Slide 1

Dr Steve Barrett

BASoc   18 Mar 2024

STAR
WARS
HAIL
RAIN
COSMIC RAYS

Slide 2 — Contents

Contents

Introduction

Background Radiation
Earth and beyond
Radioactivity
$\alpha\ \beta\ \gamma$ radiation

Cosmic Rays
100+ years of history
Air showers

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Cloud chamber
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Cosmic Sources
Galactic or extra-galactic
Magnetic fields
Ultra-high energies

Summary

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Slide 3

The BASoc lawyers require …

Risk Assessment

This talk will include a number of table-top demonstrations, some of which use radioactive samples.

The samples contain naturally occurring elements and there is no risk to any members of the audience.

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Slide 4 — Demonstrations

Demonstrations

On the table in front of me are two types of particle detector that I will be using in live demonstrations at various points throughout this talk.

Geiger-Müller detector

Cloud Chamber

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Introduction

What's that clicking?

Each click signals the arrival of a sub-atomic particle passing through the detector of what is often called a Geiger counter.

Maybe it was spat out from an atom that is lurking somewhere in this room. Maybe its origins were more distant ... the result of a supernova that went off a long time ago in a galaxy far, far away.

We can't tell just from the click itself what the particle was.

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Background Radiation

Terrestrial radioactivity and isotopes

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Background Radiation

Radiation is all around us ... all the time.

You have lived with it all your life and it is not something to fear.

Before dealing with cosmic rays, let's get some context by considering radiation from the Earth itself.

The Earth is radioactive.

It was radioactive when it was made 4.54 billion years ago and it still is today. This is a natural consequence of the properties of some elements.
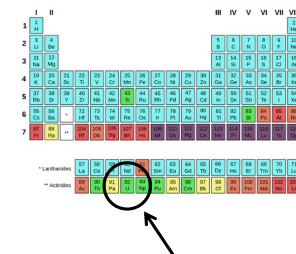
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Radioactivity

The periodic table contains many elements that are **stable** – once an atom has been made it remains essentially unchanged ... forever.

Some elements are **unstable**. They decay (change) into other elements and in the process the atomic nuclei emit sub-atomic particles.
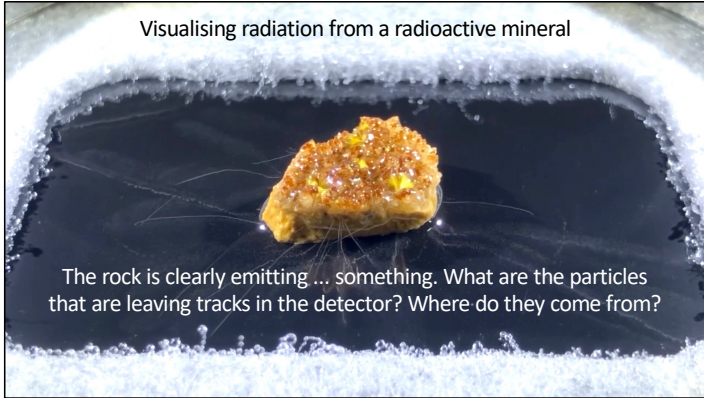
We can visualise the particles emitted by radioactive uranium ...

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Demonstration

Visualising radiation from a radioactive mineral
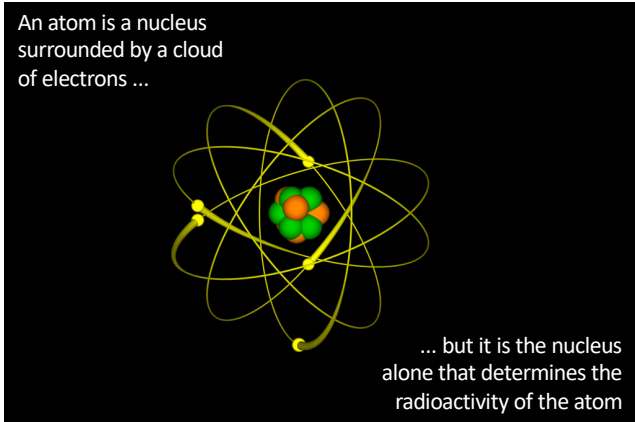
The rock is clearly emitting … something. What are the particles that are leaving tracks in the detector? Where do they come from?

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Atomic Nucleus

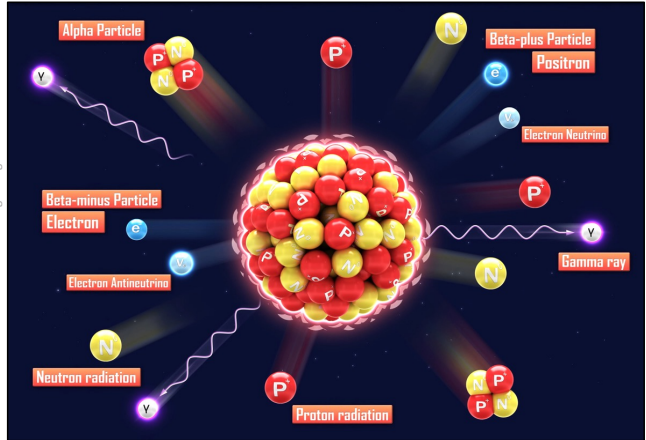An atom is a nucleus surrounded by a cloud of electrons …

… but it is the nucleus alone that determines the radioactivity of the atom

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Atomic Nucleus

Online Learning College

Alpha Particle

Beta-plus Particle
Positron

Electron Neutrino

Beta-minus Particle
Electron

Gamma ray

Electron Antineutrino

Neutron radiation

Proton radiation

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Alpha−Beta−Gamma

The most common types of radiation are labelled α, β and γ:

α Alpha rays (or alpha particles)
α = nuclei of helium atoms = 2 protons + 2 neutrons
Heavy particles that cannot travel far through matter

β Beta rays (or beta particles)
β = electrons
Lightweight particles that can penetrate further than alphas

γ Gamma radiation is rather different from α and β rays because it is a high-energy electromagnetic wave.
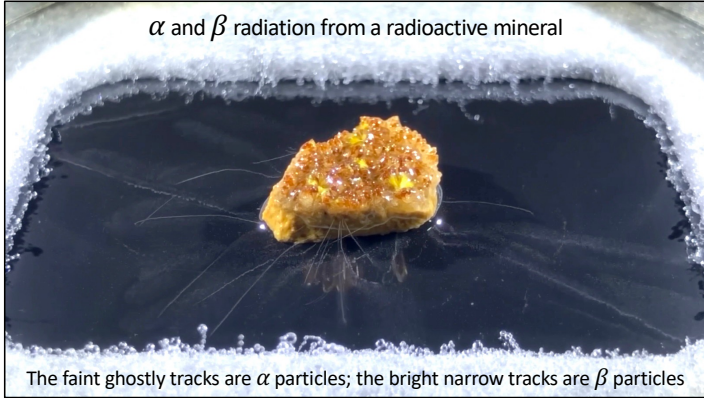
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Demonstration

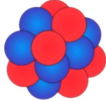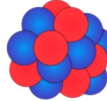α and β radiation from a radioactive mineral

The faint ghostly tracks are α particles; the bright narrow tracks are β particles

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Radioactive Isotopes

Isotopes are 'cousins' of the same type of atom. For instance ...

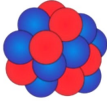All carbon atoms have **6** protons in the nucleus (by definition).

Carbon atoms that have
6 neutrons are the
stable isotope C-12

Carbon atoms that have
8 neutrons are the
radioactive isotope C-14

6 + **6** = 12

6 + **8** = 14

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Aside: Radioactive Carbon-14

Because C-14 atoms decay (change) into nitrogen atoms over 1000s of years they can be used in carbon dating organic material.

If they don't last long, where do the C-14 atoms come from in the first place?

They are being continuously replenished by cosmic rays hitting nuclei of nitrogen, kicking out protons and changing N-14 into C-14.

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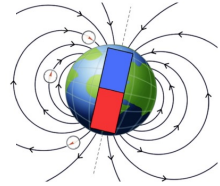
Radioactive Elements

Potassium (K) is the most abundant of the radioactive elements
  In your body, potassium atoms decay at the rate of 4000/sec
  It is one of largest contributions to natural radiation

Thorium (Th) is more abundant than uranium, and ...

Uranium (U) is more abundant than you think
  At 3 ppm there is 500 x more uranium than gold in the Earth's crust

In the Earth's core, these radioactive elements have been emitting radiation for billions of years, heating the core and keeping it molten.
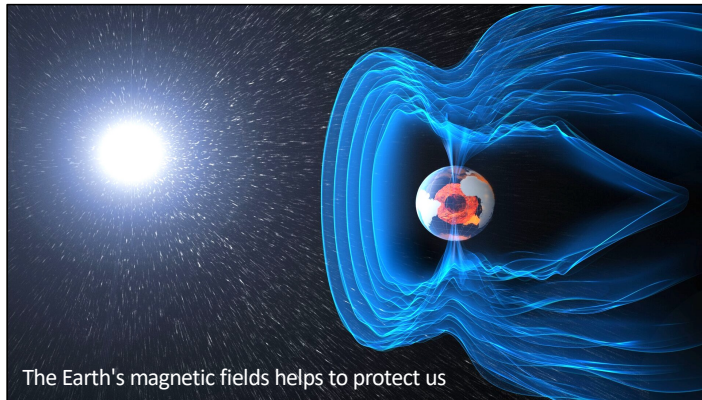
A rotating molten core is the dynamo that creates the Earth's magnetic field.

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Cosmic Rays

Earth's Magnetic Field

The Earth's magnetic fields helps to protect us

Aside: Anti-Matter

0.01% of potassium is K-40, an isotope that emits $\beta+$ radiation.

$\beta+$ particles are like electrons, but with the *opposite* electrical charge. They are particles of **anti-matter**.

Hence, foods rich in potassium emit anti-matter radiation.

This gave rise to the unit of "banana equivalent dose" (BED) that compares any dose of radiation to the dose a person would be exposed to by eating one average-sized banana.

Banana Equivalent Dose

Eating 1 banana =

Dose of cosmic rays that everybody is exposed to every day   =   (double it if you fly a lot)

Radon

Not all radioactive elements are found in solid form.

Radon is a radioactive gas formed by the radioactive decay of the small amounts of uranium that occur naturally in all rocks.

Radon concentrations vary across the UK depending on the type of ground.

For instance, radon levels are high in parts of the UK rich in granite, such as in the South West.

Radon gas atoms emit α particles.

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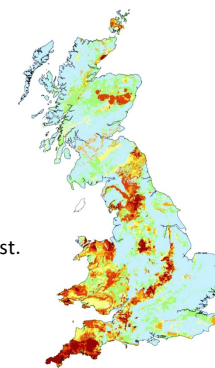
Cosmic Rays

*Having considered terrestrial sources of radiation
we can now return to the main topic of this talk*

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Slide 22

Pioneers

The pioneers studying radiation in the period 1895 – 1915 were …

Henri Becquerel
1852 – 1908

Marie Curie
1867 – 1934

Victor Hess
1883 – 1964

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Slide 23

Above or Below?

In the late 1800s it was known that gold leaf electroscopes lost their charge due to background radiation …

… but was it coming from **above** or from **below**?

In 1910 Theodore Wulf took an electroscope to the top of the Eiffel Tower.

The radiation levels decreased by far less than would be expected if the radiation was coming *only* from the ground.

Is the tower radioactive?

Is the atmosphere radioactive?

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Slide 24

Above or Below?

To resolve the question of '… from above or from below?' Hess figured that the Eiffel Tower was not high enough.

He designed detectors that would work at high altitudes and in 1911 and 1912 he took them on a series of balloon flights.

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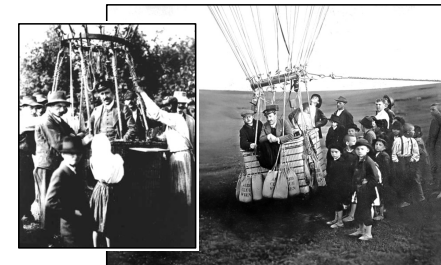
Cosmic Rays

Cosmic Radiation

1911 – Ascent to 1000 m – radiation levels essentially unchanged

1912 – Ascent to 5000 m – radiation levels **increased** dramatically

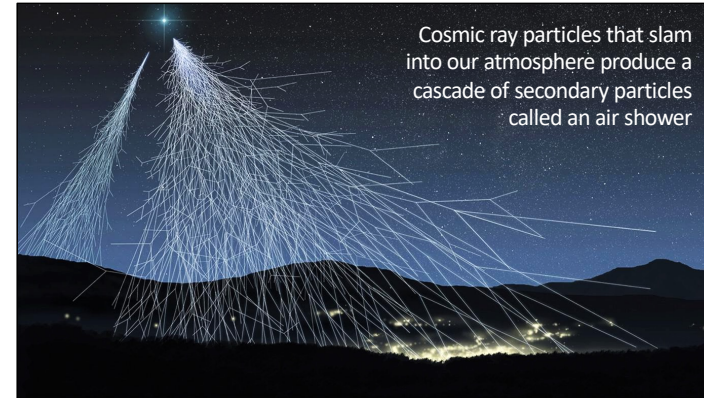Was the increase due to radiation from the Sun, or from beyond?

Measurements during a **solar eclipse** effectively ruled out the Sun as the source of cosmic rays.

In 1936 Hess was awarded the Nobel Prize in Physics for his "discovery of cosmic radiation".

17 Apr 1912

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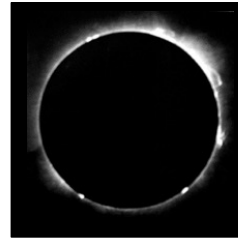
Air Showers

Cosmic ray particles that slam into our atmosphere produce a cascade of secondary particles called an air shower

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Air Showers

High-energy **primary** cosmic ray particles collide with atoms in the upper atmosphere, starting a cascade of **secondary** particles.

At each level of the cascade, new particles are created, each sharing the energy of the particle that created them.

A cascade from one primary cosmic ray particle might result in millions of secondary cosmic ray particles at sea level.
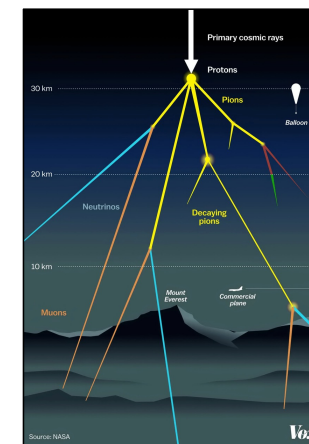
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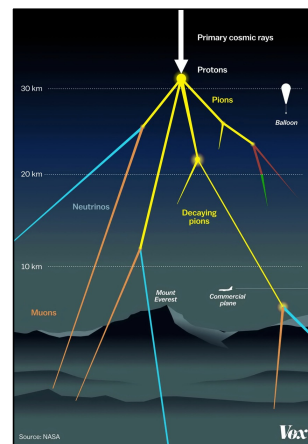
Air Showers

Many of these new particles are unstable and do not live more than a tiny fraction of a second.
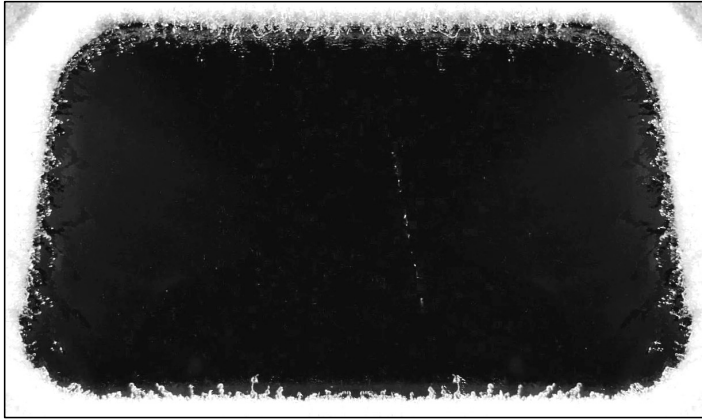
A **muon** is a particle similar to an electron, except that it is much more massive and has no part to play in making atoms.

A muon will not live for much more than a few microseconds, but that is long enough for it to reach sea level.
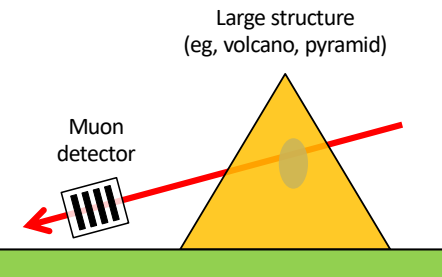
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Muon Track in Cloud Chamber

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Applications of Cosmic Ray Muons

Large structure
(eg, volcano, pyramid)

Muon
detector

If there is any variation in density (of the rock or stone) inside the structure, that will affect the absorption of muons. The process is analogous to using the absorption of x-rays to see inside matter.

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What Are the Primary Particles?

So far we have been looking at **secondary** cosmic ray particles.

What about the **primary** particles – the ones that *create* the showers?

Decades of research has told us about the primary cosmic rays ...

90% are protons (nuclei of H atoms)

9% are α particles (nuclei of He atoms)

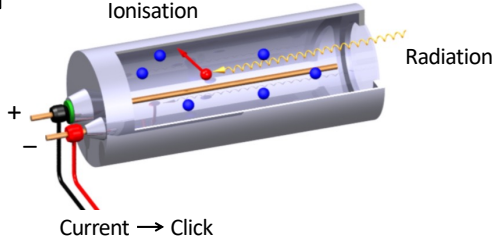1% are nuclei of heavy atoms (the same atoms as found here within the solar system)

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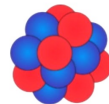
Detecting Cosmic Rays

How can we detect cosmic rays either before or after they hit our atmosphere?

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Radiation Detectors

What's going on inside the detector?

Ionisation

Radiation

\+

−

Current → Click

Cloud Chambers

Inspired by sightings of the Brocken spectre from the top of Ben Nevis in 1894, Charles Wilson developed chambers for studying cloud formation and optical phenomena in moist air.

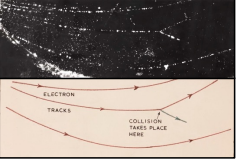In 1911 he perfected the first cloud chamber.

Cloud Chambers

Wilson realised that when charged particles passed through the cloud chamber water droplets condensed to form visible tracks.

As a result, his cloud chambers had an important role in experimental particle physics for decades.

In 1927 he was awarded the Nobel Prize in Physics for the "most original and wonderful instrument in scientific history".
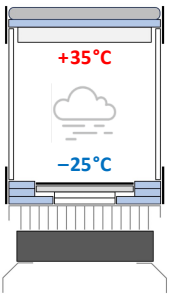
1911 → 2024
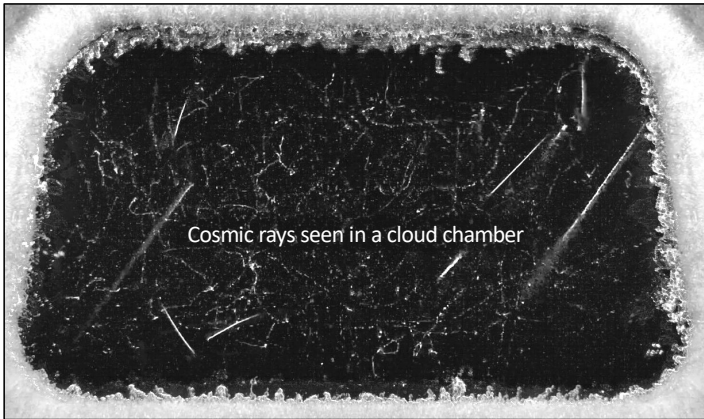
Cloud Chambers

My cloud chamber is a distant cousin of Wilson's original invention. Details of its design and construction will be left for another day.

+35°C

−25°C

Cosmic Rays

Demonstration

Cosmic rays seen in a cloud chamber
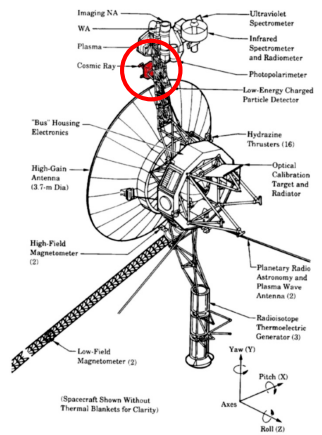
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Cosmic Ray Experiments

Voyager 1 and Voyager 2 carried instruments to measure cosmic rays as they flew through the interplanetary medium.

In 2012 Voyager 1 measured a significant increase in galactic cosmic rays, indicating that it had entered interstellar space.
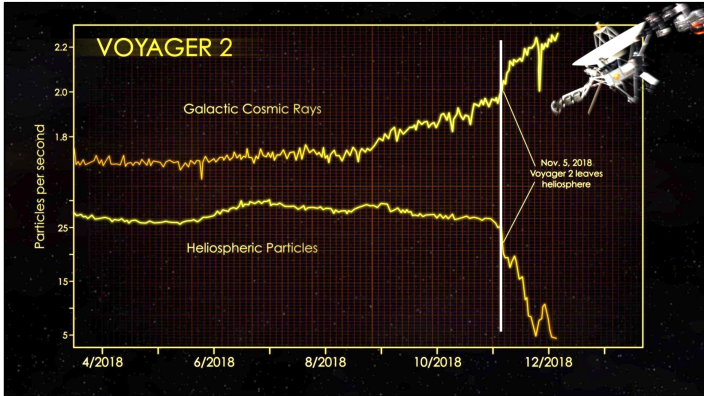
Travelling about 10% slower, Voyager 2 measured a similar increase in cosmic rays in 2018.

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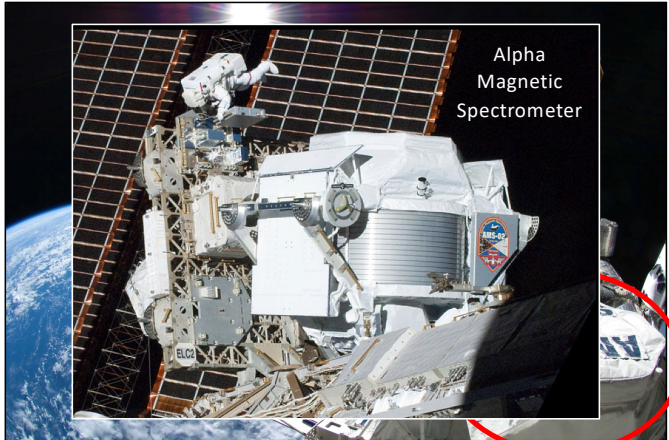
Cosmic Ray Experiments

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Cosmic Ray Experiment on the ISS

Alpha Magnetic Spectrometer

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Cosmic Ray Observatory

There are a number of ground-based cosmic ray observatories. One of the biggest is the Pierre Auger Observatory in Argentina.

To catch a reasonable fraction of the particles created in an air shower the detectors have to be spread over a large area.

For the PAO, this is the area of ... Luxembourg.

www.auger.org

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Cherenkov Radiation

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Cherenkov Radiation

Development of an air shower

It's blue, and it's spectacular

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Cherenkov Telescope Array

CTA north, La Palma, Canary Islands

CTA south, Atacama Desert, Chile

www.cta-observatory.org

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IceCube Laboratory

IceCube laboratory

Ice top

Amundsen-Scott Station

86 strings of DOMs

8,000 feet

Neutrinos and particles

Empire State Building and Statue of Liberty for scale

Digital Optical Modules (DOMs)
5,160 DOMs deployed in the ice
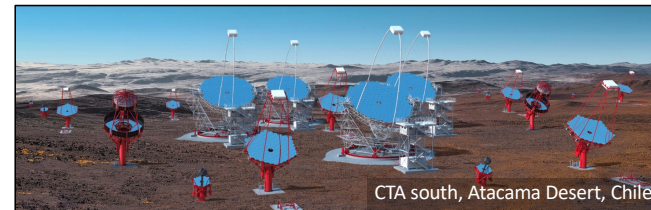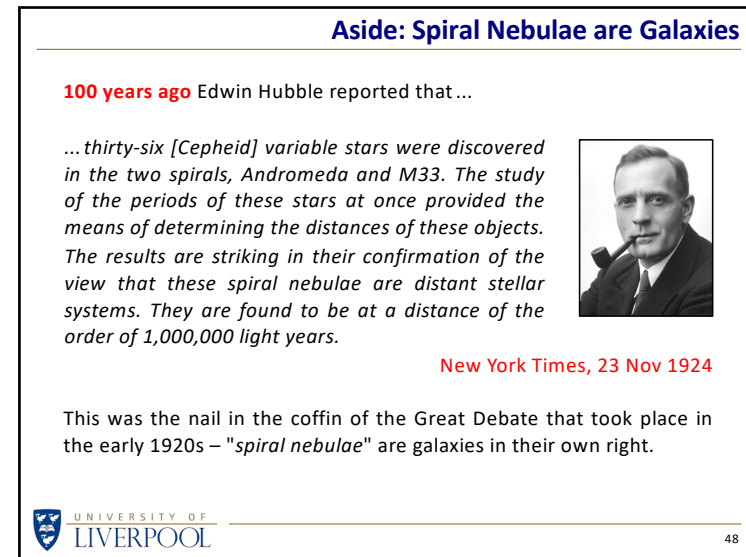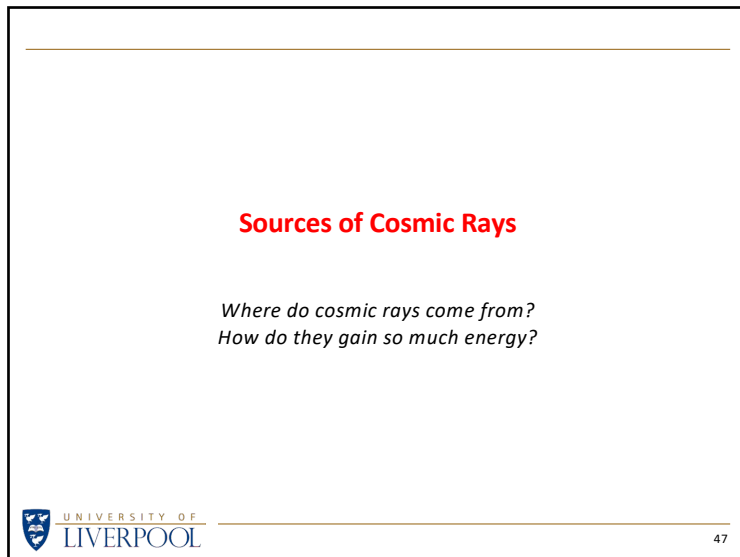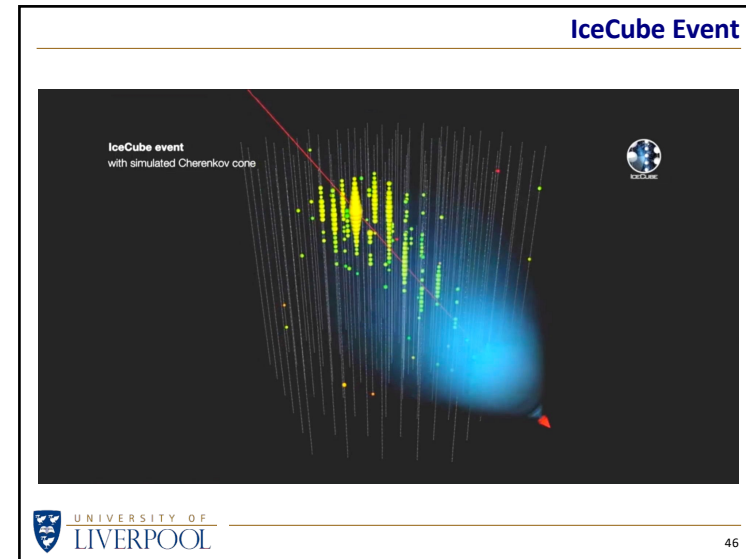
Ice

Antarctic bedrock

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icecube.wisc.edu

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IceCube Event

IceCube event
with simulated Cherenkov cone

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Sources of Cosmic Rays

Where do cosmic rays come from?
How do they gain so much energy?

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Aside: Spiral Nebulae are Galaxies

100 years ago Edwin Hubble reported that ...

... thirty-six [Cepheid] variable stars were discovered in the two spirals, Andromeda and M33. The study of the periods of these stars at once provided the means of determining the distances of these objects. The results are striking in their confirmation of the view that these spiral nebulae are distant stellar systems. They are found to be at a distance of the order of 1,000,000 light years.

New York Times, 23 Nov 1924

This was the nail in the coffin of the Great Debate that took place in the early 1920s – "*spiral nebulae*" are galaxies in their own right.

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Cosmic Rays

Cosmic Origins

Hess showed that (most) cosmic rays do *not* come from the Sun.

So where *do* they come from?

Sources in the Milky Way? ... or beyond?

Hubble's observations made in the 1920s led to a paradigm shift in our understanding of the Universe ... it is a *lot* bigger than was thought, and is full of billions of galaxies like our own.
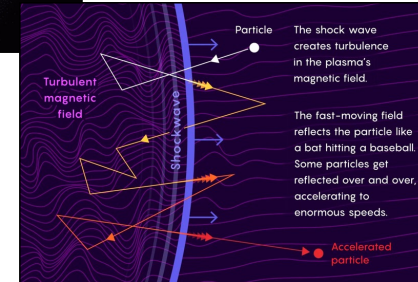
So are the sources of cosmic rays galactic, or extra-galactic?
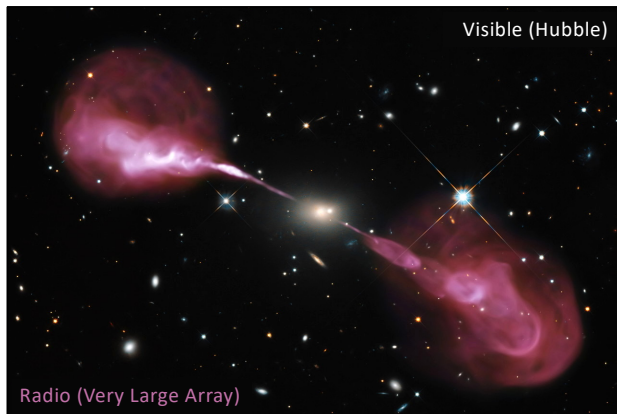
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Supernovae and SMBH

Violent events like supernovae or jets from supermassive black holes produce shock waves in the gas around them.

These shock waves can result in the acceleration of charged particles to **very** high energies.

Particle — The shock wave creates turbulence in the plasma's magnetic field.

Turbulent magnetic field

Shockwave

The fast-moving field reflects the particle like a bat hitting a baseball. Some particles get reflected over and over, accelerating to enormous speeds.

Accelerated particle

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Galactic Jets from Hercules A

Visible (Hubble)
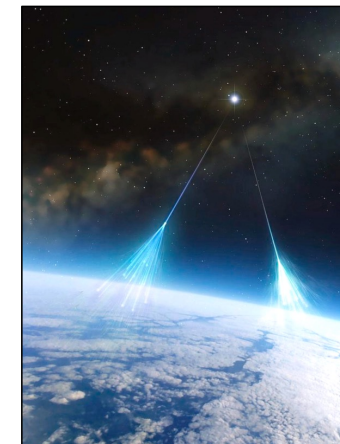
Radio (Very Large Array)

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Cosmic Sources

Pinning down the sources of cosmic rays?

Shouldn't that be easy?

Measure the direction of incoming cosmic rays and trace their direction back to the source.
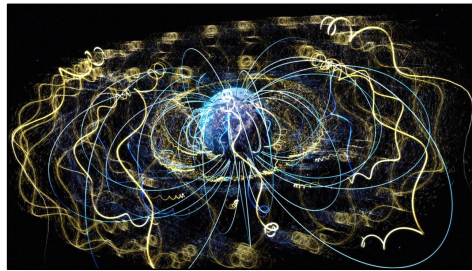
Simples!
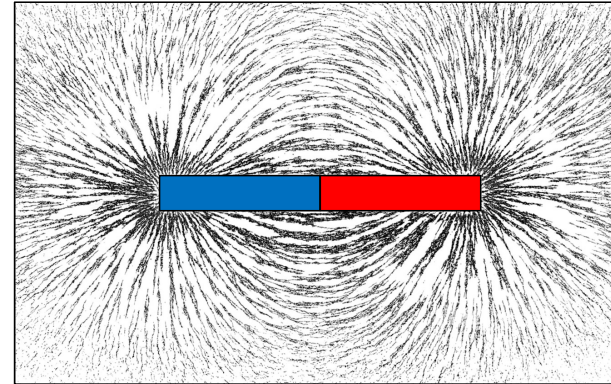
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Cosmic Rays

Magnetic Fields

No, not so simple.
The paths of charged particles are **deflected** in a magnetic field…
… and magnetic fields are everywhere.

Charged particles spiralling along Earth's magnetic field lines
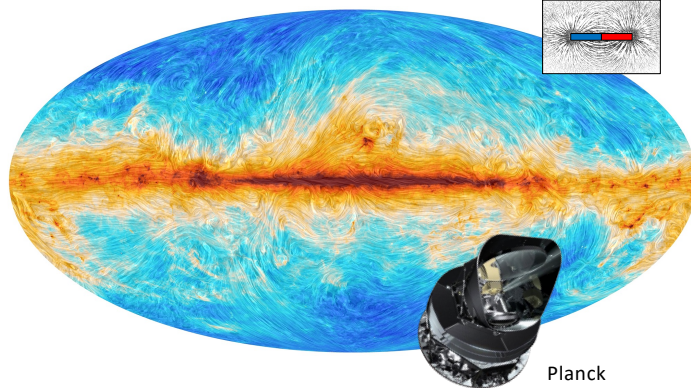
Magnetic Fields

Iron filings can reveal the magnet field around a simple bar magnet

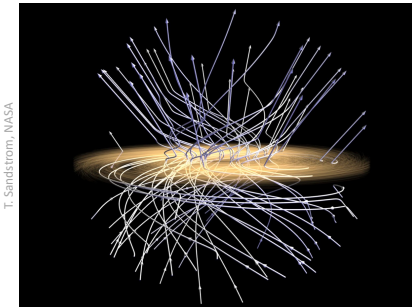## Galactic Magnetic Fields

Dust particles floating around the Milky Way behave like iron filings

Planck

Galactic Magnetic Fields

Magnetic fields embedded in the Milky Way have a complex structure.
The fields deflect charged particles and so scramble the direction from which cosmic rays appear to originate.

T. Sandstrom, NASA

Cosmic Rays

Magnetic Fields in M51

HST + SOFIA

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Inter-Galactic Magnetic Fields

Galactic magnetic fields make it difficult to trace cosmic rays to their source

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Energy Distribution

x-rays	α β γ						
			$\longrightarrow$ cosmic rays $\longrightarrow$				
eV	keV	MeV	GeV	TeV	PeV	EeV	ZeV
10^0	10^3	10^6	10^9	10^{12}	10^{15}	10^{18}	10^{21}

Particle Energy

LHC FCC
particle accelerators

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Energy Distribution

Solar

Galactic

Extra-Galactic

Flux of particles $m^2 \cdot sr \cdot s \cdot GeV$

$\leftarrow$ $1/m^2/s$

$1/m^2/yr$ $\rightarrow$

$1/km^2/yr$ $\rightarrow$

ultra-high energy CR

10^8 10^{12} 10^{16} 10^{20}

Energy / eV

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Cosmic Rays

Amaterasu Event

Osaka Metropolitan U / Kyoto U / Ryuunosuke Takeshige

Telescope Array
Utah USA

27 May 2021   APOD 5 Dec 2023

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Amaterasu Event

Osaka Metropolitan U / Kyoto U / Ryuunosuke Takeshige

Tiramisu Event

Telescope Array
Utah USA

Osaka Metropolitan University
Kyoto University/Ryuunosuke

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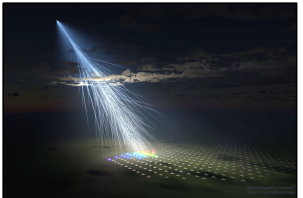
Ultra-High Energies

Ultra-high-energy cosmic rays should be deflected very little by the magnetic fields that permeate the Milky Way and inter-galactic space.

Hence, tracing back the direction of the Amaterasu event should reveal the source in the sky.

The direction points to ... nothing. No supernova, no SMBH could be identified as the source.

More observations are needed to resolve the mystery of cosmic ray origins.

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Close To the Speed of Light

Just how close to the speed of light are these ultra-high-energy cosmic ray particles travelling?

Expressed as a percentage of the speed of light, the most energetic particle yet observed (the "Oh-My-God particle") was travelling at

$$99.9999999999999999999995 \% \ c$$

We can attempt to visualise this speed by imagining a race ...

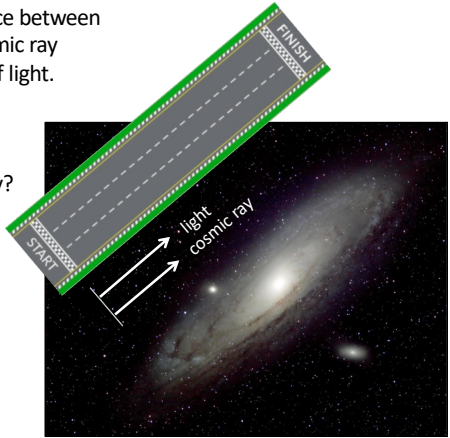UNIVERSITY OF
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Cosmic Rays

Race With Light

Imagine a 100,000 ly race between the most energetic cosmic ray particle and a photon of light.

When the light crosses the finish line, how far behind is the cosmic ray?

After 100,000 ly the cosmic ray would be about **5 mm** behind.
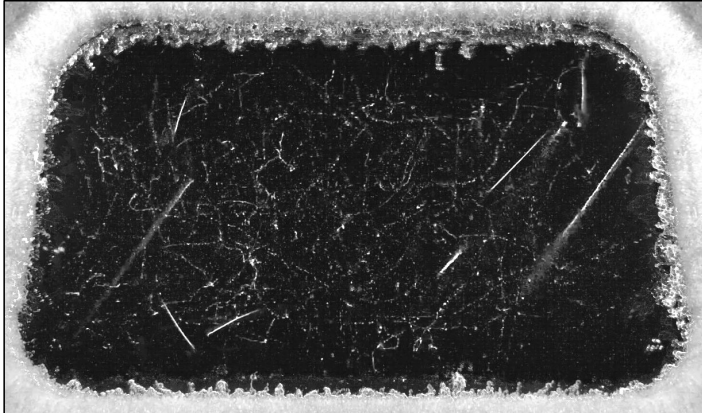
The time difference would be less than a nanosecond.

Summary

- Cosmic ray particles are accelerated ... somewhere, somehow

- **Supernovae** and **SuperMassive Black Holes** are probably sources

- Cosmic rays are **deflected** by magnetic fields
  - Lower energy particles get their paths scrambled
  - Higher energy particles travel in straighter lines

- Some particles make it past Earth's protective **magnetic field**

- Hitting the atmosphere creates an **air shower** of secondary particles

- Some of the **secondary** cosmic ray particles make it to sea level
  - These include muons, electrons and protons
  - They make clicks in Geiger counters and tracks in cloud chambers

Cosmic Rays

www.liverpool.ac.uk/~sdb/Talks

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