OBSERVATIONAL ASTRONOMY – I

Vitaly Neustroev

Contact details

- Location: MA 302
- Email: vitaly@neustroev.net; vitaly.neustroev@oulu.fi
- Telephone: 029448-1930
- Web: http://vitaly.neustroev.net/teach/autumn-2018

  - You may come to my office for help with the course material during office hours. You can also send me your questions by e-mail.
  - You are encouraged to ask questions during the lectures.

Content

- Observational Techniques in Gamma, X-ray, UV, **Optical** and Infra-Red astronomy
- Methods of Observations with the modern Space- and Ground-based Telescopes
- Observational Experiments, Calibrations and Data Reductions
- Data Analysis

Text Books

- **Astrophysical techniques** (5th Edition – 2008) – C.R. Kitchen: Taylor & Francis / CRC Press. ISBN 978-1-4200-8243-2.
- **Observational Astrophysics** (3rd Edition – 2012) – P. Léna, D. Rouan, F. Lebrun, F. Mignard, D. Pelat, Translated by S. Lyle: Springer. ISBN 978-3-642-21815-6.

- **An Introduction to Astronomical Photometry Using CCDs** (October 22, 2006) – W. Romanishin: can be downloaded from the course web-page.
- ***Observational Astronomy*** (Second Edition - 2006) – D. Scott Birney, Guillermo Gonzalez & David Oesper: Cambridge Univ. Press. ISBN 978-0-521-85370-5
- *ISSI Scientific Report Volume 9 (SR-009):* ***Observing Photons in Space*** (2010) – Edited by M.C.E. Huber, A. Pauluhn, J. Len Culhane, J. G. Timothy, K. Wilhelm and A. Zehnder. ISBN 978-92-9221-938-3.

Home exercises

- Compulsory homework sets will be assigned (return by the deadline). You are urged not to start these the night before they are due. For late exercises only one half points will be given.
- The most important thing you can learn from homework is how to solve problems yourself. This is what you need to do to succeed in the real world. Therefore, please try each problem for at least 1 hour before discussing it with anyone else.
- Please, write your homework solutions in an **extremely** clear manner. It will not be possible to give credits for work that is not clearly explained. Please, show your work since this will allow partial credit to be given if you cannot solve the whole problem.
- When it is relevant, use general formulae as long as possible and only plug in numbers at the end of a problem.

Presentation

- Presentation (15 min) on one of the suggested topics.

Exam

- There will be two questions from the required reading plus two problems similar to (or just from) the home exercises. No help from the books, lecture notes, or any other material is allowed during the exam. A standard non-programmable calculator could be used.

Assessment

Your grade will be based on:

- 50% Exam on lecture course
- 30% Homeworks (problems)
- 20% Presentation

Course Plan

- Introduction
- Continuum Radiation Processes
- Telescopes
- Detectors
- Spectral Line Processes
- Spectroscopic techniques
- Polarimetry
- Observations and Data Reduction
- Data Analysis

Introduction

Seeing the Night Sky with Our Naked Eyes

Viewing objects in wavebands other than optical

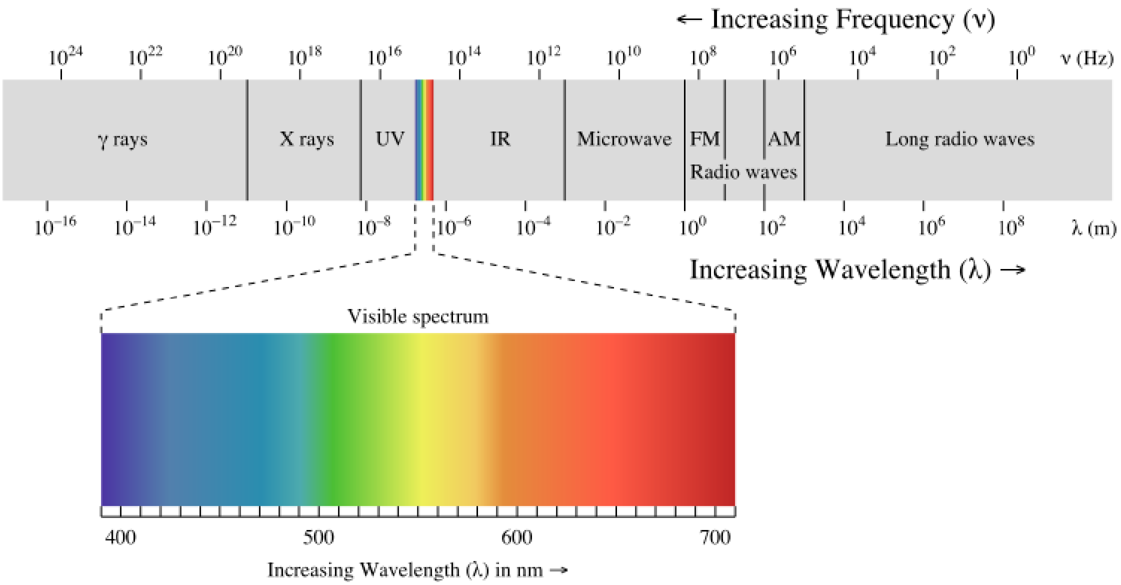
The Effect of the Earth's Atmosphere - I

Continuum Radiation Processes

Eye as a detector

Seeing the Night Sky with Our Naked Eyes

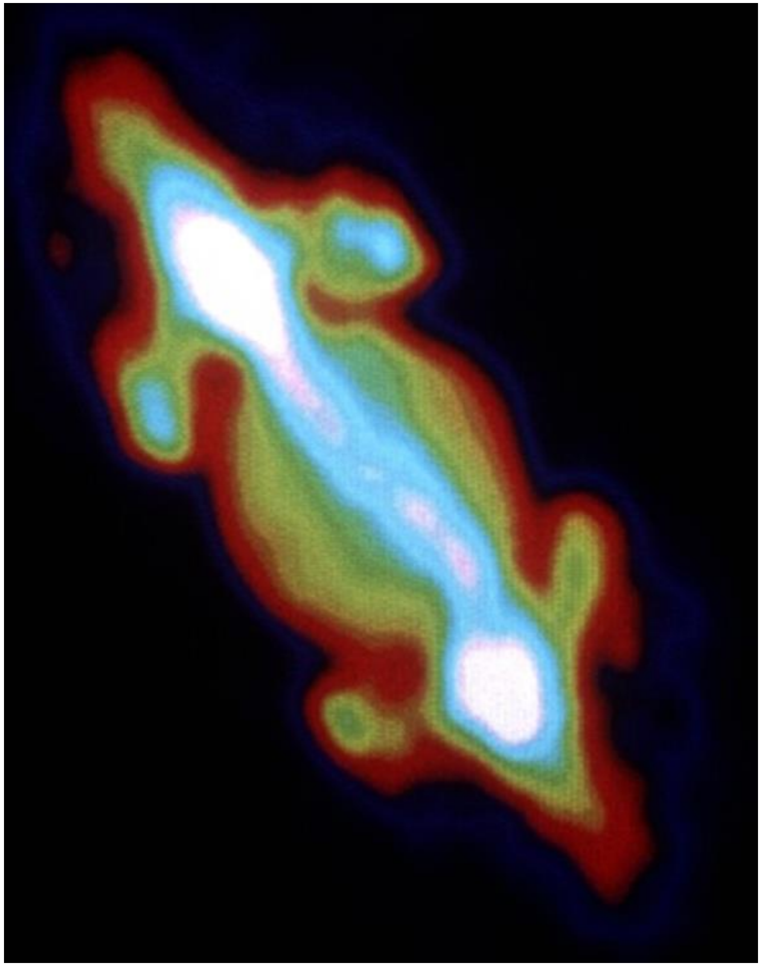
- With an unaided eye we view our universe through a very small window, from blue light to red light.
- The "big" window is the electromagnetic spectrum. This band, or range of electromagnetic energy exists from extremely long radio waves (kilometres), to the extremely energetic gamma rays.

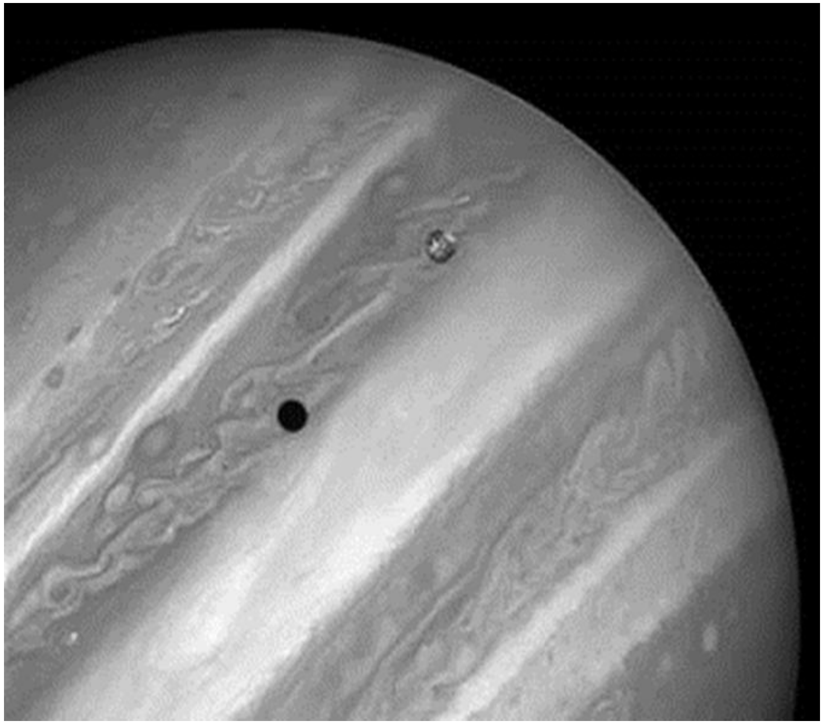


Viewing objects in wavebands other than optical

- We have a very limited view into the universe through our visual senses but with the aid of modern technology we can see things that are far beyond that. Being able to see images from radio waves to X-rays and beyond has opened up the universe for our study.

Jupiter

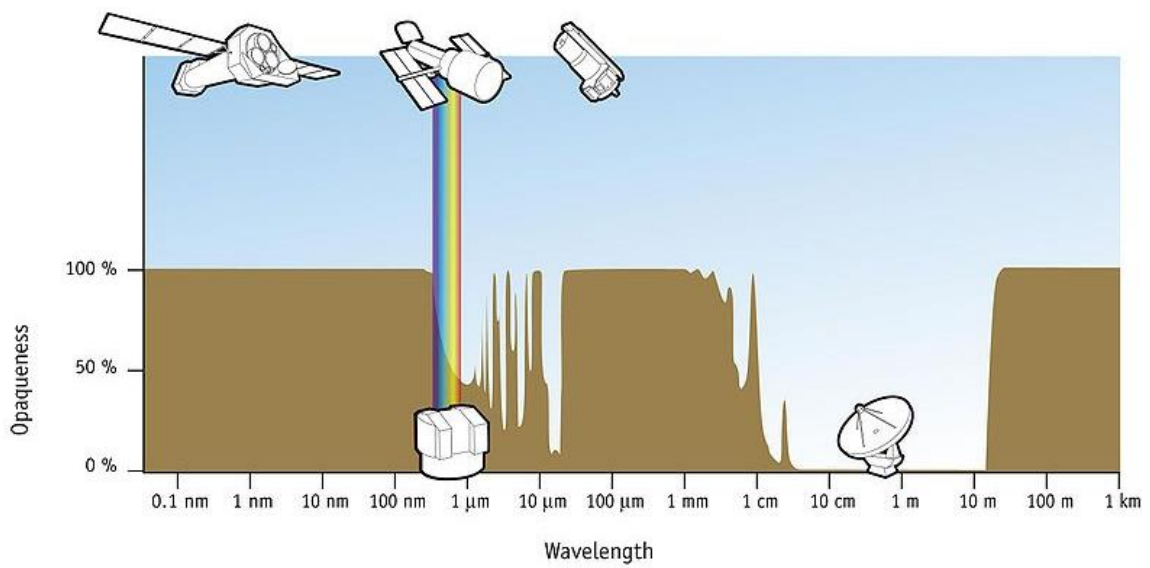




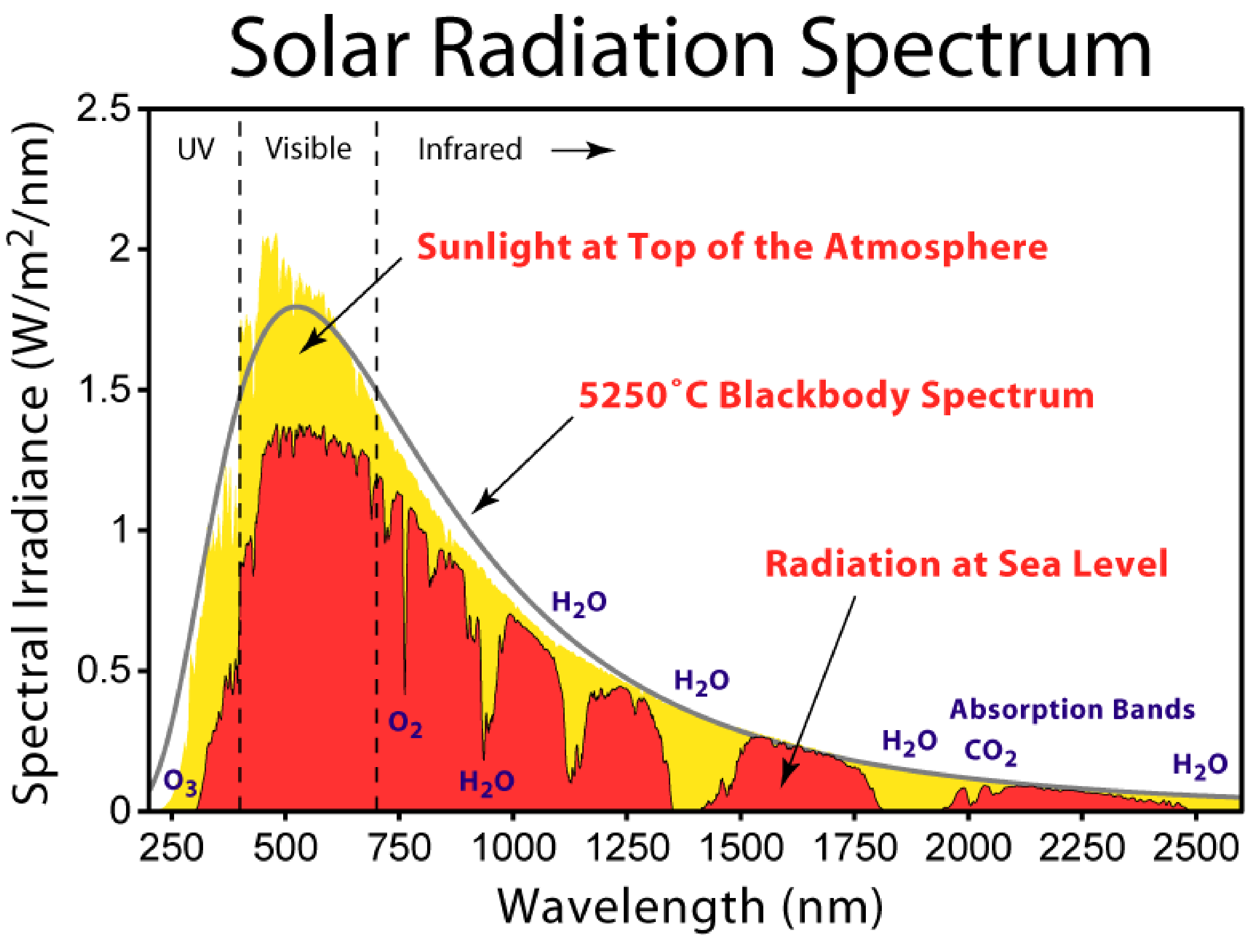
Left is in radio, synchrotron (high magnetic field); right is optical which reflected sunlight.

The Effect of the Earth's Atmosphere - I

- Ground based astronomy is heavily influenced by the Earth's atmosphere. In addition to the interruption of observations by clouds, the atmosphere affects the resolution that can be achieved, the accuracy of position and brightness measurements.
- The optical window and the radio window – the only two wavelength ranges of the electromagnetic spectrum that are not severely attenuated by the atmosphere.



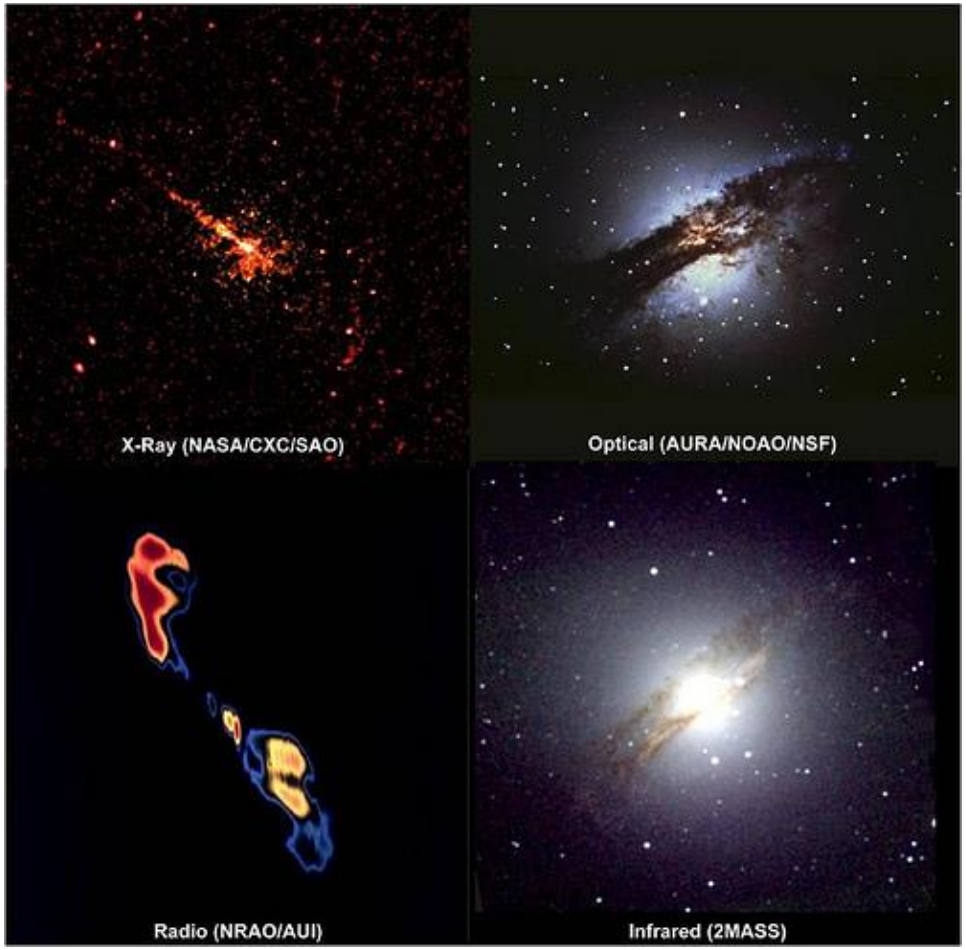
The Effect of the Earth's Atmosphere - I



The Effect of the Earth's Atmosphere - I

- The Earth's atmosphere is opaque to ultraviolet radiation, X-rays, and gamma rays and is partially opaque to infrared radiation so observations in these portions of the electromagnetic spectrum are best carried out from a location above the atmosphere of our planet.
- Another advantage of space-based telescopes is that, because of their location above the Earth's atmosphere, their images are free from the effects of atmospheric turbulence that distorts ground-based observations.

Viewing objects in wavebands other than optical

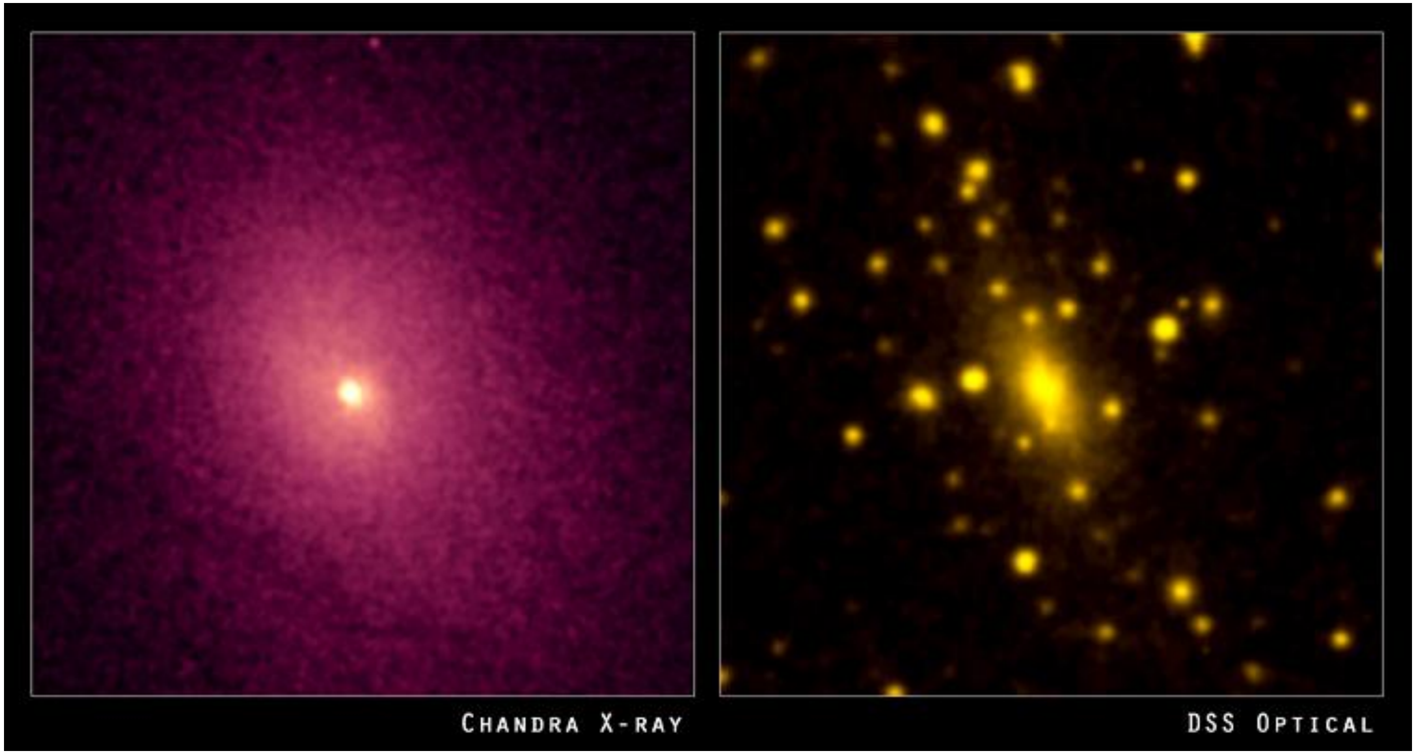


Radio Galaxy Centauri A - one of the most powerful sources of radio waves on the sky.

In **IR** one can very clearly see through the dust hiding the center of the galaxy in **optical** waveband.

X-ray and **radio** pictures show two nice jets of hot gas perpendicular to the galaxy’s plain (one has no idea about them just taking the optical/IR/UV image).

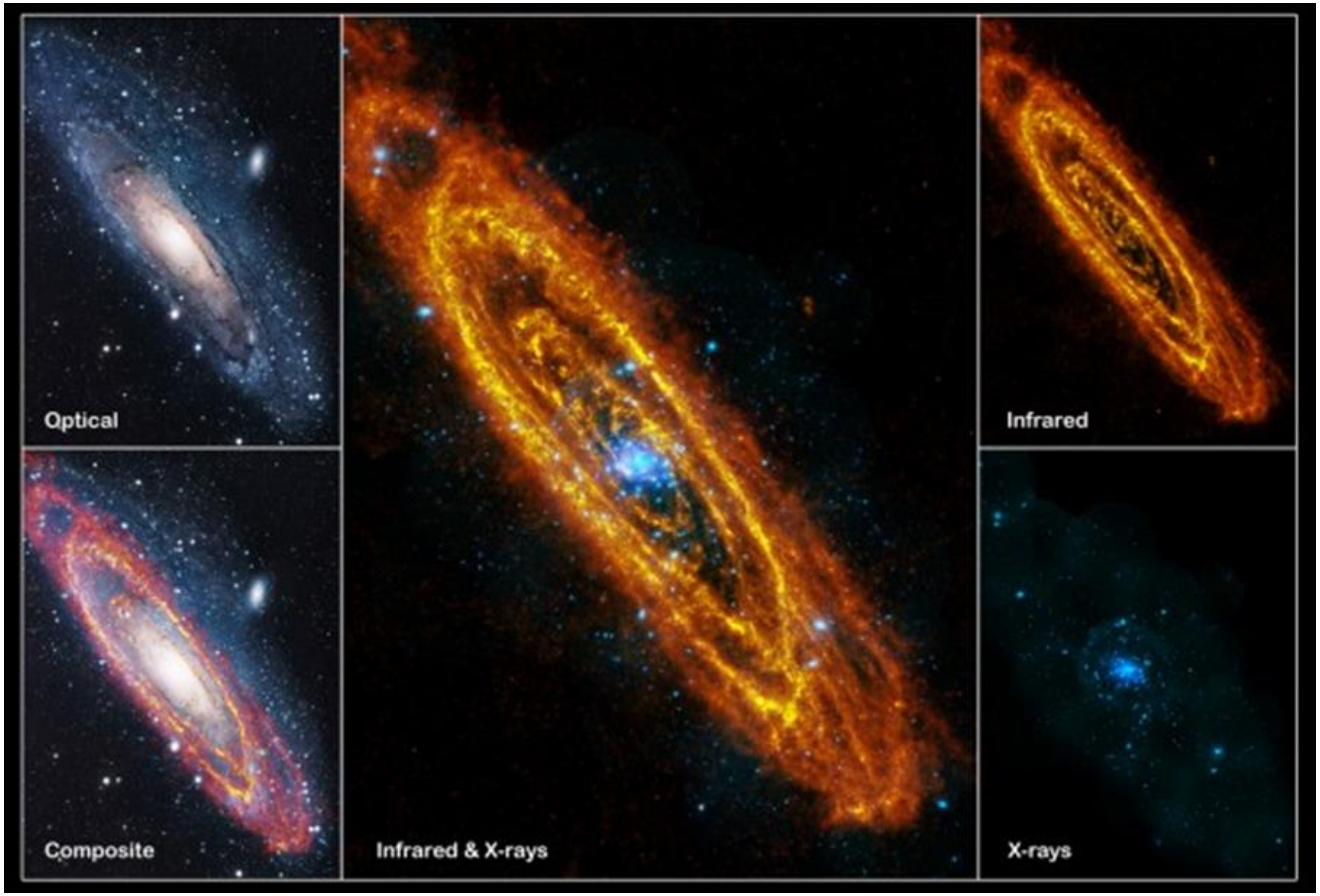
Viewing objects in wavebands other than optical



Galaxy cluster Abell 2029: In the optical waveband one can spot an extremely massive galaxy in the center of the cluster. The gas falling into the gravitational well emits huge amounts of the X-ray radiation due to the accretion .

Viewing objects in wavebands other than optical

The Andromeda Galaxy

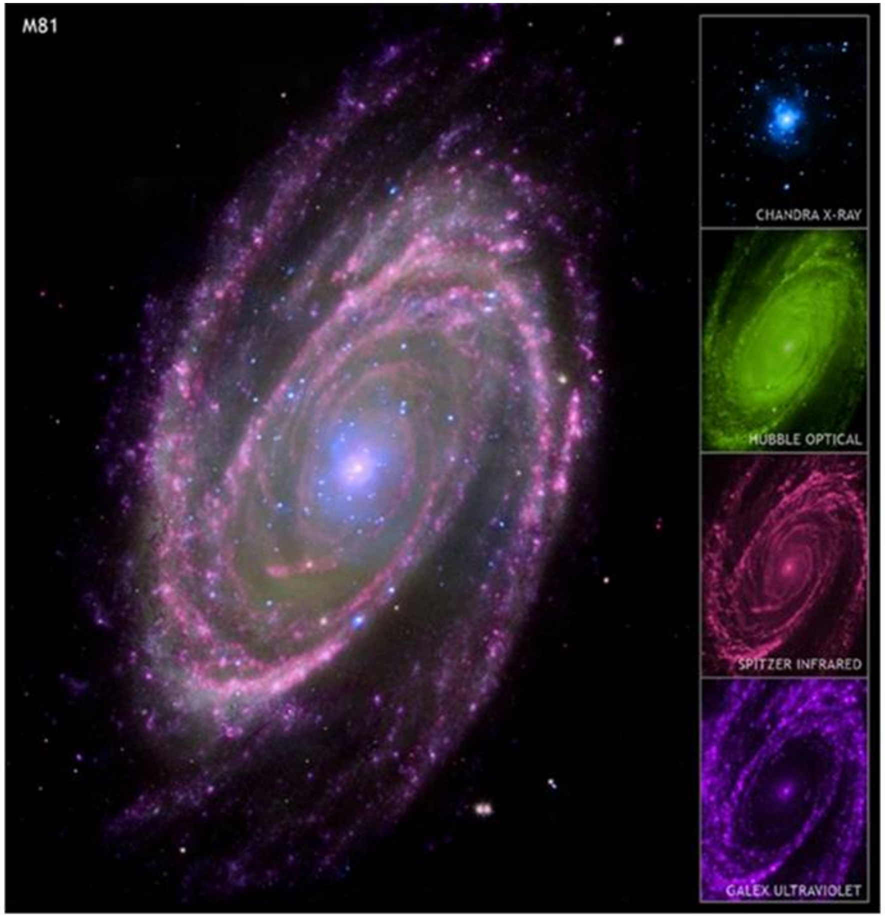


Viewing objects in wavebands other than optical

The Sombrero galaxy (M104)

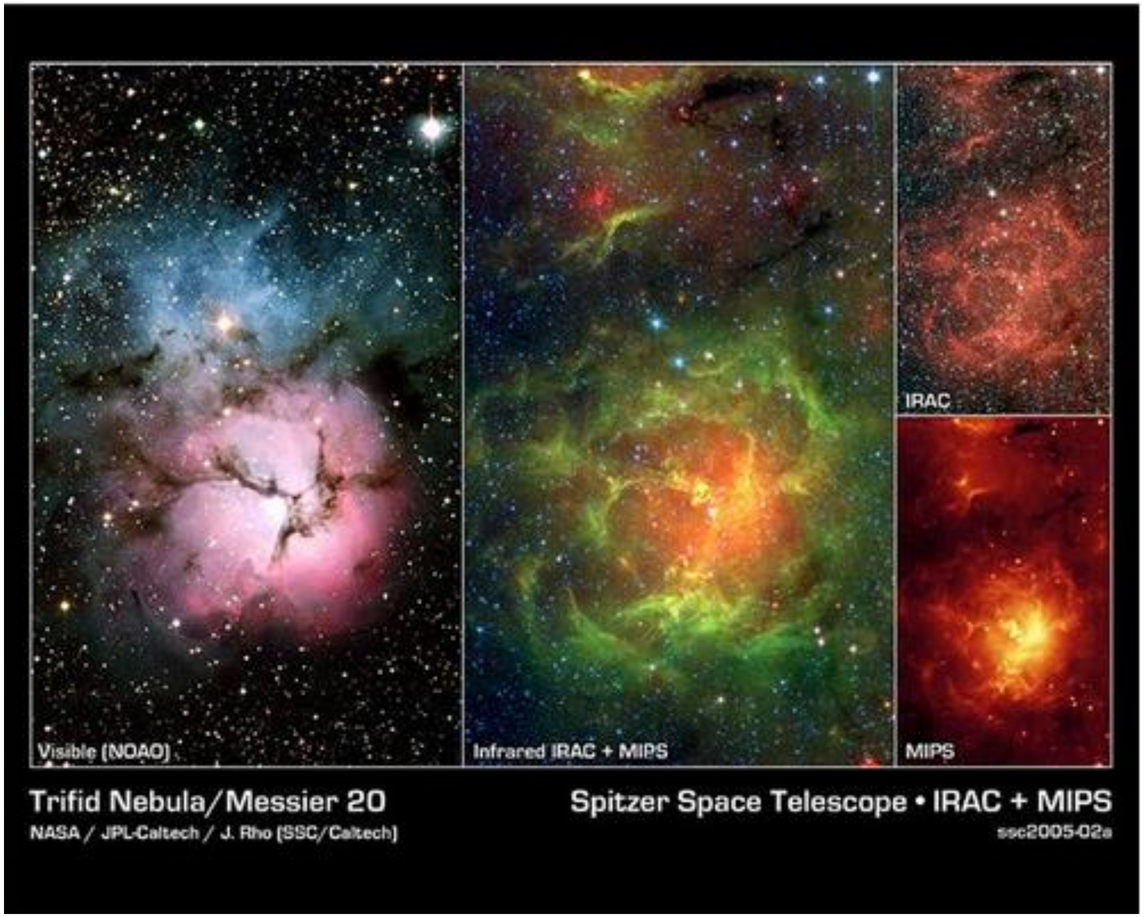
Viewing objects in wavebands other than optical

The spiral galaxy (M81)



Viewing objects in wavebands other than optical

The Trifid Nebula (M20)



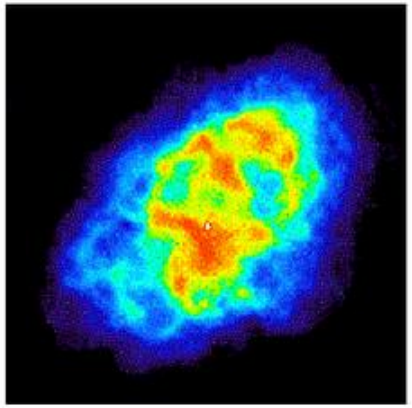
Viewing objects in wavebands other than optical

The Crab Nebula, remnant of SN 1054

X-ray is synchrotron radiation

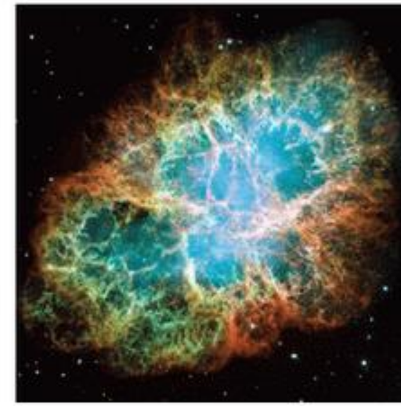
Optical and Infrared are mostly atomic line radiation

Radio is both synchrotron and thermal bremsstrahlung radiation

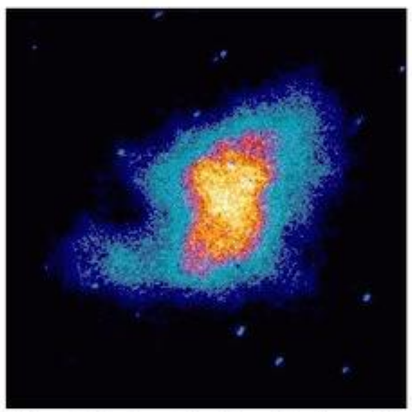


Radio wave (VLA)

Infrared radiation (Spitzer)



Visible light (Hubble)

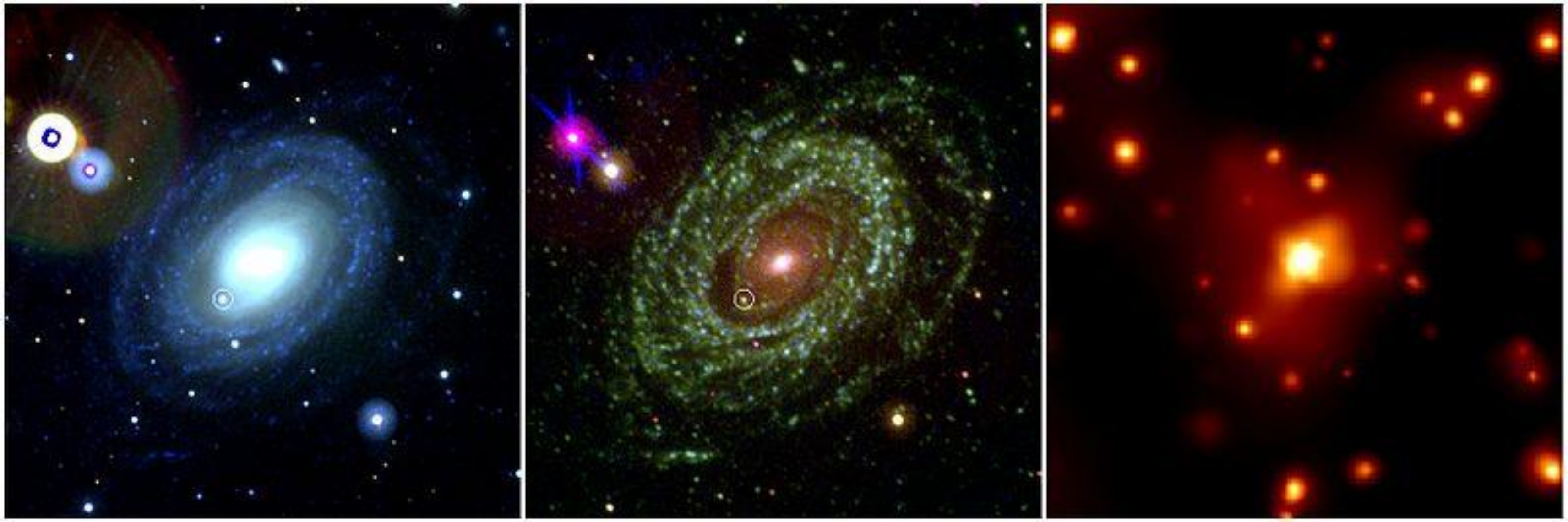


Ultraviolet radiation (Astro–1)

Low–energy X–ray (Chandra)

High–energy X–ray (HEFT)
*** 15 min exposure ***

Viewing objects in wavebands other than optical



Supernova 2005ke is a Type Ia supernova. Shown here is the explosion in optical, ultraviolet and X-ray wavelengths.

What observations in different wavebands are especially good for?

Continuum Radiation Processes

Continuum Radiation Processes

- A photon is a quantum of light, or the smallest possible packet of light at a given wavelength. It is emitted by an atom during a transition from one energy state to another;
- When we think of light as a wave, its wavelength is $\lambda = c_0 / \nu$, where ν is the frequency, and the speed of light is $c_0 \approx 3\times10^{10}$ cm/sec;
- When we think of light as particles, the energy of an individual photon is $E = h\nu$, where Planck's constant is $h = 6.626 \times 10^{-27}$ erg s.

Black Body Radiation

- Light can be produced in many ways. The most fundamental source of radiation is a so-called “black body”.
- A black body is an idealized physical body that absorbs all incident electromagnetic radiation. Because of this perfect absorptivity at all wavelengths, a black body is also the best possible emitter of thermal radiation.
- Black body radiation is thus radiation which is in thermal equilibrium and which continuous spectrum depends only on the body's temperature.

Black Body Radiation

Depending on its temperature T, a black body emits radiation according to Planck's law:

$$L_\lambda(T) = \frac{2\,h\,c_0^2}{\lambda^5}\left[\exp\left(\frac{h\,c_0}{\lambda\,k_B T}\right) - 1\right]^{-1}$$

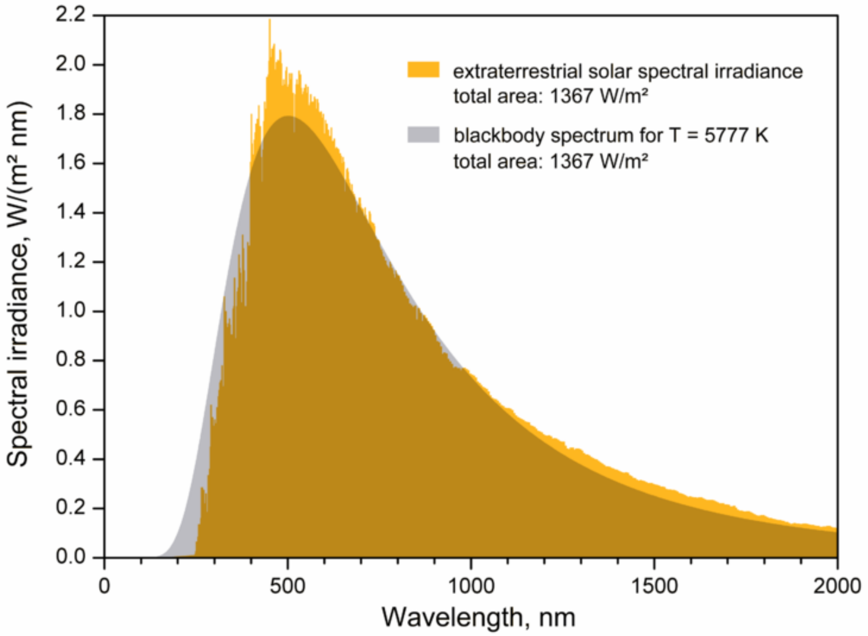
where $k_B = 1.38 \times 10^{-16}$ erg/K is the Boltzmann constant and $L_\lambda(T)$ the spectral radiance at the wavelength λ.

The corresponding formula for L_ν (T) is

$$L_\nu(T) = \frac{2\,h\,\nu^3}{c_0^2}\left[\exp\left(\frac{h\,\nu}{k_B T}\right) - 1\right]^{-1}$$

Black Body Radiation

- A black body is the extreme case of an optically thick medium. In the Universe, many plasma systems emit radiation approximately according to Planck's law, at least, in certain wavelength ranges.

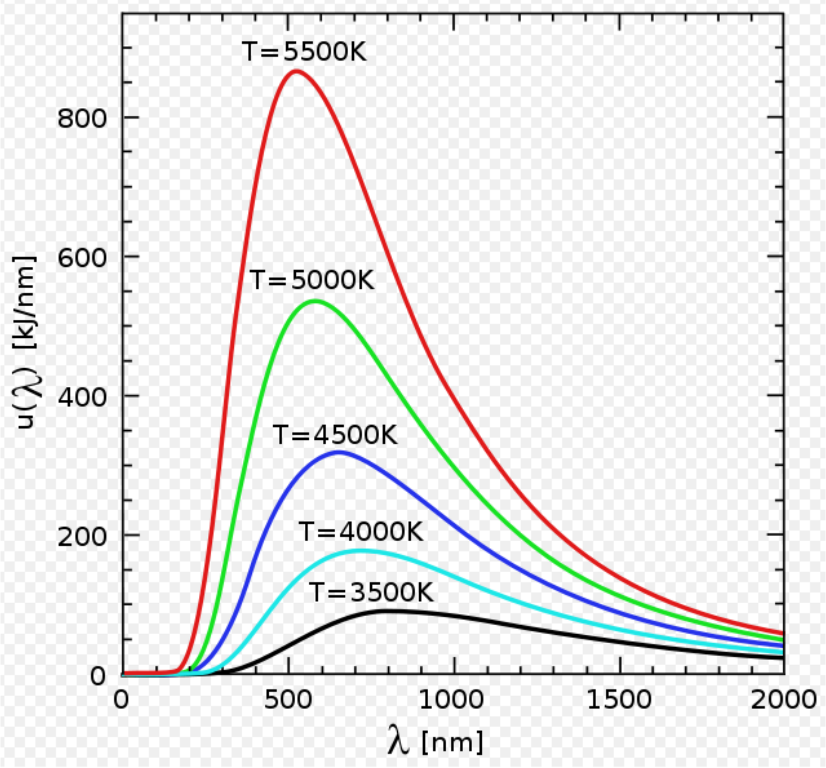


Properties of the blackbody spectrum

- As the temperature increases, the peak of the blackbody radiation curve moves to higher intensities and shorter wavelengths.
- **Wien's displacement law:**
  $\lambda_{max} \approx 0.29/T$ [cm]= $2.9x10^{7}/T$ [Å]

  λ_{max} is a function only of the temperature

  For $T=10^{7}$ K we have $\lambda_{max} \approx 2.9$ Å
  This is a typical X-ray wavelength range



L(T+ΔT) > L(T) at all λ for positive ΔT

Properties of the blackbody spectrum

- The Rayleigh-Jeans approximation is used at low frequency, particularly in Radio Astronomy.

Rayleigh-Jeans regime $h\nu \ll kT$

$$B_\nu \simeq \frac{2\nu^2}{c^2} kT$$

- Wien's law is useful at optical, UV and X-ray wavelengths.

Wien regime $h\nu \gg kT$

$$B_\nu \simeq \frac{2h\nu^3}{c^2} e^{-h\nu/kT}$$

Properties of the blackbody spectrum

The Stefan–Boltzmann law gives the total energy being emitted at all wavelengths by the blackbody:

$$E=\sigma T^4$$

where the Stefan–Boltzmann constant

$$\sigma=5.67\times 10^{-5}\ \mathrm{erg\ cm^{-2}\ s^{-1}\ K^{-4}}$$

Other radiation processes in astrophysics

- **Thermal Bremsstrahlung** (braking) radiation relates to the radiation emitted by free electrons in an ionised plasma due to encounter with ions. The braking radiation results when particles moving in an ionized plasma are accelerated by the Coulomb forces exerted by other charged particles.
- This is one of the most common continuum radiation processes in astrophysics.

Other radiation processes in astrophysics

- **Synchrotron emission** arises from the motion of relativistic electrons in a magnetic field.
- This radiation is the most important source of continuum radiation at radio wavelengths, and is seen at infra-red, optical, ultra-violet and even X-ray wavelengths.
- The synchrotron jets in radio galaxies and quasars like M87 and 3C273 can be seen at all wavelengths from low frequency radio to X-ray.

Other radiation processes in astrophysics

- **Compton scattering** is a process where energy is transferred from a photon to a free electron during an interaction between the two.
- For low photon energies ($h\nu$ **<<** $m_e c^2$) this process reduces to the classical case of Thomson scattering.
- Of more interest in astrophysics is the process where the electron is very energetic, and energy is transferred to the photon. This is known as **inverse Compton scattering radiation.**

Multi-Wavelength Observations

- Different processes dominate at different wavelengths
- To establish the physics of a source you often need to observe it at a variety of wavelengths

Multi-Wavelength Observations

X-ray binary:

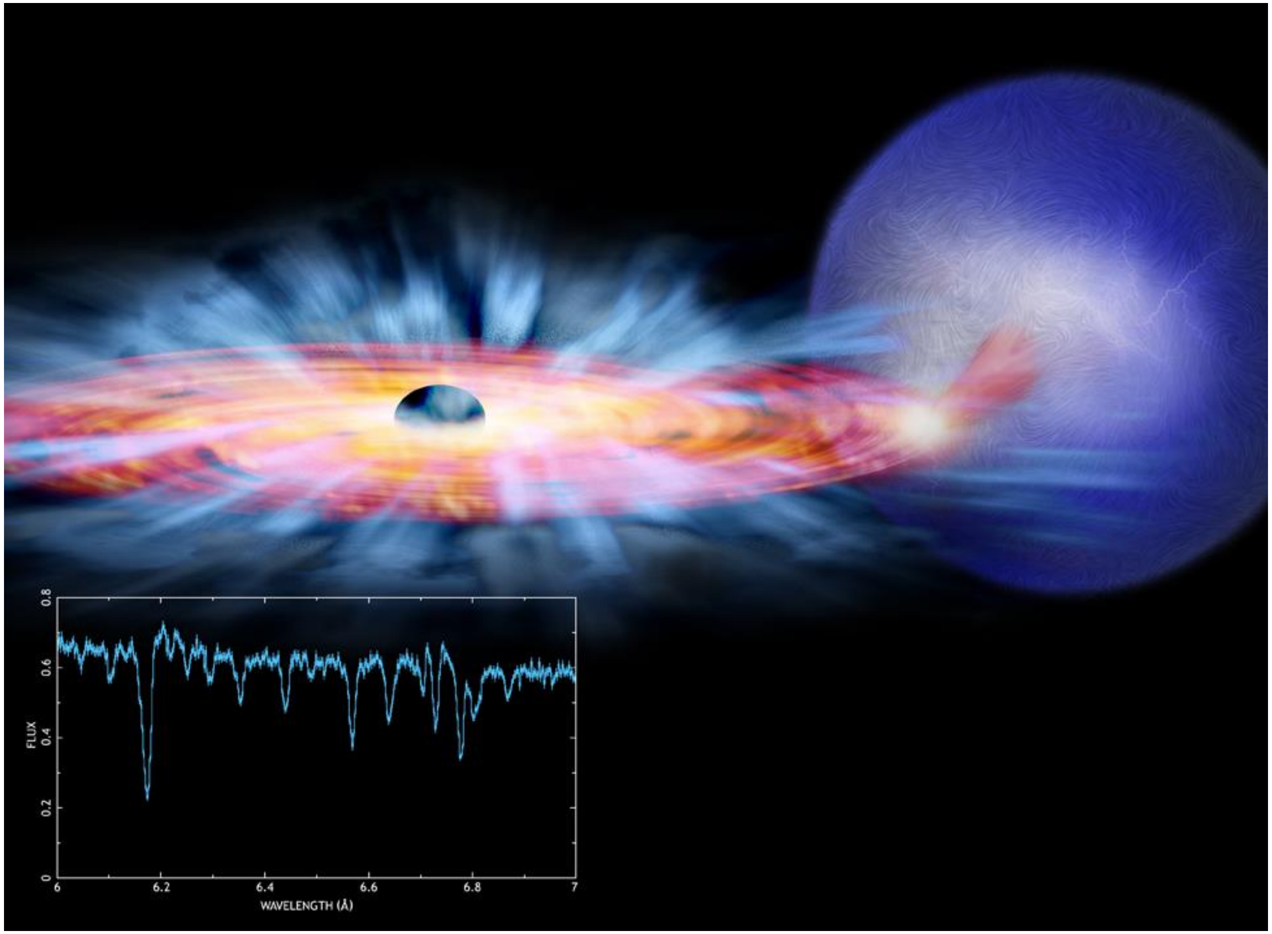
X-ray and gamma-ray

UV

Optical

Infra-Red

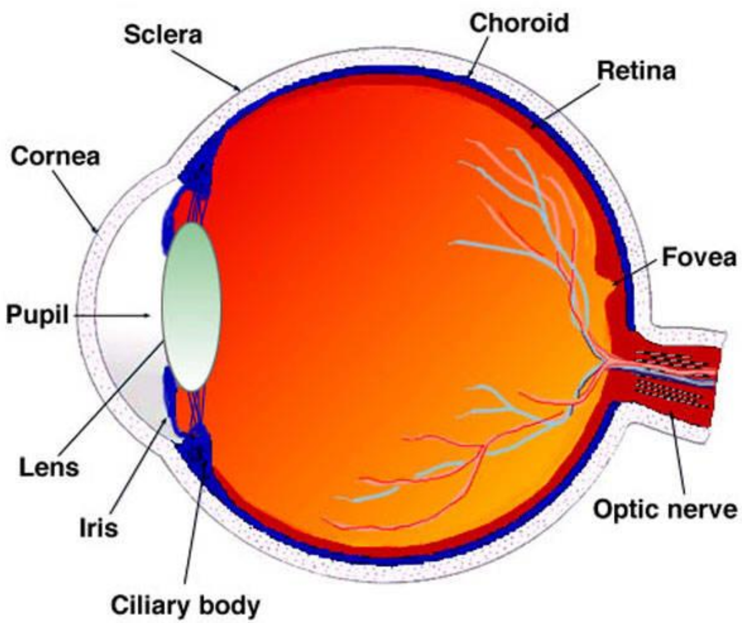
Radio



Detectors

The central theme of this course is the detection and characterization of photons with both ground-based instruments and instruments aboard spacecraft.

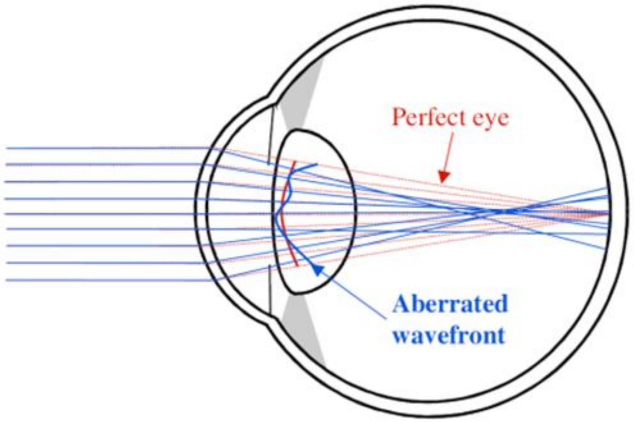
The human eye as a natural detector

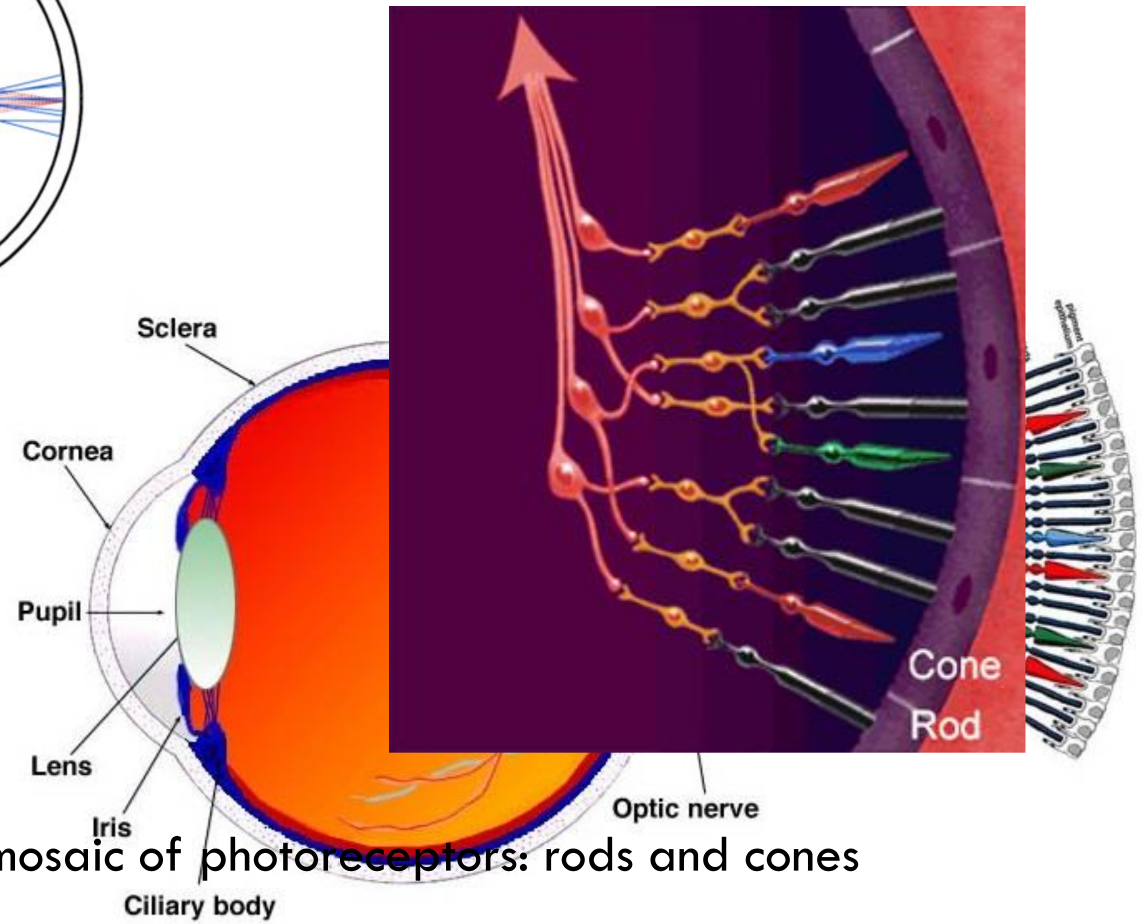


- The most fundamental of the detectors
- Rarely used for primary detection but there are still a few applications in which it performs even better than other detection systems
- The eye and brain act together in the visual process. A simple consideration of the eye on basic optical principles will be misleading

The human eye as a natural detector

A lens (as a photo-camera objective) produces an image on the retina.





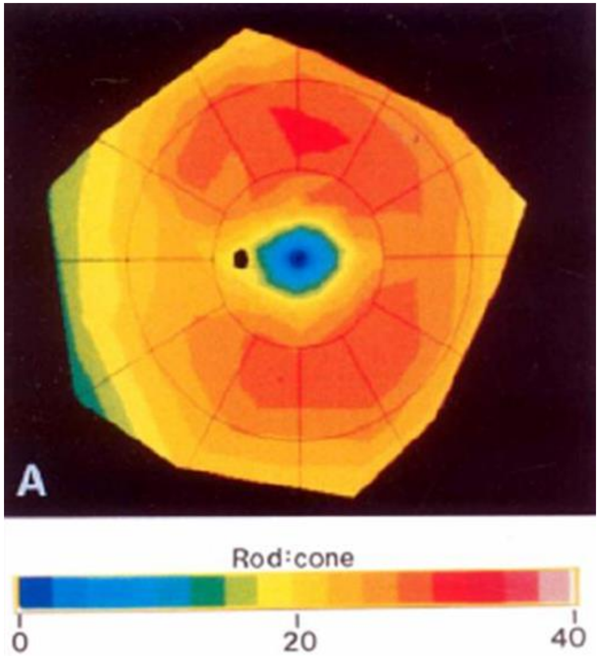
The retina is covered with a mosaic of photoreceptors: rods and cones

Photoreceptor mosaics

There are two different types of photoreceptors distributed unevenly across the retina:

- **Rods** (approximately 100,000,000) - very sensitive to low levels of light. In bright light conditions the response of the rods is saturated;
- **Cones** (approximately 5,000,000) – faster but less sensitive photoreceptors.

The rod/cone ratio is lowest in the foveal region and higher in the periphery (peripheral vision!).



Photoreceptor mosaics

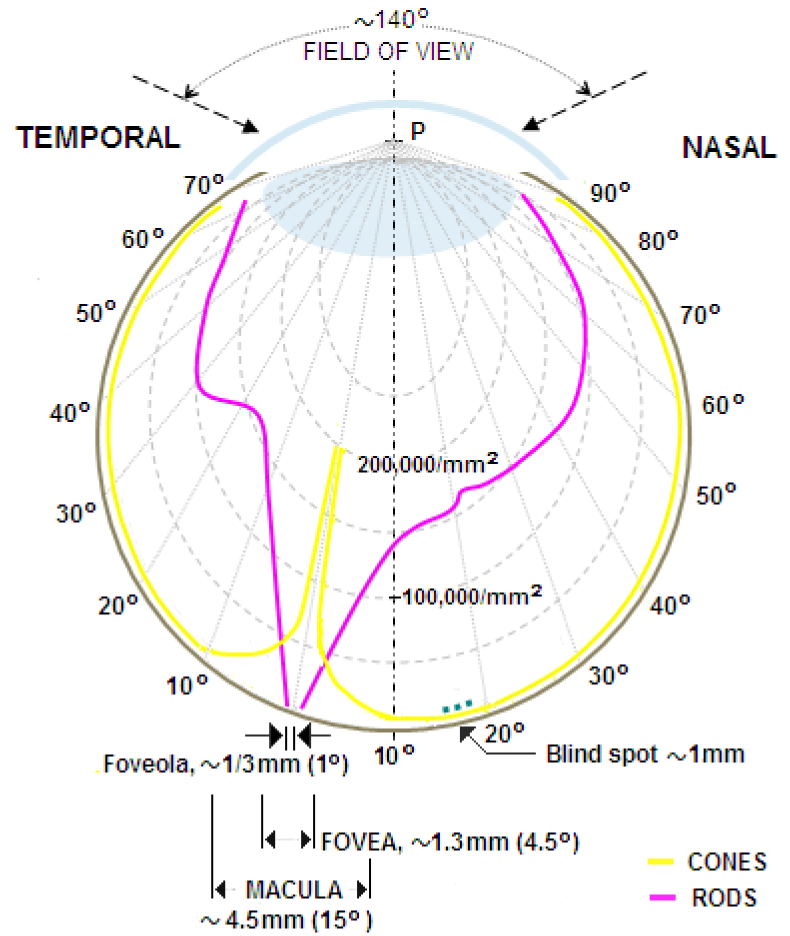
- Trade off: Sensitivity to light versus spatial resolution.
- Two parallel systems:
  - One that favour sensitivity to light (Rods)
  - One that favour resolution (Cons)

- **Rods:** low resolution image of the world that persists even in low illumination condition.
- **Cones:** high resolution image of the world in good illumination.

Photoreceptor mosaics

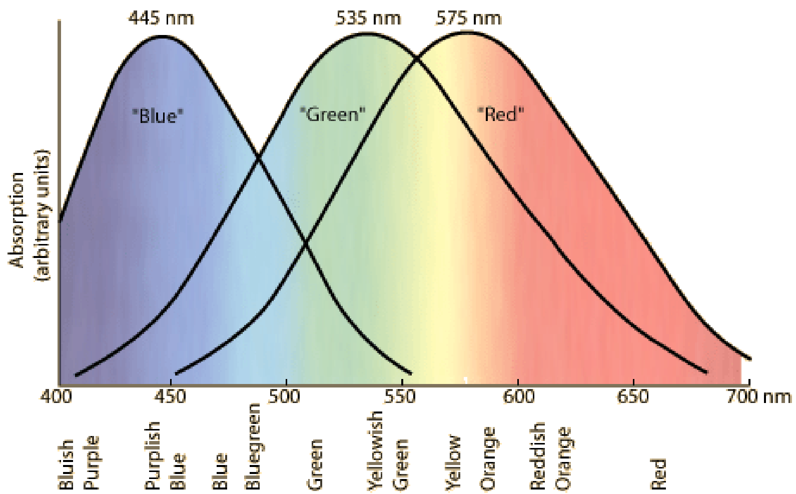
Fovea is area of highest concentration of photoreceptors

- fovea contains no rods, just cones
- approximately 50,000 cones in the fovea
- cannot see dim light sources (like stars) when we look straight at them!



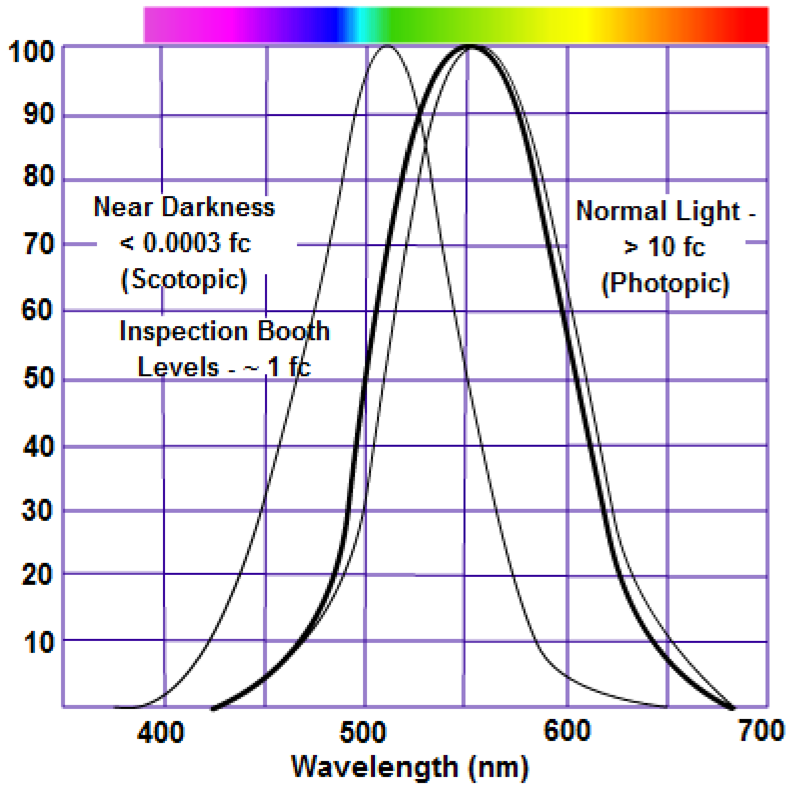
Cones and Colours

There are three types of cones, each one of them responding best to different wavelengths (short - blue, middle - green, and long - red). Their combined responses generate colour vision.



By population, about 64% of the cones are red-sensitive, about 32% green sensitive, and about 2% are blue sensitive. The "blue" cones have the highest sensitivity (~2 times) and are mostly found outside the fovea.

The Human Eye's Response to Light



The sensitivity of the cones is only about 1% of the maximum for the rods.

The Human Eye (tech. specs)

- **Quantum Efficiency (QE).** A critical performance measure of any photon detector is its quantum efficiency as a function of wavelength, $\eta(\lambda)$:

$$\eta = C/N,$$

where C is the number of counted events and N the number of incoming photons.

$$\eta_{Eye} \approx 1\%$$

The Human Eye (tech. specs)

- **Detector Linearity** is one of the most important specification for a detector that is to be used for quantitative analysis. It is defined as the range over which the detector response is linearly related to the stimulus.
- **The Weber–Fechner law** (the case of vision):
  The eye senses brightness approximately logarithmically over a fairly broad range. Hence stellar magnitude is measured on a logarithmic scale.

The Human Eye (tech. specs)

- **Angular Resolution** (spatial resolution) – describes the ability of any image-forming device to distinguish small details of an object.
  Angular resolution of the eye – 1-10 arcminutes.
- **The response time** is the time a device takes to react to a given input.
  The response time of the eye – <0.1 sec under well-lit condition and 1 sec under low light condition.