Researchers in Schools

Introduction to Space Instrumentation

Key Stage 4 Programme

Pupil Name	
Coursebook Designed by	Dr. A Duara

Contents

Timetable and Assignment Submission 1
Timetable – Tutorials 1
Timetable – Homework Assignments 1
Assignment Submission – Lateness and Plagiarism 1
Course Rationale 2
Uni Pathways Mark Scheme 2020 – science-based assignments 3
Baseline Assignment (essay based): Pupil Feedback Report 5
Final Assignment (essay based): Pupil Feedback Report 6
Subject Vocabulary 8
Launch Event 9
Tutorial 1 – Introduction to Space Instrumentation 10
What is the Purpose of Tutorial 1? 10
Space Instrumentation Physics 10
Tutorial 2 – The Cherenkov Telescope Array 16
What is the Purpose of Tutorial 2? 16
Introduction to Cherenkov Telescope Array 16
Operational Principle: Imaging Atmospheric Cherenkov Technique 16
Structure of CTA: Dividing the array into small sized, medium sized and large sized telescopes 18
Tutorial 3 – Silicon Photomultiplier Detectors and Compact High Energy Camera 24
What is the Purpose of Tutorial 3? 24
Tutorial 4 – Introduction to Very High Energy Astrophysics-1 27
What is the Purpose of Tutorial 4? 27
Supernovae 27
Pulsars 27
Binary Star Systems 28
Tutorial 5 – Title 30
What is the Purpose of Tutorial 5? 30
Introduction to the History of Gamma Ray Astronomy 30
Final Assignment 32
Tutorial 6 – Feedback tutorial 33
What is the Purpose of Tutorial 6? 33
Final assignment feedback from your Uni Pathways Teacher 33
Tutorial 7 – Final tutorial 35
Appendix 1 – Referencing correctly 37
How do I reference? 38
Notes 39

Timetable and Assignment Submission

Timetable – Tutorials

Tutorial	Date	Time	Location
1			
2			
3			
4			
5			
6 (Feedback)			
7 (Feedback)			

Timetable – Homework Assignments

Homework Assignment	Description	Due Date
Tutorial 1		
Tutorial 2		
Tutorial 3		
Tutorial 4		
Tutorial 5		

Assignment Submission – Lateness and Plagiarism

Lateness	
Submission after midnight on 9th August	10 marks deducted
Plagiarism	
Some plagiarism	10 marks deducted
Moderate plagiarism	20 marks deducted
Extreme plagiarism	Automatic fail

Course Rationale

Space instrumentation is one of the most exciting branches of physics. It is the perfect combination of physics and engineering. This branch of physics deals with research and development of advanced scientific instruments that are responsible for expanding our understanding of the universe. From instruments used in particles accelerators that look into the smallest particles in the universe to giant space telescopes that look into the largest objects in the universe, the branch of instrumentation physics deals with the most cutting-edge technologies.

In this course you will be introduced to the physics behind space instrumentation and learn about some of the most exciting space mission undertaken by various space agencies and research institutes. You will learn about:

a. The difference between space-based instrumentation and ground based instrumentation

b. Instruments used in NASA's Hubble Space Telescope

c. Instruments used in the Mars Rover

d. Instruments used in the ground based Very Large Telescope (VLT)

e. Instruments used in the Cherenkov Telescope Array (CTA)

f. Operational principle of the novel silicon photomultiplier detector

g. Sources of very-high-energy astrophysics

h. How are gamma rays detected

This course will be your very first step into becoming a space-scientist

Uni Pathways Mark Scheme 2020 – science-based assignments

	Subject Knowledge	Critical Thinking	Written Communication
1st	The work shows a depth of knowledge and understanding of key concepts and scientific methods, through engaging with relevant sources. Knowledge is used to build and support highly effective scientific arguments and explanations.	Analyses key scientific evidence, arguments, and reasoning. Interprets meaning and makes connections. Identifies and critically evaluates key scientific arguments and evidence, deciding on their credibility, strength, and relative significance, drawing convincing conclusions.	The work has a coherent flow and is well structured. The writing style is appropriate; scientific language and key scientific terms are used accurately and effectively to support the arguments and explanations made. There are no, or very few, errors in spelling or grammar. Consistent referencing, appropriate paragraphing and use of correctly labelled tables and graphs matching the style taught in the course.
2:1	The work shows an understanding of key concepts and scientific methods, drawing on relevant sources. Knowledge is used to build and support effective scientific arguments and explanations.	Analyses relevant scientific evidence, arguments, and reasoning. Identifies and critically evaluates relevant scientific arguments and evidence, deciding on their credibility and strength, drawing reasonable conclusions. Shows some understanding of the relative value of evidence and arguments.	The work is well-structured. The writing style is appropriate; scientific language and key terms are used correctly. There are few errors in spelling or grammar. Mostly consistent referencing and use of tables and figures; matching the style taught in the course.
2:2	The work shows an understanding of key concepts and scientific methods, with no major misconceptions. Beginning to apply this knowledge to build and support effective scientific arguments and explanations.	Identifies and uses basic scientific evidence, arguments, and reasoning. Showing some understanding of the quality of scientific arguments and evidence. Not yet showing understanding of the relative value of evidence and arguments.	The work has some structure. The writing style can sometimes be informal; occasionally scientific language and key terms are not used when it would be appropriate to do so. There are some errors in grammar and spelling do not get in the way of communicating the content. Referencing has some consistency; matching the style taught in the course Limited use of tables and graphs.
3rd	Shows a developing understanding of key concepts and scientific methods, with some misconceptions.	Beginning to analyse scientific evidence, arguments, and reasoning.	The grammar, spelling, style, and structure of the work need improving in order

	Does not yet apply this knowledge to build and support scientific arguments and explanations.	Describes evidence and arguments, while not yet evaluating them.	to communicate ideas to the reader. Scientific language, key terms and references are not always used correctly. Limited, or no use of tables and graphs.

Baseline Assignment (essay based): Pupil Feedback Report

Name of Pupil	
Name of School	
Name of RIS teacher	
Title of Assignment	

How your assignment is graded:

Grade	Marks	What this means
1st	70+	Performing to an excellent standard at A-level
2:1	60-69	Performing to a good standard at A-level
2:2	50-59	Performing to an excellent standard at GCSE
3rd	40-49	Performing to a good standard at GCSE
Working towards a pass	0-39	Performing below a good standard at GCSE
Did not submit	DNS	No assignment received by The Brilliant Club

Lateness	
Any lateness	10 marks deducted
Plagiarism	
Some plagiarism	10 marks deducted
Moderate plagiarism	20 marks deducted
Extreme plagiarism	Automatic fail

Marks

OVERALL MARK / 100		FINAL MARK / 100 (including any deductions)	
DEDUCTED MARKS		FINAL GRADE	

If marks have been deducted (e.g. late submission, plagiarism) the teacher should give an explanation in this section:

Mark Breakdown and Feedback

Subject knowledge	
	mark
Critical thinking	
	mark
Written communication	
	mark

Final Assignment (essay based): Pupil Feedback Report

Name of Pupil	
Name of School	
Name of RIS teacher	
Title of Assignment	

How your assignment is graded:

Grade	Marks	What this means
1st	70+	Performing to an excellent standard at A-level
2:1	60-69	Performing to a good standard at A-level
2:2	50-59	Performing to an excellent standard at GCSE
3rd	40-49	Performing to a good standard at GCSE
Working towards a pass	0-39	Performing below a good standard at GCSE
Did not submit	DNS	No assignment received by The Brilliant Club

Lateness	
Any lateness	10 marks deducted
Plagiarism	
Some plagiarism	10 marks deducted
Moderate plagiarism	20 marks deducted
Extreme plagiarism	Automatic fail

Marks

OVERALL MARK / 100		FINAL MARK / 100 (including any deductions)	
DEDUCTED MARKS		FINAL GRADE	

If marks have been deducted (e.g. late submission, plagiarism) the teacher should give an explanation in this section:

Mark Breakdown and Feedback

Subject knowledge	
	mark
Critical thinking	
	mark
Written communication	
	mark

How your assignment is graded:

Grade	Marks	What this means
1st	70+	Performing to an excellent standard at A-level
2:1	60-69	Performing to a good standard at A-level
2:2	50-59	Performing to an excellent standard at GCSE
3rd	40-49	Performing to a good standard at GCSE
Working towards a pass	0-39	Performing below a good standard at GCSE
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Marks

OVERALL MARK / 100		FINAL MARK / 100 (including any deductions)	
DEDUCTED MARKS		FINAL GRADE	

If marks have been deducted (e.g. late submission, plagiarism) the teacher should give an explanation in this section:

Mark Breakdown and Feedback

Subject knowledge	
	mark
Critical thinking	
	mark
Written communication	
	mark
Problem Set	
Comment	*mark*

Subject Vocabulary

Word	Definition	In a sentence
Supernova	An exploding star	The star turned into a supernova.
Specialisation	Focusing your work on something specific	The football player specialises in training to be a goal keeper
Particle Accelerator	Large machines that are capable of accelerating particles like protons into very high speeds	The Large Hadron Collider is a well known particles accelerator
Detectors	a device used to detect, track, and/or identify ionizing particles	The Hubble Space Telescope uses expensive detectors
Array	Group	An array of 100 telescopes were built in Chile.
Cosmic	Relating to the universe or the cosmos	Space telescope detect cosmic particles
Binary stars	A system of two stars orbiting each other	Binary stars can emit gamma rays
Neutron star	the collapsed core of a massive supergiant star	Neutron stars are extremely dense
Planetary Mission	Missions planned to visit other planets	Curiosity rover is an interplanetary mission
Gamma rays	Most energetic part of the electromagnetic spectrum	Blackholes can emit gamma rays

Launch Event

The launch event is your opportunity to learn more about this course and Uni Pathways. You will watch some videos, listen to your teacher and have some discussion. Below is some room to make notes for some of the videos you will watch during the event.

Virtual Campus Tours

Notes…

The Scholars Programme Alumni

Notes…

Student Ambassadors

Notes…

Tutorial 1 – Introduction to Space Instrumentation

What is the Purpose of Tutorial 1?

- Introduce the field of Space Instrumentation Physics
- Learn new technical words from instrumentation physics

Space Instrumentation Physics

The field of physics is branched into many specialisations. However, the basics of each specialisation is fundamental physics that you have learnt in school. The following list shows a few popular examples of physics specialisations:

1. Astrophysics: Physicists who study the science behind the universe and its contents such as star formation, supernova, blackholes, galaxies etc. Quite often the term astrophysics is used interchangeably with observational astronomy. The daily work for this specialisation often involves using large telescopes to gather data and analysing it using programming to understand the working principle of the universe.
2. Particle Physics: Physicists who study the particles that make up the universe. This includes studying the nature of particles such as protons, neutrons, electrons, positrons, muons etc. One of the most popular recent discoveries in particle physics is the discovery of the Higgs Boson. Particle physicists often work in large particle accelerators such as the Large Hadron Collider (LHC) in CERN and Diamond Particle Accelerator at Harwell Science and Innovation Campus.

Figure 1: Control room from CERN [Source: CERN]

3. Theoretical Physics: Theoretical physicists are heavily involved with the mathematics side of physics. They use mathematical models, theoretical computations and computer modelling to understand and predict the nature of different phenomenon in the universe.
4. Instrumentation Physics: Instrumentation physicists work on the applied side of physics. It's a close mixture of engineering and physics. In this branch, physicists work on physics instruments for various applications such as medical physics (for eg. MRI machines), particle physics (for eg. Detectors for particle accelerators) and astrophysics (for eg. Instruments for telescopes in space and ground).

Q1 Based on your current interests, which branch of physics do you think would interest you the most? Give some reasons
Ans.

This course will give you a detailed introduction to the field of instrumentation physics for astrophysics. Instrumentation missions for astrophysics can be broadly classified into **space-based instrumentation missions** and **ground-based instrumentation missions**.

Space based instrumentation: These are instruments that are designed for spacecrafts that are launched into orbit. Since they are designed to be operated in outer space, they are free from atmospheric hindrances while observing the universe. However, due to the cost of launching into space, size is a limiting factor. The following section will give an overview of two important space missions and the instruments onboard these spacecrafts.

1. **Hubble Space Telescope:** The Hubble Space Telescope (HST) was launched in 1990, onboard the space shuttle Discovery. The primary manufacturers of the HST were Lockheed Martin and Perkin Elmer. It orbits around Earth in the Low Earth Orbit (LEO). The current instruments onboard HST are:
   - 1.1 **Advanced Camera for Surveys (ACS):** The ACS has the capability to look at wide areas of the skies. It was designed to view the universe at visible and red wavelengths. The detectors used onboard this instruments were Charged Coupled Devices (CCDs)
   - 1.2 **Cosmic Origins Spectrograph (COS):** This instrument does not capture images. COS was designed to perform spectroscopy.
   - 1.3 **Space Telescope Imaging Spectrograph (STIS):** STIS is also designed to carry out spectroscopy of to investigate the chemical content, temperature and motion of planets, comets, stars, interstellar gas and galaxies.
   - 1.4 **Wide Field Camera 3 (WF3):** Wide Field Camera 3 is the main imager on the telescope. It has a camera that records visible and ultraviolet (UV) wavelengths of light. The WF3 instrument will be the focus of your Tutorial 2 and 3. We will be learning in much more details about the working principle of the optics and electronics behind WF3.
   - 1.5 **Fine Guidance Sensor (FGS):** The FGS was designed to precisely point and stabilize its gaze on the sky so that the other scientific instruments on HST can collect images or spectra of astronomical objects accurately.

Figure: Hubble Space Telescope [Source: NASA]

Literature Review:
Literature review is one of the most important and fun part of university level research work. This is where you are required to simply find articles and papers on a given topic. You are not necessarily required to read each of these articles in details while doing literature review. You are only creating a database of sources. An example of this will be shown in Tutorial 1.

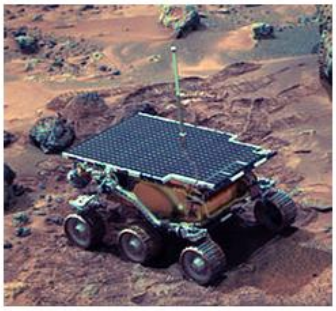
Baseline Assignement Research work:
Q2 Carry out a literature review and obtain five different academic articles/papers on:

1. Advanced Camera for Surveys
2. Cosmic Origins Spectrograph
3. Space Telescope Imaging Spectrograph
4. Wide Field Camera 3
5. Fine Guidance Sensor

Instrument	Title	Style
1. Advanced Camera for Surveys	1. 2. 3. 4. 5.	
2. Cosmic Origins Spectrograph	1. 2. 3. 4. 5.	
3. Space Telescope Imaging Spectrograph	1. 2. 3. 4. 5.	

4.	**Wide Field Camera 3**	1. 2. 3. 4. 5.	
5.	**Fine Guidance Sensor**	1. 2. 3. 4. 5.	

2. **Perseverance Mars Rover:** A Mars Rover is a buggy styled vehicle, capable of moving around the surface of Mars. Until now, 6 Rovers have been successfully operated on the Martian surface. These are:



Sojourner

Opportunity

Spirit

Curiosity

Perseverance

Zhurong

Perseverance Rover was launched in 30 July 2020. Perseverance has got seven primary instruments onboard:

2.1 **Mars Oxygen ISRU Experiment (MOXIE):** MOXIE has been developed with the primary goal of producing oxygen on Mars.

2.2 **Mastcam-Z:** The Mastcam-z is a multiple camera system, designed to take panoramic and stereoscopic photographs of the surface of Mars.

2.3 **Mars Environmental Dynamic Analyzer (MEDA):** MEDA was designed to measure the Martian weather, atmospheric pressure, temperature and humidity, wind speed and direction.

2.4 **Scanning Habitable Environments with Raman & Luminescence for Organics and Chemicals (SHERLOC):** SHERLOC has been designed to look for signs of past Martian microbial life by studying potential materials that have been altered by watery environments.

2.5 **Planetary Instrument for X-ray Lithochemistry (PIXL):** This instrument consists of an x-ray spectrometer capable of identifying chemical elements at a very small scale to look for evidence of past microbial life.

2.6 **Radar Imager for Mars' Subsurface Experiment (RIMFAX):** RIMFAX is the forst radar based tool on Mars designed to investigate potential deposits of underground ice, water, and salt.
2.7 **SuperCam:** SuperCam is an instrument designed to scan particles from upto 7 meters. This instrument also looks for sign of life on Mars.

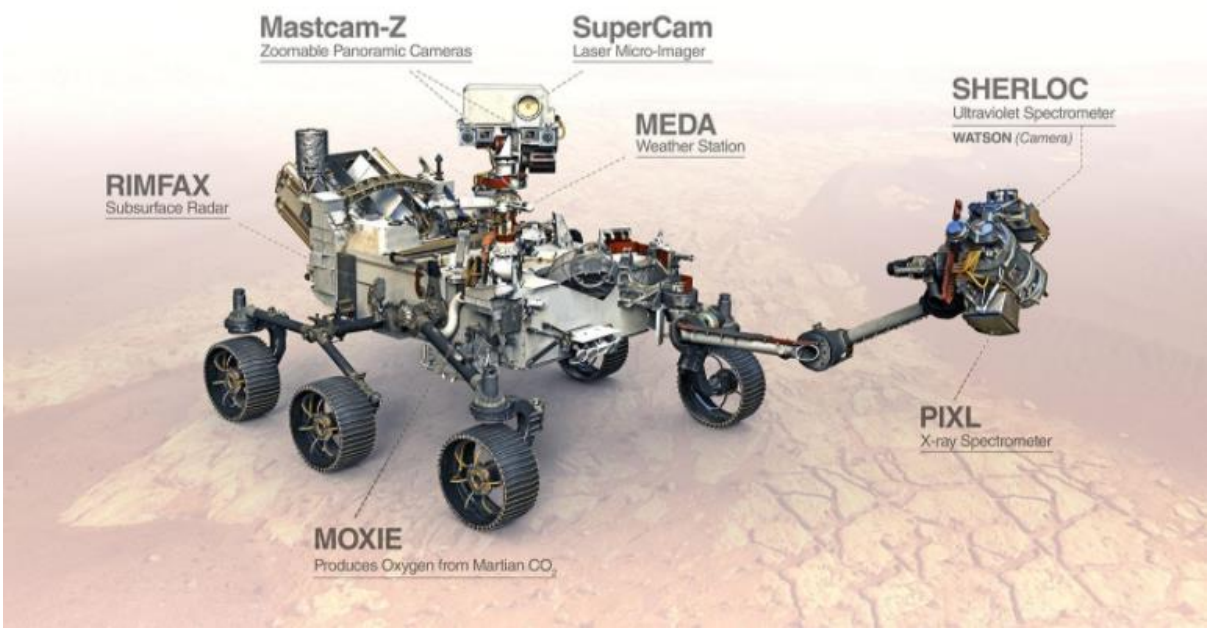


Figure: Primary Instruments onboard NASA's Perseverance Rover

Baseline Assignment Research work:
Q3 Carry out a literature review and find one research paper on each instrument onboard the Perseverance Mars Rover:

Instrument	Title	Lead Author
1. MOXIE	1.	
2. Mastcam-Z	1.	
3. MEDA	1.	
4. SHERLOC	1.	
5. PIXL	1.	
6. RIMFAX	1.	
7. SuperCam	1.	

Ground based instrumentation: These are instruments that are designed to be operated from the ground. They can be easily upgraded with time and are not restricted by size or time of operation. Many ground-based telescopes have been designed and developed over the century. The following section will briefly discuss two such telescopes:

1. **Very Large Telescope:** The Very Large Telescope (*yes, that's what the astronomers named it!)* is operated by the European Southern Observatory on Cerro Paranal in the Atacama Desert of northern Chile. It consists of four telescopes, each with a diameter of 8.2 meter allowing a combined diameter of 32.8 m (aprox 1291 inches). To give you an idea of how big this is, telescopes owned by amateur astronomers usually range from 3 inch to 16 inches!

Figure: The Very Large Telescope (VLT)

2. **Cherenkov Telescope Array:** The Cherenkov Telescope Array (CTA) is the upcoming next generation ground based gamma ray observatory. Once completed, CTA will be the largest gamma ray observatory in the world. CTA will consist an array of over 100 telescopes spread across Chile (Southern Hemisphere) and Las Palma (Northern Hemisphere). There will be three categories of telescopes in this array: The Small Sized Telescopes (SST), The Medium Sized Telescopes (MST) and the Large Sized Telescope (LST). Each telescope will look into different parts of the gamma ray spectrum.

Research work:
Q4. Make a list of 5 other ground-based observatories.
1. _____
2. _____
3. _____
4. _____
5. _____

Baseline Assignment:

Q1. Complete the research-based exercises in the orange boxes.

Q2. Based on your literature review, write a 500 word summary report on any of your chosen paper.

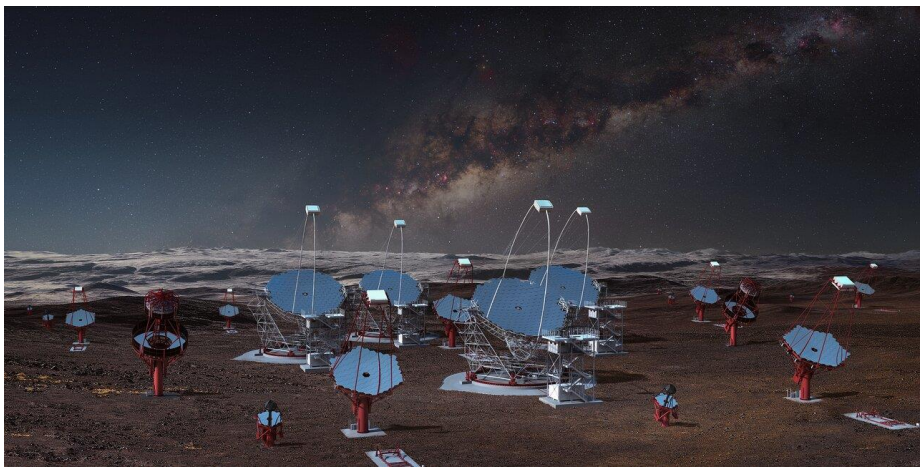
Tutorial 2 – The Cherenkov Telescope Array

What is the Purpose of Tutorial 2?

- Objective 1
- Objective 2
- Objective n

Introduction to Cherenkov Telescope Array

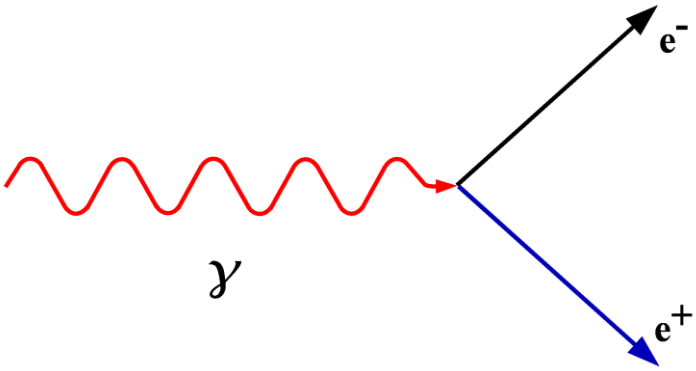
The Cherenkov Telescope Array (CTA) is the next generation ground based gamma ray observatory. It is a huge international collaboration of over 1400 scientists and 31 countries. Once completed CTA will be the largest gamma ray telescope to be ever built. Tutorial 2 and 3 will teach you further details on the operational principle, structure and scientific goal of CTA.



Operational Principle: Imaging Atmospheric Cherenkov Technique

To detect gamma rays, CTA uses a technique called *Imaging Atmospheric Cherenkov Technique* (IACT). When very high energy gamma rays travel towards Earth, they reach the Earth's atmosphere and interact with the atmospheric particles. This interaction leads to a phenomenon called pair creation.

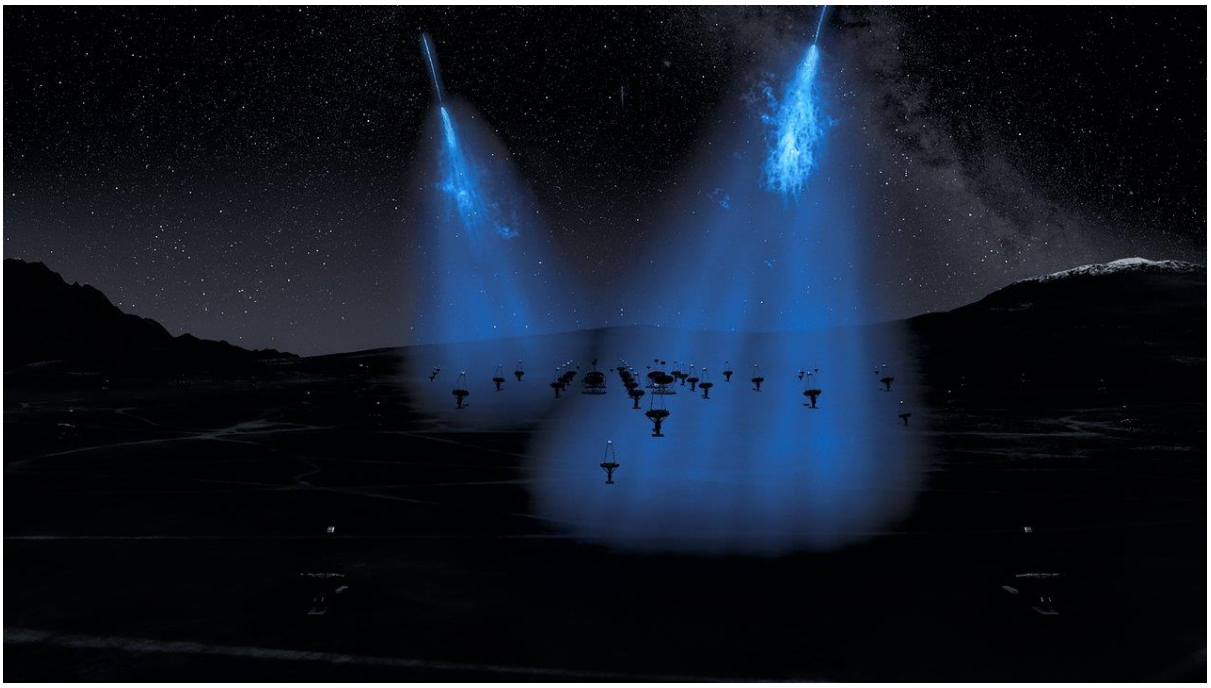
Pair creation is a process where a photon creates subatomic particles and its anti-particles. For example, a photon creating an electron-positron pair.



The gamma ray photons create an electron-positron pair in the atmosphere. These electron-positron pairs create further electron-positron pairs and so on. **These particles travel faster than speed of light in air!**

How does something travel faster than speed of light in air?
You have always learnt that nothing can travel faster than speed of light. That is true. Nothing can travel faster than the speed of light in vacuum. However, when light travels through air, the speed of light decreases slightly. And particles can go faster than speed of light in air.

When particles cross the speed of light in air, a fantastic phenomenon can be observed. It releases a blue flash of light called **CHERENKOV LIGHT. This light lasts for only 5 to 10 ns. This phenomenon takes place all the time in our sky, every time a gamma ray photon hits the atmosphere.**



Gamma ray telescopes are designed to detect this blue light. The primary challenge of detecting this blue light is time. As mentioned before, these flashes of light last only 5 to 10 ns. Therefore, developing cameras that can detect light very fast is the key.

Fact Recall:

Q5. What is the name of the technique used for detecting gamma rays in ground-based telescopes called?

Ans. _____

_____

Q6. What is pair creation?

Ans. _____

_____

_____

Q7. How is Cherenkov light formed? Explain with a diagram.

Ans. _____

_____

_____

_____

_____

_____

Research work

Q8. What is pair creation? What other particles are formed in pair creation?

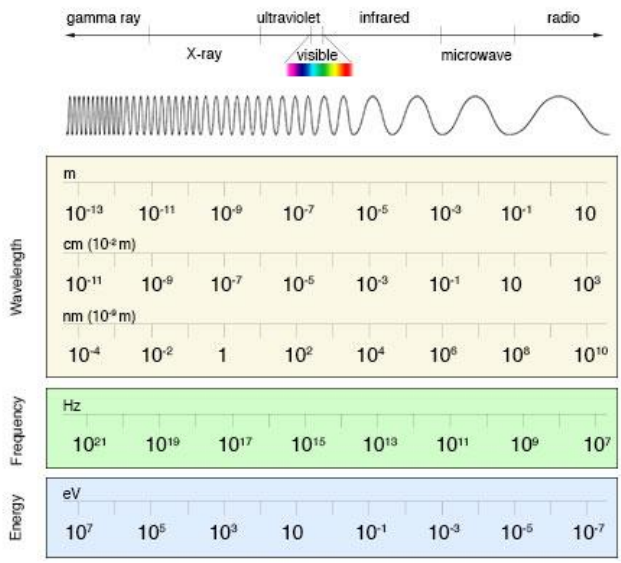
Ans. _____

_____

_____

Structure of CTA: Dividing the array into small sized, medium sized and large sized telescopes

The figure below shows the electromagnetic spectrum. You can read off the energy range of the gamma ray spectrum. Gamma rays span from energies greater than 100 keV to TeV level.

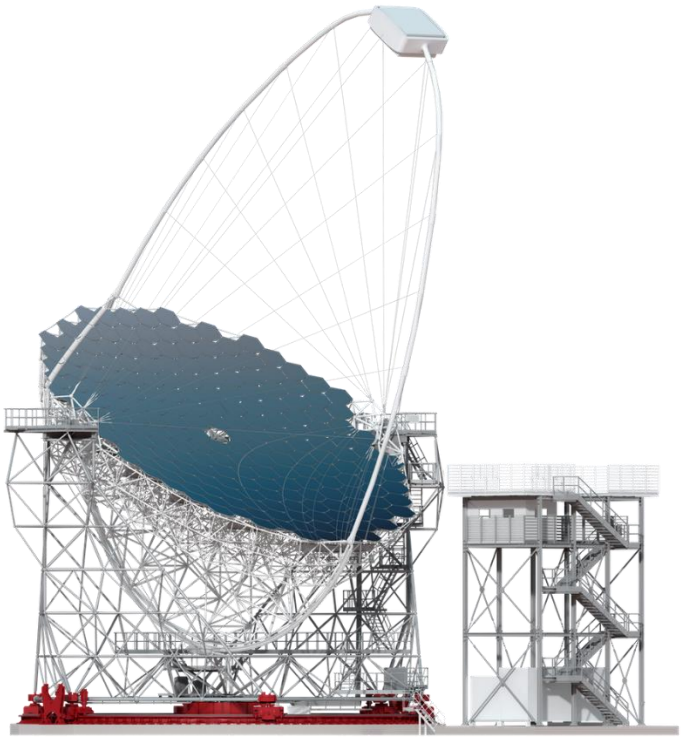


Based on the energy of the gamma ray detection, three sizes of CTA telescopes will be built:

1. The Large Size Telescopes (LST)
2. The Medium Size Telescope (MST)
3. The Small Size Telescope (SST)

The Large Size Telescope (LST)

The Large-Sized Telescope (LST) project team consists of over 100 scientists from ten countries: Brazil, Croatia, France, Germany, India, Italy, Japan, Poland, Spain and Sweden. These countries in the CTA team will be responsible for designing the LST array. Since gamma rays with lower energies produce lower levels of the blue Cherenkov light, larger mirrors are required. Hence LST is designed to capture lower energies. LST will stand 45 m tall and weigh around 100 tonnes. Despite of the huge structure, LST is extremely nimble, with the ability to re-position within 20 seconds. A photograph of the LST is shown below, followed by its specifications.



	Large-Sized Telescope (LST)
Required energy range	20 GeV – 3 TeV
Energy range (in which subsystem provides full system sensitivity)	20 GeV – 150 GeV
Number of telescopes	4 (South) 4 (North)
Optical design	Parabolic
Primary reflector diameter	23.0 m
Secondary reflector diameter	--
Effective mirror area (including shadowing)	370 m^2
Focal length	28 m
Total weight	103 t
Field of view	4.3 deg
Number of pixels in Cherenkov camera	1855
Pixel size (imaging)	0.1 deg
Photodetector type	PMT
Telescope readout event rate	>7.0 kHz (after LST array trigger)
Telescope data rates (readout of all pixels; before array trigger)	24 Gb/s
Positioning time to any point in the sky (>30° elevation)	30 s
Pointing precision	<14 arcseconds
Observable sky	Any astrophysical object with elevation > 24 degrees

The Medium Size Telescope (MST)

From the full CTA team, Austria, Germany, France, Brazil, Poland, Spain, Switzerland and the Italy are responsible for the design and construction of the MST. The MST array is designed to detect the core energy range of CTA, ranging from 150 GeV to 5 TeV. The current plan is to have 40 MSTs in the southern hemisphere and 15 in the northern hemisphere. The MST mirror will be about 12 metres in diameter. The following image shows a photo of MST followed by the specifications.

	Medium-Sized Telescope (MST)	
	FlashCam	NectarCam
Required energy range	80 GeV – 50 TeV	
Energy range (in which subsystem provides full system sensitivity)	150 GeV – 5 TeV	
Number of MST/SCT telescopes	25 (South) 15 (North)	
Optical design	Modified Davies-Cotton	
Primary reflector diameter	11.5 m	
Secondary reflector diameter	--	
Effective mirror area (including shadowing)	88 m^2	
Focal length	16 m	
Total weight	82 t	
Field of view	7.5 deg	7.7 deg
Number of pixels in Cherenkov camera	1764	1855
Pixel size (imaging)	0.17 deg	0.17 deg
Photodetector type	PMT	PMT
Telescope readout event rate (before array trigger)	>6 kHz	>7.0 kHz
Telescope data rates (readout of all pixels; before array trigger)	12 Gb/s	
Positioning time to any point in the sky (>30° elevation)	90 s	
Pointing precision	<7 arcseconds	
Observable sky	Any astrophysical object with elevation > 24 degrees	

The Small Sized Telescope (SST)

The majority of the telescopes in CTA will be SST. This book will also go into much more details about the SST. SSTs will look into the highest parts of the gamma ray spectrum between a few TeV and 300 TeV. The following photo shows the SST, followed by their specifications.

	Small-Sized Telescope (SST)
Required energy range	1 TeV – 300 TeV
Energy range (in which subsystem provides full system sensitivity)	5 TeV – 300 TeV
Number of telescopes	70 (South) 0 (North)
Optical design	Schwarzschild-Couder
Primary reflector diameter	4.3 m
Secondary reflector diameter	1.8 m
Effective mirror area (including shadowing)	8 m_2
Focal length	2.15 m
Total weight	19 t
Field of view	10.5 deg
Number of pixels in Cherenkov camera	2368
Pixel size (imaging)	0.19 deg
Photodetector type	SiPM
Telescope readout event rate (before array trigger)	>0.3 kHz
Telescope data rates (readout of all pixels; before array trigger)	2 Gb/s
Positioning time to any point in the sky (>30_o elevation)	60 s
Pointing precision	<7 arcseconds
Observable sky	Any astrophysical object with elevation > 24 degrees

Fact Recall:

Q9. What are the three categories of telescopes in the CTA array? What was the division based on?

Ans. _____

Q10. What are the energy ranges that each telescope category is aiming to detect?

Ans. _____

Q11. What are the mirror sizes of the three telescope categories?

Ans. _____

Research work:

Q12. What does SiPM stand for?

Ans. _____

Q13. What is the photoelectric effect?

Ans. _____

Q14. What is a photodiode?

Ans. _____

Q15. What does CHEC-S in CTA stand for?

Ans. _____

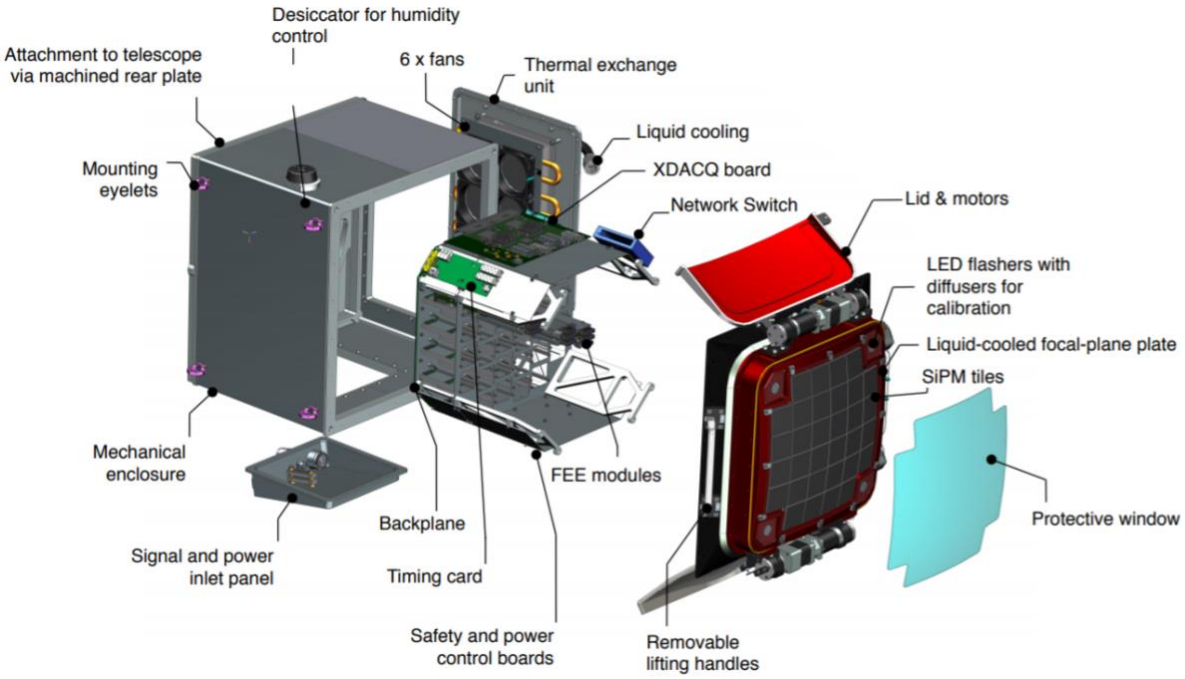
Tutorial 3 – Silicon Photomultiplier Detectors and Compact High Energy Camera

What is the Purpose of Tutorial 3?

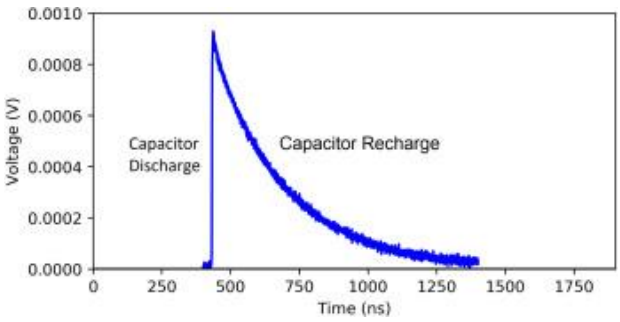
- Learn about silicon photomultiplier detectors
- Learn about the Compact High Energy Camera

SSTs require the ability to detect over a large Field-of-View (FoV). To achieve this FoV, a special dual-mirror Schwarzschild-Couder (SC) telescope design with a 9° FoV has been selected for the SSTs. This telescope design also allows the use of a more compact and low cost camera. Due to a large number of SSTs in CTA, a camera that is compact and of low cost is therefore a critical requirement. Since the SST array will be responsible for the detection of the upper end of CTA's gamma ray energy range, the compact camera used for such an array needs to be able to handle a mean Cherenkov event rate of ~ 300 Hz.
With this goal in mind, the Compact High Energy Camera (CHEC) has been developed, for implementation in the SST array of CTA. The first prototype that was commissioned was named CHEC-M. This Multi-Anode Photomultiplier Tube (MAPMT) based compact camera received its first inauguration on the Gamma Ray Cherenkov Telescope (GCT) at the Observatoire de Paris-Meudon in 2015. However, owing to the advantages of a silicon photomultiplier (SiPM) detector over PMTs, an updated second CHEC camera known as CHEC-S, with SiPM detectors as its photosensor was designed.

The mechanical structure of the camera is predominantly made up of aluminium. It consists of a focal plane plate, an internal rack, a thermal exchange unit and a lid. In addition, the CHEC-S camera also consists of an external window to protect the highly sensitive SiPMs, placed on the focal plane plate of the camera. These components are shown in an exploded CAD model in figure 2.24. For the scope of this thesis, the camera can be split into three main sections: The Focal Plane, the Front End Electronics (FEE) and the Back End Electronics (BEE). The Front End Electronics are slotted through the focal plane plate into the internal rack. A photograph of the structure of CHEC-S is shown below.



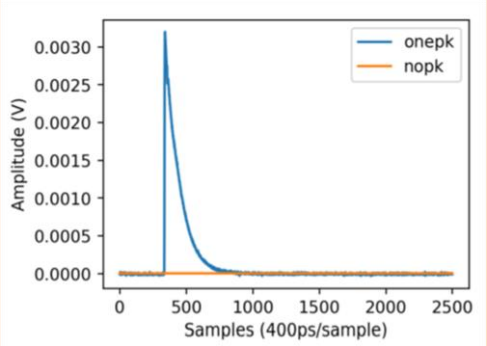
Silicon photomultiplier detectors: In the photoelectric effect, you learnt how a photon can create an electron-hole pair. A similar principle is used in a device called photodiode. In a photodiode, an incident photon creates an electron hole pair. So you get one electron from one photon. In a Silicon Photomultiplier, you get over millions of electrons from a single photon hitting the detector. These electrons are also referred to as photoelectron (p.e). Since the gain is so high, this detector will produce a pulse signal from just a single photon. The following photo shows an example of a signal you see when a photon strikes an SiPM.



The amplitude of this signal depends on how many photoelectrons were created when the photons strike the SiPM. The amplitude of the SiPM simply adds up with each photoelectron. For example: If the amplitude from 1 p.e is 2 mV, then the amplitude due to 3 p.e will simply be 6 mV. CHEC-S will enable SST to detect very high energy gamma rays. The next two tutorials will give you an introduction to very high energy astrophysics.

Data Analysis Question

Q16 What is the p.e level here, if the amplitude from a single p.e for this detector is 1.5 mV?



Ans. _____

_____

_____

Research Questions

Q17. What is a Field of View (FoV) in telescopes?

Ans. _____

_____

_____

Q18. What are photomultiplier tubes (PMTs)?

Ans. _____

_____

_____

Q19. What are the advantages of SiPMs over PMTs?

Ans. _____

_____

_____

_____

_____

_____

_____

Tutorial 4 – Introduction to Very High Energy Astrophysics-1

What is the Purpose of Tutorial 4?

- Objective 1
- Objective 2
- Objective n

Very High Energy (VHA) Astrophysics refers to studying the parts of the universe that involve highly energetic particles. This includes astronomical objects that release gamma rays. This tutorial will teach you some of the most fascinating objects in space that emit very high energy gamma rays. Mapping the universe in the gamma ray region over the past decades via many different space-based and ground-based gamma ray missions, has led to the discovery of many gamma ray sources. Although it is not possible to go into details for all these sources within the scope of this book, this section will discuss some of the primary examples of gamma ray sources. As shown by authors Cheng et al. in their book Cosmic Gamma Ray Sources, the gamma ray sources can be broadly classified into galactic sources (sources within our galaxy) and extra galactic (sources outside our galaxy). A few examples from galactic sources will be discussed in this tutorial.

Research work: THE BIG CHALLENGE OF TUTORIAL 4
Q20. This tutorial will explain you some of the galactic sources of gamma rays. Can you research online and find three sources of gamma rays that are extra galactic?
Ans. 1. _____
2. _____
3. _____

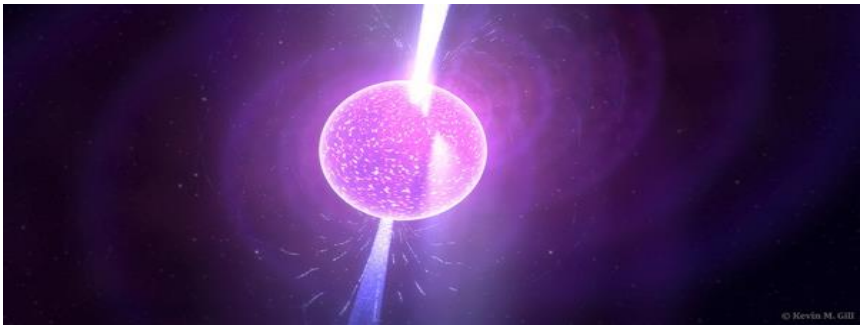
Within the galaxy, many of the gamma ray sources are identified in star forming regions, supernovae, pulsars and binary systems.

Supernovae

When stars with masses greater than the solar mass (mass of our Sun) approach the end of their lives, stellar explosion in the form of a supernova takes place. The shock winds produced in such cosmic events can reach extremely high velocities of 20,000 km/s. Particles are highly accelerated in these shock winds produced by these highly energetic supernovae. Below is a photo of a supernova.

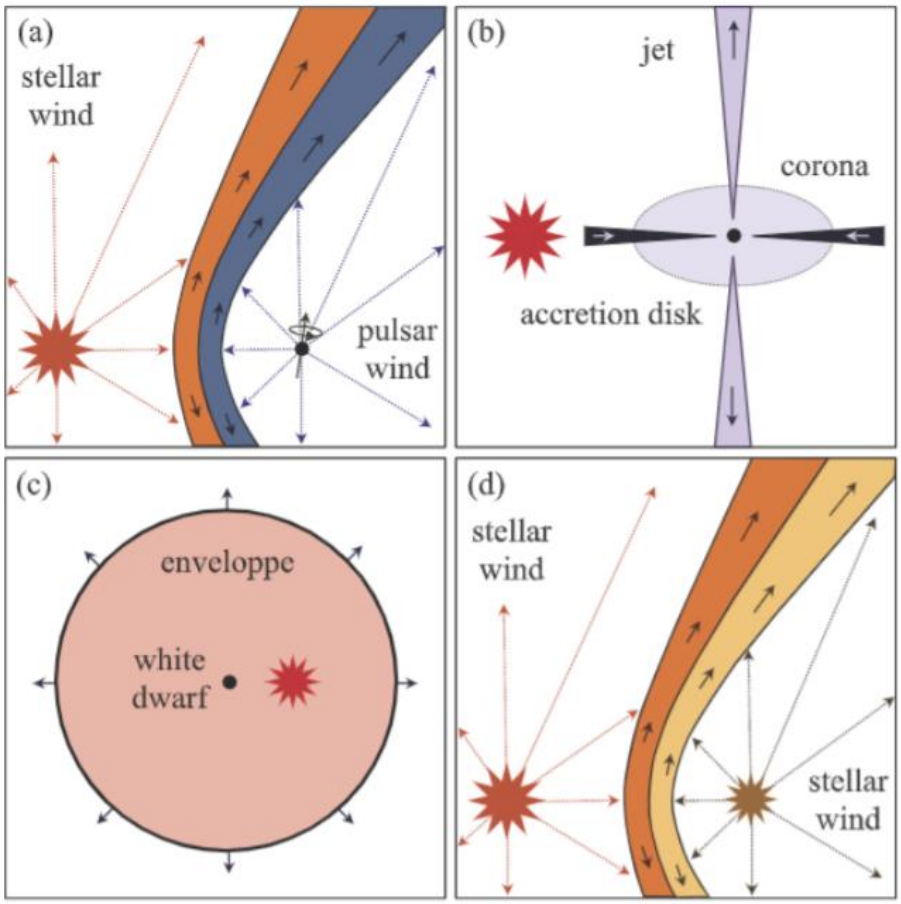
Pulsars

After a supernova explosion, depending on the mass of the original star, the core can collapse and form a neutron star. Fast rotating neutron stars whose radiation pulses can be observed at frequencies of milliseconds to seconds are called pulsars. Pulsars can generate high energy and very high energy gamma ray photons. These have very strong magnetic fields that play a critical role in the production of gamma rays via mechanisms such as synchrotron radiation.



Binary Star Systems

Pairs of stars (star-neutron star, star-pulsar or star-black hole) can orbit each other around their common centre of mass. These are called binary star systems [53]. In such systems, a flow of gas and matter between the pair can be observed. These also generate very strong magnetic fields, which act as particle accelerators and therefore produce gamma rays. Observations from much newer space based 24 and ground based missions have shown binary systems to be some of the important sources of HE and VHE gamma rays [54], [55]. The detection of HE and VHE gamma ray processes from binary systems has been classified into four categories in [56]. These are- a. gamma ray binaries which are powered by pulsars, b. microquasar-blackhole and microquasar-neutron star, c. novae-white dwarf d. interacting binary stellar winds. This is shown with an illustration below.



Research work:
Q21. Explain in your own words the following celestial objects. Go beyond the description shown in this book.
Ans.
1. Supernova: _____
_____
_____
_____
_____
_____
_____
_____
2. Pulsars: _____
_____
_____
_____
_____
_____
_____
_____
3. Binary Star System: _____
_____
_____
_____
_____
_____
_____
_____

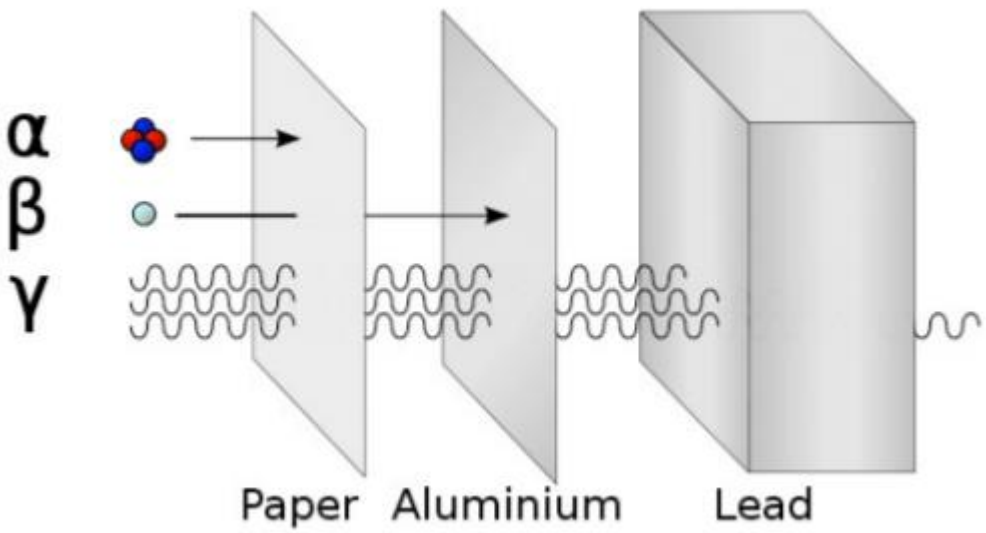
Tutorial 5 – Title

What is the Purpose of Tutorial 5?

- Be able to explain the timeline of discoveries in gamma-ray astronomy

Introduction to the History of Gamma Ray Astronomy

Humans are more susceptible to seeing and imagining the universe in the optical light, where the radiation is mostly due to thermal sources. This is because the human eye is only sensitive to the visible light spectrum. The visible light spectrum is only a small portion that ranges from ≈ 380 nm to 700 nm of the entire electromagnetic spectrum. This corresponds to energies in the range of 3.4 to 1.7 eV. The observed electromagnetic spectrum extends over 35 orders of magnitude.
Observing the universe in different bands of the electromagnetic spectrum is critical to understanding and furthering the human knowledge of the physical world. Quite often, observing cosmic sources in certain bands of the electromagnetic spectrum can provide a better insight than the others. For instance, observing the universe in the gamma ray spectrum can provide more information on the high energy sources, than in optical regime. With this goal, scientists over the last century have continuously expanded our understanding of the universe outside the domain of the optical light spectrum that the intuitive minds are most acquainted with. The following paragraph will highlight the timeline of some of the significant discoveries that had a direct impact in the field of high energy gamma-ray physics.



Many critical discoveries began in the year 1895 that includes the discovery of x-rays, radioactivity and better understanding of the atomic structure. In the following decades Earnest Rutherford discovered two important radiations: alpha radiation and beta radiation.
In 1900, French Physicist Paul Villard discovered that when the alpha radiation is removed with lead and the beta radiation is deflected off using magnetic field, a residual radiation that had the characteristics of no charge and high penetrating power could still be seen. The term gamma rays however was not coined by Villard. It was Rutherford who later confirmed their existence and named it gamma rays.
In 1910, Physicist William Bragg, while working on the view of x-rays and gamma rays showing similar particle nature, demonstrated the ionising capability of gamma rays. This was followed by Rutherford and Andrade showing the wave nature and Compton showing the particle (photon) nature of gamma rays.
In 1933 British and Italian physicists Patrick Blackett and Giuseppe Occhialini showed the generation of electron-positron pair from penetrating gamma rays.
In 1948, while working on the interaction between cosmic ray primaries and starlight photons, physicists Feenberg and Primakoff predicted the production of gamma rays in interstellar space.
The possible detection of gamma rays from supernovae was suggested by American physicist L. B Borst **in 1950.**
In 1960s, space borne instruments like Explorer 11 and Ranger 3 with the ability to detect gamma rays, were launched. Explorer 11 was the first gamma ray detecting satellite and was designed to

be able to detect gamma rays of energies ≈ 50MeV and above and data from Ranger-3 was used to study gamma rays in the energy range of 0.1 to 3 MeV.

In 1968, the first ground-based gamma ray atmospheric Cherenkov telescope was built in Arizona Mt. Hopkin observatory. This 10 m gamma ray telescope was later named the Whipple Observatory. The discovery of gamma rays by Villard opened a century of new discoveries in high energy astronomy. The more recent and currently active space-based and ground-based gamma ray instruments and their working principle have been discussed in the following chapter.

Group work:

Q22. Make a poster using photos, of the timeline of the discoveries that took place in the field of gamma ray astronomy.

Final Assignment

Your task is to write a 2000 (+/- 10%) word scientific report on any one of your chosen space-based or a ground-based mission that has already been launched. The essay should have the following structure:

i. Describe the name of your mission and who is leading it.
ii. The scientific goal of the mission
iii. Chose any one instrument onboard the mission
iv. What is the working principle of the instrument. (Use images to show the different parts)
v. Write a small paragraph on any of the results from the mission*

*This is an extended task.

Tutorial 6 – Feedback tutorial

What is the Purpose of Tutorial 6?

- To receive feedback on your final assignment
- To respond to the feedback from your Uni Pathways teacher
- To write targets for improvement on your final assignment

Final assignment feedback from your Uni Pathways Teacher

(Remember to look at the mark scheme to help you understand what you have done well so far, and how you can do even better in your final assignment)

Here are three things that my Uni Pathways Teacher thought I did well in my draft assignment
•   •   •

Here are three things that my Uni Pathways Teacher thinks that I could do to get a higher mark in my final assignment
•   •   •

Tasks from my Uni Pathways Teacher to do during the feedback tutorial to help me improve
•   •   •
My response:

Actions I will take to improve my final assignment after this tutorial…
•   •   •

Hand in date for my final assignment:	

Tutorial 7 – Final tutorial

What is the Purpose of Tutorial 7?

- To receive feedback and a grade on your final assignment.
- To reflect on the programme including what you enjoyed and what was challenging.
- To ask any questions you may have about university.

Final assignment feedback from my Uni Pathways Teacher

Final mark:	University style grade:
Feedback: Here are three things that my Uni Pathways teacher thought I did well in my final assignment • • •	

Here are three things that my Uni Pathways teacher thinks I should remember for when I am doing this kind of study in the future
• • •

University

What questions do you still have about University after taking part in Uni Pathways?
•   •   •

Reflecting on Uni Pathways

What did you most enjoy about Uni Pathways?
•   •   •

What did you find challenging about the programme?	How did you overcome these challenges?
• • •	• • •

Appendix 1 – Referencing correctly

When you get to university, you will need to include references in the assignments that you write, so we would like you to start getting into the habit of referencing in your Brilliant Club assignment. This is really important, because it will help you to avoid plagiarism. Plagiarism is when you take someone else's work or ideas and pass them off as your own. Whether plagiarism is deliberate or accidental, the consequences can be severe. In order to avoid losing marks in your final assignment, or even failing, you must be careful to reference your sources correctly.

What is a reference?

A reference is just a note in your assignment which says if you have referred to or been influenced by another source such as book, website or article. For example, if you use the internet to research a particular subject, and you want to include a specific piece of information from this website, you will need to reference it.

Why should I reference?

Referencing is important in your work for the following reasons:

- It gives credit to the authors of any sources you have referred to or been influenced by.
- It supports the arguments you make in your assignments.
- It demonstrates the variety of sources you have used.
- It helps to prevent you losing marks, or failing, due to plagiarism.

When should you use a reference?

You should use a reference when you:

- Quote directly from another source.
- Summarise or rephrase another piece of work.
- Include a specific statistic or fact from a source.

How do I reference?

There are a number of different ways of referencing, and these often vary depending on what subject you are studying. The most important to thing is to be consistent. This means that you need to stick to the same system throughout your whole assignment. Here is a basic system of referencing that you can use, which consists of the following two parts:

1. **A marker in your assignment**: After you have used a reference in your assignment (you have read something and included it in your work as a quote, or re-written it your own words) you should mark this is in your text with a number, e.g. [1]. The next time you use a reference you should use the next number, e.g. [2].
2. **Bibliography**: This is just a list of the references you have used in your assignment. In the bibliography, you list your references by the numbers you have used, and include as much information as you have about the reference. The list below gives what should be included for different sources.

    a. **Websites** – Author (if possible), title of the web page, website address, [date you accessed it, in square brackets].

    E.g. Dan Snow, 'How did so many soldiers survive the trenches?', http://www.bbc.co.uk/guides/z3kgjxs#zg2dtfr [11 July 2014].

    b. **Books** – Author, date published, title of book (in italics), pages where the information came from.

    E.g. S. Dubner and S. Levitt, (2006) *Freakonomics*, 7-9.

    c. **Articles** – Author, 'title of the article' (with quotation marks), *where the article comes from* (newspaper, journal etc.), date of the article.

    E.g. Maev Kennedy, 'The lights to go out across the UK to mark First World War's centenary', Guardian, 10 July 2014.

Notes

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