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HIGH ENERGY PHENOMENA IN ASTROPHYSICS

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I. INTRODUCTION

The nature of the relationship of astronomy to the rest of physics has fluctuated with time. In the days of Kepler, Galileo and Newton, astronomy occupied the place of honour, with very little work being done in the rest of physics. The situation changed in succeeding centuries, when important developments took place in laboratory physics. In the first few decades of this century astronomy had somewhat receded to the background and the main stage was occupied by such important developments as relativity, quantum theory, particle physics etc.

The situation has changed again in the last few years. As astronomical techniques improved and multiplied, a wealth of data about the universe became available. In some cases the laws of laboratory physics can be extrapolated, whereas in others the type of conditions are so vastly different from those produced in the laboratory that the theoretician is often at a loss. The high energy phenomena uncovered by the astronomer fall in this latter category.

The words 'high energy' can be taken to mean two different things. When applied to individual particles or quanta they imply high kinetic energy of such objects. For example, in laboratory high energy physics we talk of particles in the $10^7 - 10^{11}$ eV range. In astrophysics the range is from 10^3 to 10^{21} eV! The second meaning of "high energy" refers to the enormous reservoirs of energy found in the universe. For example, the energy released in a mega-ton H-bomb manufactured on the Earth is $\sim 4.10^{22}$ ergs. A typical extragalactic radio source has energy as high as 10^{62} ergs! In this lecture I propose to review such high energy phenomena in both senses of these words.

II. HIGH ENERGY PARTICLES

I shall first summarize the observational situation and will come to theoretical considerations later. It is convenient to divide this discussion into a number of sub-sections.

i. Type of particles

A simple calculation shows which elementary particles we may expect to see in cosmic rays coming from the different parts of the Galaxy. If τ is the life time of a particle in its rest frame, and v its velocity, then the distance it will travel in its life time is given by

$$R \sim \gamma c \tau , \qquad \gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2} . \qquad (1)$$

Setting $\gamma = 10^{11}$ for a 10^{20} eV proton, and $R \cong 10^{22}$ cms, we get

$\tau \sim 3$ secs. Of the known elementary particles, the unstable ones have lifetimes between $\sim 2.10^{-6}$ secs. for the muon and $\sim 10^{3}$ secs. for the neutron. Of these only those with lifetimes in excess of 3 secs. are likely to arrive unmolested from the edge of the Galaxy. So normally we expect to see only the stable particles such as $e^{\pm}$, p, ν_e, $\overline{\nu}_e$, ν_μ, $\overline{\nu}_\mu$ and perhaps n. These requirements are more stringent if we are talking of lower energy particles or if we require them to come from beyond the Galaxy.

Besides elementary particles we may also expect to find heavier systems such as α-particles and nuclei of higher atomic numbers. Table I gives the relative abundances of various elements found in cosmic rays at two different energies and the universal abundances of these elements. This information is of great relevance to the problem of the origin of cosmic rays.

ii. Methods of observation

The atmosphere presents problems in making cosmic ray observations. Its height is many times the interaction length of the nucleonic component and the high energy photons. Direct observations are therefore possible only above the Earth's atmosphere using balloons, rockets and satellites. This limits flux measurements to $> 10^{-8}$ particles/cm^2 sec Sr. Further, one has to distinguish between primaries and secondaries. The latter may be produced in the atmosphere, or even in the apparatus.

At low energies the solar wind magnetic field tends to distort the distributions of charged particles.

Direct measurements are possible upto energies of the order of 10^{14}eV. At higher energies, air showers provide most of the information. These make use of the above mentioned property of the atmosphere to interact with primary cosmic rays. A primary nucleon interacts with an air molecule to produce pions. Of these the π^0s decay into gamma rays:

$$\pi^0 \longrightarrow 2\gamma, \tag{2}$$

while charged pions decay into muons and electrons:

$$\pi^{\pm} \longrightarrow \mu^{\pm} \longrightarrow e^{\pm} . \tag{3}$$

Detectors on the Earth's surface placed over say 10 sq. km. or more look for coincident pulses. The secondaries then tell us about the primary composition.

iii. Quantitative information

The most remarkable aspect of cosmic rays is the energy spectrum. It follows a power law

$$I(E) = KE^{-n} , \tag{4}$$

where $I(E)$ represents the number of particles with energy in excess of E. The range of E is from 10^{10} to 10^{20} eV, and during this range n changes slightly. $n = 1.6$ for most of the range, except in the interval

$10^{15} - 10^{16}$ eV, where $n = 2.2$. The total number of particles is around $1500/m^2$ sec. Sr.

Could the value $n = 1.6$ represent some universal property? The break in the spectrum around 10^{15} eV may be due to escape of galactic component and penetration of the extragalactic one. This factor has a bearing on the problem of cosmic ray origin.

The electrons above 10^6 eV are believed to be of galactic origin and their spectrum follows the same law (4), with $n = 2.2 \pm .2$ over the range $10^6 - 10^{11}$ eV. Below this they are of solar origin.

The observed cosmic ray flux is very isotropic. The anisotropy is measured by the parameter

$$\delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \qquad (5)$$

where I_{max} and I_{min} represent the maximum and minimum values of intensity in different directions at a given energy. The value of δ is less than 0.1% for $E < 10^{14}$ eV, less than 1% for $10^{14} < E < 10^{16}$ eV and less than 3% for $E > 10^{16}$ eV. Any theory of the origin of cosmic rays must explain this isotropy.

Finally, do we have an estimate of the time scales over which cosmic rays have existed? Some information is provided by meteorites. Induced radio-activity caused by constant bombardment of cosmic rays tells us that over 10^9 years or so the flux of cosmic rays in the solar system has remained relatively unchanged.

iv. Energy content

Just how big is the cosmic ray reservoir? The average energy density of cosmic rays is $\sim 10^{-12}$ ergs/cm^3. If this is fairly uniform over the disk of the Galaxy, whose volume is $\sim 10^{67}(\mathrm{cm})^3$, the total energy content of cosmic rays is $\sim 10^{55}$ ergs. If we knew the lifetime of cosmic rays, we can estimate the rate at which this energy must be provided.

This information is provided by the data on abundances mentioned above. The over-abundance of the elements Li, Be and B and the under-abundance of C, N, O compared to the universal values suggests that the latter have decayed into former during the passage of cosmic rays through the Galaxy. Calculations show that the cosmic rays must have passed through about 3 gm of Hydrogen to achieve this. At galactic density of ~ 1 atom cm^{-3}, this corresponds to a length of $\sim 3.10^{24}$ cm, or a lifetime of $\sim 3.10^{6}$ years. Thus cosmic rays once emitted last for approximately this period. This means we require 10^{55} ergs to be produced over 3.10^{6} years, i.e., a rate of production of $\sim 10^{41}$ ergs/sec.

v. Origin of cosmic rays

Where do these high energy particles orginate? The nearest possible source, the Sun, can be ruled out for various reasons. Its magnetic field is not strong enough to contain the particles. The composition of cosmic rays is remarkably different from that of the Sun. Also, cosmic ray activity does not seem to be high when Sun is active, and vice versa. Finally, we cannot think of any violent activity going on inside the Sun which could release a flux of high energy particles.

The next obvious candidate is the Galaxy. It has exploding stars, called supernovae, which are capable of producing a flux of high energy particles. A typical supernova can release energy in the range 10^{49} to 10^{52} ergs. It is estimated that one supernova explosion occurs every 50 years or so. This corresponds to a rate of energy release of 10^{40} - 10^{43} ergs per second - well in the required range as seen above.

There are, however, problems. It is easier to see how high energy electrons might be produced by supernovae - but there is difficulty in producing the highest energy protons, or heavy nuclei. Further, there is the containment problem. Can the magnetic field in the Galaxy, which is of the order of 10^{-6} gauss, contain all the cosmic ray particles? A simple calculation suggests the following. If a is the radius of the Galaxy and H the magnetic field inside it, then for a particle of mass m, charge e, moving close to the speed of light we have

$$\gamma \approx \frac{eHa}{mc^2} . \qquad (6)$$

For a proton, with the above values of H and a, we get $\gamma \approx 5.10^9$, i.e., an energy of $\sim 5.10^{18}$ eV. This does not cover the full range of energy upto 10^{20}eV., and suggests that the highest energy particles are of extragalactic origin.

There are several candidates for extragalactic cosmic ray sources, the chief among them being strong radio sources, nuclei of galaxies and quasi-stellar objects (QSOs). These are seats of violent activity and could produce the flux of very high energy particles.

III. PHOTONS

In astrophysics we come across vast reservoirs of photons at different energies, ranging from the radio to the γ-rays. For the sake of completeness I will discuss them all together, as even the low energy photons can be of importance to high energy physics.

i. Processes of photon production

Continuum radiation is produced by several processes, the chief among these of interest to astrophysics are briefly enumerated below.

(1) Black Body radiation such as produced by hot plasma.

(2) Bremsstrahlung, i.e., radiation arising from e-e, e-p collisions.

(3) Inverse Compton Effect in which a low energy photon gets energy from a high energy electron.

(4) Synchrotron radiation arising from motion of charged particles in a magnetic field.

(5) Decay of π^0 mesons into gamma rays. This has already been mentioned before.

Apart from these line radiations are produced at various frequencies such as the 21 cm radiation in the radio range and the various spectral lines in the optical range. Recent interest in high energy photons has caused physicists to look for possible line radiations in the X-ray and γ-ray range. Some examples of these are given below.

(1) The K and L type X-rays arising from ejection of inner shell electrons by high energy particles or photons.

(2) The annihilation of e and e^- which are essentially at rest produces a γ-radiation of energy 0.51 MeV.

(3) The formation of deuterium by inverse photodisintegration, i.e., $n + p \longrightarrow d + \gamma$ produces a gamma ray of 2.23 MeV energy.

ii. Photon sources in astrophysics

It is convenient to list such sources in the order of increasing photon frequency.

(1) Radio sources are found in the Galaxy in the form of radio stars and outside the Galaxy in the form of radio galaxies and quasi-stellar radio sources. The most important process of production of radio photons in

the latter case is synchrotron emission. Burbidge(1) has estimated that a typical radio source (extragalactic) can have energy as high as 10^{62} ergs. A quasi-stellar can have energy $\sim 10^{60}$ ergs. In either case the estimates are based on 'minimum energy' requirement and maximum efficiency of production. In actual situations these estimates may have to be revised upwards.

(2) No microwave sources have been discovered so far, although there exists a microwave background. If this is thermal in origin, it would correspond to a temperature of $\sim 2.7^\circ$K. This may be the remnant of the big bang, if the universe did in fact originate with a big bang.

(3) Infrared sources have been found outside the Galaxy, and in some cases(2) a galaxy is found to emit much more in the infrared than in the visual part of the spectrum. Infrared astronomy is a new subject with many possibilities.

(4) The most common type of source is that of the visual photon. Stars, galaxies, QSOs are found to emit continuum and line radiations in the optical regions. Our Galaxy emits at the rate of $\sim 10^{44}$ ergs $\sec^{-1}$.

(5) X-rays are emitted by the sun at the rate of $\sim 10^{23}$ ergs/sec. In quiet phases the X-rays emitted are soft ones whereas in solar flares hard X-rays are emitted. More remarkable sources are, however, Sco-X-1 and the Crab. The former emits at the rate of $\sim 10^{35}$ ergs/sec. and the X-rays arise from hot plasma. In the case of Crab, the emission is $\sim 10^{37}$ ergs/sec. and is more likely due to synchrotron process. Neutron stars with hot plasma interiors are likely sources of X-rays.

We would also expect X-rays from other galaxies, since our own Galaxy is pretty well 'average'.

(6) Gamma rays can arise from cosmic rays as mentioned before. So we get them from the disk of the Galaxy. Some QSOs and exploding galactic nuclei are also likely sources of gamma rays. Observation of gamma rays and X-rays has to be carried above the atmosphere because they get absorbed in the process of reaching Earth's surface.

IV. SOME COSMOLOGICAL CONCLUSIONS

The high energy flux of particles and quanta tells important facts about the universe and is likely to be of great important to cosmology. I describe below some cosmological aspects of cosmic rays.

(1) In 1958 Gold and Hoyle(3) suggested that matter creation in the steady state universe might be in the form of neutrons. Neutrons undergo beta decay, producing electrons of high kinetic temperature $\sim 10^9$ °K. A hot intergalactic medium of this temperature produces X-rays by bremsstrahlung. Comparision with observations shows(4), however, that the calculated X-ray background is too high by at least an order of magnitude. Indeed, in order to be consistent with the observed X-ray background, the intergalactic medium should not be hotter than 10^7 °K.

(2) Gamma ray background similarly places an upper limit on the amount of antimatter in the universe. Burbidge and Hoyle(5) had suggested in

1956 that if matter were created without violating baryon and lepton numbers, then since the expansion rate of the steady state universe is about 100 times higher than the annihilation rate of matter and antimatter, we might expect to see an appreciable quantity of antimatter in the universe. However, unless this antimatter is well separated from matter, its annihilation will produce a gamma ray flux much higher than observed.

(3) The existence of microwave background produces an important effect on the high energy spectrum of protons. It can be shown(6) that at a threshold of $\sim 2.10^{20}$ eV, a proton interacts with a microwave photon to produce photopions. So if cosmic ray protons show an effective cut off beyond $\sim 10^{20}$ eV, we have some evidence of the universality of microwave background.

V. NEUTRINOS AND GRAVITATIONAL RADIATION

It is well known that neutrinos are produced in the Sun during beta decay processes. Attempts to detect them(7) through the reaction $Cl^{37} + \nu \longrightarrow Ar^{37} + e^-$ have so far produced results in disagreement with calculations. The number of neutrinos observed is small by an order of magnitude. Theoreticians are at work to examine the implications of this for stellar evolution, and also for fundamental laws of physics.

High energy neutrinos can be produced in the high temperature phases of stellar evolution through such processes as $e^+ + e^- \rightarrow \nu + \bar{\nu}$. Also explosive events can produce a flux of high energy neutrinos.

Recently Weber(8) has detected gravitational radiation at the frequency of 1660Hz coming mainly from the galactic centre. The amount of radiation is too high for comfort for most theoreticians since it requires the ejection of some $10^2 - 10^3$ solar masses every year from the galactic centre. Other experiments are underway to verify this result. If it is confirmed, it poses a serious problem to the theory of general relativity.

This concludes my brief review of high energy phenomena as seen by an astrophysicist. Whether all of the questions raised by observations can be answered by straightforward extrapolation of laboratory physics is very much an open question. I myself take the view that physics as we know it today is going to be subjected to severe, and perhaps impossible strain in order to explain all the events of high energy astrophysics.

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TABLE I

RELATIVE ABUNDANCES*

Atomic No. Z	Element	Cosmic Rays		Universal Abundances (Cameron, 1967)
		$E \sim 100$ MeV/N	$E \geqslant 1.5$ GeV /N	
1	H	4000	17200	12400
2	He	1000	1000	1000
3	Li	3.8	4.2	2×10^{-2}
4	Be	1.9	2.6	3×10^{-4}
5	B	6.3	6.5	3×10^{-3}
3-5	Li,Be,B	12.0	13.3	2.3×10^{-2}
6	C	21	24.7	6.4
7	N	5.5	6.9	1.1
8	O	21	21.4	11.3
9	F	(0.3)	(0.4)	1.7×10^{-3}
6-9	C,N,O,F	47.8	53.4	18.8
10	Ne	4.5	3.7	1.1
11	Na	(0.5)	(1.1)	3.1×10^{-2}
12	Mg	4.5	4.7	5.0×10^{-1}
13	Al	(0.5)	(0.9)	4.1×10^{-2}
14	Si	4.1	3.4	4.15×10^{-1}
15	P	(0.4)	(0.5)	6.0×10^{-2}
10-15	Ne-P	14.5	14.3	2.153

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* The numbers are taken from: Appa Rao, Biswas, Lavakare and Ramadurai Chapter III, Cosmic Ray Astrophysics, to be published by T.I.F.R.

Atomic No. Z	Element	Cosmic Rays		Universal Abundances (Cameron, 1967)
		E∼100 MeV/N	E ⩾1.5 GeV/N	
16	S	(0.9)	(0.6)	2.4×10^{-1}
17	Cl	(0.02)	(0.2)	9.4×10^{-4}
18	A	(0.4)	(0.5)	1.1×10^{-1}
19	K	(0.2)	(0.4)	1.5×10^{-3}
16-19	S-K	1.6	1.6	3.52×10^{-1}
20	Ca	(0.6)	(0.5)	3.5×10^{-2}
21	Sc	(0.2)	(0.2)	1.6×10^{-5}
22	Ti	(0.5)	(0.4)	1.1×10^{-3}
23	V	(0.4)	(0.4)	4.3×10^{-4}
24	Cr	(0.8)	(0.7)	5.9×10^{-3}
25	Mn	(0.5)	(0.7)	4.2×10^{-3}
26	Fe)	(1.5)	(1.8)	4.2×10^{-1}
27	Co)		(0.04)	1.1×10^{-3}
28	Ni)		(0.06)	2.2×10^{-2}
20-28	Ca-Ni	4.6	4.8	4.9×10^{-1}
33-40	As-Zr		$[2.4 \times 10^{-4}]$	1.2×10^{-4}
41-70	Mo-Yb		$[7 \times 10^{-5}]$	1.8×10^{-5}
> 70	⩾ Lu		$[3.1 \times 10^{-5}]$	3.3×10^{-6}
⩾84	⩾ Po		[[illegible] × 10^{-6}]	1.3×10^{-8}