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High Energy Astronomies – Indian Contributions in the 20th Century

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GLOSSARY

Active Galactic Nuclei (AGN): Quasars and Giant Black Holes. Every galaxy has a nucleus which is obscured by lot of dust and gas and cannot be seen by optical telescopes. However in some like our own Milky Way galaxy the nucleus can be figured out by the radio, infrared and X-ray~~s~~ emissions, which are able to penetrate out. The galactic nucleus ~~will have~~ has a massive concentration of stars. The emission of the radio, 1R and X-rays is indicative of ionized gas and the presence of an ionizing source. After the discovery of Black Holes the possibility of Giant Black Holes as the sources of radiation producing ionization has opened up. It is now believed that the quasars, the most powerful sources of EM radiation in all the bands, are possibly characterized by the presence of super massive black holes with mass equivalent of millions of solar masses. The Andromeda Galaxy M87 bound together to Virgo super cluster with more than 1000 galaxies, is one of the more active quasars and the observed increase of velocity of stars closer to the centre has led to the hypothesis that there is a super massive black hole of more than 5 billion solar masses at the centre.

AMANDA and ICE CUBE: Large scale under Ice installations in the Antartic ice to detect up-coming high energy neutrinos through the mu-mesons they produce in the ground below; the mu-mesons give rise to Cerenkov radiation in the ice which is extremely transparent in layers below about 1 km from the surface. AMANDA stands for Antartic Muon and Neutrino Detector for Astronomy.

β-~~DECAY~~

✓ **β-decay:** Some of the radioactive nuclei emit high energy electrons spontaneously. This process is known as β-decay. Interestingly some of the elementary particles also decay emitting electrons. The neutron decays with a proton, electron and neutrino as secondaries and the mu-meson decays into electron, and two neutrinos. So also several other elementary particles.

Bremstrahlung: Electromagnetic radiation produced when an electron or a charged particle is accelerated or decelerated while passing close to an atomic nucleus.

Cerenkov Radiation: When a charged particle moves in any medium with a velocity higher than the velocity of light in that medium, then the particle gives rise to a special type of EM radiation (optical, UV etc.,), which is collimated in the direction of movement of the particle; this radiation is known as the Cerenkov radiation. The opening angle of the radiation depends on the refractive index of the medium for light. An interesting and important aspect of this radiation is that it has a threshold for emission which depends on the velocity, and this threshold effect is exploited in the design of experiments.

COMPTEL: The high energy gamma ray observatory launched by NASA with specially designed instruments for studying the different properties of γ-ray sources. The name COMPTEL was given in honour of Arthur Compton, the discovery of Compton effect which plays an important role in the design of γ-ray detectors.

Cyclotron Emission: Electromagnetic radiation emitted by electrons traveling in circular paths in a magnetic field.

Electromagnetic radiation: Essentially EM radiation is a form of energy that propagates as alternating electric and magnitude fields orthogonal to each other and with the velocity of light (3×10^{10} cms/s). The characteristics of the radiation changes with the frequency or wave length of the oscillations – Radio waves have the longest wave length, several hundreds of meter to meters and then we have the millimeter or microwaves and then infrared or heat waves, then the optical, ultraviolet, x-ray and γ-rays. The particle corresponding to the EM radiation is the photon and its energy is connected to the frequency of the radiation by the relation $E=h\nu$ where h is the Planck constant.

Exotic Particle Astronomy: According to current quark theories in particle physics, it is possible to envisage that there could be stars in the universe which are entirely made of quark-matter similar to neutrons in neutron stars. It is possible that in the explosion of quark stars nuggets of quark-matter may be hurled into space and some of them may be reaching the earth's atmosphere. Also it is possible that in the environments of AGN's entirely new kinds of massive particles may be produced. The search for these yet unknown kinds of matter has been given the name Exotic Particle Astronomy.

Extensive Air Shower: When a high energy gamma ray enters the atmosphere, it initiates what is known as a cascade shower. The gamma ray gets converted through pair production to an electron-positron pair. These electron-positron pairs give rise to high energy gamma rays through the process of bremstrahlung. The process of pair production and bremstrahulng repeat as the particle travel down the atmosphere and give rise to what is known as a cascade shower. The energy of the incoming particle thus gets distributed among a large numbers of electron-positron pairs and γ-rays. The number of secondaries reaches a maximum when the energy of the individual gamma rays becomes lower than the threshold for pair production and then the charged particles get absorbed and the cascade number decreases. The total number of electrons and photons at the shower maximum depends on the energy of the incident γ-ray. Depending on the energy the number can run from millions to billions.

Because of the exponential nature of the atmosphere the vertical spacing between successive pair production and bremstrahlung events are large and this results in the lateral spreading of these to million to billion of particles into hundreds to thousands of square meters at mountain altitudes or sea level. This is the reason for calling this phenomenon an extensive air shower.

If a primary proton or a heavy nucleus instead of a γ-ray, is incident at the top then something more complicated happens in the atmosphere. The proton or heavy nucleus collides with an air nucleus and produces a large number of secondary charged and neutral particles – mesons, nucleons, antinuclear etc. which as they travel down produce more nuclear interacting particles, thus giving rise to a nuclear cascade. The neutral pions produced decay into gamma rays and these give rise to the electromagnetic cascades of the type discussed above. The charged pi-mesons, k-mesons will decay into muons and neutrinos. Thus the combined effect of the nuclear and electromagnetic cascade results in the production of a large number of elementary particles as part of the shower. The dominant component will be electron-positron and photon component and next in intensity will be the muons and neutrinos.

Galactic co-ordinates – Galactic hemisphere: A latitude and longitude co-ordinate system that takes the galactic plane as its equator and the galactic center as the zero point of longitudinal measurement. The galactic hemispheres are defined with respect to the galactic plane in the galactic co-ordinate system.

Galaxy: Collection of large number of stars. Our own Milky Way galaxy of which Sun is a member has the shape of double convex lens and has something like 100 billion (10^{11}) stars. In the universe it is estimated that there are 200 billion such galaxies.

Gamma-ray: Gamma radiation by convention is defined as electromagnetic radiation of energy higher than the hard X-ray region – greater than a few hundred KeV – to several hundred MeV. The nomenclature GeV corresponds to energy greater than a GeV (10^9 eV), TeV to radiation of energy greater than 1000 GeV (10^{12} eV) and PeV to greater than 1000 TeV (10^{15} eV) and Eev to energies greater than 100 PeV (10^{18} eV).

Gravitational Wave Astronomy: According to General Theory of Relativity, massive condensed objects subject to acceleration or changes in the shape will emit gravitational waves, particularly from regions where the gravity is very strong and where the velocity of movement is close to the velocity of light. Collapsing stars forming neutron stars black holes are the most likely land-dates. Rotating neutron stars and binary system are also strong candidates for gravitational radiation emission. No firm evidence yet for such emission.

HEAO-3: The third High Energy Astrophysical Observatory launched by National Aeronautics and Space Administration (NASA) of USA.

Large and Small Magellanic Clouds: Only three extragalactic objects are visible to the naked eye: the two patches of nebulosity in the southern hemisphere resembling detached pieces of our own galaxy, the Milky Way. Two of these were first observed by the famous navigator Magellan during his exploration round the world and given the names Large and Small Magellanic clouds. Being our nearest extragalactic neighbours these have attracted considerable attention and recently the explosion of a star in the Small Magellan Cloud in 1987, which has been called Super Nova 1987a became famous in the astronomical world because of the possible detection of neutrinos for the first time in a supernova explosion.

Magnitude of a Star: A measure of how bright a star is in the optical region of the EM spectrum. The smaller the number, the brighter the star. Apparent magnitude of a star is based on the observed brightness from the earth while absolute magnitude is a measure of the intrinsic brightness of the star. If two stars differ by one magnitude then their brightness differ by a factor of 2.512.

mu-meson (muon): The most penetrating (weakly interacting) charged particle in cosmic radiation was identified as the mu-meson with mass of 105 MeV. The muon (mu-meson) is not produced directly in nuclear interactions; it is the decay product of Pi-mesons and k-mesons. The muon has no neutral counterpart. The charged high-energy cosmic ray particles deep underground are all muons. The muons are produced in the interactions of neutrinos (the ν_μ type) with matter.

Naked Eye Astronomy: Even before the advent of the telescope, astronomical observation was pursued with the naked eye and considerable information on the celestial objects-planets, bright stars, constellations, explosion of stars, comets, meteors etc. had been systematized; calendars had been drawn based on the motions of sun, moon and planets and rising and setting times of bright stars.

Neutrino: Neutrino as a mass-less, charge-less, very weakly interacting particle was first introduced by Pauli to save the principles of conservation of energy and momentum in β-decay. While the neutrino is not a particle that is produced in nuclear interactions, it arises in the decay of many elementary particles – the muon, pion, kaon, etc. The neutrino has an anti-particle called antineutrino. There are three types of neutrinos – the electron neutrino, the muon neutrino and the τ-neutrino. Neutrinos are fermions and belong to the class of leptons in particle physics.

Particle Physics: The first elementary particle to be discovered was the electron in 1897 in experiments with gas discharge tubes. This was followed by the discovery of the proton and very much later the neutron in 1932. The proton and neutron as the constituents of nuclei and the electrons as the orbiting particles making the atoms electrically neutral marked the beginning of the ideas of particulate constitution of atoms and thus of all matter. Between 1932 and 1950, a large number of elementary particles were discovered in cosmic ray studies in the atmosphere – positron, μ-meson, π-meson, k-meson, Λ-hyperons, etc. A host of other extremely short-lived particles have been discovered subsequently at accelerators. A new development has been that all the "hadrons" are constituted of still more elementary particles called "quarks" while the "leptons" have remained as the most elementary particles without any structure. Hadrons are massive and strongly interacting; Leptons are relatively light and weakly interesting.

Photon: The particle corresponding to the electromagnetic radiation, which was originally conceived as a wave. An EM wave of frequency ν corresponds to a photon of energy **h**$\boldsymbol{\nu}$ where **h** is the Planck constant.

Proton Decay: Eventhough the Proton is the most stable particle among the hadrons and its stability is responsible for the stability of all matter around us, according to modern particle physics theories it could be unstable with a half life of greater than 10^{28} years or so. This instability is essential for the so called grand unification theories. However so far the proton is known to be stable atleast upto 10^{32} years, based on many experiments carried out in several laboratories in the world, including the one at the Kolar Gold Fields in South India.

Polarized Radiation: Nonrandom distribution of the electric field (magnetic field) direction with respect to the direction of propagation of EM wave. In linear polarization the electric field/magnetic field vector maintains the same direction and in circular polarization the vector rotates with same amplitude and in elliptic polarization the magnitude of the vector changes as it rotates.

Pulsar: Radio pulses with extremely accurate pulse repetition frequency were detected by Cambridge radio astronomers from certain stellar objects in the sixties and were given the name pulsars. Later they were identified as rotating neutron stars having spot like regions for radio emission essentially the magnetic poles. Hundreds of pulsars have been discovered over the last thirty years and many of then pulsate in optical, X-ray, γ-ray and TeV regions of EM spectrum. A category of pulsars is the millisecond pulsars, which have repetition frequency of a few milliseconds.

QPO: Quasi Periodic Oscillations – these are X-ray sources whose oscillation periods change from day to day in unpredictable manners and are strong candidates for neutron stars and black holes.

Radio Astronomy: Karl Guthe Jansky who was investigating the disturbance produced in the radio band of the electromagnetic spectrum (by thunderstorms) discovered accidentally in 1933 that radio waves were coming from the direction of the center of the Milky Way Galaxy. This was the beginning of a new field of astronomy, i.e. Radio Astronomy, which has been pursued all over the world in the post second world war years, and has led to major discoveries and radically changed our conception of the universe based only optical astronomy pursued till then. Entirely new types of celestial objects and physical environments and processes have been discovered through Radio Astronomy (See the article on Radio Astronomy in this volume.)

Super Nova: Explosion of a star. Such stellar explosions were noticed even in the times of naked eye astronomy as sudden brightening of stars by several orders of magnitude and the brightness decreasing slowly over a period of several weeks. The frequency of such explosions in any single galaxy is on the average once in 50 to 100 years.

The Crab Nebula: The most studied object in the sky next to the Sun is perhaps the Crab Nebula, which is a glowing gaseous volume of gas that is continuously expanding. This gaseous glowing mass is now recognized to be the result of a stellar explosion that took place on the 4th July 1054 AD witnessed and recorded by the Royal Chinese Astronomers. The high fraction of polarized light from the nebula led Schlovsky to propose that this may be an indication of the presence of high energy electrons gyrating round magnetic fields and giving rise to polarized optical radiation by synchrotron process. Though the predicted emission of high energy gamma rays from the nebula were not discovered in the early 1950's, when the first attempts were made, they were discovered with more sophisticated experiments carried out in the 70's and 80's of the last century. One of the fastest pulsars was discovered in the center of the nebula and identified with a neutron star, the remnant of the 1054 AD explosion. The neutron star gives rise to pulsations in all bands of electromagnetic radiation (radio to TeV). The Crab Nebula has become a standard candle for measurements of X-ray emission from different sources.

X-rays: Electromagnetic radiation more penetrating than the visible light which is also EM radiation. While the energy of a visible photon is a few electron volts, that of a soft X-ray photon could be a 1000 times more (1 keV) and that of a hard X-ray photon 20,000 more (20 keV).

21 cm line: Radio Wave Emission with a characteristic wavelength of 21 cm, which arises due to the spin flip of a neutral hydrogen atom. This case of line emission in radio astronomy has played a very significant role in unraveling many aspects of the universe (see article on Radio Astronomy in this volume).

High Energy Astronomies – Indian contributions in the 20th Century

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Introduction

Astronomy is the oldest of all sciences. In fact it is astronomy that played a significant role in the definition and evolution of the scientific methodology of systematizing observations, devising suitable mathematical equations, generalizing and predicting new results followed by experimental/observational verification. This stream of activity as is well known began with the accumulated data on observations of planetary movements and eclipses. Naked eye astronomy is undoubtedly thousands of year old. On a clear dark moonless night one can observe with the naked eye something like four thousand stars. Even with a one inch diameter telescope, this number increases to twenty thousand. With the large aperture telescopes 100–200″, the number of estimated galaxies each containing a couple of hundred billion stars themselves, amount to more than a hundred billion. With the employment of spectroscopes at the focal planes of these telescopes it not only became possible to know the chemical composition of the stars, but also their distances from the earth. One of the most startling revelations has been the scale of the universe. The most distant celestial objects are at a distance of more than 10 billion light years – light traveling at the rate of 186,000 miles per second takes 10 billion years to reach us. Even more startling was the discovery that the universe comprising these billions upon billions of objects is continuously expanding – each galaxy is running away from the other because of the expansion of the fabric which we call empty space in between the stars, the galaxies etc. It was only in the thirties of the 20th century the radio window on the universe got opened up just by accident or serendipity. It became known in the 1930's that the sun and several other objects in the sky are emitters of radio waves of the same type that had been produced in the laboratory and transmitted over long distance by Marconi in Italy and J.C. Bose in India in the late 90's of the 19th century and that became the work horse of global communication in subsequent years. It is only after the second world war that Radio Astronomy made rapid progress utilizing the high level technical expertise that had been developed in the war years in the fields of electronics and antenna design associated with the development of Radars. Apart from revealing entirely new kinds of celestial objects – radio stars, radio jets, quasars, pulsars etc., Radio astronomy in the decades of the 50's and 60's of the last century led to the recognition of several new features of the universe around us, which had particular significance to the field of cosmology dealing with the fundamental questions of the origin and evolution of the universe and of life – the discovery of the 21 cm line of hydrogen, the universal 3^o microwave radiation, the presence of extraterrestrial complex organic molecules etc. While the gravitational force played the all important role of determining the structures of the celestial objects at various levels – stars, the galaxies etc, the recognition of the super high temperature environments of the stars and stellar systems at the levels of millions to hundreds of million degrees providing opportunities for a free play of very high energy electromagnetic and nuclear processes, and formations of plasmas, high magnetic fields, made these locations a unique kind of celestial laboratories. Developments in the fields of experimental and theoretical quantum electrodynamics, nuclear physics and particle physics pursued in the terrestrial laboratories in the 20th century led to a clearer understanding of the happenings in the celestial environments and as should be expected, in turn, astronomical observations with more and more sophisticated focal plane instruments at the larger and larger aperture telescopes complemented and extended the knowledge gained in the terrestrial laboratories, on fundamental particles and high energy processes.

Just when this closer link and interaction between astronomers and physicists was developing in the late 50's and early 60's of the 20th century, another major breakthrough for astronomical research happened – the developments in the field of stratospheric balloons and rockets that been developed for defence purposes were released from the strong hold of military secrecy and made available for the use of research scientists. This enabled astronomers over the next several decades to make observations in radiations like infrared, ultraviolet, x-rays and gamma rays which undergo severe attenuation in the gases of the earth's atmosphere and so cannot be observed from ground. In the last 40 years, these space astronomies as they have come to be known pursued with balloons, rockets and satellites have led to several exciting new results on the nature of a new categories of celestial objects and also on new peculiar high energy processes going on in these objects.

In the early 50's of the last century, the observation of a relatively high level of polarized optical radiation from the Super Nova remnant, the Crab Nebula, led the soviet physicist Shlovsky to propose that such high level of optical polarized radiation was indication of emission of synchrotron radiation that could be produced by the gyrations of electrons of the nebula round the magnetic field lines in the filaments of nebula. Assuming magnetic fields of the order of 10^{-3} gauss, Schlovsky deduced that to account for the observed extent of polarized optical radiation, the electrons would have to have an energy greater than 10^{12} eV. It there are electrons of this energy, then there is no reasons why protons of the nebula should not be accelerated to similar energies. Protons of such high energy would naturally interact with the nuclear material of the nebula and give rise to charged and neutral pions. The neutral pions would decay into gamma rays. Thus the nebula would be source of high energy – hundreds of GeV – gamma rays. If this is so in the case of the Crab nebula, similar should be the case of other supernova remnants.

The search for very high energy gamma rays – now known as TeV astronomy (Trillion Electron Volt Astronomy) began in the Soviet Union in the early 60's with a new technique known as the night air Cerenkov radiation technique which we will describe later. The essential point to note is that while the earth's atmosphere was an obstruction for the pursuit of low energy gamma ray and X-ray astronomies, for the pursuit of TeV astronomy the atmosphere plays an extremely important role. This astronomy is pursued from sea level and high altitude mountain stations. While the early efforts to detect TeV gamma rays from the Super Nova remnants like the Crab Nebula resulted in the setting up only upper limits to the fluxes, the later developments that followed the detection of Pulsars in several of the S N Remnants gave a boost to this field of astronomy and extremely interesting results have emerged on several of the sources in the TeV energy range.

As an extension of the TeV range and also because of other interests in the field of cosmic ray studies, these investigations have been extended into the Pev (10^{15} eV) and the still higher EeV (10^{18} eV) energy ranges by a variety of hybrid techniques which we shall discuss subsequently. In all these, the method of extensive air showers in which special types of detector assembles spread over large areas (extending to several tens of square kilometers) and employed to record the intensities and times of arrival of the different constituents of the showers that emerge from nuclear and electromagnetic cascades initiated in the atmosphere by the entry of very high energy cosmic ray particles (protons or heavy nuclei) or super high energy gamma rays.

For astronomers, the special interest in the investigations of the nature of the spectrum of cosmic rays at the highest energies ($>10^{17}$ eV) arises because of two very important astrophysical predictions: (i) There should be a cut off the cosmic ray spectrum because of the nuclear interactions of cosmic rays with the 3° microwave radiation, if the cosmic rays are from extragalactic sources and the 3° radiation is universal (ii) If cosmic rays do have such high energy particles then the sources and mechanisms of acceleration of particles to such high energy point to environments surrounding Giant Black Holes (AGN's) .

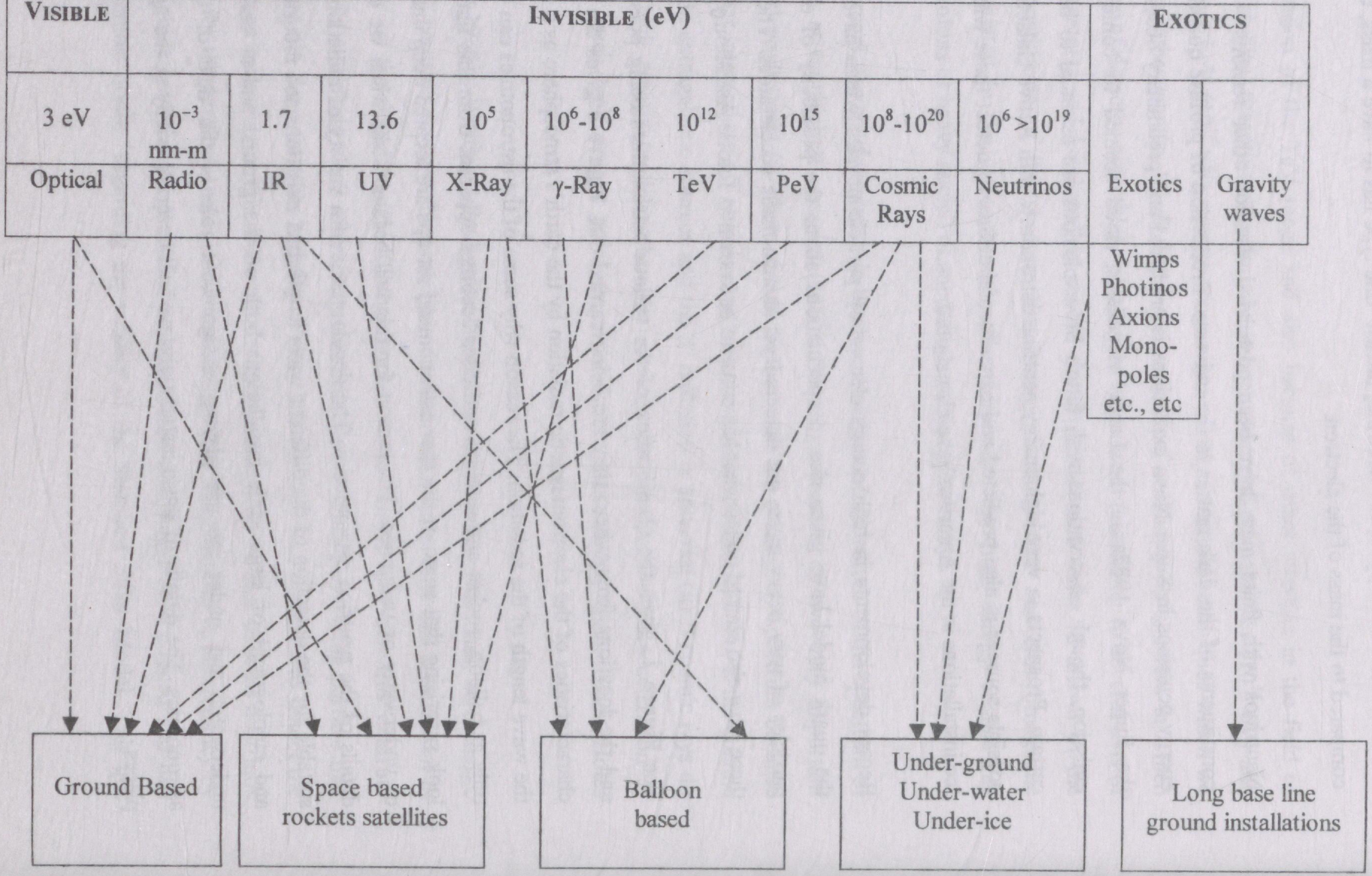
In the early 1930's, Wolfgang Pauli postulated the existence of a zero mass, zero charge particle, the neutrino to save the principle of conservation of energy and momentum in the β-decay of the neutron and of other nuclei. It has turned out that this neutrino because of its extremely weak interacting character, is the most penetrating particle that can penetrate out deep from the interior of stars like the sun. The attempts to detect the solar neutrinos were on from the 60's and the measurement of the flux of solar neutrinos was crucial for the verification of the so called Standard Solar Model. A Discrepancy by a factor of three between the predicted and measured fluxes had been noticed and had cast considerable doubt regarding the validity of the Standard Solar Model. This got resolved only recently with the establishment of the neutrino oscillation phenomenon. For this oscillation to happen, the neutrino, atleast one type has to have a mass, though small compared to the mass of the electron.

Neutrinos with finite mass have been postulated also for other reasons – as possible constituents of the dark matter in the universe. Production of profuse quantities of high energy neutrinos in Super Nova explosions is predicted and preliminary observation with the Super Nova 1987a in the Large Megallanic cloud seemed to confirm neutrino emission, though observations with future SN-explosions are essential to be absolutely certain. Prospects in very high energy neutrino astronomy, with Active Galactic Nuclei as possible sources is also predicted and experimental efforts to detect these with the under Ice installations in the Antartica have also started.

Recent developments in high energy elementary particle physics which have confirmed the quark model have given rise to speculations about the possibility of other exotic particles of very heavy mass, not detected yet at man-made accelerators. The search for these have also started under what has come to be known as Exotic Astronomy.

The **Figure 1**, gives the classification of the various astronomies being pursued to-day and the locations from where they are being carried out. **Figure 2** gives the absorption characteristics of the electromagnetic radiation by the earth's atmosphere as a function of the wave length of the radiation. The reason why some of the astronomies can be pursued only at balloon, rocket and satellite altitudes becomes apparent from this figure. It may look surprising that some of the new astronomical set-ups are located deep underground, or underwater or under ice. The reason for this will became clear when we discuss the details of the neutrino astronomies. The development of a variety of radiation detectors suitable for the detection of the different wave length EM radiations and focusing devices and employment of large scale installations both on the ground and at underground, underwater and under ice are playing a significant role in the field of these new astronomies. The details of these installations we will describe briefly at the appropriate places.

Figure 1. Classification of Modern Astronomies pursed from different locations – Ground, space, underground, under water and under ice.



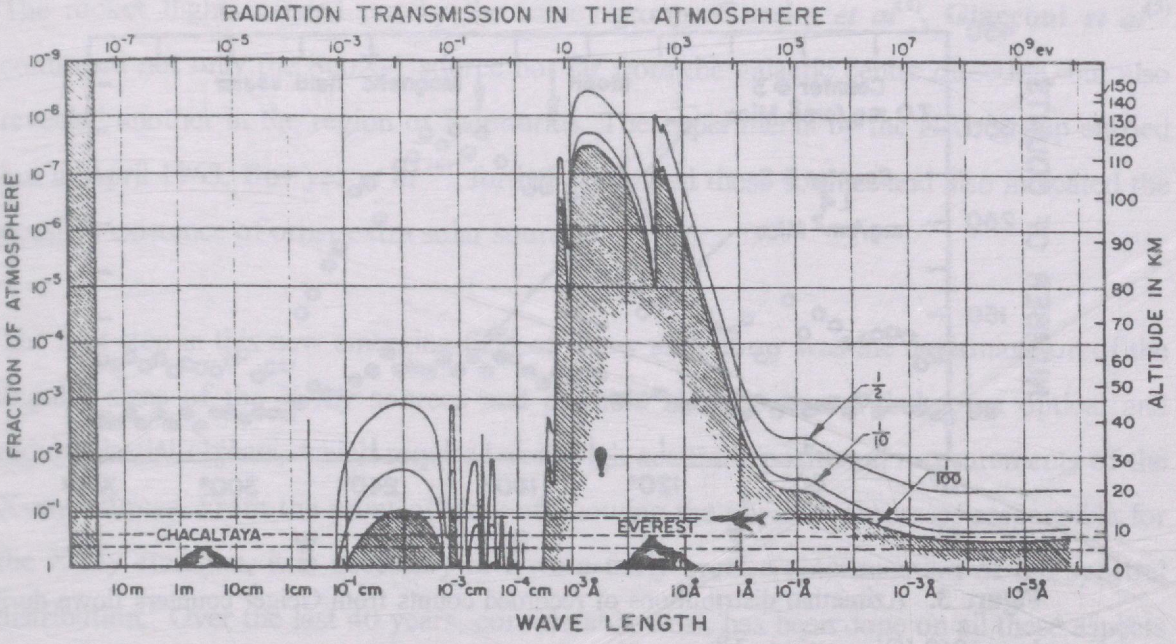


Figure 2. The absorption characteristics of the atmosphere as a function of the wave length (energy) of the electro-magnetic radiation.

Over the last 50 years, India has been able to make front line contributions in practically all the fields of astronomies. The accomplishments in the fields of optical, radio and infrared astronomies are covered in the other articles in this volume. In this paper we will concentrate essentially on X-ray, Gammy-ray, TeV, PeV and Neutrino Astronomies being carried out in India in the context and status of the world effort in these fields.

X-ray Astronomy

X-rays were first discovered from the Sun by **Burnight**(1) as early as 1948 using covered photographic plates, flown to an altitude of 96 km. This was followed by experiments of **Purcell and collaborators**(2) and by the Naval Research Laboratory in the late 50's using not so sensitive soft X-ray detectors flown on rockets and set an upper limit of 10^{-8} erg.cm^{-2} sec. The first positive detection of X-rays from an extra solar source was made by **Giacconi, Gursky, Paolini and Rossi**(3) in June 1962. The circumstances that led to this discovery are interesting to narrate.

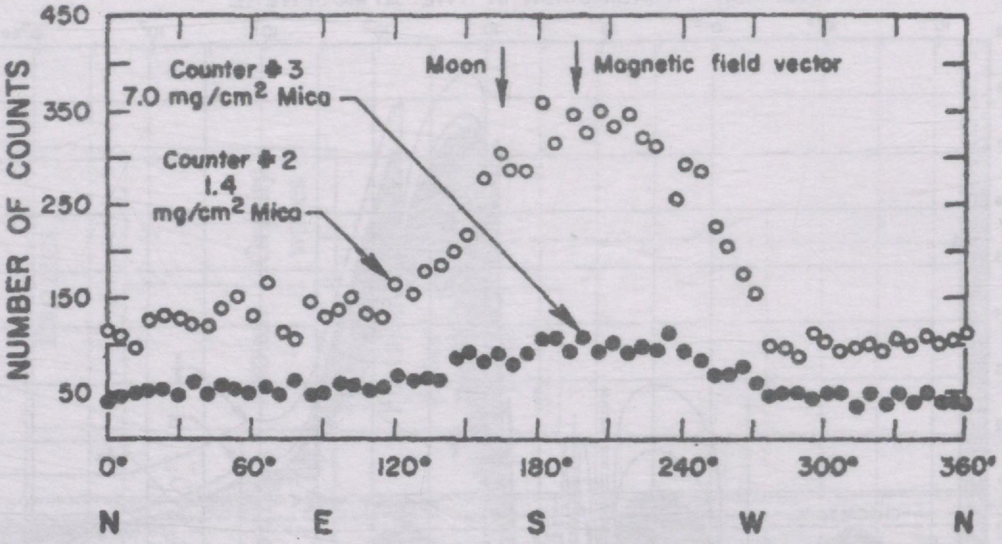


Figure 3. Azimathal distributions of recorded counts from Geiger counters flown during June 1962 (Giacconi *et al*[(3)]).

Immediately after the discovery of high velocity solar wind by space probes in the post 2nd world war years it was thought that the moon could be a source of X-rays because of the impact of the electrons in the solar wind and also because of the X-ray fluorescence produced by solar X-rays striking the moon. A simple rocket experiment with 3 Geiger counters having thin mica windows each of area 20 cm^2 and with an x-ray detection efficiency of 10 to 20%, mounted at an angle of 55° with respect to the spinning axis of the rocket, with a collimators-less wide field of about ±60°, was launched on the night of June 12, 1962. Only two of the counters operated properly and the counting rate rose when the rocket went beyond 80 kms and leveled off at an altitude of 100 kms. When the counting rate was plotted as a function of azimuth, there was a pronounced increase in the counting rate in the direction of the local south, and the rate dropped on either side **(Figure 3)**. Surprisingly the azimuth of the maximum was away by about 30° from that of the moon. The excess flux corresponded to 5 photons per cm^2 sec., which meant that the X-ray emission recorded was 10 to 100 million times greater than the X-ray flux of the quite Sun. Subsequent experiments established that the most powerful X-ray source ScoX-1, was sitting next to the moon on the night of June 12, 1962 and revealed itself.

The rocket flights carried out by the same groups **Gursky *et al*⁽⁴⁾**, **Giacconi *et al*⁽⁵⁾** confirmed not only the ScoX-1 source not far from the galactic centre direction, but also revealed another in the region of Sagittarius. The experiments by the NRL group carried out in April 1963, **Bowyer *et al* ⁽⁶⁾**, further confirmed these sources and also indicated the possible existence of other extra solar sources.

The nest step in this new emerging field of X-ray astronomy was the determination of the angular sizes of the X-ray sources and possible identification with known optical and radio celestial objects, which required very high accuracy positional measurements of the X-ray sources. From the point of view of knowing the physical processes responsible for the X-ray emission, it is necessary to have a fairly precise determination of the spectral distribution. Over the last 40 years, considerable work has been done on all these aspects using data collected from specially designed experiments on rockets, balloons and most importantly on satellites. A new feature that was brought into focus by the field of X-ray astronomy, was the recording of extremely short duration time variations in intensity of many of the sources which were later identified with compact binaries in which one of the companions was a neutron star a or black hole. In fact, while the first evidence for neutron stars among the celestial objects came from the detection of pulsars in the radio band, the evidence for the existence of black holes came from the fast time variations of X-ray intensity of the hard X-ray source Cygnus X-1 and the establishment of its binary nature and determination of the binary parameters. To give a flavour of how this field of astronomy developed rapidly and the kind of excitingly new information it provided we give below a few typical examples.

In what might be called the **Golden Decade of X-ray Astronomy⁽⁷⁾ (1962-1972)** five X-ray sources – ScoX-1, CygX-1, TauX-1, CygX-3 and Her X-1 showed themselves up prominently with very different characteristics unique to each one of them.

SCOX-1

This is the very first X-ray source discovered accidentally on the night of June 12, 1962 by the AS&E group, and turned out to be the most powerful X-ray source in the sky and has remained so even now among the thousands of X-ray sources that have been detected subsequently. The angular size and location of this source was determined by the technique of modulation collimators in a rocket flight carried out in **1966 by the MIT and AS&E Collaboration**(8). With the reasonably accurate position identification of the source it became possible to search for the optical counter part using the Mt. Palomar telecope. The optical counter part turned out to be a 12.5 magnitude star which till then had not made any impression on the optical astronomers.

The Doppler shift of spectral lines in the optical and the time variations in x-rays suggested a binary structure for this source with a period of 0.787 days. Simultaneity of optical and X-ray variations and lack of any delay between signals has been interpreted in terms of optical emission arising from the bombardment of X-rays on the matter of the accretion disc close to the neutron star, rather than the bombardment of X-rays on the companion object. In ScoX-1, there is a correlation between X-ray intensity and spectral shape. Another interesting feature of ScoX-1 has been the discovery of the associated Quasi Periodic Oscillations (QPO) activity which is generally supposed to be due to the interaction of the magneto-sphere with the accretion disc whose period of revolution is not so regular. The radio astronomers look upon ScoX-1 as a mini-quasar. ScoX-1 is suspected to be emitting ultra high energy cosmic rays on occasions though the evidence has not been conclusive. The flattening of the ScoX-1 spectrum beyond 40 KeV was first established by the experiments done at Hyderabad by **Agrawal et al**(9), see **Figure 4**.

CYGX-1

The X-ray source which brought X-ray astronomy to limelight with in a few years of its inception is Cygx-1. Right from the time of its discovery in soft X-rays with rocket based experiments and in hard X-rays with balloon based experiments, it was noted that this source is a highly variable intensity source, varying in very short intervals of time. The observations with the very first X-ray satellite UHURU showed time variations of this source on various time scales right down to fractions of a second. With the identification of the optical counterpart of this source it became evident that it is a binary system with a 5.6 day period. The determination of the binary parameters enabled mass

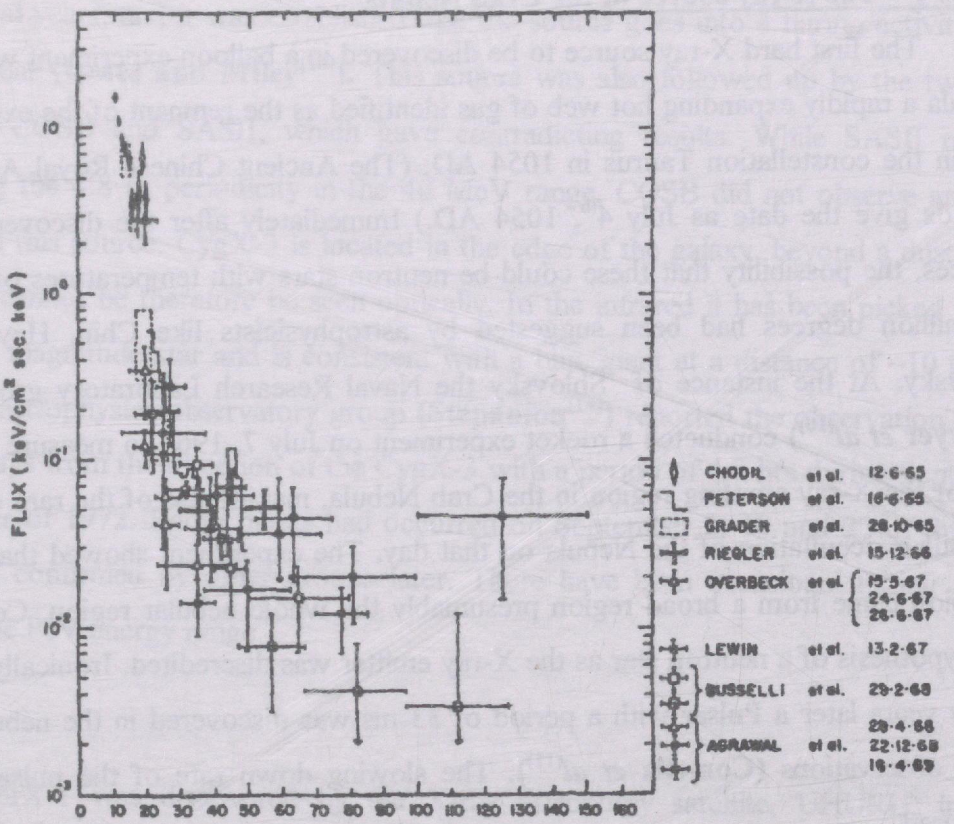


Figure 4. The flattening of the spectrum of ScoX-1 at energies higher than 40 kEV first observed by **Agrawal** *et al*[9] at Hydrabad.

limits to be set on the two components. A very conservative lower mass limit of the X-ray emitting companion was greater than 3 solar masses. The mass of the non X-ray emitting object was very much higher than this. With these characteristics and the time scales of the observed variations of the X-ray emission, CygX-1 because the very first strong candidate for a black hole. It satisfied the criteria of bimodal spectra, ultra soft high state, power law tail and flickering in time intervals less than 10 million seconds, which have been prescribed as necessary for qualifying as candidates for black holes. The HEAO-3 γ-ray data reveal a complex 3-state spectra for CygX-1, extending up to 1.5 MeV. A bump around one MeV in the spectrum is also considered as supporting the black hole hypothesis.

TauX-1 – The X-ray source in the Crab Nebula

The first hard X-ray source to be discovered in a balloon experiment was the Crab Nebula a rapidly expanding hot web of gas identified as the remnant of the explosion of a star in the constellation Taurus in 1054 AD. (The Ancient Chinese Royal Astronomical records give the date as July 4th, 1054 AD.) Immediately after the discovery of X-ray sources, the possibility that these could be neutron stars with temperatures of more than 10 million degrees had been suggested by astrophysicists like Chiu, Hayakawa and Shlovsky. At the instance of Shlovsky the Naval Research Laboratory group in USA **(Bowyer *et al*(10))** conducted a rocket experiment on July 7, 1964 to measure the angular size of the X-ray emitting region in the Crab Nebula, making use of the rare opportunity of a lunar occultation of the Nebula on that day. The experiment showed that the X-ray emission came from a broad region presumably the whole nebular region. Consequently the hypothesis of a neutron star as the X-ray emitter was discredited. Ironically, however, a few years later a Pulsar with a period of 33 ms was discovered in the nebula through radio observations **(Comella *et al*(11))**. The slowing down rate of the pulsar was also measured.

These features identified the existence of a neutron star in the Crab Nebula with a magnetic field of $\sim 10^{12}$ gauss. The presence of pulsed X-rays from other neutron stars were detected later in many experiments both in the soft and hard X-ray regions.

CygX-3

CygX-3 entered the catalog of astronomical objects in 1966 as one of brightest X-ray sources discovered in that decade. The first X-ray satellite UHURU **(Giacconi *et al*(12))** and later the Copernicus X-ray satellite revealed a 4.79 hour periodicity in X-rays and was naturally interpreted as a binary system. However, no pulsations were recorded from this source. Attempts at identification of a radio source associated with this strong X-ray source revealed that the radio emission was very weak. However, on September 2, 1972, a Canadian astronomer by sheer chance observed that the radio intensity of this source had increased by a factor of 100. This increase was confirmed by other observers. The intensity decreased after 10 days. Since then a radio watch was kept on this source for several years; and it was established that the source goes into a flaring activity about once a year **(Braes and Miley(13))**. This source was also followed up by the two γ-ray satellites COSB and SASII, which gave contradicting results. While SASII reported observing the 4.8 hr periodicity in the 40 MeV range, COSB did not observe any γ-ray flux from this source. CygX-3 is located in the edge of the galaxy, beyond a dusty spiral arm and cannot be therefore be seen optically. In the infrared it has been picked up as a 11 or 12 magnitude star and is consistent with a blue giant at a distance of ~10 pc. The Crimean astrophysics observatory group **(Stepanion(14))** reported the observation of TeV gamma rays from the direction of the CygX-3 with a period of 4.8 hrs during September-November of 1972. Radio bursts had occurred on September 2, 19 and 22 of that year. This was confirmed by other groups later. There have been occasional flaring activity even in the PeV energy range.

HerX-1

HerX-1 was discovered by the X-ray astronomy satellite, UHURU, in 1972 **(Tananbaum(15))**. It was first seen as a hard X-ray source by TIFR group **(Manchanda *et al*(16))** in 1973, in their balloon flight from Hyderabad. There are three distinct periodicities associated with this source: (i) a 1.2 second pulsation, (ii) a 1.7 day binary orbit period and (iii) a 35 day cycle that modulates the intensity of the source in an irregular fashion of approximately 9 bright days and 26 dim days. From the companion star HZ-Hercules the reprocessed IR and optical pulses are seen. A very important landmark was the discovery of the 53 keV line feature **(Trumper *et al*(17))** in 1978 which was clear evidence for cyclotron emission. For the first time this result established unambiguously the presence of magnetic fields in the neighbourhood of neutron stars is as high as ~10^{12} gauss. The slowing down of the pulsar in Herx-1 is occasionally erratic. The pulse profile also fluctuates. HerX-1 has been detected as a pulsed TeV source on occasions. **(Dowthwaite *et al*(18), Weekes *et al*(19))**. One of the most pronounced TeV burst lasting ~20 mins has been recorded by the TIFR group operating in Pachmarhi. Pulsed 10^{15} eV emission has also been recorded on several occasions **(Dingus *et al*(20), Gupta *et al*(21))**. An anomaly is that the signals do not conform to what is expected of pure γ-ray showers, since the muon content is comparable to hadron showers.

Active Galactic Nuclei – Quasars, Seyferts, BL-Lacerta, Cataclysmic Variables

One of the first extragalactic X-ray source to be detected is the quasar 3c273 in rocket experiments. As early as 1971, UHURU (**Gursky *et al*(22)**) found evidence of x-ray emission from the Seyfert Galaxies NGC1275 and NGC4151. In the case of NGC1275 the X-ray flux at emission was ~10^{44} ergs/sc which was equal to the total optical emission of the galaxy. In the case of NGC4151 the X-ray emission was 10^{42} ergs/sc comparable to the emission of the nucleus of the galaxy. UHURU also established that the galaxy NGC5128 at the centre of the radio source CEN-A is a dominant X-ray source. The notion that active galaxies are powered by the accretion on to super massive black holes has steadily gained ground. The black hole masses could be as high as 10^6 to 10^9 solar masses. The dynamical scales in these areas are of the order of 100 sc., the mass accretion rate about a solar mass per year. In the case of NGC6841 time variations in intensity have been observed on time scales of a few hundred seconds. Many Seyferts have shown time variations on the scale of days. In the case of NGC4151 an X-ray flare lasted for less than an hour. These variations indicate that the size of the X-ray emitting region is small ~10^{15} cms supporting the hypothesis of giant black holes at the centres of these active galactic nuclei.

The spectral features of AGN show roughly comparable amounts of power in each logarithmic interval of energy in the GV and also the characteristic of high energy X-rays extending to the γ-ray region of 1.5 MeV. However, there is a pronounced ultra violet bump at 10 eV followed by a power law X-ray spectrum. This scenario leads to an interesting speculation, of relevance to high energy neutrino astronomy. If we consider the active galactic nucleus having a fast rotating accretion disc around a giant black hole and an accretion shock formed at some distance due to the in fall of matter gravitational energy is converted to highly relativistic particles and the AGN could became sources of 10^{14}-10^{20} eV neutrinos through the decay processes of particles produced by the relativistic particles. What is exciting is that the estimated energy fluxes of neutrinos fall within the range of detection possibilities in the present day underwater and under ice installations. These we will discuss later in the section on Neutrino Astronomies (**Barwick *et al*(23)**).

The first X-ray satellite UHURU revealed some 400 X-ray sources. Over the last three decades more than 20 satellites for X-ray astronomy alone have been launched with a variety of increasingly more sophisticated detector systems and focusing devices. These include position sensitive proportional counters, gas scintillation counters, imaging telescopes with changeable focal plane instruments, etc. There have been a large number of hard X-ray experiments flown on stratospheric balloons. The outcome has been the realization that practically every type of astronomical object – stars, binary systems, RSCV-n binaries, supernova remnants, ordinary galaxies, radio galaxies, seyfert galaxies, Quasi Stellar Objects (QSO's) are all X-ray emitters. Time variation studies over large range of time scales – fraction of a second to months have been carried out. X-ray astronomy brought a special focus on compact binaries in globular clusters, and low mass binaries in the galactic bulge. Neutron star masses have been determined and several black hole candidates identified. About 300 accreting X-ray binaries have been detected in our Milky Way galaxy and in the neighbouring Large Magellanic and Small Magellanic clouds. A large majority have neutron stars as one of the binaries and in about 25 cases the X-ray emitting object is a black hole. The pulsar periods range from few milliseconds to 600 seconds.

There are two classes of X-ray binaries – low mass and high mass. The low mass binaries have a low magnetic field ($< 10^{11}$ gauss) and do not show X-ray pulsation. The orbital period range from 1 to 10 hrs and they show X-ray eclipses and irregular dips in their light curves and also show Quasi Periodic Oscillation (QPO) phenomena. The high mass binaries have typically $10^{12} - 10^{13}$ gauss magnetic fields and show X-ray pulsations.

As mentioned earlier, CygX-1 was the first candidate for a black hole. In recent years many transient x-ray sources have been identified as candidates for black holes (~3 to 10 $M_{\otimes}$). Some typical examples are GS1124-68 (Nova MUS 1991), GRO J 11655-40 (Nova Sco 1994) and GRO JO422+32 (Nova Per 1992). With the Chandra X-ray satellite a black hole of mass >500 $M_{\otimes}$ has been discovered (**P Kaaret *et al*(24)**).

The detection of non-thermal X-ray emission from SN remnants like CasA, SN1006 and VelaSNR (**Favata *et al*[(25)]**) has given support to the theory that SN remnants could be the sites for the origin of high energy cosmic rays. Spectroscopic studies with ASCA and Chandra have enabled the mapping of the abundance of elements and the temperatures of the shocked gas regions of SN.

The Indian Contribution in the Field of X-ray Astronomy

The equatorial latitudes have a distinct advantage for observations in X-ray and γ-ray astronomies. This advantage comes from the fact that because of higher geomagnetic cut-off of cosmic ray primaries, the induced background of secondary photons in the upper layers of the atmosphere is low compared to high latitudes. Also, fortuitously several of the hard X-ray sources like ScoX-1, CygX-1, TauX-1, HerX-1 etc are available at high zenith angles at meridian transit. Recognizing this advantage hard X-ray astronomy programme was initiated at Hyderabad in 1967 by Tata Institute of Fundamental Research (TIFR), Bombay and Physical Research Laboratory (PRL), Ahmedabad groups. These early experiments provided valuable information on time variations, bursts and spectral characteristics of these sources **(Figure 4)**. The TIFR experiments were the first to record hard X-rays from HerX-1. In 1975, during the lunar occultation of the Crab Nebula two hard X-ray telescopes were flown with in minutes of each other from Hyderabad as a collaborative effort of TIFR and the Institute of Aeronautics and Space Sciences Tokyo and the University of Nagoya (**Fakunda *et al*[(26)]**) and the structure of the hard X-ray emitting region of the Nebula was explored **(Figures 5)**.

These early experiments were followed in subsequent years by flying large area high pressure xenon counters and assemblies of phoswitch detectors.

The equatorial latitudes of Indian rocket launching stations at Thumba and Sriharikota (SHAR) proved particularly advantageous for soft X-ray astronomy experiments because of the low background due to cosmic ray induced secondaries and also electron precipation is a minimum compared to high latitude launching stations. Several large area

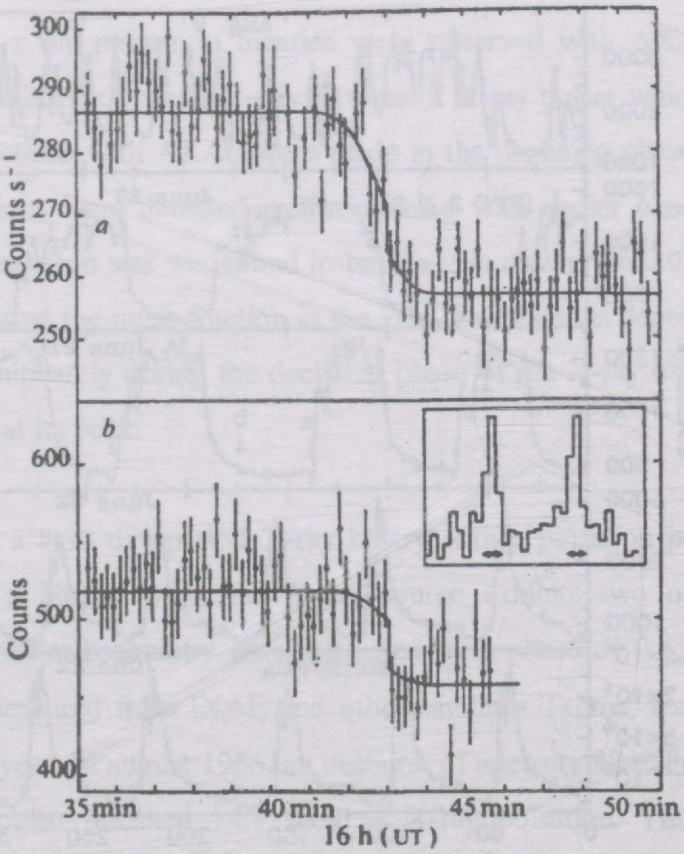


Figure 5. The lunar occultation of the Crab Nebula in hard X-rays observed from a balloon experimental launched from Hyderabad on 24th January 1975 (**Fakuda *et al***[(26)]).

thin window X-ray proportional counters were launched from these stations by the TIFR group and about 40% of the sky was mapped in the energy range 0.1 to 2.5 KeV. These early results on soft X-rays in the energy range 0.1 to 0.4 KeV showed that the spatial distribution in the north galactic hemisphere has a patchy structure with intensity generally increasing towards higher latitudes. The observations also revealed prominent limb brightening in the north polar spur and a hot spot in Eridanus in the sourthern galactic hemisphere.

The first Indian X-ray Astronomy Satellite Experimented (IAXE) payload was launched on March 21, 1996 aboard the IRS-P3 satellite and worked very satisfactorily. The X-ray instrument composed three pointed mode multi-anode proportional counters with 25 micron thick Mylar windows equipped with 2.3° × 2.3° collimator and were co-aligned.

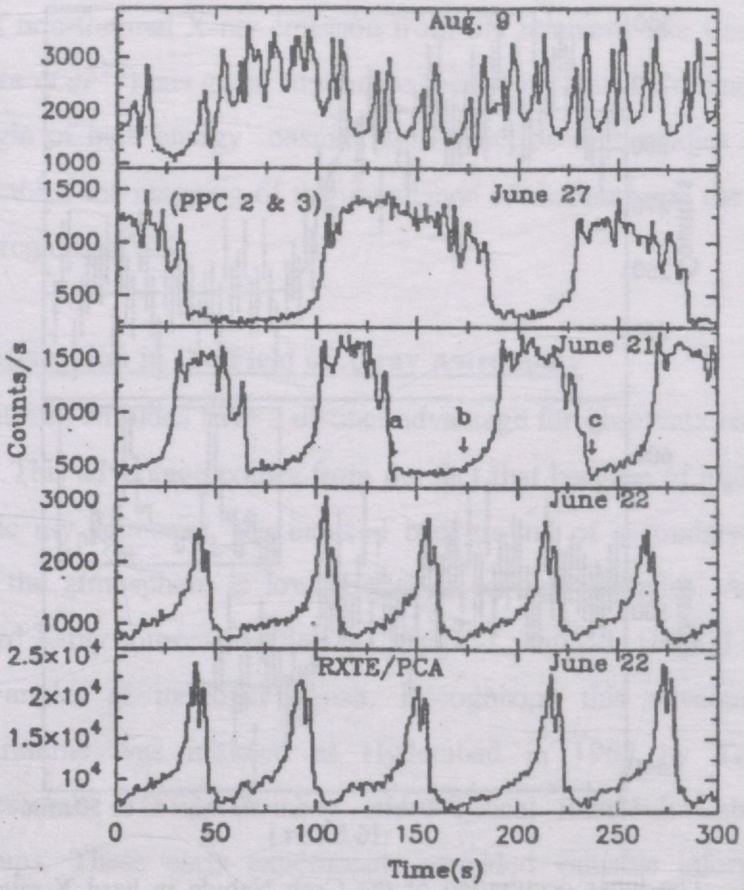


Figure 6. Various types of bursts seen in GRS 1915 using the Indian X-ray Astronomy Experiment. The burst are classified as regular (top panel), irregular (second panel) and quasi regular (third panel) Regular bursts seen on 1997 June 22 by IAXE are shown in the 4th panel along with similar bursts seen by RXTE-PCA (last panel). (**P C Agrawal and A P Rao**(27)).

The experiment lasted for more than 5 years in orbit. Study of X-ray Pulsars and Black Holes have yielded very significant results (**P C Agarwal and A P Rao**(27)).

IAXE tracked successfully several of the galactic transients that had been recorded by the earlier satellites CGRO, RXTE, ASCA and Beppo-SaX. The most significant result was on the galactic super luminal jet GRS 1915+105. The **Figure 6** shows the various types of bursts seen in this source by IAXE – regular, irregular and quasi-regular. Such bursts have given evidence for matter disappearance in the event horizons of black holes (**Paul**

et al(28)). Several x-ray pulsars in binaries were observed with AXAE including some very slow X-ray pulsars. Cepheus X-4 is a transient X-ray pulsar which undergoes bright outbursts. Observations with AXAE were made in the declining phase of this pulsar and 66 second pulsations were detected and combining with earlier observations by Ginga and ROSAT, the neutron star was found to have a spin-down rate 0.02 seconds per year. It was also found that the pulse fraction in the 2-18 KeV band is dependent on luminosity and decreases significantly during the declining phase of the X-ray outburst compared to the one measured at its peak.

4U 1907 + 09 is a 8.38 day period X-ray binary with a pulsation period of about 440 seconds. During a binary cycle, the X-ray source exhibits two outbursts a primary outburst and a weaker secondary flare separated by a phase of 0.45 seconds. Its spin-down rate was measured from IXAE and other satellites Tenma, Exosat to be +0.23 ± 0.01 seconds per year. In august 1966, an outburst of intensity 88 millicrabs was recorded with AXAE and also transient 14.4 seconds X-ray pulsation. This feature has been attributed to a transient accretion disc formed around the neutron star from enhanced mass accretion rate.

XTE J1946+274 is another transient X-ray source observed by IXAE during September 18-30 in 1999 and June 28 – July 7, 2000. The X-ray intensity varied sinusoidally between 5 and 50 mcrab. A spin-up rate of 1.86×10^{-9} second per second has been derived for this system. A Multi-wavelength Astronomy Satellite (ASTROSAT) with optical, X-ray and UV detectors is planned to be launched by Indian Space Research Organization (ISRO) 2006 from SHAR. The scientific objectives and the instrumental details are available in the Review Article of **P C Agrawal and A R Rao**(27).

Gamma Ray Astronomy

The domain of the electromagnetic spectrum beyond a few hundred KeV X-ray region is conventionally known as the Gamma Ray Region. Experimental detection of these celestial gamma rays posed a serious problem for a long time since the efficiency of the gamma ray detectors was low, the background due to cosmic rays and other sources

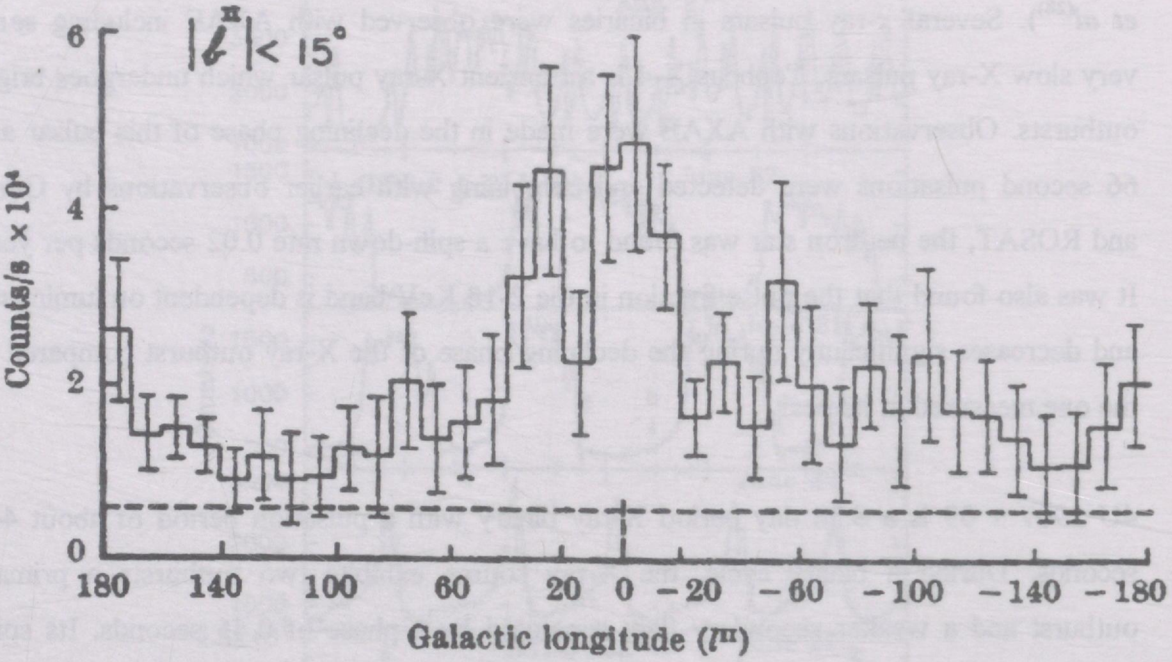


Figure 7. OSO 3 data showing the dependence of γ-ray intensity on galactic longitudes near the disk. The dotted line shows the average rate at high galactic latitudes.

high and the expected fluxes of incoming celestial γ-rays very low. However, this region of astronomy was recognized to be important for several reasons – the electron-positron annihilation giving rise to 500 KeV line, antimatter-matter annihilation giving rise to MeV γ-rays and background γ-rays from extragalactic sources, nuclear excitation gamma ray lines and the extension of the X-ray spectra due to all the processes responsible for X-ray emission bremstrahlung, inverse Compton etc. While X-ray astronomy was not predicted, prospects in γ-ray astronomy had been predicted (**Morison**(29)).

Real breakthrough came with the dawn of the satellite era. Explorer II experiment for cosmic gamma rays led to the setting up of an upper limit of 3 x 10^{-4} photons/cm^{2}sc. st. for energies greater than 100 MeV. No discrete γ--ray source was detected in this experiment. In 1968, **Clark *et al***(30) succeeded in detecting γ-rays with a detector onboard OSO-3 satellite. The observed anisotropy proved that the γ-ray flux indeed was of cosmic origin. The results of this pioneering observation is given in **Figure** 7. The increase in the counting rate as the detector crossed the galactic equator is unmistakable. The variation with galactic longitude with intensity having a maximum at the galactic center is also indicated. An isotropic background intensity of (1.1 ± 0.2) × 10^{-4} photons/cm^2 sc.st. was deduced from the data, with the galactic plane intensity being higher by a factor of 3.

A landmark in this field of astronomy was the launching of the Compton Gamma Ray Observatory (CGRO) in 1990. The four detector systems in this satellite covered the enormous energy range 15 KeV to 50 GeV and the four detectors BATSE, OSSE, COMPTEL and EGRET covered different aspects of gamma ray search, and led to different discoveries.

The aspects on which for reliable information were sought from the CGRO, in the light of earlier rather sketchy experimental results from other satellites and balloon based experiments were:

- (i) The Diffuse Gamma Ray emission
- (ii) Emission from the Galactic Disk
- (iii) The Spectrum – Diffuse and Line
- (iv) Galactic and Extragalactic Sources – distribution
- (v) Gamma Ray burst distribution
- (vi) Gamma Ray Emission from S N Remnants, Pulsars, Black Holes, Binaries, Unidentified sources, Molecular clouds, Active Galactic Nuclei, Galactic clusters etc.

On all these aspects the CGRO has provided valuable information and some of the results are reproduced in **Figure 8 and 9.** The review articles by **V A Dogiel(31)** and by **V Schonfelder(32)** in the *Proceedings of the 24th International Conference on Cosmic Rays* held at Rome (in 1995) provide very detailed information on all these aspects.

Very High Energy Gamma Ray Astronomy

The name very High Energy Gamma Ray Astronomy is given to the domain beyond about 100 GeV and in recent years has come to be known as TeV (10^{12} eV) astronomy. This region of astronomy evoked considerable interest in the early 50's of the

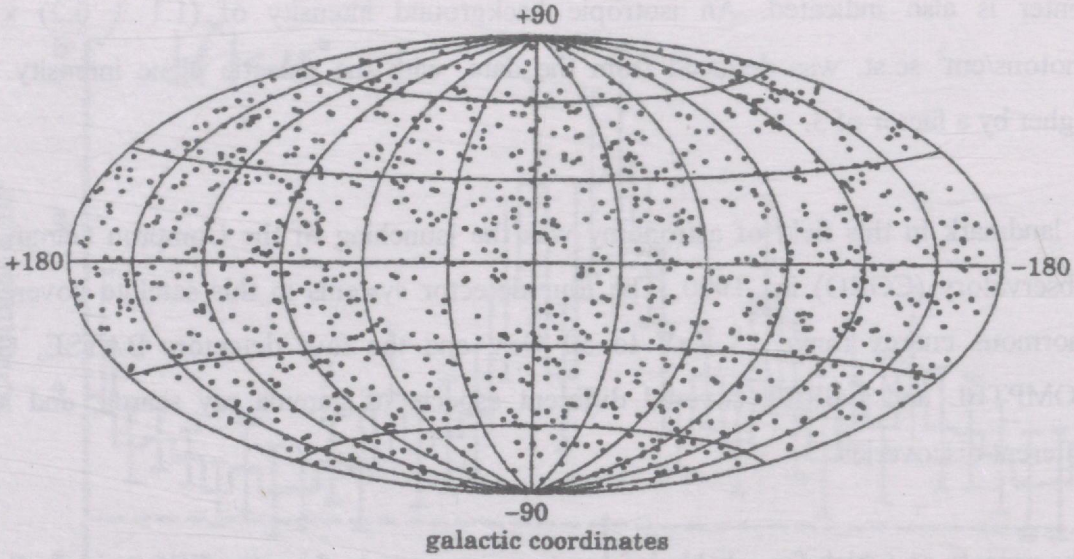


Figure 8. BATSE Sky Map of Gamma Ray Bursts (V.A. Dogiel, 24th ICRC, 1995, p. 671).

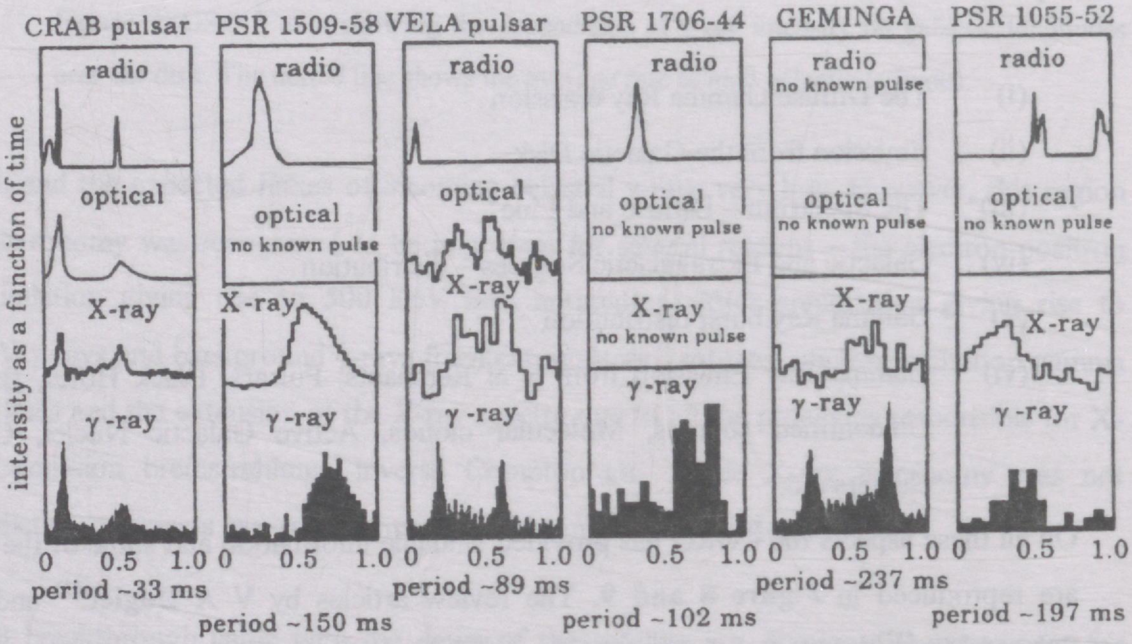
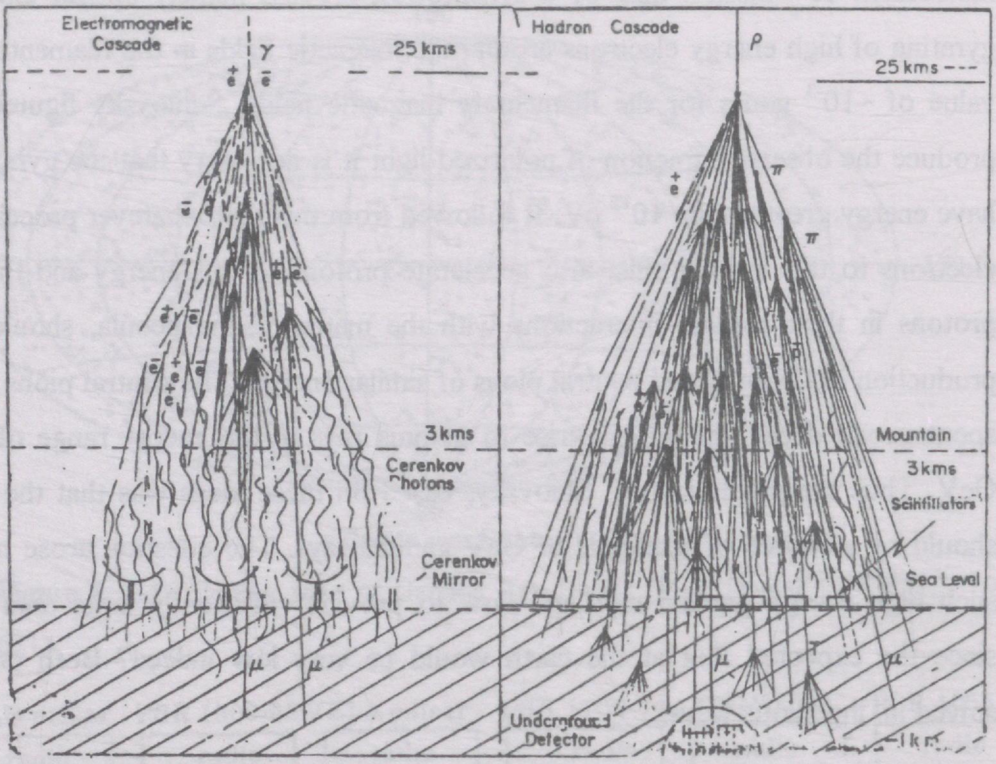


Figure 9. Light curves of γ-ray pulsars (V.a. Dogiel, 24th ICRC (Rome), 1995, p. 671).

20th century for some very special reasons advanced by the soviet astronomer **Schlovsky**(33) in 1953 and later presented at the 1954 conference on Cosmic Rays in New Mexico when the rest of the world came to know of this work. Optical astronomers had observed a high percentage of polarization in the light received from the Crab Nebula. To explain this high intensity of polarized light, Schlovsky proposed that the underlying mechanism of emission may be a synchrotron process namely optical emission by the gyrating of high energy electrons around the magnetic fields in the filaments. Assuming a value of $\sim 10^{-3}$ gauss for the filamentary magnetic fields, Schlovsky figured out that to produce the observed fraction of polarized light it is necessary that the gyrating electrons have energy greater than 10^{12} eV. It followed from this that whatever process accelerated electrons to this energy must also accelerate protons to this energy and the accelerated protons in their nuclear interactions with the matter in the nebula, should lead to the production of charged and neutral pions of similar energy. The neutral pions through their spontaneous decay should give rise to gamma rays in the energy range of hundreds of GeV. Thus the prediction of Shlovsky, based on these ideas was that the Crab Nebula should be a source of hundreds of GeV gamma rays. The question arose how to detect such high energy gamma rays and how to provide sufficiently large area of detection since the expected flux at the earth would be very low indeed? Both problems were solved in ingenious ways.

When a high energy γ-ray enters the top of the earth's atmospheres it initiates an electromagnetic cascade which develops longitudinally and spreads laterally because of the exponential nature of the density variation of the atmosphere. The constituents of the shower cascades are electrons, positrons and γ-rays and a negligible fraction of muons. Depending on the energy of the incident γ-ray, the number of these shower particles reaches a maximum in the atmosphere and then starts decreasing due to absorption. Because of the large vertical distance separation between the sequential bremstrahlung and pair production events, even small angular deviations of the secondaries with respect to the primary in each of these, will lead to large lateral separation. In fact by the time the shower reaches mountain altitude or sea level the spread could be as wide as several tens of meters (**Figure 10**). It so happens that the electrons and positrons in the shower are sufficiently relativistic that velocities exceed the velocity of light in the atmospheric air. This is the condition under which a charged particle emits a new kind of radiation known as the Cerenkov radiation and quite an appreciable fraction of this radiation is in the optical band. A special feature of this radiation is that it is emitted only in the direction of travel



(a) **(b)**

Figure 10. Extensive Air Shower development initiated by a ultra high energy (a) γ-ray (b) proton. While the γ-ray shower has few muons, the proton shower has a large content of nuclear active particles and muons.

of the charged particle and the angular deviation of emitted light in a medium like the atmosphere is very small. Consequently the shower gives rise to a pool of optical radiation central around the projection to the ground of the incident direction of the TeV γ-ray incident at the top of the atmosphere – the region around the axis of the cascade shower being the region of highest density. An array of parabolic minors (~1 m dia) with their exes aligned in the direction of the suspect γ-ray source and mounted on orientation platforms designed to follow the source as a function of time, sample this pool of light at different locations at the level of observation. The light from each minor is focused on to a photo multiplier which measures the intensity of light (**Figure 11a**). The registered Cerenkov light intensity is then matched to the lateral distributions of the Cerenkov light simulated of γ-ray induced showers through Monte Carlo methodology. Naturally, this technique of detecting γ-ray showers through the air Cerenkov radiation in the optical band works only on moonless, cloudless nights.

In the early 60's, the Soviet cosmic ray scientists **Chudakov** ***et al*****(34)** used this Night Air Cerenkov method to see whether super nova remnants like the Crab Nebula are emitters of very high energy γ-rays. They could not record any finite flux, but could only set upper limits to the flux from several supernova remnants and interestingly the first results were reported at the 7th International Conference held in Jaipur, India in 1963.

The real breakthrough in very high energy gamma ray astronomy came with the discovery of pulsars, candidates for neutron stars, by the Cambridge radio astronomers in 1968. The pulsed emission characteristic with extremely regular period provided an additional feature by which the background interference could be reduced by orders of magnitude in the search for high energy γ-rays from the direction of pulsars if they did emit pulsed TeV gamma rays. A strong incentive was the fact that the association of pulsars with neutrons stars meant that the magnets fields around these objects could be in the region of $10^{12} - 10^{14}$ gauss, and would require much lower threshold energies for the electrons to produce synchrotron radiation even in the ultra high energy gamma ray region. Several groups in the world started looking for the pulsed gamma radiation from neutrons star candidates and one of the earliest was the TIFR group in India, which started observations first at the Cosmic Ray Laboratory at Ootacamund, South India and later shifted the installation to Pachmarhi, in Madhya Pradesh, because of more favourable cloud free sky conditions for longer periods in the year. The different Cerenkov Telescopes that were operating in the world a few years ago are listed in the **Table 1.**

To improve the signal to noise ratio several ingenious methods have been developed over the years. One of the most effective has been the Cerenkov Imaging Technique developed by the Whipple group **(Weekes(35))** and now adopted by many others. The imaging camera is shown in the **Figure 11b.** It is a 10 m diameter multi-minor telescope with 91 photo multipliers each 2.5 cm. dia at the focal plane surrounded by an outer ring of 18 photo multipliers each 5 cms in diameter – all in a hexagonal pattern. The collecting area of the Cerenkov telescope corresponds to 3×10^4 m^2 and the threshold is 300 GeV.

Table 1. Cerenkov telescopes operated by various groups (From *Extensive Air Showers*, M V S Rao and B V Sreekantan, World Scientific Publishing Ltd., Singapore).

Observatory (Group)	**Latitude (°)**	**Depth ($g\ cm^{-2}$)**	**Remarks**
Akeno (ICRR, Tokyo)	36N	930	20 mirrors
Crimea (Crimean Astrophys. Obs.)	45N	890	mirror array
Dugway (Durham)	40N	860	telescope array
Dugway (Univ. of Utah)	40N	860	3 mirror array
Gulmarg (Bhabha Atomic Res. Ctr.)	33N	765	6 mirrors
Haleakala (Hawaaii-Wiscinsin Coll)	21N	715	6 mirrors
Malta (Dublin, Harwell)	36N	1010	4 mirrors
Narrabri (S.A.O. Sydney)	31S	1010	2 mirrors
Narrabri (Durham)	31S	1020	2 mirrors
Ootacamund (Tata Institute)	11N	790	Mirror array
Potchefstroom (Univ. Potchefstroom)	27S	840	4 telescope array
Sandia (Riverside, Iowa)	35N	980	2 mirrors
Targasone (Saclay, Dublin, Bordeaus, Turin)	43N	840	solar array (10 m)
Tien Shan (Lebedev Inst., Crimean A.O.)	43N	690	3 mirrors
Whipple Obsy. (S.A.O., Dublin, Iowa, Hawaii)	32N	780	2 mirrors (10 m, 11 m)
WhiteCliffs (Aelaide Univ)	31S	1010	3 mirror array
Woomera (Univ. Adelaide)	31S	1010	3 mirrors
ASGAT	42N		7 mirror array
Pachmarhi (Tata Institute)	22N	900	Multi-mirror array
BlackBirch Range (JANZOS Collab.)	42N	930	3 mirrors

The imaging with the photo-multiplier pixel assembly enables distinction between Cerenkov light from γ-ray showers and the background cosmic ray proton showers which have a different angular distribution because of the finite opening angles of the π^o-mesons produced in the proton-air nuclei interactions of the nuclear cascades.

The angular spread of photons and therefore of the Cerenkov Image is larger for proton showers than γ-ray showers. Also the γ-ray showers give rise to an elliptical image. These

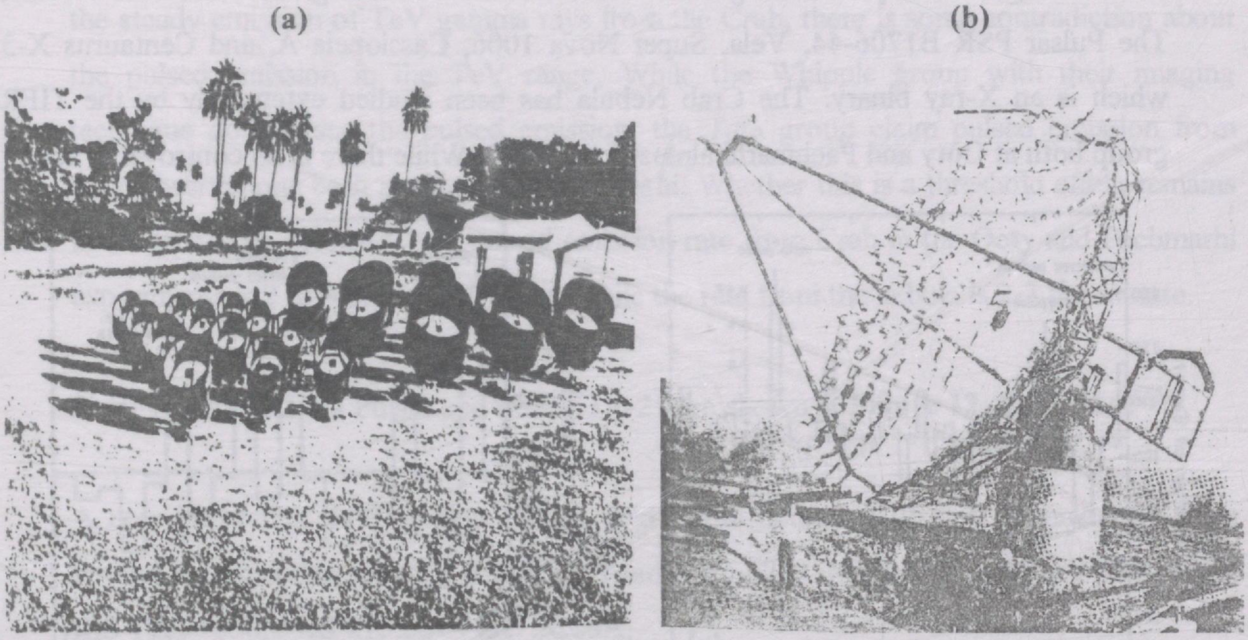


Figure 11. (a) An aerial view of the array of gamma-ray telescopes at Pachmarhi. (b) The 10 m optical reflector at Mt. Hopkins, Arizona, used by Smithsonianobservatory to search for cosmic γ-rays at TeV energies (Weekes *et al*[(19)]).

characteristic differences are effectively used to reject about 97% of the background cosmic rays showers.

Yet another method, which has proved effective in gaining in signal to noise ratio is to use the difference in the lateral distribution of Cerenkov light at the observational level between proton and γ-ray showers. This approach has been adopted by the TIFR group at Pachmarhi (**P.N. Bhat**[(36)]). The lateral distribution does not have a secondary hump in the case of proton induced showers. The set up at Pachmarhi has 13 banks of reflectors each containing two or more mirrors of area 2.5 m^2 spread over an area of 80 m × 100 m.

They measure "the flatness" parameter for each shower, which is essentially the ratio of the variance to the mean of photon densities recorded in all the mirrors and select gamma ray showers by making a cut in this parameter.

As of 2000, the most prominent galactic sources at the TeV energies are the Crab Nebula, The Pulsar PSR B1706-44, Vela, Super Nova 1006, Cassiopeia A, and Centaurus X-3 which is an X-ray binary. The Crab Nebula has been studied extensively by the TIFR group both at Ooty and Pachmarhi almost from 1970. While there is no controversy about

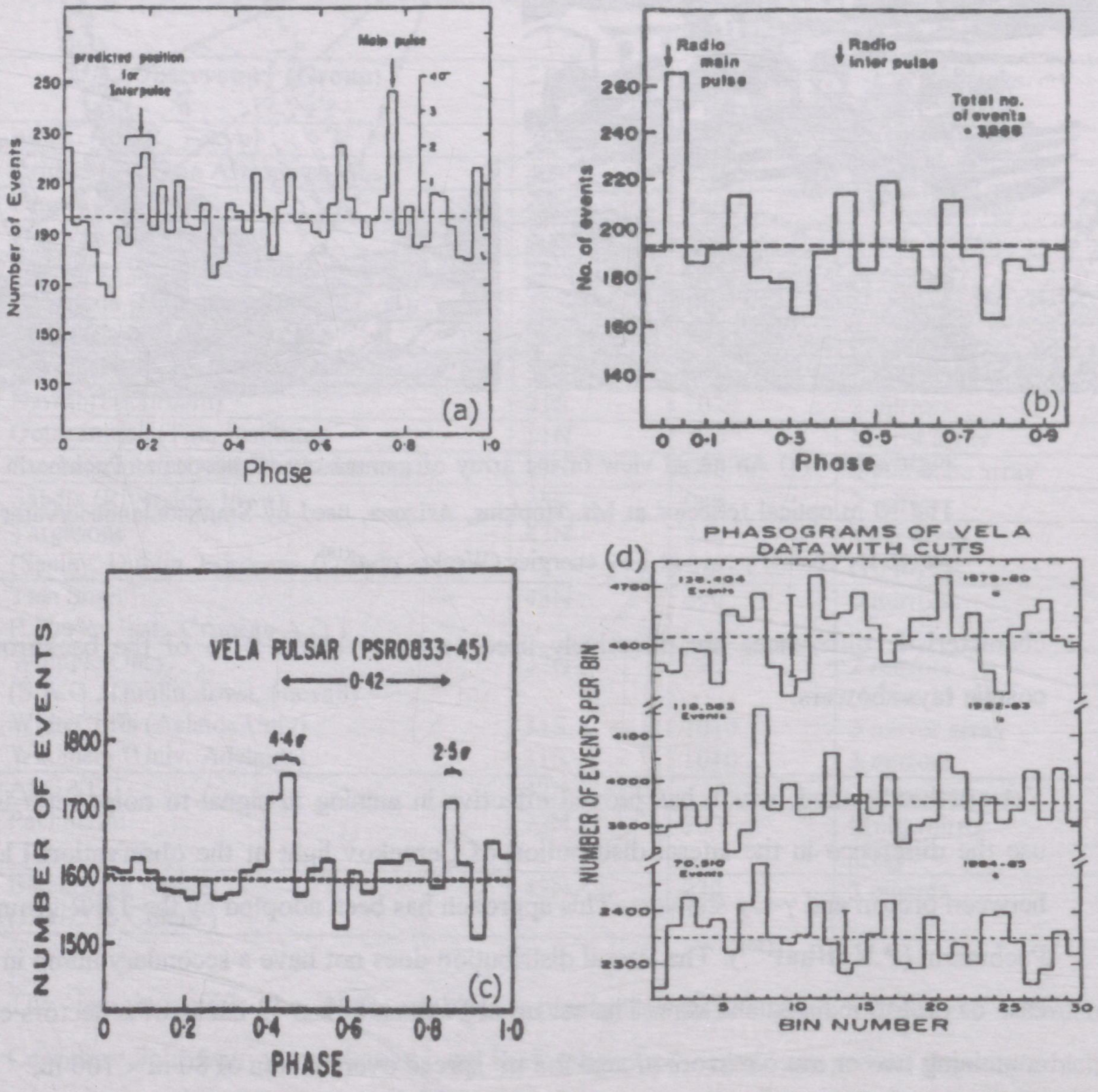


Figure 12. (a) Phasogram of PSR 0531+21 for γ-ray energy >4.5 TeV. Two significant peaks separated by the characteristic 0.42 of the Pulsar Phase could be seen. (b) Phasogram of PSR0531+21 in TeV γ-rays during 15 mins 1711-1726 UT on January 23, 1985. (c) Phasogram of about 5000 showers of Vela Pulsar PSR 0833-45. The data were collected during February-March 1979. (d) Phasogram of the three data-sets for Vela Pulsar after applying cuts to reject higher energy showers. Results from Pachmarhi TeV array **P.N. Bhat**[36].

the steady emission of TeV gamma rays from the Crab, there is some contradiction about the pulsed emission in the TeV range, While the Whipple group with their imaging technique do not see the pulsed emission, the Tata group claim pulsed emission from their observations both at Ooty and Pachmarhi. Whether this is a threshold effect remains to be seen. The detected TeV pulsed emission rate from Crab in the Ooty and Pachmarhi experiments is 2 to 3 photons per hour while the rate from the nebula is 2-3 per minute.

Some results on Vela Pulsar and PSR0531+21 are shown in **Figure 12 (P.N. Bhat(36))**

A new interesting development in this field is the detection of TeV gamma rays from several extragalactic sources. These are Markarian 421, Markarian 501, IES 2344+514, IES 1959+650, PKS 2155-304 and 3C66A.

The Srinagar group in India (**C L Bhat and R K Kaul(37)**), which also started making observation quite early in the 70's has now moved to Mount Abu where arrays of imaging telescopes (TACTIC and MACE) have been set up and this has started yielding exciting results on sources like the Crab, Mkn421, Mkn501.

<u>Particle Astronomy at the Highest Energies (10^{15} eV) PeV, EeV, Astronomies – Cosmic Ray Astronomy</u>

So far we have considered the astronomical knowledge that has been gained through the different windows of the electromagnetic spectrum. It has to be emphasized that astronomical information is also coming to us through a variety of charged and neutral particles.

The mystery surrounding the presence of a penetrating ionizing radiation at the surface of earth which had persisted from the time of Coulomb (1785) was resolved by Victor Hess only in 1912 through the discovery of an extra-solar radiation bombarding the earth's atmospheres all through the day and night and from all directions. This radiation which was given the name 'Cosmic Rays' by Millikan in 1925 has played an extremely important role not only in advancing the field of elementary particle and high energy

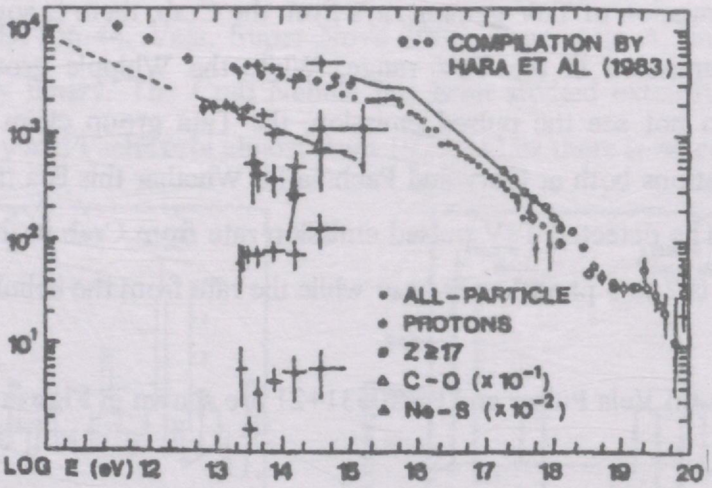


Figure 13. Compilation of the primary energy spectrum from direct as well as air shower measurements (**Teshima, 1993$^{(38)}$**).

physics, but also in focusing attention on high energy nuclear and electromagnetic processes going on in the environments of some of the exotic celestial surroundings like neutron stars and giant black holes.

Even after almost a century of discovery, the sources of cosmic rays and the mechanisms by which the particles are accelerated to the super high energies are not clear.

The **Figure 13** gives a comprehensive spectrum of the cosmic radiation extending over the energy band 10^{11} to a few times 10^{21} eV, almost 10 decades in the energy scale (**M. Teshima$^{(38)}$**). Upto energies of a few tens of TeV the radiation consists primarily of Protons (~42%), α-particles (~24%), CNO (~13%), Si (~10%), Fe-group (~11%). The spectral characteristic changes, and there is a steeping of the cosmic ray spectrum around 10^{15} eV (which is known as the Knee regime) and again there is a flattening beyond 10^{17} eV, (the Ankle region). One of the crucial questions that has come up after the discovery of the universal 3° microwave radiation is the nature of the cosmic ray spectrum beyond 10^{19} eV. The collisions of such high energy particles with the 3° microwave photons will result in the production of mesons and the energy of the particles will therefore drop considerably. It has been shown by **Zatsepin and Kuzmin$^{(39)}$** and independently by **Greisen$^{(40)}$** that this will result in a steepening of the cosmic ray spectrum beyond 10^{19}

eV if those are of extragalactic origin. There are no known possible sites within the Galaxy or even in the near by galaxies that have the necessary environments to accelerate particles to such high energies. However, in recent years, observational evidence is accumulating that there are particles in cosmic rays that have energies greater than 10^{20} eV. The **Table 2** lists the characteristics of these few cases.

Table 2. Details of the three highest energy events in cosmic rays recorded by Yakutsk, Fly's eye and AGASA groups (From Extensive air showers, M V S Rao & B V Sreekantan, World Scientific, Singapore, 1998).

Group	**Yakutsk**	**Fly's eye**	**AGASA**
Date of observation	May 7, 1989	October 15, 1991	December 3, 1993
Energy	2.3×10^{20}	3.2×10^{20}	$(1.7 \sim 2.6) \times 10^{20}$
α (°)	75 ± 10	86 ± 1	18.9
δ (°)	45 ± 4	44 ± (10 ~ 20)	21.1
b (°)	3	8	-41
I (°)	162	167	131

One of the interesting features to note is that all the three events have come within 50° of the anti-galactic centre. In fact the space angle between the arrival directions of the Yakutsk and Fly's eye events is only 7° and within the errors of angle estimates. The interpretation of these events has posed a big challenge regarding the nature of the primaries responsible. In the first two cases neither nuclei, protons, neutrons nor gamma rays can survive at these energies from a distance of more than 50 mega par secs. The puzzle is that there is no likely candidate source within this distance. The third event which comes from a totally different direction has similar problems.

With evidence that is accumulating on the existence of Giant Black Holes in the cores of active Galactic Nuclei, from a variety of astronomical observations we have already discussed, the possibility of the highest energy cosmic rays being produced in these environments is considered quite seriously. Such high energy particles can then give rise to very high energy neutrinos. This is opening up prospects in very high energy neutrino astronomy which we shall discuss next.

Very High Energy Neutrino Astronomy

Eventhough the neutrinos are the most weakly interacting particles (an MeV neutrino can go through a planet fifty times the diameter of the earth without suffering a nuclear encounter), the detection of solar neutrinos and the neutrinos from the 1987a Super Nova Explosion opened up the field of neutrino astronomy in the last decades of the 20th century. The serious problem connected with the fact that the observed solar neutrino flux was down by a factor of 3 compared to the calculations based on the Standard Solar Model, has been cleared up only in the last few years with the detection of the neutrino oscillation phenomenon. However, there persists several anomalies with the claimed neutrino detection from SN1987a. As stated above, the Active Galactic Nuclei are possible sources of very high energy cosmic rays and through their nuclear collisions with the matter around the galaxies can give rise to high energy mesons which then decay and give rise to high energy neutrinos. It has been established by several groups very convincingly that the AGN's – the Markarian 421 and Markarian 501 are definite sources of TeV (10^{12} eV) gamma rays. Even if the gamma rays are due to the acceleration of electrons in the environments of AGN's the same process that accelerates electrons should also accelerate protons and these being massive do not suffer energy loss by radiation and can therefore in principle get accelerated to still higher energies than electrons, and can perhaps be accelerated to energies beyond 10^{19} eV.

The Diffuse Neutrino background extending beyond 10^{11} eV from all the AGN's calculated by Szabo and Protheroe, Stecker *et al*, Bierman, Slokora and Begelman are shown in **Figure 14 (M V S Rao and B V Sreekantan(41))**.

The neutrinos have to be detected by the muons they produce. What is most exciting is that the new large volume and under ice setups, have the capability of detecting these neutrino produced muons in reasonable periods of operation despite their

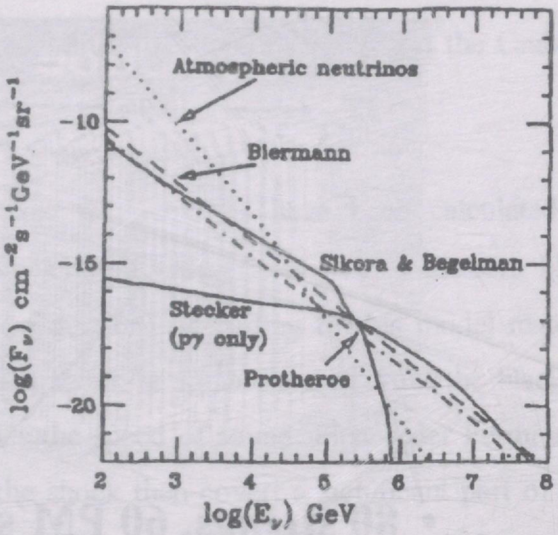
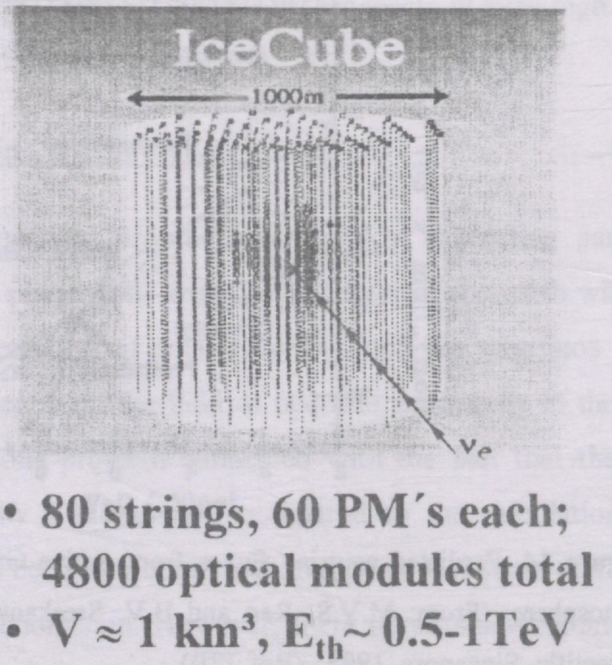


Figure 14. Predicted neutrino fluxes from Active Galactic Nuclei and from the earth's atmosphere. (From: M.V.S. Rao and B.V. Sreekantan, Extensive Air Showers, World Scientific, Singapore, 1998, (Ref. [7]))

very low flux. The enormous increase in the cross-section of neutrino interaction with matter at these high energies has been a crucial feature in this endeavour.

One of the large volume detector known as AMANDA (Antartic Muon and Neutrino Detector, (**S Tilav *et al*[42]**) has been operating under ice to detect the upward going high energy muons produced by the neutrinos that are incident from below the earth at Antartica. The muons are detected by a vertical string of (downward looking) photomultipliers and mounted in vertical holes in the ice extending down to more than a kilometer. The separation between the photomultipliers along each string is about 10 m and the separation between the multiple strings is about 30 m and the effective area of the installation for recording neutrinos is about 10^4 m^2 at TeV neutrinos and 25,000 m^2 at 100 TeV. A much more ambitious plan for neutrino astronomy is underway also at Antartic with a detector which is known as the ICE CUBE. The ICE CUBE will have 80 strings with 60 photomultipliers on each and the effective volume will be 1 km^3 with threshold at about one TeV (**Figure 15**).



- **80 strings, 60 PM′s each; 4800 optical modules total**
- **$V \approx 1\ \mathrm{km}^3$, $E_{th} \sim 0.5\text{-}1\,\mathrm{TeV}$**

Figure 15. The Ice Cube-array set up in Antartica to detect neutrino induced upward coming muons (Figure from John Learned[(42)] – Review 27th ICRC, Hamburg, 2001).

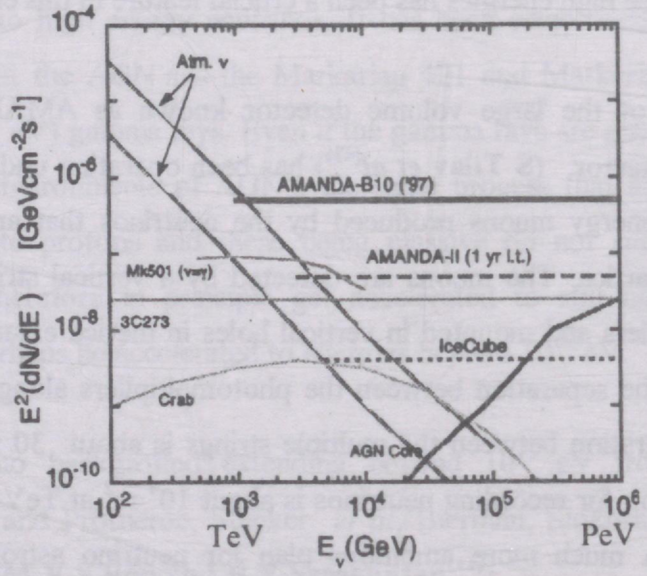


Figure 16. Comparison of the calculated fluxes of neutrinos and the limits by AMANDA and capabilities of Ice cube (Figure from John Learned[(42)] – Review 27th ICRC, Hamburg, 2001).

The **Figure 16** shows the relative detector effectiveness of AMANDA and ICECUBE as a function of neutrino energy. Shown also is the calculated flux of neutrino from atmosphere, Markarian 501, the quasar 3C273 and the Crab and AGN core (**John Learned**(43)).

The neutrino fluxes from AGN's have been calculated by **Stecker *et al***(44) combining the shock acceleration of particles near a massive black hole and the pγ mechanism of neutrino production. According to this model matter infalling to a black hole forms an acceleration shock at some distance from the black hole where the radial velocity of matter reaches the speed of sound. First order Fermi acceleration mechanism of charged particles at the shock then covert a significant part of gravitational energy to kinetic energy of the particles having a typical power law spectrum. The protons accelerated at the shock cannot diffuse upstream and are dragged by the gas flow. A consequence of this is that the very high energies the protons interact with the dense photon field of the AGN core and through the mechanism $\gamma p \rightarrow \Delta \rightarrow N\pi^+$, produce positively charged pions which decay into muons and neutrinos. The photon field is defined from the measured X-ray and UV fluxes from AGN. Fluxes of high energy neutrinos from individual AGN's are thus calculated and the diffuse flux by integrating the fluxes from all taking into account their cosmological evolution.

At the Kolar Gold Fields in India, two large size fine grain tracking calorimeters were operated at depths of 2 and 2.3 kms for over a decade (see **Adarkar *et al***(45) for details) for detection of Proton Decays. The data collected could be used to set upper limits on the flux of high energy muons produced by high energy neutrinos from celestial sources like AGN's. The **Figure 17** shows the flux of muons of energy 1 TeV and 10 TeV as a function of zenith angle calculated from AGN's based on flux estimates of neutrinos by **Stecker *et al***(44)) compared with the Recorded muon flux. One can say from this comparison no muon of energy greater than 10 TeV from AGN's have been observed in the KGF experiments (**Adarkar *et al***(46)).

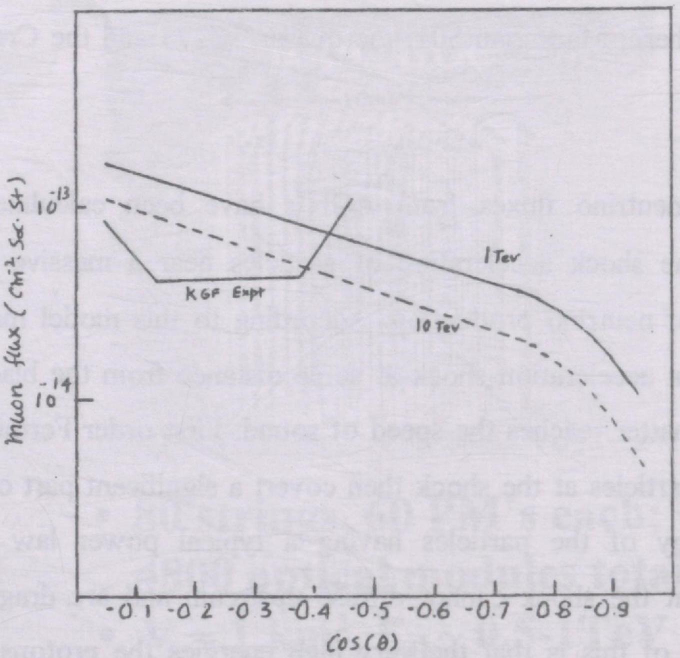


Figure 17. 90% C.L upper limit on the flux of neutrino induced muons of energy ≥ 10 TeV as a function of zenith angle obtained from the KGF data. The solid lines and the dashed line are expected flux of muons based on Stecher's flux as calculated by Stanev *et al* for $E_{\mu} \geq 10$ TeV and 1 TeV from Active Galactic Nuclei (Adarkar *et al*[(46)]).

From the 20th to 21st Century Universe

An attempt has been made in this article to present a bird's eye view of the recent developments in the field of high energy astronomy which is a relatively young field having its beginnings in the post second world war years. The field has depended very heavily on contemporary developments in a variety of new technologies – radiation detectors, electronics, space, communications and computers. What is remarkable is that India which was no where in these technologies caught on very speedily and Indian scientists could latch on to the world effort in the field of high energy astronomies and make significant and substantial contributions and also forge major international collaborations.

From the rather drab and boring picture of a static universe with a fixed system of stars and constellations and a lone planetary system with the sun as the center, the picture of the universe changed in the 20th century to a dynamic, vibrating, expanding and even accelerating universe composed of a variety of billions of celestial objects of mind boggling and unimaginable characteristics – super high densities, temperatures, pressures, magnetic fields, spewing out vast amounts of energy in the form of radiations and particles. The 20th century astronomy brought into our knowledge the exploding stars, the quasars, the neutron stars and black hole binaries, the Active Galactic Nuclei with Giant Black Holes in their cores, the X-ray and γ-ray bursters and so on. The pursuit of simultaneous multiband uninterrupted observations of special and spectacular events picked up in any one of the bands of observations and their analysis has become a new feature of collaborative research and is contributing towards a deeper understanding of the very high energy processes.

Neutrino astronomy, Exotic particle astronomy and Gravitational wave astronomy which are already in forefront of astronomical research in the 21st century may bring in entirely new kinds of information opening up new vistas and may be give evidence for new constituents and new forces. Our knowledge is always limited and inadequate and there is need for more, reminding us of the Rig Vedic lines

"*Aāno Bhadrāh kratavoyānthu viswatah*"

"Let winds of knowledge come from every side".

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