

# Variation of Elements in Nature

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by V.S. Venkatavaradan

There are an infinite variety of things in an infinite variety of shapes, colours and states in nature. Despite varied properties, these multitudes of objects are composed of around ninety basic elements, from hydrogen to uranium. In most cases they are composed of only a few of these elements. This rich variety of material in nature is due to the relative abundance of elements, and the ways in which they are combined. On the one hand we see pure and extremely simple materials such as a diamond, which is made up of only carbon atoms, and on the other we see rocks which are highly complex, consisting of almost all elements, from hydrogen to uranium.

What is the reason for such diversity of material in nature? Why is it that nature is not homogenous? Even if a sample of homogenous material consisting of all the elements were to be found, it would separate and become heterogenous. Given the conditions (such as suitable temperature, pressure, concentration), it is only a question of time before a homogenous mixture becomes a heterogenous one. The causes of such variation of elements in nature are known to lie in the forces of nature – gravitational, electromagnetic, nuclear, etc.

The major causes may be broadly divided into physical and chemical. Besides these *natural* causes, there are of course the *man-made* ones responsible for changes in the elemental composition of a given system. It is these natural forces which are responsible for the formation of planets with varying composition. Again, it is these forces which give rise to different kinds of rocks on earth. All the variations on earth, and in the solar system, in stars in our galaxy and even throughout the Universe can be explained as the result of the action of one or more of these forces. In spite of their varied nature, all natural objects show a general similarity in their pattern – be they terrestrial rocks, lunar samples, meteorites or stars. In general, the lighter elements are more abundant, and the abundance of heavier elements drops off somewhat exponentially from iron onwards with characteristic fluctuations. There are, of course, individual variations which are typical; for instance, lunar rocks are rich in titanium and iron compared to terrestrial rocks; the meteorites are rich in noble metals like gold, indium and osmium. Even among terrestrial rocks there are differences in composition depending on the mode of formation. Among stars some are rich in metals while some are poor. The subject of *cosmo-chemistry* aims at explaining these variations; sometimes there may be a single cause but often there is more than one cause for the observed variations. A study of these variations (both isotopic and elemental) will give clues to the processes operating on the system today or in the distant past.

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## NUCLEAR INTERACTIONS IN THE UNIVERSE

The most important reason for variation of elements in nature is nuclear interaction. But for this the Universe might have contained probably only hydrogen. It is from hydrogen that the other elements are created in nuclear reactions in the interior of stars. In the Sun and the stars it is the nuclear transmutation of light elements into heavier ones that keeps the fire burning. On the earth and on the other planets, the transmutation of long-lived radionuclides goes on all the time. Without the heat which is released during their decay, the geological history of the earth would be different. Even in the supposed void of interstellar space, cosmic rays undergo transmutations by interacting with thinly dispersed interstellar matter to produce typical light and medium weight elements which give a clue to their origin, age etc. If nuclear forces are responsible for the occurrence of different elements in nature, it is the chemical forces that make the compounds, giving rise to the nearly infinite variety of things in the universe. Biochemical forces give rise to long chains of organic compounds which are the building blocks of life.

It is not certain how it all began. Probably all the matter in the universe was concentrated in a 'Primeval Fire Ball' at a temperature of the order of many billion degrees. It is speculated that this fire ball exploded and started expanding about 15 billion years ago. The fire ball was mainly made up of hydrogen and, during the initial expansion, nuclear reactions could have produced helium from hydrogen. Heavier elements could have also been produced in smaller quantities. (Even if the steady state theory of the Universe is correct, the later discussions regarding elemental variation would be essentially correct.)

During its expansion, the fire ball cooled and matter was dispersed thinly all over. However, in certain places matter got concentrated thus giving rise to galaxies of stars. These stars can be called the first generation stars meaning that they were condensed out of material from the original fire ball which was mainly made up of hydrogen. When the mass of hydrogen starts contracting (condensing) to form a star, it gets heated up due to gravitational energy. The heat is soon sufficient to initiate thermonuclear reactions in the interior of the star. The pressure due to this reaction stops the contraction. The star reaches the equilibrium state and derives its energy mainly from the fusion of the hydrogen nuclei to form helium. In this state, the star may exist for millions to billions of years depending on its initial mass. When the hydrogen in the core gets exhausted there is no force now to balance the gravitational contraction and the core begins to contract again. This heats up the core further resulting in a condition suitable for the fusion of three helium nuclei to form a carbon nucleus. (Normally it would be very difficult to fuse three helium nuclei. But due to certain matching of nuclear parameters this reaction has a high cross-section — resonance — and without this resonance there would not be much of carbon in nature.) This releases enough energy to prevent further contraction. When helium is also nearly exhausted, the core contracts further, initiating fusion reactions involving carbon, and so on. Such fusion reactions will produce elements like oxygen, neon, magnesium, silicon etc., up to iron. Neutrons may also be produced during this time giving rise to a number of nuclides.

Thermonuclear fusion reactions can build nuclides only up to iron as any further addition of particles to iron needs addition of energy (in contrast to the earlier reactions where energy is released). Once all the core material is converted to iron, the thermonuclear reactions become less important and the core begins to contract again, leaving a shell of material enriched in elements upto iron. The core contraction is catastrophic, releasing

a large amount of energy and a high flux of neutrons. A large number of neutron-induced reactions take place which produce elements up to uranium and beyond in a short time before the star explodes throwing a lot of material into interstellar space, enriching it with heavier elements. This matter can condense at a later stage to form second generation stars which will go through a similar history. Their explosions will further enrich the interstellar matter which will form the future generation of stars. Our Sun is probably a third or later generation star. It contains, apart from primordial hydrogen (and helium), heavier elements produced by the previous generations of stars.

## NUCLEOSYNTHESIS

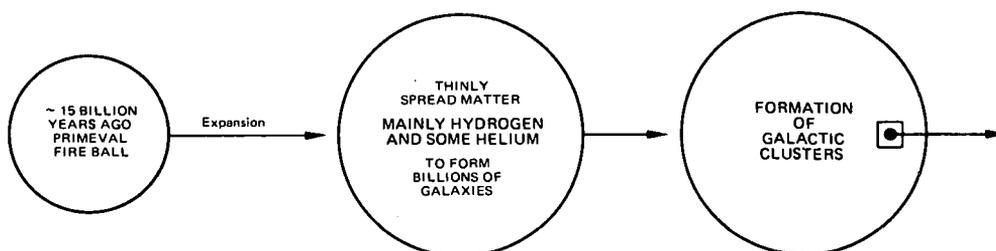
The simplified picture of element creation in a star will have a lot of variation depending on the size of the star and its initial elemental abundance. A very heavy star will explode as a supernova leaving behind a neutron star. Stars of mass comparable to the Sun may end up as white dwarves. Old stars which formed when interstellar matter was poor in heavy elements will have their atmospheres consisting mainly of light elements. Later generation stars will show enhancement of heavy elements which can be seen from their spectral characteristics. The process of creation of various elements is called 'Nucleosynthesis'. At this stage it is worth remarking that the atoms in us were once synthesised in the interior of hot stars to be thrown out in the coldness of interstellar space a number of times before finally forming the solar system.

In general, we can consider variation of elements in two categories: (i) closed systems, (ii) open systems. In nature, all systems are open but in a number of cases they may be approximated to closed systems. Whereas variations of elements in closed systems are entirely due to processes operating within the systems, variations in open systems could be due to addition from external sources or depletion by escape from the system.

When deep ocean sediments were analysed it was found that the nickel content of the sediments showed a curious distribution. There was more nickel in sediments with low sedimentation rate and less nickel in high sedimentation rate cores. This observation was intriguing until it was proposed that a part of the nickel in sediments may be of extraterrestrial origin.

The earth is constantly receiving interplanetary matter (meteoritic) which is enhanced in nickel. The influx of this dust is more or less uniform over the globe. If a region has a low sedimentation rate (most of the sediments being terrestrial in origin), it will have a comparatively high fraction of extraterrestrial component with high nickel and vice versa. A similar observation was made on the lunar samples returned from Apollo missions.

Some major processes in the universe which alter the composition of elements and isotopes in nature.



It was found that there was more nickel in the lunar soil than in lunar rocks, the extra nickel in the lunar soil again being meteoritic in origin. The earth is receiving a few hundred tonnes of cosmic dust every day.

Helium is one of the elements which is in great abundance in the Universe. In fact, this element is second only to hydrogen in abundance. But its presence on the earth is very small. This is because, so far as helium is concerned, the earth is an open system. Helium being a light gas, the earth's gravity cannot hold it and it therefore escapes into space. All the original helium which was present on the earth during condensation must have escaped long ago.

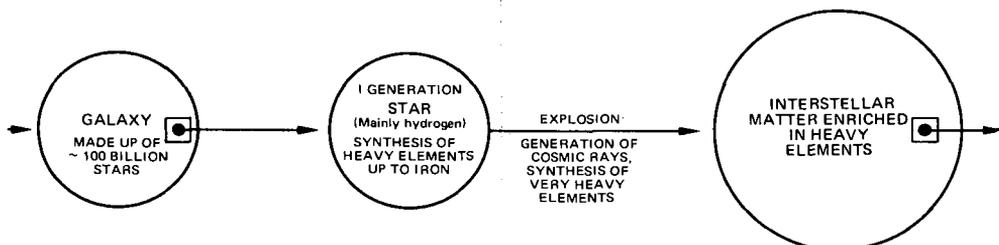
The small amount of helium in the earth's atmosphere is derived from the decay of radioactive elements like uranium and thorium in the earth's crust. Helium in the atmosphere is in dynamic balance, with the amount escaping into space being compensated by fresh decay of uranium and thorium series. Hydrogen also escapes from the earth's atmosphere.

This explains the very low percentage of free hydrogen in the earth's atmosphere. However, hydrogen is reactive, and is bound to oxygen in the form of water. Since water molecules are heavy they do not escape from the earth. It is the chemical reactivity of hydrogen that has made it possible for it to exist in appreciable quantity on earth. From the Moon even heavier gases can escape due to its low gravity. This explains the lack of any atmosphere on the Moon.

Hydrogen and helium, however, do not escape from massive planets like Jupiter and Saturn. Their gravity being very high and their atmospheric temperatures very low, these gases are trapped and exist in their primordial composition. An analysis of these gases from the atmosphere of these planets will tell us a lot about the conditions which existed in the beginning of the solar system.

## CORE FORMATION

Gravitation also plays a major role in fractionation of elements in planets. When the planets are formed from smaller objects by gravitational accretion their composition should be more or less uniform (probably similar to a class of meteorites called *carbonaceous chondrites* which are supposed to be the most primitive objects in the solar system). The whole mass could have been accreted at a comparatively low temperature. It is hypothesized, at least in the case of the earth, that sometime after the accretion, the decay of radioactive elements like  $^{40}\text{K}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$  and  $^{232}\text{Th}$  contributed to the heating of the planetary body. This resulted first in partial melting of the object. When the mass was molten, heavier metals



like iron and nickel sank down whereas the lighter silicates floated up. The sinking of iron gave rise to further melting due to the additional gravitational energy available because of the sinking. This melting resulted again in iron and other heavy metals sinking further down. This led to a catastrophic core formation with heavier elements concentrated at the centre.

In the case of the earth, the molten core of iron-nickel is due to this mechanism, which is also responsible for its magnetic field. If a planetary body is not sufficiently heated up, such a separation may not take place. The Moon and planet Mercury are two examples where the whole object has more or less a uniform composition.

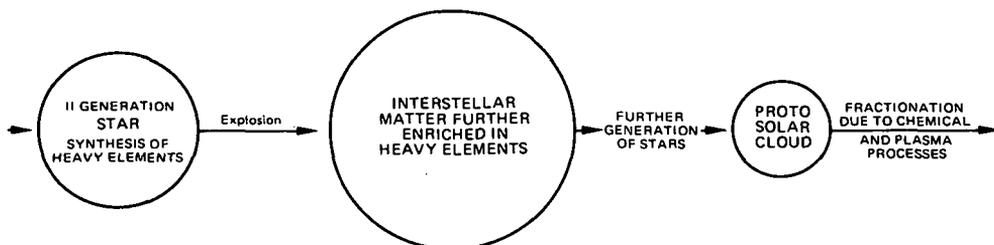
## RADIOACTIVE DECAY

Yet another cause for the variation of elements in a system is radioactive decay. We have said that the helium in the atmosphere is due to the decay of uranium and thorium in the crustal rocks. Another important constituent of the earth's atmosphere, argon, is also derived from the decay of potassium-40 in the crustal rocks.

Argon forms about one per cent of the earth's atmosphere and nearly all of it is derived from radioactive decay. The universal abundance of argon-40 is very low. The abundance ratio of  $^{40}\text{Ar}/^{36}\text{Ar}$  in the Sun is about 0.01, whereas in the earth's atmosphere it is about 300. The very high increase in the ratio is due to the accumulation of radiogenic argon over billions of years. In fact, analysis of sedimentary rocks have shown that the argon-40 content of the early atmosphere was much less. In the primordial earth's atmosphere relative abundance of argon-40 must have been very small, typical of solar abundance.

Most of the helium and argon from the decay of radioactive nuclei are trapped in the rocks and the amount of these gases is proportional to the age of the rocks. Thus, a measurement of helium and argon will enable us to determine the time of formation of various rocks. Such a determination for terrestrial rocks has shown that the oldest rock on earth is about 3.5 billion years old. Lunar rocks and meteorites have also been 'dated' by this method. The age of lunar rocks is found to vary from about 4 billion years to about 2 billion years. Some of the meteorites have ages of about 4.6 billion years, as old as the Earth and the Moon.

The decay products of potassium-40, uranium, etc. are accumulated over billions of years due to the long mean life of these radioactivities. There are yet other radioactive nuclides whose mean lives are shorter compared to the age of the solar system. The decay products of such activities like plutonium-244 (half-life = 82 million years), iodine-129 (half-life = 17 million years) can be accumulated by a rock only if it is cooled soon after the formation



of these nuclides in the nucleosynthetic process discussed earlier. By measuring the gases which are produced by such decay (iodine-129 decays to xenon-129 and plutonium-244 fission yields a number of xenon isotopes) the time of formation of solar system objects after the last nucleosynthetic event can be determined. It is estimated that solid objects condensed after a few tens of million years from an event which gave rise to radioactive nuclides like plutonium-244 and iodine-129.

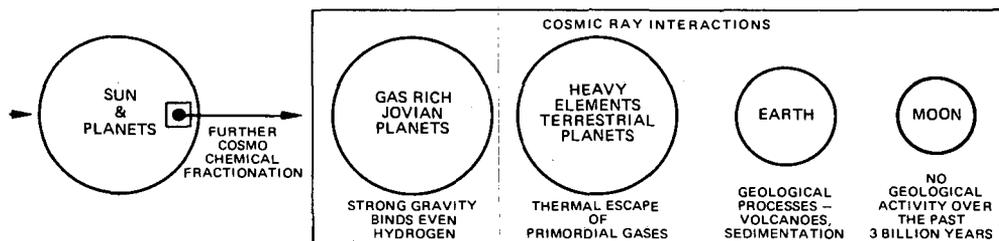
## COSMIC RAYS

Cosmic rays are energetic particles coming from extraterrestrial space. A majority of these particles are protons. About one per cent of the flux is electrons. Helium and heavy nuclei are also present in cosmic rays. In fact, cosmic rays contain all the elements that are found in nature but the abundance distribution is different. A study of the isotopic and elemental abundances of cosmic ray nuclei would give information regarding the sources of cosmic rays (supernovae, pulsars, etc.) and also about interstellar space. Cosmic rays interact with interstellar matter and undergo changes which are typical and can be distinguished. For instance, the sources of cosmic rays in general have a high ratio of  $^4\text{He}/^3\text{He}$ . When the helium-4 nuclei interact with interstellar hydrogen, part of it is converted into helium-3 (and also helium-2). The ratio of  $^3\text{He}/^4\text{He}$  thus will increase with the amount of matter travelled. From the measurement of this ratio it has been estimated that cosmic ray nuclei have travelled a matter of about 4 gms/cm<sup>2</sup> during their passage from the source to the earth.

Recently we have studied the very low-energy cosmic rays, using detectors exposed in the Skylab orbiting laboratory. The observations show unusual variations in composition of heavy nuclei in comparison with high energy cosmic rays. These results point to a distinctly different source for this low energy component.

Cosmic ray particles, during their traversal in interplanetary space, interact with interplanetary dust, meteorites, the Moon and the Earth's atmosphere. They cause a variety of transmutations resulting in the production of radioactive nuclides of mean lives varying from seconds to billions of years. Measurement of these activities in meteorites has revealed the near constancy of cosmic rays in the past hundreds of million years and probably even billions of years.

Due to meteoritic impact a crater is formed on the lunar surface and a number of rocks are strewn on the surface of the Moon. When the rocks are buried deep, cosmic rays do not interact with them. However, on exposure to cosmic rays at the surface, their isotopic composition undergoes typical changes due to nuclear interactions. The amount of helium-3, for instance, increases with exposure time. A measurement of these variations



(such as the amount of helium-3 or neon isotopes) gives the exposure ages of these rocks. It has been found from such measurements that lunar rocks have a surface exposure age of a few million years. The surface dynamics, due to meteoritic impact and consequent sedimentation processes in the lunar regolith, limits the exposure to only millions of years.

## GEOPHYSICAL APPLICATIONS

The interaction of cosmic rays with the earth's atmosphere produces radionuclides whose analysis has made it possible for us to understand various processes such as in atmospheric circulation, oceanography and hydrology. Carbon-14, an isotope produced by the interaction of neutrons on atmospheric nitrogen, has applications, apart from hydrology and oceanography, in archaeological dating. In the geophysical applications, the radioactivities which are mainly produced in the upper atmospheres are used as tracers.  $^7\text{Be}$ ,  $^{22}\text{Na}$ ,  $^{32}\text{Pa}$ , etc. have been used in atmospheric circulation studies. Very short lived nuclides are used in closed formation studies. The analysis of these activities are carried out in rain water or air filters. Tritium, an isotope of hydrogen, is used in groundwater age determination.

Radon-222 is a radioactive gas released during the decay of uranium-238 chain with a short half-life of about 4 days. It is released into the atmosphere by slow diffusion from the earth's crust. The amount in the atmosphere is in equilibrium with decay and fresh release from the crust. Since the land mass contains more of uranium than the water mass, the radon content over land is much more than over water. From a study of the radon content (it was unusually high) of monsoon air over Bombay, it has been suggested that the air mass must have travelled from African and Arabian coasts instead of the conventional assumption that the monsoon air comes straight from the Indian Ocean. There are some controversies regarding this hypothesis. A detailed study of radon distribution will give a lot of understanding regarding monsoon circulation.

It has also been known that the radon content of the atmosphere increases before the onset of an earthquake. This is due to the building up of strain in the rocks before earthquakes which enables radon to diffuse faster. Thus, an analysis of radon content of air masses over potentially dangerous earthquake regions will help in forecasting an earthquake.

## MAN-MADE ISOTOPES

Apart from natural and cosmic-ray-induced radioactivities in the atmosphere, there is yet another cause for the injection of radionuclides into the atmosphere. These are the atmospheric nuclear explosions. A lot of radioisotopes like strontium-90, tritium and carbon-14 are produced during nuclear explosions. From the observed variation of carbon-14 in the atmospheric air over a period of time, it has been found that the mixing time of stratospheric air (where the radioactivity is injected) with the troposphere is about a few years.

Until the Stone age, all the changes in elemental variations were mainly due to the work of nature. It is with the evolution of civilization that man became important in changing the natural distribution of elements. He learnt to exploit the ores, concentrate metals and produce industrial products. Until the development of nuclear physics, these changes were purely in the realm of chemistry. With the modern nuclear techniques — accelerators, nuclear reactors — man has played quite an important role in transmuting elements. Nuclear

reactors constantly change the elemental and isotopic constituents during energy generation. Many artificial radioactive isotopes are being created — isotopes which never existed on earth in such large concentration. With the development of fusion bombs, man has caused changes which, until now, were known to take place only in the interior of stars.

### NATURAL NUCLEAR REACTOR

Probably many may think that the nuclear reactor is the work of man which nature cannot duplicate. However, it has been found in certain uranium ores that the ratio of  $^{235}\text{U}/^{238}\text{U}$  is less than 1/137, which is the normal ratio found in most of the ores. This suggests that uranium-235 has been preferentially removed from the ore body. This is possible during induced fission in a nuclear reactor with natural uranium as fuel. Uranium-235 fissions and uranium-238 is stable against thermal neutrons. The ratio of  $^{235}\text{U}/^{238}\text{U}$  will diminish with time. But how could it diminish in the ore itself? The only explanation is that probably in the past, there was a concentration of uranium on the earth enough to sustain a chain reaction. The underground water could have acted as a moderator creating a natural reactor. It is also speculated that such natural nuclear reactors — or sometimes natural nuclear explosions — in the past could have contributed energy for the movement of continents — the so-called continental drift.

### BIOLOGICAL VARIATION OF ELEMENTS

Biological processes are also responsible for variation of elements in nature. Plants take carbon dioxide from the atmosphere and release oxygen in a photosynthetic process. Their complex biological chemistry also concentrates many elements from soil. Marine organisms concentrate calcium from sea water in the form of lime in their shells. Certain other organisms concentrate silicon.

It has been found that trace elements in human blood resemble the distribution in rocks. It is also known that hair concentrates many trace elements from the blood. The elements of hair thus depend on food habits, environment, diseases, etc., which affect the trace element concentration in blood. Thus, distribution of elements in hair can be used in such wide fields as archaeology, geophysics, medicine and for crime detection. Recently, it has been found that cancer cells concentrate trace elements in large quantities compared to the normal cells. In fact, by analysing elements like copper in body cells, one can diagnose cancer in its early stage.

### ANTIMATTER

We have so far discussed the variation of elements in normal matter. It is likely that in some parts of the Universe objects may be made of antimatter. It is difficult, maybe impossible, to distinguish these objects by the light they emit. However, if antimatter interacts with normal matter, it gets annihilated and this results in the creation of a number of elementary particles. A search for nuclear antiparticles has been made in cosmic rays but no positive evidence exists for their presence (positrons which are the antiparticles of electrons have however been observed in cosmic rays which may be due to secondary interactions during the traversal of cosmic rays in interstellar space).

If a lump of antimatter were to interact with the earth's atmosphere, it may cause sufficient change in the elemental distribution to be observed. When the antimatter interacts with

atmospheric nuclei, they produce a lot of K-mesons which, on further interaction, will produce neutrons. These neutrons can produce carbon-14 from atmospheric nitrogen. Thus, if there is a fresh impact of antimatter in a certain region, there will be an enrichment of carbon-14 in that place. The meteoric impact of Tunguska in USSR during 1908 was attributed to antimatter. However, radioactive analysis of carbon-14 in this region has not confirmed this hypothesis. Today, the existence of antimatter in large quantities to make up stars and galaxies is only a possibility and still only a speculation. Future astrophysical observations may give clues to this exciting speculation.

## **SOME CAUSES OF ELEMENTAL AND ISOTOPIC VARIATIONS**

### **NATURAL PROCESSES**

**Physical:** Gravitational, Electromagnetic, Nuclear Reactions and Decay, Erosional

**Chemical:** Geochemical, Cosmochemical, Biological, Geobotanical

### **MAN-MADE**

Industrial processes such as exploitation of ores and manufacture of chemicals

Pollution due to industrial processes

Fossil fuel burning

Nuclear reactors and bombs