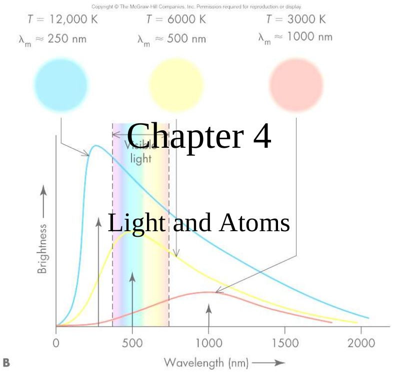
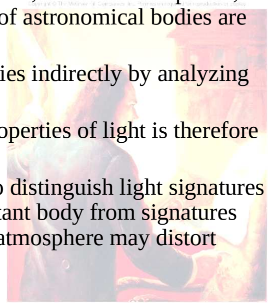


Chapter 4

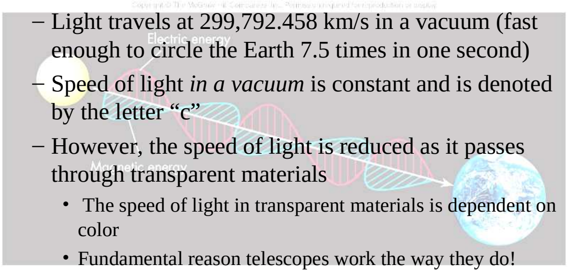
Light and Atoms

Light – the Astronomer's Tool



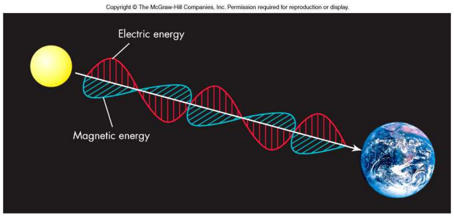
- Due to the vast distances, with few exceptions, direct measurements of astronomical bodies are not possible
- We study remote bodies indirectly by analyzing their light
- Understanding the properties of light is therefore essential
- Care must be given to distinguish light signatures that belong to the distant body from signatures that do not (e.g., our atmosphere may distort distant light signals)

Properties of Light



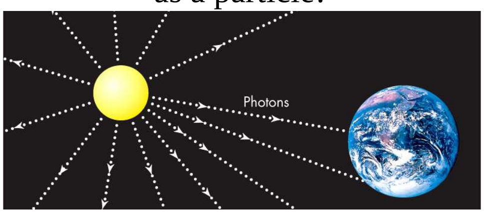
– *Light* is radiant energy: it does not require a medium for travel (unlike sound!)
– Light travels at 299,792.458 km/s in a vacuum (fast enough to circle the Earth 7.5 times in one second)
– Speed of light *in a vacuum* is constant and is denoted by the letter "c"
– However, the speed of light is reduced as it passes through transparent materials
  - The speed of light in transparent materials is dependent on color
  - Fundamental reason telescopes work the way they do!

Sometimes light can be described as a wave…



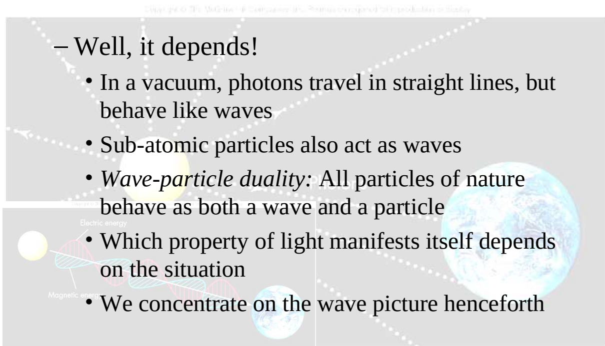
– The wave travels as a result of a fundamental relationship between electricity and magnetism
– A <u>changing</u> magnetic field creates an electric field and a <u>changing</u> electric field creates a magnetic field

…and sometimes it can be described as a particle!



– Light thought of as a stream of particles called ***photons***
– Each photon particle carries energy, depending on its ***frequency*** or ***wavelength***

So which model do we use?

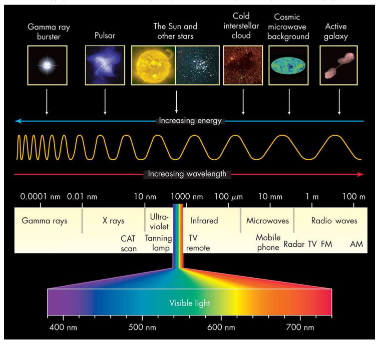


– Well, it depends!
  - In a vacuum, photons travel in straight lines, but behave like waves
  - Sub-atomic particles also act as waves
  - *Wave-particle duality:* All particles of nature behave as both a wave and a particle
  - Which property of light manifests itself depends on the situation
  - We concentrate on the wave picture henceforth

Light and Color

- Colors to which the human eye is sensitive is referred to as the ***visible spectrum***
- In the wave theory, color is determined by the light's ***wavelength*** (symbolized as λ)
  - The ***nanometer*** (10^{-9} m) is the convenient unit
  - Red = 700 nm (longest visible wavelength), violet = 400 nm (shortest visible wavelength)

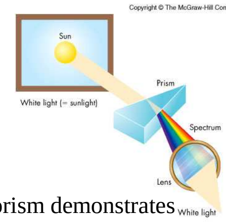
The Visible Spectrum

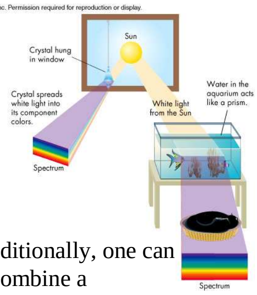


Frequency

- Sometimes it is more convenient to talk about light's frequency
  - ***Frequency*** (or ν) is the number of wave crests that pass a given point in 1 second (measured in Hertz, Hz)
  - Important relation: $\nu\lambda = c$
  - Long wavelenth = low frequency
  - Short wavelength = high frequency

White light – a mixture of all colors





- A prism demonstrates that white light is a mixture of wavelengths by its creation of a spectrum
- Additionally, one can recombine a spectrum of colors and obtain white light

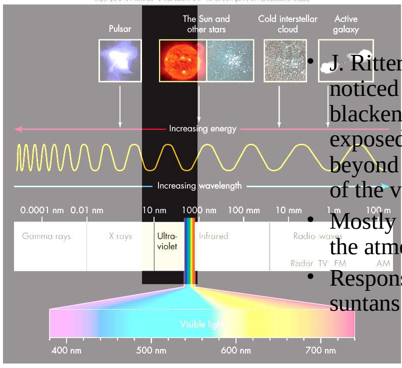
The Electromagnetic Spectrum

- The ***electromagnetic spectrum*** is composed of radio waves, microwaves, infrared, visible light, ultraviolet, x rays, and gamma rays
- Longest wavelengths are more than 10^3 km
- Shortest wavelengths are less than 10^{-18} m
- Various instruments used to explore the various regions of the spectrum

Infrared Radiation

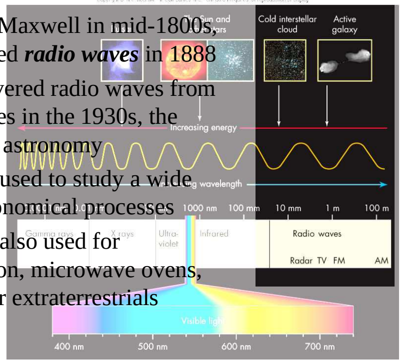
- Sir William Herschel (around 1800) showed heat radiation related to visible light
- He measured an elevated temperature just off the red end of a solar spectrum – ***infrared*** energy
- Our skin feels infrared as heat

Ultraviolet Light



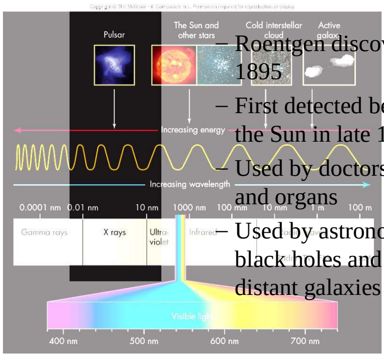
- J. Ritter in 1801 noticed silver chloride blackened when exposed to “light” just beyond the violet end of the visible spectrum
- Mostly absorbed by the atmosphere
- Responsible for suntans (and burns!)

Radio Waves



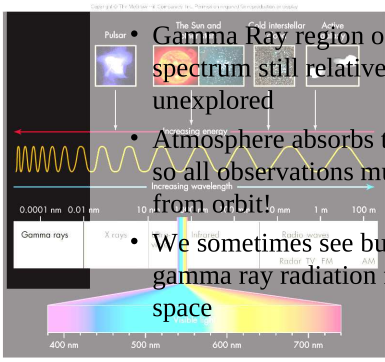
- Predicted by Maxwell in mid-1800s, Hertz produced ***radio waves*** in 1888
- Jansky discovered radio waves from cosmic sources in the 1930s, the birth of radio astronomy
- Radio waves used to study a wide range of astronomical processes
- Radio waves also used for communication, microwave ovens, and search for extraterrestrials

X-Rays



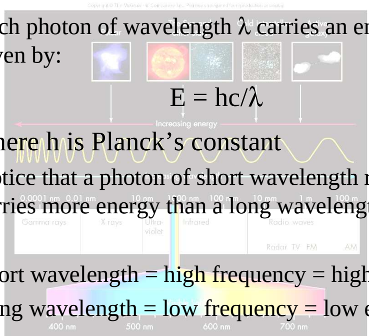
– Roentgen discovered X rays in 1895
– First detected beyond the Earth in the Sun in late 1940s
– Used by doctors to scan bones and organs
– Used by astronomers to detect black holes and tenuous gas in distant galaxies

Gamma Rays



- Gamma Ray region of the spectrum still relatively unexplored
- Atmosphere absorbs this region, so all observations must be done from orbit!
- We sometimes see bursts of gamma ray radiation from deep space

Energy Carried by Electromagnetic Radiation



– Each photon of wavelength λ carries an energy E given by:

$$E = hc/\lambda$$

where h is Planck’s constant

– Notice that a photon of short wavelength radiation carries more energy than a long wavelength photon
– Short wavelength = high frequency = high energy
– Long wavelength = low frequency = low energy

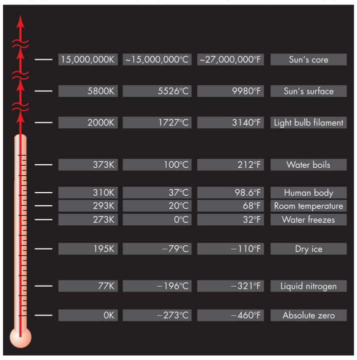
Matter and Heat

- The Nature of Matter and Heat
  – The ancient Greeks introduced the idea of the atom (Greek for “uncuttable”), which today has been modified to include a nucleus and a surrounding cloud of electrons
  – Heating (transfer of energy) and the motion of atoms was an important topic in the 1700s and 1800s

A New View of Temperature

- The Kelvin Temperature Scale
  - An object's temperature is directly related to its energy content and to the speed of molecular motion
  - As a body is cooled to zero Kelvin, molecular motion within it slows to a virtual halt and its energy approaches zero ⇒ no negative temperatures
  - Fahrenheit and Celsius are two other temperature scales that are easily converted to Kelvin

The Kelvin Temperature Scale

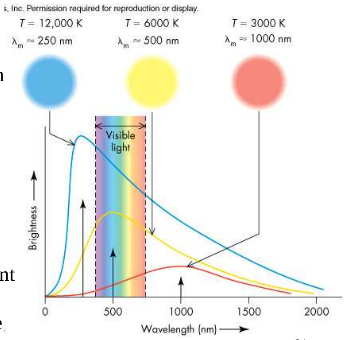


Radiation and Temperature

- Heated bodies generally radiate across the entire electromagnetic spectrum
- There is one particular wavelength, λ_m, at which the radiation is most intense and is given by ***Wien's Law:***

$$\lambda_m = k/T$$

Where k is some constant and T is the temperature of the body



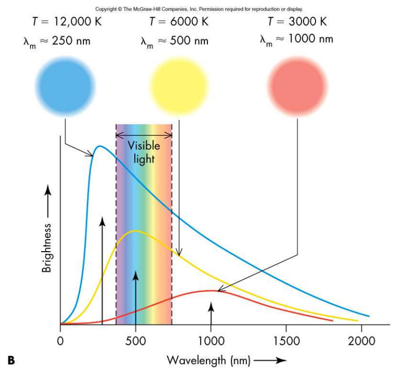
Radiation and Temperature

- Note hotter bodies radiate more strongly at shorter wavelengths
- As an object heats, it appears to change color from red to white to blue
- Measuring λ_m gives a body's temperature
- Careful: <u>Reflected light</u> does not give the temperature

Blackbodies and Wien's Law

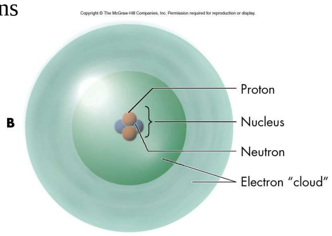
- A ***blackbody*** is an object that absorbs all the radiation falling on it
- Since such an object does not reflect any light, it appears black when cold, hence its name
- As a blackbody is heated, it radiates more efficiently than any other kind of object
- Blackbodies are excellent absorbers and emitters of radiation and follow Wien's law
- Very few real objects are perfect blackbodies, but many objects (e.g., the Sun and Earth) are close approximations
- Gases, unless highly compressed, are not blackbodies and can only radiate in narrow wavelength ranges

Blackbodies and Wien's Law



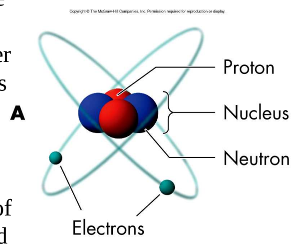
The Structure of Atoms

- Nucleus – Composed of densely packed neutrons and positively charged protons
- Cloud of negative electrons held in orbit around nucleus by positive charge of protons
- Typical atom size: 10^{-10} m (= 1 Å = 0.1 nm)

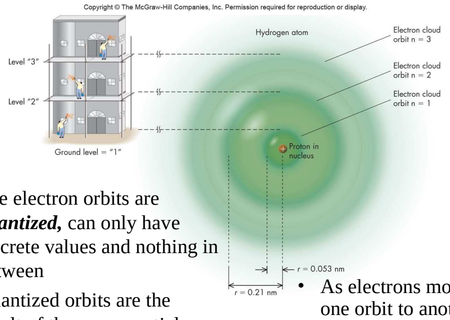


The Chemical Elements

- An ***element*** is a substance composed only of atoms that have the same number of protons in their nucleus
- A neutral element will contain an equal number of protons and electrons
- The chemical properties of an element are determined by the number of electrons



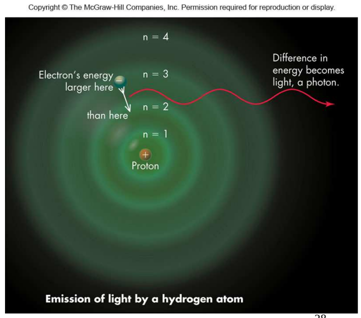
Electron "Orbits"



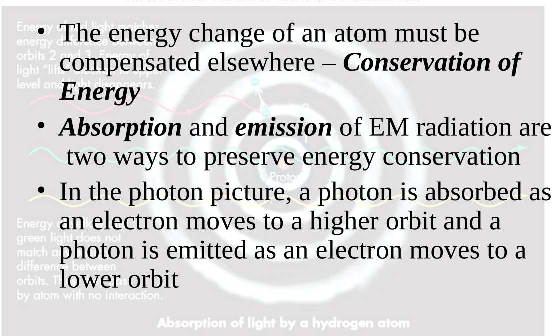
- The electron orbits are ***quantized,*** can only have discrete values and nothing in between
- Quantized orbits are the result of the wave-particle duality of matter
- As electrons move from one orbit to another, they change their energy in discrete amounts

Energy Change in an Atom

- An atom's energy is increased if an electron moves to an outer orbit – the atom is said to be ***excited***
- An atom's energy is decreased if an electron moves to an inner orbit

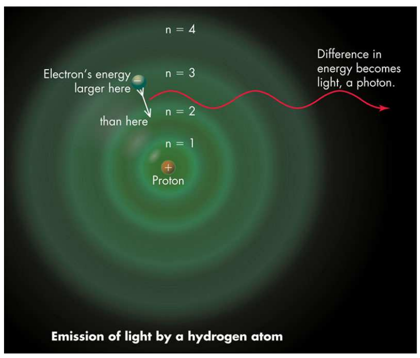


Conservation of Energy

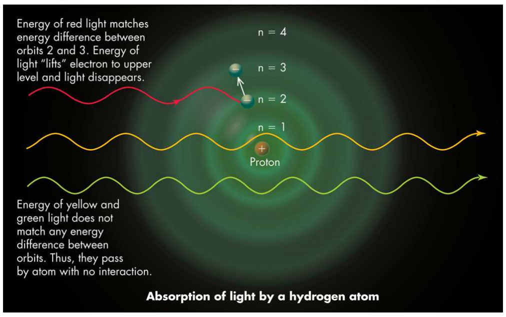


- The energy change of an atom must be compensated elsewhere – ***Conservation of Energy***
  - ***Absorption*** and ***emission*** of EM radiation are two ways to preserve energy conservation
  - In the photon picture, a photon is absorbed as an electron moves to a higher orbit and a photon is emitted as an electron moves to a lower orbit

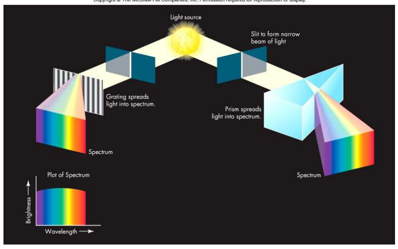
Emission



Absorption

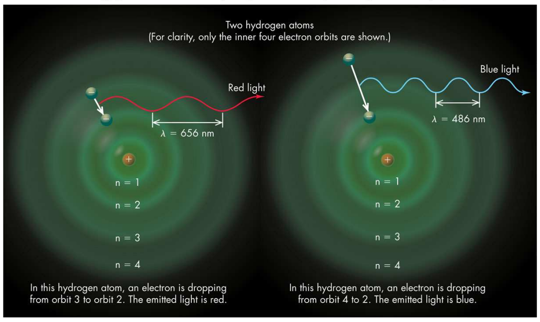


Spectroscopy



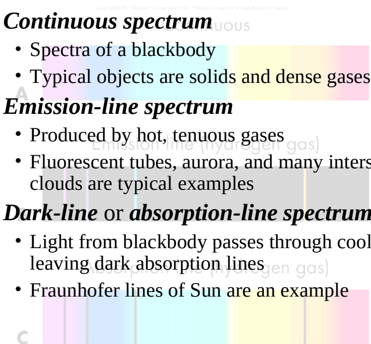
- Allows the determination of the composition and conditions of an astronomical body
- In ***spectroscopy***, we capture and analyze a spectrum
- Spectroscopy assumes that every atom or molecule will have a unique spectral signature

Formation of a Spectrum



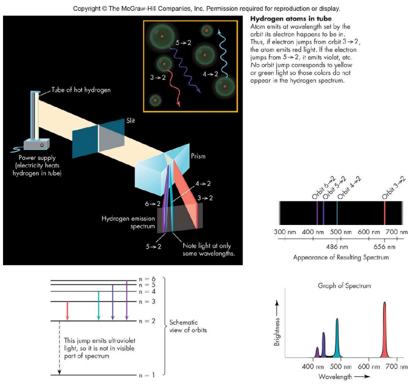
- A transition in energy level produces a photon

Types of Spectra

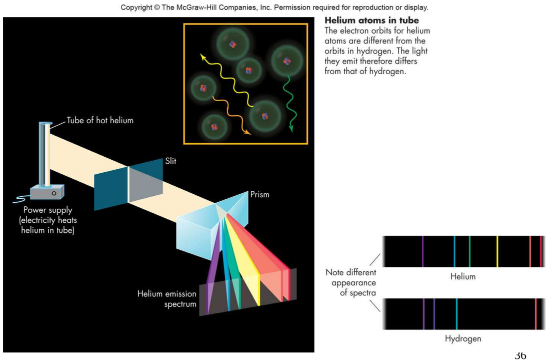


- ***Continuous spectrum***
  - Spectra of a blackbody
  - Typical objects are solids and dense gases
- ***Emission-line spectrum***
  - Produced by hot, tenuous gases
  - Fluorescent tubes, aurora, and many interstellar clouds are typical examples
- ***Dark-line*** or ***absorption-line spectrum***
  - Light from blackbody passes through cooler gas leaving dark absorption lines
  - Fraunhofer lines of Sun are an example

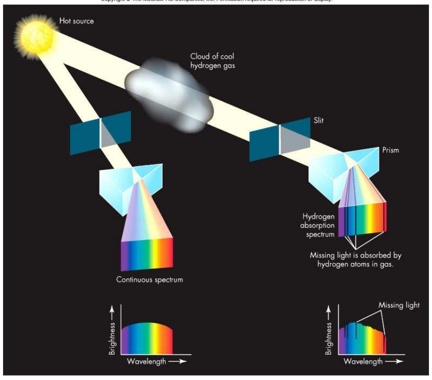
Emission Spectrum



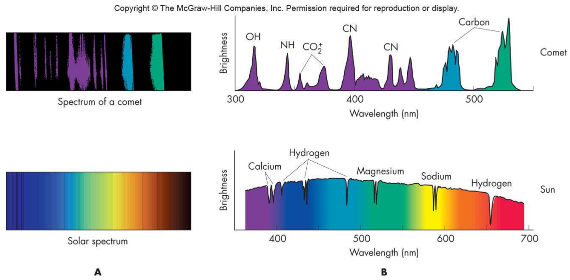
Emission Spectrum



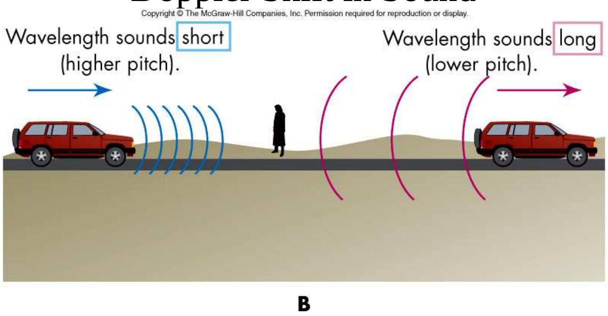
Continuous and Absorption Spectra



Astronomical Spectra

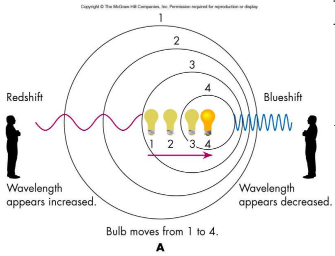


Doppler Shift in Sound



- If the source of sound is moving, the pitch changes!

Doppler Shift in Light



– If a source of light is set in motion relative to an observer, its spectral lines shift to new wavelengths in a similar way

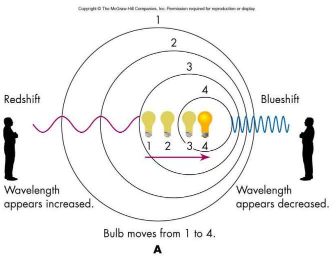
– The shift in wavelength is given as

$$\Delta\lambda = \lambda - \lambda_o = \lambda_o v/c$$

where λ is the observed (shifted) wavelength, λ_o is the emitted wavelength, v is the source non-relativistic <u>radial velocity</u>, and c is the speed of light

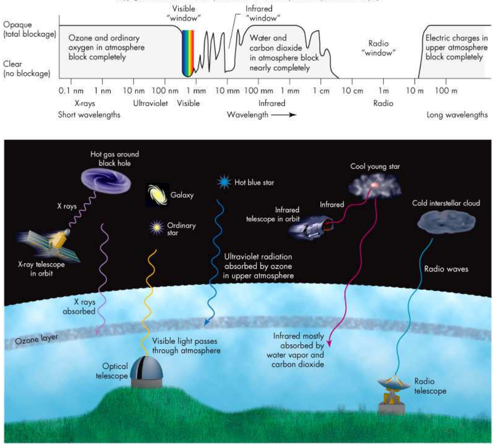
Redshift and Blueshift

- An observed increase in wavelength is called a <u>redshift</u>, and a decrease in observed wavelength is called a <u>blueshift</u> (regardless of whether or not the waves are visible)
- Doppler shift is used to determine an object's velocity



Absorption in the Atmosphere

- Gases in the Earth's atmosphere absorb electromagnetic radiation to the extent that most wavelengths from space do not reach the ground
- Visible light, most radio waves, and some infrared penetrate the atmosphere through ***atmospheric windows***, wavelength regions of high transparency
- Lack of atmospheric windows at other wavelengths is the reason for astronomers placing telescopes in space


Opaque (total blockage)
Clear (no blockage)
Ozone and ordinary oxygen in atmosphere block completely
Visible "window"
Infrared "window"
Water and carbon dioxide in atmosphere block nearly completely
Radio "window"
Electric charges in upper atmosphere block completely
0.1 nm
1 nm
10 nm
100 nm
1 mm
10 mm
100 mm
1 mm
1 cm
10 cm
1m
10 m
100 m
X-rays
Ultraviolet
Visible
Infrared
Radio
Short wavelengths
Wavelength
Long wavelengths
Hot gas around black hole
X rays
X-ray telescope in orbit
Galaxy
Ordinary star
Hot blue star
Ultraviolet radiation absorbed by ozone in upper atmosphere
Infrared telescope in orbit
Infrared
Cool young star
Cold interstellar cloud
Radio waves
X rays absorbed
Ozone layer
Visible light passes through atmosphere
Optical telescope
Infrared mostly absorbed by water vapor and carbon dioxide
Radio telescope