ASTROSAT

The Indian Astronomy Mission

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FOREWORD

Man has always been curious to understand the universe and began astronomical observations with his naked eye. In the last 100 years, observational astronomy has witnessed revolutionary developments with introduction of newer technologies and instruments, access to space-based observations as well as observing techniques in the full range of electromagnetic spectrum. Understanding various processes taking place in the celestial objects has been based on the interpretation of such observations. Astronomy today is a multidisciplinary activity encompassing many branches of science.

In 1975, with a launch of 'ARYABHATA' to carry out studies in X-ray astronomy, Aeronomy and Solar Physics, ISRO began its space-based astronomy activities 40 years ago. There have been many instruments launched by ISRO for various space science studies later on. Aiming to establish a full-fledged space-based astronomy observatory, on September 28, 2015 ISRO placed into orbit 'ASTROSAT', having multi-wavelength observational capabilities, heralding a new era in Indian space-based astronomy. Prominent national institutions working in astronomy and related areas have been actively involved in this mission designing and developing its instruments with encouragement from ISRO. Results of the initial observations conducted have been satisfactory. Making available ASTROSAT observing time to both Indian as well as international astronomy community is in the offing.

Aiming at introducing various facets of space-based astronomy to the students community as well as general public to attract them towards space science R&D activities, ISRO is brining out this booklet titled **'ASTROSAT: The Indian Astronomy Mission'** elucidating information about observing the universe, recent advances, the mission and the payloads, science objectives and broad band observation perspective of the mission, in a simple way.

I am sure; this booklet will find its way to the minds and thoughts of the space enthusiasts among the student community and the general public.

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1.0 Introduction

The word “Astronomy” means “law of stars” in Greek. The word “खगोलशास्त्र” (Sanskrit: Khagol - meaning "celestial" and Sastra – meaning "rules") denotes celestial rules. Astronomy is one of the oldest sciences.

Astronomy is a branch of science that deals with celestial bodies and the study of their size, composition, position, motion and origin. In other words, astronomy is the study of anything beyond the Earth. Astrophysics deals with the application of physics in understanding Astronomy. It provides the theoretical framework for understanding astronomical observations.

The history of astronomy goes back to more than two thousand years. Till the middle of the 20th century, astronomers learnt all they knew about sources in the sky from only the tiny fraction of electromagnetic radiation that is visible to the eye, often termed the optical or visible band. Advances in technology during last few decades have made it possible to detect radiation outside this visible part of the spectrum, allowing us to 'see' the Universe in all its magnificence. However, our atmosphere is opaque to most of these wavebands and it was only when mankind learnt how to launch satellites into space, did these new windows to the universe open up to us. These new space telescopes have revealed a universe that is completely different from what was known before.

Today modern astronomy has many branches including, gamma-ray astronomy, X-ray astronomy, ultraviolet astronomy, visual (optical) astronomy, infrared astronomy, microwave astronomy, and radio astronomy. ASTROSAT is India's first major space observatory and will be able to observe the universe simultaneously in the ultraviolet, optical and X-rays.

1.1 Astronomy in the Indian space programme

The Indian space programme has the primary goal of promoting and establishing a vibrant space science, technology and applications programme to assist in the overall development of the nation.

ISRO has successfully demonstrated its capability to build state-of-the-art remote sensing and communication satellites as well as launch vehicles. This opened up possibilities for modest space-borne astronomical experiments. Studies in space science and particularly space astronomy began early on in the form of several experimental opportunities. Starting from sounding rockets, balloons and several rocket-borne experiments to study hard X-ray emission from discrete X-ray sources, an X-ray payload was flown onboard Aryabhata, the first Indian satellite, in 1975.

The Indian Cosmic Ray Experiment, Anuradha was launched onboard Space Shuttle Spacelab-3 during 1985. It was designed to measure the ionization states of low energy cosmic rays in near-earth space. The first significant Indian space astronomy instrument was a Gamma Ray Burst (GRB) detector developed for the SROSS series of satellites. Onboard the SROSS-C2 satellite launched in 1994, the experiment (often referred as payload in satellites) detected around sixty GRB events in the 20 keV to 3000 keV range and studied their temporal and spectral properties in the gamma ray band.

This was followed by the Indian X-ray Astronomy Experiment (IXAE) payload on IRS-P3 satellite launched in 1996. Observational studies of many bright X-ray binary star systems including X-ray pulsars and stellar mass black hole candidates have been carried out. Studies of mass accretion around neutron stars and black hole binaries were some of the major outcomes from this experiment.

The success of these astronomy experiments triggered a discussion about a dedicated astronomical satellite, ASTROSAT. As a major astronomical mission, this is expected to bring together various scientific institutes and universities and provide much needed inspiration to the young students of the country to undertake careers related to astronomy.

During the same period, the experimental activity continued with a Solar X-ray Spectrometer (SoXS) which was flown onboard GSAT-2 in 2003. This payload observed the intensity, peak energy and width of spectral line features due to iron atoms in the spectra of several solar bursts.

A low energy gamma-ray spectrometer experiment, RT-2 was flown onboard Russian CORONAS-Photon mission on 30 January 2009 to study hard X-rays from the Sun in the energy range of 15 keV to 150 keV extended to 1 MeV.

These various endeavours provided sufficient confidence and human resources to undertake the huge step towards ASTROSAT.

ASTROSAT is an IRS-class satellite with a mass of about 1515 kg, and power generation capacity of about 1600 W. It is launched from Satish Dhawan Space Centre (SDSC), Sriharikota on 28th September 2015 by PSLV C30 (XL) to a 650 km near-equatorial orbit with an inclination of about 6 degrees. We expect ASTROSAT to function and deliver exciting new data for 5 years after launch.

2.0 Observing the Universe

Astronomy is restricted to studying what we can observe remotely from the Earth. Not being able to perform laboratory experiments like in other branches of science, astronomers continue to innovate in order to see farther, fainter and clearer. For centuries, we could measure only angles and times. Sixteenth century astronomers like Tycho Brahe (1546-1601 A.D) at Uraniborg (Fig. 2.1) in Denmark and Ulugh Beg (1344-1499 A.D) at Samarkand in present day Uzbekistan built huge instruments (Fig. 2.2) to do just this. Careful observations made with observatories like these led to breakthroughs like Copernicus's heliocentric theory and Kepler's laws of planetary motion. In India, we all know of the five Jantar Mantars (Fig.2.3.) that Sawai Jai Singh (1688-1743 A.D) built during 18th century in order to accurately measure the positions of celestial objects and refine the astronomical tables of those days.

For many centuries though, the human eye was the only optics and detector astronomers had access to. An astonishing piece of equipment, the eye has a 180 degree field-of-view, a contrast ratio of a million to one at any given time, and a resolution of 0.6 arc minutes (0.01 degrees) that is given by the size of the

Fig. 2.1: Engraving of the mural quadrant from Tycho Brahe's book Astronomiae instauratae mechanica (1598)

Fig.2.2: Some of the instruments used by Tycho Brahe, the Danish astronomer

lens. It can adjust and focus the rays from distant and near objects using this lens and the cornea, onto the retina, whose rods and cones detect light from the focussed image (Fig.2.4).

Fig.2.3: Jantar Mantar, New Delhi

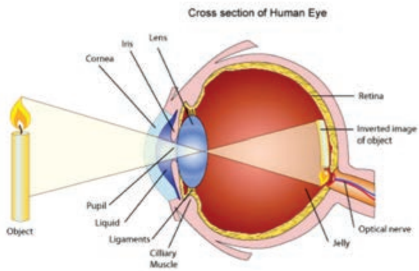


Fig.2.4: The eye is a simple telescope with some extraordinary properties. However, it is limited to visible light

In 1609, Galileo Galilei improved the then recently invented telescope (Fig.2.5) and using one with an aperture of about 4 cm turned it towards the sky, thus revolutionising observational astronomy. Ever since, we have been on a quest to build larger and larger telescopes to peer far into the Universe and understand what it is made of. Since Galileo's time, we have been patiently measuring the amount of light emitted by objects at unimaginable distances through our powerful telescopes. Interpreting our measurements using our knowledge of physics, we have since unraveled the nature of the stars, deciphered the structure and origin of galaxies, and have even decoded the origin of the Universe itself!

Both refracting telescope (like that used by Galileo) and reflecting telescope (like the one popularised by Newton) have an optical element which collects and focuses light. It is a lens in the former case and a mirror in the latter case. The focused image is further magnified using an eyepiece (Fig.2.6). However, modern telescopes do not have eyepieces. Instead, sophisticated recording instruments are placed at the focus to record images of the sky (using a CCD camera, like in our cellphones and digital cameras) or to record spectra (intensity of light as a function of wavelength, dispersed using a prism or a grating).

Telescopes generally help us see distant objects better. In the astronomical context however, where the nearest stars are already very far,

Fig.2.5: Galileo's 20x telescope

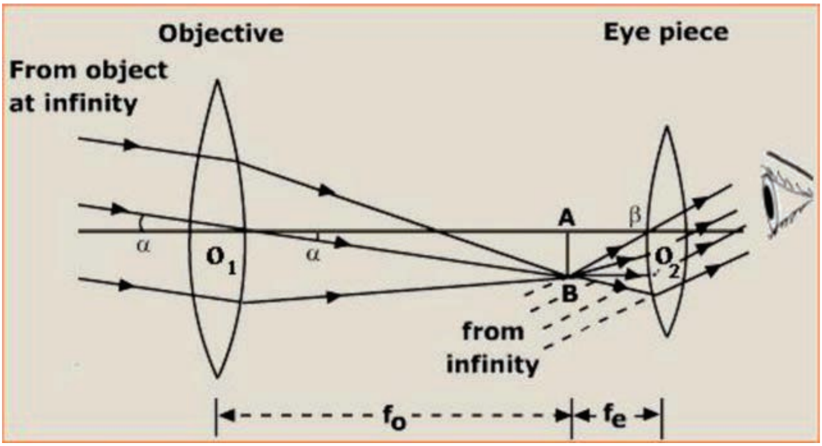


Fig.2.6: How a simple refracting telescope works

larger telescopes are used to collect more light, which help us see fainter objects (just as our pupils dilate after a while in a dark cinema hall, letting us see faint detail around us). The amount of light collected increases as the area of the aperture of the telescope. In addition, larger the lens or mirror, better is its resolving power. This is the ability to tell apart two closely spaced objects, or how fine the image is. This scales with the wavelength of light used and inversely as the size of the lens or mirror. The largest telescope working in the visible wavelengths has a mirror that is 10 m in diameter. However, the astronomy community is reaching far beyond even this, and are building two new telescopes for the future – the Thirty Metre Telescope with a 30 m diameter mirror that India is also a part of, and the European Extremely Large Telescope with a 39 m diameter mirror. We have indeed come a long way from the few centimetres sized lenses of Galileo!

Fundamental breakthroughs in astronomy have arisen not just due to the ever increasing size of telescopes but also because of the sophisticated instrumentation available at their focus. Efficient large area CCD detectors operating in different wavebands and high dispersion spectroscopic techniques have yielded exciting discoveries.

The eye can only see light whose wavelength is between 4000 and 7000 Angstroms (400-700nm), and these different wavelengths are perceived as colours (Fig.2.7). The colours of the spectrum of white light are violet, indigo, blue, green, yellow, orange and red (VIBGYOR). Each colour is associated with light of a particular wavelength. Red light has longer wavelength than the blue light.

In general, radiation, being an electromagnetic wave, can have any wavelength, and is classified, in decreasing order of wavelength, as radio, microwave, infrared, visible, ultraviolet, X-ray and gamma ray. In modern times, we are familiar with many of

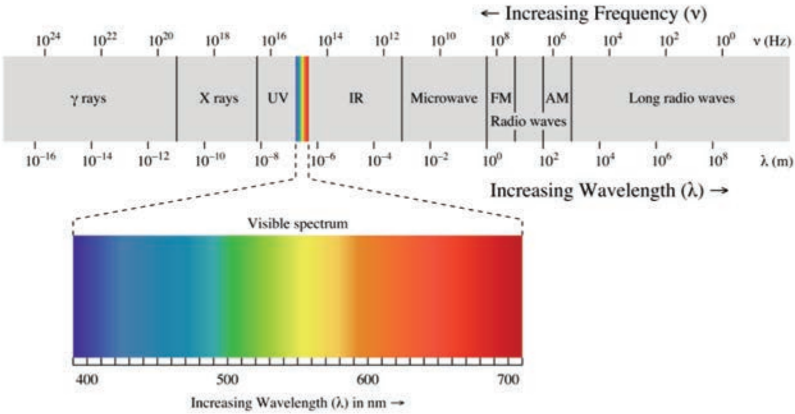


Fig.2.7: Light, an electromagnetic wave, can have any value of wavelength, or frequency, ranging from long wavelength radio waves to very short wavelength gamma rays. ASTROSAT will explore the Universe in the Ultraviolet to X-ray range

these wavebands in our daily lives. Our television sets and cellphones use radio waves, night vision goggles and heat sensors use infrared, fake currency detectors use ultraviolet, doctors use X-rays to image our fractured bones, and gamma rays are used to sterilise food and in medical procedures.

With development in technology, we are no longer limited to 'see' the universe only in the visible range. We can build telescopes and detectors that operate in the radio, microwave, infrared, ultraviolet, X-ray and even gamma rays, opening entirely new windows onto the universe. However, our atmosphere is a blanket covering us, and this blanket is transparent only in a few wavebands (Fig. 2.8). Apart from the visible, radio, and parts of infrared and microwave, the atmosphere is completely opaque. Hence, to study the universe in the far infrared, ultraviolet, X-ray and gamma ray, we need to place our telescopes in space. ASTROSAT is one such endeavour, to study the universe in

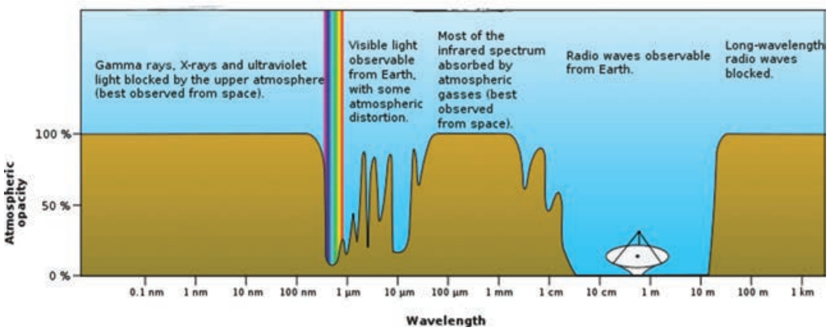


Fig.2.8 : Space Telescopes were built since our atmosphere is opaque in the ultraviolet and X-rays

ultraviolet and X-ray radiation, giving us a view of the Universe that Galileo would not even have dreamt of!

Ultraviolet rays (which have wavelengths less than 4000 Angstroms) are absorbed by molecules of ozone (O_3), oxygen (O_2) and nitrogen (N_2) leading to dissociation of the molecule. This is a good thing, since prolonged exposure to ultraviolet rays from the Sun can cause cancer. X-rays and gamma rays are completely absorbed by the atmosphere due to photo-electric absorption since the energy of these photons is higher than the ionization energy of the atoms. For X-rays entering from space, our atmosphere is equivalent to 5 metres of opaque concrete!

Our atmosphere may be transparent to visible light, but it still creates problems for our telescopes. The refractive index of air depends on its temperature and density, both of which vary constantly (over timescales of milliseconds) due to turbulence in the atmosphere. This causes the incoming plane wavefront from distant objects to become warped, leading to distorted images

(Fig. 2.9). When we observe a star at low elevation, near the horizon, we see it through a larger column of air, and it is this distortion that manifests itself as twinkling. Twinkling stars may look pretty but are not very useful to astronomers. These distortions limit the resolution of even the largest optical telescopes to about 0.5 arcseconds, compared to the theoretical value of 0.01 arcseconds expected for these large telescopes. The Hubble Space Telescope, of course, was launched into space precisely to avoid this problem. In recent decades, however, new techniques have been developed to correct for this effect for ground based telescopes as well.

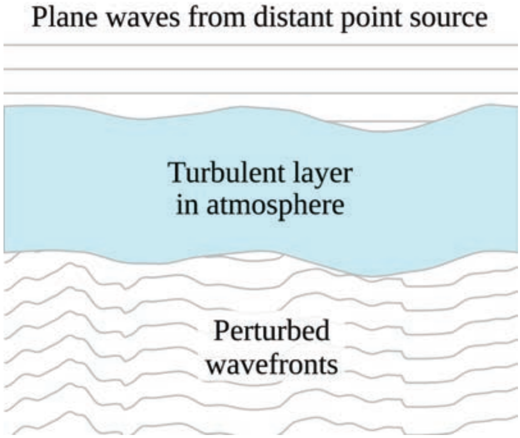


Fig. 2.9: The wavefront perturbed by the turbulent atmosphere of the Earth causes images of distant objects to be distorted

2.1 Challenges in Space Based Astronomy

Space based astronomy is not easy. To start with, we need to be able to build telescopes that can withstand the rocket launch and also operate in space conditions of extreme vacuum of lesser than 10^{-8} torr (compared to a pressure of 760 torr at the Earth's surface) as well as temperature variations. In addition, most astronomical objects are extremely faint in their X-ray emission. Only objects at a few million Kelvin temperature are hot enough to emit X-rays, which is why astronomers initially expected to see no sources in the X-ray sky.

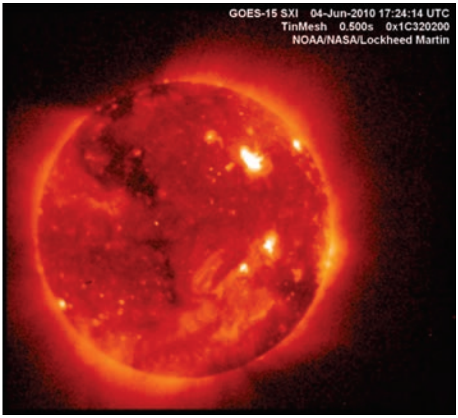


Fig. 2.10: The sun in X-rays, as seen by the GOES SXI telescope

The Sun's radiation across most of the electromagnetic spectrum can be described as a 'blackbody' at 6000 K temperature. A blackbody is an object that absorbs all the radiation that is falling on it, and is the most efficient radiator at its temperature. Its wavelength-dependent emission is given by a universal law that was derived by Max Planck, which depends only on its temperature. The Sun's emission is brightest in the visible range. If its X-ray emission too was described by a blackbody at 6000 K, then it would be so faint and hence emit so few photons per unit time, that you would have to wait for longer than the age of the universe itself, to see a single X-ray photon from the Sun. In reality, the sun is quite bright in the X-ray because of its million Kelvin hot atmosphere, called the Corona (Fig.2.10). How the 6000 K solar surface manages to heat its atmosphere to a million degrees is still an unsolved problem in astrophysics. But even this corona is about 10 million times as faint as the visible sun (Fig.2.11).

The farther away an object is, the fainter it appears to us on Earth, of course. In addition, since most celestial sources are intrinsically faint in X-rays compared to other wavebands, the other bright sources in the X-ray sky are a million times fainter than the X-ray sun, as seen from the Earth! The brightest X-ray sources in the sky however are not stellar coronae, but X-ray binaries which contain either a neutron star or a black hole as one component of

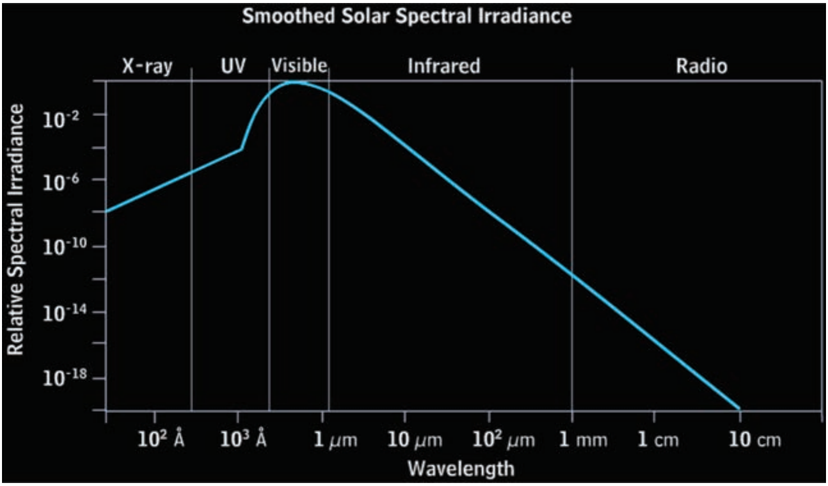


Fig. 2.11 : Even the million degree corona of the Sun is a few million times fainter than the visible sun!

the binary. The luminosity of these binaries, in X-rays, is in fact 1000 - 100,000 times the luminosity of the Sun! However, we do receive much less photons at a satellite around Earth's orbit, due to the distances these sources are at. The brightest source in the X-ray sky, as seen from a satellite around Earth, apart from the Sun, is 'Sco X-1', from which we receive almost 100 X-ray photons every second in a 1 square cm area. ASTROSAT will be studying objects that are about a million times fainter than this. X-ray emission from bright sources like Sco X-1 is neither a blackbody nor similar to that from the Sun's corana. Instead it is powered by an extremely efficient process of accretion. However, they still appear faint due to their large distances from us. Similarly, the ultraviolet sky is much fainter than the visible sky and is therefore much emptier.

All this requires very sensitive detectors and sophisticated instrumentation in order to detect each of these photons. For example, consider an instrument like the Large Area X-ray

Proportional Counter (LAXPC) of ASTROSAT having 8000 cm^2 area. This will take the few tens of electrons that an incoming photon produces, and amplify it by factors of many tens of thousands before the photon can be finally detected. Similarly, every ultraviolet photon incident on the telescope will be amplified many fold before detection.

X-ray astronomy is further complicated by the necessity to distinguish X-ray photons emitted by the object being observed from unwanted signal, called the background. The X-ray sky, apart from individual sources (Fig.2.12), is not completely dark, but there is a diffuse X-ray background comprised of low energy X-rays from the solar neighbourhood, and high energy X-rays from a myriad of unresolved distant objects.

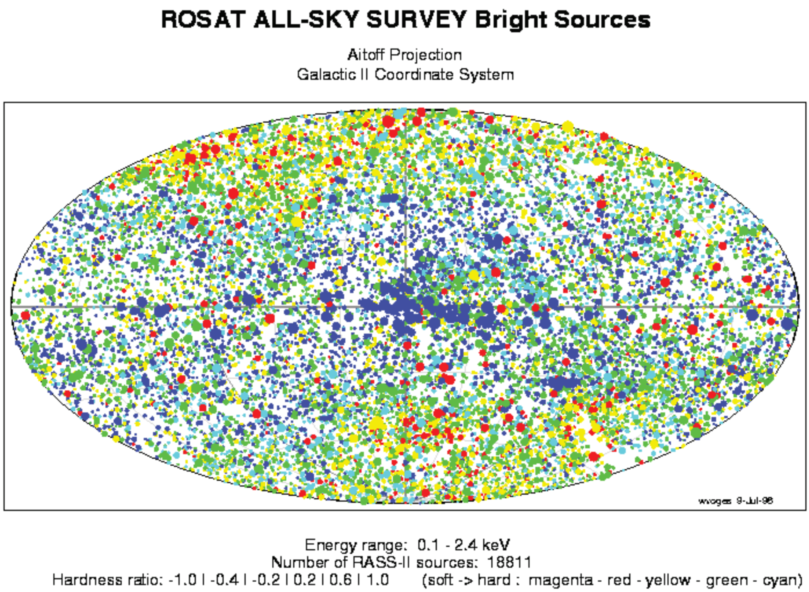


Fig.2.12: All-sky survey map of bright galactic sources

Another problem for X-ray telescopes is electrically charged particles. These are fast moving particles like electrons, protons, and some heavier nuclei and are energetic enough to pass right through the detectors. While doing so, they knock electrons off the detector's atoms in their path. These electrons can masquerade as real X-ray signals from the object being studied. Many clever ways have been evolved to differentiate between these background particles and the X-ray photons that we would like to measure from the celestial object. But where do these charged particles come from?

The sun emits a continuous stream of high energy charged particles, called solar wind and there also exists a background of charged particles called galactic cosmic rays, some of which reach the earth. However, the earth has a magnetic field, shaped as if there is a bar magnet at its centre. Since these cosmic ray particles are charged, they cannot easily cross these magnetic field lines, and some of them are trapped inside this field,

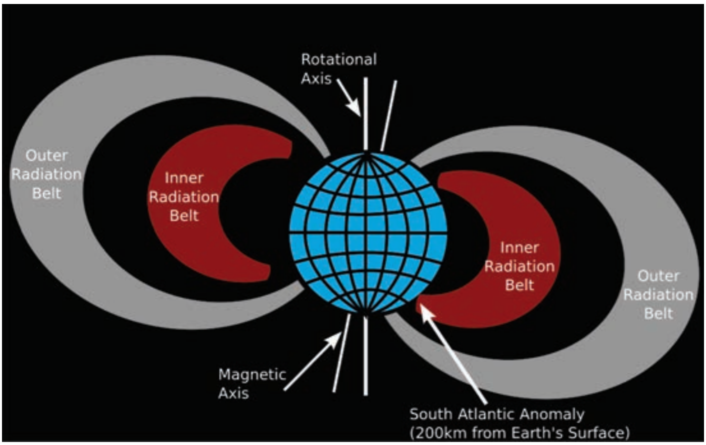


Fig. 2.13: The two Van Allen belts, which have a huge concentration of energetic charged particles

oscillating between the magnetic poles. These trapped particles form two belts, called the Van Allen belts. The inner belt extends from a height of 1000 km to 6000 km and the outer belt from 13000 to 60000 km (Fig.2.13). Recent studies indicate possibility of a third belt too!

Since these belts are a strong source of charged particles, all satellites including X-ray satellites avoid them, and are flown either below the inner belt (like ASTROSAT) or above the outer belt. There is, however, an added complication. The earth's magnetic axis is not aligned with its rotation axis, and the intersection point of these two is shifted roughly 500 km from the centre of the Earth. This means that the Van Allen belts are not exactly symmetric about the Earth's surface. In fact, the inner belt extends much lower near the South Atlantic Ocean, down to a height of 200 km called the South Atlantic Anomaly, or the SAA (Fig. 2.14), this is a headache for X-ray satellites like ASTROSAT.

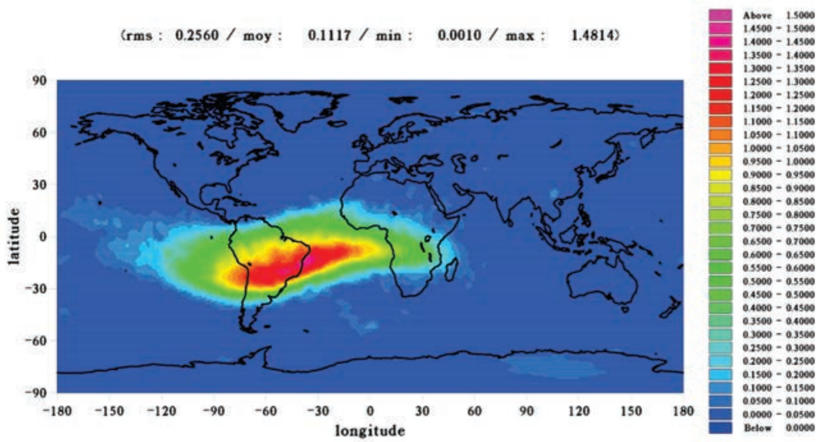


Fig. 2.14: The South Atlantic Anomaly

When the satellite is passing through the SAA, the charged particle flux is high enough to damage the detectors. Hence the detectors have to be powered low, or even shut off. In fact the orbital inclination of ASTROSAT is chosen to be as low as 6 degrees to minimise the effects of SAA. Charge particle background rejection in large X-ray detectors without optics is often done by removing simultaneous pulses in the main detector and a surrounding background detector/veto cells.

ASTROSAT carries an instrument called the Charged Particle Monitor, or the CPM that will serve as a warning system against the SAA. The CPM expects roughly 1 detection per second at usual times. However, this could rise to many 100 detections per second while passing through the SAA. Hence, when this CPM starts detecting a high rate of cosmic rays as the satellite is entering the SAA, it will warn the other instruments which can then lower their operating voltage or even shut down temporarily.

3.0 Recent updates in X-ray and UV astronomy

There have been several extremely sophisticated space observatories flown by international space agencies in the last two decades. There has been the Hubble Space Telescope (HST), a NASA-ESA mission, which has been continuously enhanced with its multiple servicing missions. One of the most significant science contributions of the HST is the discovery of faint supernovae and hence that the Universe is accelerating, leading to the concept of dark energy. HST has also provided a more accurate distance scale of the Universe. The deep field studies of HST contributed to better understand stellar and galactic evolution. HST has also contributed to studies of extra solar planets and afterglows of gamma ray bursts.

Amongst the X-ray missions, the NASA's Rossi X-ray timing Explorer (RXTE) has the best timing observations of X-ray sources with the discovery of their quasi periodic oscillations

(QPOs) indicating how matter flows around these sources. It was also the mission which enabled the estimation of the spin of black holes and the discovery that the stellar sized black holes indeed behave similar to supermassive black holes called microquasars. The NASA's Chandra X-ray observatory and the ESA's XMM-Newton telescopes elevated X-ray astronomy to another level with their large area, imaging and spectroscopic capabilities in X-rays, to compete with that in optical astronomy. Significant amongst the contribution of Chandra and XMM-Newton are the capability to image supernovae remnants in individual elemental lines, resolve deep fields, determine spin in black holes, resolve sources in the centre of our galaxy, winds around black hole sources and even the detection of X-rays from planets.

In the UV band, NASA's GALEX mission has been extremely successful in developing the largest catalogue of UV sources, enabling the study of the evolution of galaxies, and discovering that old galaxies could have stellar material left around them.

The Swift mission of NASA was primarily aimed at detection of gamma ray bursts and finally settled the location of these sources to cosmological distances with its capability to turn immediately towards them and study their afterglows in X-ray and UV bands.

4.0 Story of ASTROSAT

In the new millennium, the international astronomy community is planning many space missions to launch powerful telescopes that will push the boundaries of astronomy knowledge like never before.

In the Indian context, around fifty Indian astronomers from various institutions and universities met around 1996 to deliberate on a dedicated astronomy mission which could be developed and launched by ISRO primarily for studying stellar objects. Working groups were formed by ISRO to study the various possible scenarios. The community then submitted a science plan to ISRO in 2000. Based on this document, ISRO decided in 2002 to develop a set of four complex X-ray payloads that were identified for this mission. An Ultra-Violet Imaging Telescope was also included in the mission after further discussion.

This ambitious Indian mission is expected to provide Indian scientists with access to new electromagnetic windows, a capability to explore exotic objects like white dwarfs, neutrons stars and black holes, and a potential for new exciting discoveries. In addition, this project would be helpful to train a new generation of young scientists in astronomy research and analysis of big data.

Hence, a detailed investigation was undertaken which looked at scientific objectives, design specifications, development of science payloads, spacecraft main bus elements, launch, data reception, data management and utilization by scientists, budget, human resources and time schedules. Based on this study, the Government of India approved ISRO's proposal for the multi-wavelength astronomical observatory mission, ASTROSAT in 2004.

5.0 Spacecraft and Launch Vehicle

A spacecraft or satellite is a body that orbits a planet. There are natural satellites such as our Moon and artificial ones like remote sensing and communication satellites. Schematic (solar panel stowed and deployed) and actual views of the spacecraft are in figs.5.1 – 5.3.

The cuboid shaped ASTROSAT spacecraft (size: 1.96 metre x 1.75 metre x 1.30 metre), covered with a golden coloured thermal blanket, weighs about 1515 kilograms. The satellite is folded and

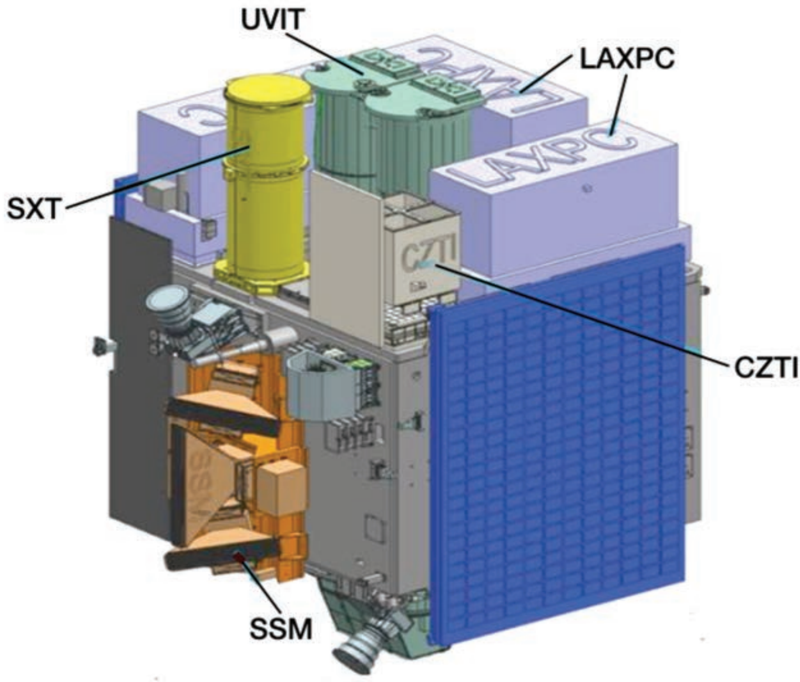


Fig. 5.1: Stowed view of the Spacecraft

packed in the payload fairing of the rocket which is the launch vehicle. Payload fairing is the topmost section of the launch vehicle which protects the spacecraft during launch through the Earth's atmosphere. Once above the atmosphere, the satellite is put into orbit and then the satellite deploys its solar panels, antenna, rotating and pointing mechanisms etc.

A platform called the "bus" connects all the main systems including the battery, computer, antennas, solar arrays, payload instruments and communication equipment that a satellite uses to perform its functions.

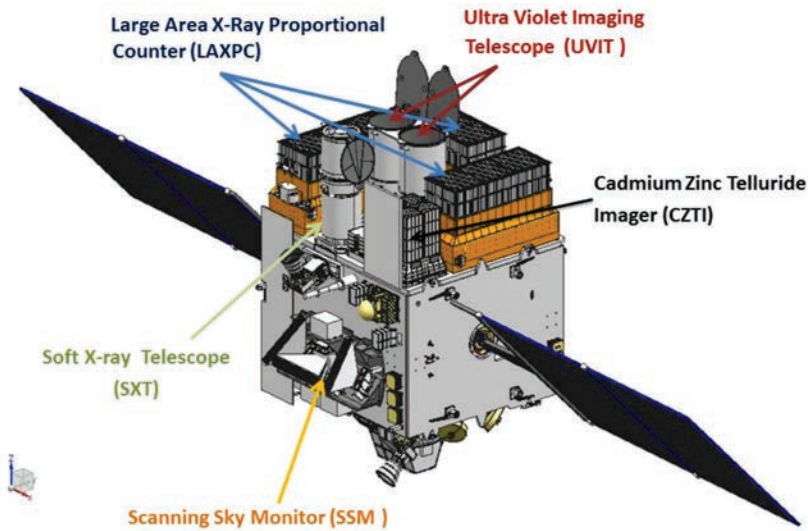


Fig. 5.2: Deployed view of the Spacecraft

The solar panels of the spacecraft generate required electric power by converting sunlight to electricity. ASTROSAT has two deployable arrays of two panels which will generate about 1600 watts power. Two lithium ion batteries supply power to the spacecraft when sunlight is not falling on the solar panels. Each battery is connected to the bus system, from where it is charged.

A host of sun and star sensors, magnetometers as well as sensitive gyroscopes provide the reference essential for the proper orientation of the satellite. This vital information is used by the Attitude and Orbit Control System (AOCS) of the satellite, which acts like its electronic brain and provides the stability for the satellite to focus its attention towards the target of interest (in this case celestial sources) or to change its orientation. Four fast spinning reaction wheels perform this action after receiving the command from the control system. The pointing accuracy is 0.05°. Although the forces on a satellite in orbit are in balance, there are minor disturbing forces that would cause a satellite to slightly drift

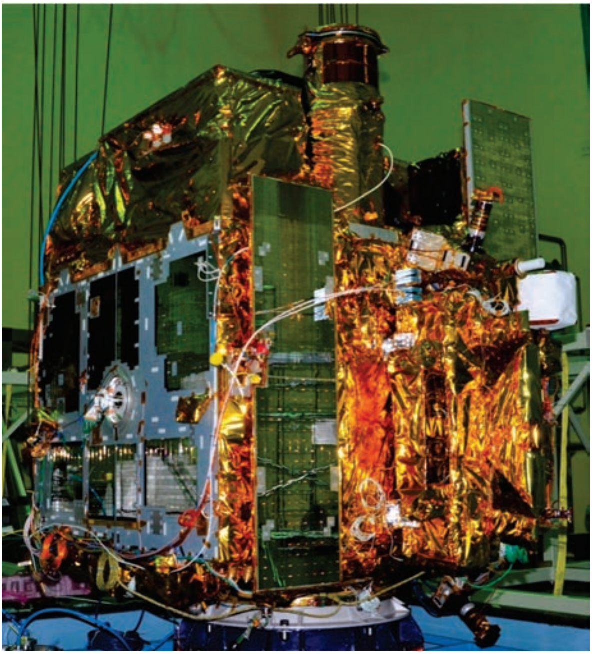


Fig. 5.3: Actual view of the Spacecraft

out of its orbit. The drift rate is expected to be less than 0.5 arcsec per second. A large number of heaters and sensors will provide thermal control of all the payloads and subsystems as specified by each subsystem. When the spacecraft undergoes an intentional change in orientation to realign instruments with another target, it is called slew. The slew rate of ASTROSAT is 0.6° per second.

The Telemetry, Tracking, and Command (TT&C) network receives control signals from the ground to initiate spacecraft maneuvers or to configure or change the state of the payload instruments. The TT&C unit also sends back telemetry information to the ground about the state of the spacecraft including measurement data from equipment and sensors.

Fig.5.4: PSLV-XL lift-off from Sriharikota

The data from the instruments is stored in a solid-state recorder which has the storage capacity of 200 Gbits. Once the satellite is visible to the Ground station antenna, then the payload data and health parameters are transmitted to Earth.

The task of launching ASTROSAT was entrusted to the Polar Satellite Launch Vehicle PSLV, the workhorse launch vehicle of ISRO (Fig.5.4). The four stage PSLV, which is also equipped with six strap-on motors that surround the first stage, stands 15 storeys tall. The XL version of the PSLV which was chosen to launch ASTROSAT weighs 320 tons at lift-off and this mission was designated as PSLV-C30. This is the thirty first launch of the versatile PSLV. It took about 23 minutes for PSLV-C30 to place the spacecraft in its designated orbit.

ASTROSAT was launched in a 650 km altitude near-equatorial orbit with 6 degree orbital inclination on 28th September 2015. The path followed by a satellite is its orbit. Orbits can be polar or equatorial, depending on the purpose of the satellite. The angle between the orbital plane and the equatorial plane is called its inclination. ASTROSAT takes 97 minutes to complete one orbit.

6.0 Observing with ASTROSAT

The satellite was allowed to get stabilized after reaching the designated orbit.

The payloads were switched ON one at a time keeping all safety issues in mind and it took couple of months to start observing in the visible, ultraviolet and X-ray regions of the electromagnetic spectrum. The operational sequence of the payloads is provided below.

Date	Payload made operational
28 September 2015	ASTROSAT launch and in orbit
29 September 2015	CPM
05 October 2015	CZTI
12 October 2015	SSM
20 October 2015	LAXPC
26 October 2015	SXT
30 November 2015	UVIT

The performance of the payloads will be verified and on-orbit calibration will be carried out. Once the performance verification is done, the observation time is allotted to the instrument teams. By studying the universe with these five instruments simultaneously, one can get a deeper insight into the way our universe works.

A certain percentage of observation time of ASTROSAT is planned to be provided to proposers from Indian scientific community one year after launch and to the international scientific community from second year after its launch. The data will be stored at the Indian Space Science Data Centre (ISSDC).

7.0 Scientific Payloads

The ASTROSAT carries onboard a total of 6 experiments including the Charged particle monitor already mentioned. We give here a brief description of the experiments (payloads) which will cover optical, UV and X-ray bands.

7.1 Ultraviolet Imaging Telescope (UVIT)

The Ultra-Violet Imaging Telescope, or the UVIT, is a remarkable 3-in-1 imaging telescope. Weighing all of 230 kg, the UVIT can simultaneously observe in the visible, the near-ultraviolet (NUV) and the far-ultraviolet (FUV). UVIT comprises of two separate telescopes. One of them works in the visible (320-550 nm) and the NUV (200-300 nm). The second works only in the FUV (130-180 nm). Remember that the famous Lyman-α line of Hydrogen is at 121.6 nm, at the far end of the FUV, and even beyond that is the X-ray band for which ASTROSAT has four different telescopes.

UVIT has a spatial resolution of 1.8 arcseconds and a field of view of 0.5 degree. In comparison, GALEX, an ultraviolet telescope that was launched by NASA had a larger field of view of 1.2 degrees but a resolution of about 5 arcseconds.

Each of the two Ritchey-Chretien type telescopes of UVIT have a primary mirror of 37.5 cm diameter, specially coated with material that very efficiently reflects ultraviolet photons. These mirrors, hyperbolic in shape in order to minimise optical errors, reflect the incoming light to a secondary mirror, which in turn focuses the light onto a filter wheel and the detector.

Just as optical telescopes have filters to image the sky in the red or blue or green range of wavelengths, so also the UVIT has filters to image the NUV and FUV (and the visible) in different narrow

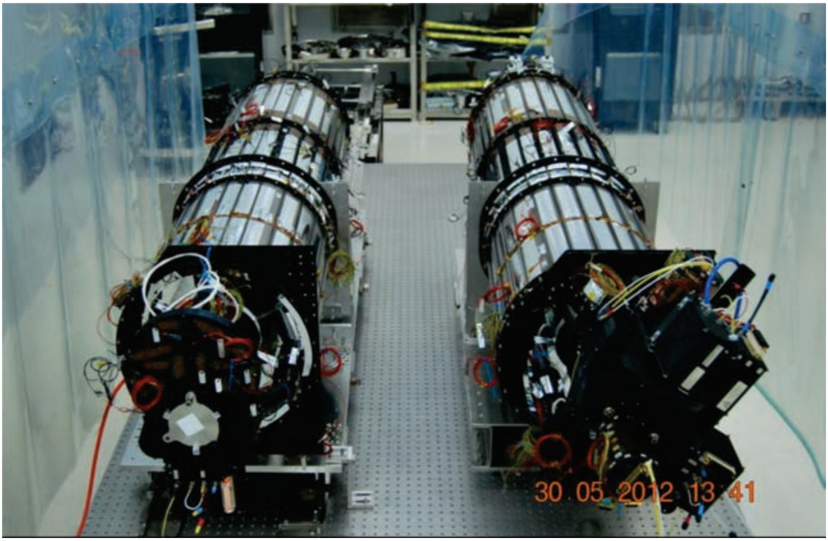


Fig.7.1: View of UVIT

wavelength bands. These filters are mounted on wheels which can be spun to bring whichever filter the astronomer wants into the light path.

After the filters, the actual detectors are mounted. These are photon counting detectors and can measure the location and time of incidence of each photon individually. They can also operate in the integration mode (like a CCD camera) and the visible channel will mostly be operated in this mode. These photons are then read out using 'intensified CMOS' readout cameras. Objects are far fainter in the ultraviolet than in the visible and hence each photon is first hugely amplified before it is allowed to fall on the 0.25 Megapixel camera. The UVIT is now sensitive enough to detect a single ultraviolet photon and time of its arrival to within 5 millisecond accuracy! The UVIT can image the field of view 30 times a second (and in special cases, even 200 times a second).

UVIT was a challenging instrument to design and build. It had to deal with the unique problems of ultraviolet astronomy, incorporate modern technology and also withstand the intense mechanical vibrations during launch and the thermal and radiative extremes of outer space.

The intensified CMOS detector works by converting incoming photons to electric charges. Hence, the UVIT can be permanently damaged if it is exposed to very bright light. Sunlight scattered from the satellite, the light reflected from the Earth's surface, emission from molecules (like O_2) in Earth's outer atmosphere when excited by the Sun and even sunlight scattered off the dust in the solar system can threaten the safety of UVIT. Hence, the telescope observes only at night, and has a number of electronic and mechanical features to safeguard its sensitive insides, to ensure that it produces pathbreaking science in the years to come. The geometric area and mass of UVIT are 1250 cm^2 and 231.8 kg.

Indian Institute of Astrophysics (IIA), Bangalore and Inter University Centre for Astronomy & Astrophysics (IUCAA), Pune in collaboration with Canadian Space Agency (CSA) has developed this payload.

7.2 Soft X-ray Telescope (SXT)

SXT is a X-ray focusing telescope operating in the energy range 0.3-8.0 keV (X-rays are often again detected as individual photons. They are quantified in terms of their energy rather than their wavelength, purely due to initial development of X-ray detectors without optics. 1 keV photon is approximately 1.2 nm (for comparison, a blue light photon has an energy of about 3 eV)).

At normal incidence, silver and aluminium reflect over 90% of all visible light which is why metallic coatings are applied to visible light telescope mirrors made of glass. The amount reflected increases at grazing angles of incidence. However, X-rays do not reflect off mirrors the same way that visible light does. Because of their high-energy, X-ray photons penetrate into the mirror in much the same way that bullets slam into a wall. X-rays are either completely absorbed or pass right through the material at normal incidence depending on their energy. However, these X-ray photons reflect off the surface of few materials if grazing incidence angles are used. This principle is used in construction of X-ray telescopes.

Fig.7.2: View of SXT

The SXT uses one such geometry, the Wolter Type I geometry (Fig.7.3) Here the X-rays are reflected twice, first by a paraboloid mirror section and then by a hyperboloid mirror section before being focused. The mirrors are made as conical approximation to these cross sections using gold coated Aluminium foils and can achieve resolution of few arcminutes. This allows the telescope to be lighter than the much heavier but much more accurate telescopes of Chandra and XMM-Newton. The word 'soft' is used to imply that the telescope can focus X-rays of relatively low energies, in the range 0.3 - 8.0 keV. The length of SXT is nearly 2.5 m while the telescope envelope diameter is 38.6 cm. The telescope has 320 nested mirror foils to increase the collecting area of X-rays. Each foil of thickness 0.2 mm is made of aluminium and coated with gold for reflectivity (Fig. 7.4).

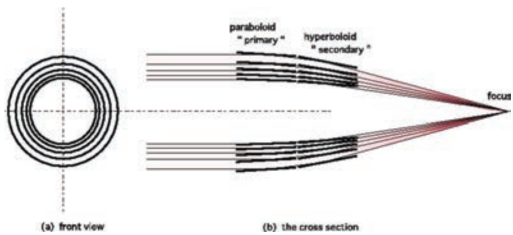


Fig.7.3: Wolter-I geometry

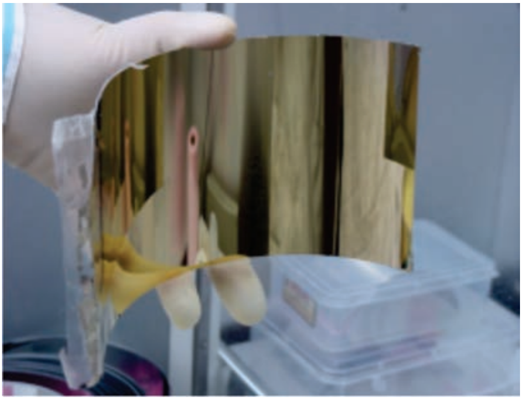


Fig. 7.4: A shaped and gold coated foil segment

The focused X-ray photons are collected by a cooled charge-coupled device (CCD) with 600 x 600 pixels. The total field-of-view is 41.3 minutes of arc across. The CCD is cooled to a temperature lower than -80 °C to avoid stray noise photons being generated. This is particularly important since the rate of X-ray photons from astronomical objects are very few in number in contrast to longer wavelengths such as optical or infrared. The SXT-CCD can also separate X-ray photons of different energies between 0.3 - 8.0 keV, and so simultaneously provides a spectral resolution of about 150 eV at 6 keV. The geometric area and mass of SXT are 250 cm^2 and 73.6 kg.

This payload is developed by Tata Institute of Fundamental Research (TIFR), Mumbai. The focal plane camera with a cooled CCD is from University of Leicester, UK.

7.3 Large Area X-ray Proportional Counter (LAXPC)

The LAXPC comprises three large area proportional counters to carry out timing and broad band spectroscopy over the energy band of 3-80 keV X-rays for variable astrophysical sources. Proportional counters are made of large enclosures filled with gas and two electrodes held at a potential difference. The entry of a X-ray photon is marked by its absorption in the gas with the creation of photoelectrons. This then triggers further multiplication due to the potential difference by ionising the gas atoms and producing further electrons. This results in a charge pulse between the electrodes that is detected, converted to voltage, amplified and measured. The amplitude of the pulse is therefore proportional to number of electrons and ions produced and can be used to derive the energy of the original X-ray photon from the celestial source. The number of such events gives the count rate detected and therefore the strength or brightness of the celestial source. With these two, one can measure the flux and continuum spectrum of the source.

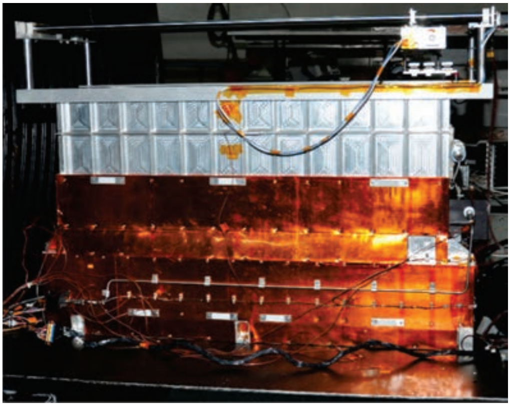


Fig.7.5: View of LAXPC

LAXPC has three co-aligned proportional counters with a total effective area of about 8000 cm^2 at 5-30 keV. The inert gas mixture contains predominantly Xenon and a small percentage of Methane at a pressure of 1520 torr (~2 atmospheres). Most of the gas is inert to avoid both absorption of electrons as well as chemical reactions with detector components. A small amount of methane is added to absorb photons produced during the ionisation of Xenon atoms by the X-ray. The field of view of each proportional counter is 1 degree, and this is determined by a mechanical collimator placed on the detector.

The special feature of the LAXPC instrument is its ability to measure X-ray spectra at very short time scales. Not only can these spectral measurements be made over periods as short as few milliseconds if the source is bright enough, up to few hundreds of seconds, but these spectra can extend over a large range of

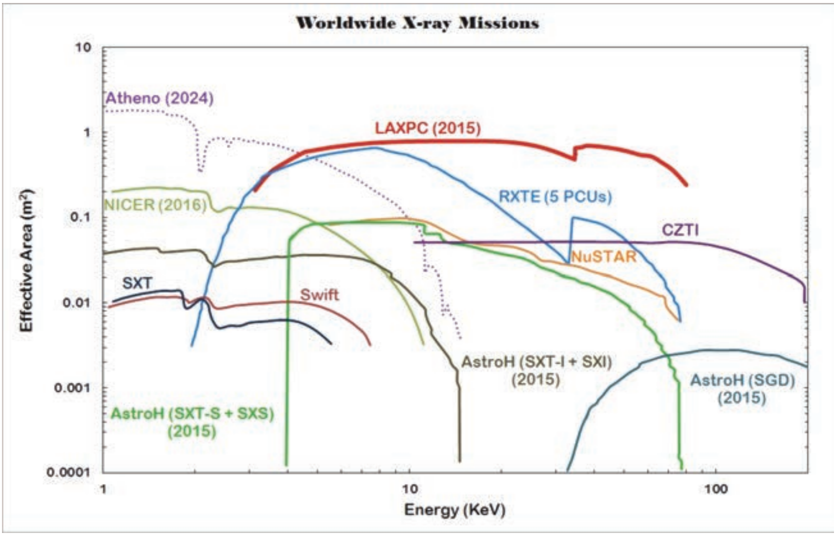


Fig.7.6: Comparison of effective area of LAXPC with international X-ray missions

energies viz. 3-80 keV. The LAXPC can even look at how the brightness of a celestial source varies over tens of microseconds ! Hence, this is the perfect instrument to study a wide variety of celestial objects that undergo sudden outbursts, which we will discuss later in detail.

The Rossi X-ray Timing Explorer (RXTE) was a X-ray telescope launched by NASA. The LAXPC of ASTROSAT will be more sensitive than RXTE's Proportional Counter Array at high energies (> 25 keV). Due to its large collecting area, the LAXPC is also expected to be a superior instrument for precise timing measurements. The geometric area and mass of LAXPC are 10,800 cm^2 and 415.5 kg.

Tata Institute of Fundamental Research (TIFR), Mumbai has developed this payload.

7.4 Cadmium Zinc Telluride Imager (CZTI)

Cadmium - Zinc - Telluride Imager (CZTI) is truly a hard X-ray imaging instrument in the energy range 10-100 keV with a collecting area of 976 cm^2. This is a solid state detector and the entire detector assembly is divided into four identical and independent quadrants. In each quadrant, 16 CZT modules each of area 15.25 cm^2 are used. CZT modules are pixelated with pixel size 2.46 mm x 2.46 mm and 5 mm thickness. Individual pixels are connected with an electronic assembly to detect the incident X-ray photons as output voltage. Very high energy particles can simply pass through the CZT detector with a partial energy deposition and is a source of background noise. A Cesium - Iodide - Thallium [CsI(Tl)] crystal is used just under the CZT detector panel for background rejection. An X-ray photon in the energy range 10-100 keV deposits the full energy only in the CZT whereas a high energy charged particle deposits energy both in the CZT and the CsI detectors. This can be used to detect which events are due to X-ray photons and which are due to charged particles. The detector has a detection efficiency of 95% in 10-100 keV range.

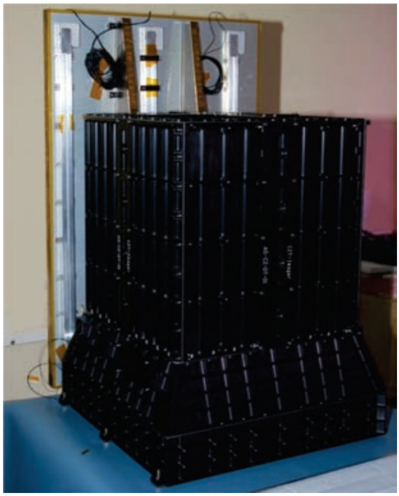


Fig.7.7: View of CZTI

A collimator, made of 0.07 mm thick Tantalum sheet sandwiched between 0.2 mm thick Aluminum with a field of view 4.6° × 4.6°, is placed above the CZT detector assembly allowing nearly parallel incidence of photons onto the detectors. A Coded Aperture Mask (CAM) made of 0.5 mm tantalum is placed above the collimator. The CAM consists of predetermined pattern of rectangle/square holes matched with the size of the CZT pixel straight down to it and the CAM casts a shadow onto the detector with 50% transparency (roughly equal number of close and open cells). The exact position of the source above the detector can be determined from the pattern of the shadow that it casts. CZT modules perform best in the temperature range 0°-15°C and hence the heat generated by the detector assembly is drained out continuously by a radiator panel assembly. The geometric area and mass of CZTI are 976 cm^2 and 56 kg.

This payload is developed by Tata Institute of Fundamental Research (TIFR), Mumbai, Vikram Sarabhai Space Centre (VSSC), Trivandrum and IUCAA.

7.5 Scanning Sky Monitor (SSM)

The Scanning Sky Monitor (SSM), as the name indicates, is to scan the portion of sky away from sun to look for any transient behaviour in X-ray sources. In any space mission such an instrument is mandatory because it can scan a large portion of the sky in a few hours. Hence, the SSM is good for detecting and locating any transient event in outbursting phase in the energy range 2.5-10 keV. Also, at the output of SSM, if some interesting source is found in a particular location, other instruments on-board ASTROSAT as well as ground based observatories can be alerted to conduct detailed observation towards that position. Hence SSM needs to have large field of view (FOV) and good angular resolution. SSM consists of three nearly identical one dimensional position sensitive proportional counters each having a FOV of about 22° x 100°. The assembly is mounted on a rotating platform to scan the sky. The working principle of the detector of SSM is similar to the proportional counter for LAXPC but in this case the anode wire is position sensitive and therefore functions as a 1-D position sensitive detector. The charge is proportionally

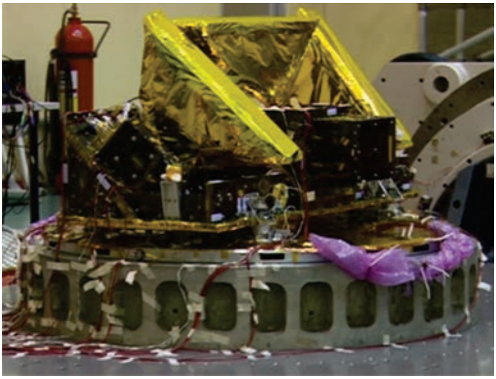


Fig.7.8: View of SSM

divided to the two ends of the anode wire and therefore provides an estimate of where the incident X-ray created the charge cloud. The position resolution along the wire is 0.7 mm at 6 keV. The top part of each of the three SSM instruments consists of different coded aperture mask (CAM) patterns which forms the imaging element, which is joined sideway and the image of the shadow casted by the mask is deconvolved (same as for CZTI) using software application to find the location of the source in the sky. The angular resolution of SSM is ~ 12 arcmin (1° = 60 arcmin) in the coding direction and across is ~ 2.5°. The geometric area is 57.6 cm^2 per SSM unit and total mass is 75.5 kg.

This payload is developed by ISRO Satellite Centre (ISAC), Bangalore and IUCAA.

7.6 Charged Particle Monitor (CPM)

Fig.7.9: View of CPM

CPM is a Scintillator Photodiode Detector (SPD) with a Charge Sensitive Preamplifier for detecting charged particles. Even though the orbital inclination of the satellite is 6 degree, in about 2/3rd of the orbits the satellite will spend a considerable time (15 - 20 minutes) in the South Atlantic Anomaly

(SAA) region which has high fluxes of low energy protons and electrons. The high voltage will be lowered or put off using data from CPM when the satellite enters the SAA region to prevent damage to the detectors as well as to minimize ageing effect in the Proportional Counters. The mass of the payload is about 2 kg. This instrument is developed by Tata Institute of Fundamental Research (TIFR), Mumbai.

8.0 Science Objectives and Capabilities of ASTROSAT payloads

The **UVIT** is a remarkable telescope with a unique advantage compared to previous ultraviolet telescopes. Though far smaller than the HST, the UVIT has a field of view which is about 80 times larger. UVIT is one of the best UV telescope with very good position resolution (~1.8 arcsec) and large FOV, in both FUV and NUV bands. Also, though GALEX had a larger field of view, UVIT's better resolution of 1.8 arcseconds compared to 5 arcseconds for GALEX is expected to be a game changer. Hence UVIT's strength is in deep field study and imaging objects in the Milky Way and nearby galaxies.

The frequency, and hence the energy, of ultraviolet photons is higher than that of visible photons. Hence, ultraviolet photons are emitted by celestial objects that are much hotter than those that are bright in the visible range. In fact, we need objects that are tens of thousands of Kelvin to see them prominently in the ultraviolet. Of course, since X-ray photons have even higher frequencies, they are emitted by even more extreme objects which are millions of Kelvin in temperature! (Often X-rays are emitted also by processes such as black body emission, a brief mention of which is given in the following pages).

For this reason, the ultraviolet sky is much less crowded than the visible sky. Stars like our Sun, radiating at a relatively cool 6000 K, are not very prominent. So what would we see if we have ultraviolet eyes? Objects like massive young stars, white dwarfs and exotic binary star systems, and spectral lines from heavier atoms dominate the ultraviolet sky, and these are what the UVIT will mainly focus on.

The heavier the star is, the hotter it is. Young massive stars are very bright in the ultraviolet and the UVIT is expected to identify them and study their properties. Stars like our sun too get their turn at being hot enough to shine bright in the ultraviolet. At the end of their lifetime, when the fuel for nuclear fusion has run out and the outer layers are thrown outwards, the core shines bright as a hot white dwarf. UVIT is an excellent instrument to measure the properties of the white dwarfs which have already been formed by the evolution of slightly more massive stars than the Sun.

Emission throughout the entire ultraviolet band arises in these hot objects described above. However, strong spectral lines are also emitted in the ultraviolet band at specific wavelengths by heavy atoms like carbon, oxygen, etc in their ionised states. The dispersion grating in the UVIT can be used to study these spectral lines albeit with a moderate resolution, from objects like HII regions (gas nebulae heated by massive young stars) and planetary nebulae (gas nebulae produced by the outer layers of massive stars that are thrown outwards).

Stars like our sun are born alone. However, many stars are born in groups of a few to a few thousand. Globular Clusters, though, are gravitationally bound clusters of hundreds of thousands of stars packed into a region smaller than about 30 light years, and orbiting the galaxy as a group. At the centre of a globular cluster, the density of stars is so high that there are many near-collisions and even mergers between the stars ! These close encounters lead to the formation of many exotic stars, like the Blue Stragglers and

Low Mass X-ray Binaries (LMXBs, a system of two stars orbiting each other, one of which is a compact star formed from a massive star and the other is a low mass star which feeds matter to the compact companion). These stars are hot and hence ultraviolet-bright, and in addition, most of the normal stars in globular clusters are very faint in the ultraviolet. Hence, UVIT will be able to discover many such unusual stars in globular clusters in our galaxy.

Peculiar double star systems like LMXBs are highly variable in X-rays. This variability gives us important clues about how the compact star (that could be a neutron star or a black hole) pulling in matter from its companion star. Studying how the ultraviolet emission varies at the same time as the X-ray variability is an important tool to understand the physics of these objects. This ability is, of course, the main strength of ASTROSAT.

UVIT is expected to image many nearby galaxies in great detail, mainly studying regions of extremely recent star formation. It can also measure the ongoing rate of star formation in many other galaxies farther away. In addition to all this, UVIT will also undertake a survey of a large part of the ultraviolet sky. This will be first survey ever done at these wavelengths at a resolution comparable to the ground-based surveys in the visible. History has taught us that large sky surveys always throw up new and interesting surprises. Let us wait and see what the UVIT will tell us!

The various X-ray instruments aboard the ASTROSAT together cover an energy range of 0.3-100 keV. These different instruments are designed such that there is a significant overlap in energy range among them. This allows us to understand the X-ray spectrum (mostly continuum) in the energy range 0.3-100 keV where different part of the spectrum are dominated by different physical processes. For example, the soft X-ray part (0.3 - 8 keV) is mostly dominated by fluorescent emission lines from highly ionized heavy nuclei such as Iron, Silica, Sulphur, Calcium, Argon etc on the top of a black body continuum whereas high energy part (hard X-ray ~ 15-100 keV) is mostly power-law type due to inverse Comptonization (photon can gain energy due to scattering with high energy electrons) of low energy photons. The temperature of the sources emitting in such a high energy must correspond to 10^6-10^9 Kelvin. Also these sources are very bright in X-ray (e.g.: for the Sun, the X-ray photon flux is a billion times less than its optical photon flux, whereas for Crab nebula this ratio is only hundred). In this booklet, we highlight some important aspects of such sources and how different X-ray instruments on ASTROSAT are going to reveal those science issues.

SXT covers a very important energy range of the broad spectrum to be observed with ASTROSAT, and will be able to investigate some very intriguing scientific problems. Various astrophysical sources are known to emit or reflect X-rays. These range in scales from the humungous galaxy clusters to supermassive black holes in active galactic nuclei (AGN) to small, dense objects in our own galaxy such as supernova remnants, stars, and binary stars containing a white dwarf, a neutron star or a black hole. SXT has a good sensitivity combined with very good spectral resolution and arc-minute imaging capability in X-rays. This will help in the separation of confusing multiple sources as well as spatially resolved spectroscopy and time variability studies of X-ray emitters. Some specific studies planned are mentioned below.

Highly ionised Silicon, Sulfur, Argon, Calcium and Iron can be found in hot, thermal coronal plasmas. SXT will be able to resolve the K-line spectral emission from these. It will also have the capacity to resolve fluorescent line emission in media that are photo-ionized by strong X-ray continuum in X-ray sources that are powered by accretion of matter onto dense bodies viz. neutron stars, stellar mass black-holes, super-massive black-holes etc.

SXT will also carry out spectroscopy of hot plasmas that are a big source of X-rays. Properties of hot thin plasmas in galaxies, clusters of galaxies, nuclei of active galaxies, quasars, supernova remnants and stellar coronae can be studied with better resolution spectroscopy with SXT. Carrying out spatially resolved spectroscopy of supernova remnants and clusters of galaxies is also possible with the very fine resolution of SXT.

While studying the physics of astrophysical shock wave fronts and accretion disks, coronae, photo-ionized regions etc., SXT observations can provide better information about their density, temperature, ionization degree, and elemental abundance.

X-rays also get absorbed by various media lying between the source and observer. A study of low energy absorption and the nature of absorbers with SXT will reveal details, like whether the medium is cold (neutral) or warm (ionized).

Astronomers can use the unprecedented combination of SXT with other sensitive hard X-ray detectors for carrying out simultaneous, wide-band spectral studies and obtaining time-resolved spectra of thermal as well as non-thermal plasmas in the universe. Special studies of soft X-ray excesses, due to a blackbody emission in AGNs and in binary X-ray pulsars, can also be taken up in conjunction with other higher energy X-ray instruments on board the ASTROSAT.

LAXPC is capable of detecting continuum emission in the energy range 3-80 keV with a energy resolution that is moderate compared to the SXT. Nevertheless, this is a very sensitive detector because of its large collecting area and it also has very good time resolution (of roughly 10 microsecond). Hence, this is a perfect instrument to detect very faint X-ray sources as well as carry out time variability studies. This can be done by repeated surveys wherein the change in the luminosity of various sources is measured repeatedly at various time intervals. These type of studies can reveal the existence of stellar-mass (3-20 solar mass) as well as super massive (10^6 - 10^9 solar mass) black hole candidates in our galaxy and neighbouring galaxies. The LAXPC is also expected to yield new discoveries about the nature of X-ray binaries, supernova remnants, Active Galactic Nuclei (galaxies with a central region very bright in X-ray powered by a super massive black hole) etc. We can determine the density and temperature of the X-ray emitting plasma from the nature of the continuum spectra measured by the LAXPC.

The fantastic time resolution of LAXPC will be very useful in studying a whole host of time variable phenomena associated with X-ray pulsars (rotating neutron stars), X-ray binaries, AGNs etc. There can be periodic variability as well as non-periodic in nature. Examples of periodic variability include pulsations, quasi-periodic oscillations or QPOs and binary light curves. Non-periodic variability can take the form of outburst activity, flaring activity etc.

Neutron stars are known to have very strong magnetic field (~ 10^{10} Gauss, compared to the Earth's magnetic field of just 0.5 Gauss!) and X-ray pulsars show characteristic cyclotron lines in the energy range 15-60 keV. Measurement of the strength of the magnetic field in X-ray pulsars is possible by detecting and studying the cyclotron lines using LAXPC.

The hard X-ray instrument, **CZTI** has a significant overlap in energy range with LAXPC but it can detect photons with good efficiency extending upto 100 keV. This is a solid state detector and made mainly to extend the energy range and for spectral study for fields with no source confusion. This instrument also can detect continuum X-ray emission from X-ray binaries, Pulsars, AGNs etc. and can reveal the physical processes behind the characteristic continuum emission. Also the continuum X-ray spectrum sometime shows an exponential decrease (high energy cut-off) of flux depending on the temperature of the thermal plasma. This instrument has good energy resolution to detect the high energy cut-off in the observed continuum spectrum.

This instrument will also study the behavior of Quasi Periodic Oscillations (QPOs) produced in hard X-rays which arise from close to the compact objects in X-ray binaries. A combined study of the spectral behavior and time evolution of the QPOs can provide new insight into X-ray binary studies. CZTI is capable of detecting cyclotron lines from pulsars and the characteristic hard X-ray emission from the magnetars (non rotating neutron stars with magnetic field stronger than pulsars).

The X-ray photons of energy < 100 keV can enter into CZTI only through a field of view 4.6°×4.6° because the collimator material of CZTI is opaque to X-ray photons of energy <100 keV. But the collimator as well as CAM is progressively transparent to photons of energy >100 keV. Hence CZTI behaves like an open detector (large field of view as if collimator does not exist) for photon energy >100 keV and has a good potential to detect Gamma Ray Bursts (GRBs: Exotic event which emit radiation in hard X-ray to gamma ray in a very short time scale ~ seconds) occurring anywhere in the large part of the sky and study the light curves of GRBs early emission called prompt emission.

The polarization measurement of X-ray photons is another challenging area of research in X-ray astronomy. In case of accretion around compact objects, X-ray photons are produced close to compact object and a polarization measurement of X-ray photons gives informations about the inclination of the inner accretion disc and intrinsic spin of the black holes in compact binary systems. CZTI has the capability of measuring the polarization of hard X-ray photon of energy >100 keV but the sensitivity is limited only to the bright sources.

Many of the X-ray binaries harboring a black hole, remain below detection level (quiescent state) for most of the time. When they brighten, they are referred as 'outbursting' (since they suddenly become very bright - sometimes brighter than the brightest X-ray objects in the sky - and they can be studied in detail in this phase. They remain in this otbursting state for few months only. These sources are therefore referred to as X-ray transients. In order to study these sources, it is necessary therefore to detect them as early as possible in the outbursting phase. The **SSM** in meant to keep scanning the sky to locate when the sources go into this state. SSM will then provide an alert which can be followed by any of the observatories in the world. ASTROSAT can be pointed to view this source in detail.

9.0 Expected science details from ASTROSAT

Among the many diverse ground-based and space-based observatories that exist around the world today, ASTROSAT has a very unique niche. This satellite can simultaneously cover an unprecedented large range in energy (or wavelength), from the optical and ultraviolet around 550 nm right upto hard X-rays at 100 keV, with large collecting areas. This will allow us to perform simultaneous broad-band astronomical observations of various classes of objects that are not yet well understood.

In systems powered by accretion onto compact objects like white dwarfs, neutron stars and black holes (e.g. AGNs, X-ray binaries, etc.), the higher energy X-rays are produced much closer to the compact objects than optical or UV photons. Hence multi-wavelength studies can reveal, the properties of emission coming from far out in the system where accretion begins, to very close to the compact objects. The relative brightness, spectral characteristic and variability of the same object in different wave bands can provide information about the cause of emission and how it gets modified or triggers other emissions within the overall

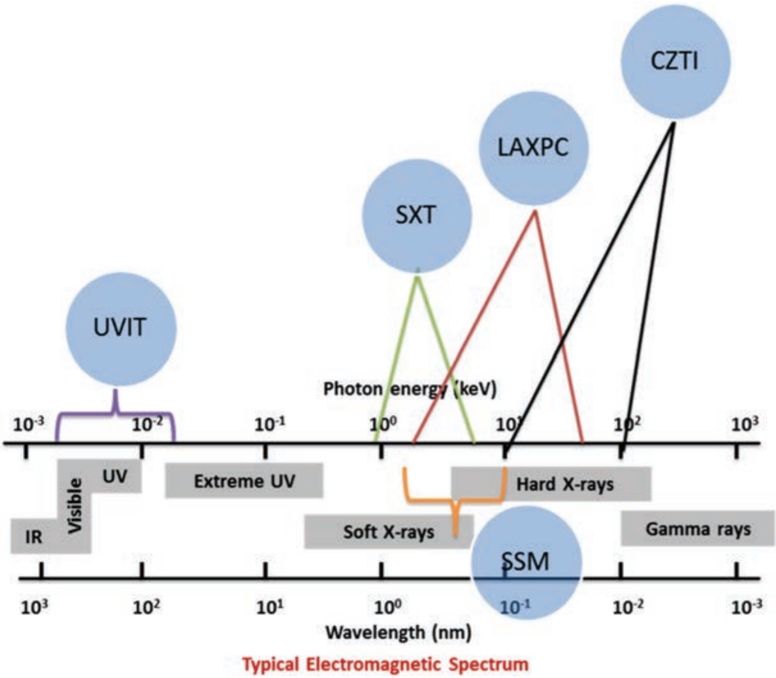


Fig.9.1: ASTROSAT payloads' wavelength coverage

environment around the compact object. Emission in different wavebands occur due to different physical processes arising under differing physical conditions and hence multi-wavelength observations are essential to understand the various physical mechanisms that produce these radiations.

Multi-wavelength studies among different instruments on ASTROSAT can be made in many different modes depending on the specific science case.

Temporal observations (intensity variations with time) can be used to study features in intensities (like bursts) and how the time of occurrences of these features change with wavelength.

Whichever wavelength leads is more likely to be the cause of the feature and the observation of these features in other wavelengths which lag, may be due to re-emission in these wavelengths.

The simultaneous broadband radiation spectra for persistent sources (active always /most of the time) like X-ray binaries, microquasars, AGNs etc. can be studied using all instruments on ASTROSAT, subject to possibility due to observational constraints. A broadband spectrum reveals the change in spectral characteristic, brightness among different bands. The simultaneous observations reveal the time lag among different waveband, say time lag between optical-UV, UV-X-ray, optical-X-ray etc, and this is important to understand the time evolution of the source. Time lags can also be observed within X-ray band between low energy and high energy X-rays.

SXT, LAXPC and CZTI have overlapping energy ranges which allow observing target sources over the broad energy range of 0.3-100keV. SXT and LAXPC will allow frequency resolved and time resolved spectroscopy (never been done before). Time resolved spectroscopy can help in understanding variation in some features as a function of time / orbital period of the system. Broad band spectra can provide spectral energy distribution (SED) and its variation over time.

Fig. 9.2 highlights the variation in flux across different energy ranges, and hence the need to cover a wide energy range. The reader can cover portions of the wavelength band and realise that we have very minute information in one waveband.

While most of the X-ray and UV coverage will be using ASTROSAT, co-ordination with ground based observatories is essential for obtaining the types of observations indicated above. Studies on emission of jets and their correlation with high energy

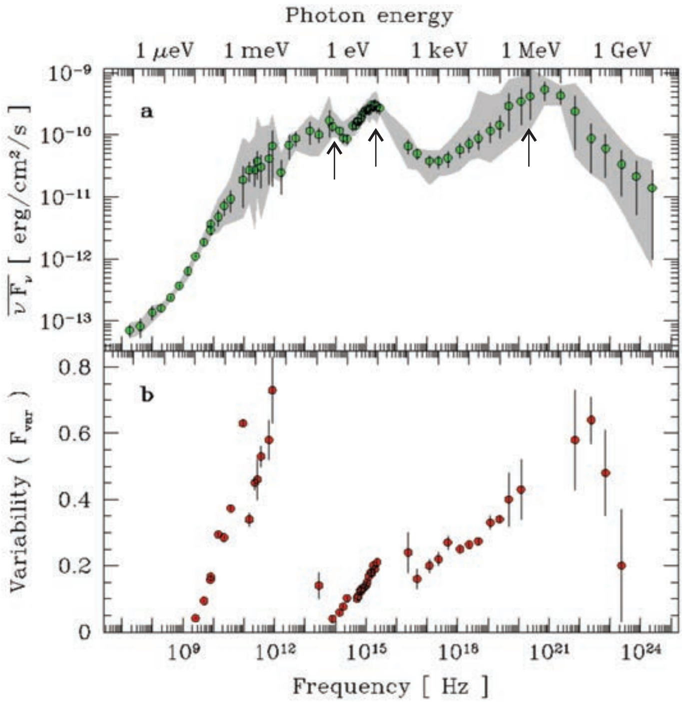


Fig.9.2: Top panel: Average spectral energy distribution of 3C 273 from radio to gamma-rays (points), spanning from 4 to 44 years of observations depending on the wavelength. The error bars are calculated as the standard deviation from the mean values and the grey area represents the observed range of variations. (Ref: Soldi S., Türler M., Paltani S., et al., 2008, A&A, 486).

The grey portions are the range of variation in the particular spectral band. This indicates that the features in the average spectrum of 3C 273 remain fairly stable over time. The hump in optical-UV is the UV hump displayed by many AGNs, the IR showing the synchrotron peak and the high energy showing the Compton peak.

Bottom panel: Fractional Variability of the same AGN (3C273) from radio to gamma rays. Fractional-variability, Fvar , spectrum of 3C 273 from radio to gamma-rays, after removal of flares in the infrared band. The above figure is derived from the variability observed in light curves.

emission in X-rays has been done by co-ordinated observations between satellites and ground based observatories.

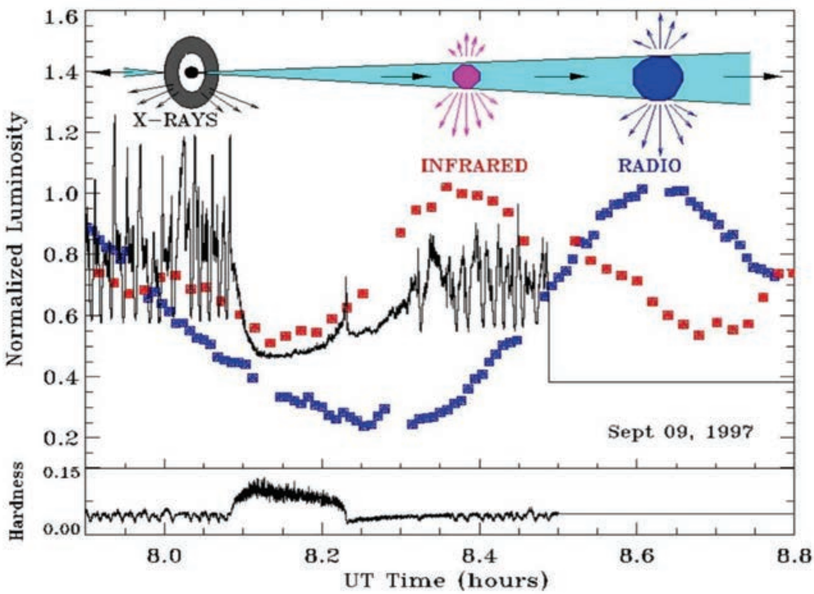


Fig.9.3: The intensity variation observed in X-rays, IR and Radio bands around the time of emission of the jet for microquasar GRS 1915+105. Time lags in different bands are observed.

These are light curves at the time of the infrared flare detected on Sep 9, 1997. The infrared flare starts during the recovery from the X-ray dip, when an X-ray spike was observed. These observations show the connection between the rapid disappearance and follow up replenishment of the inner accretion disk seen in the X-rays, and the ejection of relativistic plasma clouds observed as synchrotron emission at infrared and radio wavelengths. The emission regions in different waveband are also shown at the top of the figure. The hardness ratio (13–60 keV) / (2–13 keV) is shown at the bottom. (Ref: Mirabel I. F., Dhawan V., Chaty S. et al., 1998, A&A, 330, L9)

Thus ASTROSAT when combined with data from many other space based (like NuSTAR, Suzaku) as well as ground based observatories existing nationally (Like the Giant Meter Radio Telescope at Khodad near Pune, the 3.6 m optical telescope at Devasthal near Nainital, the 2 m optical-infrared telescope at Hanle near Leh etc) and internationally (10 m Keck telescope, Hawaii, USA, 8.2 m VLT at Chile, VLA at USA etc) is expected to provide scientific results which can alter the way we understand the target sources.

10.0 ASTROSAT Summary

Mission Objective	To design, develop and realize a space astronomy mission to study the celestial sources in X-ray, optical and UV spectral bands simultaneously.
Scientific Objectives	The science objectives are to understand high energy processes in binary systems, search for black hole sources in the Galaxy, measure magnetic fields of neutron stars, study high energy processes in extragalactic systems, detect new transient X-ray sources and do limited deep field survey in UV.
Scientific Payloads & wavelength coverage	◆ Ultra Violet Imaging telescope (UVIT), FUV (130-180 nm), NUV (200-300 nm), Visible (320-550 nm) ◆ Soft X-ray Telescope (SXT) ; 0.3 to 8 keV.

	◆ Large Area X-ray Proportional Counters (LAXPCs) ; 3-80 keV band ◆ Cadmium Zinc Telluride Imager (CZTI) ; 10-100 keV. ◆ Scanning Sky Monitor (SSM) ; 2.5-10 keV ◆ Charge Particle Monitor (CPM); an ancillary payload
Payload Mass	855 kg
Space craft	Cuboid shape, 1.96m x 1.75m x 1.30m
Spacecraft Mass	~ 1515 kg
Launch Vehicle	Polar Satellite Launch Vehicle - PSLV-C30 (XL)
Orbit	650 km near-equatorial orbit with 6 degree inclination
Mission life	Minimum five years
Communication System (Telemetry, Tracking, Command, payload data reception)	11-m Antenna
Mission Operations Complex, Bangalore	Responsible for all spacecraft operations and data reception
Indian Space Science Data Centre (ISSDC), Bylalu	Acts as a repository of scientific data obtained from payloads onboard ASTROSAT

Reference & Credit to the figures

2.1. Wikimedia

2.2. Cal Poly Pomona University; https://www.cpp.edu/

2.3. www.amusingplanet.com

2.4. www.passmyexams.co.uk

2.5. Encyclopædia Britannica, Inc.

2.6. Wikispaces

2.7. Wikimedia

2.8. www.wordpress.com

2.9. Wikimedia

2.10. GOES-15 Solar X-ray Imager (SXI), NASA/NOAA/ Lockheed Martin

2.11. www.windows2universe.org

2.12. ROSAT; http://www.mpe.mpg.de/

2.13. Wikimedia

2.14. http://www.aviso.altimetry.fr/

Spacecraft, Launch vehicle, payload and related figures: ASTROSAT Project team, ISAC and payload managers / teams.

Useful links

www.isro.gov.in

http://astrosat.iucaa.in

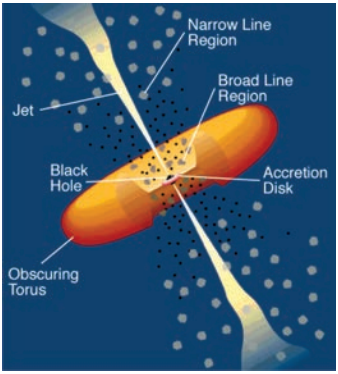
http://www.issdc.gov.in/astro.html

Acronyms & Expansion

CMOS	Complementary metal–oxide–semiconductor
CAM	Coded Aperture Mask
CORONAS	Complex Orbital Observations Near-Earth of Activity of the Sun
CZTI	Cadmium-Zinc-Telluride Imager
CPM	Charged Particle Monitor
GRB	Gamma Ray Burst
GSAT-2	Geostationary Satellite – 2
GOES SXI	Geostationary Operational Environmental Satellite - Solar X-ray Imager
HST	Hubble Space Telescope
IXAE	Indian X-ray Astronomy Experiment
IRS-P3	Indian Remote Sensing satellite – P3
LAXPC	Large Area X-ray Proportional Counter
PSLV	Polar Satellite Launch Vehicle
QPOs	Quasi Periodic Oscillations
ROSAT	Röntgen Satellite
RASS-II	ROSAT All Sky Survey
RXTE	Rossi X-ray Timing Explorer
RT-2	Roentgen Telescope – 2
SROSS	Stretched Rohini Satellite Series
SoXS	Solar X-ray Spectrometer
SXT	Soft X-ray Telescope
SSM	Scanning Sky Monitor
TT&C	Tracking, Telemetry and Command
UVIT	Ultraviolet Imaging Telescope
XMM	X-ray Multi-Mirror Mission

Definitions

Active Galactic Nuclei (AGN): Galaxies with a central region very bright in X-ray powered by a supermassive black hole.



Model of an AGN (Credit: C.M. Urry and P. Padovani)

Accretion: Accumulation of dust and gas in to larger bodies.

Accretion disk: A disk of gas which accumulates around a centre of gravitational attraction, such as a white dwarf, neutron star, or black hole. As the gas spirals in, it becomes hot and emits light or even X-ray radiation.

Afterglows: The fading fireball of a gamma ray burst. After an initial explosion, an expanding GRB slows and sweeps up surrounding material, generating the glow which is visible for several weeks or months. The afterglow is extremely faint, making it difficult to locate and study.

Black hole binaries: A system of two stars orbiting around a common center of mass that are bound together by their mutual gravitational attraction. An black hole binary is where one of the stars is a black hole, and the separation between the stars is small enough so that matter is transferred from the normal star to the compact star, producing X-rays in the process.

Blue Stragglers: Blue stragglers (BSS) are main-sequence stars in open or globular clusters that are more luminous and bluer than stars at the main-sequence turn-off point for the cluster.

Collimator: A collimator is a device that narrows a beam of particles or waves. To "narrow" can mean either to cause the directions of motion to become more aligned in a specific direction (i.e., make collimated light or parallel rays), or to cause the spatial cross section of the beam to become smaller (beam limiting device).

Compact star: Compact star (sometimes compact object) is used to refer collectively to white dwarfs, neutron stars, other exotic dense stars, and black holes.

Cyclotron radiation: Electromagnetic radiation emitted by moving charged particles deflected by a magnetic field. The force on the particles acts perpendicular to both the magnetic field lines and the particles' motion through them, creating an acceleration of charged particles that causes them to emit radiation as a result of the acceleration they undergo as they spiral around the lines of the magnetic field.

Dark energy: Dark energy is an unknown form of energy which is hypothesized to permeate all of space, tending to accelerate the expansion of the universe.

Deep fields: A Deep Field is an image of a small region of space.

Elemental lines: Emission line for individual element like silicon, sulphur, iron etc.

Field of view (FOV): A telescope's viewing area, measured in degrees, arc minutes or arc seconds. A telescope that can just fit the full moon into its complete viewing area has a field of view of roughly 30 arc minutes.

Gamma-ray Burst (GRB): A brief, intense and powerful burst of gamma rays, the highest-energy, shortest-wavelength radiation in the electromagnetic spectrum. These bursts emanate from distant sources outside our galaxy and last only a few seconds. They are the brightest and most energetic explosions known.

Grazing angle of incidence: When dealing with a beam that is nearly parallel to a surface, it is sometimes more useful to refer to the angle between the beam and the surface, rather than that between the beam and the surface normal, in other words 90° minus the angle of incidence. This small angle is called grazing angle. Incidence at grazing angles is called "grazing incidence".

Gyroscopes: A gyroscope is a spinning wheel or disc in which the axis of rotation is free to assume any orientation. When rotating, the orientation of this axis is unaffected by tilting or rotation of the mounting, according to the conservation of angular momentum.

Hot plasma: Hot plasma is one which approaches a state of local thermodynamic equilibrium (LTE). A hot plasma is also called a thermal plasma, in order to distinguish it from a thermonuclear fusion plasma. Such plasmas can be produced by atmospheric arcs, sparks and flames.

Hard and soft X-rays: X-rays with photon energies above 5–10 keV (below 0.2–0.1 nm wavelength) are called hard X-rays, while those with lower energy are called soft X-rays.

HII regions: HII regions are emission nebulae created when young, massive stars ionise nearby gas clouds with high-energy UV radiation. They are composed primarily of hydrogen, hence the name (the term HII to refer to ionised hydrogen, HI for neutral hydrogen), and have temperatures of around 10,000 Kelvin. They can extend over several hundred light years or be so compact that they do not even stretch 1 light year across. Correspondingly they have a large range of densities, from a few atoms/cm3, to millions of atoms/cm3 for the most compact regions.

Inverse Comptonization: Photon can gain energy due to scattering with high energy electrons.

LMXB: A low-mass X-ray binary (LMXB) is a binary star where one of the components is either a black hole or neutron star. The other, donor, component usually fills its Roche lobe and therefore transfers mass to the compact star. The donor is less massive than the compact object, and can be on the main sequence, a degenerate dwarf (white dwarf), or an evolved star (red giant).

Luminosity: The amount of energy radiated into space every second by a celestial object, such as a star. It is closely related to the absolute brightness of a celestial object.

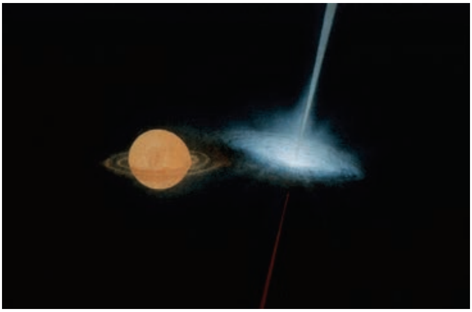
Lyman-alpha line: The Lyman-alpha spectral line has a wavelength of 1216 Å, which is in the ultraviolet portion of the electromagnetic spectrum. The Lyman-alpha absorption lines in the quasar spectra result from intergalactic gas through which the galaxy or quasar's light has travelled.

Mass accretion: Accumulation of dust and gas into a massive object by gravitational attraction, typically gaseous matter in an accretion disc.

Magnetometer: Magnetometers are measurement instruments used for two general purposes: to measure the magnetization of a magnetic material like a ferromagnet, or to measure the strength and, in some cases, the direction of the magnetic field at a point in space.

Magnetar: A magnetar is a type of neutron star with an extremely powerful magnetic field. The magnetic field decay powers the emission of high-energy electromagnetic radiation, particularly X-rays and gamma rays.

Micro-quasars: X-ray binaries with strong radio jets but luminosity is much smaller than quasars



Artist's rendition of a micro-quasar (Source: Wikipedia)

Neutron Star: A Neutron star is the core remnant left over after a supernova explosion. The core of the star collapses, and crushes together every proton with a corresponding electron turning each electron-proton pair into a neutron. The neutrons, however, can often stop the collapse and remain as a neutron star. Neutron stars are extremely dense, they are only 10 km or so in size, but have the mass of an average star (usually about 1.5 times more massive than our Sun). A neutron star that regularly emits pulses of radiation is known as a pulsar.

Quasi-stellar radio sources (Quasars): These are AGNs which have jets very bright in radio wave

Artist's rendition of a Quasar (Source: http://www.astro.caltech.edu/)

Pointing accuracy: Pointing accuracy is a measure of the difference between the intended and actual positions when pointing a spacecraft at a desired target.

Polarization: A property of waves that can oscillate with more than one orientation. Electromagnetic waves such as light exhibit polarization, as do some other types of wave, such as gravitational waves.

Photo-ionized region: Interaction between a photon, from a nearby star say, and a molecule or atom, may lead to dissociation of the molecular bond, and/or ionisation of the atom. And so the process of molecule formation, which makes a cloud cool, get denser, and eventually form stars, can be completely reversed when the newly born star starts to ionise and heat its surroundings.

Reaction wheels: A reaction wheel is a type of flywheel used primarily by spacecraft for attitude control. They are particularly useful when the spacecraft must be rotated by very small amounts, such as keeping a telescope pointed at a star.

Ritchey-Chretien: A Ritchey–Chrétien telescope (or simply RC) is a specialized Cassegrain telescope invented in the early 20th century that has a hyperbolic primary mirror and a hyperbolic secondary mirror designed to eliminate optical errors. They have large field of view free of optical errors compared to a more conventional reflecting telescope configuration.

Shock wave: A shock wave is a type of propagating disturbance. When a wave moves faster than the speed of sound in a liquid, gas or plasma (a fluid, in physics terminology) it is a shock wave. Like an ordinary wave, a shock wave carries energy, and can propagate through a medium. It is characterized by an abrupt, nearly discontinuous change in pressure, temperature and density of the medium.

Stellar Coronae: The outermost layer of the atmosphere of a star, including the Sun.

Solid state detector: Solid-state detector is also called Semiconductor Radiation Detector, radiation detector in which a semiconductor material such as a silicon or germanium crystal constitutes the detecting medium.

Supernovae: The explosion of a star, which is one of the most energetic explosive events. These occur at the end of a star's lifetime, when its nuclear fuel is exhausted and it is no longer supported by the release of nuclear energy. If the star is particularly massive, then its core will collapse and will release a huge amount of energy. This will cause a blast wave that ejects the star's envelope into interstellar space. The result of the collapse may be, in some cases, a rapidly rotating neutron star that can be observed many years later as a radio pulsar.

Stowed and deployed view: View of the spacecraft with solar panels folded to its sides and opened up.

Sun sensor: A sun sensor is a navigational instrument used by spacecraft to detect the sun's position.

Spatial resolution: The measure of how closely lines can be resolved in an image is called spatial resolution, and it depends on properties of the system creating the image, not just the pixel resolution in pixels per inch (ppi).

Spin in black holes: Astronomers usually measure the angular momentum of black holes in the units of their mass. Such measure is called spin and it can have value from zero (for a non-rotating black hole) to one.

Synchrotron emission: A type of non-thermal radiation generated by charged particles (usually electrons) spiralling around magnetic field lines at close to the speed of light. Since the electrons are always changing direction, they are in effect accelerating and emitting photons with frequencies determined by the speed of the electron at that instant.

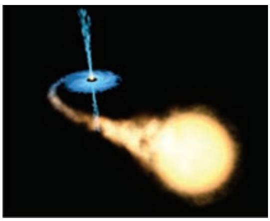
Temporal and Spectral properties: The properties of a cosmic object which vary with respect to time are called temporal and the properties at different energies (or, equivalently, wavelengths or frequencies) are called spectral properties.

Torr: Torr is a unit of pressure based on an absolute scale, now defined as exactly 1/760 of a standard atmosphere. Thus one torr is ~133.3 Pa.

White dwarf: A whitish star of high surface temperature and low intrinsic brightness with a mass approximately equal to that of a Sun but with a density many times larger. The remnant of a star, at the end of its life, consisting of a carbon and oxygen core supported by electron degeneracy pressure. The surface has a very high temperature and radiates mainly in the ultraviolet, but it is only about the size of the Earth (hence dwarf).

X-ray sky and X-ray Sun: The sky and the Sun as observed in X-ray wavelength.

X-ray binary System: A binary system in which one of the objects is a white dwarf/neutron star/black hole and it forms an accretion disc by gravitationally attracting materials from the companion. The accretion disc is very hot and emits X-rays.



Artist's rendition of a black hole with an orbiting companion star (Source:Wikimedia Commons)

X-ray transients: Objects show sudden increase in X-ray brightness over a small time scale. These objects are seen in our galaxy as well as in other galaxies.

Wavelength

Optical & UV light has its characteristic measured in wavelength i.e. units of length. Astronomers however describe energetic light like X-rays, Gamma-rays, which have very short wavelengths (below 1 angstrom) in terms of their energy. We must remember that the shorter the wavelength, the higher the energy of the photon (as well as of the source that produces it). However, a photon essentially carries very little energy and even for very energetic photons, an unit like the joule proves very large and cumbersome. Hence a unit called the electron-volt (eV) becomes useful. This has a value of 1 eV = 1.602×10^{-19} Joules and is close to the equivalent wavelength of 1.24×10^{-6} meter. This is quite suitable to use for describing high energy photons, which have energies above a kilo eV. Since this kind of light can cause ionisations or is emitted from hot, ionised media, the unit easily indicates what known ions and ionisation can be invoked when talking about a particular high energy photon and its source. ASTROSAT instruments will essentially cover a range of X-rays from 0.3 to 100 keV.

Of course it is easy to find the corresponding wavelength by using the natural relation of $E = hc/\lambda$. (E - energy of photon, h - Planck constant, c - speed of light and λ - wavelength of light)

Type of radiation	Wavelength	Frequency (Hz)	Photon Energy (eV)
Gamma ray	< 0.01 nm	> 3×10^{19}	100×10^{3} eV – 300×10^{9} eV
X- ray	0.01-10nm	$3\text{x}10^{17}$-$3\text{x}10^{19}$	120 eV – 120×10^{3} eV
Ultraviolet	10nm-400nm	$7.5\text{x}10^{14}$-$3\text{x}10^{17}$	3 eV – 124 eV
Visible	390nm-750nm	$4.3\text{x}10^{14}$-$7.5\text{x}10^{14}$	1.7 eV – 3.3 eV
Infrared	750nm-1 mm	$3\text{x}10^{12}$-$4.3\text{ x}10^{14}$	$1.24\text{x}10^{-3}$ eV- 1.7 eV
Microwave	1mm-1 meter	$3\text{x}10^{9}$-$3\text{x}10^{12}$	$1.24\text{x}10^{-6}$ eV- $1.24\text{x}10^{-3}$ eV
Radio	1 mm-km	$<3\times10^{9}$	$1.24\text{x}10^{-9}$ eV- $1.24\text{x}10^{-3}$ eV

Frequency, Wavelength and Energy of the electromagnetic spectrum (Source: Tutorvista and csep10.phys.utk.edu)

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