Cosmic Ray Chemistry

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What are Cosmic Rays ?

Cosmic rays are energetic charged particles originating in space

89% of cosmic rays are protons

9% are alpha particles

1% are electrons

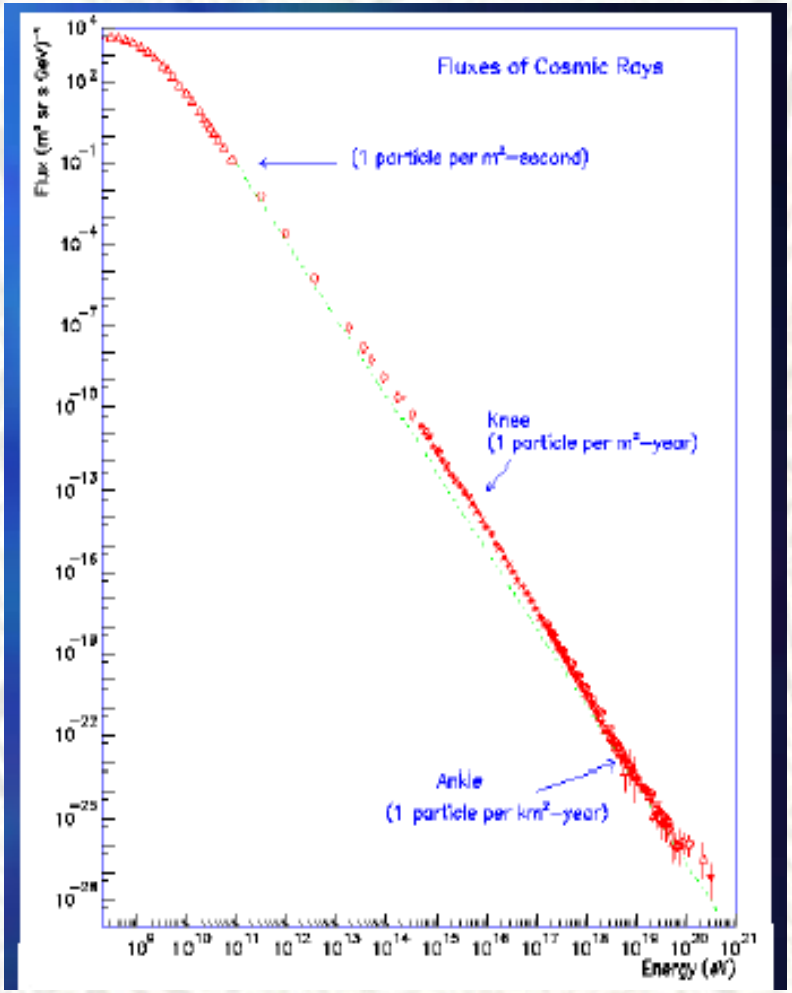
<1% heavier nuclei

(few antiprotons and positrons)

Cosmic Ray Energy

Cosmic rays are amongst most energetic species in the Universe

Energies of over 10^{20} eV
far higher than the 10^{12} to 10^{13} eV terrestrial particle accelerators can produce



The discovery

The discovery

"At six o'clock on the morning of August 7, 1912, a balloon ascended from a field near the town of Aussig, in Austria…"

from *Cosmic rays*, Bruno Rossi

Victor F. Hess took with him three electroscopes up to an altitude of about 16000 feet (without oxygen!).

"The results of my observations are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above."

Physikalische Zeitschrift, November 1912

Hess won the Nobel prize in 1936 for his discovery of cosmic rays. Millikan gave the name *cosmic rays* to the new radiation.

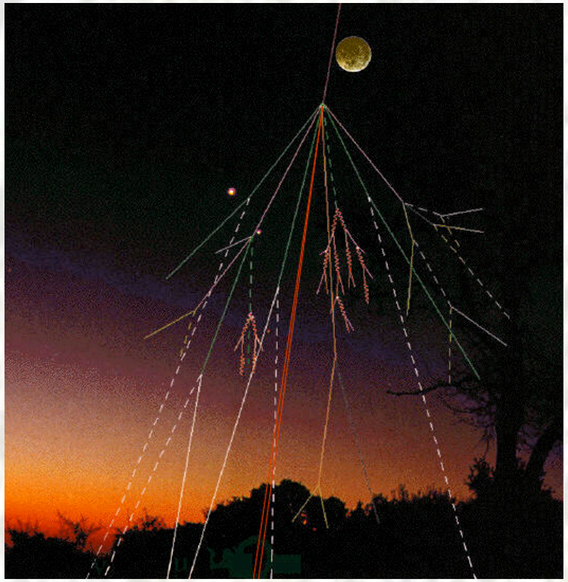
Cosmic Rays on Earth

- Cosmic rays form part of the natural radiation background
- 100,000 pass through you per hour

- Cosmic rays constitute a fraction of the annual radiation exposure of human beings on the Earth. For example, the average annual radiation exposure in Australia is 0.3 mSV due to cosmic rays, out of a total of 2.3 mSv.

Influence of Cosmic Rays

Cosmic rays play a role in;
Atmospheric chemistry
hence possibly climate change



Cosmic rays damage and interference in electronics
E.g. satellites 2010 malfunction aboard the Voyager 2 space probe

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Cosmic Rays and electronics

- Studies by IBM suggest that computers typically experience about one cosmic-ray-induced error per 256 megabytes of RAM per month.
- Cosmic rays are suspected as a possible cause of an incident in 2008 where a Qantas Airbus A330 fell hundreds of feet between Singapore and Australia.
- Accident investigators determined that the airliner's flight control system had received a data spike that could not be explained, and that all systems were in perfect working order.

Cosmic Rays and electronics

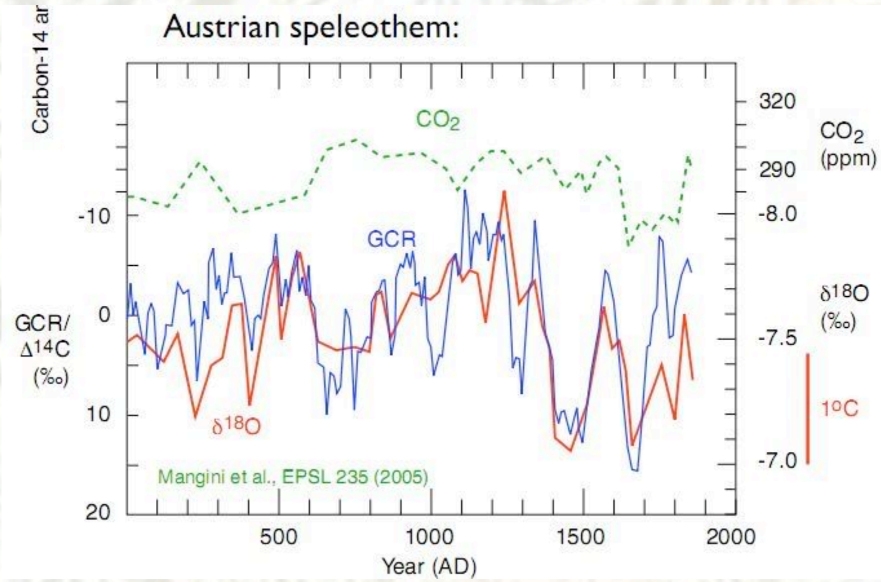
- Corrections
- This has prompted a software upgrade to all A330 and A340 airliners, worldwide, so that any data spikes in this system are filtered out electronically.
- INTEL proposed a cosmic ray detector that could be integrated into future high-density microprocessors allowing the processor to repeat the last command following a cosmic-ray event

Cosmic Rays and Climate

Do cosmic rays influence our climate ?

Henrik Svensmark – leads to increased aerosol growth and thence cloud cover

"During the last 100 years cosmic rays became scarcer because unusually vigorous action by the Sun batted away many of them. Fewer cosmic rays meant fewer clouds—and a warmer world.



Cosmic Rays and Climate

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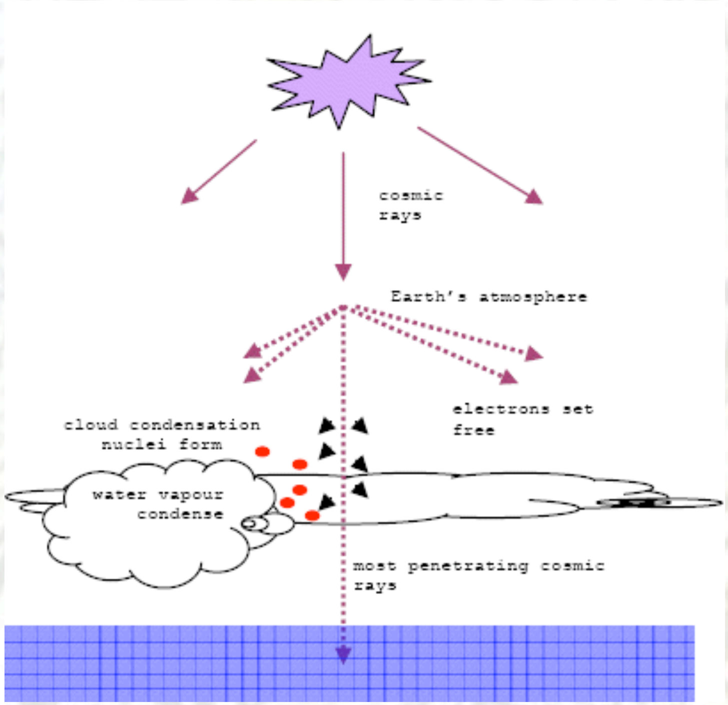
Do cosmic rays influence our climate ?

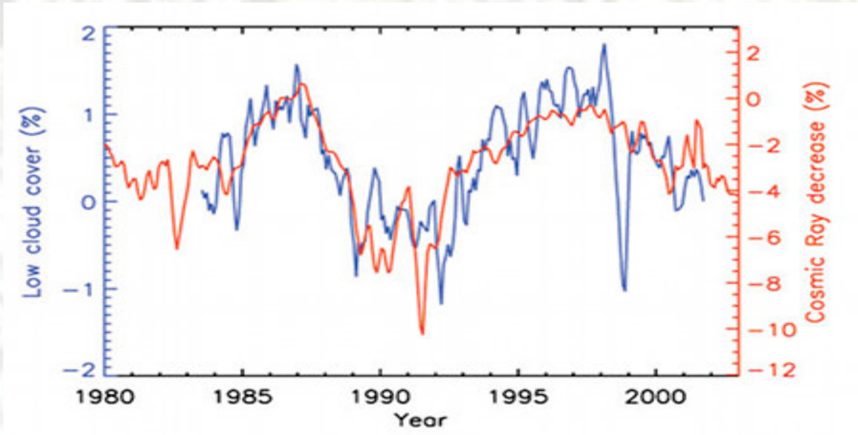
Test hypothesis via CERN Experiment (Sky and Cloud)

But others/most are skeptical

Do expts in lab *no background* (Boulby mine, UK)

Use accelerator to mimic incoming Cosmic Rays





Where are cosmic rays made?

Their extremely high energies
mean they need to be produced by
a powerful mechanism.

So events like supernovae or
regions around **black holes** seem to
Be likely candidates.

Or Dark matter ?

But still not clear !

Where are cosmic rays made?

Fermi gamma-ray telescope (GLAST)

Older remnants, like the supernova remnant IC443, are bright in GeV gamma-rays but relatively dim in TeV gamma-rays.

Younger remnants, like Cassiopeia A, are bright in both GeV and TeV gamma-rays.

Cosmic Ray Chemistry

Due to their high energy cosmic rays can induce reactions

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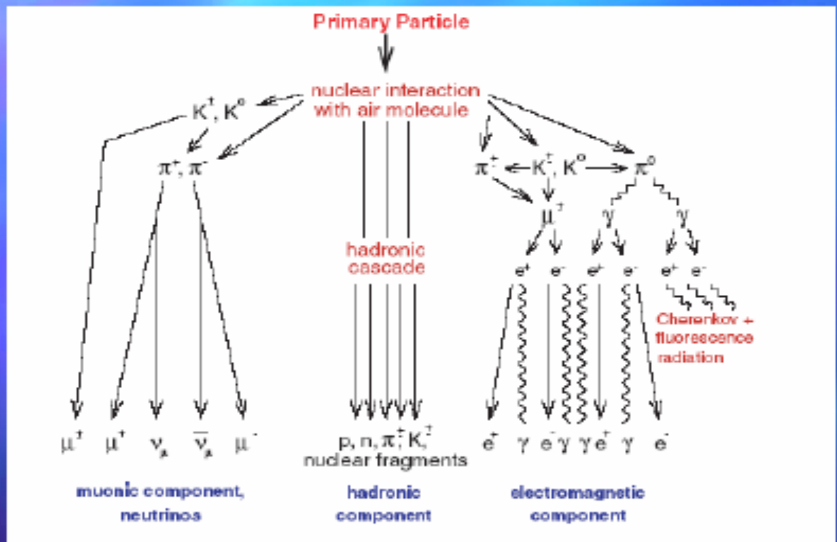
Shower development



A high-energy primary CR particle (e.g. a proton) collides with a nucleus (O, N, Ar) in the atmosphere producing other particles, mainly pions and kaons. These particles have energies high enough to produce more particles (mainly hadrons). This is called air shower (or hadronic cascade). At very high energies this is an Extensive Air Shower (EAS).

Neutral pions quickly decay into two photons, which start electromagnetic cascade. Photons produce e^+e^--pairs, which generate photons in their turn via bremsstrahlung radiation. Eventually, π, K and other unstable particles decay into muons and neutrinos (or electrons and neutrinos), whereas low energy electrons lose energy via ionization without generating more photons.

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Cosmic ray chemistry in the Interstellar medium

- Cosmic rays are a global source of ionization distributed through the Galaxy.
- The fractional ionization is a fundamental parameter, distinguishing the different physical regimes that occur in the interstellar medium.
- The fractional ionization determines the strength of the coupling and is a crucial aspect of the evolution of the interstellar gas and the formation of stars and planets.
- Ionization rates differ in dense and diffuse clouds and in the intercloud medium.

Cosmic ray chemistry in the Interstellar medium

Cosmic rays (cr) cause ionization of H_2 and He but H_2^+ is quickly converted to

$$H_2 \xrightarrow{cr} H_2^+ \xrightarrow{H_2} H_3^+$$

$$He \xrightarrow{cr} He^+$$

This H_3^+. and He+ are largely responsible for driving an efficient ion-molecule chemistry.

Cosmic ray chemistry in the Interstellar medium

Because H_2 is by far the most abundant species, if another species can react with it, that species will be removed primarily by H_2.

Thus, proton transfer followed by a sequence of hydrogen abstraction reactions is important for the chemistry of several abundant elements.

$$C \xrightarrow{H_3^+} CH^+ \xrightarrow{H_2} CH_2^+ \xrightarrow{H_2} CH_3^+ \xrightarrow{e^-} CH,\ CH_2$$

$$CH \xrightarrow{O} HCO^+ \xrightarrow{e^-} CO \xrightarrow{He^+} C^+$$

Cosmic ray chemistry in the Interstellar medium

As illustrated above, a molecular ion that does not react non radiatively with H_2 is removed primarily by dissociative recombination (or by reactions with trace neutral species).

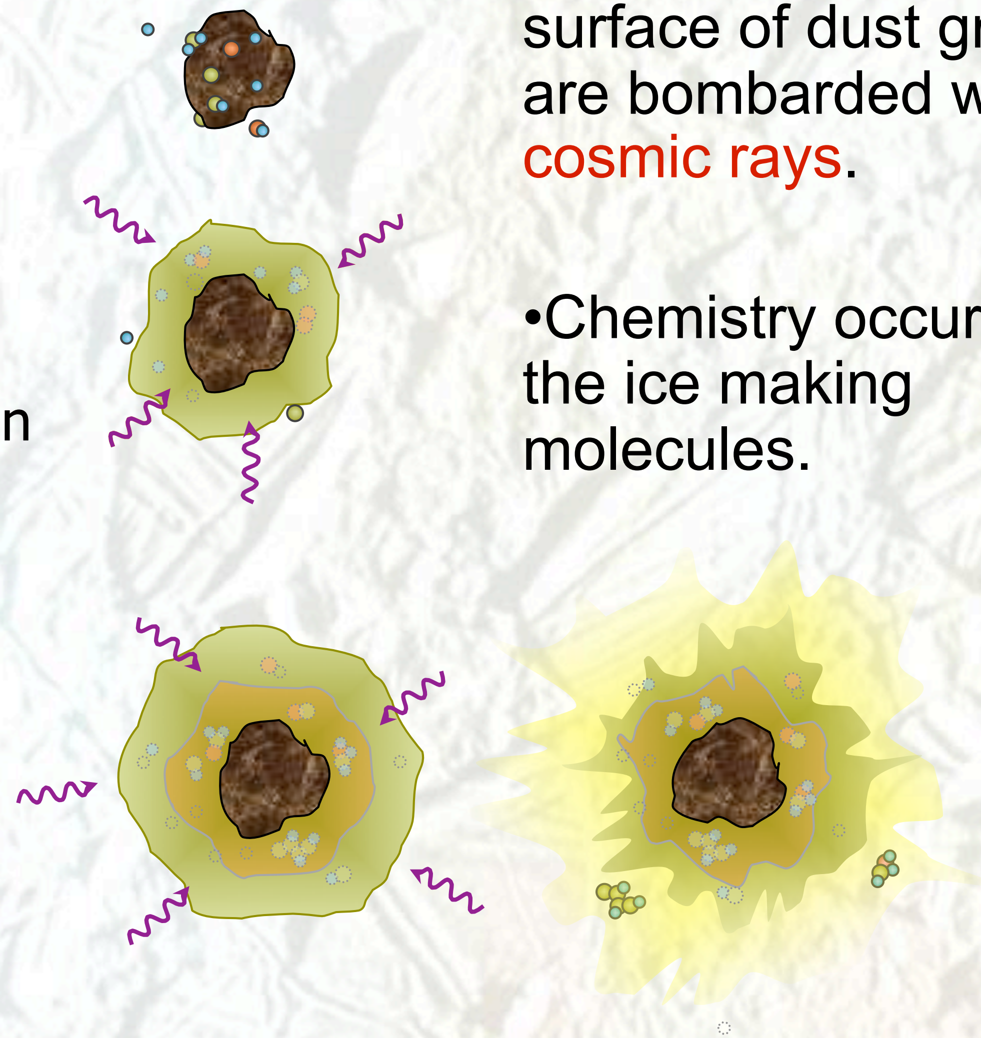
OH and H_2O as well as NH, NH_2, and NH_3 are formed in a manner similar to CH and CH_2.

Cosmic ray chemistry on dust grains

Gas phase routes produce many of the smaller detected interstellar species.

However some contribution From surface reactions is also required.

E.G to form H_2



•The ices on the surface of dust grains are bombarded with cosmic rays.

•Chemistry occurs in the ice making molecules.

Cosmic ray induced surface chemistry

Irradiation of ice leading to molecular synthesis

Lecture 2

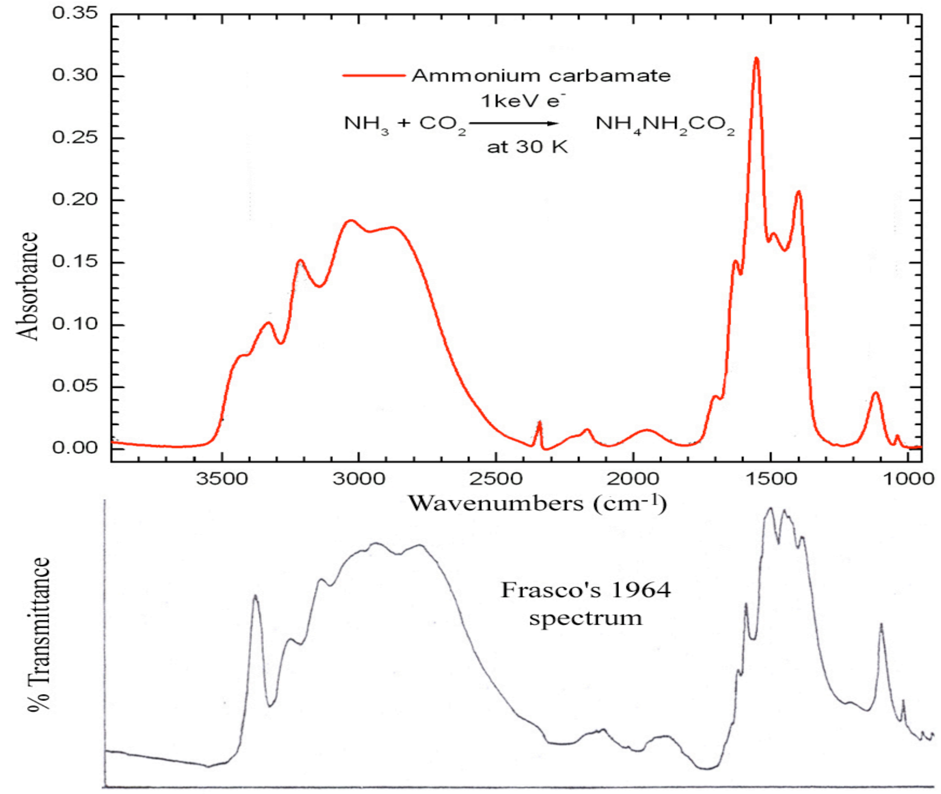


Fig. 5-5: IR spectra of $NH_3:CO_2$ (1:1), (a) post-irradiation (58 min) and after warm-up (220 - 270 K); and (b) comparing Frasco's actual 1964 experimental spectrum at 248 K

Ice chemistry not just in ISM !!

- Cosmic Ray induced Chemistry plays a key role in Planetary Science

Ices in the Solar System

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Ices in the Outer Solar System

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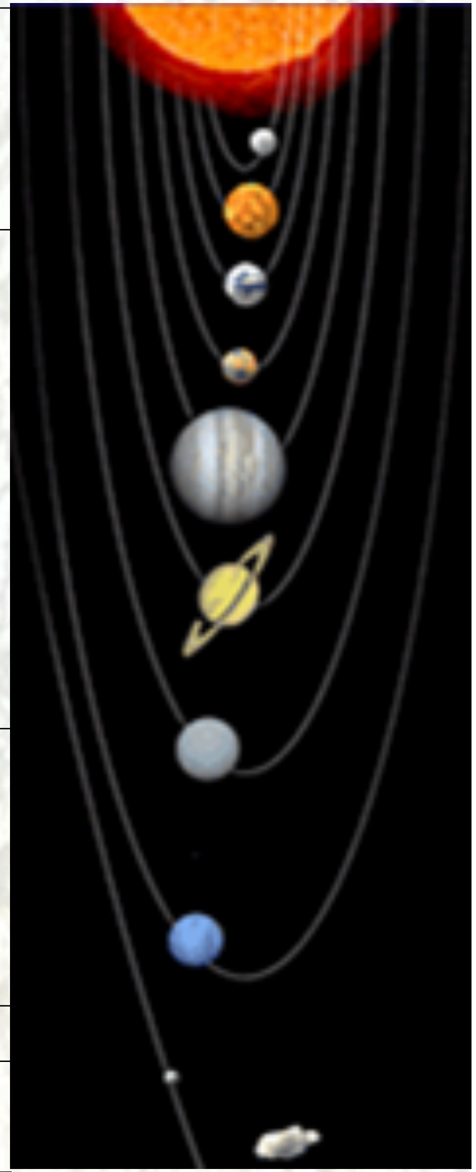
Ehrenfreund and Fraser (2003)

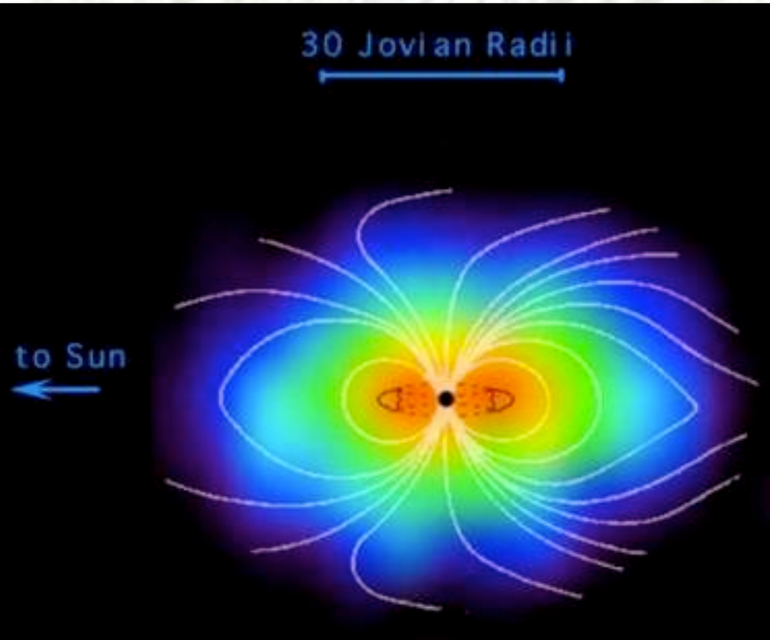
Planet	Satellite	Ices
Jupiter	Io	SO_2, SO_3, H_2S?, H_2O?
	Europa	H_2O, SO_2, SH, CO_2, CH, XCN, H_2O_2, H_2SO_4
	Ganymede	H_2O, SO_2, SH, CO_2, CH, XCN, O_2, O_3
	Callisto	H_2O, SO_2, SH, CO_2, CH, XCN
Saturn	Mimas	H_2O
	Enceladus	H_2O
	Tethys	H_2O
	Dione	H_2O, C, HC, O_3
	Rhea	H_2O, HC?, O_3
	Hyperion	H_2O
	Iapetus	H_2O, C, HC, H_2S?
	Phoebe	H_2O
	Rings	H_2O
Uranus	Miranda	H_2O, NH_3
	Ariel	H_2O, OH?
	Umbriel	H_2O
	Titania	H_2O, C, HC, OH?
	Oberon	H_2O, C, HC, OH?
Neptune	Triton	N_2, CH_4, CO, CO_2, H_2O
Pluto	Charon	H_2O, NH_3, NH_3 hydrate
		N_2, CH_4, CO, H_2O
KBOs		H_2O, HC-ices (CH_4, CH_3OH), HC, silicates



Ions in the Solar System

- Solar wind → 95% hydrogen + electrons, 4 % helium, 1% heavier elements (C, N, O, Ne, Mg, Si & Fe)
- Cosmic rays → 86 % hydrogen, 11 % helium, 1% heavier elements, 2% electrons
- Plasma in planetary magnetospheres e.g. Jupiter, Saturn… → include solar wind particles + sputter products off satellites

- E.g. Jovian Magnetospheric ions comprise of:
  H^+, He^+, O^{6+} and C^{6+} - solar wind
  H^+, H_2^+ and H_3^+ - ionosphere
  O^+, O^{2+}, O^{3+}, O^{4+}, S^+, S^{2+}, S^{3+}, S^{4+}, S^{5+}, S_2^+, SO_2^+, Na^+ and K^{2+} - Volcanic emissions from Io
  H_2O^+, H_3O^+ and OH^+ - sputtering off icy satellites
- Low energy and multiply-charged ions constitute a high proportion of the ion flux



Ion Interactions with Planetary Surfaces

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Nature **292**, 38 - 39 (02 July 1981)

Evidence for sulphur implantation in Europa's UV absorption band

Arthur L. Lane, Robert M. Nelson & Dennis L. Matson

The International Ultraviolet Explorer (IUE) spacecraft has obtained observations of the galilean satellites over the past 2 years …………
………….. We report here the discovery of an absorption feature at 280 nm in Europa's reflection spectrum. Observations with the IUE show that this absorption is strongest on Europa's trailing hemisphere (central longitude 270°). We identify the feature as an SO_2 absorption band and hypothesize that SO_2 may form when energetic jovian magnetospheric sulphur ions are injected into Europa's water-ice surface.

Nature **388**, 45 - 47 (1997)

Detection of ozone on Saturn's satellites Rhea and Dione

K. S. NOLL, T. L. ROUSH, D. P. CRUIKSHANK, R. E. JOHNSON & Y. J. PENDLETON

The satellites Rhea and Dione orbit within the magnetosphere of Saturn, where they are exposed to particle irradiation from trapped ions. A similar situation applies to the galilean moons Europa, Ganymede and Callisto, which reside within Jupiter's radiation belts. All of these satellites have surfaces rich in water ice[1, 2]……
………….. Here we report the identification of O_3 in spectra of the saturnian satellites Rhea and Dione. The presence of trapped O_3 is thus no longer unique to Ganymede, suggesting that special circumstances may not be required for its production.

Nature **373**, 677 - 679 (1995)

Detection of an oxygen atmosphere on Jupiter's moon Europa

D. T. Hall, D. F. Strobel, P. D. Feldman, M. A. McGrath & H. A. Weaver

EUROPA, the second large satellite out from Jupiter, is roughly the size of Earth's Moon, but unlike the Moon, it has water ice on its surface[1]. ……..
………… Here we report the detection of atomic oxygen emission from Europa, which we interpret as being produced by the simultaneous dissociation and excitation of atmospheric O_2 by electrons from Jupiter's magnetosphere. Europa's molecular oxygen atmosphere is very tenuous, with a surface pressure about 10^{-11} that of the Earth's atmosphere at sea level.

SCIENCE VOL 287 7 JANUARY 2000

Evidence for Crystalline Water and Ammonia Ices on Pluto's Satellite Charon

Michael E. Brown[1] and Wendy M. Calvin[2]

Observations have resolved the satellite Charon from its parent planet Pluto, giving separate spectra of the two objects from 1.0 to 2.5 micrometers. The spectrum of Charon is found to be different from that of Pluto, with water ice in crystalline form covering most of the surface of the satellite. In addition, an absorption feature in Charon's spectrum suggests the presence of ammonia ices. Ammonia ice–water ice mixtures have been proposed as the cause of flowlike features observed on the surfaces of many icy satellites. The existence of such ices on Charon may indicate geological activity in the satellite's past.

Hence need to study effect of ions induced chemistry in ices

- Chemistry depends on many different parameters
- Both of the ion and the ice
- *Give some examples….*

Experimental parameters

- Ice morphology - Crystalline vs Amorphous (sponge surface)
- Ice Temperature
- Ion Energy
- Ion Charge state e.g. C^{+} C^{2+}
- Type of ion – Chemically reactive (H^{+} O^{+} C^{+}) or non reactive (He^{+})

Ion v Photon

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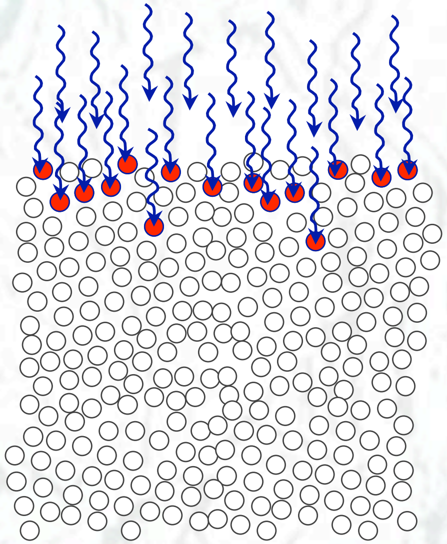
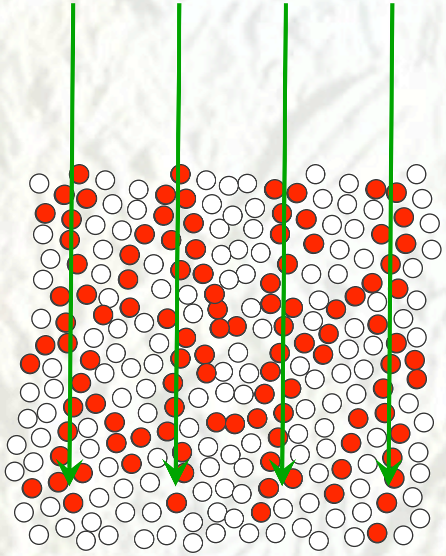


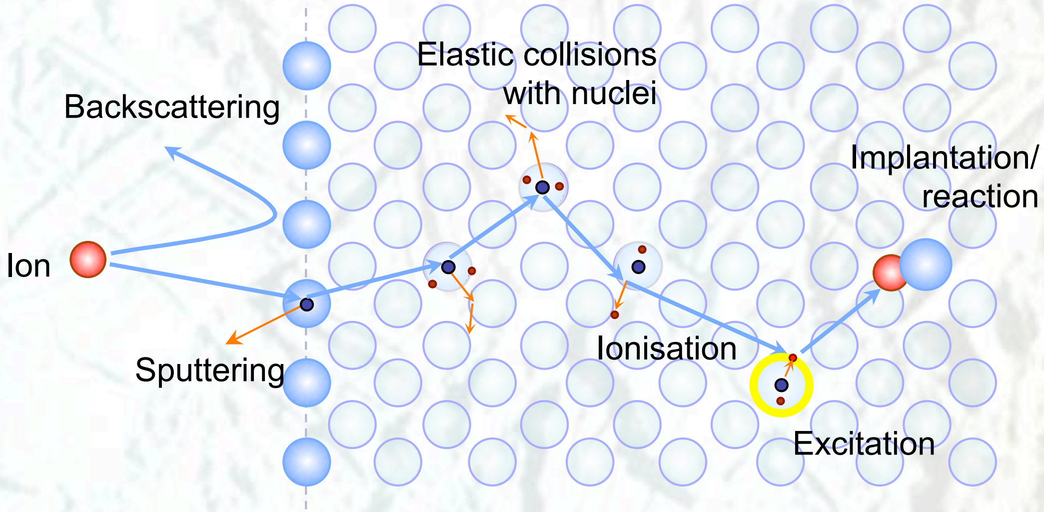


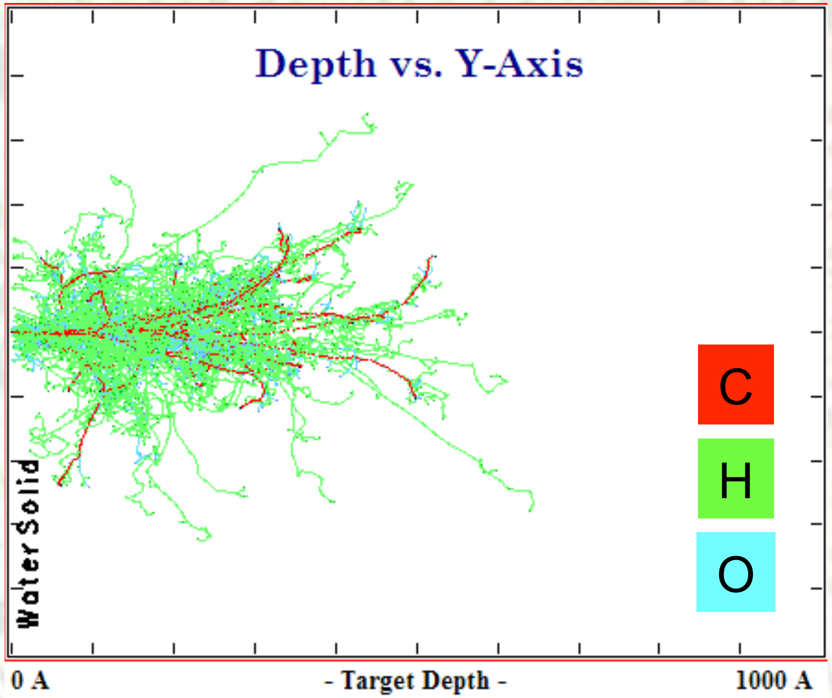
- One-off absorption of a photon (selection rules)
  - Dissociation, ionisation, excitation
  - Secondary electrons
- Penetration depth depends on the optical properties of the material

- Ions interact with many atoms/molecules along the ion tracks
  - Dissociation, ionisation, excitation
  - Dislocations
  - Primary, secondary... knock-on particles
  - Secondary, tertiary... electrons
  - Sputtering
  - Implantation (reactive species)
- Penetration depth depends on the ion energy and mass and the stopping power of the ice

Ion-solid interactions

- Ion energy loss per unit path length dE/dx
  - **Nuclear Stopping (S_n) → elastic collisions with the target nuclei**
  - **Electronic stopping (S_e) → inelastic collisions with the electrons**



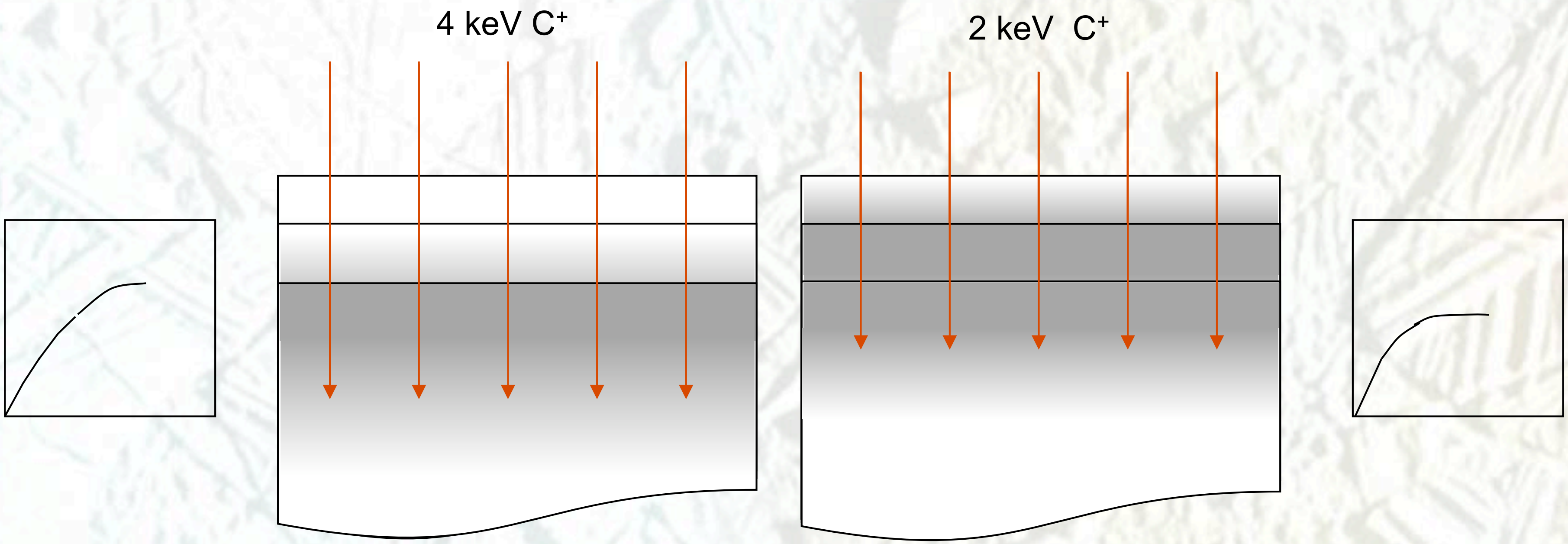


SRIM simulation: 4 keV C^+ in solid H_2O (calculated 50 ions)

Example Energy Dependence

- 4 keV: Range = 188 A, sputtering yield = 2.21 atoms/ion @ 45°
- 2 keV: Range = 105 A, sputtering yield = 2.08 atoms/ion @ 45°

From SRIM theoretical calculations



Learning Outcomes Lecture 1

- Cosmic rays have energy to induce physical and chemical change
- They may play a role in many different phenomena - e,g, climate
- We will explore how they can induce chemistry in ice surfaces on dust grains in ISM or on lunar surfaces.
- Lecture 2 demonstrates some of the chemistry they can induce and how we study it!