High energy universe – Satellite missions

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Abstract. A variety of satellite missions to observe the high energy universe are currently operating and some more with more versatility and capability are on the anvil. In this paper, after giving a brief introduction to the constituents of the high energy universe and the related plasma physical problems, general as well as specific features of the current and future x-ray and gamma-ray satellite missions are described.

Keywords. Gamma ray astronomy; x-ray astronomy; satellite missions; active galactic nuclei; gamma ray bursts.

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1. Introduction

The high energy universe is revealed when we observe it using the tools of the ultraviolet, the x-ray and the gamma ray astronomies. This high energy radiation often arises in plasmas of temperatures larger than millions of degree Kelvin. At these temperatures, hydrogen and helium are fully ionized. Heavier elements are stripped off most of their electrons except perhaps the inner K or L shell electrons. They produce high energy line emission such as the well identified line of iron at 6.4 KeV in addition to the continuum x-ray and gamma ray radiation. The line radiation in particular offers an important diagnostics for understanding the workings of the cosmic objects.

The HE (high energy) and the SHE (super high energy) universe consist of objects from comets to cosmic rays and everything in between. Active galaxies, gamma ray bursts, pulsars, single and binary, supernovae, clusters of galaxies, galactic and extragalactic background diffuse radiation and closer at home – solar flares are some of the prominent emitters of high energy radiation. In this paper, I shall describe a few defining characteristics of the gamma ray bursts – the present obsession of astronomers, the active galactic nuclei and more briefly the clusters of galaxies, the diffuse background radiation, the related puzzles and the plasma physical problems. I, then go on to describe the salient features of some of the x-ray and γ-ray ongoing and future satellite missions which hold a great promise in enhancing our understanding of the SHE and the HE universe.

2. Gamma ray bursts

The gamma ray bursts have been recognized to be the biggest explosions since the Big Bang [1]. They generate a luminosity of 10^{51} erg/sec and that would happen if matter of

one solar mass is completely converted into energy in one second, say by thermonuclear fusion. The bursts have a duration of a few seconds. Their variability over a time scale of a few milliseconds gives them barely a size of one hundred kilometers, suggesting them to be highly compact objects. The bursts have been observed from random directions in the sky at a rate of one per day. Their isotropic distribution could arise if they are either associated with stars at a distance of 100 parsec or with cosmological distances of 100 megaparsec. There is no underlying quiescent emission associated with the bursts. The light curve exhibits a fast rise and a slow decay resembling a stretched exponential of the form $\exp\left(-(t/t_0)^a\right)$. The spectrum is essentially nonthermal and broad band. The gamma rays (figure 1) are observed for a few seconds after which the x-ray part is seen for hours to days followed by the ultraviolet and optical radiation which lasts for days to weeks. The statistical correlation of the gamma ray bursts with other objects such as the clusters of galaxies, if found, would help us to needle them down in the haystack of the skies.

The small, the compact and the energetic nature of pulsars makes them the most favoured candidates for generating γ-ray bursts. Pulsars often form binaries. Such a pair of neutron stars spiraling around each other will essentially coalesce due to their shrinking orbit caused by the emission of the gravitational radiation. The merger is explosive in nature and could generate the energies of the γ-ray bursts in a matter of a few seconds. The rate of merger is estimated to be one per 100,000 galaxies.

The big puzzle, however, is the production of a nonthermal spectrum from an explosion. The ejecta of an explosion will most expectedly scramble the photons producing more like a black body spectrum. The literature is replete with scenarios which invoke an expanding fireball developing internal shocks within the ejecta and external shocks when it interacts with the external medium. The other issues awaiting resolution are the optical identification of the harbouring galaxy, cosmological vs noncosmological origin, causes of time variability, modeling the entire light curve from gamma rays to radio radiation and the last but not the least the physics of the entire chain of processes of acceleration of particles and generation of radiation.

3. Active galactic nuclei

Active galactic nuclei (AGN) are in the class of the most distant and the most luminous objects. They emit luminosities of the order of 10^{47} erg/sec, over the entire electromagnetic spectrum [2]. The spectrum is nonthermal with branches with different spectral indices. The radiation is highly variable with extremely short time scales. Superimposed on the nonthermal continuum are the absorption and emission lines of elements in different states of ionization. More recent observations place AGN as strong gamma ray emitters. In some objects the peak of emission actually resides in the gamma ray region up to TeV energies (figure 2).

Popular models of AGN consist of a supermassive black hole surrounded by an accretion disk containing hot plasma and cold torii of gas and dust [3]. The composition and the configuration of the material around the black hole are modified as per the diktat of the new observations. The continuum radiation is believed to originate from close to the black hole. The gas and dust give rise to the atomic line spectrum which carries the signatures of the distortions caused by the strong gravitational effects and reveal to us the conditions around black holes. Accretion disks play a fundamental role in many astrophysical settings and many issues remain to be understood. One of the most basic questions is the nature of
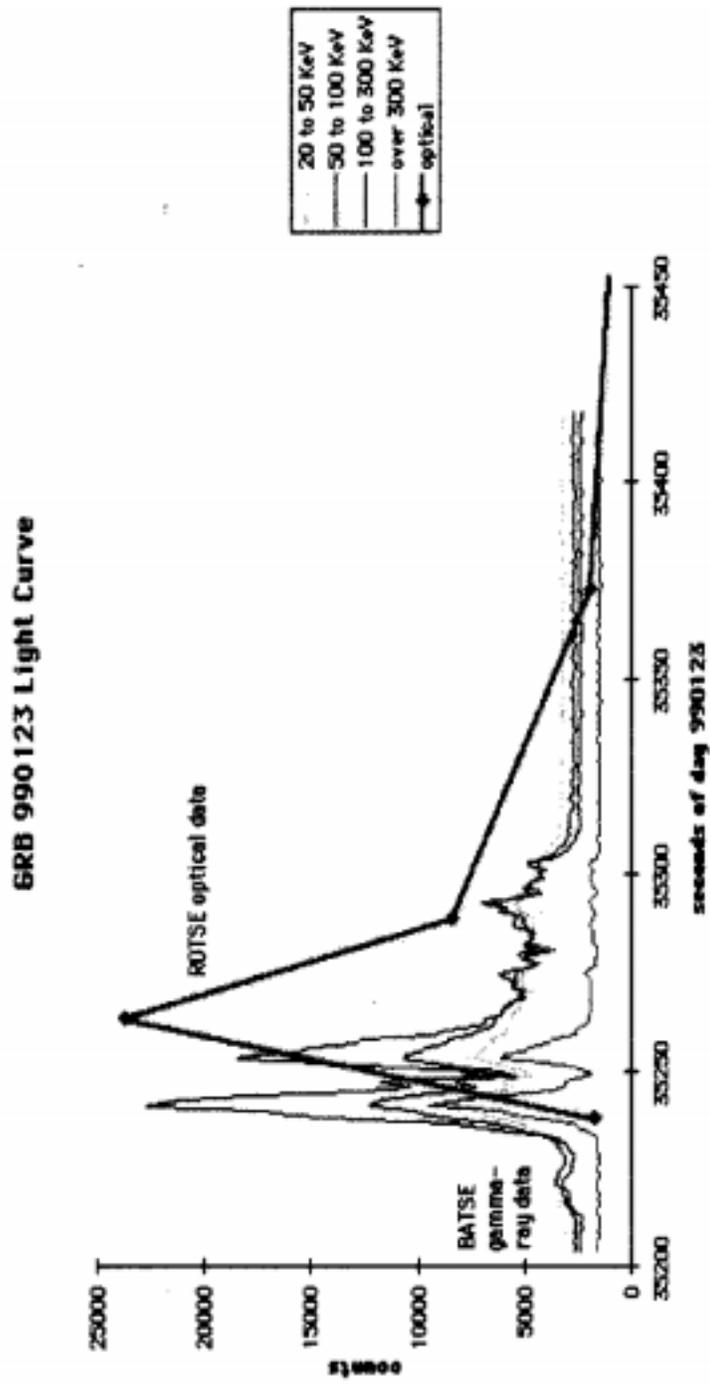
Figure 1. Light curve of the gamma-ray burst GRB 990123 in different energy bands.
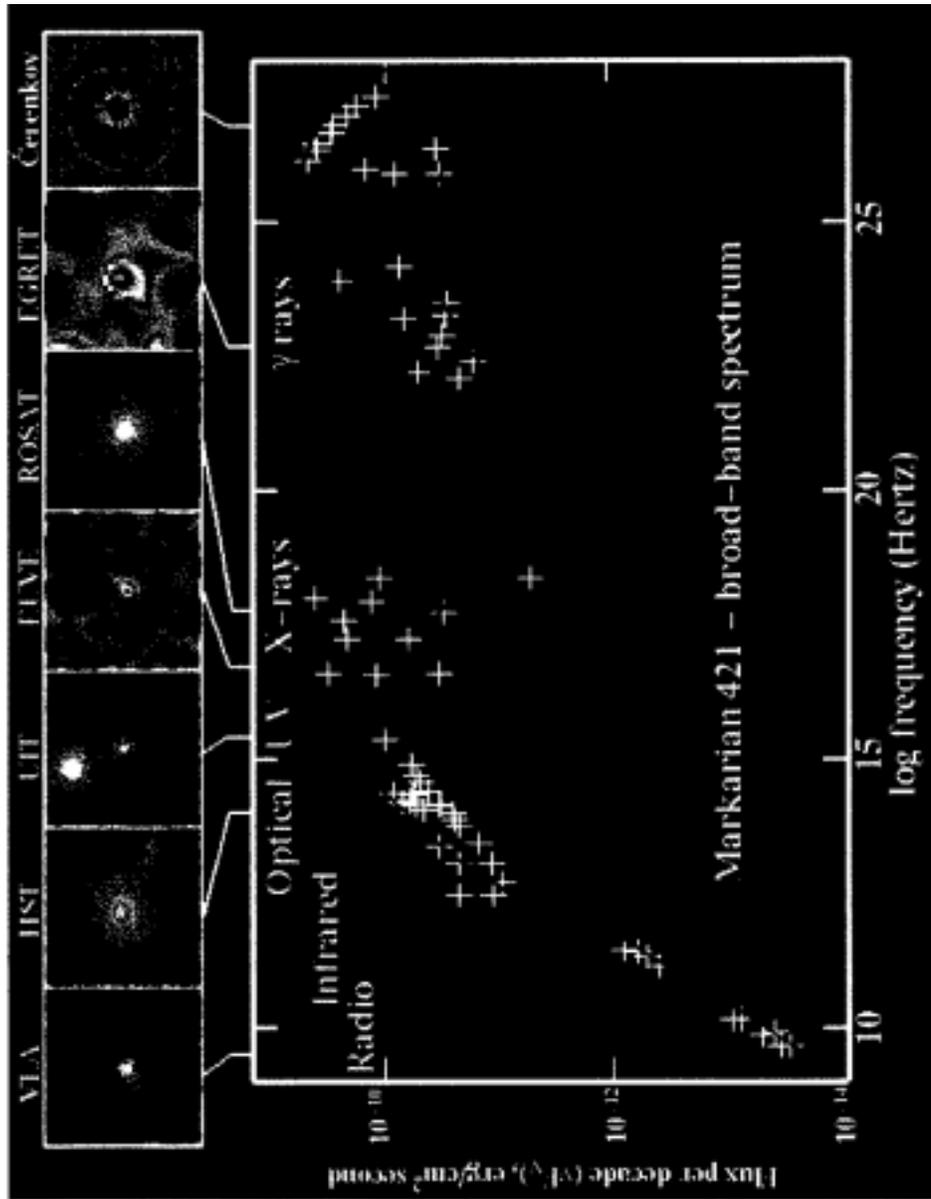
Figure 2. Continuum emission from the AGN Markarian 421.

the viscosity which drives the accretion flow into the black hole determining the amount of the released gravitational energy. The stability or otherwise of the disks for different accretion rates, advection and mass outflows leading to the formation of jets are the problems which can be fixed with the tools of relativistic magnetohydrodynamics. The microscopic aspects such as acceleration of particles and radiation from them need to be integrated with the macroscopic physics in order to work out the jigsaw puzzle of AGN.

4. Clusters of galaxies

The much believed homogeneity and the isotropy of the universe came in question with the detection of large concentrations of mass such as clusters and superclusters of galaxies in different regions of the sky. Further, the galaxies in a cluster were seen to be floating in a soup of a hundred million degree gas. Such a gas was detected through its x-ray emission. The hot gas which is almost as massive as all the cluster galaxies put together is believed to be confined in the gravitational potential of the so called dark matter. It is conjectured that some of the dark matter candidates may annihilate to create gamma rays [4].

5. Cosmic x-ray and γ-ray backgrounds

The universe is permeated isotropically with x-ray and γ-ray background radiations. No association with localized and discrete sources have been found. The radiation spectrum observed at x-ray energies fits well with that from a gas nearly at a temperature of four million degrees Kelvin. However the total mass of the gas needed to account for the background radiation is much larger than the mass of all the visible and dark matter [5,6]. In fact the mass of the gas is enough to halt the expansion of the universe. The spectrum becomes a power law with the spectral index of 2.2 in the gamma-ray region. What keeps the gas at millions of degree Kelvin? Are exploding galaxies and quasars responsible for heating the gas? Or alternatively is the background a result of a superposition of radiation from discrete sources? These are some of the questions that the new generation x-ray and γ-ray astronomies will take head-on.

6. Plasma-physical problems

The acceleration of charged particles and the emission of radiation from them are the two major features of all high energy objects. The most popular acceleration processes are the Fermi processes. In the second order Fermi process, proposed first, plasma clouds in the interstellar medium act as moving magnetic mirrors and scattering of charged cosmic rays off them produces acceleration. The random gain of momentum and energy by the charged particles make this process a second order process and not an efficient one. In the first order Fermi process, in the rest frame of a shock front, the material both up and down stream moves towards the shock. A charged particle trapped between the up and down regions gains energy every time it crosses the shock as it always suffers reflection. The maximum energy gained by the particle depends on the lifetime of the shock. In supernovae shocks, it has been shown that particles can gain energies up to TeV range. Hot plasmas are nearly

collisionless. The collisionless shocks were first observed in space plasmas [7]. One of the major issues in this context is what replaces the particle-particle collisions in collisionless shocks. Since plasmas support a variety of waves, it is the wave particle collisions that provide the dissipation mechanisms. Several different wave-modes with different dispersive properties may operate simultaneously in a single shock or a multiplicity of shocks may arise due to different wave modes. The physics of shock waves has been explored with success in explaining cosmic ray energies by supernovae shocks and is being extended to the phenomenon of the gamma ray bursts. Other plasma mechanisms for acceleration of charged particles such as the beat-wave acceleration should be studied for their applicability in astrophysical situations. In many astrophysical sources, the plasmas exist in the regime of strongly coupled plasmas with coupling factor, i.e. the ratio of the electrostatic potential energy to the thermal energy, as large as 10^5. Under such circumstances, the transport parameters such as the electrical resistivity and the thermal conductivity will strongly depend on the strong correlations among the particles and need to be studied in astrophysical situations [8].

Associated with acceleration of charged particles is the emission of radiation. The standard radiation processes are the bremsstrahlung, synchrotron and the inverse Compton and the Raman scattering. Often a combination of these processes is used to account for the observed radiation spectrum as for example in AGN [9]. In addition to the multiplicity of radiation processes, it becomes essential to invoke multi-phase plasma medium with different densities, temperatures and possibly magnetic fields to model the observations. This then leads to the question of coexistence and stability of these plasma phases. This is where the satellite missions hold a great promise as they provide high quality data inaccessible from the ground. The additional processes called into account for gamma ray radiation are associated with electron-positron pair production and annihilation. More often than not, the cross sections of these processes are calculated in vacuum. But in reality they occur in a plasma. The plasma plays two roles: first as a dispersive medium in that the photon dispersion relation in a plasma must be used and second as a source of various plasma waves which can serve as a scattering agency. As is well known that the processes of the Compton scattering, the pair production and the pair annihilation need two photons to interact with electrons and positrons for reasons of energy and momentum conservation. In a plasma, one of the photons could be replaced by one of the plasma waves. This gives rise to new contributions to cross sections which now depend on plasma density and temperature [10]. The decay of radioactive nuclei, for example, in supernovae, provide other ways of making gamma rays.

7. Satellite missions

Before I describe some specific missions, let me mention the general features of a satellite mission. These consist of energy band of the receiver, energy resolution, spatial resolution, collecting area of the detector, orbit altitude of a satellite in order to avoid, for example, Earth's radiation belts, detection mechanisms of radiation e.g. through photoelectric effect or some other means, the corresponding detector, whether simultaneous observations in different bands such as optical x-ray and γ-ray, imaging the object with or without spectroscopy and finally the lifetime of a mission.

For detecting x-rays, metallic mirrors are used. X-rays reflect from mirrors in the manner of a stone skipping over the surface of water. Thus grazing incidence in which the

reflection just slightly bends the path of x-rays is used. This necessitates a large f-ratio, the ratio of the diameter of the mirror to its focal length, mirror and hence an elongated size of the x-ray telescope. The detectors are charged couple devices – CCD which use the photoelectric effect to produce electrons when x-ray photons knock at an appropriate material. The gamma rays are identified by the electron-positron pairs they create in a thin converter material. The energy and direction of the electron-positron pair determine the energy and direction of the gamma ray. Gamma rays can also be observed, from the ground, by observing the atmospheric air showers they produce through the Cerenkov emission process.

8. X-ray satellites

There are several already operating x-ray observatories and several new are under preparation for launch in the next few years. Some of the current missions (1996–2000) are: ROSAT – the Rontgen Satellite, ASCA – Advanced Satellite for Cosmology and Astrophysics, RXTE – the Rossi X-ray Timing Explorer.

The upcoming missions (1999–2006) are: AXAF – the Advanced X-ray Astrophysics Facility, now named as CHANDRA after the Nobel Laureate astrophysicist S Chandrasekhar, SXG – Spectrum X-ray and γ-ray, XMM – X-ray Multi-Mirror and Constellation – X-ray observatory.

The Chandra operates in the energy band – 0.7–10 KeV or 1–200 Å with an energy resolution of 10^{-3}eV and an angular resolution of half an arc sec. The time resolution of a few microseconds makes it an ideal system to explore extremely rapid time variability of the high energy radiation. The spectroscopic data from the Chandra can be fully understood and interpreted only after similar spectroscopic studies are carried out in terrestrial laboratories under the astrophysical conditions. The Chandra has a f-ratio of 8.3, the mirror diameter of 1.2 m and is about 13.8 m long. The Chandra rides high in the sky with an apogee of 14000 km and a perigee of 10000 km. From this height the Chandra observes unobtrusively, the earth appearing as a 5 degree distraction. It is expected to last up to 2007.

The constellation-X is a multi telescope observatory expected to be launched in 2007. Its broad energy band of 0.25–40 KeV uses two types of telescope systems, one for the 0.25–10 KeV band and the other for 2.6–40 KeV band. It can measure energy flux as small as 10^{-14} erg/cm^2 sec with a spectral resolution ($\delta\nu/\nu$) of 300–3000 and a velocity sensitivity of 20 km/sec. It is a multi space craft observatory carrying a variety of optics. Its main aim is to do x-ray spectroscopy and provide plasma diagnostics of regions with densities of 10^8-10^{14}/cm^3 and temperatures of 1–100 million degrees Kelvin.

9. Gamma-ray satellites

The major gamma ray observatories current and planned are: CGRO – the Compton Gamma Ray Observatory, INTEGRAL – International Gamma Ray Astrophysics Laboratory, GLAST – Gamma Ray Large-Area Space Telescope and SWIFT, not an acronym but named after an australian bird which feeds itself while flying.

The CGRO, launched in 1991 has four instruments onboard: BATSE – the Burst and Transient Source Experiment, OSSE – the Oriented Scintillation and Spectrometer Ex-

periment, COMPTEL – the Imaging Compton Telescope in the energy range 1–30 MeV and EGRET – the Energetic Gamma Ray Experiment Telescope which can observe point sources up to 30 GeV energy.

The INTEGRAL is scheduled to be launched in September 2001. It has its orbit apogee 153000 km and perigee at 10000 km which has been chosen to minimize the background noise due to radiation belts. The science payload consists of two main instruments – the spectrometer in the energy range 20 KeV–8 MeV for detection of emission lines from the radioactive elements such as Al^{26}. The second instrument is an imager with an angular resolution of 12 arc minute in the energy range 15 KeV–10 MeV. Along with an x-ray monitor in the energy range 3–35 KeV, it also has an optical monitoring camera. It has a continuum sensitivity of 2×10^{-7} photons/cm^2 sec at KeV energies and the narrow line sensitivity of 5×10^{-6} photons/cm^2/sec at 1 MeV. It is the first time that a space facility to observe a single source simultaneously in optical, x-ray and gamma rays has been built. It is expected to operate for 2–5 years.

The GLAST is scheduled to be launched in 2005. The primary instrument onboard would be a pair conversion telescope operating in the energy range 20 MeV–300 GeV with an effective collecting area of 8000 cm^2 and an energy resolution of 10%. Its field of view is two steradians with an ability to locate a source within 1–5 arc minutes. It works at a time resolution of 10 microseconds. Its operating modes are all sky survey as well as the pointed mode with a capacity to look in any direction at any time. It can do all this for at least 5 years.

The SWIFT – a multiwavelength observatory for gamma ray burst astronomy will be launched in 2003. It is expected to observe 300 gamma ray bursts per year along with their afterglows. After detecting a gamma ray burst, within 50 seconds, it repoints to obtain x-ray and optical data. It can send the initial coordination of the burst to the ground within 15 seconds and the high resolution coordinates within 50 seconds. The distance to the burst can be determined in about 1000 seconds. It is expected to discover 400 or more supermassive black holes.

10. Conclusion

The time is ripe for plasma physicists to enter the fascinating field of the high energy universe. With the promise of a high quality data of the remote, energetic and enigmatic regions of the universe, the sophisticated tools of plasma physics should be put to use to understand the hot plasmas, in particular the acceleration and the radiation processes which are responsible for highly variable, nonthermal x-ray and gamma-ray radiation.

Acknowledgement

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