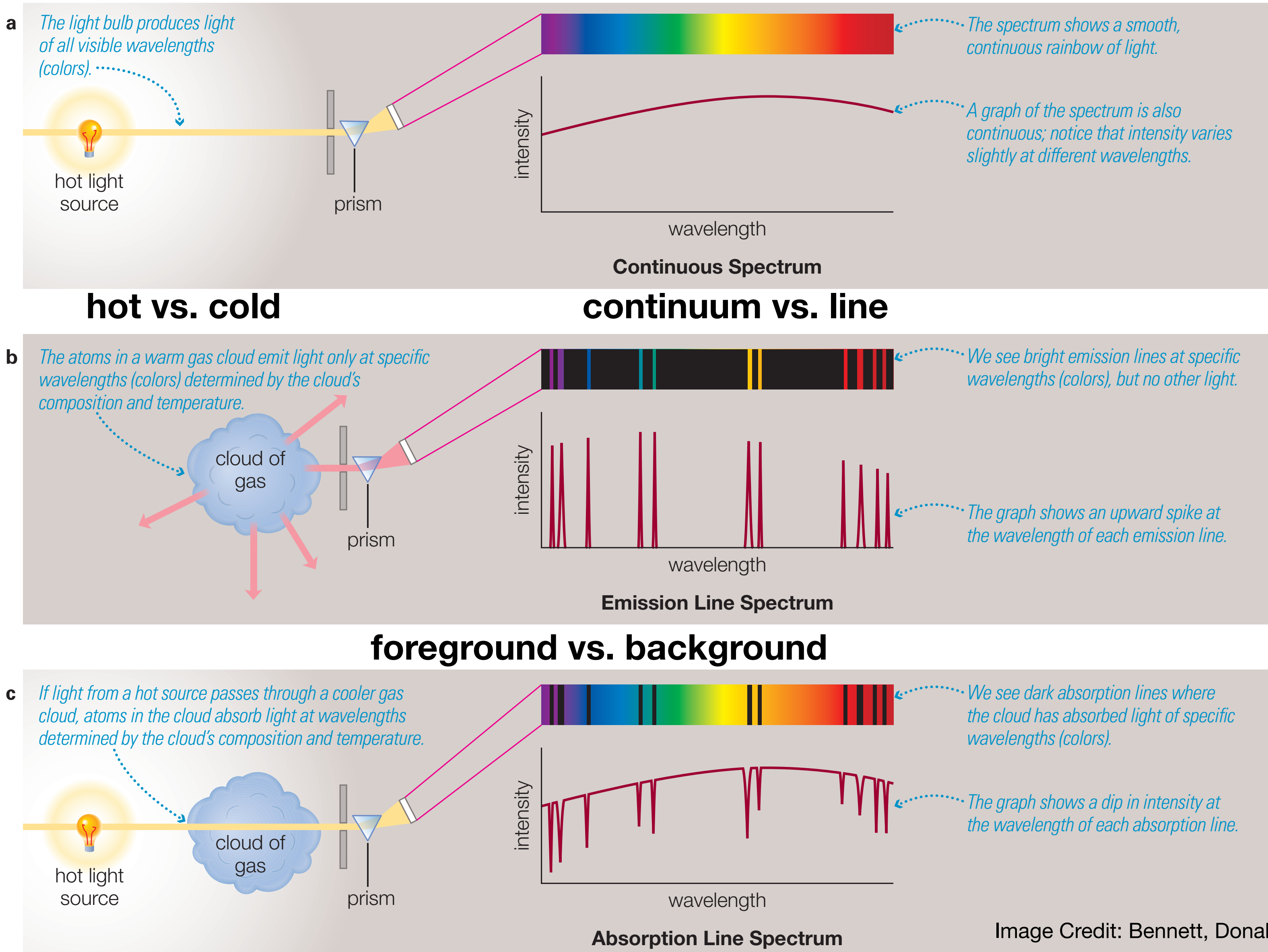
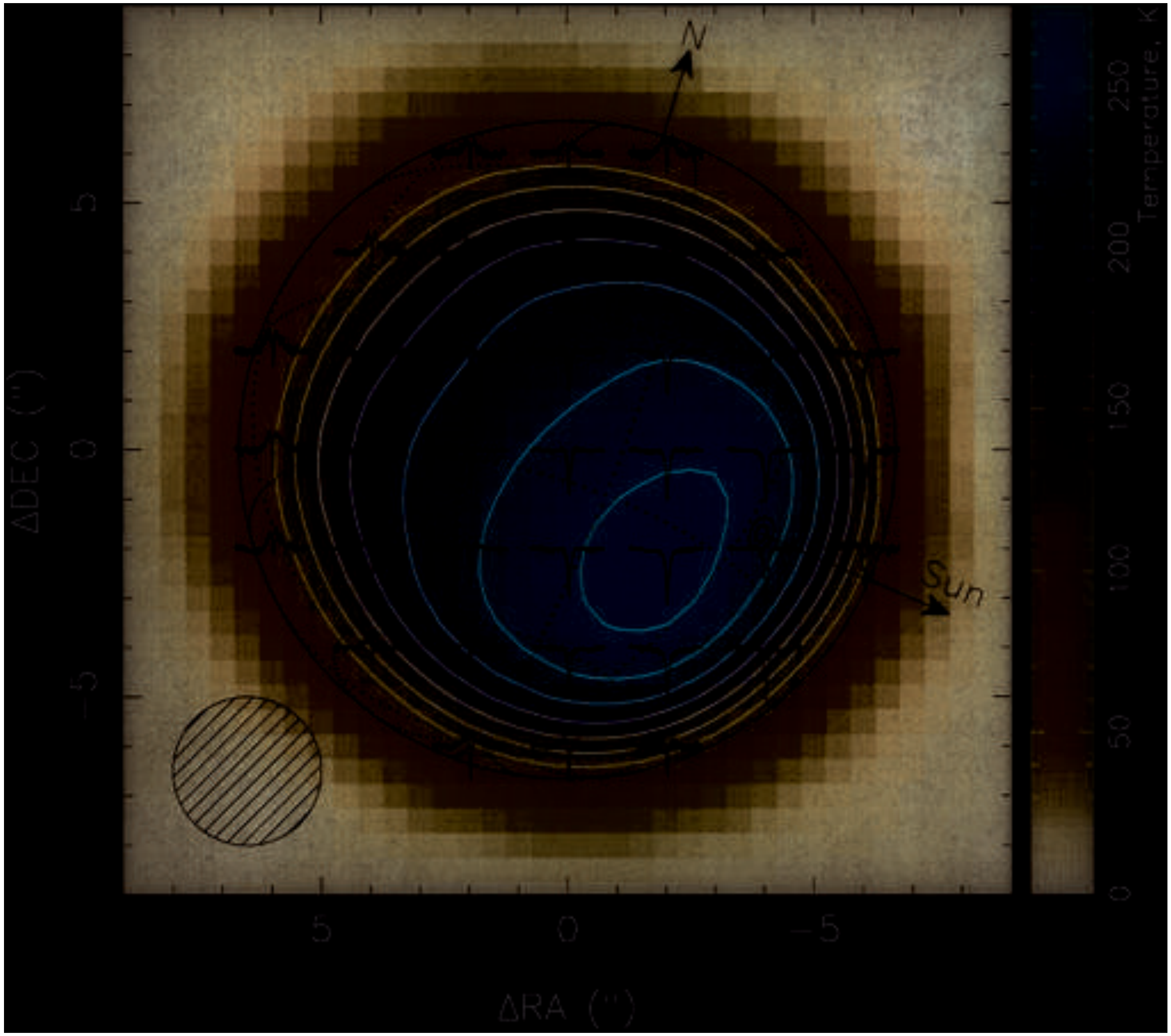


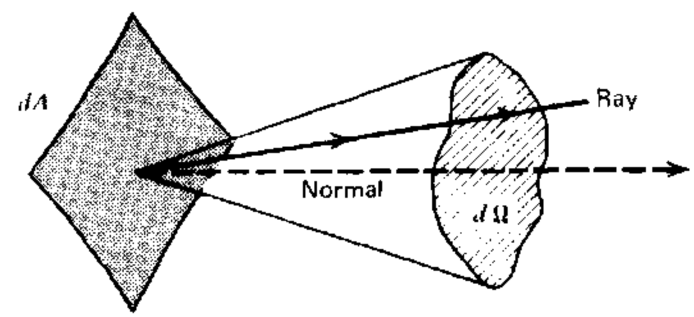
Image Credit: Bennett, Donahue, Schneider, Voit



N
Sun
ΔDEC (″)
ΔRA (″)
Temperature, K

How bright is it?
Radiation Fundamentals

- Specific Intensity I_ν : $dE = I_\nu \; d\sigma \; cos\theta \; d\omega \; d\nu \; dt$
    - or Intensity, or Brightness, or Brightness Temperature
    - rate of energy transport, along a particular direction, per unit area, per unit solid angle, and per unit frequency
    - conserved along a ray through free space
    - unit: e.g. $erg \; s^{-1} \; cm^{-2} \; Hz^{-1} \; Sr^{-1}$
- Flux Density S_ν (or F_ν) : $\int I_\nu(\omega \; cos(\theta) \; d\omega$
- Flux F : $\int S_\nu \; d\nu$
    - energy per time per area, depends on the relative position of source and the observer
- Power P : $\int F \; d\sigma$
    - or Luminosity
    - energy per time given off by a source



Geometry for normally incident rays.

Image Credit: Rybicki and Lightman

How bright is it?
Radiation Fundamentals

- Specific Intensity I_ν : $dE = I_\nu \; d\sigma \; cos\theta \; d\omega \; d\nu \; dt$
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    - or Luminosity
    - energy per time given off by a source

Recall: Approximations

$$B_\nu(T) = \frac{2h\nu^3}{c^2} e^{-\frac{h\nu}{k_B T}}$$ Wien (ν >>1)

$$B_\nu(T) = \frac{2\nu^2 k_B T}{c^2}$$ Rayleigh-Jeans (ν <<1)

Radiative Transfer (of EM wave)

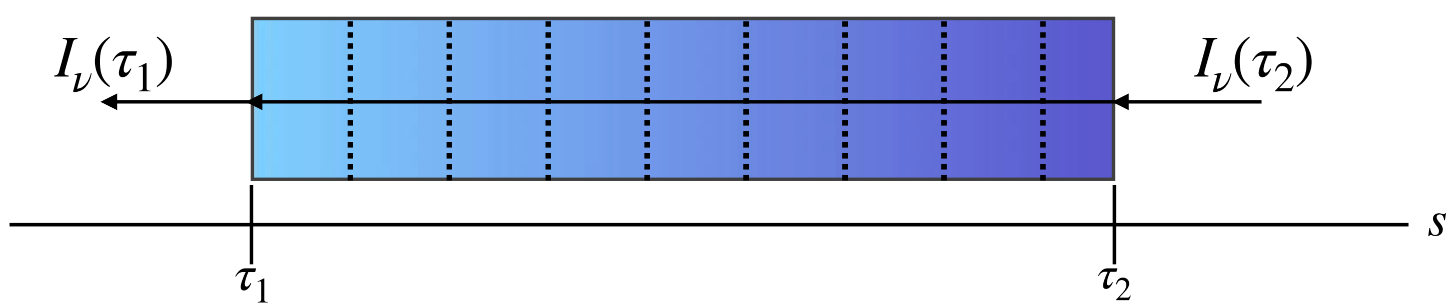
- Basic equation of (radiative) transfer

- $dI_\nu = j_\nu \ ds - \kappa_\nu \ I_\nu \ ds$
    - j_ν : emission coefficient
    - α_ν: absorption or extinction coefficient (cm^{-1}) = $\kappa_\nu \rho$ where κ_ν is the mass absorption coefficient
    - Both j_ν and α_ν are a function of intrinsic properties and physical condition of the medium
- $\dfrac{dI_\nu}{\alpha_\nu ds} = -I_\nu + \dfrac{j_\nu}{\alpha_\nu}$
    - $S_\nu \equiv \dfrac{j_\nu}{\alpha_\nu}$; $d\tau_\nu \equiv \alpha_\nu \ ds$ where τ_ν is the optical depth

$$\frac{dI_\nu}{d\tau} = -I_\nu + S_\nu$$

Radiative Transfer (of EM wave)

- Differential form
  - $\frac{dI_\nu}{d\tau} = -I_\nu + S_\nu$
- A general solution in integral form (considering a one dimension plane parallel slab geometry)
  - $I_\nu(\tau_1) = I_\nu(\tau_2)\ e^{-(\tau_2-\tau_1)} + \int_{\tau_1}^{\tau_2} S_\nu(t)\ e^{-(t-\tau_1)} dt$



Radiative Transfer (of EM wave)

- Differential Form
  - $\dfrac{dI_\nu}{d\tau} = -I_\nu + S_\nu$
- A general solution in integral form (considering a one dimension plane parallel slab geometry)
  - $I_\nu(\tau_1) = I_\nu(\tau_2)\ e^{-(\tau_2-\tau_1)} + \int_{\tau_1}^{\tau_2} S_\nu(t)\ e^{-(t-\tau_1)}dt$
- The above equation can be fully solved if S_ν is known. However, S_ν generally depends on the (local) radiation field. Namely, the emission and absorption properties of the material may depend on I_ν. Hence, given the physical condition, one needs to solve I_ν and S_ν numerically and iteratively.

Radiative Transfer (of EM wave)

- Differential Form
  - $$\frac{dI_\nu}{d\tau} = -I_\nu + S_\nu$$
- A general solution in integral form (considering a one dimension plane parallel slab geometry)
  - $$I_\nu(\tau_1) = I_\nu(\tau_2)\ e^{-(\tau_2-\tau_1)} + \int_{\tau_1}^{\tau_2} S_\nu(t)\ e^{-(t-\tau_1)} dt$$
- Think about special cases
  - No foreground emission term, namely, first term only
  - No background emission term, namely, second term only
  - constant source function in optically thick case vs. optically thin case

Mechanisms (of EM Waves) = Radiative Processes

Radiative Processes (of EM wave)

	Continuum (SED: spectral Energy Distribution)	Line (Intensity, Frequency Center and Width, or Profile)
Thermal (characterized by a single (kinetic) temperature)	Free-Free Dust Inverse Compton Scattering	Atomic (Recombination) Molecular/Ionic Line
Non-Thermal (characterized NOT by a single (kinetic) temperature) but energy distribution, e.g.)	Synchrotron	Maser

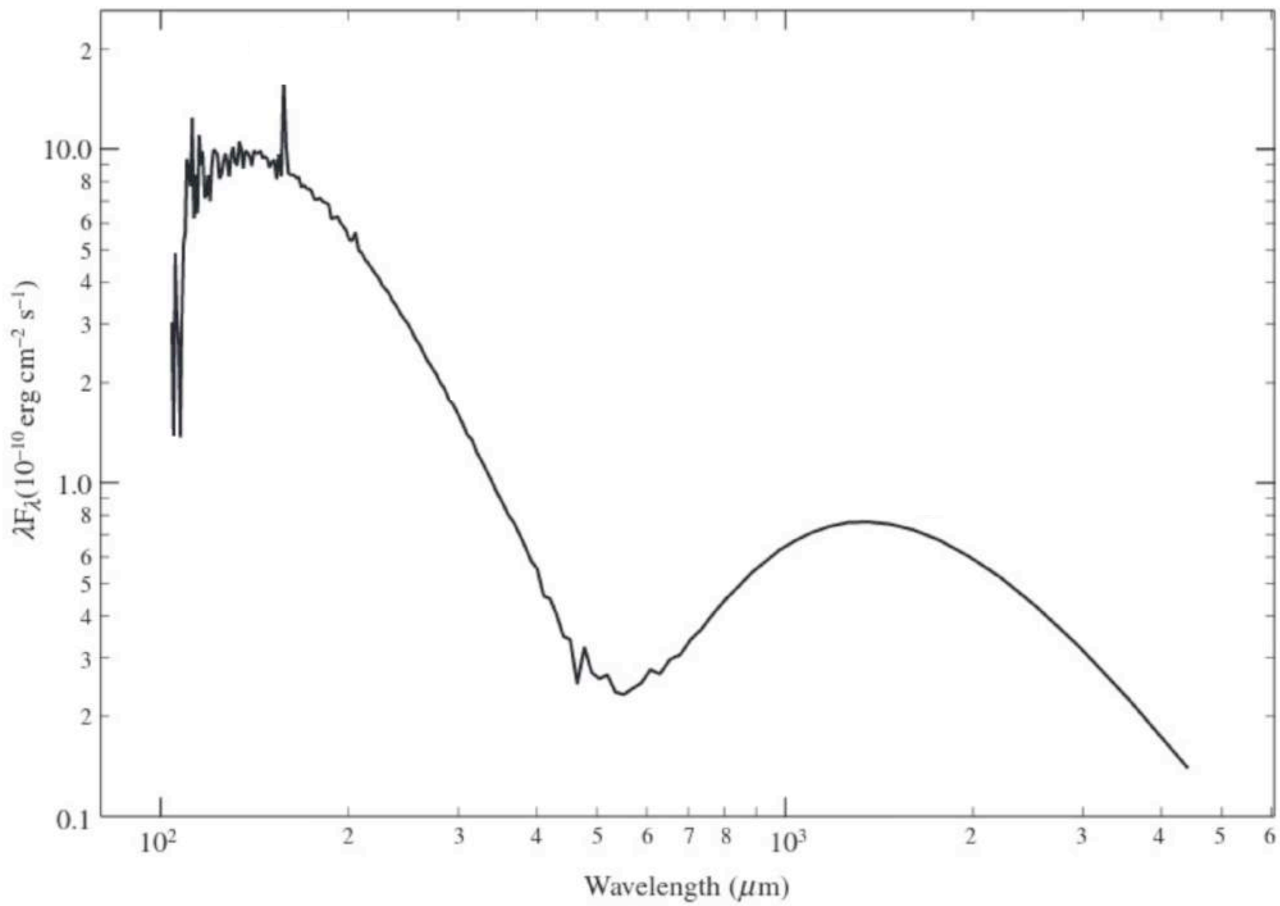


Figure 1.3

The integrated spectrum of the galactic plane as observed by the *Cosmic Background Explorer (COBE)* satellite.

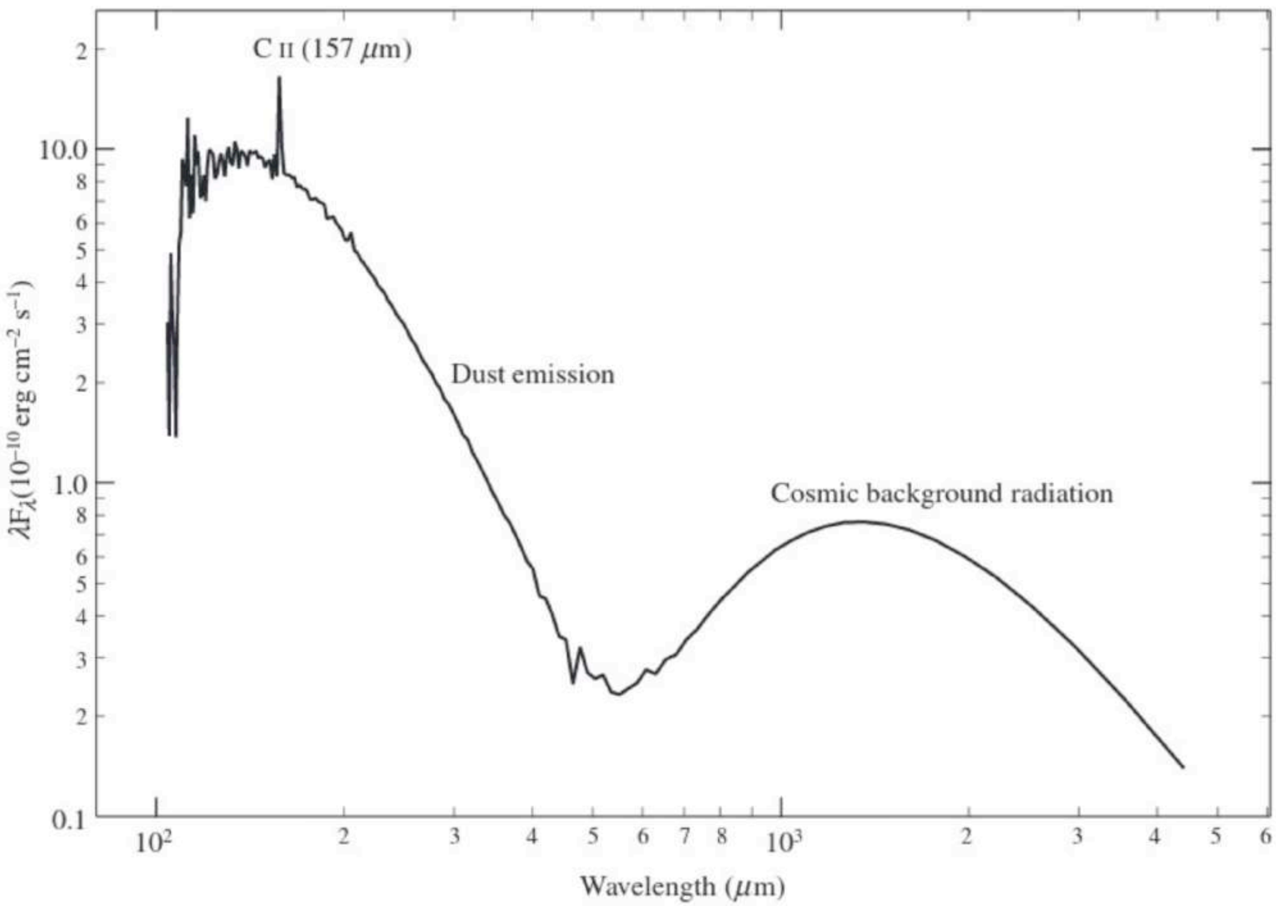
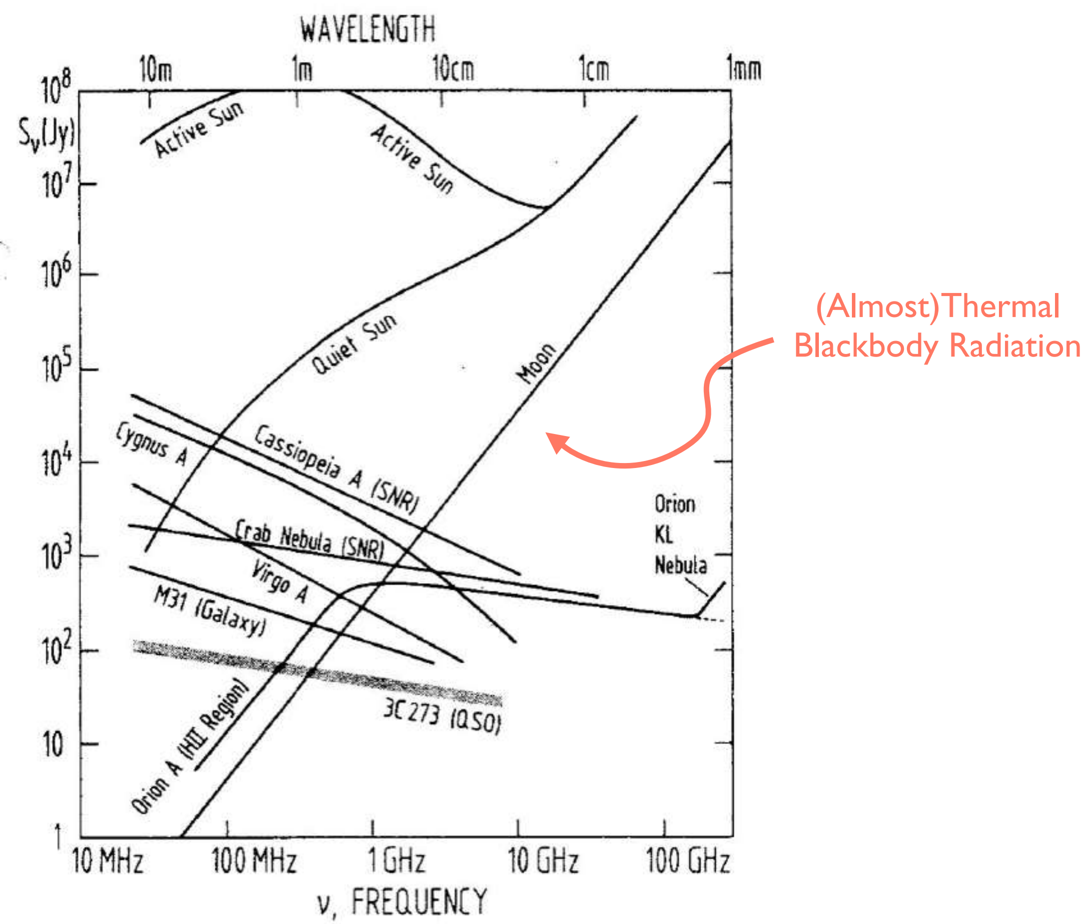


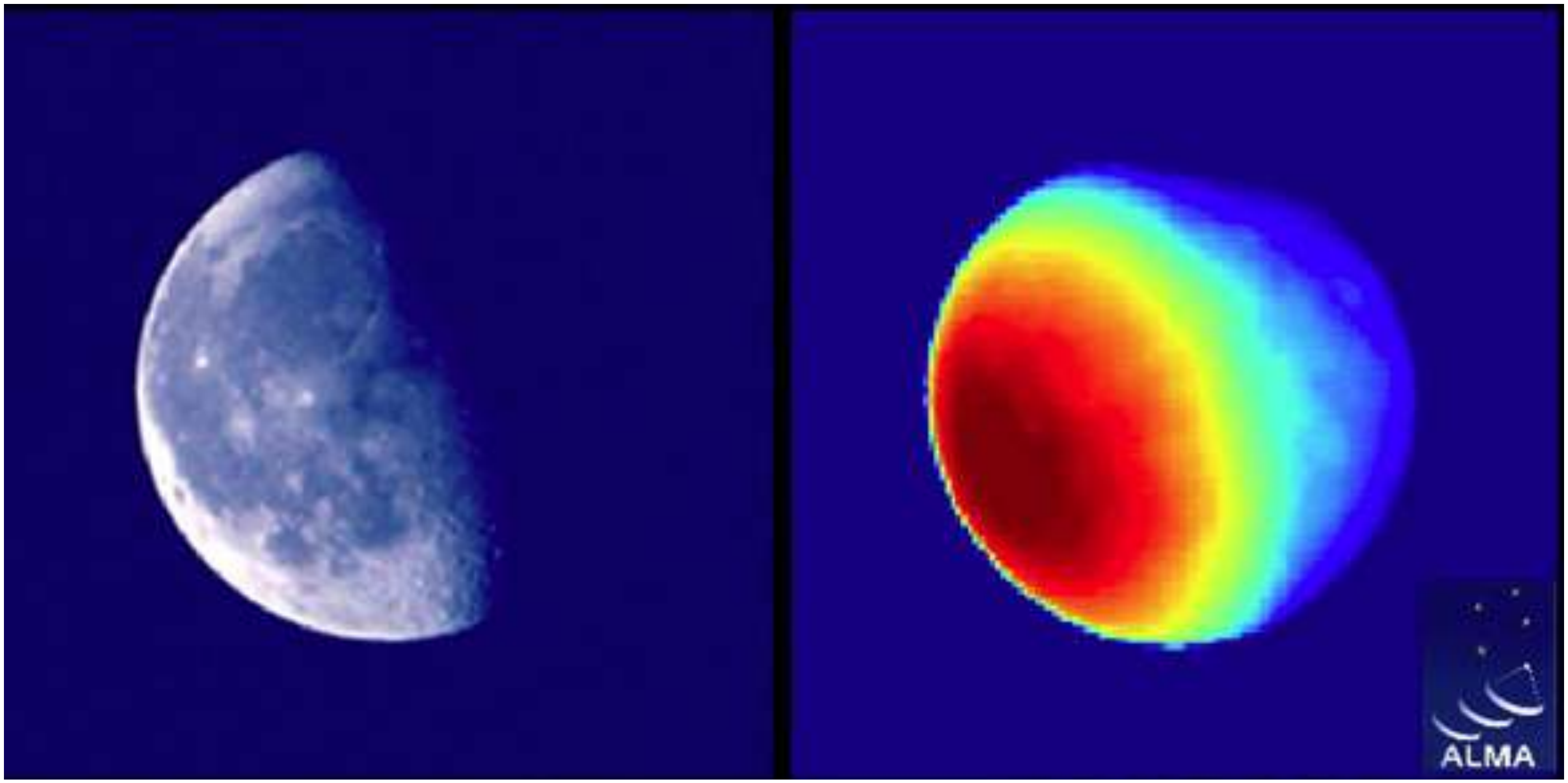
Figure 1.3

The integrated spectrum of the galactic plane as observed by the *Cosmic Background Explorer (COBE)* satellite. Other than the cosmic background radiation, which is seen over the whole sky, the ISM shows strong continuum emission from cool dust of a temperature of ~ 20 K. A line due to ionized carbon is also prevalent on the galactic plane.

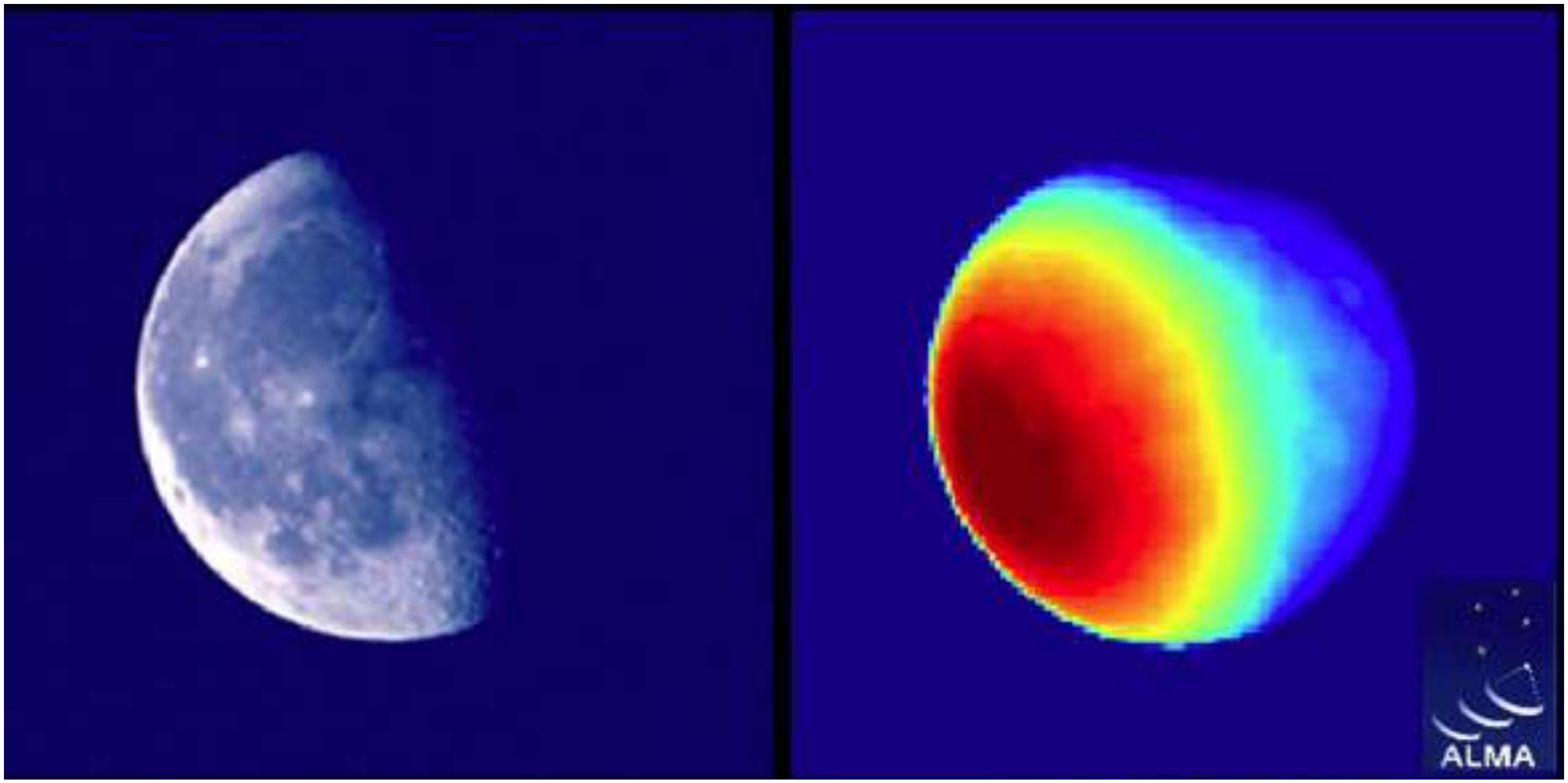
Spectral Energy Distribution (in radio regime)



The Power Spectrum (in radio regime)

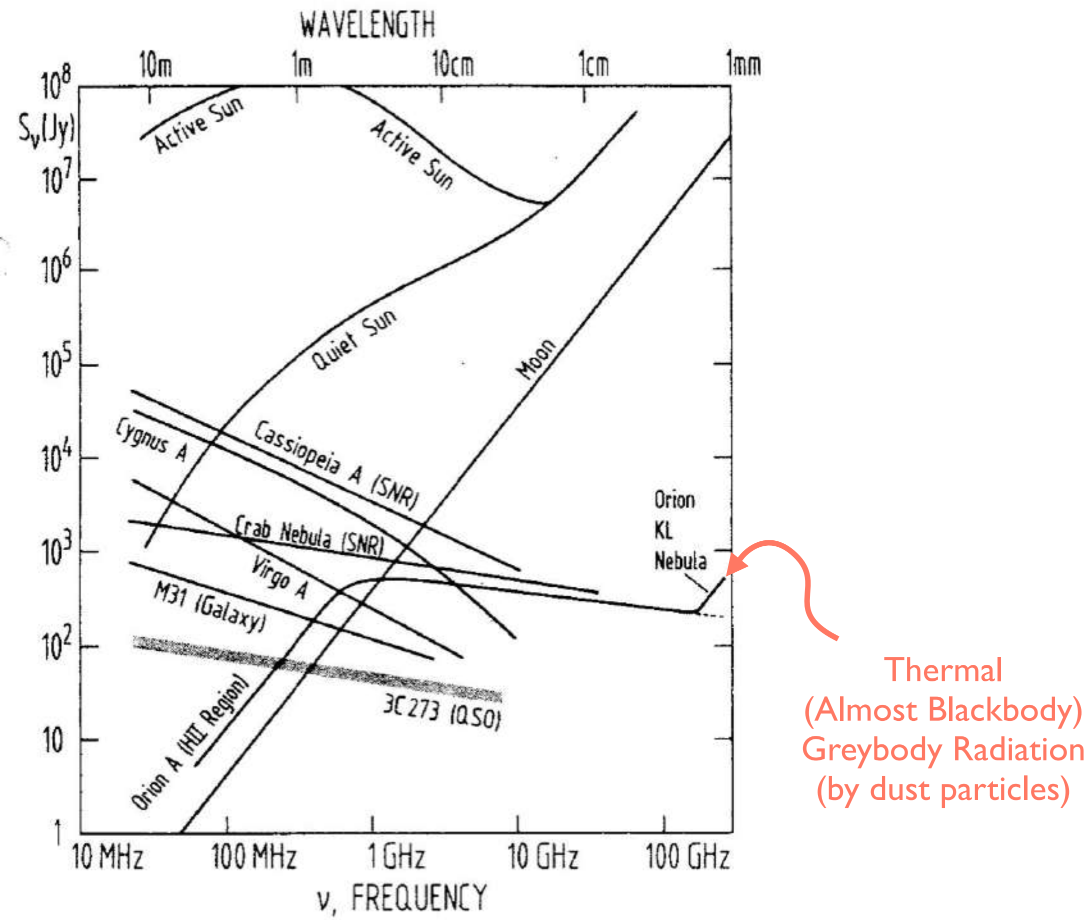


The Power Spectrum (in radio regime)

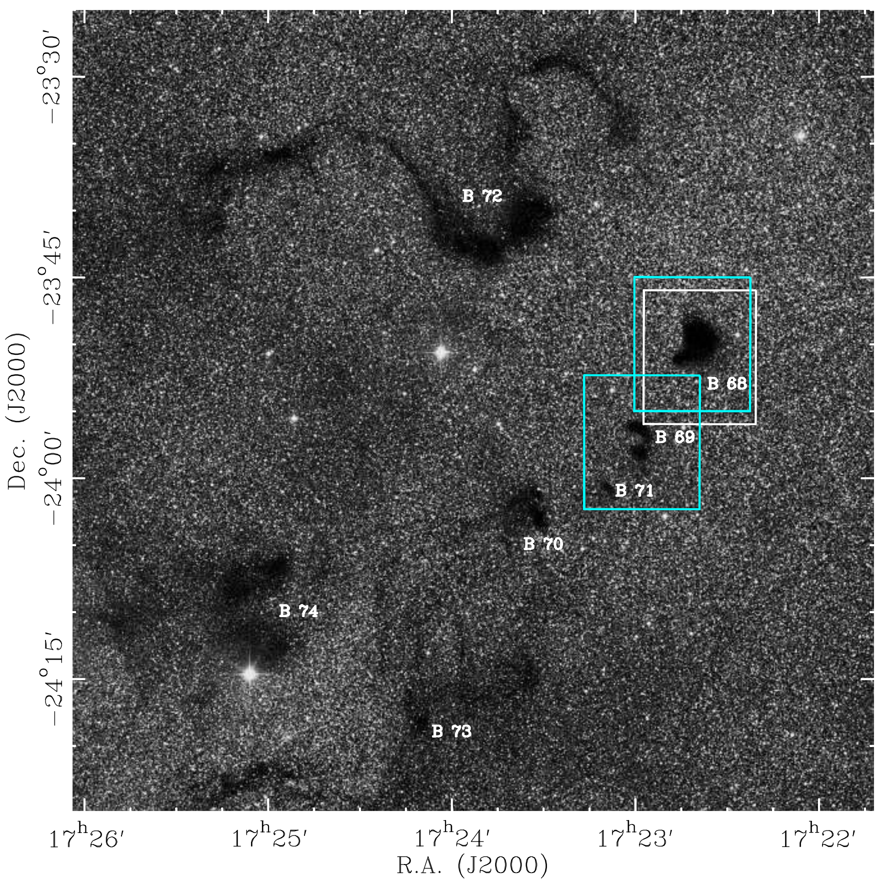


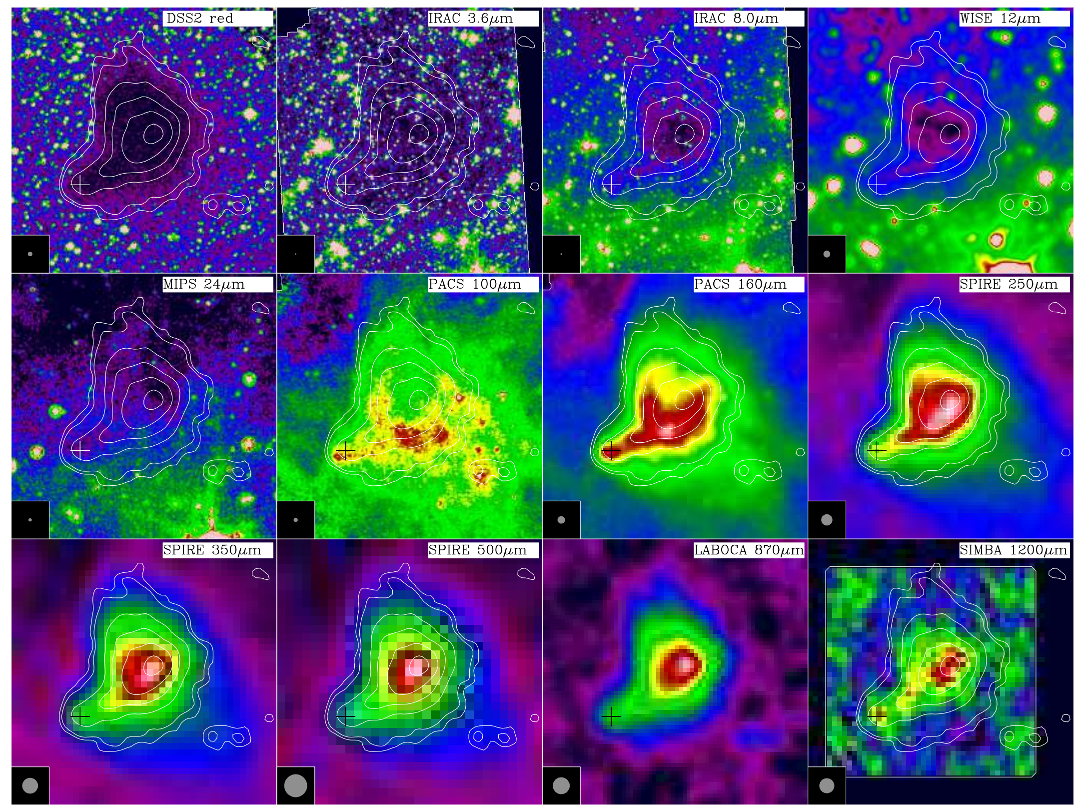
First radio image of the Moon taken with a 12-meter ALMA antenna. The optical image at left shows the sunlight reflected by the Moon's surface, whereas the radio image shows the physical temperature distribution of the Moon. The ALMA image clearly shows the temperature distribution of the Moon, including weak radio emission from the dark side of the Moon.
(Source: https://public.nrao.edu/gallery/moon-as-seen-by-alma/)

Spectral Energy Distribution (in radio regime)

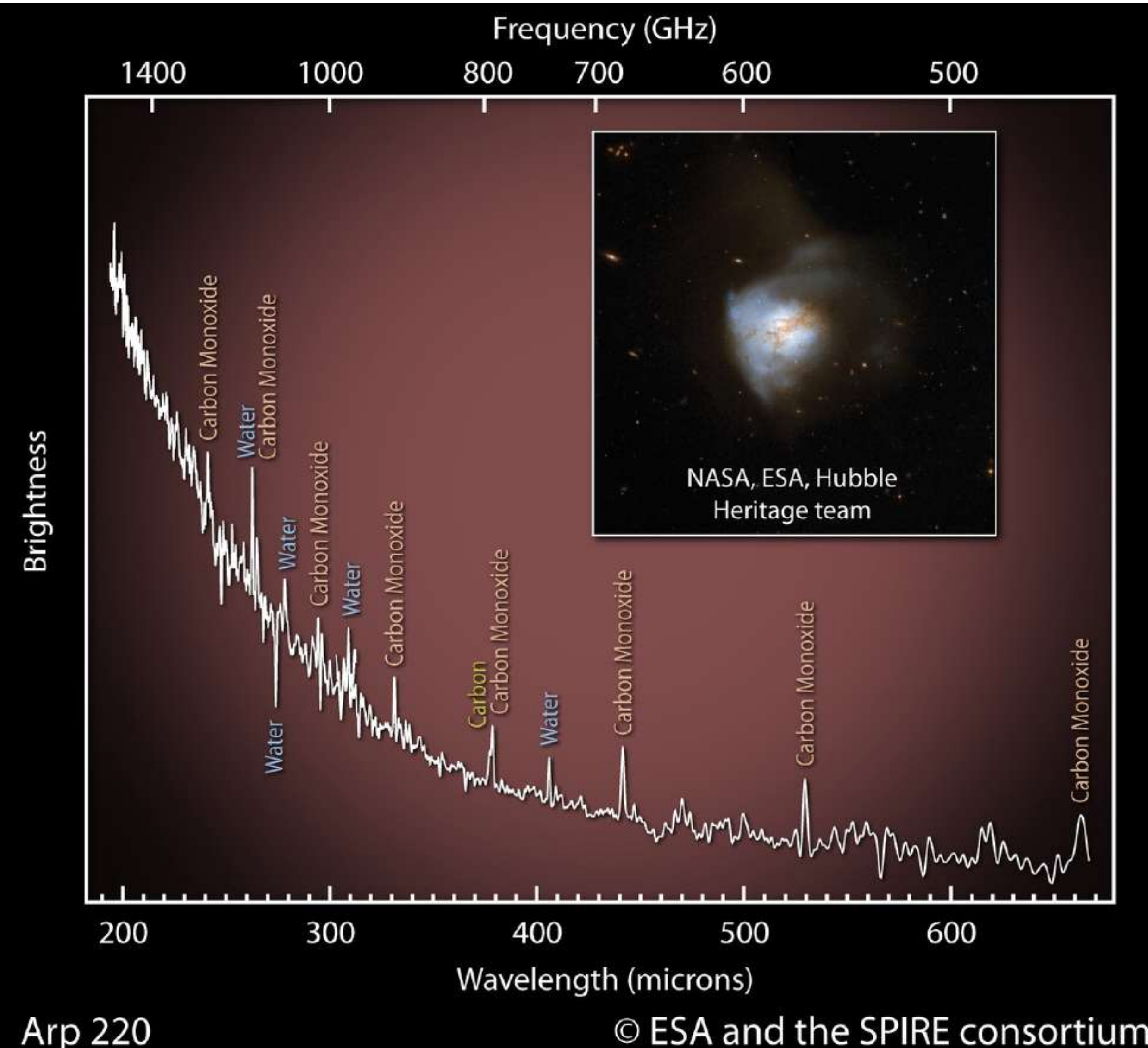


Bok Globule B68





Nielbock et al. (2012) A&A



https://www.herschel.caltech.edu/image/nhsc2009-021e

Radiative Process (Thermal Dust)

- dust extinction (absorption + scattering) and (nearly BB) emission

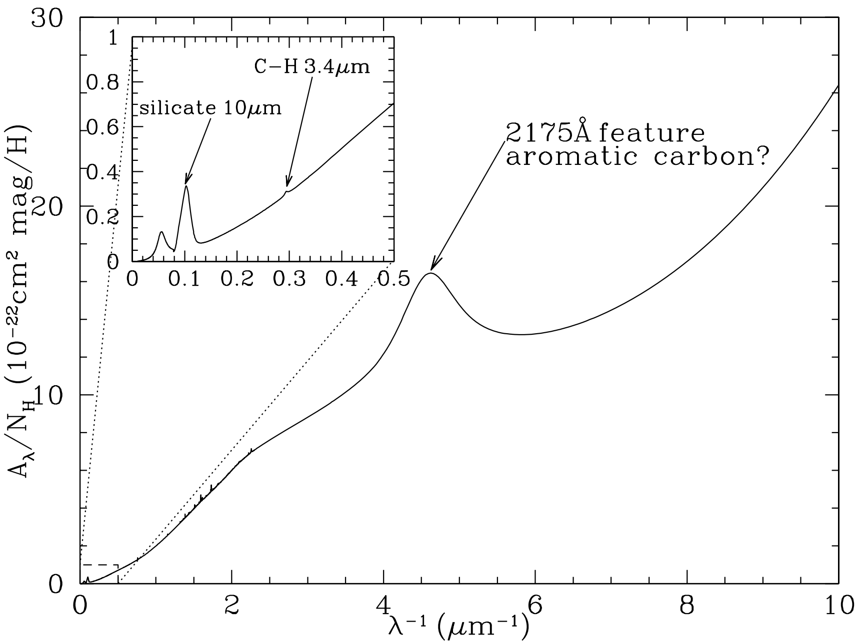
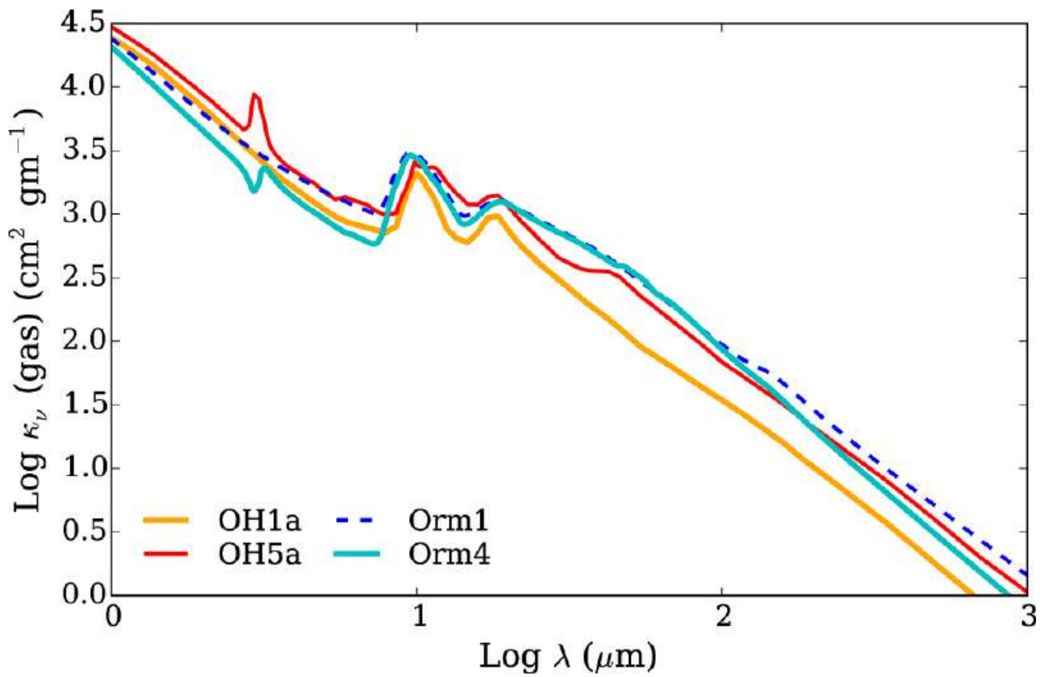


Figure 21.1 Extinction versus inverse wavelength λ^{-1} on a typical sightline in the local diffuse ISM. The inset shows the extinction at $\lambda > 2\,\mu$m.

Draine (Physics of Interstellar and Intergalactic Medium)



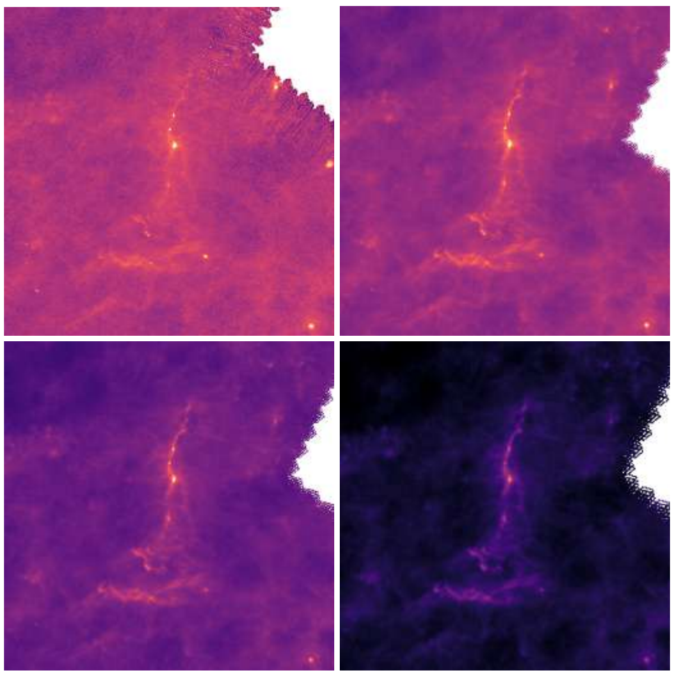
Webb et al. (2017)

Slide Credit: Seamus Clarke

Column density estimation

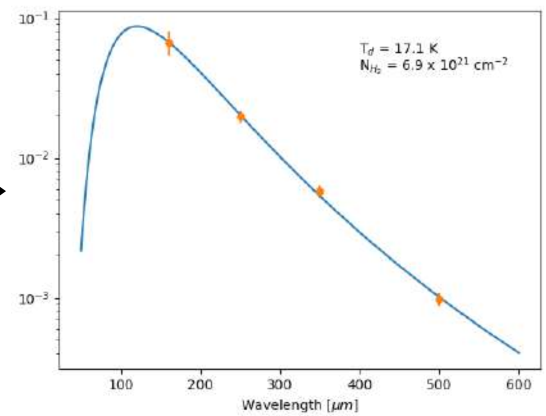
Fitting spectral energy distributions

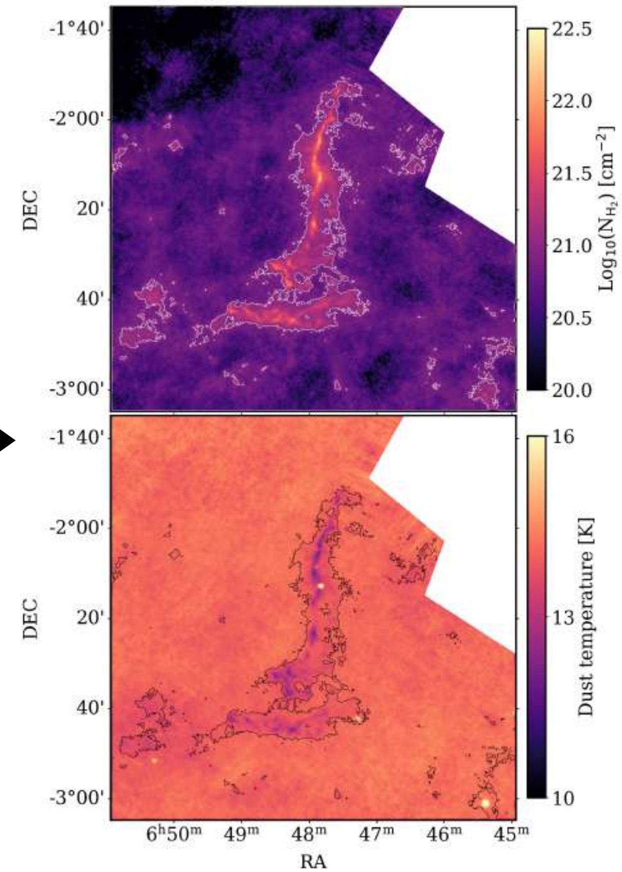
160 µm 250 µm



350 µm 500 µm

$$I_{\nu,\mathrm{obs}} = \tau_\nu B_\nu(T_d) = \kappa_\nu N_d B_\nu(T_d)$$





Slide Credit: Seamus Clarke

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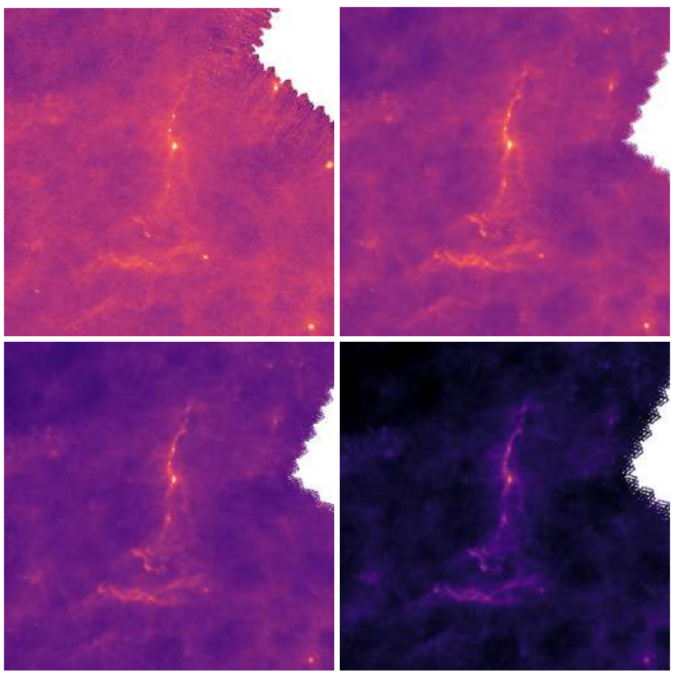

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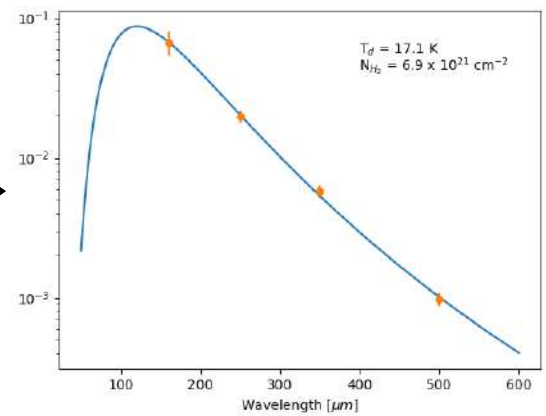
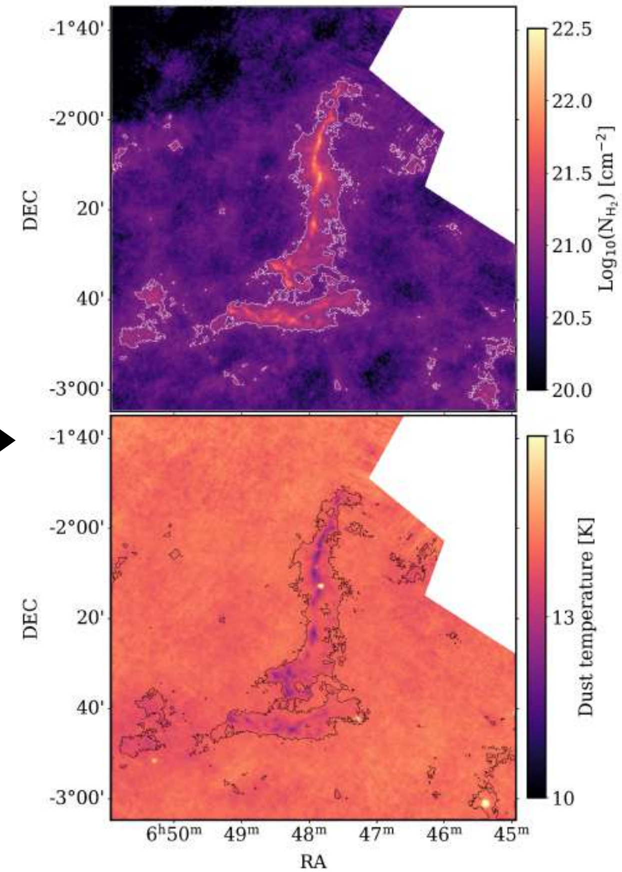
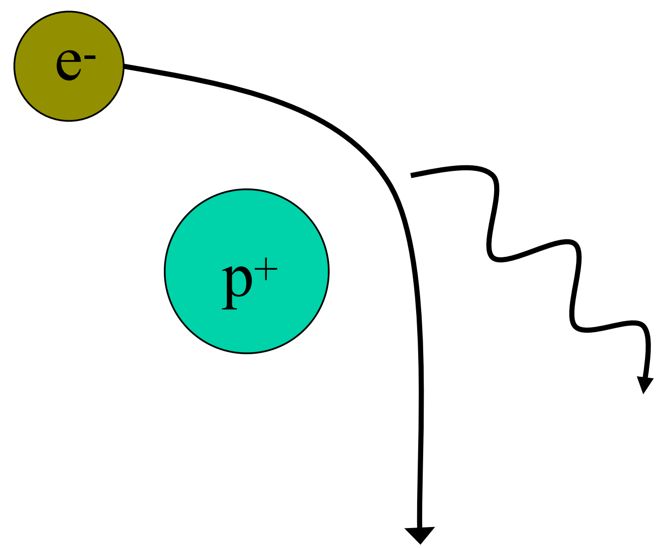




Radiative Process (Free-Free)

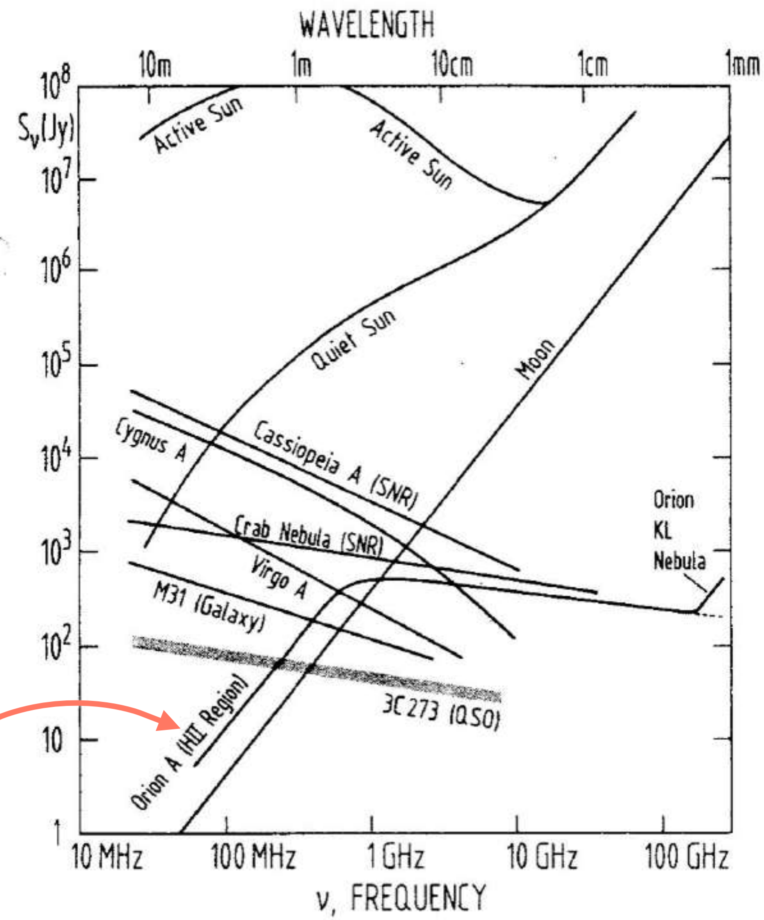
Bremsstrahlung (free–free)



Ionized gas:
e.g., H II region
Intracluster medium

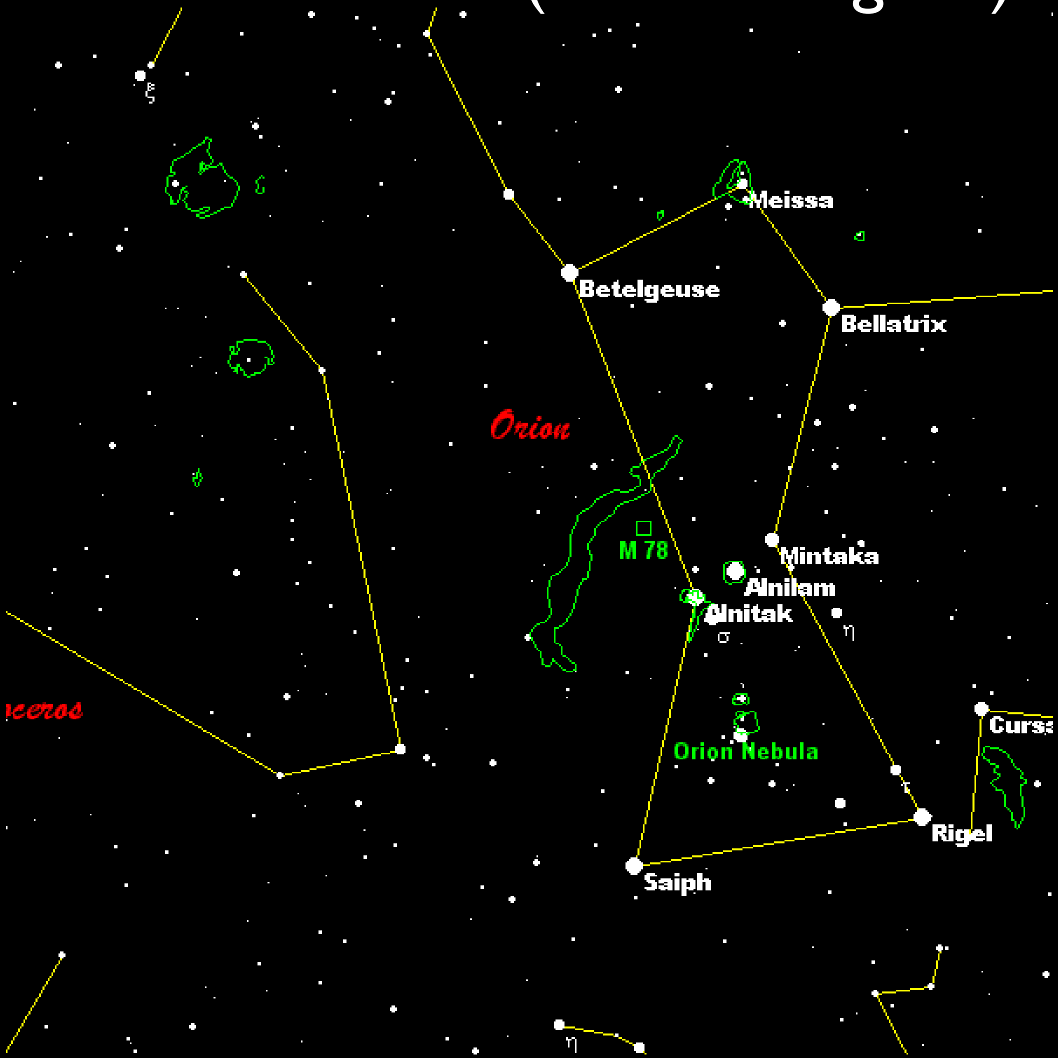
Image Credit: Hiro Hirashita

Spectral Energy Distribution (in radio regime)



Thermal Bremsstrahlung Radiation
(charged particles moving in ionized gas)

Orion Nebula (in radio regime)



Orion Nebula (in radio regime)

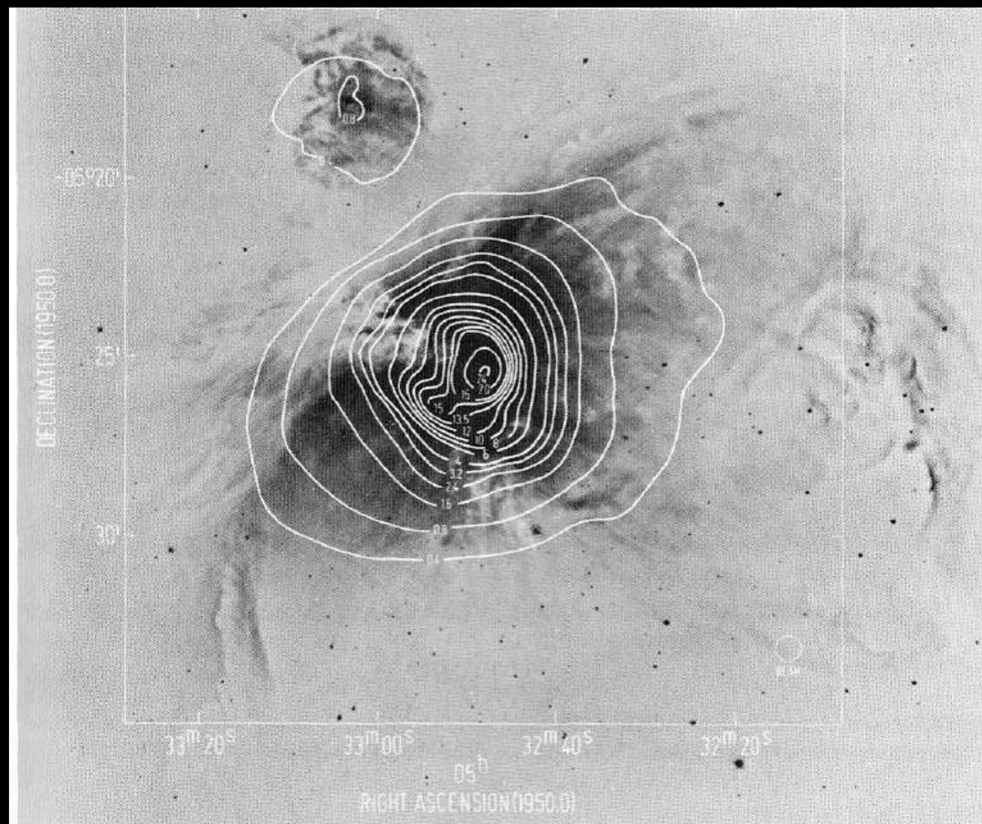


Fig. 2.3. The 23-GHz radio continuum contours, in units of main-beam brightness temperature, on a optical photo in Hα and [NII] of NGC 1976 (Orion A, M42), below, and NGC 1982 (M43), above. Th angular resolution is 42″, which at the distance of Orion A, corresponds to a linear resolution o

Spectral Energy Distribution (in radio regime)

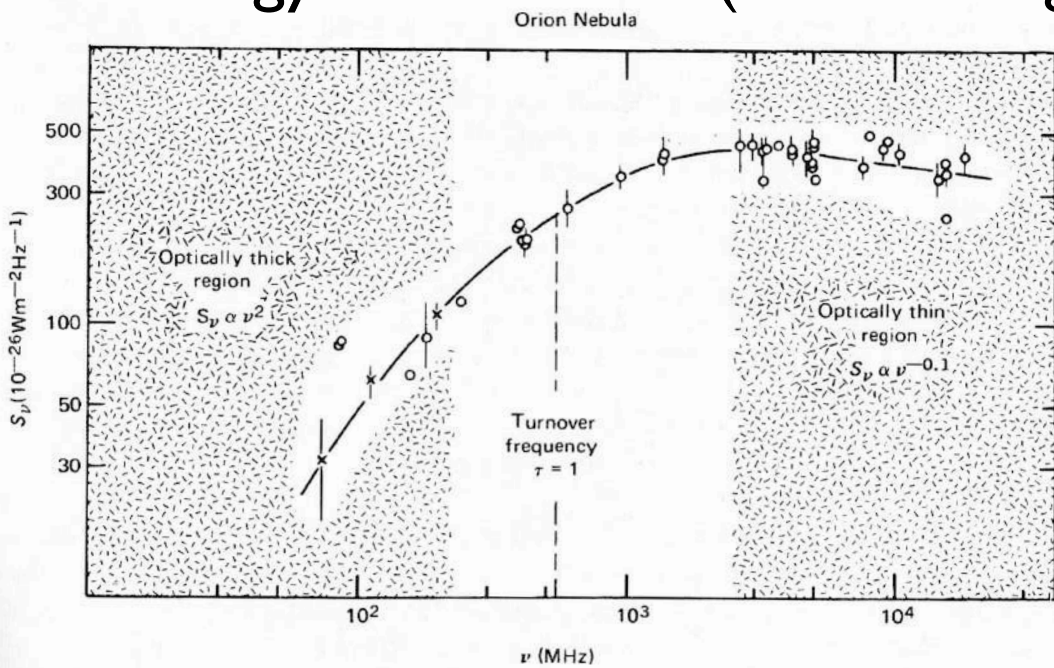


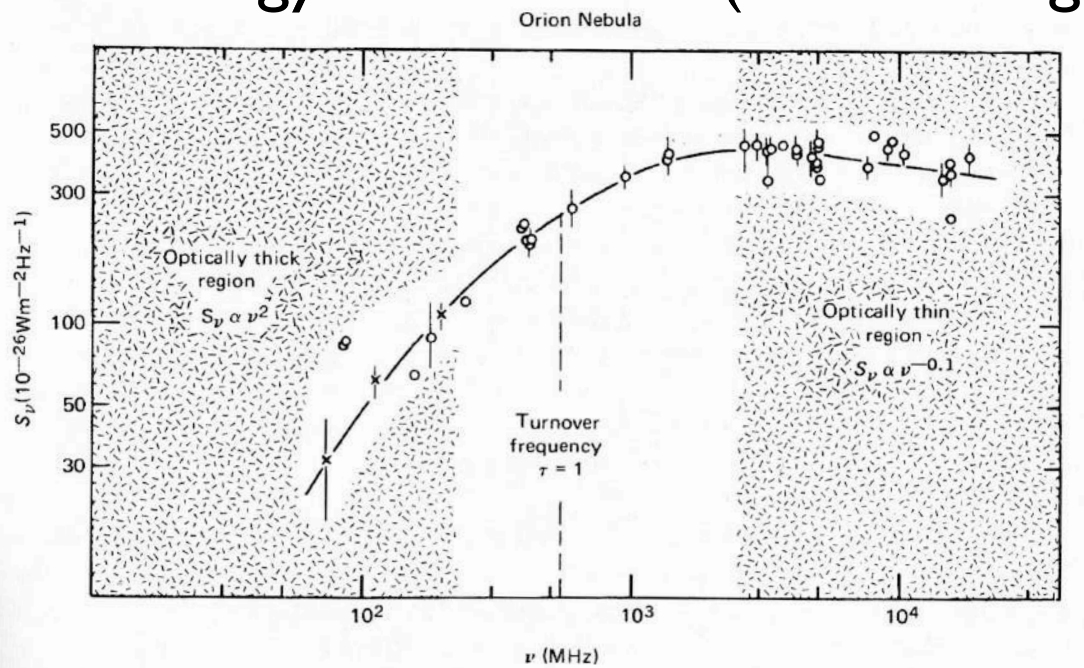
Fig. 2.2. Spectral flux density of the Orion Nebula plotted against frequency. The shaded regions mark the optically thick and thin regions of the spectrum. (Reprinted with permission by Gordon and Breach Science Publishers from: Terzian, Y. and Parrish A., *Astrophysical Letters.* Vol. 5(1970), pp. 261.

$$\tau_\nu \approx 8.235 \times 10^{-2} \left(\frac{T_e}{K}\right)^{-1.35} \left(\frac{\nu}{GHz}\right)^{-2.1} \left(\frac{EM}{pc\ cm^{-6}}\right) \alpha(\nu, T)$$

$$\frac{EM}{pc\ cm^{-6}} = \int \left(\frac{n_e}{cm^{-3}}\right)^2 d\left(\frac{s}{pc}\right)$$

$$\alpha(\nu, T) \sim 1$$

Spectral Energy Distribution (in radio regime)



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Emission Measure

$$\frac{EM}{pc\ cm^{-6}} = \int \left(\frac{n_e}{cm^{-3}}\right)^2 d\left(\frac{s}{pc}\right)$$

Radiative Process (Spectral Line)

Radiative transition

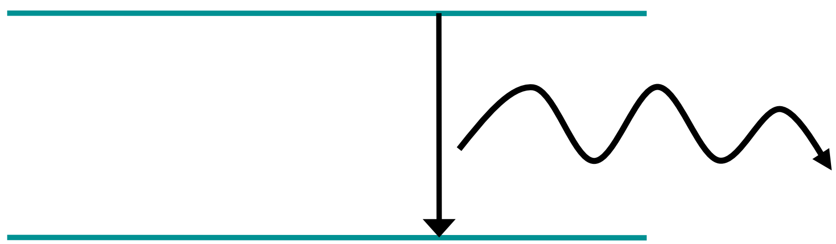
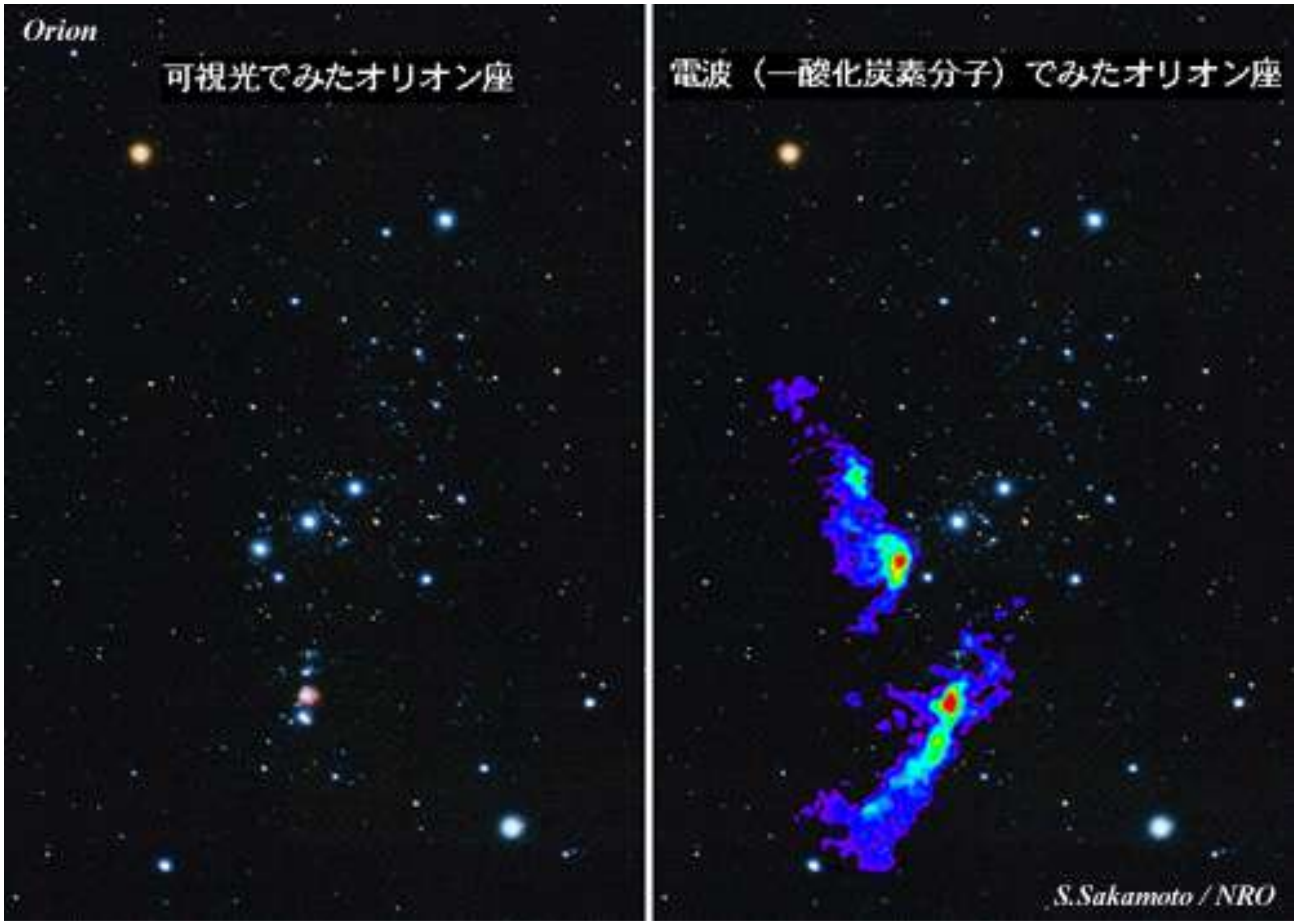


Image Credit: Hiro Hirashita

electric ~ UV, optical
molecular vibrational ~ near-IR
molecular rotational ~ radio

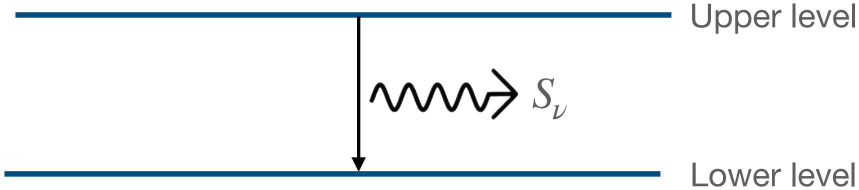
Radiative Process (Spectral Line)



Slide Credit: Seamus Clarke

Radiation sources

Line emission



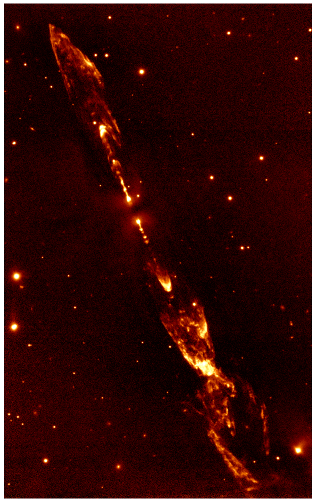
Simeis 147

Electronic transitions:

Optical - UV wavelengths

e.g. Hα, [OIII], [SII]

HH212

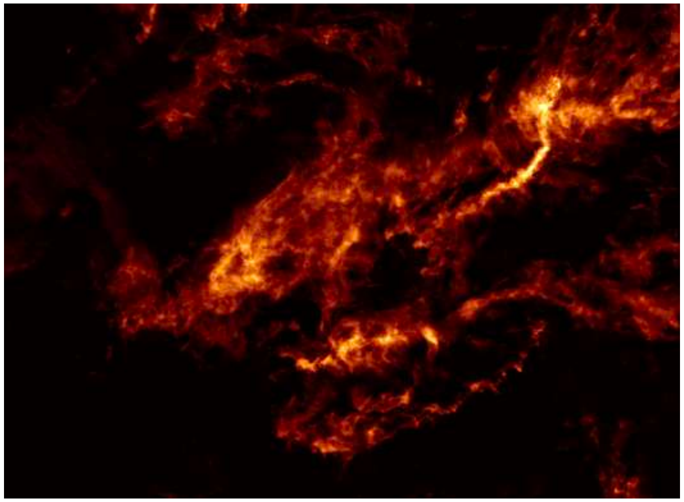


Molecular vibrational transitions:

Near-IR wavelengths

e.g. H_2 2.12 μm

Taurus molecular cloud



Molecular rotational transitions:

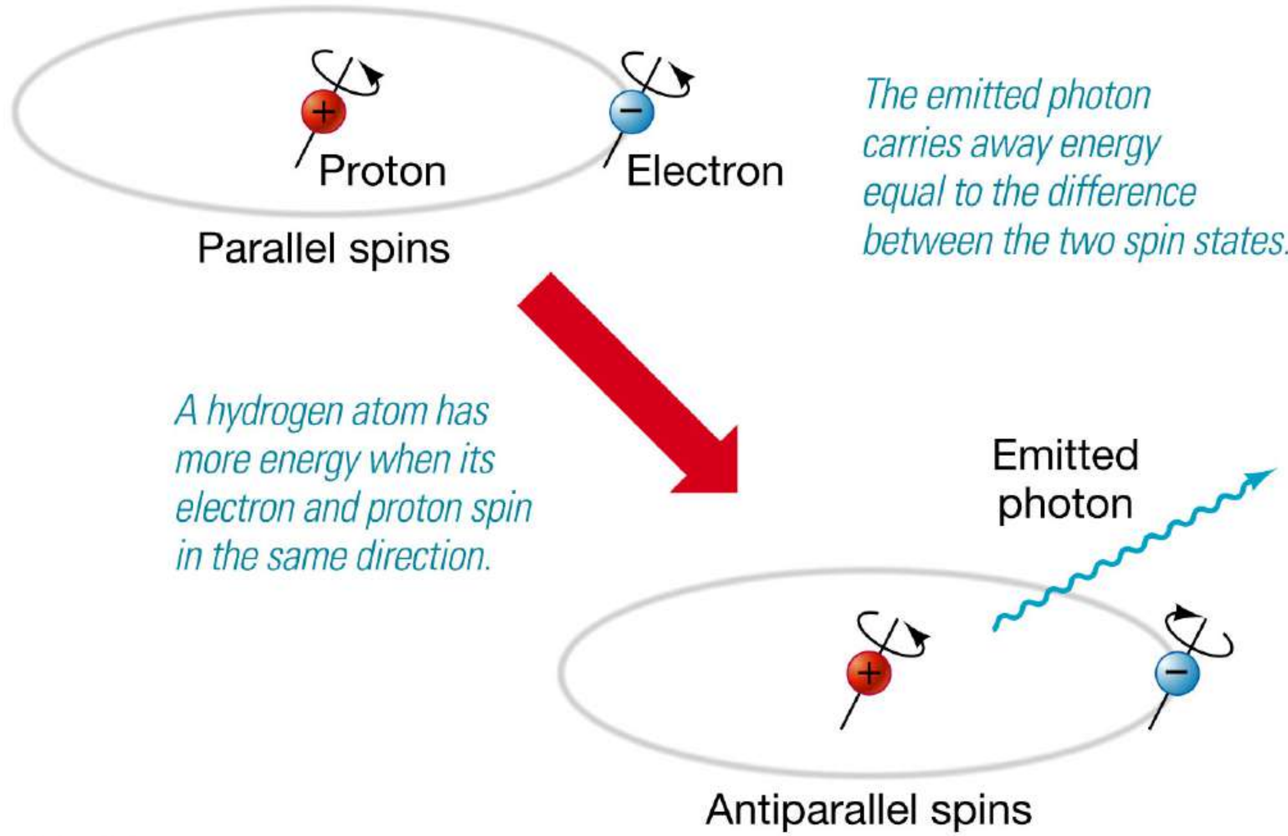
Sub-mm - radio wavelengths

e.g. CO, NH_3, CH_3OH

Image credit: Nicolas Kizilian, Mark McCaughrean, Paul Goldsmith

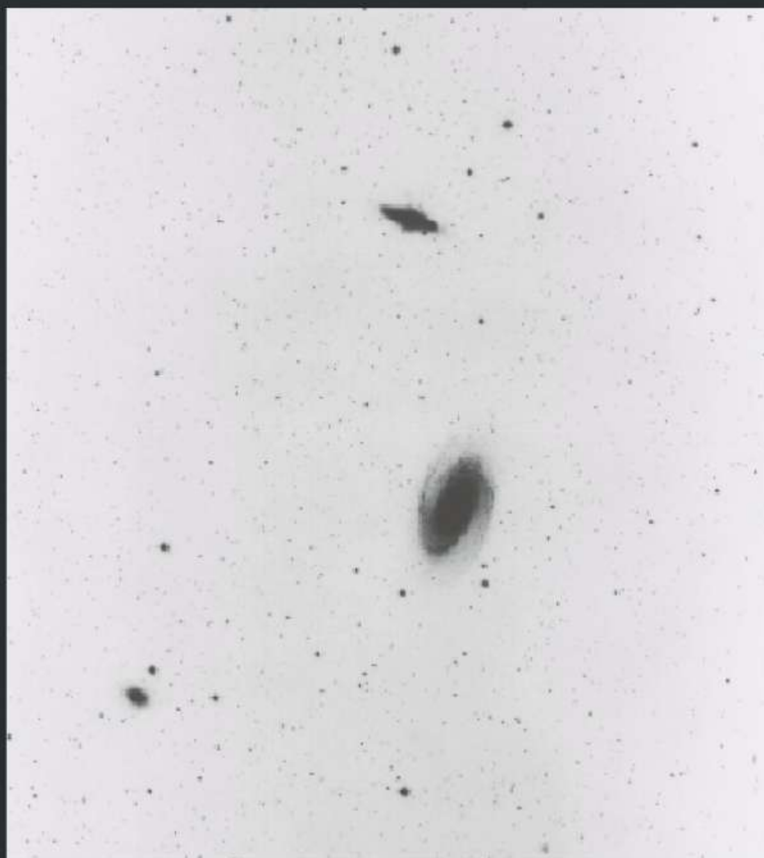
18.4 21-Centimeter Radiation

Interstellar gas emits low-energy radiation, due to a transition in the hydrogen atom

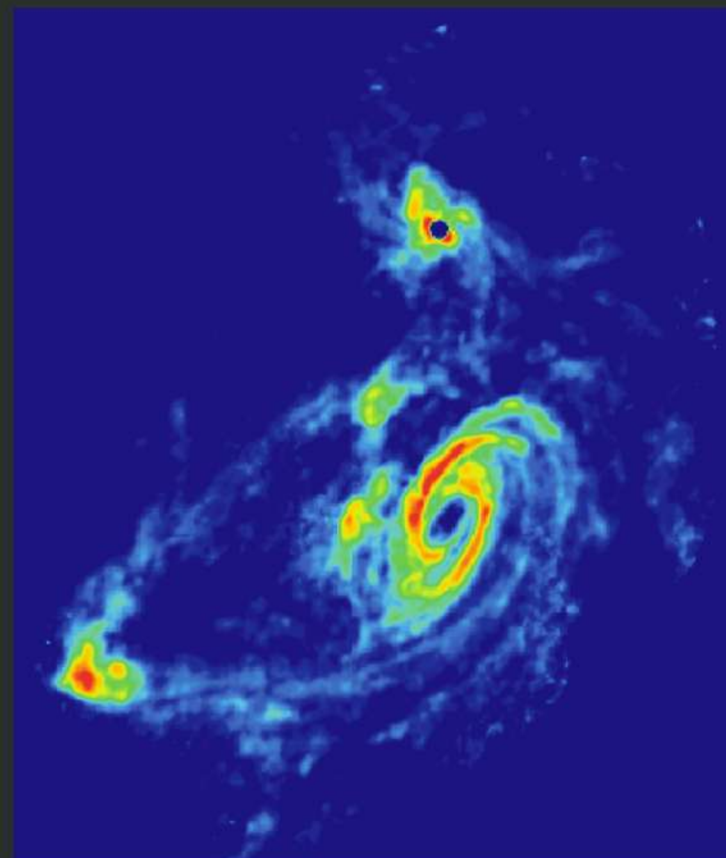


TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution



21 cm HI Distribution



(NRAO Archive)

Line Radiation

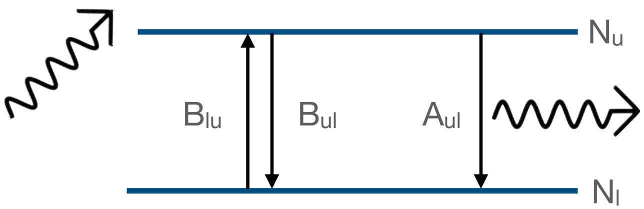
- Spectral Line Radiation
  - Peak Frequency : velocity
  - Peak Intensity : opacity (hence column density, if with known excitation)
  - Line-width : thermal and non-thermal (turbulence and pressure) broadening
  - Polarization : splitting (due to magnetic fields)

Slide Credit: Seamus Clarke

Population levels and excitation

The paper Mangum & Shirley (2015) “How to calculate molecular column density” is excellent for this section

Level occupation



We wish to determine what would the absorption and emission terms be for this system.

First we need some additional definitions.

Fractional occupation number

$$n_i = \frac{N_i}{N}$$

$$\sum_i^{all} n_i = 1$$

Thermally distributed states (LTE)

$$\frac{n_i}{n_j} = \frac{N_i}{N_j} = \frac{g_i}{g_j} e^{-(E_i - E_j)/k_B T}$$

The partition function

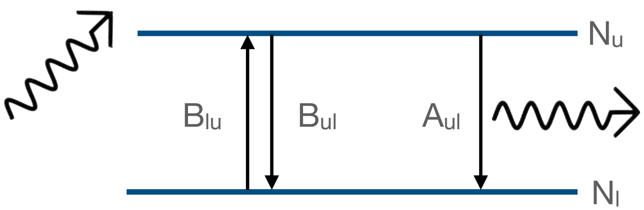
$$Z(T) = \sum_i^{all} g_i e^{-E_i/k_B T}$$

$$n_i = \frac{1}{Z(T)} g_i e^{-E_i/k_B T}$$

Slide Credit: Seamus Clarke

Population levels and excitation

Emissivity and absorption



$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu$$

So how do we go about determining these two quantities?

Energy per photon

Rate of photon release per unit volume

$$j_\nu = \frac{h\nu_{ul}}{4\pi} A_{ul} N_u \phi(\nu)$$

Per steradian

Line profile

Rate of photon absorption per unit volume per unit intensity

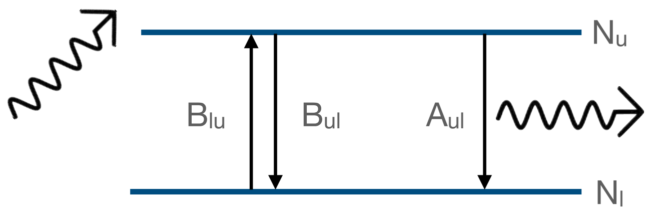
$$\alpha_\nu = \frac{h\nu_{ul}}{4\pi}(N_l B_{lu} - N_u B_{ul})\phi(\nu)$$

$$N_l B_{lu} I = \text{Rate of stimulated absorption}$$

Slide Credit: Seamus Clarke

Population levels and excitation

Einstein's relations



Einstein's relations

$$A_{ul} = \frac{2h\nu_{ul}^3}{c^2} B_{ul}$$

$$g_u B_{ul} = g_l B_{lu}$$

Assume that LTE is valid

$$\frac{N_u}{N_l} = \frac{g_u}{g_l} e^{-(E_u - E_l)/k_B T} = \frac{g_u}{g_l} e^{-h\nu_{ul}/k_B T_{ex}}$$

$$j_\nu = \frac{h\nu_{ul}}{4\pi} A_{ul} N_u \phi(\nu)$$

$$\alpha_\nu = \frac{h\nu_{ul}}{4\pi} (N_l B_{lu} - N_u B_{ul}) \phi(\nu)$$

$\rightarrow$

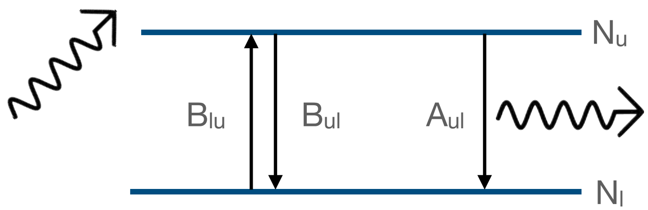
$$\alpha_\nu = \frac{c^2}{8\pi\nu_{ul}^2} \left(e^{h\nu_{ul}/k_B T_{ex}} - 1\right) A_{ul} N_u \phi(\nu)$$

$$S_\nu = \frac{2h\nu_{ul}^3}{c^2} \frac{1}{(e^{h\nu_{ul}/k_B T_{ex}} - 1)} = B_\nu(T_{ex})$$

Slide Credit: Seamus Clarke

Population levels and excitation

Einstein's relations



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→

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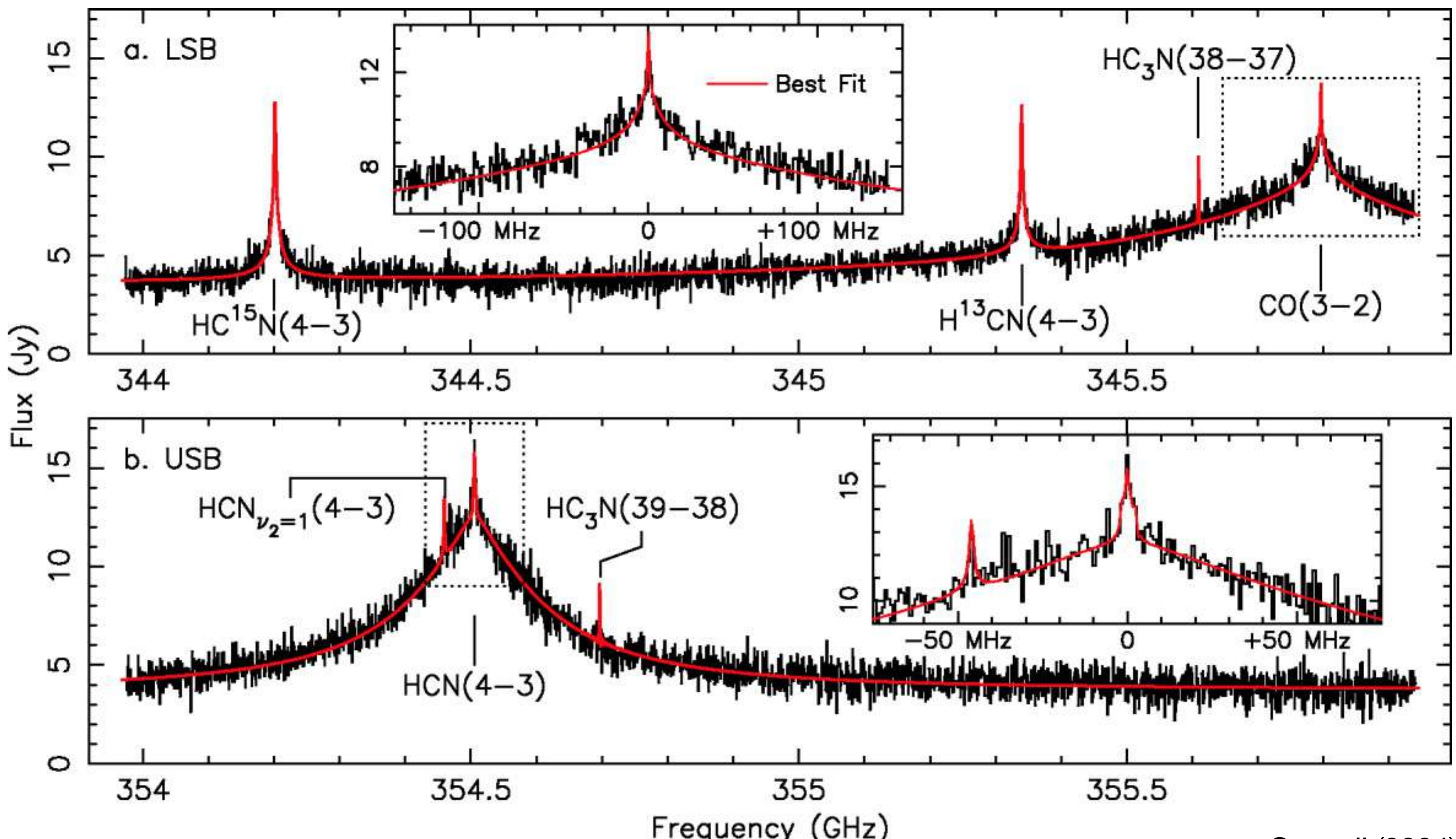
Line Radiation [broadening]

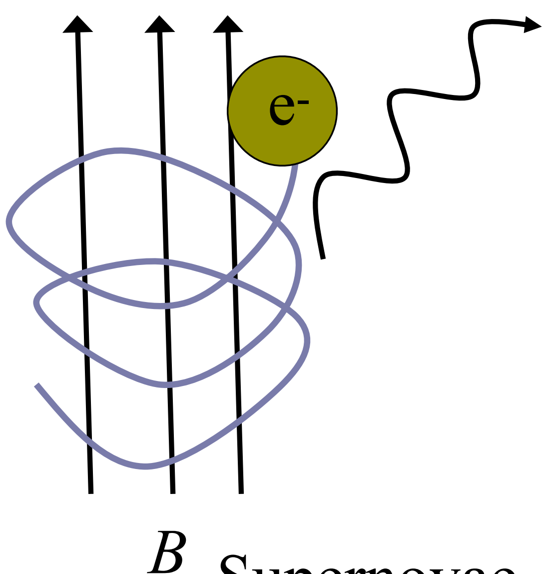
Submillimeter Observations of Titan: Global Measures of Stratospheric Temperature, CO, HCN, HC_3N, and the Isotopic Ratios $^{12}C/^{13}C$ and $^{14}N/^{15}N$



Gurwell (2004)

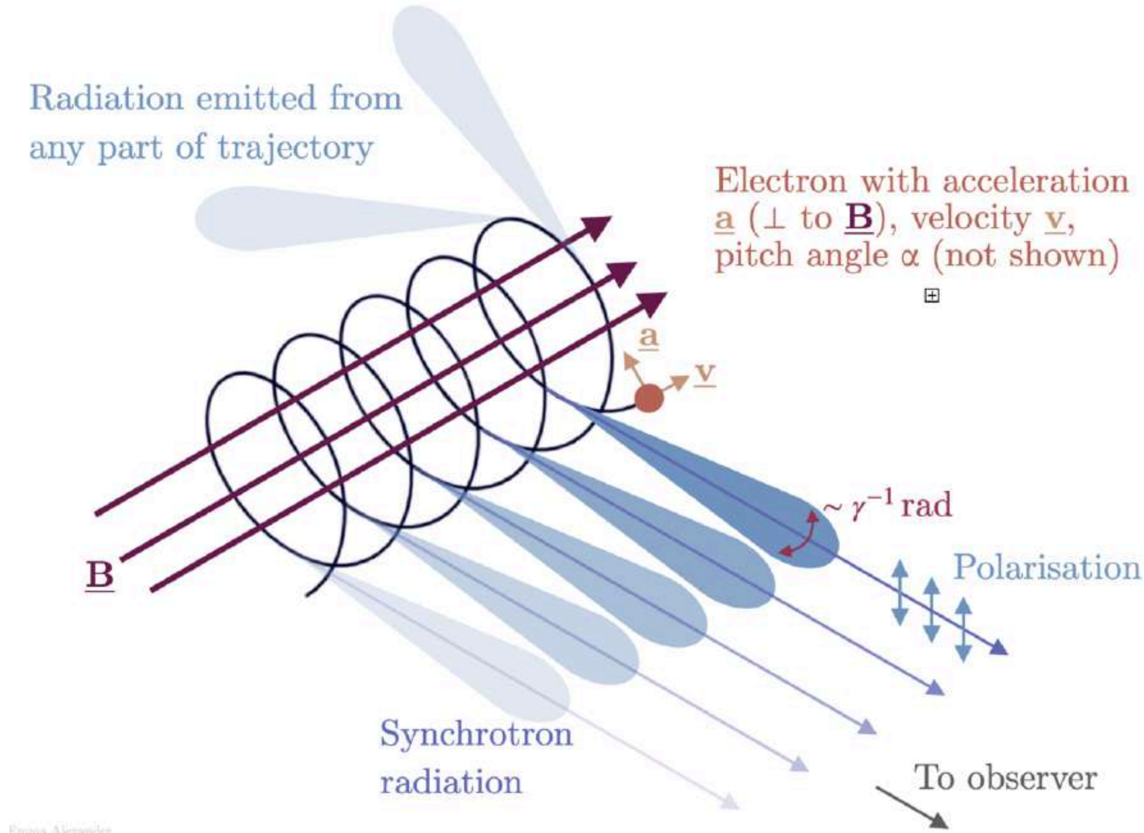
Radiative Process (Synchrotron)

Synchrotron (magnetic bremsstrahlung)



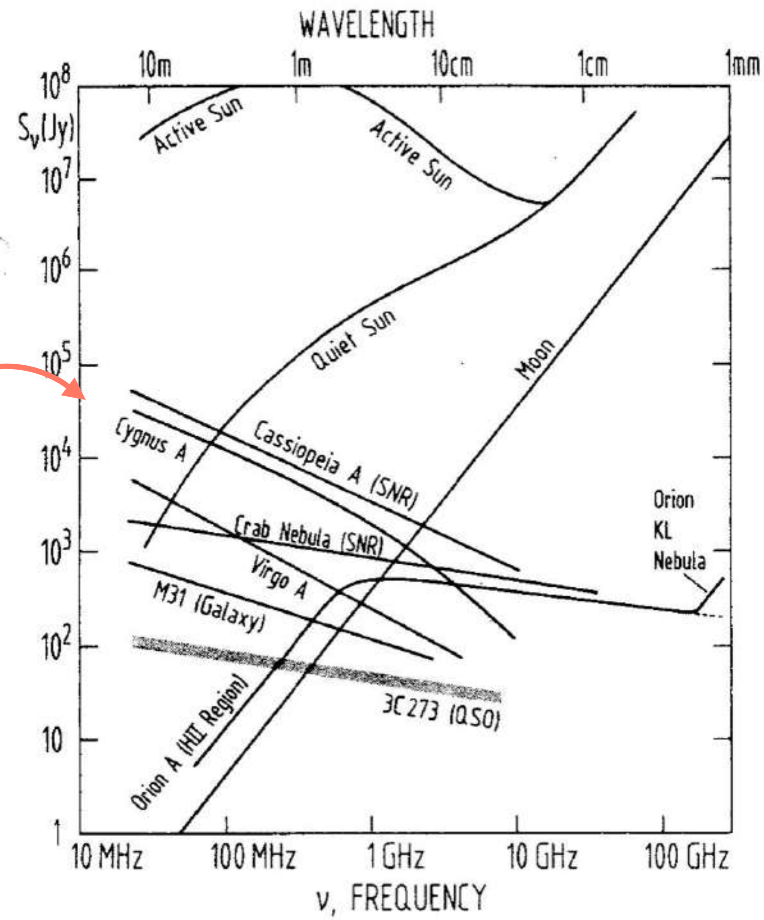
Supernovae
AGN jet

Image Credit: Hiro Hirashita



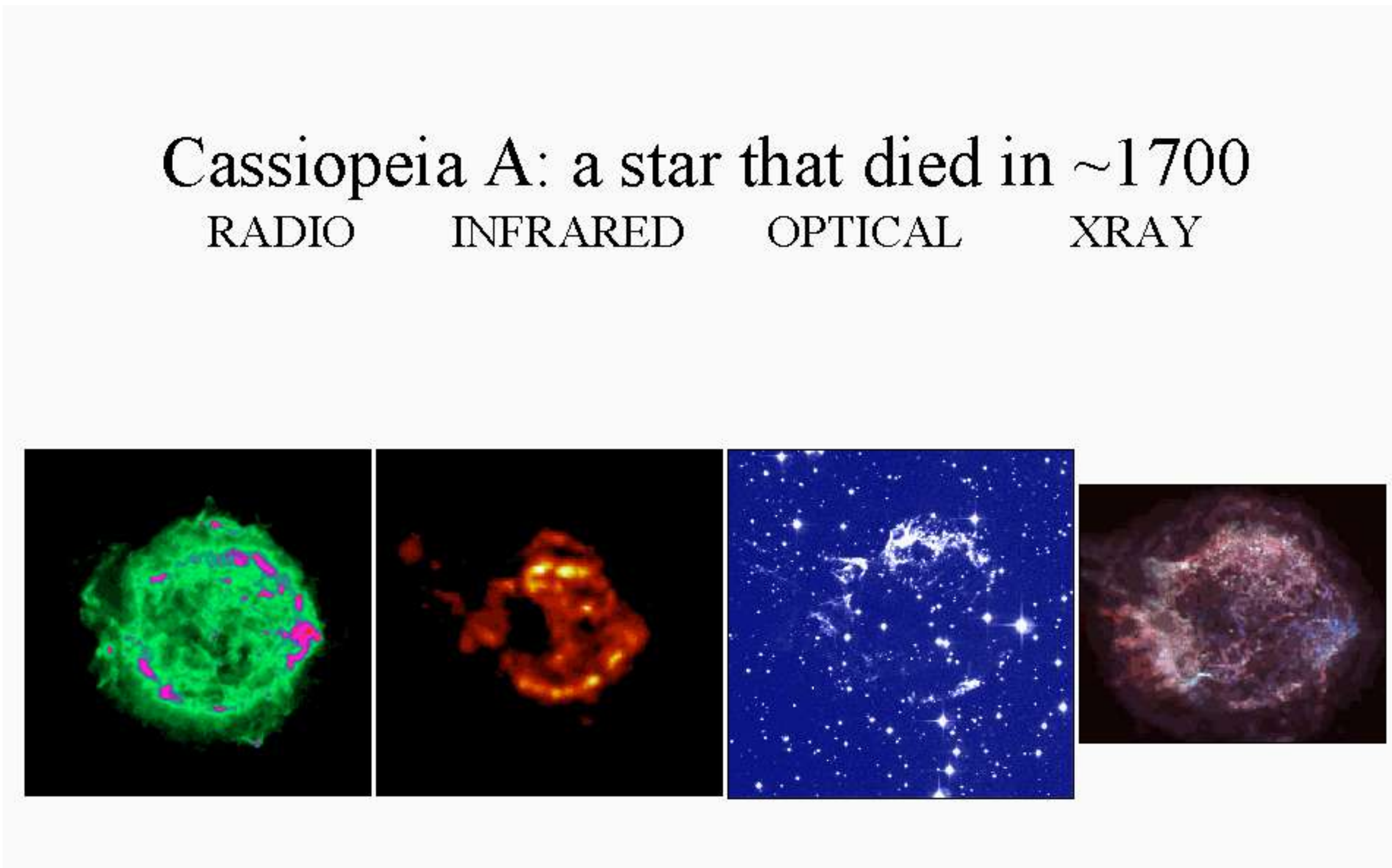
https://en.wikipedia.org/wiki/Synchrotron_radiation

Spectral Energy Distribution (in radio regime)



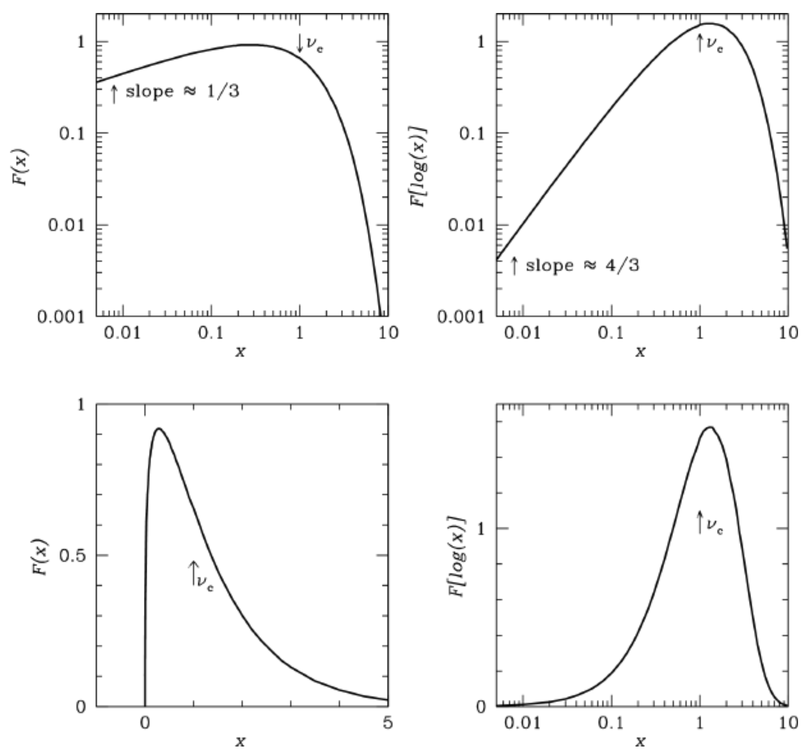
Non-Thermal Synchrotron Radiation (relativistic electrons moving in B-fields)

Spectral Energy Distribution (in radio regime)



Synchrotron Radiation (single particle)

- synchrotron radiation
  - spectrum $$P(\nu) = \frac{\sqrt{3}e^3 B sin\alpha}{m_e c^2}(\frac{\nu}{\nu_c})\int_{\nu/\nu_c}^{inf} K_{5/3}(\eta)d(\eta)$$ with $$\nu_c = \frac{3}{2}\gamma^2\nu_G \; sin\alpha$$



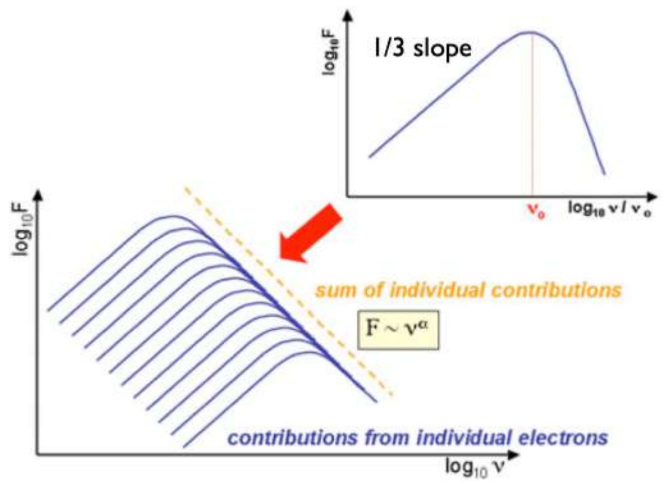
relatively flat spectrum at frequencies lower than the critical frequency and tailing off roughly at the maximum frequency

$$\nu_c = \left(\frac{3}{2}sin\alpha\right)\left(\frac{E}{mc^2}\right)^2\frac{eB}{2\pi m_e c} \propto E^2 B_\perp$$

$$\nu_{max} \approx \pi\gamma^2\nu_G sin\alpha \propto \gamma^2 B_\perp$$

Slide from Fabian Walter Lecture 2

Synchrotron Spectrum



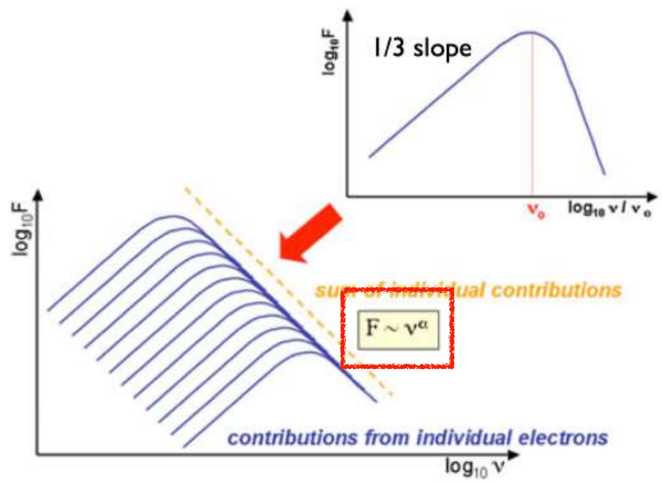
- Powerlaw.
- Observed spectrum is a superposition of the individual electron spectra.

Strong dependence on the Lorentz factor

$\nu_{max} = \nu_e \gamma^2$ $\quad$ $P_e \sim 2\, \gamma^2\, U_{mag}$

- Since (γ >> 1) this boosts the emission frequency of synchrotron emission into the radio domain.

Synchrotron Spectrum



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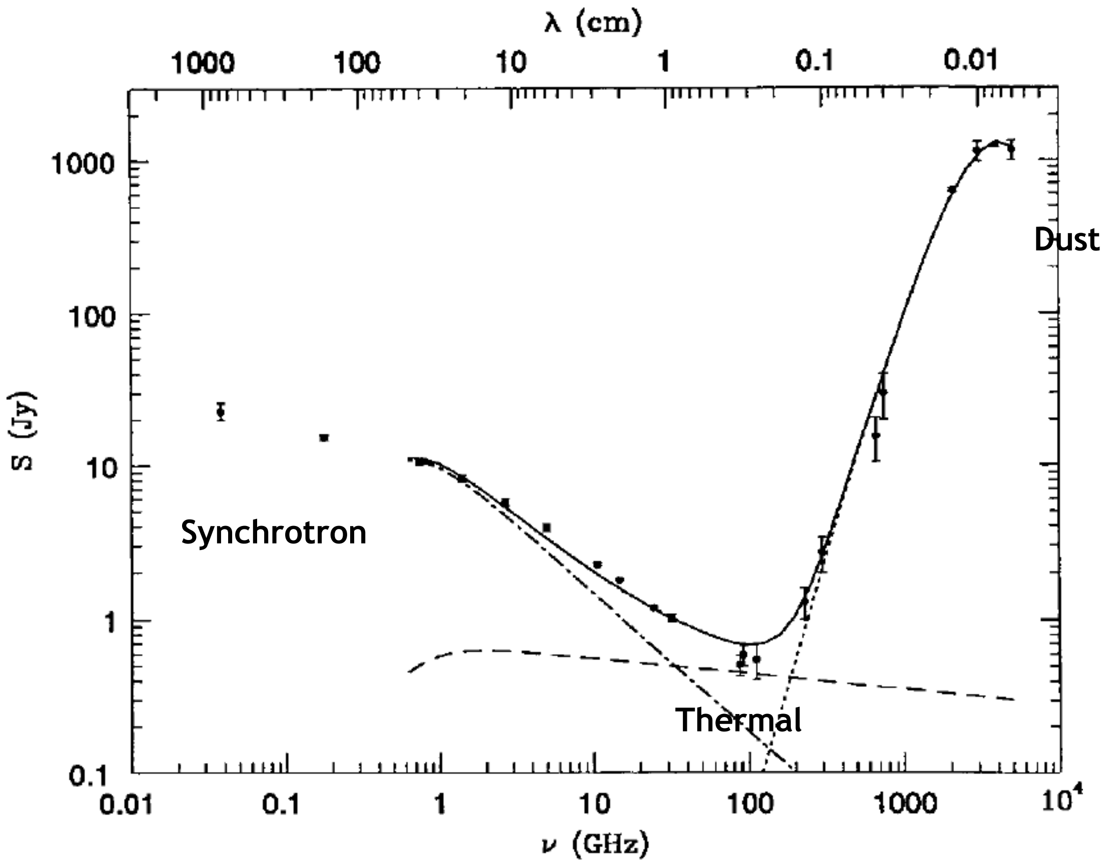
Galactic Radio Astronomy - SNR

- SNR in extragalactic sources : e.g. M82

Credit: Josh Marvil (NM Tech/NRAO), Bill Saxton (NRAO/AUI/NSF), NASA

"Nonthermal emission" Synchrotron emission: electrons spiraling around a magnetic field at relativistic velocities.



Radiative Process (Inverse Compton)

(Inverse) Compton Radiation

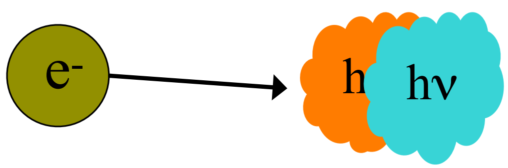
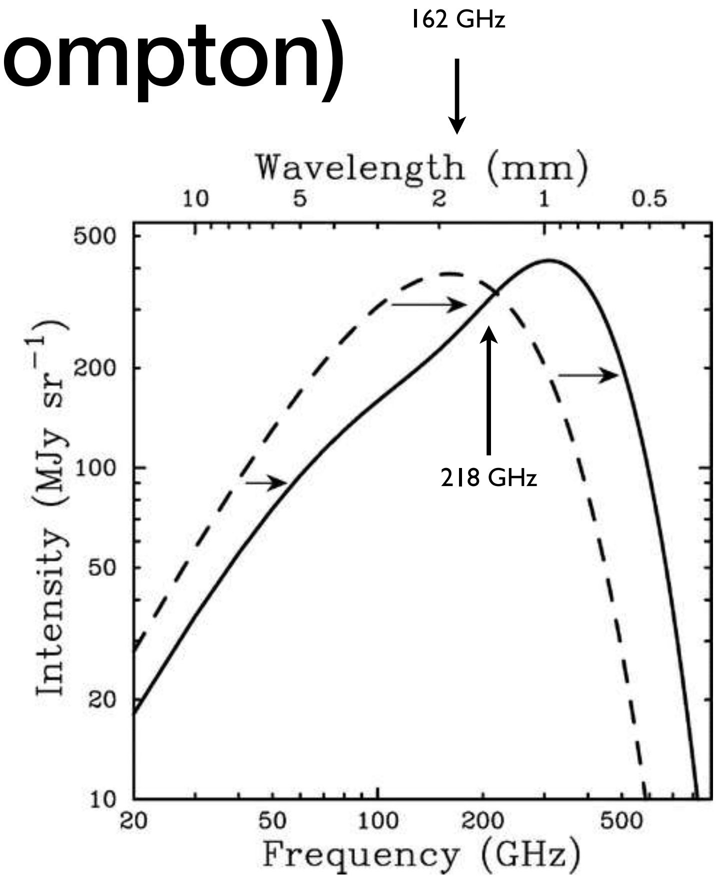


Image Credit: Hiro Hirashita

Intracluster medium
(Sunyaev-Zeldovich effect)
AGN jet, accretion disk

- Sunyaev-Zel'dovich effect
  - Sunyaev & Zel'dovich (1970)
  - CMB photons interact with 10^8 K plasma in clusters, typically extend on the Mpc scale (angular size of several arcmins)
  - no confirmed results until late 1990's



$$\frac{\Delta T}{T} = \frac{2kT_e}{m_e c^2} \sigma_T N_e L$$

$$\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 = 6.65\ 10^{-25} cm^{-2}$$

$$= 2.24\ 10^{-34}\ T_e N_e L$$

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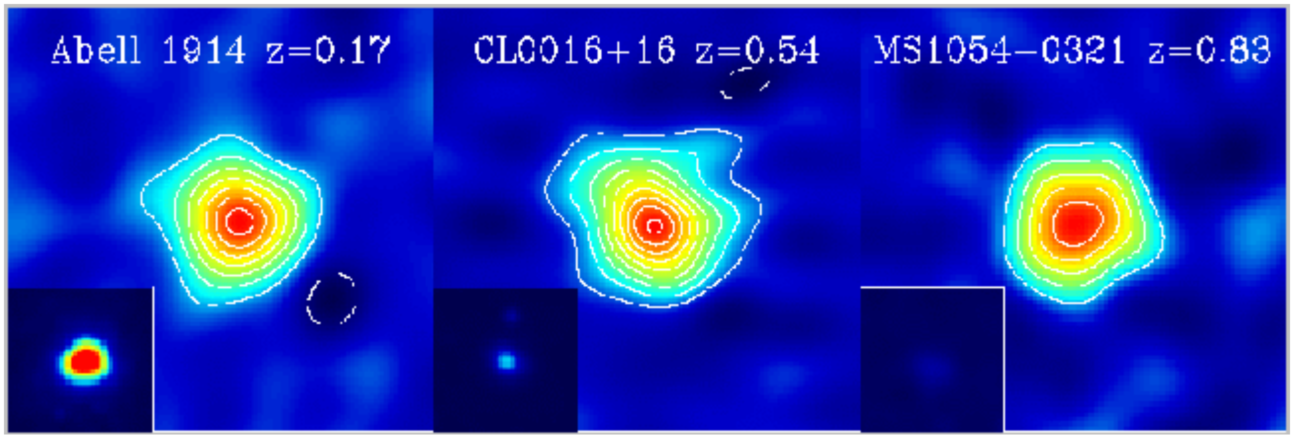
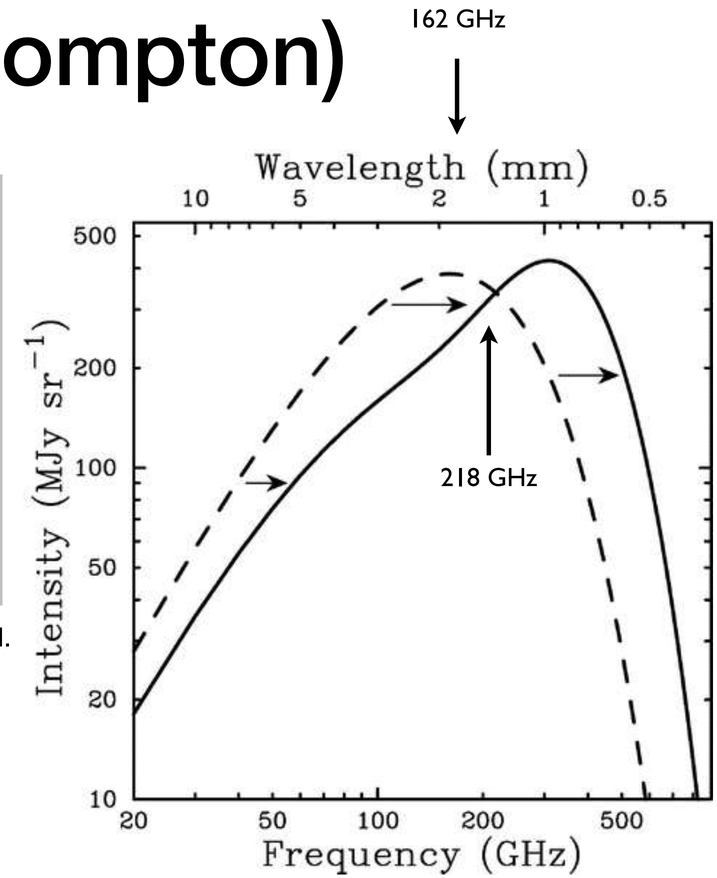


Image Credit: Carlstrom et al.



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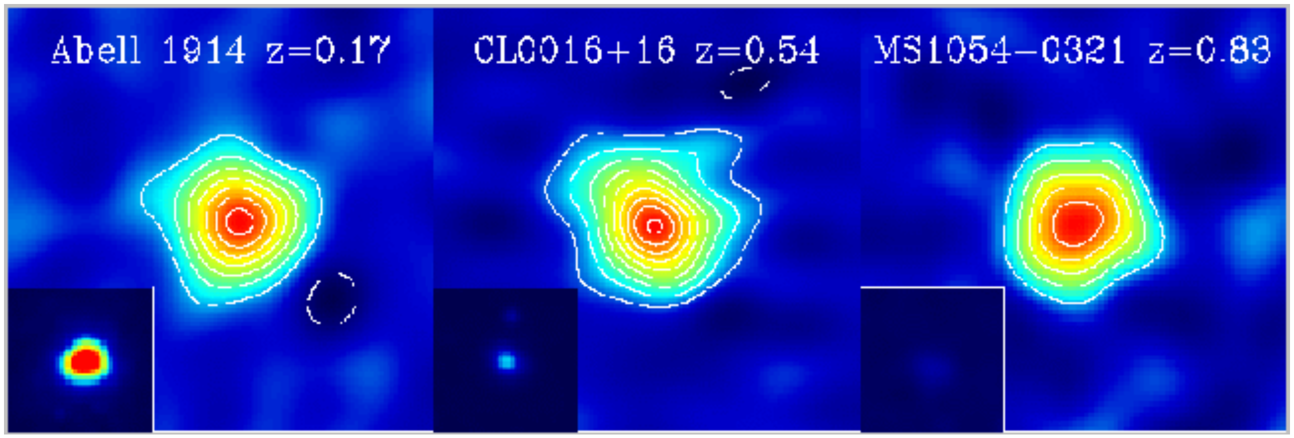

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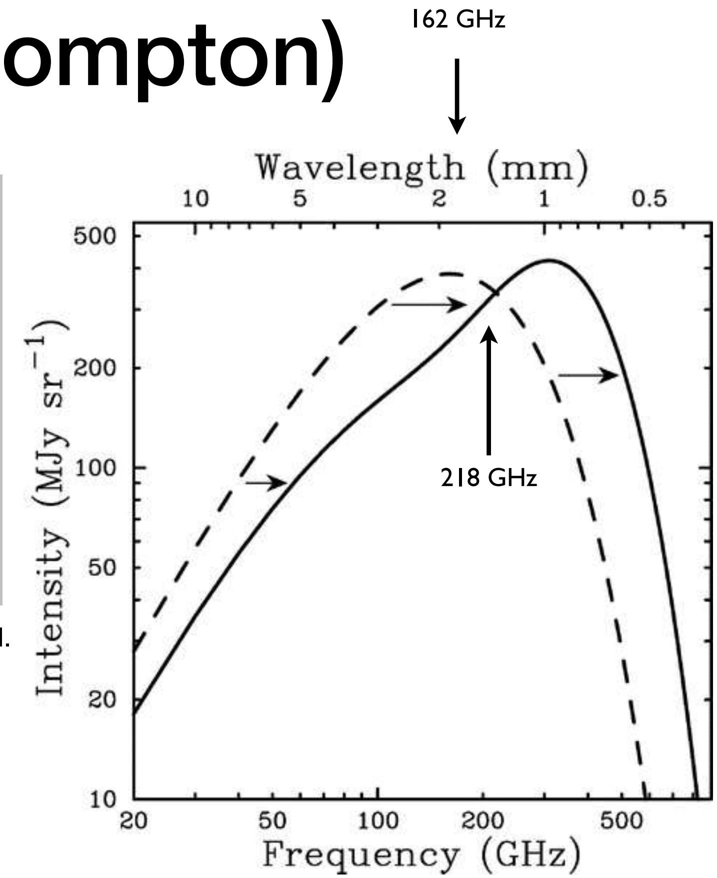

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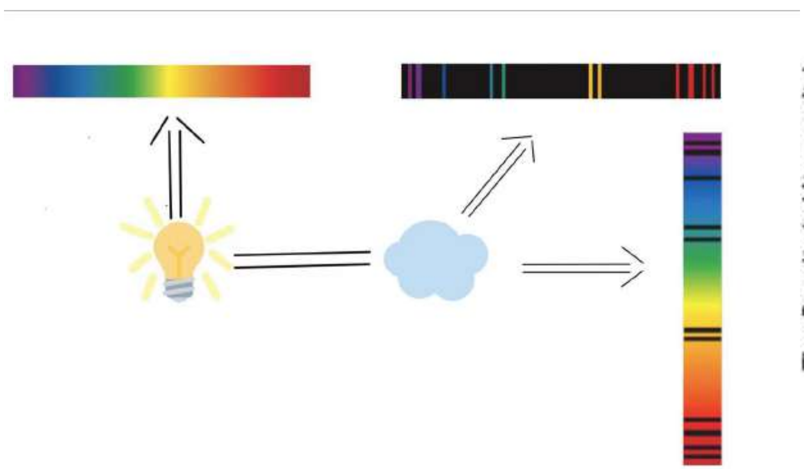
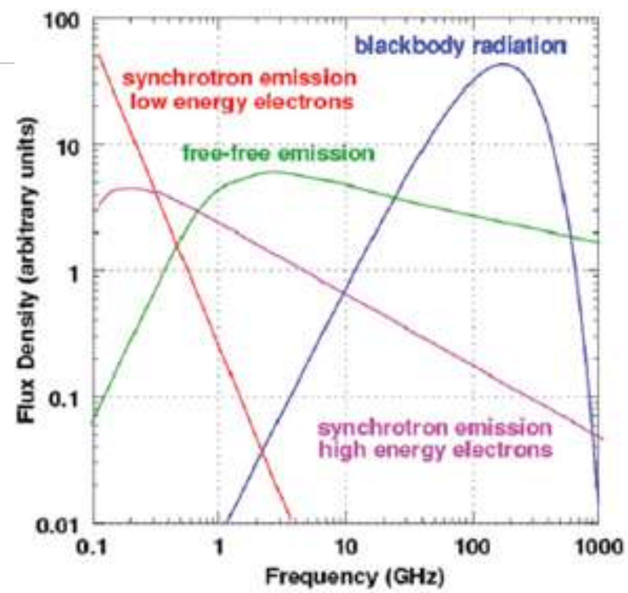
Take Home Message -

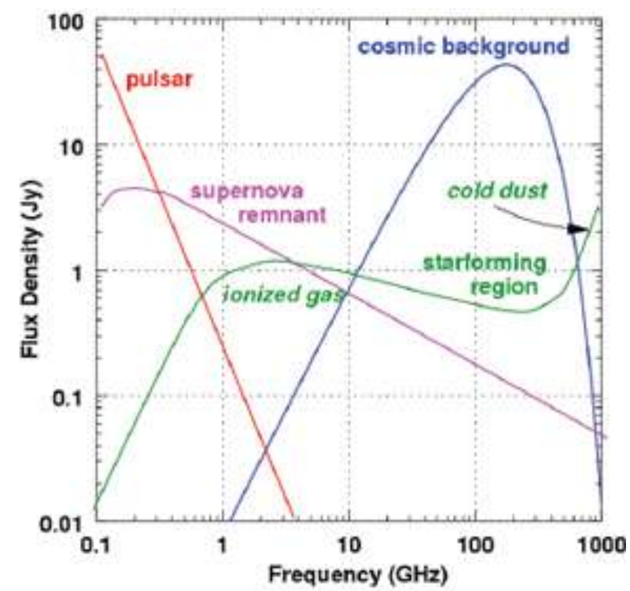
Think about what physical parameters can we extract?

Radiative Transfer



Radiative Processes





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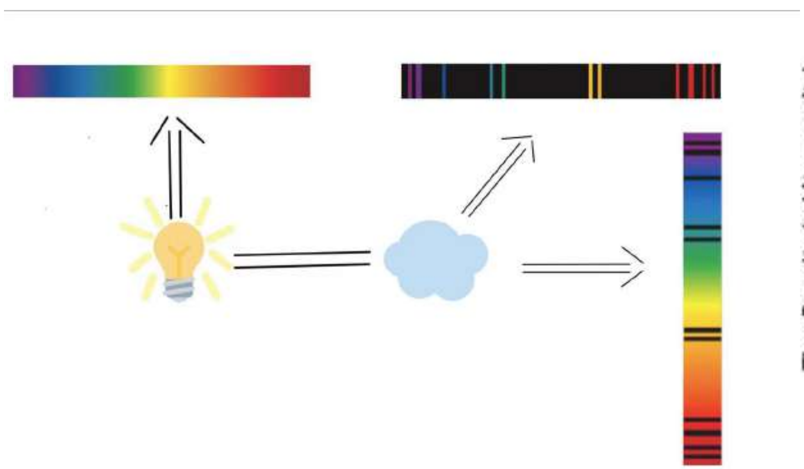
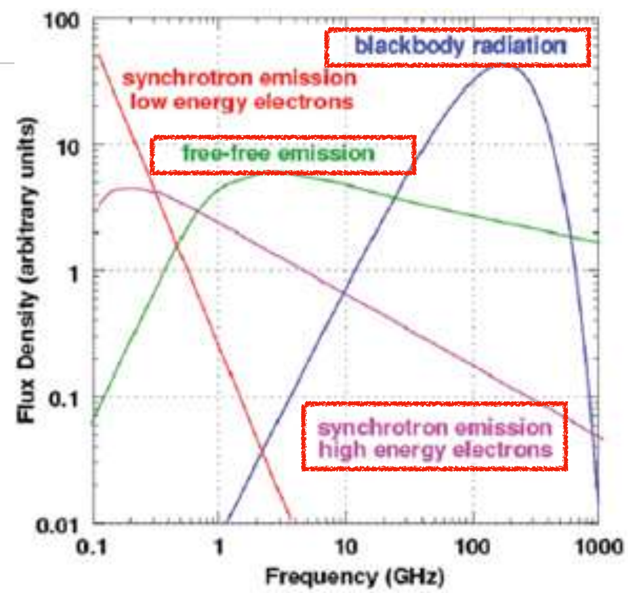
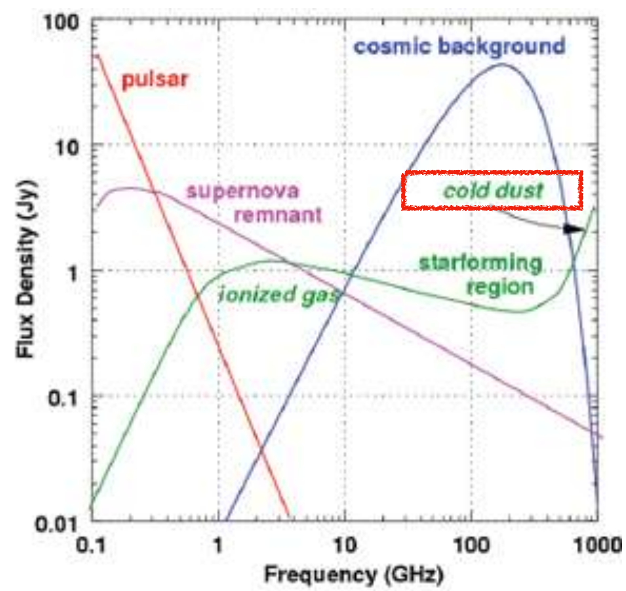
Radiative Transfer

Radiative Processes







References

- Rybicki & Lightman, “Radiative Processes in Astrophysics”
- Draine, “Physics of the Interstellar and Intergalactic Medium”
- Seamus Clarke, ASIAA 2022 SSP Lecture, “Radiative Transfer”
- Hiroyuki Hirashita, ASIAA 2020 SSP Lecture, “Radiative Transfer”