The Color Index

Flux usually is measured through color filters, e.g., U, B or V filters. Flux through e.g., B filter is called *B magnitude* written *B* or m_B.

$$U - B \propto -\log \frac{F_U}{F_B}$$

$$B - V \propto -\log \frac{F_B}{F_V}$$

are *color indices* of a star. Smaller *B-V* => bluer star. Color indices indicate temperature.

A blackbody temperature that reproduces a star's *B-V* or *U-B* is called a "color temperature".

More Precisely

Relation between apparent magnitude and incident flux, e.g. for U:

$$U = -2.5\, log_{10}(\int_0^{\infty} F_\lambda S_U d\lambda) + \ C_U$$

F_λ is monochromatic incident flux at λ.

S_U is "sensitivity function" of U filter. Function of λ.

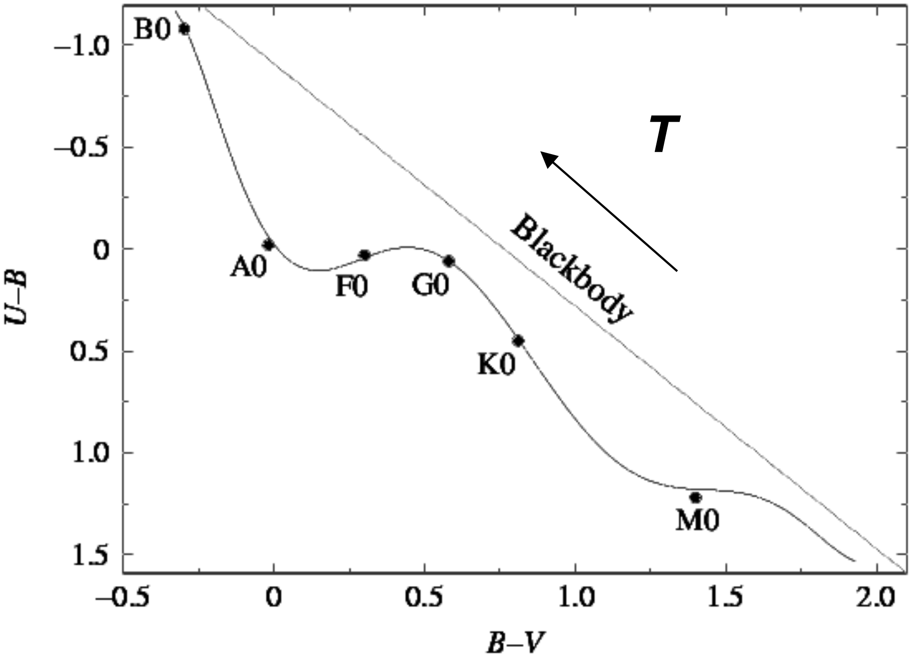
C_U is a constant.

C_U, C_B, C_V chosen such that U=B=V=0 for Vega (arbitrary).

$$U - B = -2.5\, log_{10}(\frac{\int_0^{\infty} F_\lambda S_U d\lambda}{\int_0^{\infty} F_\lambda S_B d\lambda}) + C_U \ - C_B$$

$$C_{U-B} \equiv C_U \ - \ C_B$$

Color-color diagram



more UV

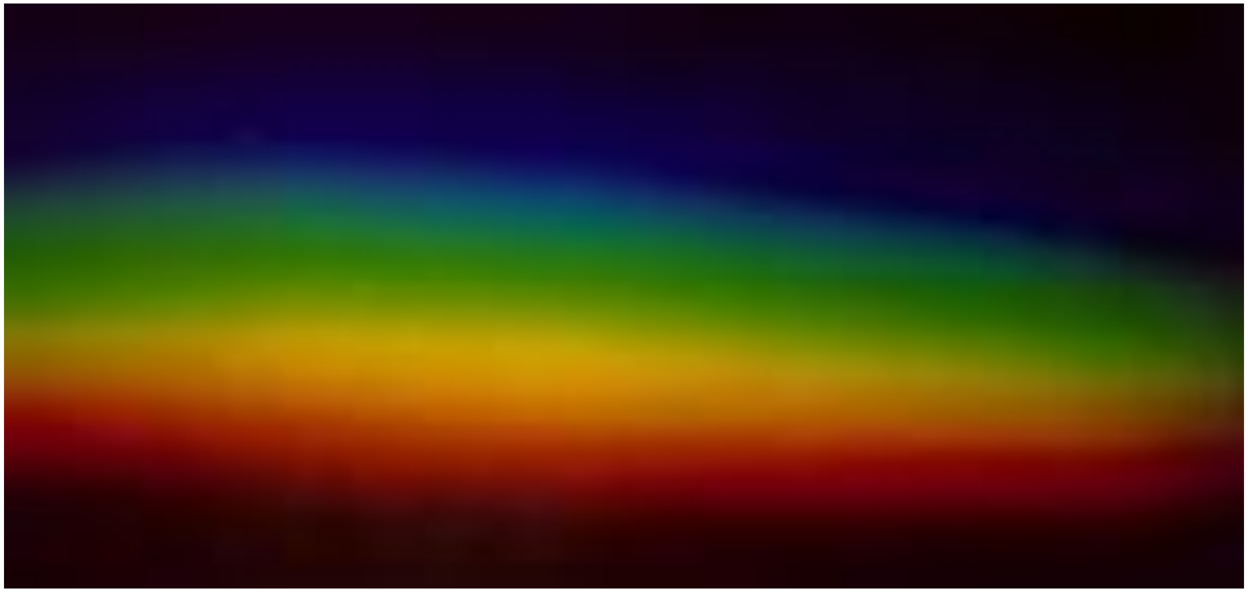
less UV

more blue

less blue

Stars are not true blackbodies!

Astronomy 421



Lecture 4: Radiation

Four Corners Meeting

UNM Organizing Committee

- David Dunlap
- Douglas Fields
- Wolfgang Rudolph
- Greg Taylor

The 25th Anniversary Four Corners Meeting of the American Physical Society

October 14-15, 2022 at the University of New Mexico

Physics & Astronomy and Interdisciplinary Science Building https://fourcorners2022aps.unm.edu

Cost

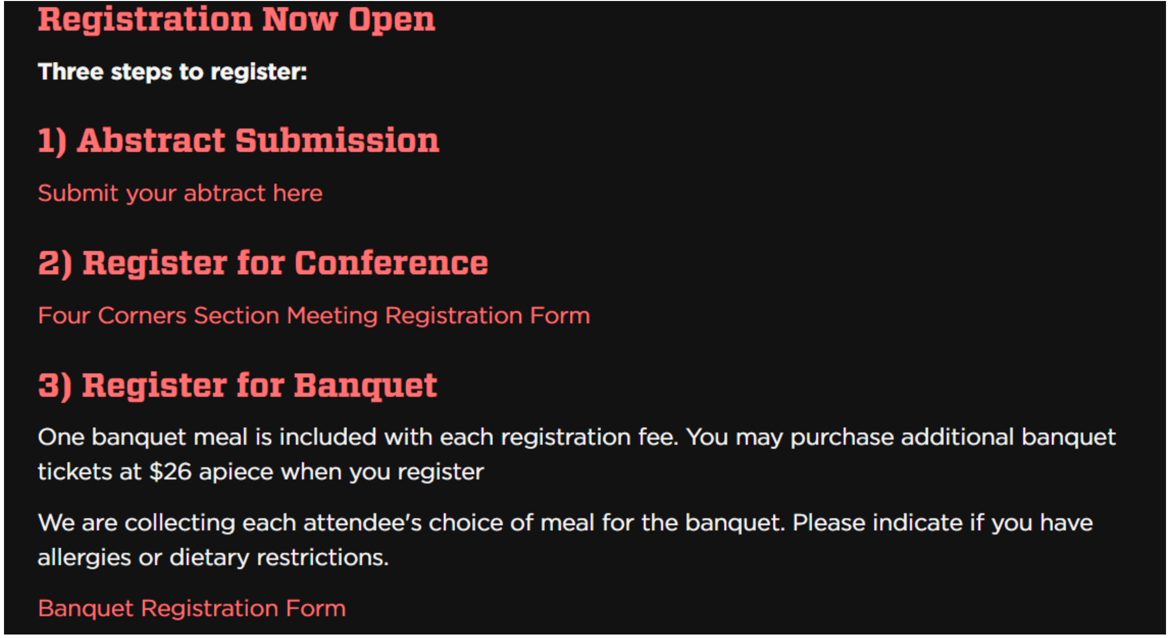
- Early registration fee: $100 (Student rate: $50)
- Late registration fee (after September 30): $120 (Student rate: $70)

Registration Deadlines

- Early Registration Ends: **Friday, September 30, 2022**
- Late Registration Begins: **Saturday, October 1, 2022**
- Registration Ends: **Tuesday, October 4, 2022**
- Cancellation with refund deadline: **Tuesday, October 4, 2022**

Abstract Submission Deadlines

- Abstract Submission Deadline: **Friday, September 16, 2022**
- Withdrawal deadline: **Friday, October 7, 2022**



Registration Now Open

Three steps to register:

1) Abstract Submission

Submit your abtract here

2) Register for Conference

Four Corners Section Meeting Registration Form

3) Register for Banquet

One banquet meal is included with each registration fee. You may purchase additional banquet tickets at $26 apiece when you register

We are collecting each attendee's choice of meal for the banquet. Please indicate if you have allergies or dietary restrictions.

Banquet Registration Form

https://fourcorners2022aps.unm.edu

Banquet Speaker

Sara Kendrew

Instrument & Calibration Scientist with the European Space Agency at the Space Telescope Science Institute

Highlights from James Webb Space Telescope Commissioning and Early Science

Since the launch of James Webb Space Telescope on December 25th 2021, we have witnessed the start of a new era in observational astronomy. After decades of development, JWST is finally in space, opening a new window on the Universe in the infrared. Operating at L2, JWST provides continuous spectral coverage from 0.6 to 28.5 micron with a rich suite of instrumentation, in a stable cold temperature environment. During the 6-month commissioning period, the observatory was successfully deployed and, following meticulously planned and much rehearsed procedures, the segmented telescope was phased, aligned and focused. During the final 2 months of commissioning the 4 science instruments - NIRCam, NIRISS, NIRSpec and MIRI - were fully checked out and readied for the start of the observatory's exciting science mission - culminating in the release of a first set of science images, the Early Release Observations. I will present some highlights of the commissioning program and first exciting science results from JWST.

Approximate Schedule:

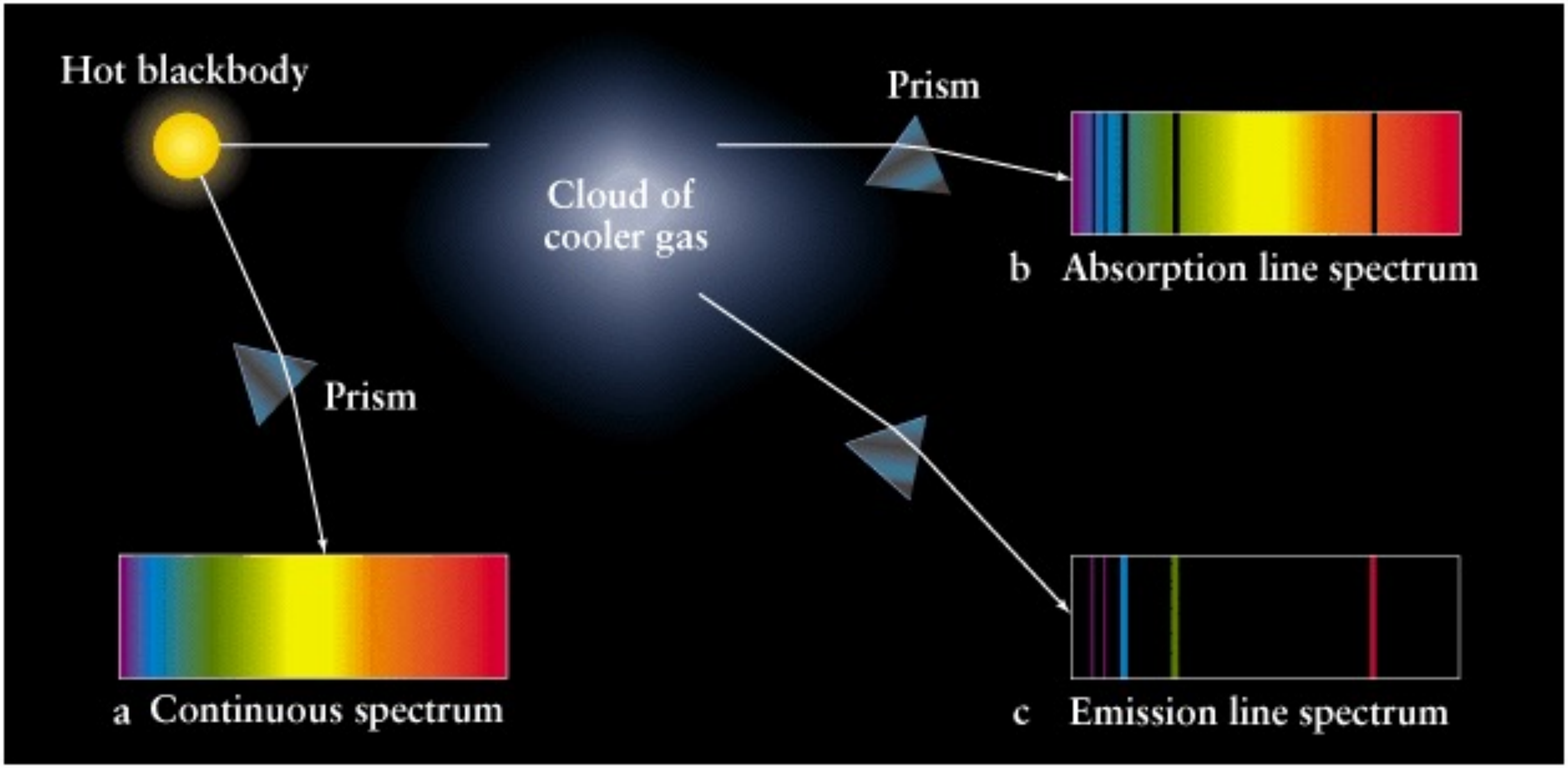
Friday: 7:30 Breakfast/Coffee
Friday: 8:30 – 9:30 Plenary Session I (2 talks) in 1100
Friday: 9:30 – 10:00 Coffee Break
Friday: 10:00 – 12:00 Parallel Sessions
Friday: 1:00-2:30 Parallel Sessions
Friday 2:30-3:30 Plenary Session II (2 talks) in 1100
Friday 3:30-4:00 Coffee Break
Friday 4:00-6:00 Posters in PAIS on ground floor and on 2nd floor.
Friday 6:00-8:00 Banquet in SUB ballroom C
Friday 8:00-9:00 Banquet talk by Sarah Kendrew in ballroom C
Saturday 7:30 Breakfast
Saturday 8:00-9:30 Parallel Sessions
Saturday 9:30 Coffee Break
Saturday 10:00-12:00 Parallel Sessions
Saturday 1:00-2:30 Parallel Sessions
Saturday 2:30 – 4:00 Plenary III (3 talks) in 1100
Saturday 4:00 Awards in 1100

Key Concepts:

Wave-particle duality of light

Heisenberg's uncertainty principle

Quantized energy of atoms


Hot blackbody
Cloud of cooler gas
Prism
Prism
b Absorption line spectrum
a Continuous spectrum
c Emission line spectrum

Kirchoff's laws:

1. A hot, dense gas or hot solid object produces a continuous spectrum with no dark spectral lines.
2. A hot, diffuse gas produces bright spectral lines (emission lines).
3. A cool, diffuse gas in front of a source of a continuous spectrum produces dark spectral lines (absorption lines) in the continuous spectrum.

Empirical! What is the *physical* basis?

First bullet (1): This was the topic of the last lecture… Continuous spectrum of BB $B_\lambda(T)$ and $B_\nu(T)$ radiation emitted at any T>0 K.

Q: How warm must a BB be to emit in the visible?

Second and third bullets come from quantum mechanics:

Planck introduced *h* to explain frequency distribution of radiation from a black body. He made an ad hoc assumption that energy was exchanged between the BB and the radiation field in discrete quantas of size *hv*.

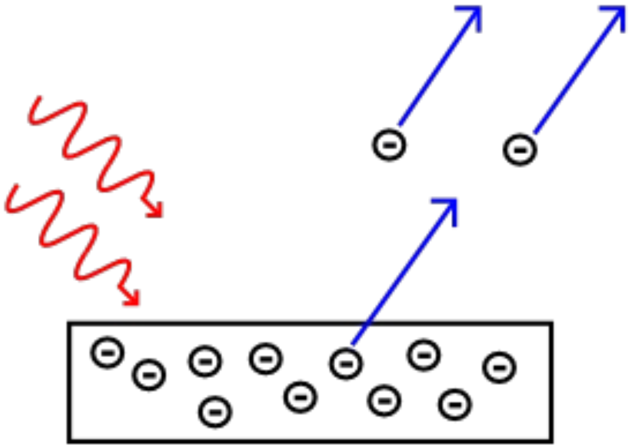
$$E = h\nu = \frac{hc}{\lambda}$$

This would imply that there are not an infinite number of higher modes that are populated and thus avoid the UV catastrophe of RJ law.

…direct evidence for photon energy quantization had to wait for Einstein.

The photoelectric effect:

Increasing incident light intensity increased number of photoelectrons, but not their maximum kinetic energy.



Red light did not cause any photoelectrons (regardless of intensity).

Violet light ejected a few photoelectrons.

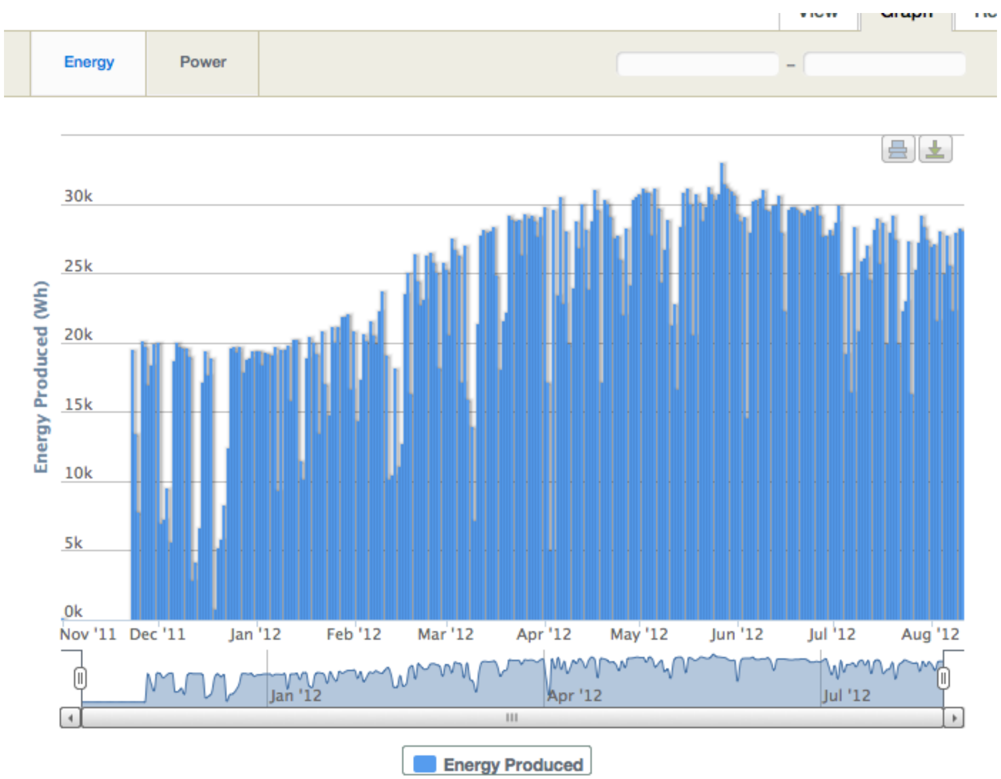
Their maximum KE > than those for intense light at longer wavelengths.

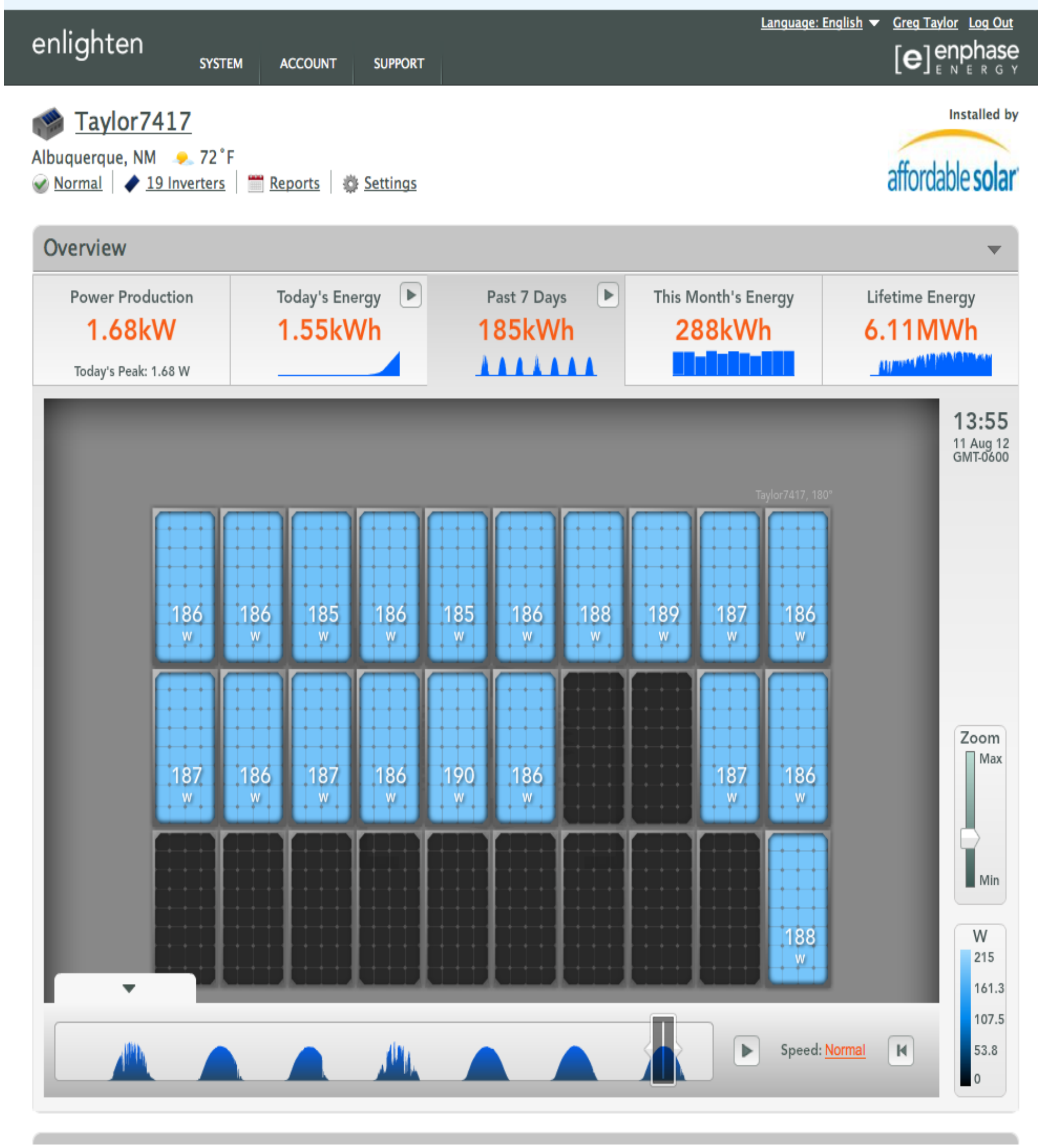
Thus: ejection energy independent of the total energy of illumination

=> the interaction must be like that of a particle giving all of its energy to the electron.

The photoelectric effect - can be understood only if light comes in discrete packets (photons) of energy => light is a particle.

Photovoltaics





Taylor7417

Albuquerque, NM 72˚F

Power Production 1.68kW

Today's Peak: 1.68 W

Today's Energy 1.55kWh

Past 7 Days 185kWh

This Month's Energy 288kWh

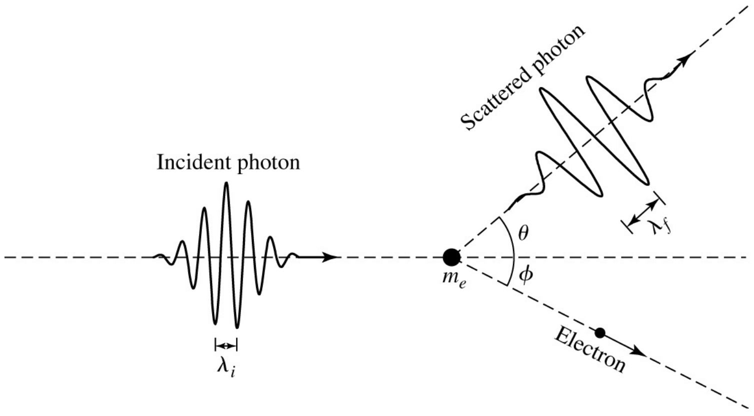
Lifetime Energy 6.11MWh

13:55
11 Aug 12
GMT-0600

186 W	186 W	185 W	186 W	185 W	186 W	188 W	189 W	187 W	186 W
187 W	186 W	187 W	186 W	190 W	186 W			187 W	186 W
									188 W

Further evidence: change in λ due to scattering off electron - the Compton effect.

$$\Delta\lambda = \left(\frac{h}{m_e c}\right)(1 - \cos\theta)$$

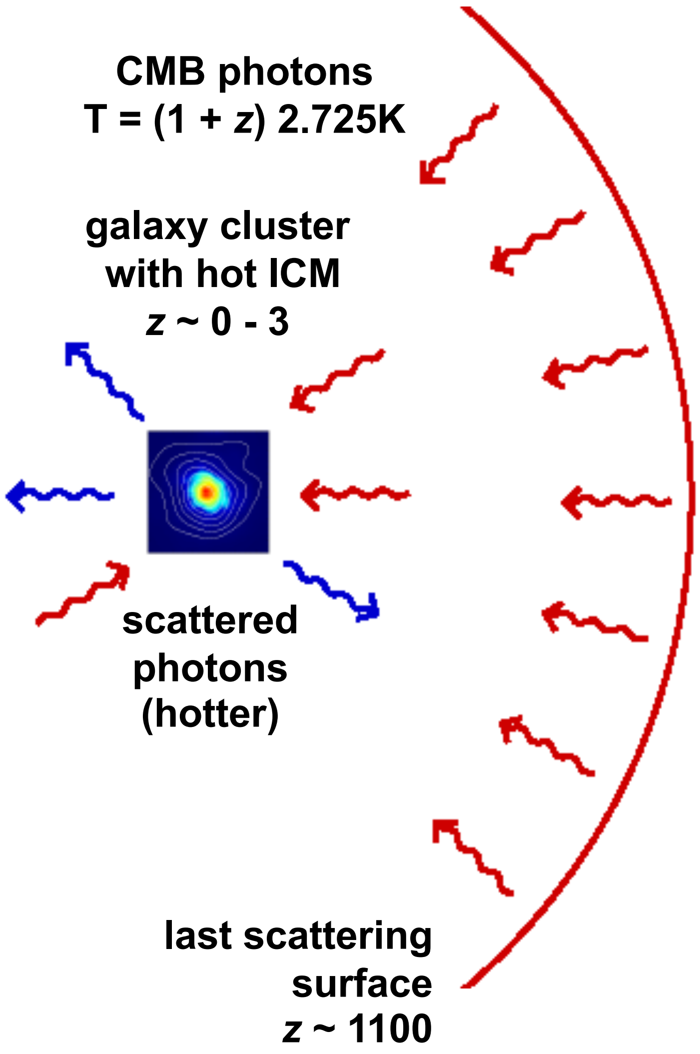


The electron is initially at rest, gains energy - a result of that the photon has momentum.

In general: $E^2 = p^2c^2 + m_{rest}^2c^4$

For photons: $E_{\text{photon}} = pc$

The Sunyaev-Zel'dovich effect, predicted in the 1970s.

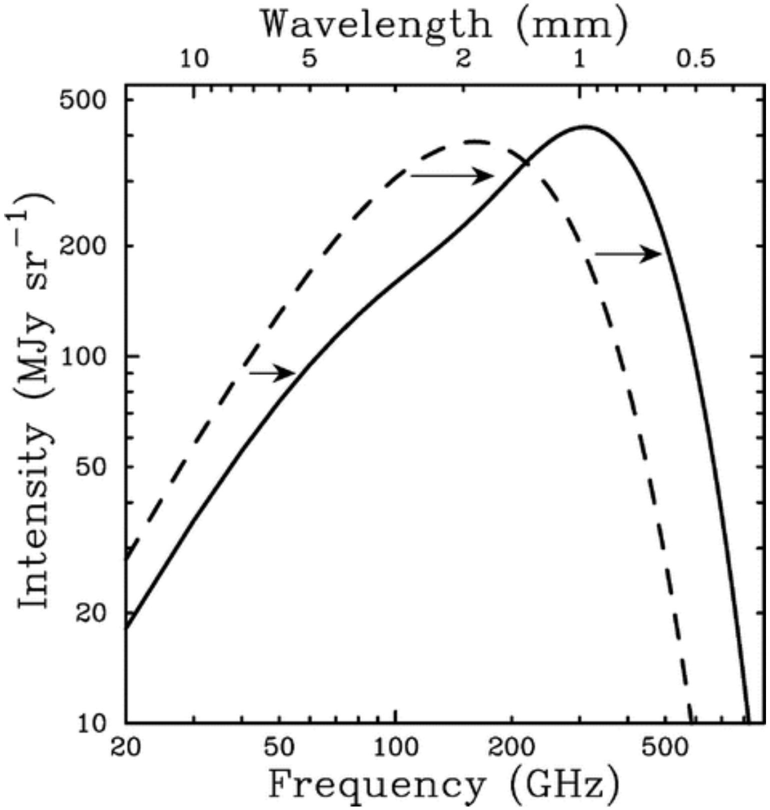


CMB photons
T = (1 + *z*) 2.725K

galaxy cluster
with hot ICM
***z* ~ 0 - 3**

scattered
photons
(hotter)

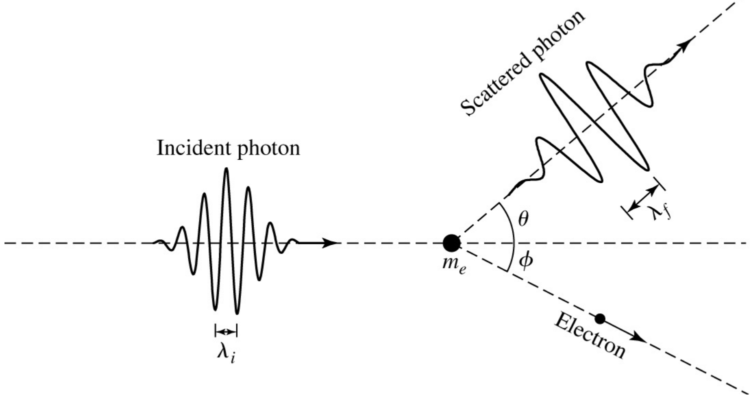
last scattering
surface
***z* ~ 1100**



CMB photons have a ~1% chance of inverse Compton scattering off of the ICM electrons; photon *number* is conserved

Further evidence: change in λ due to scattering off electron - the Compton effect.

$$\Delta\lambda = \left(\frac{h}{m_e c}\right)(1 - \cos\theta)$$



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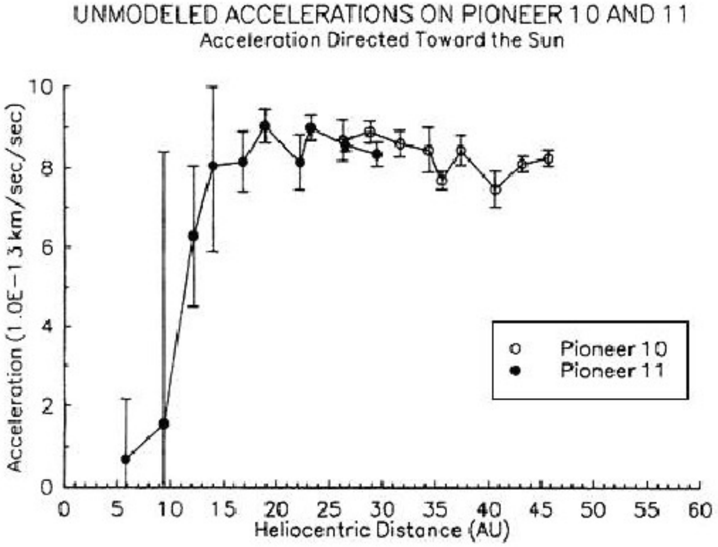
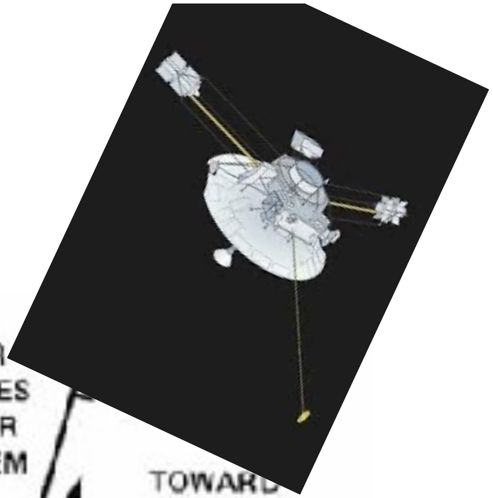
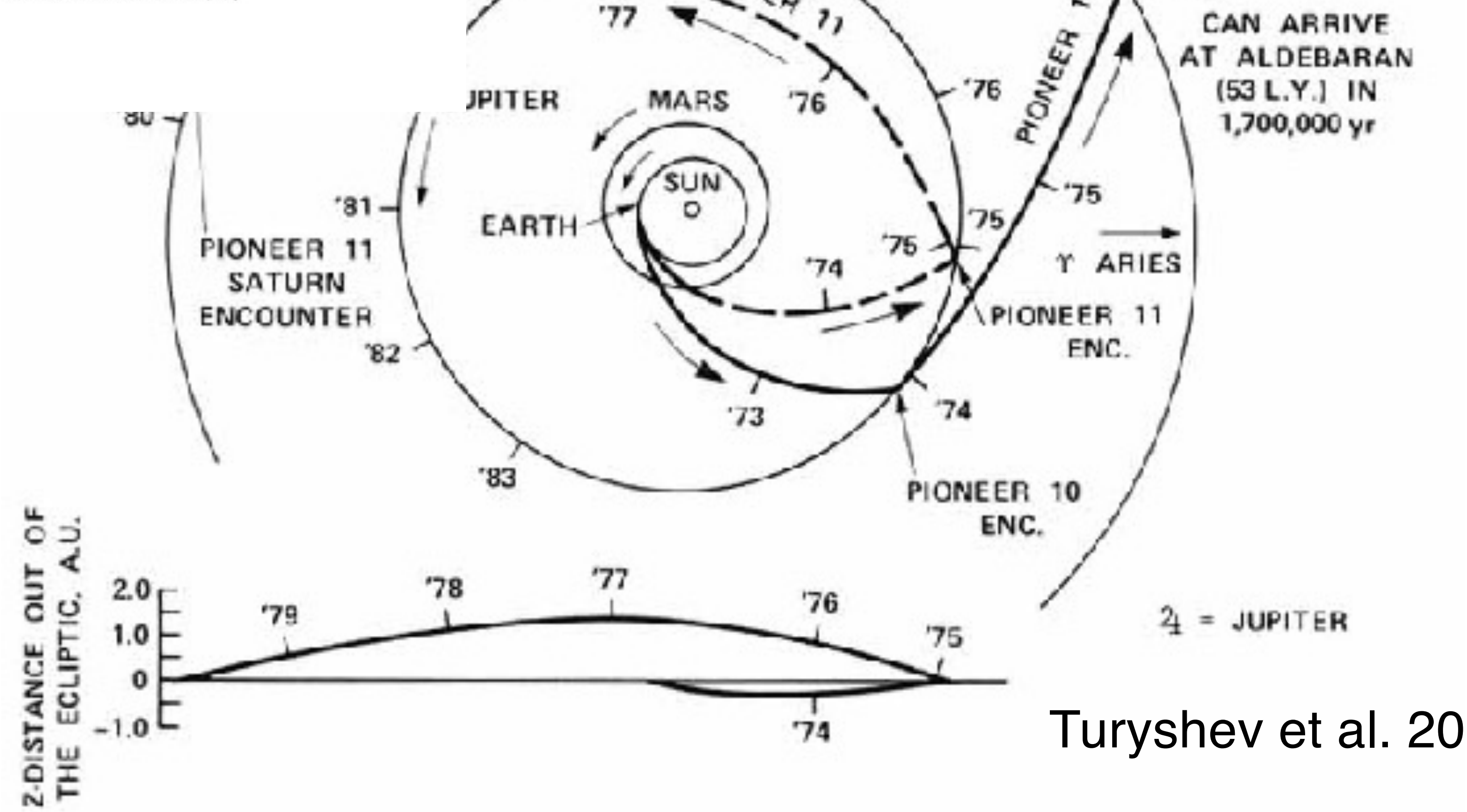
For photons: $E_{\text{photon}} = pc$

Astrophysical manifestation: radiation pressure.

Pioneer Anomaly

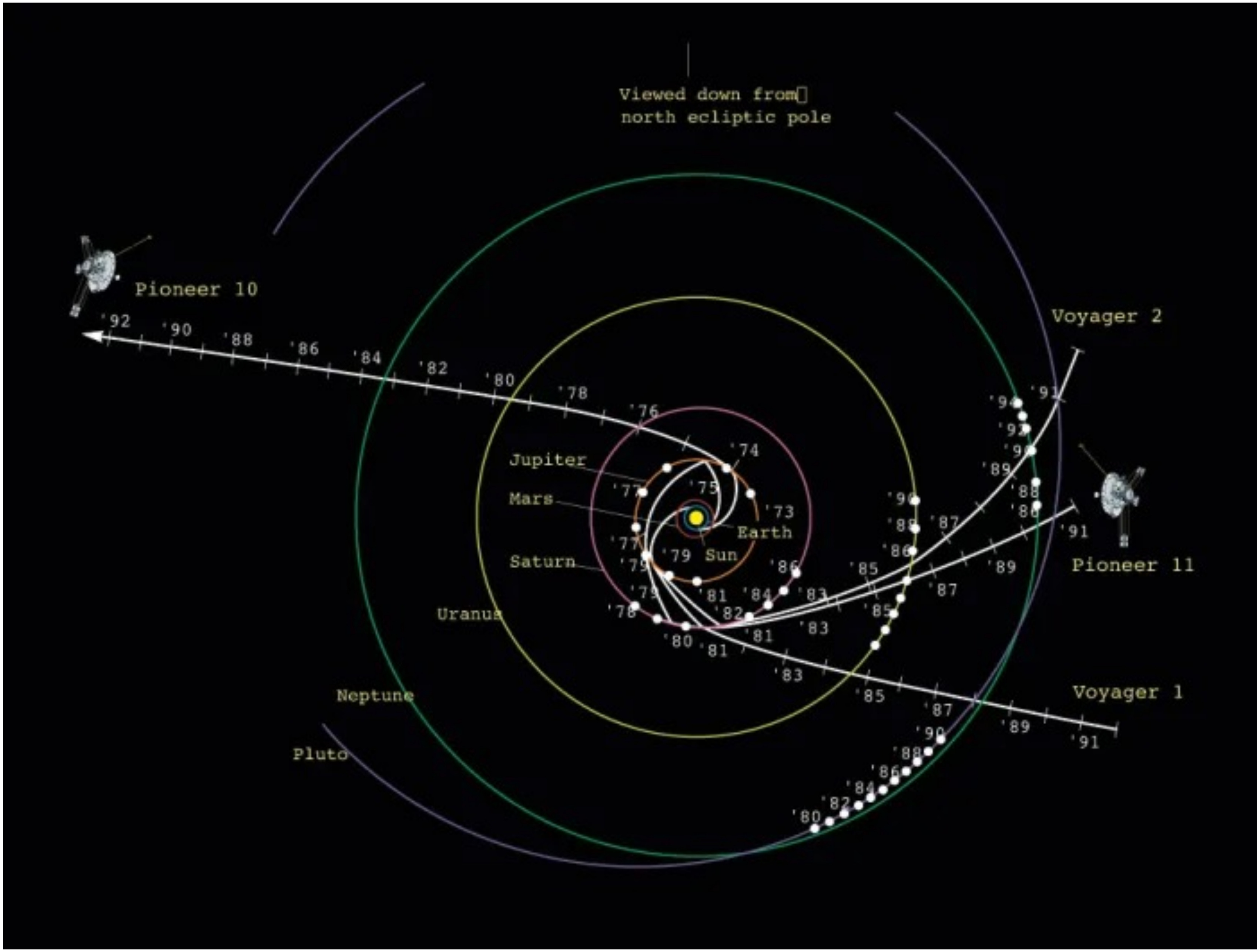






Turyshev et al. 2012

Where are they now?



More on wave-particle duality:

We have, for photons:

$$E = pc$$

$$E = \frac{hc}{\lambda} \qquad \Rightarrow p = \frac{h}{\lambda}$$

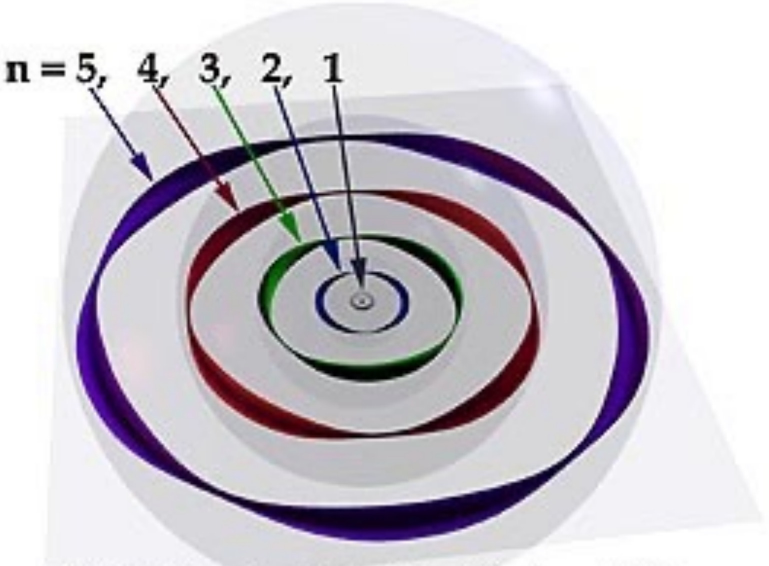
de Broglie relation

<u>de Broglie proposal (also true for *massive* particles):</u>

wavelike behavior of particles (and bowling balls!) with a characteristic wavelength

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

The Bohr-de Broglie model: how electrons perform within the atom



Niels Bohr - Louis de Broglie atom, 1924

An electron in a Bohr orbit possess a wavelength of the right dimension to form standing waves.

The electron can move between shells through changing electrical levels (via electrical work, or emitting/absorbing light).

Shells quantized => so is the wavelength.

QM is probabilistic! Square of wave amplitude $|\psi|^2$ at a certain place describes the probability of finding particle there.

We cannot say with 100% certainty *where* a particle is and *what* its energy is.

Heisenberg's uncertainty principle:

$$\boxed{\Delta x \Delta p_x \geq \frac{\hbar}{2}}$$

"Nature is intrinsically fuzzy"

Often you will see this form for making estimates:

$$\boxed{\Delta x \Delta p_x \approx \hbar}$$

Or, in terms of energy and time:

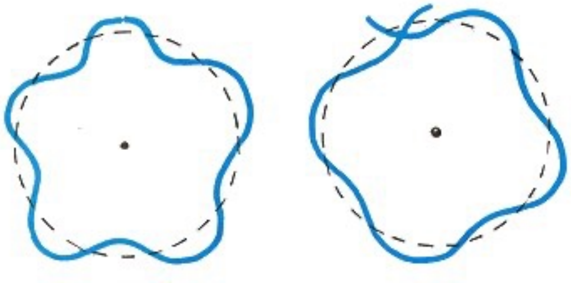
$$\boxed{\Delta E \Delta t \approx \hbar}$$

The last statement means that spectral lines cannot be perfectly sharp. This is called *natural broadening.*

Back to wave like properties of matter:

$$\lambda = \frac{h}{p}$$ de Broglie wavelength

Apply to hydrogen atoms:



If the number of wavelengths in an orbit is not an integer (right) that orbit is not allowed.

Bohr accounted for the structure of H atoms by postulating that e^- orbit in circular orbits with quantized angular momentum, $L = n\hbar$ and don't radiate, except when they jump from high to low *n* levels.

de Broglie (less ad hoc): radius e$^-$ orbit is not arbitrary, but must satisfy

$$2\pi r = n\lambda$$

$$\lambda = \frac{h}{p} = \frac{h}{m_e v}$$

$$\Rightarrow (2\pi)^2 r^2 = \frac{n^2 h^2}{m_e^2 v^2}$$

where m_e = e$^-$ mass, v = orbital velocity.

Balancing centripetal force & coulomb attraction:

$$\frac{m_e v^2}{r} = \frac{e^2}{4\pi\epsilon_0 r^2} \Rightarrow v^2 = \frac{e^2}{4\pi\epsilon_0 m_e r}$$

Substituting for v^2:

$$(2\pi)^2 r^2 = \frac{n^2 h^2}{m_e^2 e^2} \frac{4\pi\epsilon_0 m_e r}{e^2}$$

Then:

$$r = \frac{4\pi\epsilon_0}{m_e e^2}\left(\frac{h}{2\pi}\right)^2 n^2 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} n^2 = a_o \times n^2$$

where n = principal quantum number and a_0 is the Bohr radius.

(NB: C&O carefully do this with reduced mass, μ = 0.9994556 m_e. Close enough.They also use a different Bohr derivation, compare to above treatment.)

Notes about e^- orbits:

• What does r really mean? Does an e^- really "fall" from n_{high} to n_{low}, e.g., can we ever find it during its fall between levels?

• The e^- loses energy $\Delta E = E_{\rm high} - E_{\rm low}$, carried off by a single photon.

What is the energy of the e^- "orbits"?

$$E = \frac{1}{2}m_e v^2 - \frac{1}{4\pi\epsilon_0}\frac{e^2}{r}$$

$$\text{we know :} \quad m_e v^2 = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r}$$

$$\Rightarrow E = \frac{1}{2}\left(\frac{1}{4\pi\epsilon_0}\frac{e^2}{r}\right) - \frac{1}{4\pi\epsilon_0}\frac{e^2}{r} = -\frac{1}{2}\left(\frac{1}{4\pi\epsilon_0}\frac{e^2}{r}\right)$$

$$\text{since} \quad \mathrm{r} = 4\pi\epsilon_0 \mathrm{n}^2\left(\frac{\hbar^2}{\mathrm{m_e e^2}}\right)$$

$$\boxed{E = -\frac{m_e e^4}{32\pi^2\epsilon^2\hbar^2}\frac{1}{n^2} = -13.6\mathrm{eV}\frac{1}{n^2}}$$

Quantized energy of a hydrogen atom.

So energy of a photon produced by a "jump".

$$E_{photon} = E_{high} - E_{low}$$

leading to an expression for wavelengths:

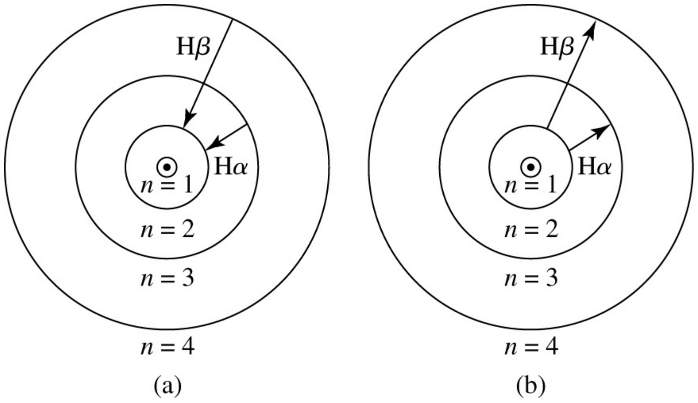
$$E_{photon} = \frac{hc}{\lambda} = \left(-\frac{m_e e^4}{32\pi^2\epsilon^2\hbar^2 n_{high}^2}\right) - \left(-\frac{m_e e^4}{32\pi^2\epsilon^2\hbar^2 n_{low}^2}\right)$$

$$\Rightarrow \frac{1}{\lambda} = \frac{m_e e^4}{64\pi^3\epsilon^2 c\hbar^3}\left(\frac{1}{n_{low}^2} - \frac{1}{n_{high}^2}\right)$$

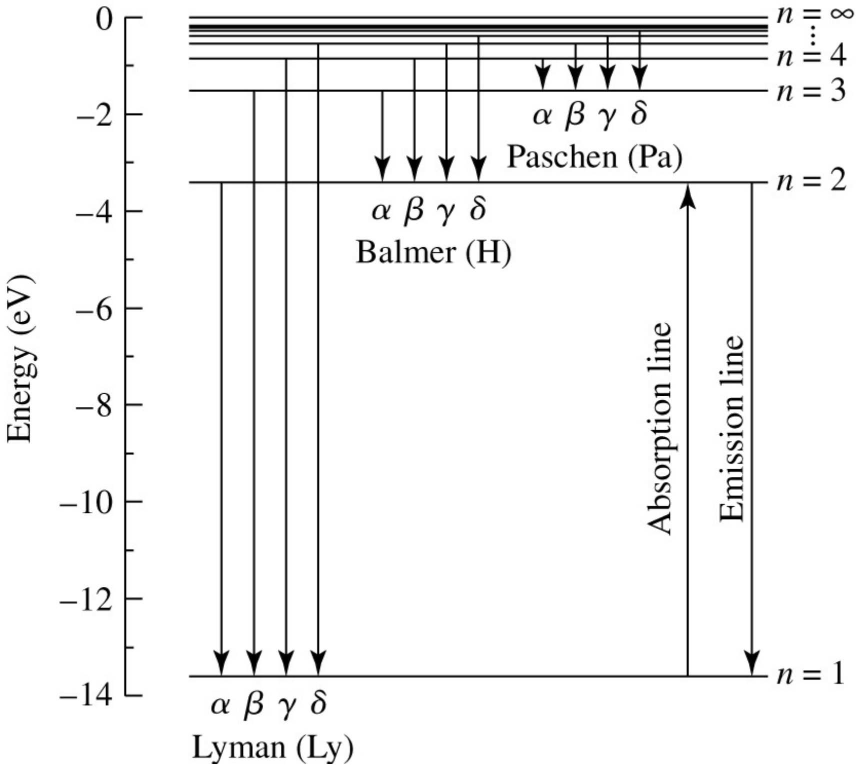
$$\text{or} \quad \frac{1}{\lambda} = R_H\left(\frac{1}{n_{low}^2} - \frac{1}{n_{high}^2}\right)$$

where R_H is the Rydberg constant for hydrogen.

H atom emission and absorption lines:



Series	n_{low}	n_{high}
Lyman	1	≥ 2 (UV)
Balmer	2	≥ 3 (Optical)
Paschen	3	≥ 4 (IR)
Brackett	4	≥ 5 (IR)
Pfund	5	≥ 6 (IR)



Key lines:

Lyα	(2->1)	121.6 nm
Hα	(3->2)	656.3nm
Hβ	(4->2)	486.1nm

Of course, we know that the Bohr model is not fully quantum mechanical - orbits are more like fuzzy clouds of probability.

Solution of the Schrödinger equation:

- same allowed energies as Bohr
- quantization of:
  - a) orbital angular momentum

$$L = \sqrt{l(l+1)}\hbar \quad l = 0, 1, 2, ...n-1 \quad (\text{not Bohr's } L = n\hbar)$$

  - b) *z* component of *L*

$$L_z = m_l \hbar \qquad\qquad m_l = 0, \pm 1, \pm 2, ... \pm l$$

  - c) spin angular momentum
    - Fermions: $m_s = \pm\frac{1}{2}$ e.g. e, p, n
    - Bosons: $m_s = \pm 1, 0$ e.g. photons

Fermions obey the Pauli exclusion principle:

No two fermions can occupy the exact same quantum state (completely defined by n, l, m_l, m_s).

The exclusion principle does not apply to photons, which can occupy the same quantum state, thus reinforcing wave like properties => visible macroscopically

The wave properties of fermions cannot reinforce => they wave "one at a time".

We will spend time on practical applications of quantum atom to stellar atmospheres, since the study of spectral lines yields info on:

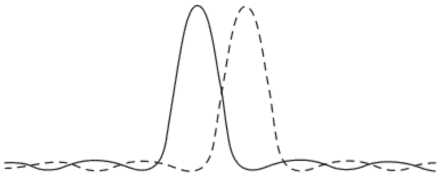
- composition
- temperature
- density
- pressure
- bulk motion
- rotation
- magnetic fields

A similar bonanza awaits for study of emission lines from HII regions, planetary nebulae, supernova remnants, AGN - anything with spectral lines!

Example: Resolving power of a lens.

From the wave theory of light, the smallest angle a telescope can resolve is

$$\theta_{\rm diff} \simeq 1.22\frac{\lambda}{D}$$



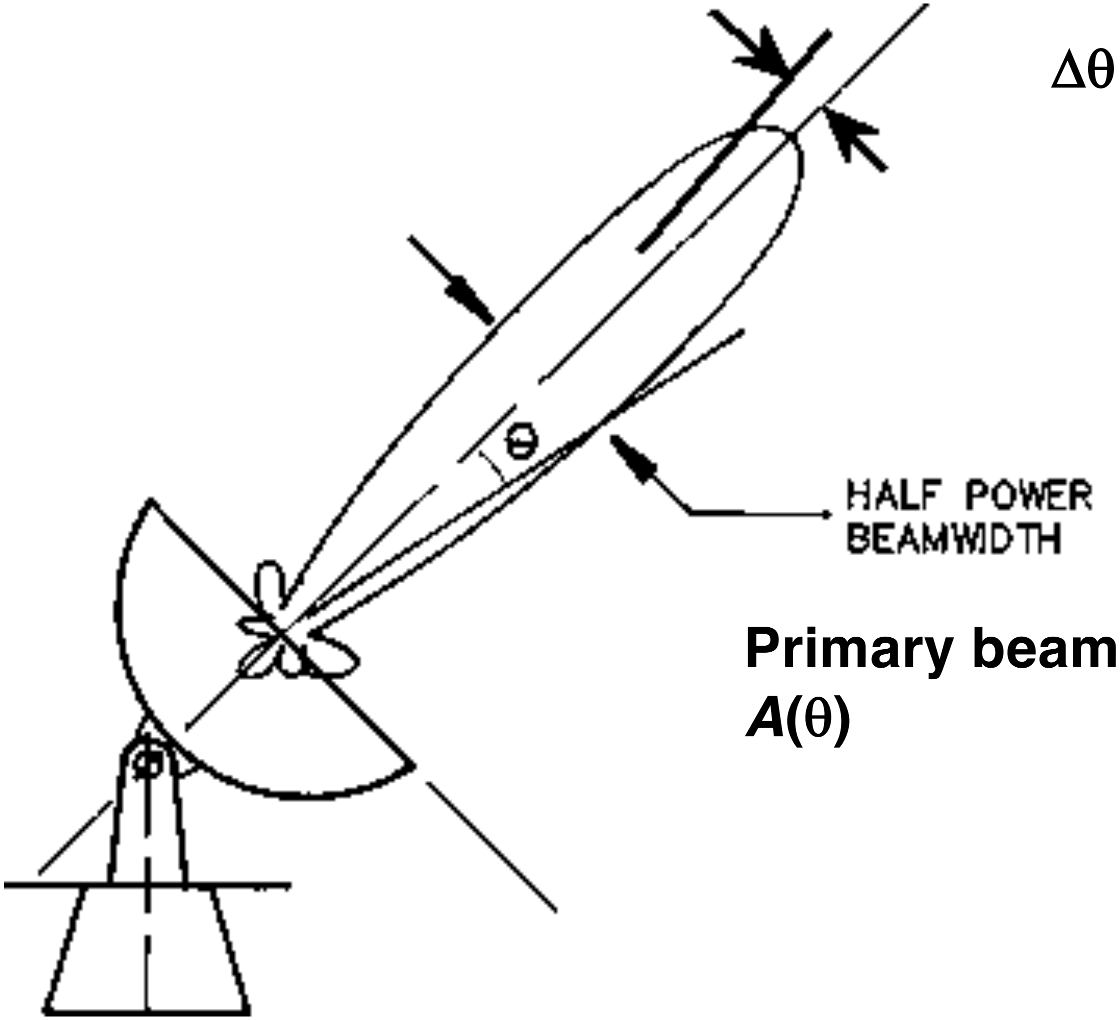
where *D* is the diameter of the telescope, and λ is the wavelength of the EM radiation.

We can derive this as a direct consequence of the uncertainty principle.

Antenna Beam Parameters

Pointing Accuracy

$\Delta\theta$ = rms pointing error



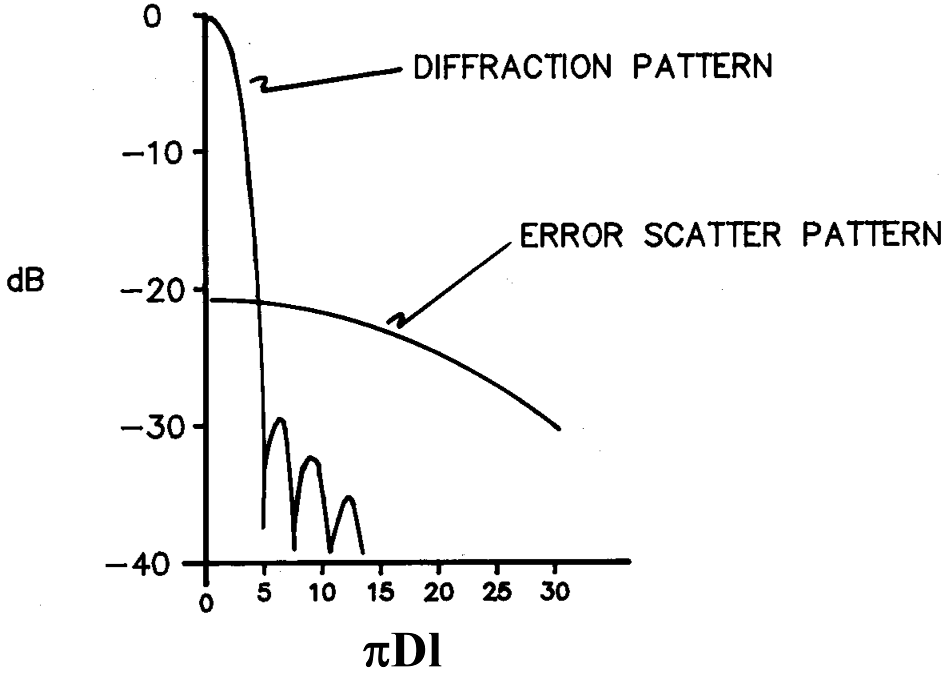
$\Delta\theta$

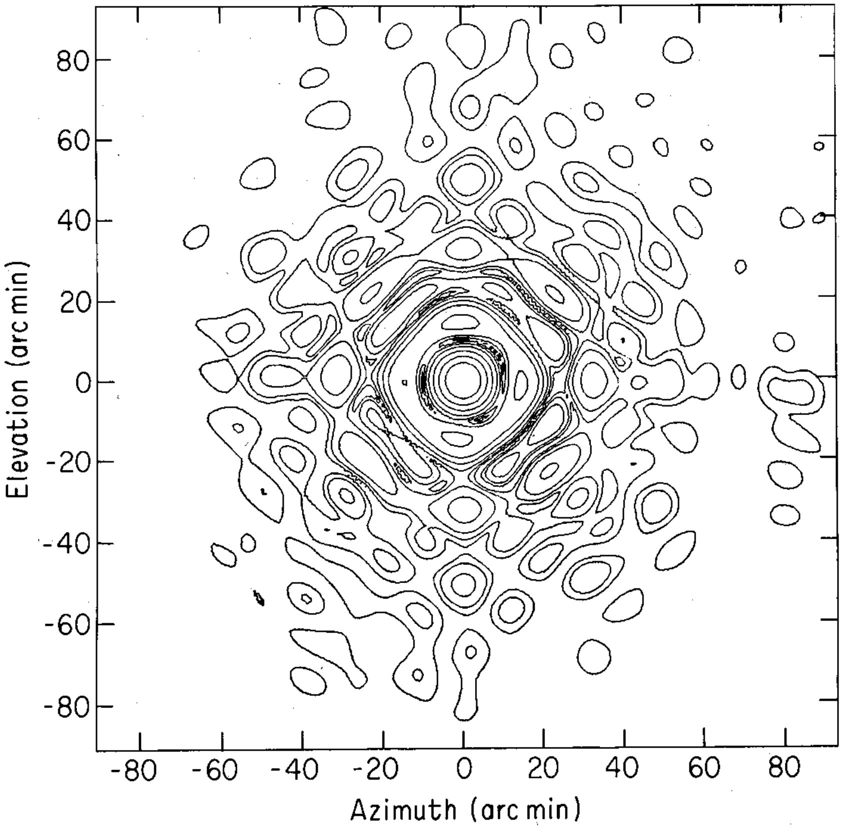
θ_{3dB}

Primary beam
A(θ)

Beam Pattern

Primary Beam





l=sin(θ), D = antenna diameter in wavelengths

contours:–3,–6,–10,–15,–20,–25, –30,–35,–40 dB

dB = 10log(power ratio) = 20log(voltage ratio)

For VLA: θ_{3dB} = 1.02/D, First null = 1.22/D