DARA
DEVELOPMENT IN AFRICA
WITH RADIO ASTRONOMY

DARA Basic Training

NAMIBIA-BOTSWANA 2019

UNIT 1: INTRODUCTION TO ASTROPHYSICS

Windhoek, 7 –18 January 2019

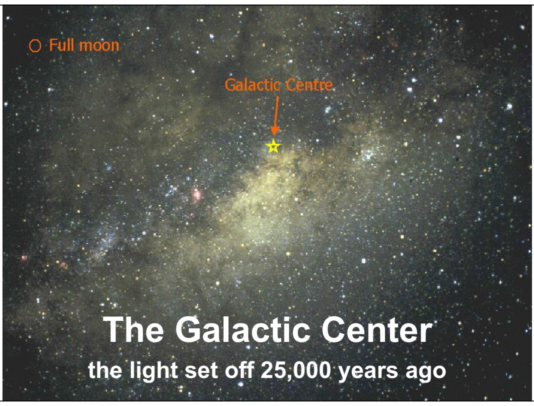
Lecture 1: Introduction

The Universe as a Time Machine

Object	Light travel time	Context
Sun	8.3 minutes	Here!
Pluto	3½ hours	Dreaming?
Nearest star	4.2 years	High school
Orion Nebula	1500 years	Vikings
Galactic Centre	25,000 years	Ice Ages

Hubble Space Telescope :
Orion Nebula

Light set off 1500 years ago

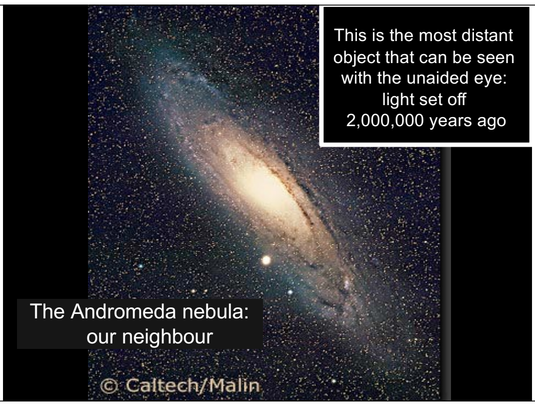


The Galactic Center

the light set off 25,000 years ago

The Universe as a Time Machine

Object	Lookback Time	Context
Andromeda Galaxy	2 million years	First humans
"Nearby" galaxy clusters	200 million years	Dinosaurs
"Distant" galaxy clusters	3 billion years	First multi-cellular life
Most distant known galaxies	12 billion years	Universe only 15% present age

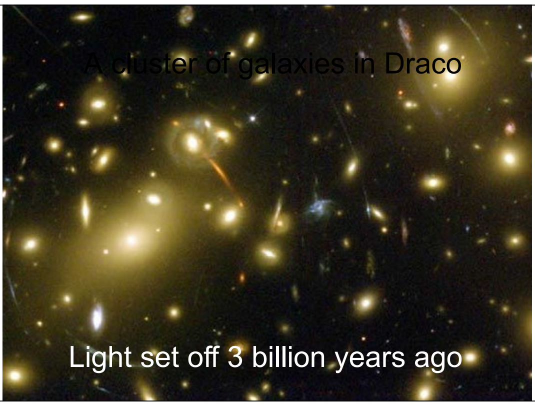


This is the most distant object that can be seen with the unaided eye: light set off 2,000,000 years ago

The Andromeda nebula: our neighbour

© Caltech/Malin

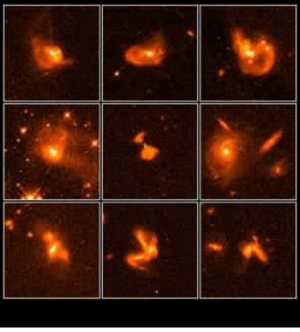
Coma cluster of galaxies

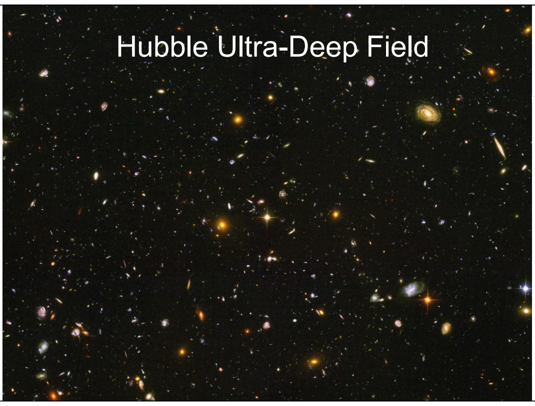


A cluster of galaxies in Draco

Light set off 3 billion years ago

Light set off 5 billion years ago, when the Earth formed.





Hubble Ultra-Deep Field

Observing the whole EM spectrum (and beyond)

Modern astronomical telescopes and detectors span the observational range from tens of metres in the radio to hundreds of TeV for the highest energy gamma rays. The classification of different astronomical wavebands is generally driven by the technology used in the detectors.

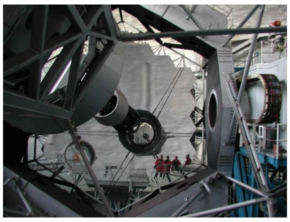
- Radio (from ~ 10 MHz to ~ 100 GHz) very highest spatial resolution because coherent detection of the EM field allows interferometry.

- Millimetre, sub-millimetre and far-infrared (~ 0.3 mm to ~ 10 μm). Bolometers onboard satellites and high-altitude terrestrial sites.

- Infrared (10 μm to 1 μm) and optical (1 μm to 0.3 μm). Almost all of "traditional" astronomy. Most stars put out most of their energy in this range. Unsurprisingly the human eye is adapted to use these wavelengths!
- Ultraviolet (0.3 μm to $\sim$ 3 nm). Satellite-borne instruments are needed because the atmosphere is opaque now; but we can still use essentially "ordinary" telescopes.
- X-rays (3 nm to $\sim 3\times10^{-12}$ m; 0.4 keV to $\sim$ 100 keV). Satellite- and rocket-borne instruments are needed. Special grating-incidence mirrors are used to focus X-rays.

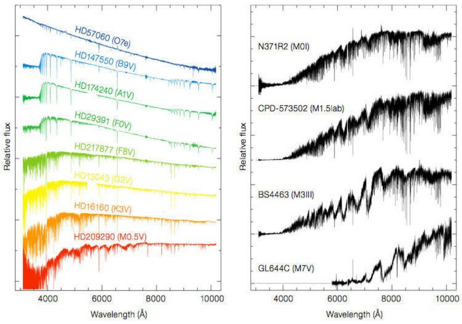
- Gamma-rays ($\sim$ 100 keV up to hundreds of GeV). Again telescopes are satellite-borne. Use similar detectors to particle physics experiments.
- Very high-energy photons and particles entering the Earth's atmosphere produce *Cherenkov radiation*. This is detected by very large "light bucket" telescopes which don't need finely-figured mirrors.
- Beyond the EM spectrum: gravitational waves, neutrinos

W.M. Keck observatory, Mauna Kea, Hawai'i.



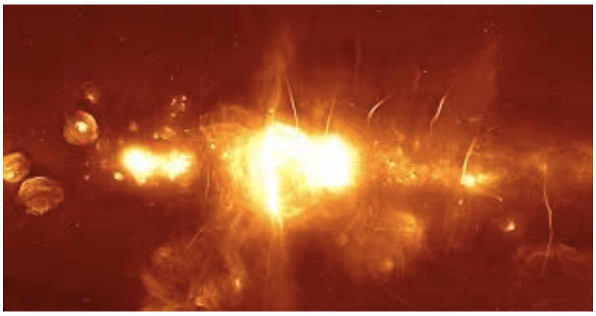
Keck telescope 10-m segmented mirror.

European Southern Observatory, Cerro La Silla, Atacama Desert, Chile
August 2011

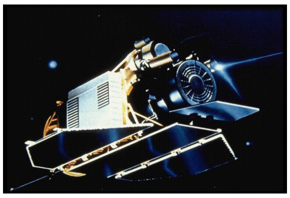


The sky as it would appear if we could see at 1.4 GHz. Almost all the sources lie far beyond the Milky Way. (Credit: NRAO / AUI / NSF)

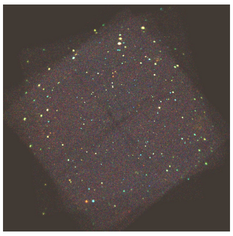
MeerKAT is now operational!



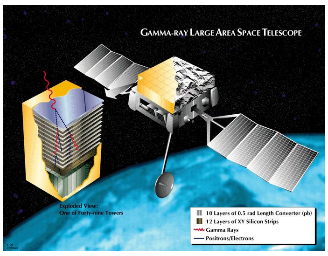
Centre of Milky Way as seen by MeerKAT



ROSAT (Röntgensatellit) X-ray observatory 1990—2011

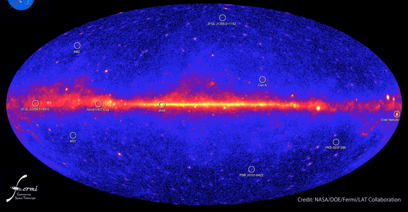


X-ray “zoom-in” from the high-resolution *Chandra* satellite.
We can now see the individual X-ray sources.

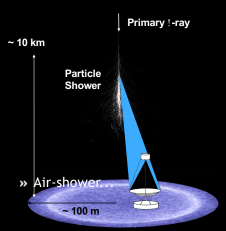


Fermi Gamma-Ray Space Telescope, launched June 11 2008.

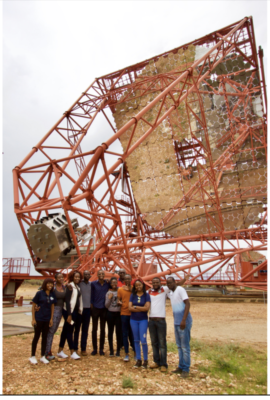
Fermi two-year all-sky map



Credit: NASA/DOE/Fermi/LAT Collaboration

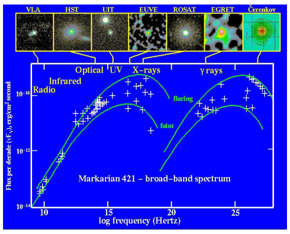


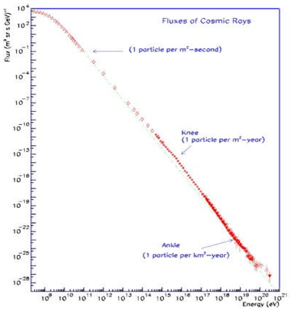
Cherenkov technique (figure from Prof J. Hinton, CTA collaboration).



DARA students at HESS, January 2017

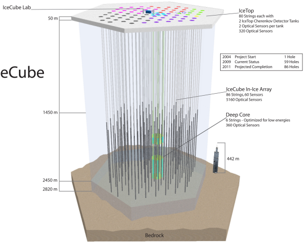
Active galaxies: broad-band spectra

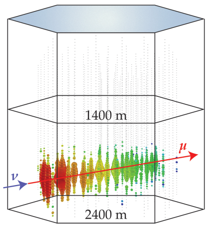


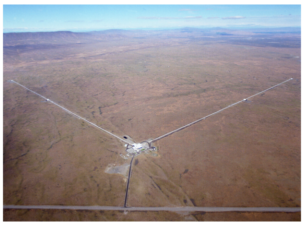


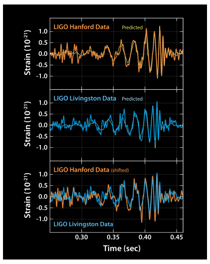
Cosmic rays – high-energy particles created by astronomical objects, hitting the earth directly

IceCube





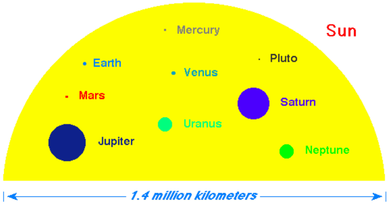


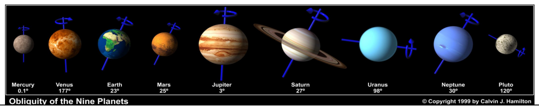


Gravitational waves

Lecture 2 : The Sun and Starlight

The Solar System

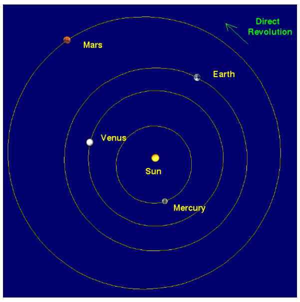




Obliquity of the Nine Planets

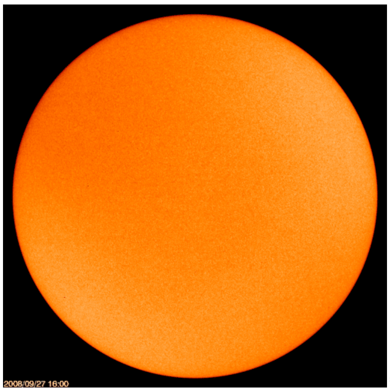
© Copyright 1999 by Calvin J. Hamilton

The Solar System



The Sun

- Properties
- Lifetime
- Energy Source
- Solar Atmosphere



science.nasa.gov

Basic parameters

- Mass = 2 x 10^{30} kg = 1 $M_{¤}$
  - (Kepler’s Law – later in the course)
- Distance = 1.5 x 10^{11} m = 1 au
  - (Kepler’s Law)
- Radius = 7 x 10^{8} m = 1 $R_{\odot}$
  - (angular size and distance)
- Luminosity = 4 x 10^{26} W = 1 $L_{\odot}$
  - (Flux and distance)

Lifetime

- Geological evidence
  - → at least 5 x 10^9 years
- Stellar evolution theory
  - 10 x 10^9 years
- Energy required

$$\begin{aligned} E &= L\tau \\ &= 4.10^{26} \times 10.10^{9} \times 3.10^{7} \\ &= 1.10^{44}\ \mathrm{J} \end{aligned}$$

Nuclear Fusion

- In the core of the Sun
  T=1 x 10^7 K
  P=10^9 atmospheres
- Sufficient for fusion of hydrogen into helium

$$4\,{}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \nu + \gamma$$

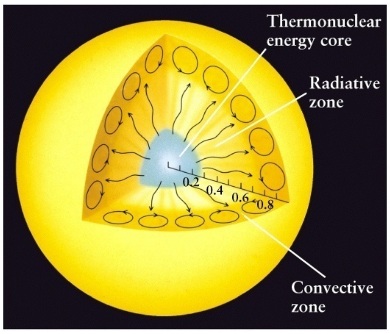
- Energy arises from mass difference

$$\mathrm{m}(4\,{}^{1}\mathrm{H}) - m({}^{4}\mathrm{He}) = 0.0286\ \mathrm{amu}$$

or 0.7% of the mass.

- Core of the Sun contains about 10% of the total mass
- Total energy available

$$\begin{aligned} &= \Delta m c^2 \\ &= 0.10 \times 0.007 \times 2 \times 10^{30} \times \left(3 \times 10^{8}\right)^2 \\ &= 1 \times 10^{44}\ \mathrm{J} \end{aligned}$$



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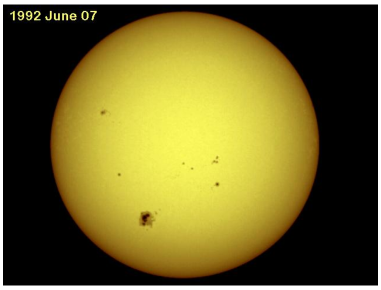
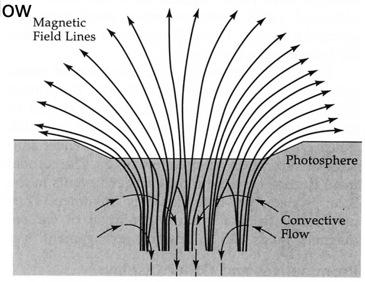
Sunspots

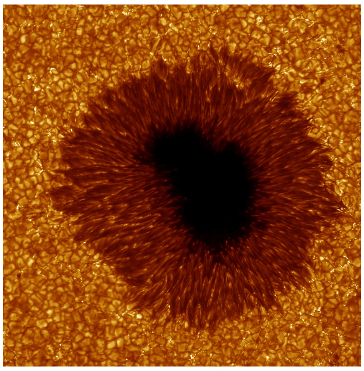


http://solarscience.msfc.nasa.gov/

- Spot cooler and lower than surroundings
- Strong (B~0.1T) vertical magnetic field prevents heat transfer from convective flow

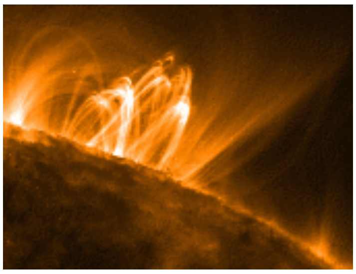


Zeilik &
Gregory
Fig 10-21

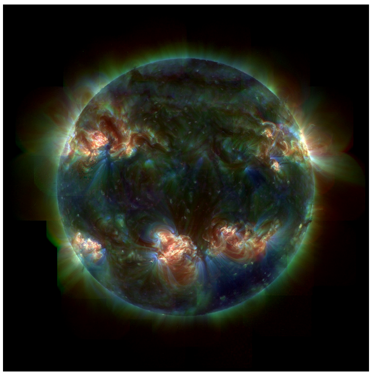


Close-up of sunspot. Credit: Royal Swedish Academy of Sciences www.solarphysics.kva.se

- Pairs of spots usually linked by loop of hot, magnetic plasma



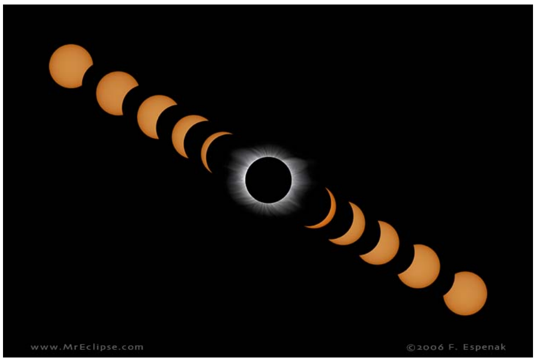
TRACE Satellite Stanford-Lockheed Institute for Space Research & NASA (trace.lmsal.com/POD/images)

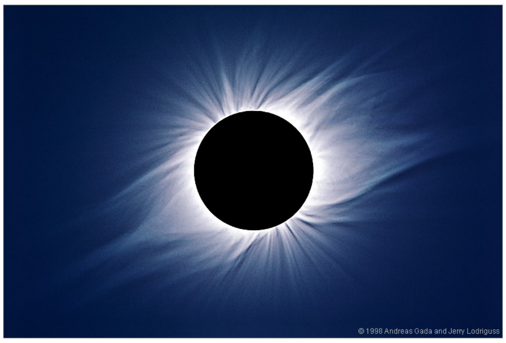


TRACE Satellite Stanford-Lockheed Institute for Space Research & NASA (trace.lmsal.com/POD/images)

Corona

- The outer atmosphere of the Sun is very hot (T~10^6 K) and tenuous
- White halo seen during eclipses extends several solar radii
- Also emits strongly in UV and X-rays observed from satellites and at radio wavelengths





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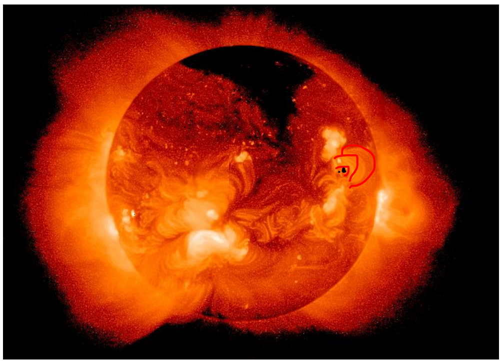

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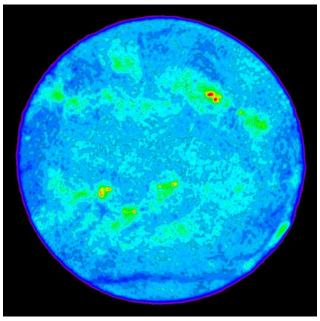


VLA radio image at 5 GHz
http://images.nrao.edu/506

The Sun: Summary

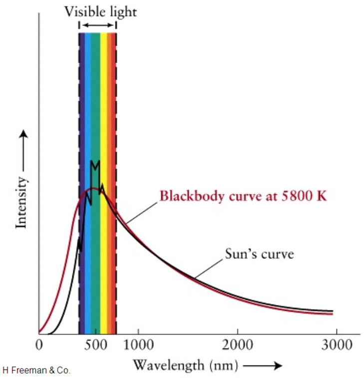
- The Sun is a very average star about half way through its 10 billion year lifetime
- Energy generated in core by nuclear fusion is transported by radiation and convection to the photosphere
- Surface activity is powered by magnetic fields generated by dynamo action through convection and differential rotation

Starlight

- Continuum spectrum
- Blackbody radiation
- Wien's Displacement Law
- Luminosity and Flux

Continuum Spectrum

- The intensity of light from the Sun peaks at a wavelength λ=500nm
- Falls off rapidly towards the blue and more steadily to the red
- Continuum spectrum is approximately that of a perfect blackbody with T=5800 K



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Blackbody Radiation

- A *blackbody* is a body which emits and absorbs radiation perfectly.
- The intensity of radiation from a perfect blackbody is described by the *Planck function*

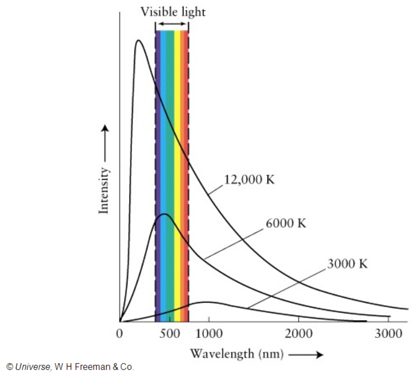
$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_\mathrm{B} T}} - 1}$$

Wien Displacement Law

- The wavelength of the peak of the emission from a blackbody of temperature *T* is given by

$$\lambda_{\max} = \frac{3.10^{-3}}{T}$$

- The hotter the blackbody the shorter the wavelength of the peak emission



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Luminosity of a Blackbody

- The total power in the radiation from a sphere of radius *R* emitting blackbody radiation with temperature *T* is

$$L = 4\pi R^2 \sigma T^4$$

where σ is the Stefan-Boltzmann constant

Effective Temperature

- The *effective* temperature of a star is the surface temperature that a spherical blackbody with the star's radius would have to have, to provide the star's luminosity. i.e.

$$L = 4\pi R^2 \sigma T_{eff}^4$$

Luminosity and Flux

- We can also determine the luminosity of the Sun (or any star) by finding the total flux of radiation reaching Earth as long as we also know the distance
- When we observe the spectrum of a star we are measuring the flux of radiation as a function of wavelength

Monochromatic Flux

- monochromatic flux of radiation f_λ is defined as the amount of energy crossing a unit area per unit time per unit wavelength interval (Js^{-1}m^{-2}m^{-1} or Wm$^{-2}\mu$m^{-1})

Total Flux

- The flux of radiation, *f*, is defined as the amount of energy crossing a unit area per unit time (Js^{-1}m^{-2} or Wm^{-2})
- It is the sum of the monochromatic fluxes over all wavelengths

$$f = \int_0^\infty f_\lambda d\lambda$$

- At a distance, *d*, from the Sun it is given by

$$f = \frac{L}{4\pi d^2}$$

- Note that flux falls with the inverse square of the distance
- Hence, the luminosity can be found from

$$L = 4\pi d^2 f$$

Starlight: Summary

- The Sun and stars radiate from their surfaces very much like a blackbody
- The effective temperature of a star can be found using Wien's law
- The luminosity of a star can be found by measuring its flux and using the inverse square law

DARA Unit 1

Classwork 1

1. The theoretical angular resolution of a single reflecting telescope is given by

$$\theta = \frac{1.2\lambda}{D} \text{ radians}$$

where D is the diameter of the telescope and λ is the operating wavelength. Radians are not a convenient unit for the small angles in astronomy so we use arcseconds. There are 60 arcseconds (") in an arcminute (') and 60 arcminutes in a degree (°). Hence, how many arcseconds are there in a radian? Using this information, evaluate the theoretical resolution in arcseconds for some well known telescopes that cover a range of different wavelengths.

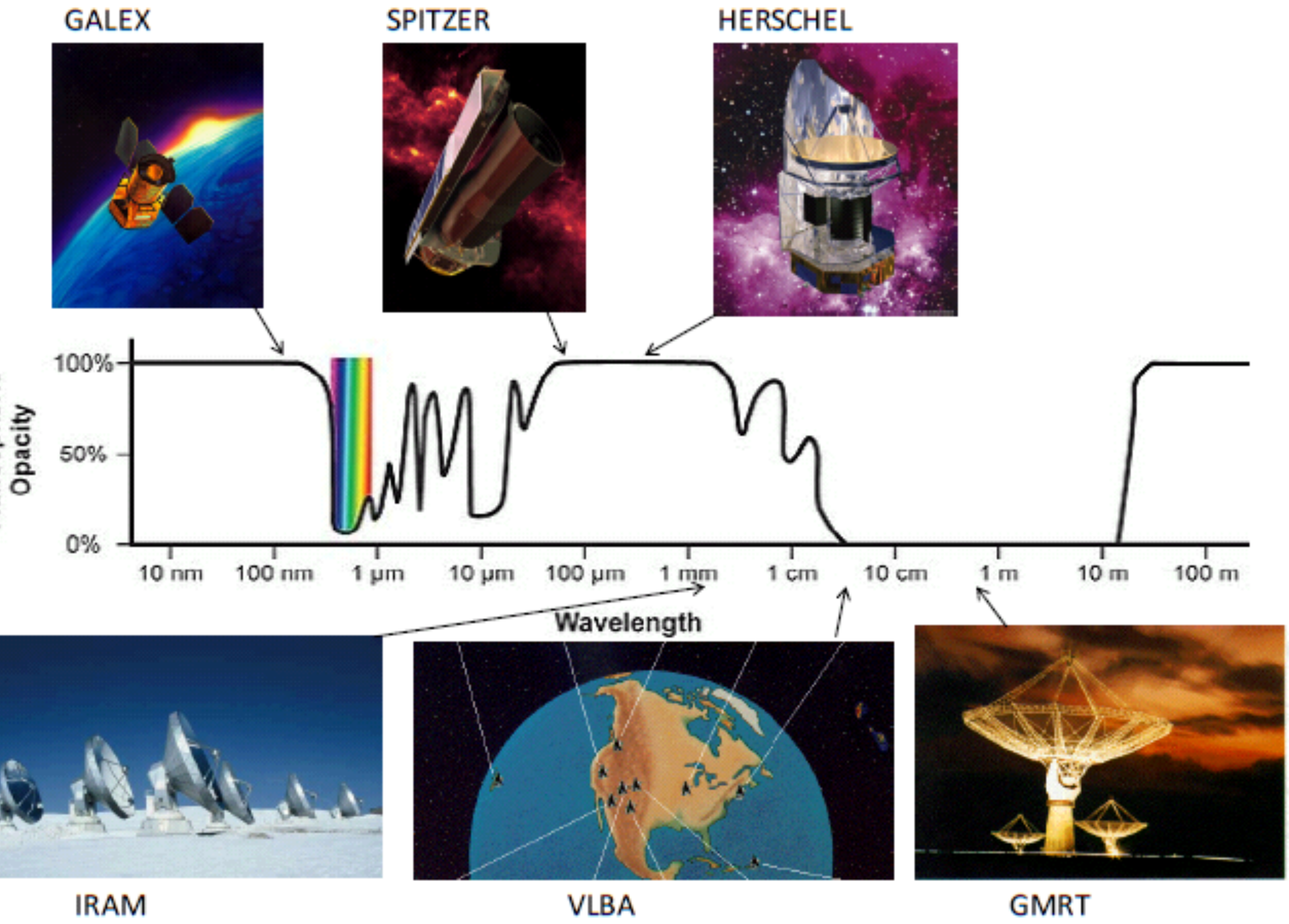
2. Arrays of more than one telescope can operate together as an interferometer. The resolution is then determined by the separation of the telescopes or baseline, b, rather than the size of the individual telescopes.

$$\theta = \frac{1.2\lambda}{b} \text{ radians}$$

Evaluate the resolution for some arrays of telescopes and compare them to the case in which the telescopes are operating individually. Why is doing interferometry difficult for arrays of large optical telescopes such as the VLTI?

3. Derive a formula for the angular size of a distant object using trigonometry and the small angle approximation, where l is the size of the object and d is the distance of the object (and they have to be in the same units). Evaluate the angular sizes in arcseconds of some common objects and compare to the angular resolutions you computed in 2 to find out which telescopes and wavelengths can resolve these objects.

4. From the atmospheric transmission plot which wavebands need to be observed from space? The HST operates in the visible waveband so why is it in space?


GALEX
SPITZER
HERSCHEL
100%
50%
0%
Opacity
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
Wavelength
IRAM
VLBA
GMRT

DARA Unit 1

Homework 1

1. Use the atomic masses of ^{1}H and ^{4}He (from any physical data handbook) to show that 0.7% of the rest mass is converted to energy during the nuclear fusion process in the Sun.

2. Calculate the effective temperature of the Sun given that it has a radius, $R=7.10^8$ m, and luminosity, $L=4.10^{26}$ W.

3. Calculate the wavelength at which the continuum emission from the star Betelgeuse with $T_{eff}=3500$ K peaks. In which part of the electromagnetic spectrum does this fall?

4. Evaluate the total flux of radiation from the Sun reaching the Earth. How would this compare with the flux from one of the nearest stars Alpha Centauri – a solar like star 1.3 pc away? (1 pc = 3.1×10^{16} m).

5. Assuming that the Sun emits like a blackbody such that the flux at the surface is given by $f_\nu = \pi B_\nu$ estimate the radio flux observed at the Earth at a frequency of 5 GHz. Convert this from SI units ($Jm^{-2}s^{-1}Hz^{-1}$) to the commonly used unit of flux in radio astronomy – the Jansky (Jy) – where 1 Jy = 10^{-26} $Jm^{-2}s^{-1}Hz^{-1}$. Then calculate what this radio flux would be if we were to observe Alpha Centauri from Earth.