

Astro 501: Radiative Processes
Lecture 27
October 31, 2018

Announcements:

- **Problem Set 8** due next time

Last time: curve of growth

Q: equivalent width—what's that?

Q: how does it change if continuum flux goes up?

Q: what's the curve of growth? why useful? what's growing?

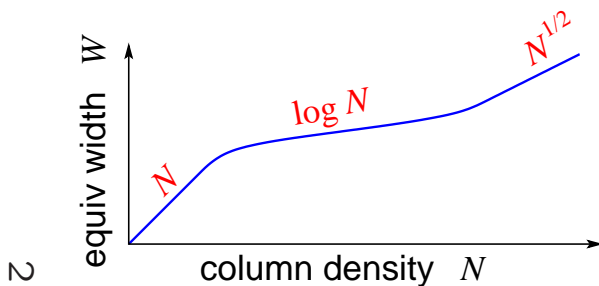
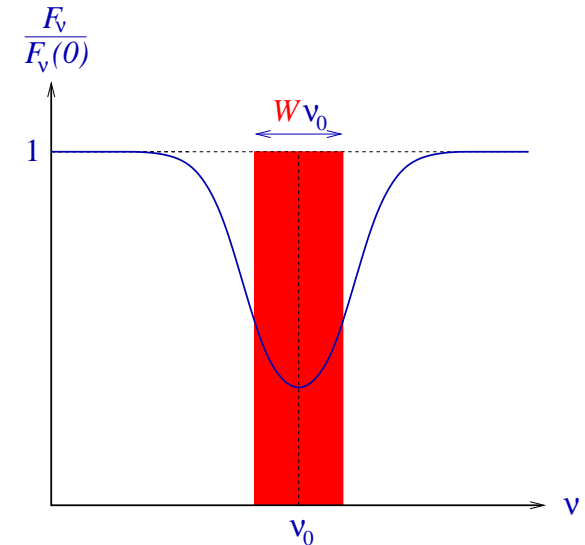
Q: regimes in the curve of growth?

Equivalent Width

equivalent width

$$W = \int_{\Delta\nu_{\text{line}}} \frac{F_\nu(0) - F_\nu}{F_\nu(0)} \frac{d\nu}{\nu_0}$$

so $W\nu_0$ equivalent to
 width of 100% absorbed line
 i.e., *saturated* line with “rectangular” profile
 and W is width as fraction of ν_0



Curve of Growth: W vs $N = \int n ds$

- optically thin: $W \propto N$
- saturated: $W \propto \log N$
- damping wings: $W \propto \sqrt{N}$

Quasar Absorption Line Systems

quasars are distant, high-redshift *backlighting*
to all of the foreground universe

but thanks to big-bang nucleosynthesis, we know:
cosmic *baryonic** matter mostly made of *hydrogen*

if universe *uniformly filled* with H in $1s$ ground state, then:

- *at redshift z* , Ly α $1s \rightarrow 2s$ absorption
at absorber-frame $\lambda_{\text{Ly}\alpha}$, and observer-frame $\lambda_{\text{obs}} = (1+z)\lambda_{\text{Ly}\alpha}$
absorption should occur at all $\lambda < (1+z_{\text{qso}})\lambda_{\text{Ly}\alpha}$
- absorbers have same comoving density at each z
so optical depth τ_λ and hence transmission *spectrum*
should be *smooth* as a function of λ

ω

*in cosmo-practice: a *baryon* = *neutron* or *proton* or combinations of them
= *anything made of atoms* = *ordinary matter* \neq dark matter

Observed quasar spectra:

- *do* show absorption shortwards of the quasar Ly α !
- but transmitted spectrum is not smooth continuum, rather, a series of many separate *lines*

Implications:

- diffuse intervening neutral hydrogen exists!
→ there is an **intergalactic medium**
- intergalactic neutral gas is not uniform but *clumped* into “clouds” of atomic hydrogen

note: low- z quasars show few absorption lines

high- z quasars show many: **Lyman- α forest**

a major cosmological probe

‡

Q: what information does each forest line encode?

The Lyman- α Forest: Observables

each forest *line* \leftrightarrow *cloud of neutral hydrogen*

- absorber z_{abs} gives *cloud redshift*
- absorber depth gives cloud *column density* $N(\text{H I})$

note that absorbers span wide range in column densities

- most common: optically thin “*forest systems*”
correspond to *modest overdensities* $\delta\rho/\rho \sim 1$
- rare: optically thick “*damped Ly α systems*”
damping wings of seen in line profile $\rightarrow N(\text{H I}) \gtrsim 10^{20} \text{ cm}^{-2}$
correspond to *large overdensities: protogalaxies!*

51 WWW: zoom into damped Ly α system

Atomic Hydrogen: the Lyman Series and Lyman Limit

neutral hydrogen in the ground state has transitions to all excited states; lines form the **Lyman series**

www: Grotrian diagram

- Lyman- α : $n = 1 \leftrightarrow 2$; $\lambda_{\text{Ly}\alpha} = 1215.67 \text{ \AA}$
Q: EM regime? implications?
- Ly β : $n = 1 \leftrightarrow 3$; Ly γ : $n = 1 \leftrightarrow 4$, etc

Lyman series line $n = 1 \leftrightarrow n_f$ has

$$\lambda_{n_f} = \left(1 - \frac{1}{n_f^2}\right) \frac{hc}{B_H} \quad (1)$$

for $n_f \gg 1$, line *pileup* of lines

at **Lyman limit** $\lambda_{n_f \rightarrow \infty} = hc/B_H = 911.75 \text{ \AA}$

o

but note: real spectra do not show infinite lines near Ly limit

Q: Why not? What will we really see?

The Lyman Limit

there are infinitely many transitions near the Lyman limit
but each line has a *finite width*
typically due to thermal broadening

lines overlap and *blend* when

$$\text{line width} \lesssim \text{line spacing} \quad (2)$$

$$\frac{v_{\text{FWHM}}}{c} \lambda_n \lesssim \lambda_n - \lambda_{n-1} \approx \frac{\partial \lambda_n}{\partial n} \quad (3)$$

occurs when $1/n^3 \lesssim v_{\text{FWHM}}/c$, and thus
quantum number $n \gtrsim 67 (2 \text{ km s}^{-1}/v_{\text{FWHM}})^{1/3}$, and wavelength

$$\lambda \approx 911.75 + 0.2 \left(\frac{v_{\text{FWHM}}}{2 \text{ km/s}} \right)^{2/3} \text{ \AA} \quad (4)$$

- www: Lyman limit QSO absorption line system
- Q: what about atoms from elements with $\lambda(n = 1 \rightarrow 2) < 912 \text{ \AA}$?

Atomic Resonance Lines

for neutral atoms, *permitted* lines due to transitions from the *ground state* are called **resonance lines**

we saw: neutral H atoms absorb all photons with $\lambda < 912 \text{ \AA}$ in *bound-bound transitions* to $n_f \gg 1$ for λ near limit or for smaller λ , in *bound-free transitions* that ionize H

but H is the most abundant element in the Universe!

thus for atoms with all resonance lines $\lambda < 912 \text{ \AA}$

local hydrogen absorbs photons that can drive these transition

→ *cannot observe these elements in sightlines with H I!*

∞ Q: *are any atoms excluded this way? if so, which?*

Good news:

the only atoms excluded this way are He and Ne
noble gasses, first excited states at very high energies
all other atoms have resonance lines $\lambda > 912 \text{ \AA}$!

Bad news:

for most atoms and ions, resonance lines have $\lambda < 3000 \text{ \AA}$

Q: why is this bad?

Q: how to get around the badness?

“Metal” Lines

quaint astro-lingo: **“metal”** any element \neq H, He including, e.g., famous “metals” C, N, O

most metal atoms and ions have resonance lines $\lambda < 3000 \text{ \AA}$
this is in the UV, blocked by Earth’s atmosphere

www: atmosphere transmittance

for such species, can only see absorption lines:

- by going to space
- when looking at high-redshift objects

www: metal lines in QSO spectrum

but nature has not been totally unkind

a few atoms and ions have resonance lines with $\lambda > 3000 \text{ \AA}$

examples: Na I D doublet $\lambda = 5891.6, 5897.6 \text{ \AA}$,

Ca II doublet at 3934.8, 3969.6 \AA

www: solar lines

Atomic Hydrogen: the 21 cm Line

in *hydrogen*, both e and p have spin $S = 1/2$ (fermions!)
coupled via *spin-spin* or *hyperfine* interaction
with Hamiltonian $H_{\text{spin-spin}} = H_{\text{hf}} \vec{s}_e \cdot \vec{s}_p$
radiation is *magnetic dipole*

hydrogen ground state has two possible *spin configurations*

- proton and electron spins *parallel*: $\uparrow_e \uparrow_p$
excited state: $S_u = 1, g_u = 3$
- spins *antiparallel*: $\downarrow_e \uparrow_p$
ground state: $S_\ell = 0, g_\ell = 1$

transition $u \rightarrow \ell$ requires electron *spin flip* $\Delta s \neq 0, \Delta n = \Delta \ell = 0$

$$A_{ul} = 2.8843 \times 10^{-15} \text{ s}^{-1} = (11.0 \text{ Myr})^{-1}$$

$$\Delta E = E_u - E_\ell = 5.86 \times 10^{-6} \text{ eV} = k_B (0.06816 \text{ K})$$

$$\nu_{ul} = 1420.4 \text{ MHz} \quad \lambda_{ul} = 21.106 \text{ cm}$$

implications of A value? ΔE ? λ ?

Einstein coefficient:

$$A_{ul} = (11.0 \text{ Myr})^{-1}: \text{ very slow rate}$$

- spontaneous emission only occurs after a ~ 11 Myr if the atoms has been *undisturbed*: no collisions!
- spontaneous emission never observed in the laboratory! can only measure transition via stimulated emission!
- but can occur in low-density astrophysical environment
- excited state lifetime $A^{-1} \ll$ age of Universe
→ need some collisions to replenish excited state

EM regime:

$\nu = 1420.4$ MHz and $\lambda = 21.106$ cm: “21 cm radiation” in radio

Thermal Properties:

$\Delta E/k_B = 0.06816$ K small splitting

→ easy to thermally populate excited state

Q: recall that today, $T_{\text{cmb}} = 2.725$ K; implications?

Spin Temperature

the CMB has $T_{\text{CMB}} \gg \Delta E/k \rightarrow$ can populate upper level!

if states in thermal equilibrium at *excitation* or *spin temperature* with $T_{\text{ex}} \equiv T_{\text{spin}} \gg \Delta E/k$, then

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-h\nu_{ul}/kT_{\text{spin}}} \approx \frac{g_u}{g_l} = 3 \quad (5)$$

a nearly fixed ratio *independent of temperature*, so that

$$n_u \approx \frac{3}{4}n(\text{H I}), \quad n_l \approx \frac{1}{4}n(\text{H I}) \quad (6)$$

thus: 21-cm emissivity also independent of spin temperature

$$j_\nu = n_u \frac{A_{ul}}{4\pi} h\nu_{ul} \phi_\nu \approx \frac{3}{16\pi} A_{ul} h\nu_{ul} n(\text{H I}) \phi_\nu \quad (7)$$

Q: *absorption coefficient?*

21-cm Absorption Coefficient

as usual, absorption coefficient has true and stimulated terms:

$$\alpha_\nu = n_l \sigma_{lu} - n_u \sigma_{ul} \quad (8)$$

$$= n_l \frac{g_u A_{ul}}{g_l 8\pi} \lambda_{ul}^2 \phi_\nu \left[1 - \frac{n_u g_l}{n_l g_u} \right] \quad (9)$$

$$= n_l \frac{g_u A_{ul}}{g_l 8\pi} \lambda_{ul}^2 \phi_\nu \left[1 - e^{-h\nu_{ul}/kT_{\text{spin}}} \right] \quad (10)$$

but in practice we always have $e^{-h\nu_{ul}/kT_{\text{spin}}} \approx 1$, so
stimulated emission correction is very important!

using $e^{-h\nu_{ul}/kT_{\text{spin}}} \approx 1 - h\nu_{ul}/kT_{\text{spin}}$, we have

$$\alpha_\nu \approx n_l \frac{3}{32\pi} A_{ul} \frac{hc\lambda_{ul}}{kT_{\text{spin}}} n(\text{H I}) \phi_\nu \quad (11)$$

and thus $\alpha_\nu \propto 1/T_{\text{spin}}$

Q: what determines ϕ_ν in practice?

since $A = \Gamma$ is very small, 21-cm line intrinsically very narrow
 → width entirely determined by *velocity dispersion*
 of the emitting hydrogen

for a random, Gaussian velocity distribution

$$\phi_\nu = \frac{1}{\sqrt{2\pi}} \frac{c}{\nu_{ul}} \frac{1}{\sigma_v} e^{-u^2/2\sigma_v^2} \quad (12)$$

with $u = c(\nu_{ul} - \nu)/\nu_{ul}$, we have

$$\alpha_\nu \approx n_\ell \frac{3}{32\pi} \frac{1}{\sqrt{2\pi}} \frac{A_{ul} \lambda_{ul}^2}{\sigma_v} \frac{hc}{kT_{\text{spin}}} n(\text{H I}) e^{-u^2/2\sigma_v^2} \quad (13)$$

and optical depth

$$\tau_\nu = 2.190 \left(\frac{N(\text{H I})}{10^{21} \text{ cm}^{-2}} \right) \left(\frac{100 \text{ K}}{T_{\text{spin}}} \right) \left(\frac{1 \text{ km/s}}{\sigma_v} \right) e^{-u^2/2\sigma_v^2} \quad (14)$$

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Q: implications?

21 cm Emission: Optically Thin Case

21 cm optical depth:

$$\tau_\nu = 2.190 \left(\frac{N(\text{H I})}{10^{21} \text{ cm}^{-2}} \right) \left(\frac{100 \text{ K}}{T_{\text{spin}}} \right) \left(\frac{1 \text{ km/s}}{\sigma_\nu} \right) e^{-u^2/2\sigma_\nu^2} \quad (15)$$

real interstellar lines of sight can have $N(\text{H I}) > 10^{21} \text{ cm}^{-2}$
 → *self-absorption can be important!*

But in the optically thin limit, for $N(\text{H I}) \lesssim 10^{20} \text{ cm}^{-2}$
 then absorption is small and

$$I_\nu \approx I_\nu(0) + \int j_\nu ds = I_\nu(0) + \frac{3}{16\pi} A_{ul} h\nu_{ul} N(\text{H I}) \phi_\nu \quad (16)$$

with $N(\text{H I}) = \int n_{\text{H I}} ds$

if $I_\nu(0)$ is known Q : *how?*, then

$$\int [I_\nu - I_\nu(0)] d\nu = \frac{3}{16\pi} A_{ul} h\nu_{ul} N(\text{H I}) \quad (17)$$

in terms of antenna temperature, integrating in velocity space

$$\int [T_A - T_A(0)] du = \int \frac{c^2}{2k\nu^2} [T_A - T_A(0)] c \frac{d\nu}{\nu} = \frac{3}{16\pi} A_{ul} \frac{hc\lambda_{ul}^2}{k} N(\text{H I})$$

measures *hydrogen column* $N(\text{H I})$ independent of spin temperature!

integrating over solid angles gives flux density

$$F_{\text{obs}} = \int F_\nu d\nu = \int I_\nu \cos\theta d\Omega d\nu \approx \int I_\nu d\Omega d\nu \quad (18)$$

and thus the integrated flux

$$F_{\text{obs}} \propto \int N(\text{H I}) d\Omega = \frac{\int n_{\text{H I}} ds dA}{D_L^2} \propto \frac{M_{\text{H I}}}{D_L^2} \quad (19)$$

measures the *total hydrogen mass* $M_{\text{H I}}$
if we know the (luminosity) distance D_L

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useful for H I clouds in our own Galaxy,
and measuring H I content of external galaxies

consider cold, diffuse atomic H in a galaxy that has bulk internal motions with speeds $v_{\text{bulk}} > \sigma_v$

Q: how would this arise?

Q: what spectral pattern would uniform rotation give?

Q: what is a more realistic expectation?

Awesome Example: Galaxies in 21 cm

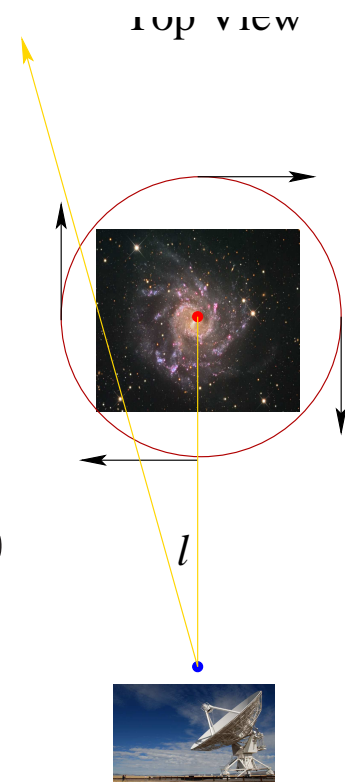
spiral galaxies observed in 21 cm emission, ellipticals are not
→ spirals are gas rich, ellipticals gas poor www: THINGS survey

spiral galaxies also rotate:

bulk line-of-sight motion imprinted on 21 cm
via Doppler shift at different sightlines

spectrum depends on *rotation curve* $V(R)$

- uniform rotation: $V = \omega_0 R \propto R$
small V near center, only large at edge
→ 21 cm peak near galaxy systemic speed $V = 0$
- “flat” curve: $V(R) \rightarrow V_0$, a constant
small V only near center, large elsewhere
→ 21 cm peak at $V = \pm V_0$



www: observed 21 cm spectrum

Awesome Example: the 21 cm Milky Way

the Galactic plane is well-mapped in 21 cm

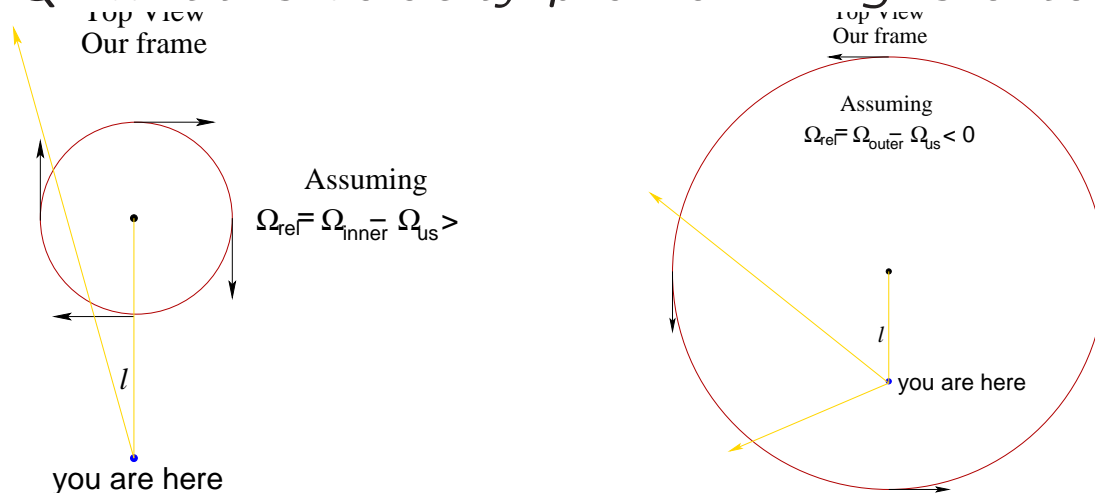
Q: what do we expect for the intensity map?

Q: what do we expect for the velocity map?

Hint: imagine single *rings* of rotating gas

Q: what is velocity profile if ring is interior to us?

Q: what is velocity profile if ring is exterior to us?



www: observed MW velocity profile

Awesome Example: Cosmic 21 cm Radiation

CMB today, redshift $z = 0$, has $T_{\text{cmb}}(0) = 2.725 \text{ K} \gg T_{\text{ex},21 \text{ cm}}$ but what happens over cosmic time?

fun & fundamental cosmological result:

(relativistic) *momentum redshifts*: $p \propto 1/a(t)$, which means

$$p(z) = (1 + z) p(0) \quad (20)$$

where $p(0)$ is observed momentum today ($z = 0$)

why? photon or de Broglie wavelength λ is a *length*, so

$$\lambda(t) = a(t) \lambda_{\text{emit}} = \frac{\lambda_0}{(1 + z)} \quad (21)$$

and quantum relation $p = h/\lambda$ implies $p \propto (1 + z)$

Q: implications for gas vs radiation after recombination?

Thermal History of Cosmic Gas and Radiation

until recombination (CMB formation) $z \geq z_{\text{rec}} \sim 1000$

(mostly) hydrogen gas is ionized, tightly coupled to CMB
via Thomson scattering: $T_{\text{cmb}} = T_{\text{gas}}$

after recombination, before gas decoupling $z_{\text{dec}} \sim 150 \lesssim z \leq z_{\text{rec}}$

- most gas in the Universe is *neutral*
but a small “residual” fraction $x_e \sim 10^{-5}$ of e^- remain ionized

- Thompson scattering off residual free e^- ($x_e \sim 10^{-5}$)
still couples gas to CMB $\rightarrow T_{\text{cmb}} = T_{\text{gas}}$ maintained

- until about $z_{\text{dec}} \sim 150$, when Thomson scattering ineffective,
gas *decoupled*

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Q: *after decoupling, net effect of 21 cm transition?*

radiation transfer along each sightline:

$$I_\nu = I_\nu^{\text{cmb}} e^{-\tau_\nu} + I_\nu^{\text{gas}} (1 - e^{-\tau_\nu}) \quad (22)$$

with τ_ν optical depth to CMB

in terms of *brightness or antenna temperature* $T_B = (c^2/2k\nu^2)I_\nu$

$$T_b = T_{\text{cmb}} e^{-\tau_\nu} + T_{\text{gas}}(1 - e^{-\tau_\nu}) \quad (23)$$

when $T_{\text{gas}} = T_{\text{cmb}}$ (really, $T_{\text{spin}} = T_{\text{cmb}}$)

gas is in equilibrium with CMB: emission = absorption

→ $T_b = T_{\text{cmb}}$: no net effect from CMB passage through gas

after gas decoupling, before reionization $z_{\text{reion}} \sim 10 \lesssim z \leq z_{\text{dec}}$

separate thermal evolution: $T_{\text{cmb}} \sim E_{\text{peak}} \propto p_{\text{peak}} \propto (1+z)$

but matter has $T_{\text{gas}} \sim p^2/2m \propto p^2 \propto (1+z)^2$

→ *gas cools* (thermal motions “redshift”) *faster than the CMB!*

Q: net effect of 21 cm transitions in this epoch?

21 cm Radiation in the Dark Ages

before the first stars and quasars: **cosmic dark ages**
first structure forming, but not yet “lit up”

during dark ages: intergalactic gas has $T_{\text{gas}} < T_{\text{cmb}}$

$$\delta T_b \equiv T_b - T_{\text{cmb}} = (T_{\text{gas}} - T_{\text{cmb}})_z (1 - e^{-\tau_\nu})_z \quad (24)$$

we have $\delta T_b < 0$: gas seen in 21 cm *absorption*

Q: what cosmic matter will be seen this way?

Q: what will its structure be in 3-D?

Q: how will this structure be encoded in δT_b ?

The “21 cm Forest”

what will absorb at 21 cm?

any neutral hydrogen in the universe!

but after recomb., most H is neutral, and most baryons are H
so absorbers are *most of the baryons in the universe*

thus absorber spatial distribution is *3D distribution of baryons*
i.e., intergalactic baryons as well as seeds of galaxies and stars!
baryons fall into potentials of dark matter halos, form galaxies
so *cosmic 21 cm traces formation of structure and galaxies!*

gas at redshift z absorbs at $\lambda(z) = (1 + z)\lambda_{lu}$

and is responsible for decrement $\delta T_b[\lambda(z)]$

→ thus $\delta T_b(\lambda)$ *encodes redshift history* of absorbers
a sort of “21 cm forest”

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Q: *what about sky pattern of $\delta T_b(\lambda)$ at fixed λ ?*

and at fixed λ , sky map of $\delta T_b(\lambda)$
gives baryon distribution in “shell” at $1 + z = \lambda/\lambda_0$
→ a radial “slice” of the baryonic Universe!

so by scanning through λ , and at each
making sky maps of $\delta T_b(\lambda)$
→ we build in “slices” a *3-D map of cosmic structure evolution!*
“cosmic tomography”! a cosmological gold mine!
encodes huge amounts of information

sounds amazing! and it is! but there is a catch!

Q: why is this measurement very difficult to do?

Hint: it hasn't yet been done

21 cm Cosmology: The Challenge

The 21 cm cosmic goldmine lies at redshifts $z \sim 6$ to 150 corresponding to:

- $\lambda_{\text{obs}} \sim 1.5 - 30$ m

enormous wavelengths! www: LOFAR

- $\nu_{\text{obs}} \sim 200 - 10$ MHz

but ionosphere opaque $> \nu_{\text{plasma}} \sim 20$ MHz

for highest z (most interesting!) have to go to space! in fact, have to go to far side of the Moon Q: why?

www: proposed lunar observatories

But wait! It's worse!

at these wavelengths, dominant emission is *Galactic synchrotron*

with brightness $T_{\text{B,synch}} \sim 200 - 2000$ K $\gg T_{\text{cmb}} \gg T_{\text{B,21 cm}}$

www: radio continuum sky

Q: implications? how to get around this?

sky intensity $T_{\text{B,synch}} \sim 200 - 2000 \text{ K} \gg T_{\text{cmb}}$

→ Galactic synchrotron foreground dominates cosmic 21 cm
curse you, cosmic rays!

But there remains hope!

recall: cosmic-ray electron energy spectrum is a power law
so their *synchrotron spectrum is a power law*

i.e., $I_{\nu,\text{synch}}$ is *smooth function of ν*

compare 21 cm at high- z : a “forest” of absorption lines
not smooth! full of spectral *lines & features*

→ can hope to measure with very good spectral coverage
and foreground subtraction

∞ also: can use spatial (i.e., angular) distribution
e.g., consider effect of first stars (likely massive) Q : *namely?*

first stars: likely massive → hot → large UV sources
ionizing photons carve out “bubble” neutral H
→ corresponding to a *void* in 21 cm
→ sharp bubble edges may be detectable
→ 21 cm can probe *epoch of reionization*

hot, ongoing research area!

stay tuned!

Director's Cut Extras

Absorption Line Spectroscopy: Doublets

what if absorbing level ℓ has transitions to
two “neighboring” excited states u_1 and u_2 ?
i.e., $\ell \rightarrow u_1$ and $\ell \rightarrow u_2$ both allowed

Q: how will this imprint on the spectrum?

Q: if both lines optically thin, what is equiv width ratio W_2/W_1 ?

Q: what is notable about this?

Q: how will W_2/W_1 ratio change with N_ℓ ?

Q: what is notable about this?

Doublet Line Ratios

if the states u_1 and u_2 are “neighboring” levels
then spectra will show two neighboring lines: a **doublet**

in the optically thin limit, $W \rightarrow (\pi e^2/m_e c^2) N_\ell f_{lu} \lambda_{lu}$
so if both lines are *optically thin*, then

$$\frac{W_2}{W_1} \approx \frac{f_{lu_2} \lambda_{lu_2}}{f_{lu_1} \lambda_{lu_1}} \quad (25)$$

- ratio set entirely by atomic line properties
- transition with *larger* $f_{lu_2} \lambda_{lu_2}$ has stronger line
sketch curve of growth for both lines

as N_ℓ increases: optical depth increases
 stronger line first enters *flat part of curve of growth*
 equivalent width set by thermal width: $W = 2b/c\sqrt{\ln \tau_0 / \ln 2}$
 → W_2/W_1 *drops*, until weaker line also in flat part:

$$\frac{W_2}{W_1} \approx \sqrt{1 + \frac{\ln(f_{lu_2}\lambda_{lu_2}/f_{lu_1}\lambda_{lu_1})}{\ln \tau_{lu_1} / \ln 2}} \rightarrow 1 \quad (26)$$

→ limit is *independent of atomic properties*

as absorber column N_ℓ increases further
 the stronger line first enters the damping wing regime
 line ratio increases again, approaching

$$\frac{W_2}{W_1} \approx \frac{\lambda_{lu_2}}{\lambda_{lu_1}} \sqrt{\frac{f_{lu_2}\Gamma_{lu_2}}{f_{lu_1}\Gamma_{lu_1}}} \quad (27)$$

→ set by atomic properties and *total damping width*

Q: *why is all of this useful?*

thus *doublet ratio is diagnostic of curve-of-growth regime*

Strategy:

compare observed W_2/W_1 value to

optically thin limiting value $f_{lu_2}\lambda_{lu_2}/f_{lu_1}\lambda_{lu_1}$

- agreement verifies both lines optically thin
- $W_2/W_1 \approx 1$ is warning: flat part of curve of growth
- $W_2/W_1 \rightarrow$ damping wing ratio gives $\Gamma_{lu_2}/\Gamma_{lu_1}$
and thus collisional broadening & hence pressure/density