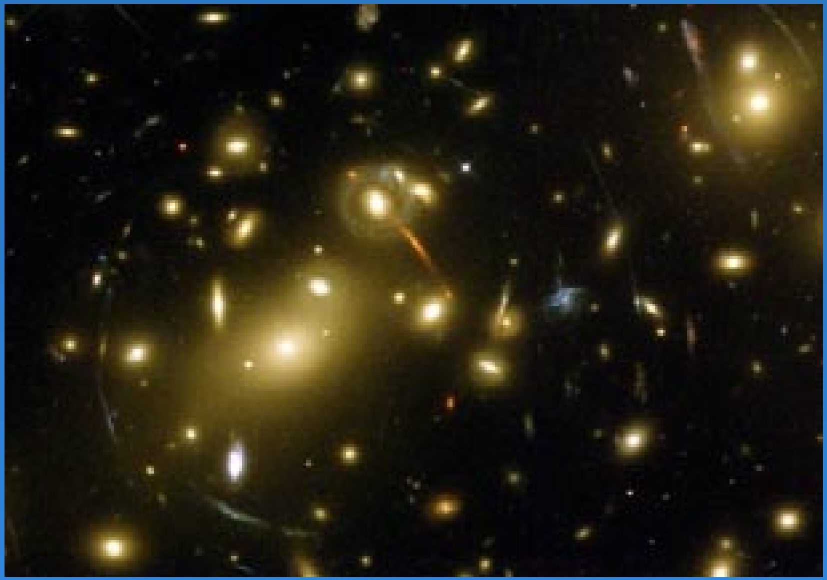


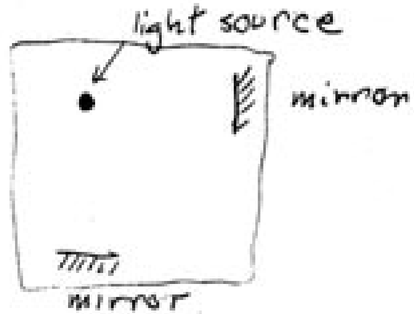
Astronomy 80 B: Light

Lecture 3: Light waves, light sources

8 April 2003

Jerry Nelson

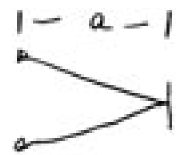
Measuring our speed through the ether



Michelson-Morley experiment
1887

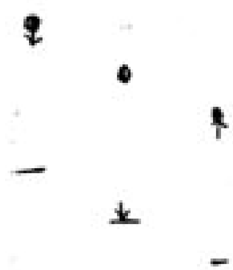
let v_e = our speed through aether
c = speed of light
a = distance to mirrors

$\perp$ path



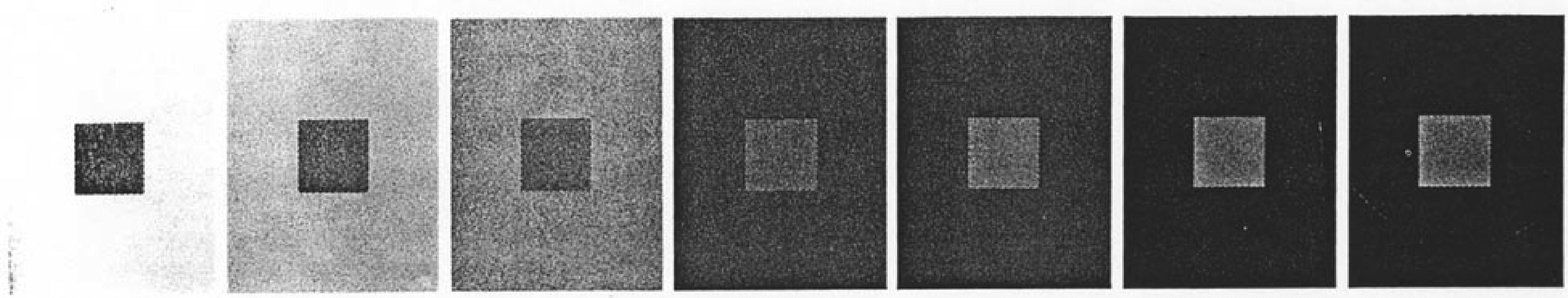
$$t_\perp = \frac{2a}{c}\frac{1}{\sqrt{1-\frac{v_e^2}{c^2}}}$$

$\parallel$ path



$$t_\parallel = \frac{2a}{c}\left(\frac{1}{1-\frac{v_e^2}{c^2}}\right)$$

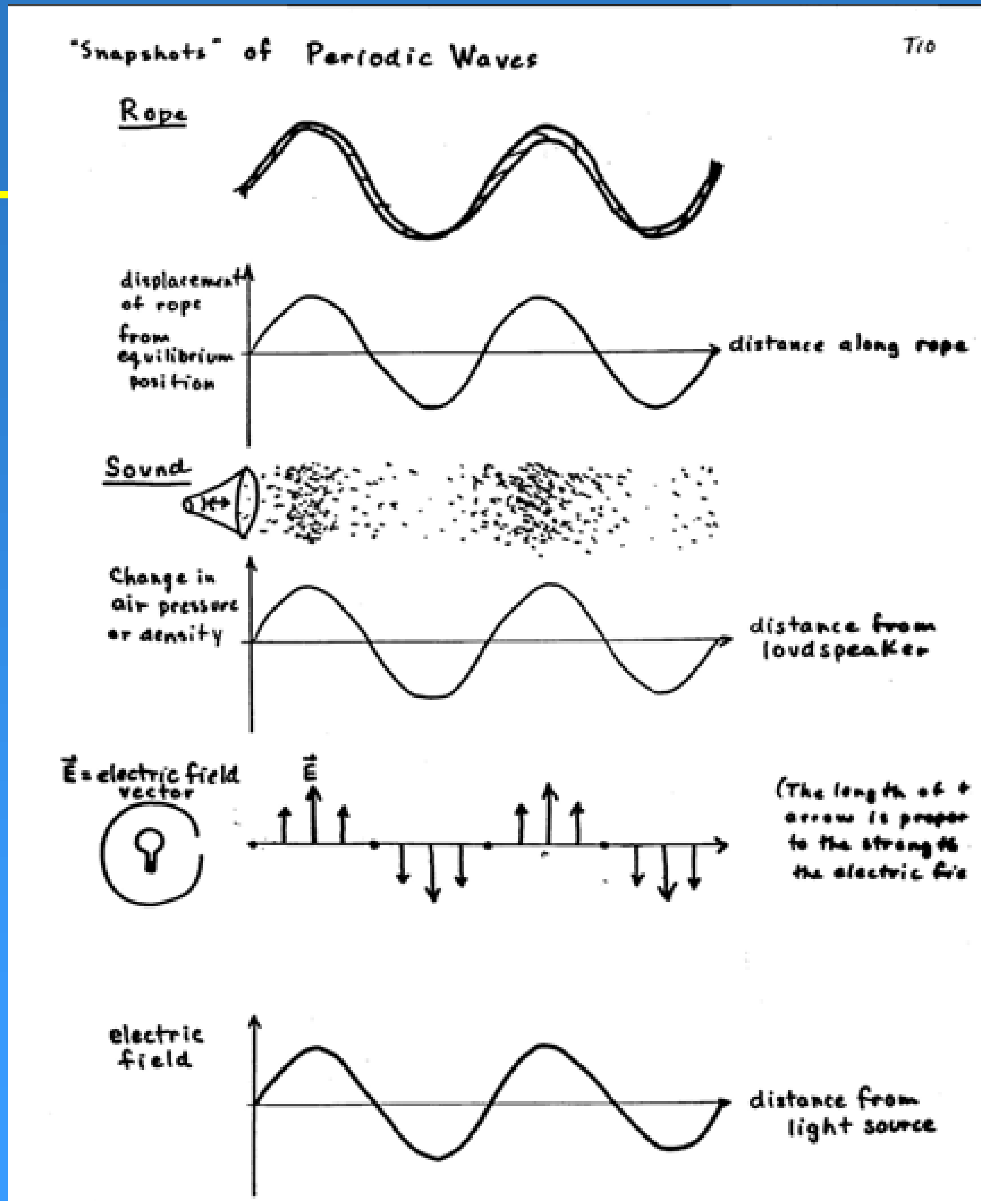
so $$\frac{t_\perp}{t_\parallel} = \sqrt{1-\frac{v_e^2}{c^2}}$$



Lightness contrast: The inner squares appear to vary in shade because the lightness of the surrounding squares varies.

Ideas of Light-3

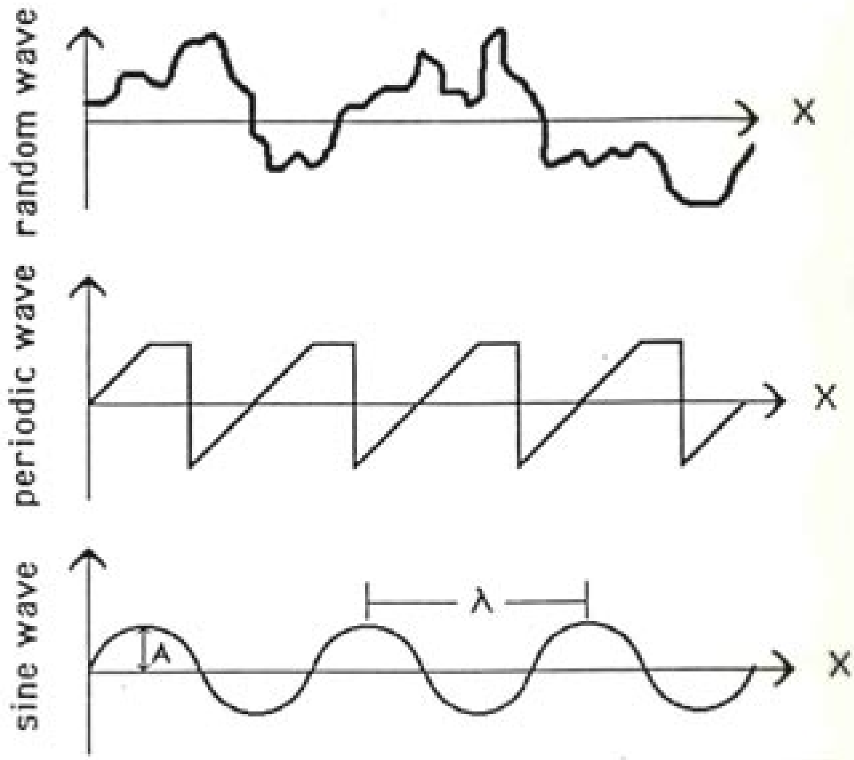
- **Modern model of light**
  - Quantum electrodynamics (QED) very complete but subtle model
  - has many wave characteristics
  - shaking electric charge causes undulations in electric field
  - has particle characteristics
  - photoelectric effect
  - light carries specific amount of energy (photons)
  - Wants to get to destination as quickly as possible (principle of least time)
  - Non deterministic theory: express results as probabilities
- **no known violations to its predictions**



"Snapshots" of Periodic Waves
T10
Rope
displacement of rope from equilibrium position
distance along rope
Sound
Change in air pressure or density
distance from loudspeaker
E = electric field vector
E
(The length of the
arrow is propor
to the strength
the electric fie
electric field
distance from light source

$c = \lambda f$

<u>"Snapshots" of sample waves</u>



$f = \nu = 1/\tau$

A = amplitude

λ = wavelength [meters]

ν = frequency [Hz, osc/sec, 1/sec]

τ = period [sec]

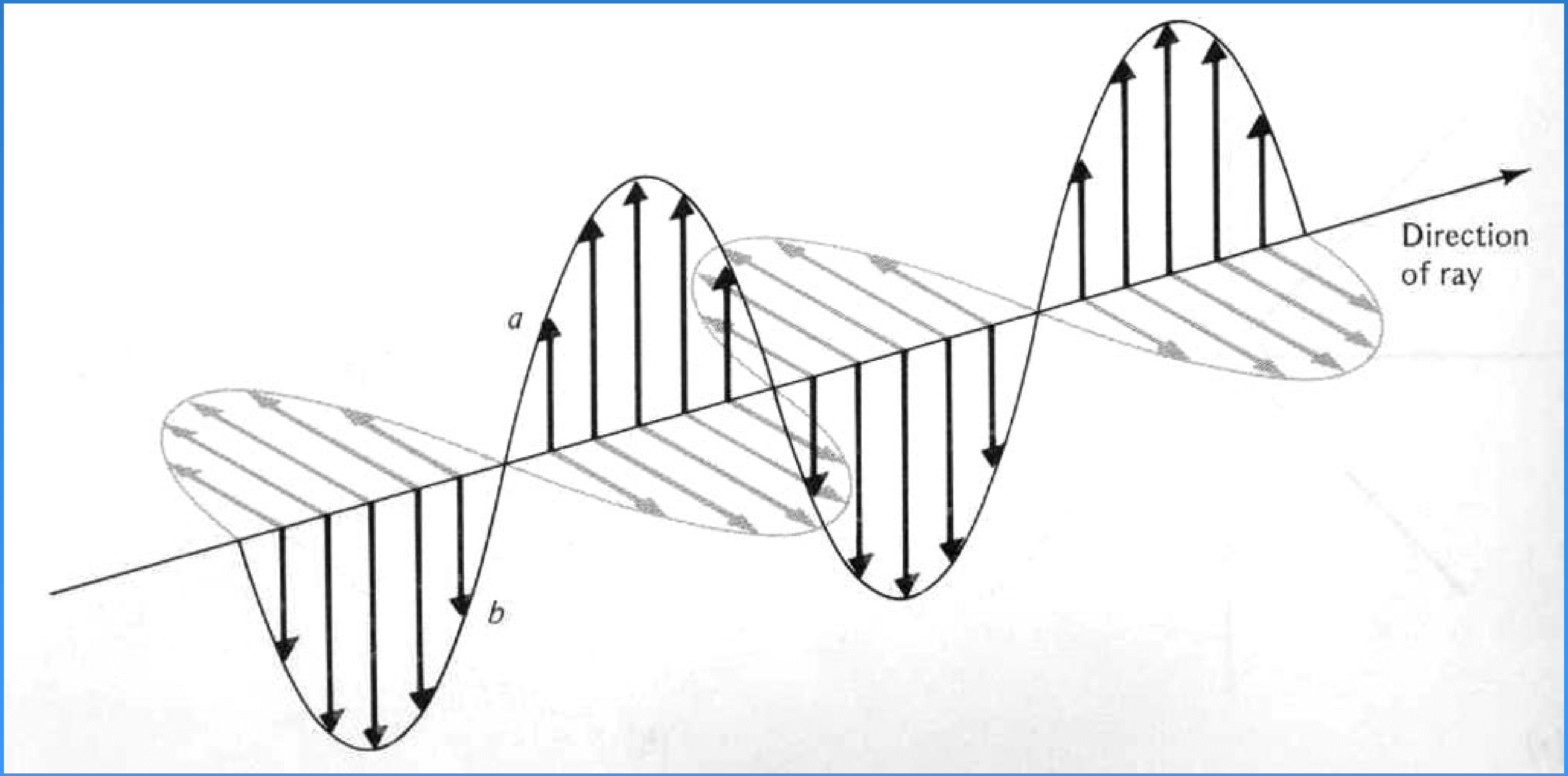
v = velocity [m/s, miles/s]

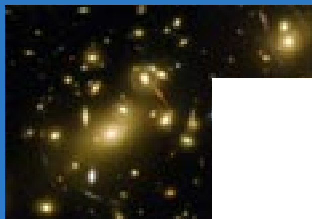
$v = \lambda\nu$

1.3

$d = vt, \quad v = \frac{d}{t} = \frac{\lambda}{\tau} = \lambda f = \lambda \nu$

Electromagnetic wave





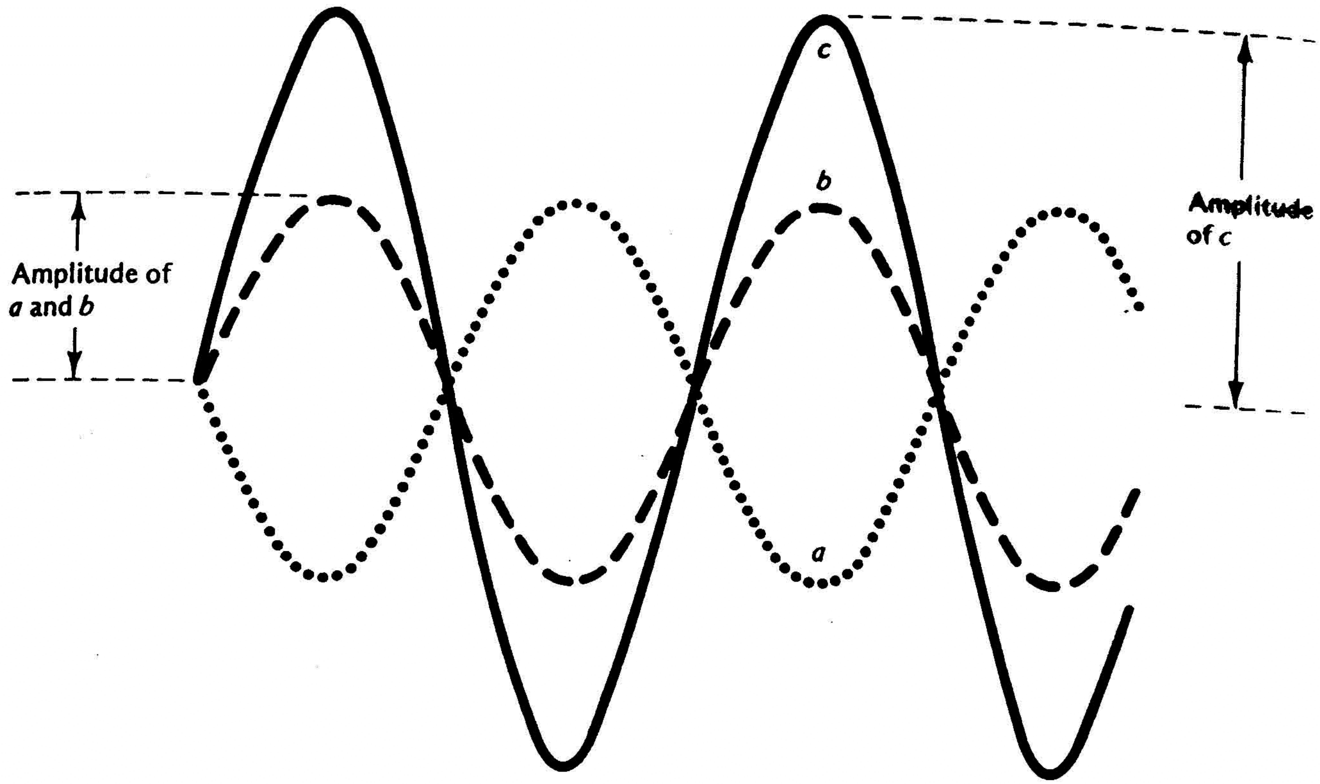
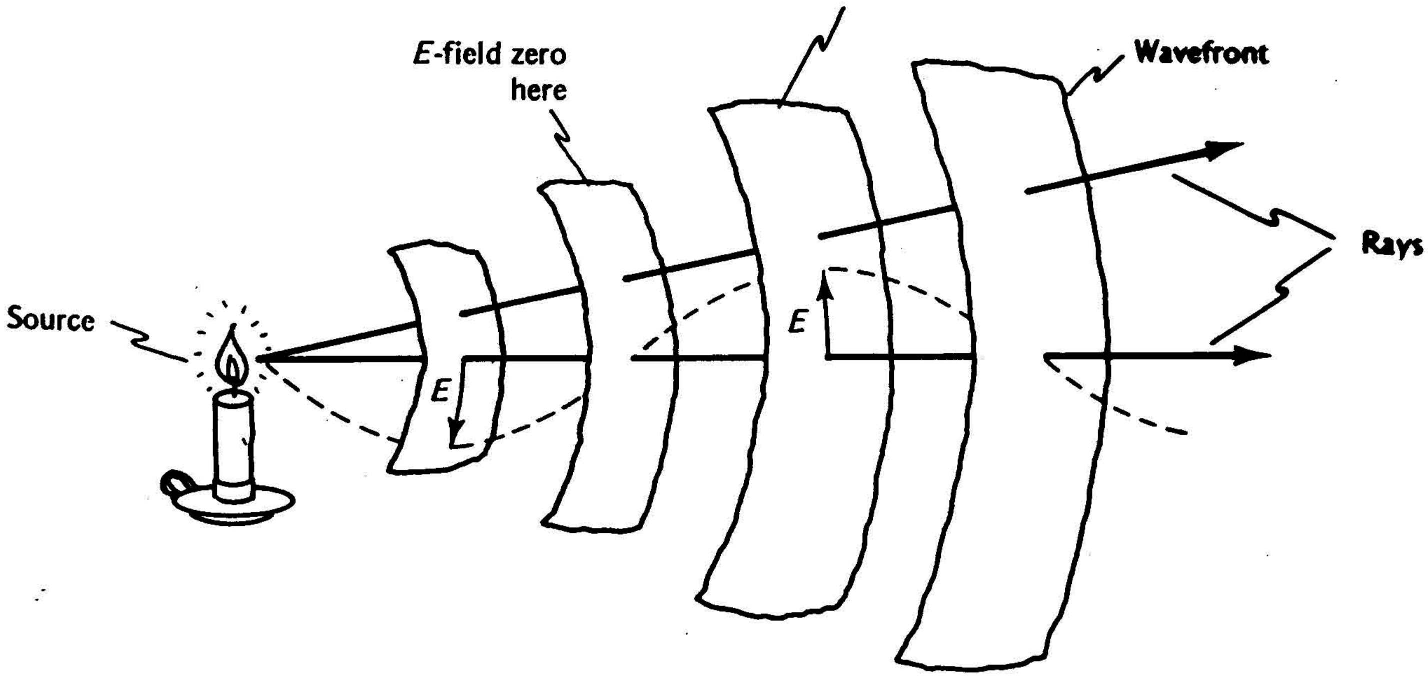


FIGURE 1.16

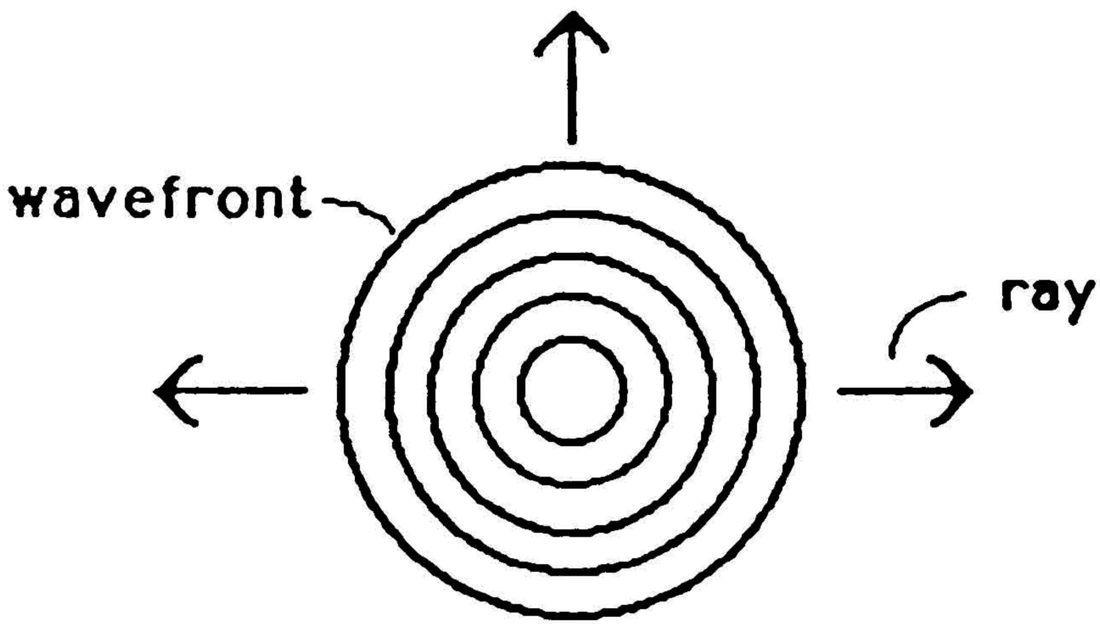
Three waves of different amplitudes and phases.

FIGURE 1.17

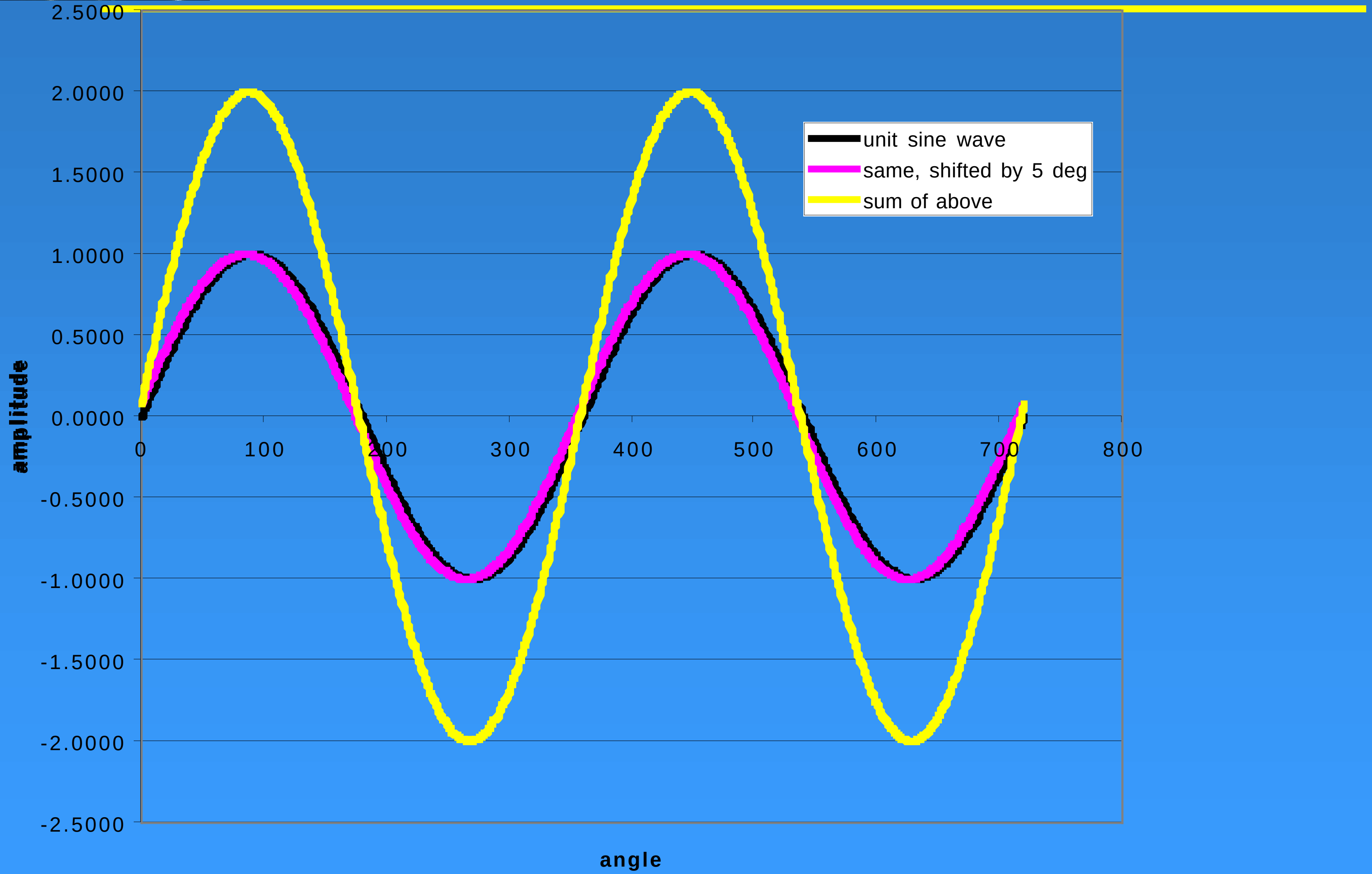
A snapshot of a wave traveling away from a small source showing the wavefronts. The rays are also marked. (Real candlelight is unpolarized.)



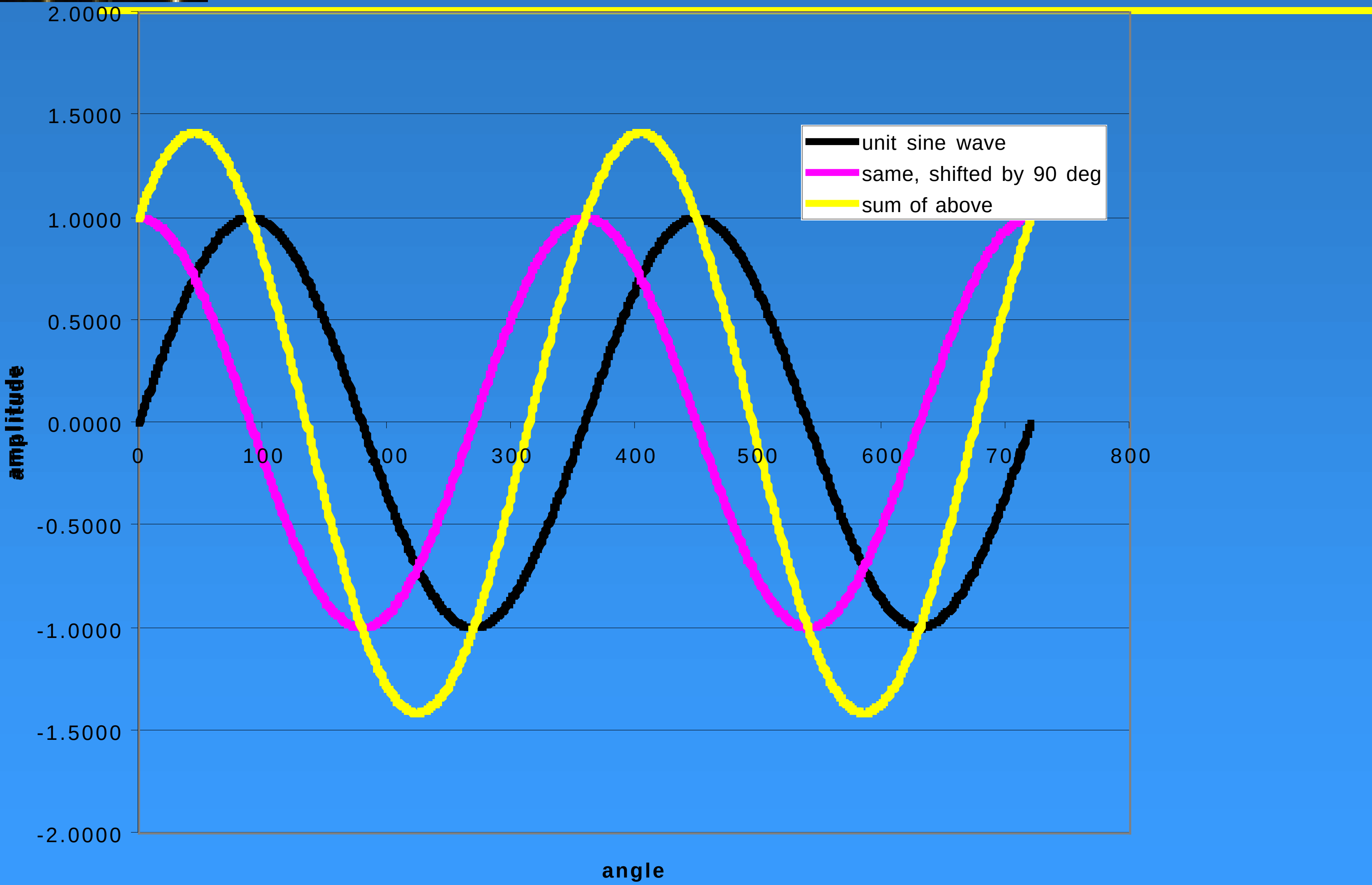
Wavefronts and rays



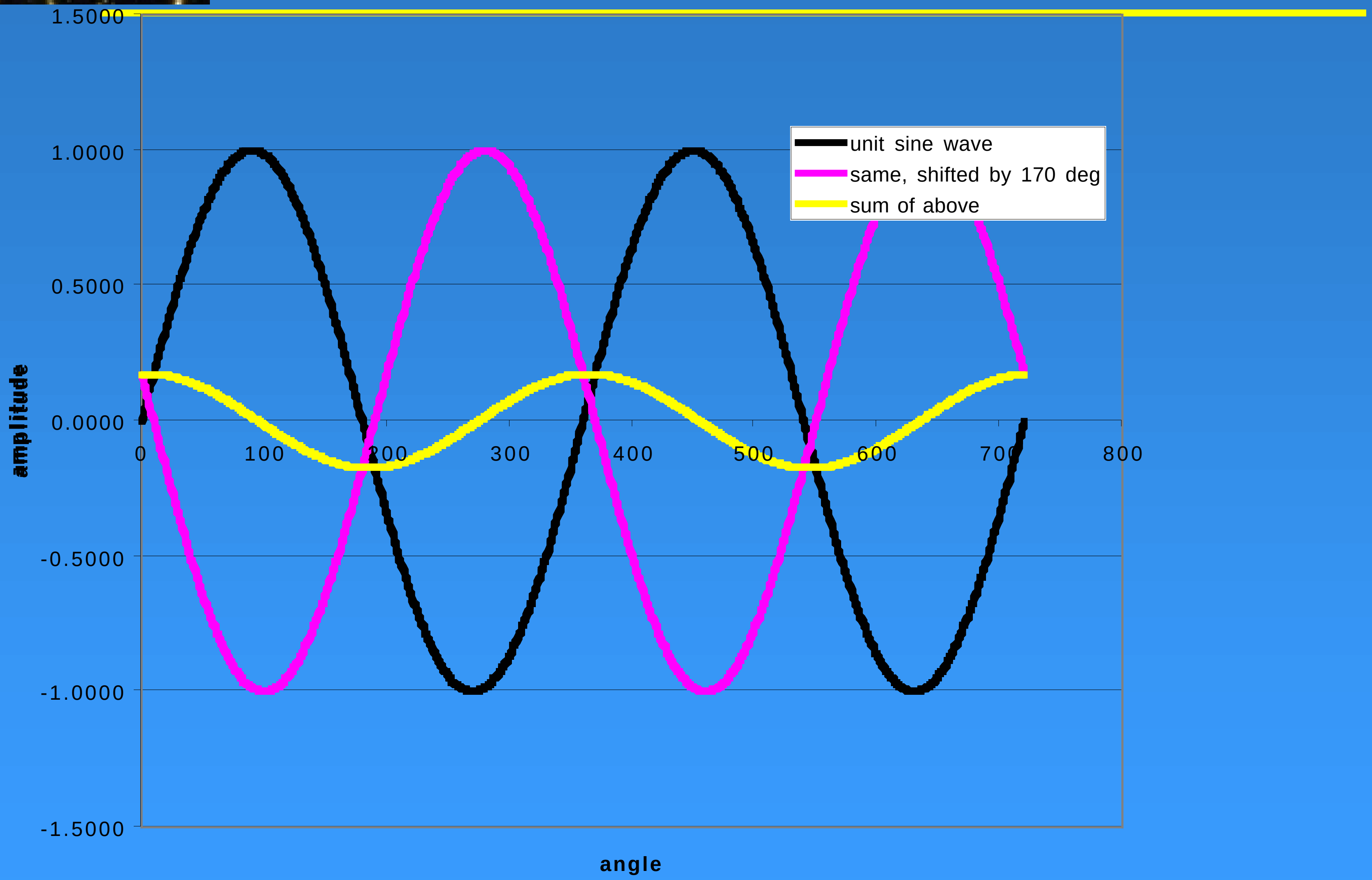
Adding sine waves



Adding sine waves



Adding sine waves



Demos

- **Demo of waves on overhead**
  - Wire machine
  - Moire pattern

Wave Nature of Light

- **Waves in general**
  - Have a wavelength λ
  - Have a frequency f
  - Have a speed c
  - $f\lambda = c$
- **This is true for sound waves, water waves, light waves**
  - Examples:
  - Visible light has $\lambda = 500$ nm, so $f = c/\lambda = 3\text{x}10^8$ m/s / $500\text{x}10^{-9}$ m $= 6\text{x}10^{14}$ /s $= 6\text{x}10^{14}$ Hz
  - FM radio has f = 100 MHz = $1\text{x}10^8$ Hz
  - Or $\lambda = c/f = 3\text{x}10^8$ m/s / $1\text{x}10^8$ /s = 3m wavelength

Wave Nature of Light-2

- **Waves can interfere with each other**
  - Wave amplitudes add if they are in the same place
  - Details of the "addition" depend on the relative phases
  - Interference can be constructive (add in phase)
  - Interference can be destructive (add out of phase)

Brief History of Understanding of Light, color, optics, vision

- **Date** **Person** **Contribution**
- **Classical**
  - 250 BC Euclid — Greek mathematician: law of rectilinear propagation; law of reflection
  - 100 BC Hero — Greek scientist: principle of shortest path; law of reflection
  - 100-170 Claudius Ptolemy — Greek astronomer: approx. law of refraction; additive color mixing
  - 965-1039 Alhazen — Middle East scientist: sources illuminate objects; optics of eye; camera obscura

Brief History of Understanding of Light, color, optics, vision-2

- **Date Person Contribution**
- **Middle Ages and Renaissance:**
  - 1266?-1337 Giotto — emphasis on realism stimulate
    Florentine painter — an interest in perspective and optics
  - 1401-1428? Masaccio — perspective painter
    Italian
  - 1377?-1446 Brunelleschi — perspective painter, architect
    Italian
  - 1495-1575 Francesco Maurolico — recognized role of lens in eye
    Benedictine monk — for causing rays to converge
  - 1452-1519 Leonardo da Vinci — pinhole camera
    Italian painter
  - 1564-1642 Galileo Galilei — telescope, speed of light
    Italian scientist

Brief History of Understanding of Light, color, optics, vision-3

- **Date Person Contribution**
- **Middle Ages and Renaissance:**
  - 1571-1630 Johannes Kepler, German astronomer — approx. law of refraction, theory of lenses
  - 1591-1626 Willebrord Snell, Dutch mathematician — measured law of refraction
  - 1596-1650 Rene Descartes, French philosopher — law of refraction, particle model
  - 1601-1655 Pierre de Fermat, French — principle of least time, particle model
  - 1642-1727 Isaac Newton, English scientist — particle model, color, refraction, interference
  - 1644-1710 Olaf Römer, Danish astronomer — speed of light measurement

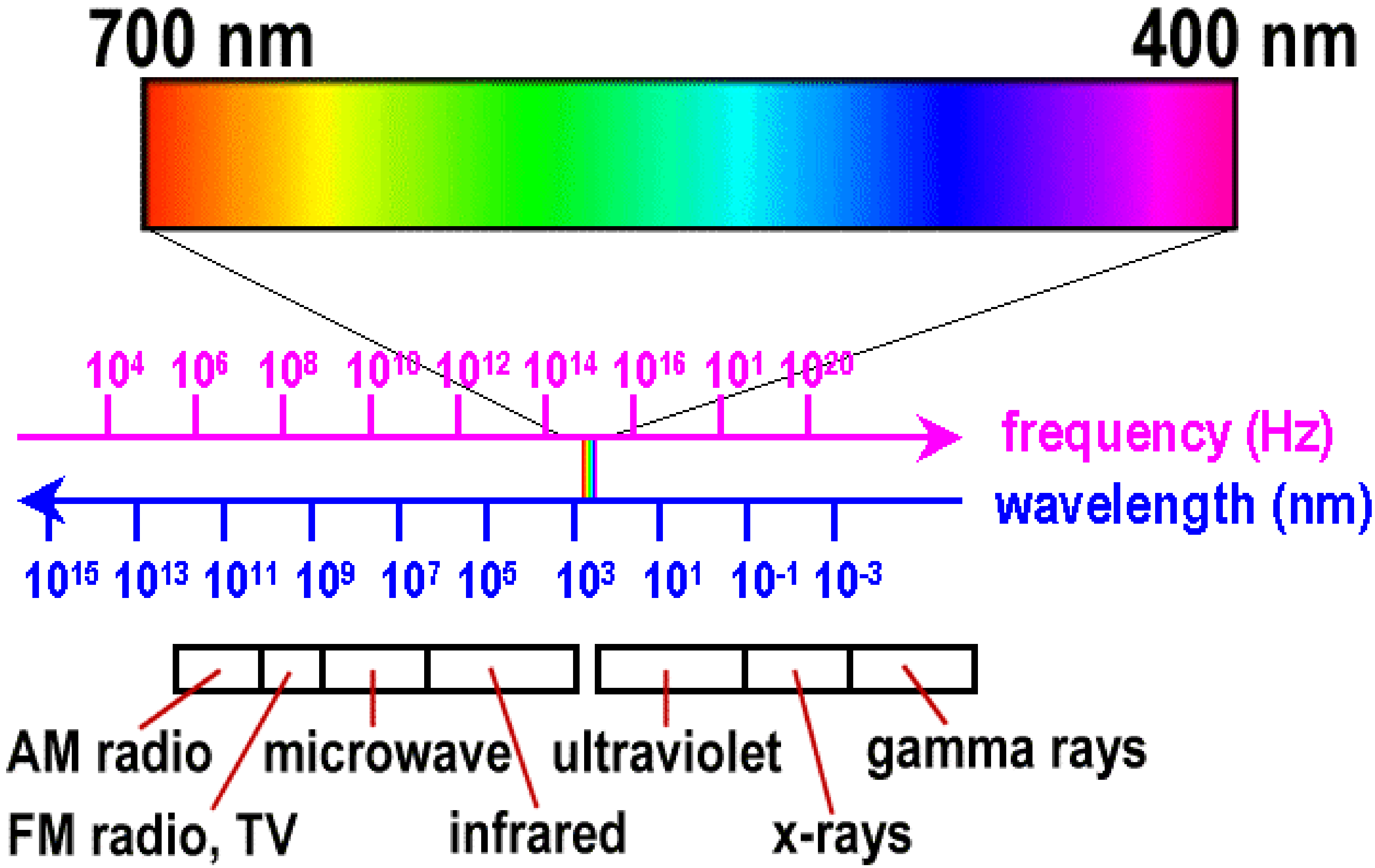
Brief History of Understanding of Light, color, optics, vision-4

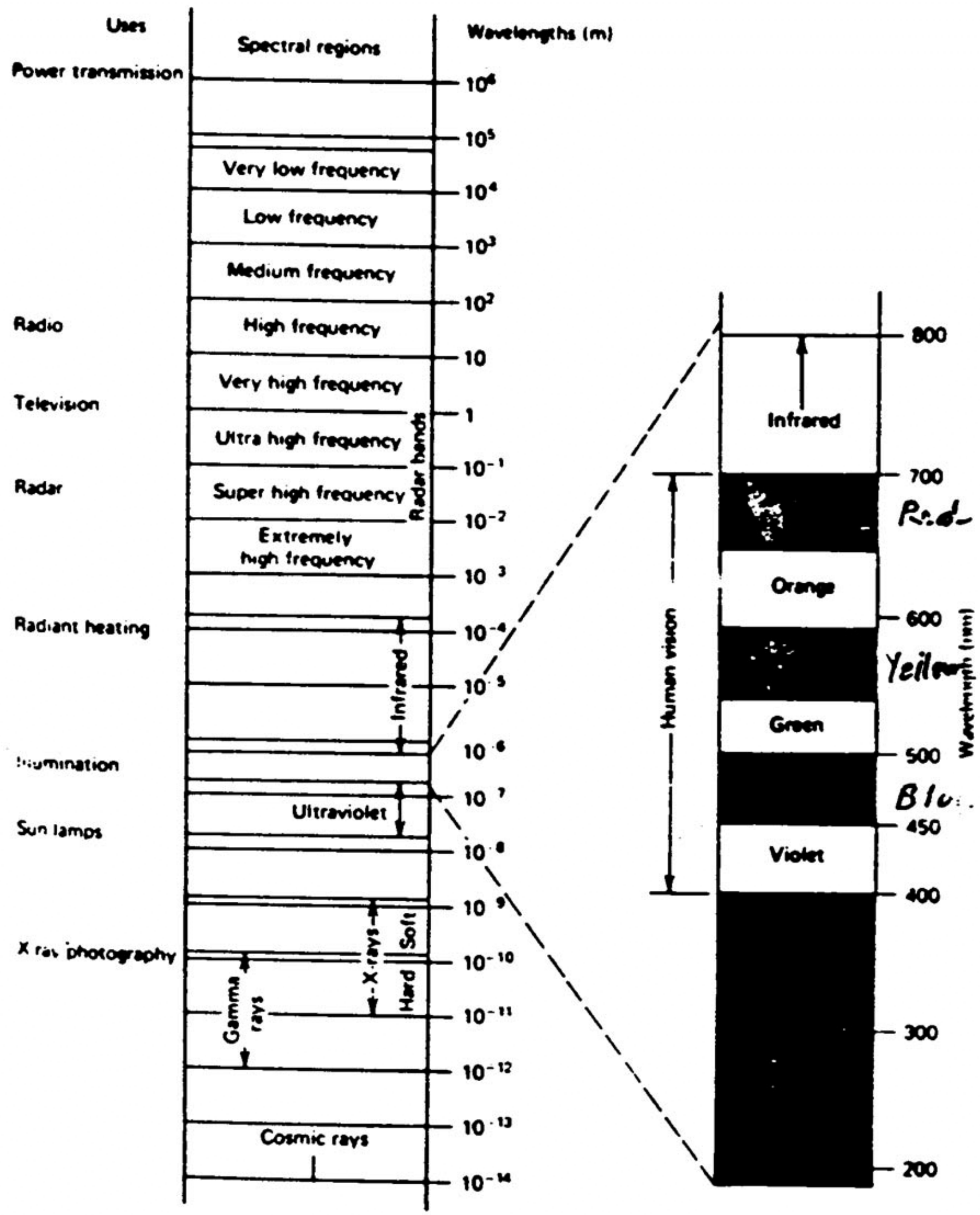
Date	Person	Contribution
Wave nature of Light		
1618-1663	Francesco Grimaldi Italian scientist	wave theory of light
1635-1703	Robert Hooke English physicist	wave theory of light
1629-1695	Christian Huygens Dutch physicist	wave theory of light
1773-1829	Thomas Young English physicist	interference
1788-1827	Augustin Fresnel French physicist	diffraction
1787-1826	Joseph von Fraunhofer German physicist	diffraction

Brief History of Understanding of Light, color, optics, vision-5

- **Wave nature of Light and modern theory**

Date	Person	Contribution
1821-1894	Hermann Helmholtz German physiologist	wave theory, color mixing physiological optics
1831-1879	James Clerk Maxwell Scottish physicist	science of colorimetry first color photograph theory of electromagnetism
1858-1947	Max Planck German physicist	proposed electromagnetic energy is quantized
1879-1955	Albert Einstein German physicist (US citizen >1940)	deduced that energy of photon is proportional to its frequency
1918-1988	Richard Feynman	Quantum electrodynamics

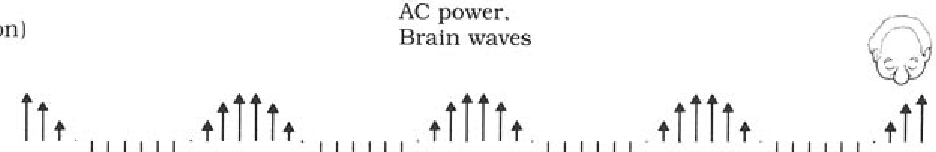

700 nm
400 nm
10^{4} 10^{6} 10^{8} 10^{10} 10^{12} 10^{14} 10^{16} 10^{1} 10^{20}
frequency (Hz)
wavelength (nm)
10^{15} 10^{13} 10^{11} 10^{9} 10^{7} 10^{5} 10^{3} 10^{1} 10^{-1} 10^{-3}
AM radio
microwave
ultraviolet
gamma rays
FM radio, TV
infrared
x-rays

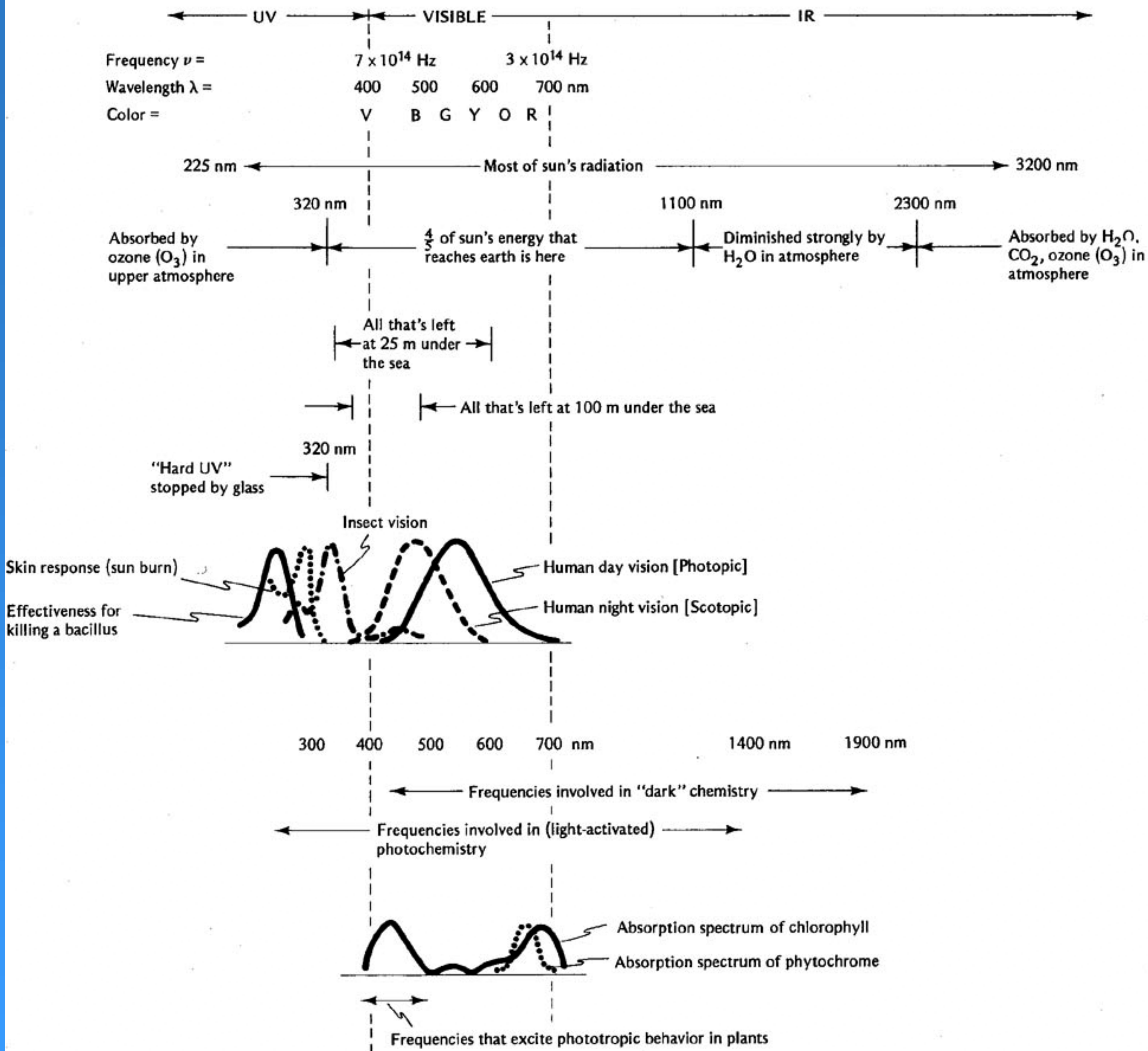


Uses
Spectral regions
Wavelengths (m)
Power transmission
Very low frequency
Low frequency
Medium frequency
High frequency
Radio
Very high frequency
Television
Ultra high frequency
Radar
Super high frequency
Radar bands
Extremely high frequency
Radiant heating
Infrared
Illumination
Ultraviolet
Sun lamps
X ray photography
X-rays
Soft
Hard
Gamma rays
Cosmic rays
10⁶
10⁵
10⁴
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
Infrared
Human vision
Orange
Green
Violet
Wavelength (nm)
800
700
600
500
450
400
300
200

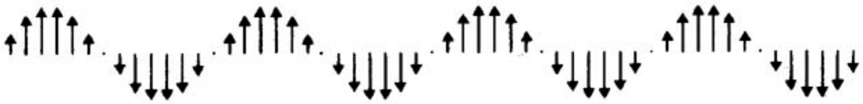
TABLE 1.1 *Electromagnetic radiation*

Detected by	*Frequency in hertz*	*Wavelength in meters*	*Name*	*Examples of use*
Photon counters; Photographic emulsion	10^{23}	10^{-15} (size of nucleus)		
	10^{22}			
	10^{21}		Gamma rays	
	10^{20}			Cancer treatment
Photocells	10^{19}			
	10^{18}	10^{-10} = 1 Å (size of atom)	X-rays	Materials testing Medical x-rays
	10^{17}			
	10^{16}		Ultraviolet (UV)	Atomic structure
Human eye	10^{15}			Germicidal "Black light," sun tan
Thermal detectors	10^{14}	10^{-6} = 1 μm (diameter of bacteria)	Visible	OPTICS IR photos, heat lamps
	10^{13}			"Heat rays," forest fire detection
	10^{12}		Infrared (IR)	Molecular structure, human body radiation
	10^{11}			
	10^{10}	10^{-2} = 1 cm (size of a mouse)	Microwave	Atomic clocks, Space research
Tuned circuits	10^{9}			Radar, microwave ovens (3×10^9 hertz)
	10^{8}	10^{0} = 1 m (size of a man)		Radio astronomy TV, UHF: 470–890 MHz, VHF: 54–216 MHz, FM: 88–108 MHz
	10^{7}			International shortwave
	10^{6}		Radio frequency (RF)	CB:27 MHz AM radio broadcast: 550–1600 kHz
	10^{5}	10^{3} = 1 km (size of a village)		Longwave broadcast
	10^{4}			Long-range navigation
	10^{3}	10^{6} (distance from Washington, D.C. to Chicago)		
	10^{2}		Audio frequency	
	10	10^{8} (distance to moon)		AC power, Brain waves

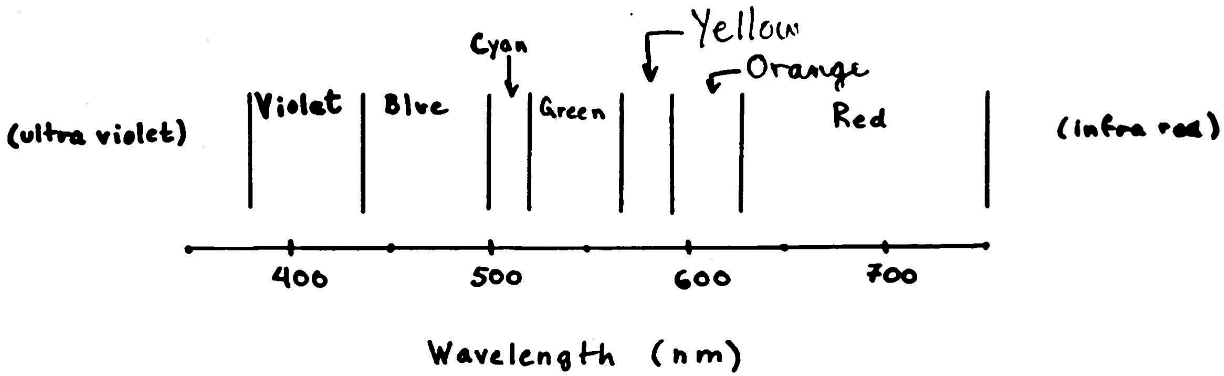




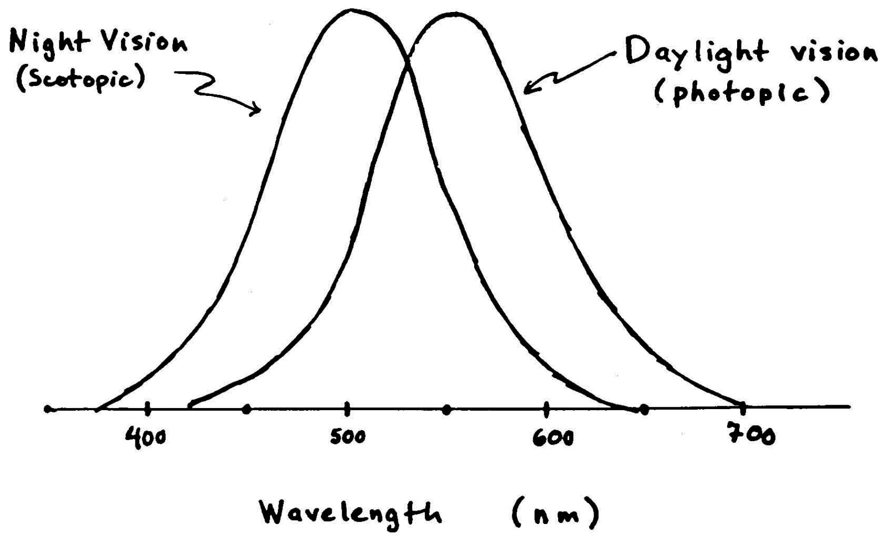
UV
VISIBLE
IR
Frequency ν =
7 x 10[14] Hz
3 x 10[14] Hz
Wavelength λ =
400 500 600 700 nm
Color =
V B G Y O R
225 nm
Most of sun's radiation
3200 nm
320 nm
1100 nm
2300 nm
Absorbed by ozone (O3) in upper atmosphere
4/5 of sun's energy that reaches earth is here
Diminished strongly by H2O in atmosphere
Absorbed by H2O, CO2, ozone (O3) in atmosphere
All that's left at 25 m under the sea
All that's left at 100 m under the sea
320 nm
"Hard UV" stopped by glass
Insect vision
Skin response (sun burn)
Effectiveness for killing a bacillus
Human day vision [Photopic]
Human night vision [Scotopic]
300 400 500 600 700 nm
1400 nm
1900 nm
Frequencies involved in "dark" chemistry
Frequencies involved in (light-activated) photochemistry
Absorption spectrum of chlorophyll
Absorption spectrum of phytochrome
Frequencies that excite phototropic behavior in plants



Visible Light



Relative Sensitivity Curves for Daylight and Night Vision



Review of wave properties of light

– light has a wavelength λ
– light has a frequency f
– light has a velocity c (c = 299,792,500 m/s)
– or 300,000,000 m/s
– or 3×10^8 m/s,
– or 186,000 miles/s

- **$\lambda \cdot f = c$**

– examples:
– if λ = 1m, f = 3×10^8 Hz
– if λ = 1mm, f = 3×10^{11} Hz
– if λ = 1000 nm f = 3×10^{14} Hz
– (10^{-6} m)

– if f = 2×10^3 Hz λ = 150,000 m = 1.5×10^5 m

Review of wave properties of light-2

- **if we change c, such as occurs in transparent materials, then the wavelength will change.**
  - **Continuity requires that the frequency does not change**
  - if $c = 2x10^8$ m/s (approximate speed in glass)
  - then if $f = 3x10^{14}$ Hz, $\lambda = c/f = 6.7x10^{-7}$ m or 670 nm

- **Given the idea of waves, the energy carried by a wave is proportional to the square of its amplitude**

Review of particle properties of light

- **light behaves as though it occurs in discrete lumps (photons)**
  - The energy of a photon is given by
    - $E = h \cdot f$ or $E = hc/\lambda$
    - where h = Planck's constant
      6.63×10^{-34} Joule-seconds
      4.14×10^{-15} eV-seconds
  - an eV is the energy an electron gains falling through a voltage of 1 Volt.
  - examples:
    - $\lambda = 500$ nm E = 3.98×10^{-19} Joules
      2.48 eV
    - E = 1eV $\lambda =$ 1.24 microns
      1.24×10^{-6} m
      1240 nm

Review of particle properties of light-2

– Sunlight power is about 1000W/m^2 How many photons /s does this represent? Assume most of the light is at visible wavelengths of 500 nm. A Watt is 1 Joule/s.

– $N = P/E = P\lambda/hc = 10^3 \cdot 500\times10^{-9} / (6.63\times10^{-34} \cdot 3\times10^8)$

– $= 2.5\times10^{21}$ photons/m^2/s

Sources of Light

- **Black bodies**
  - Stars
  - the Sun
  - molten lava
  - blast furnaces
  - the moon?
  - the blue sky?
- **Chemical combustion**
  - wood fire
  - candles
  - alcohol fire
  - blowtorch
  - gas mantle lantern

Sources of Light-2

- **Electrical sources**
  - lightning
  - incandescent lights (tungsten filament)
  - carbon arc
  - discharge lamps (mercury vapor, sodium)
  - fluorescent lights (mercury vapor + phosphor coating)
  - high intensity discharge lamps (high pressure)
  - lasers
  - phosphors from TV set (electron bombardment)
- **Biological**
  - fireflies
  - some fish

Black Body Radiation

- **A “black body” is an object that completely absorbs any radiation that falls on it.**
  - Objects that appear black to us are good candidates, but our eyes only see in certain wavelength ranges, so its not foolproof. Copper is a good black body (its black in the infrared).
  - Black bodies with finite temperature radiate away their thermal energy by giving off radiation.
    - $F = \sigma T^4$ (Watts/m^2)

      F = radiant flux from black body (Watts/m^2

      σ (Stefan - Boltzmann constant) = 5.68×10^{-8} Watts/m^2/K^4

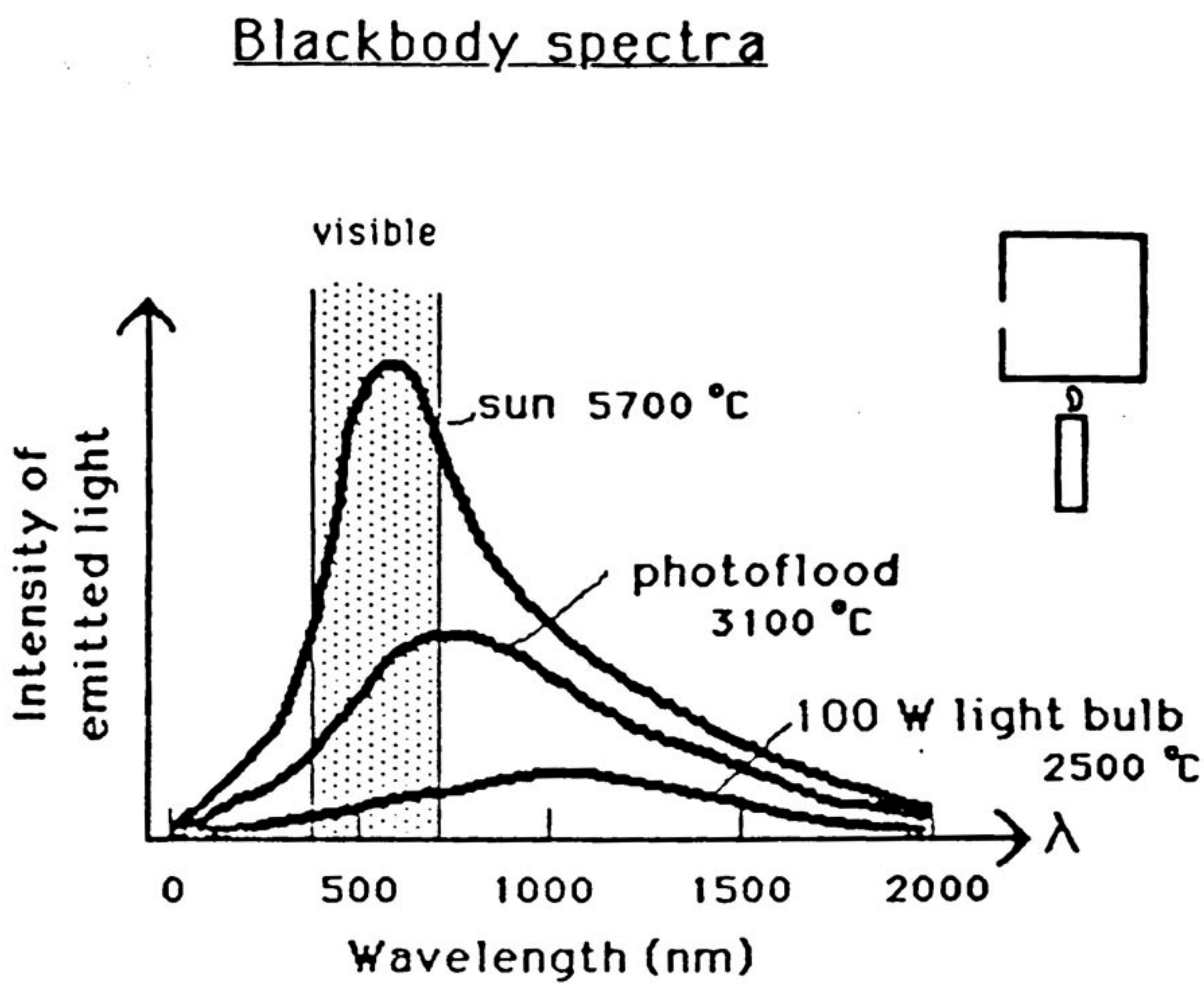
      T = Temperature (°K)

      Also, the wavelength carrying the most power * the temperature, is a constant!

      $\lambda_{max} T_{BB}$ = constant = 2.9×10^{-3} m·K

Black Body Radiation-2

- **example: Our bodies (A = 2m^2, T = 300°K) radiate**
  - $P = 2*\sigma*T^4 = 920$ W.
  - They radiate most profusely at $\lambda_{max} = 9.6\ \mu m$
  - Fortunately, our bodies also absorb radiant energy from the environment, so the net heat loss is usually small.
  - Suppose our environment is 10°C colder than our bodies
    - Then power absorbed is
    - $P = 2*\sigma*T^4 = 803$ W
    - Thus the net power we would need to generate to maintain our body temperature is 117W (or about 2400 kcal/day)



Blackbody spectra
visible
sun 5700 °C
photoflood
3100 °C
100 W light bulb
2500 °C
Intensity of
emitted light
0
500
1000
1500
2000
λ
Wavelength (nm)

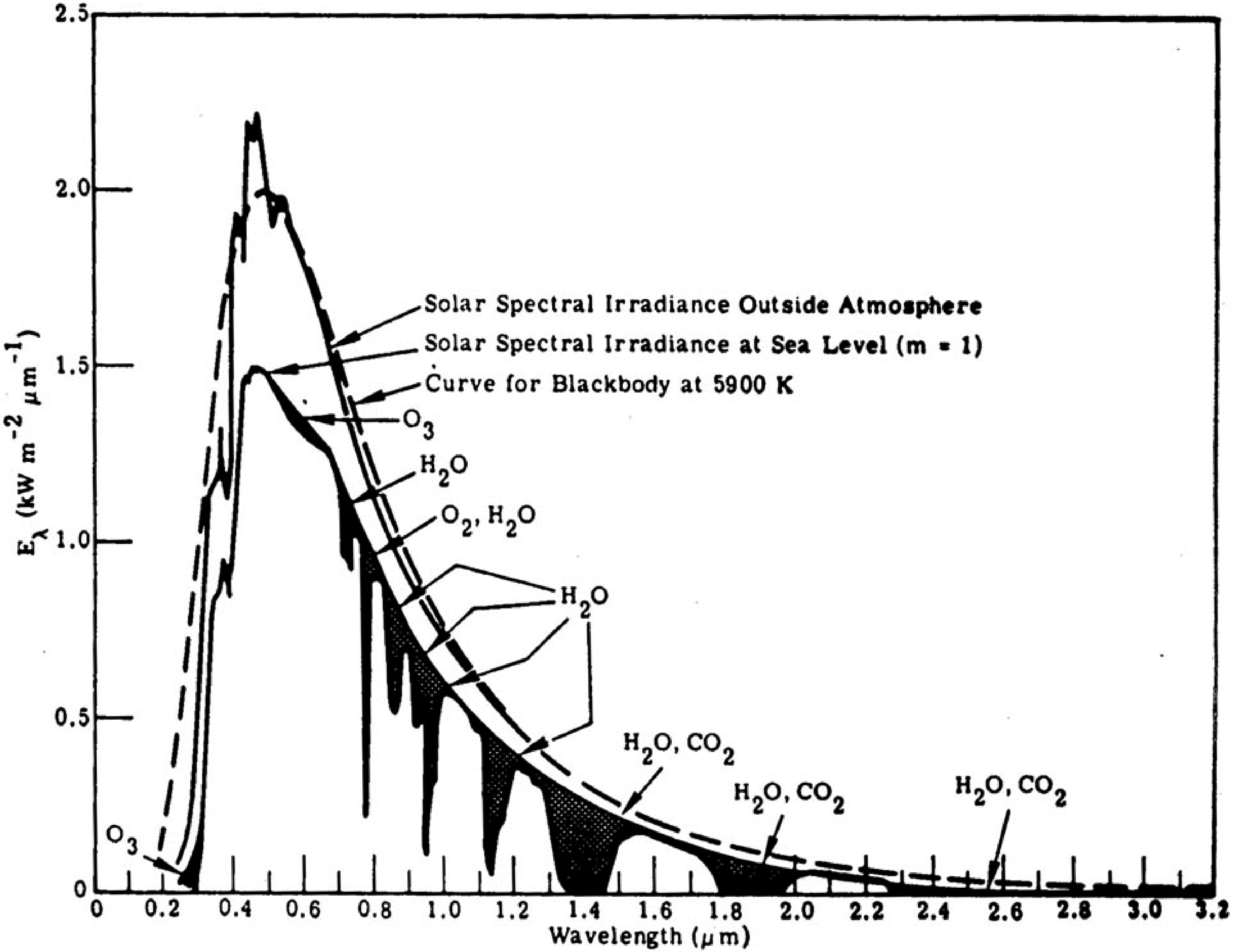


Fig. 3.3 Spectral distribution curves related to the sun. **The shaded areas indicate absorption at sea level due to the atmospheric constituents shown.**

Demos

- Pass out gratings
- Demo of line lamps
- Demo of incandescent source (carbon arc lamp)
- Demo of tungsten filament (incandescent) lamp
- Demo of light emitting diode (LED)
- Demo of laser
- Demo of luminescent eye and string

Tungsten Bulb

•

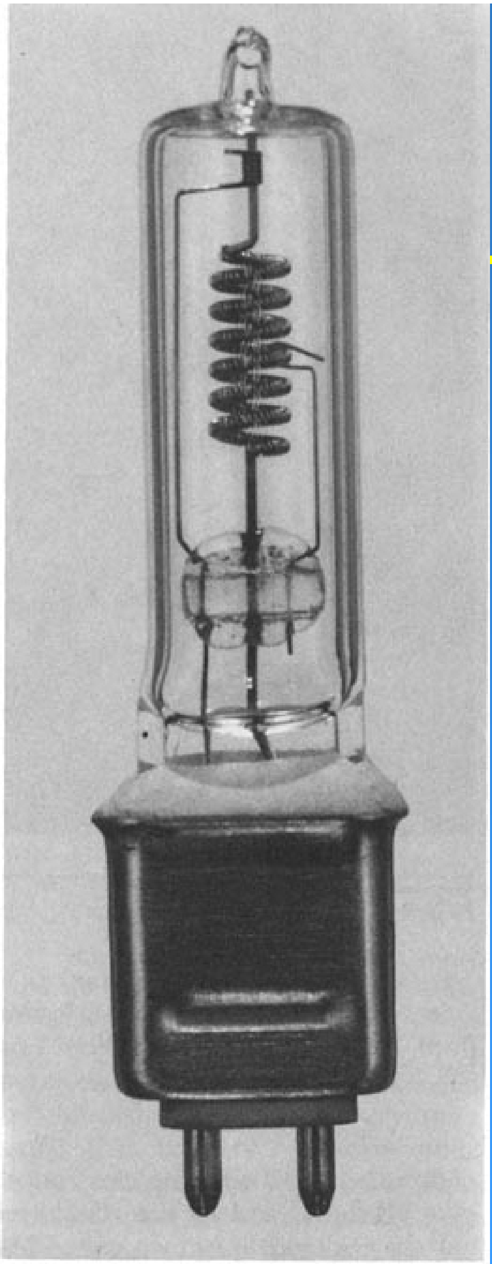


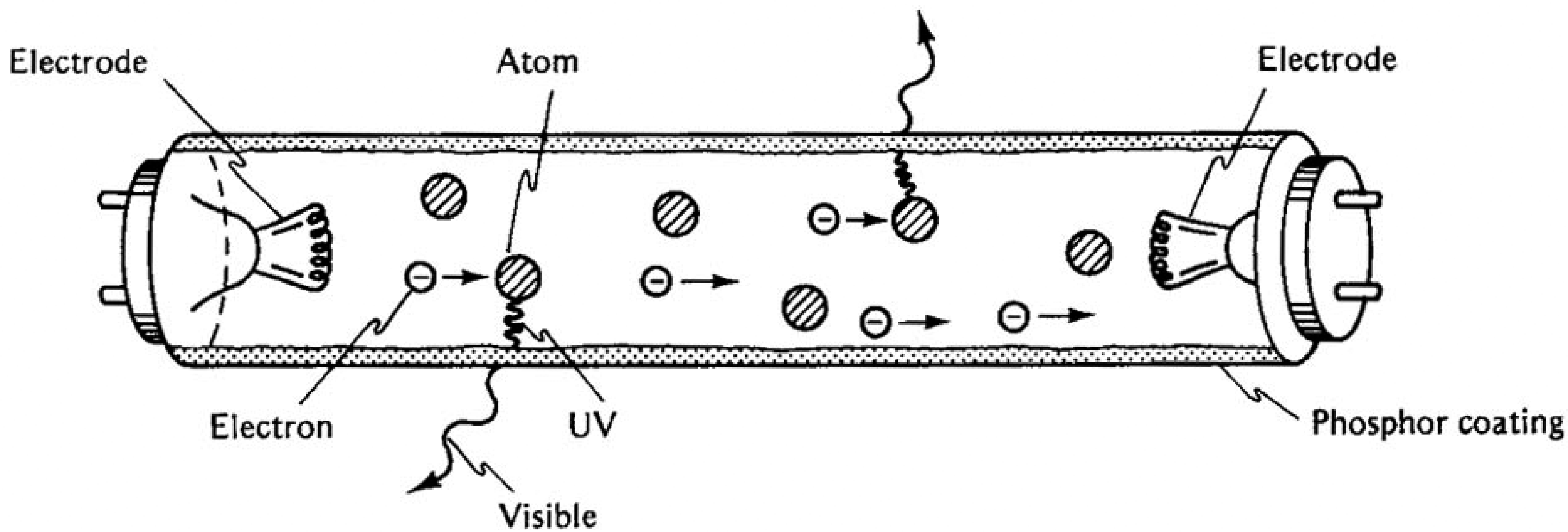
FIGURE 1.23

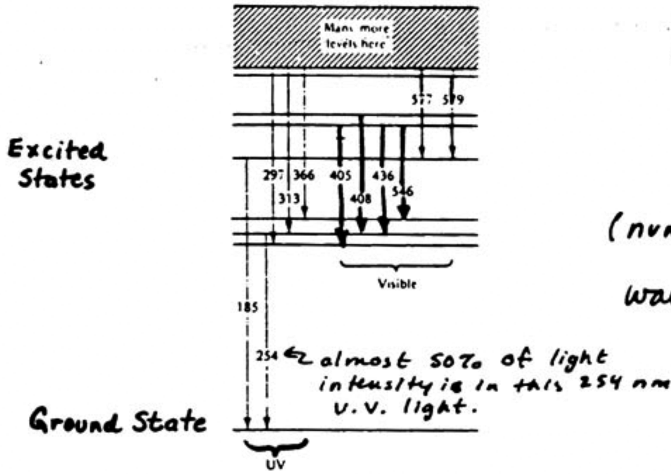
Tungsten-halogen lamp.

Fluorescent Light

FIGURE 1.24

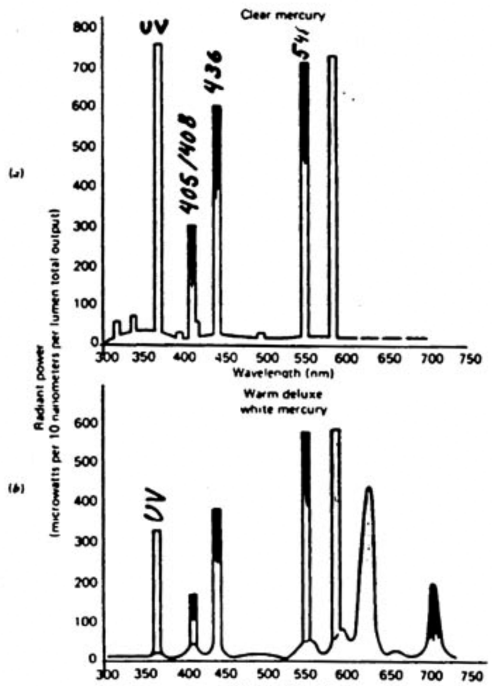
A fluorescent tube first makes UV light in an electric gas discharge and then converts most of the UV to visible light.





Energy level diagram for Mercury.

(numbers represent wavelength in nm)



Mercury arc lamp with transparent bulb.

Bulb coated with phosphor.

Fluorescent lamp spectra

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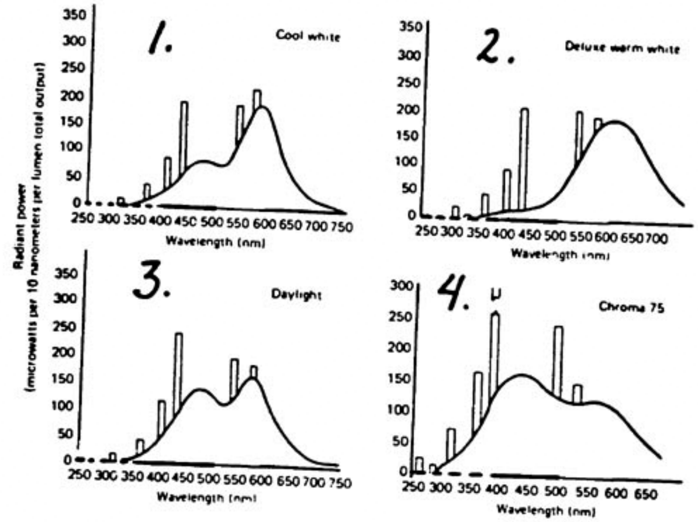
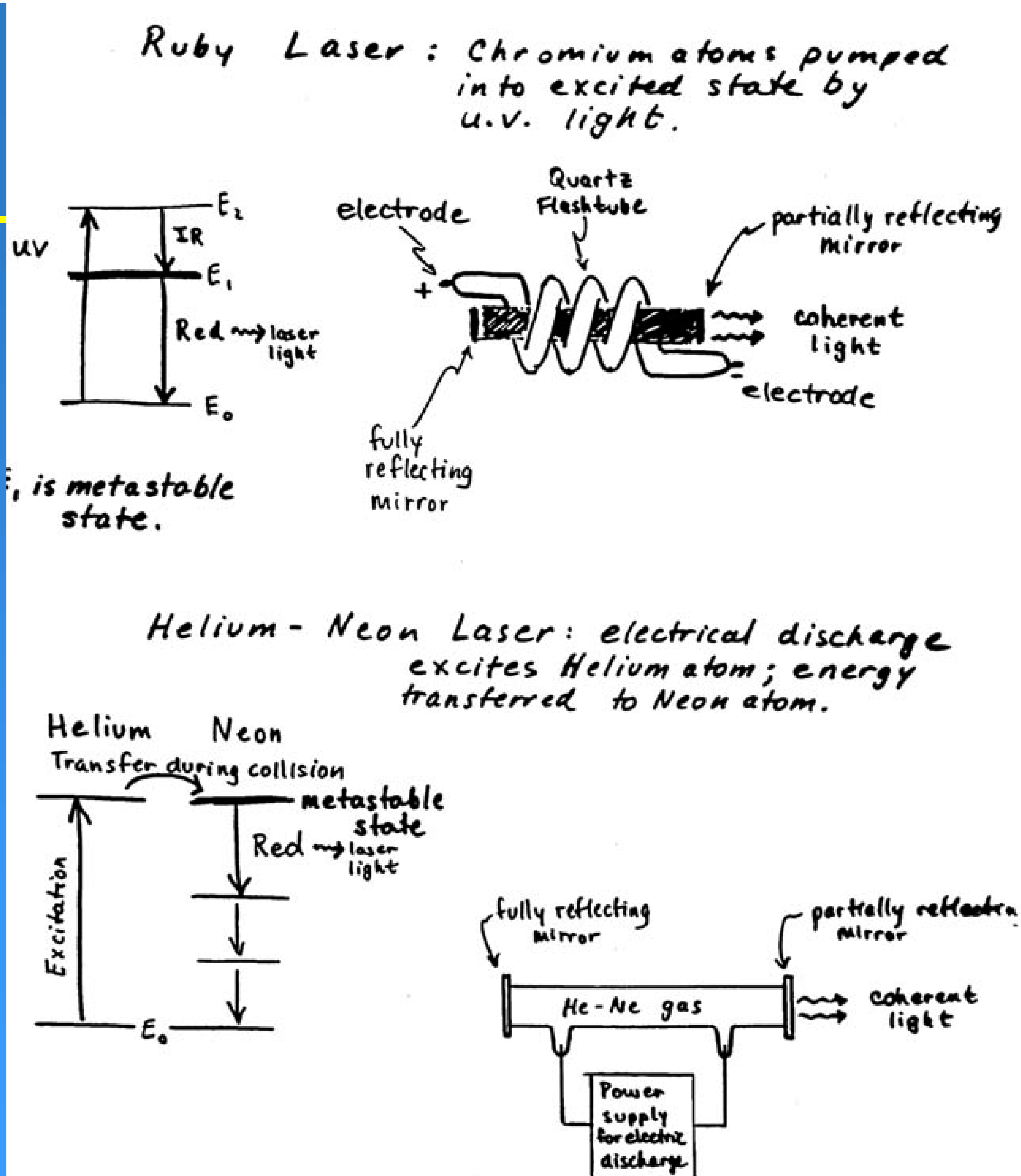
Spectra emitted by four different Fluorescent Lamps T23



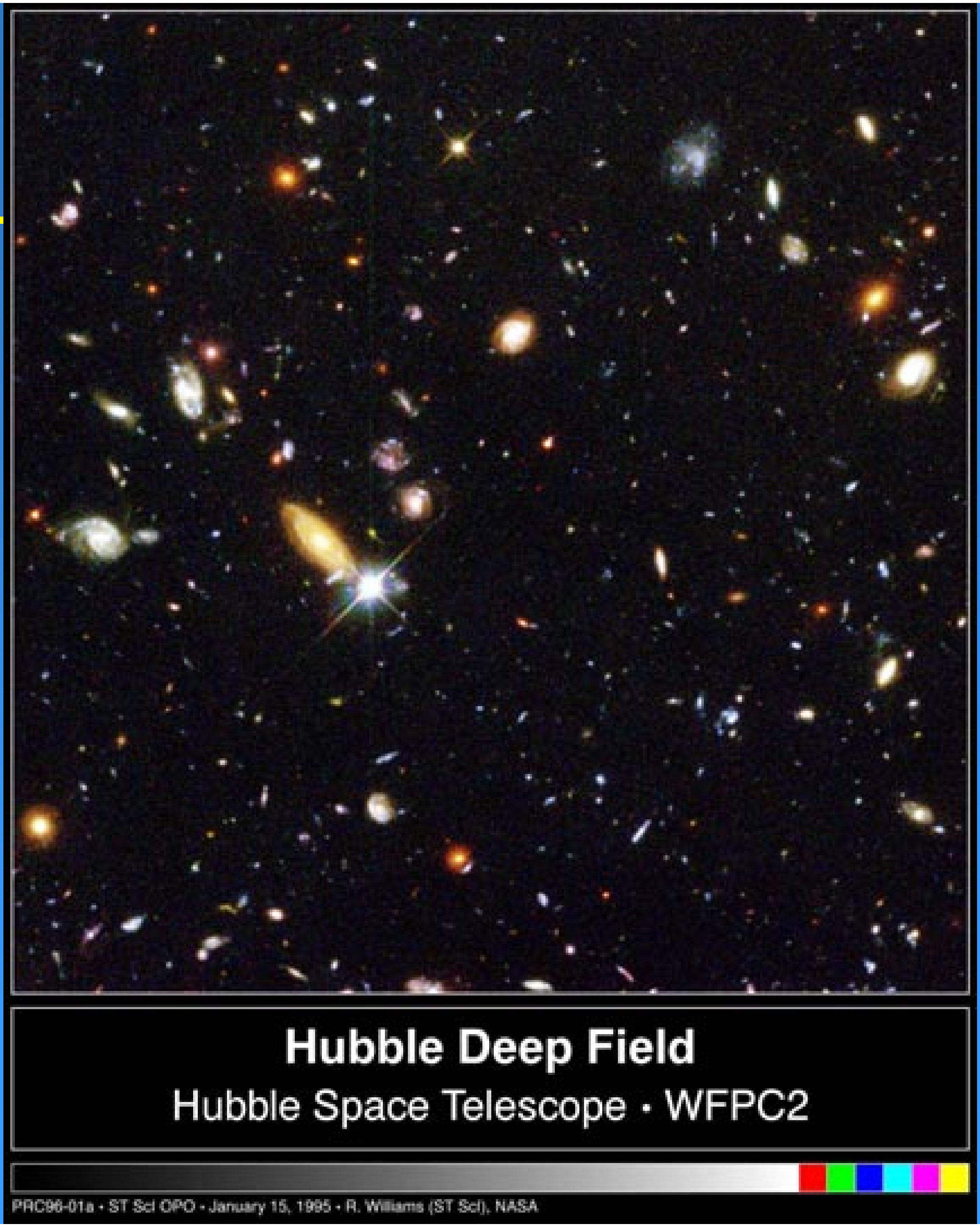
1. "Cool white": highest efficiency consistent with acceptable color rendition in many applications.
2. "Deluxe warm white": skin tones appear more natural because of extra power in red.
3. "Daylight": more even spectral power distribution.
4. "Chroma 75": approximates north sky light (peaks in the blue).

Lasers

•



Ruby Laser: Chromium atoms pumped into excited state by u.v. light.
E₂
IR
E₁
UV
Red ⇝ laser light
E₀
E₁ is metastable state.
electrode
Quartz Flashtube
partially reflecting mirror
+
coherent light
−
electrode
fully reflecting mirror
Helium - Neon Laser: electrical discharge excites Helium atom; energy transferred to Neon atom.
Helium
Neon
Transfer during collision
metastable state
Red ⇝ laser light
Excitation
E₀
fully reflecting mirror
partially reflecting mirror
He - Ne gas
coherent light
Power supply for electric discharge


Hubble Deep Field
Hubble Space Telescope • WFPC2
PRC96-01a • ST ScI OPO • January 15, 1996 • R. Williams (ST ScI), NASA

2003 April 3