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ASTROSAT: status and science

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Abstract. Indian Astronomy satellite, code named ASTROSAT is designed to carry out multiwavelength studies of a variety of galactic and extragalactic sources from ultraviolet band (1000-3000 Å) to soft and hard X-ray bands in the range 0.3 to 100 keV. Five different payloads presently under development will achieve the above mission targets.

Keywords : X-ray astronomy – space vehicles: instruments – balloons – history of astronomy

1. Introduction

Since the discovery of the first extra-solar X-ray source Sco X-1 in 1962, growth in X-ray astronomy has been phenomenal. X-rays from a variety of stellar objects and galactic binary sources, quasars, high red-shift galaxies and clusters of galaxies have been observed. The first complete sky survey using an imaging telescope was made by the ROSAT satellite in 0.1-2.4 keV band and a catalog of almost 150,000 X-ray sources has become available. A key feature of the majority of the X-ray sources is their pronounced variability both in their luminosity and the spectral features. From the temporal and spectral studies of different varieties of sources, a host of new discoveries have emerged which include, the millisecond X-ray pulsars, black hole candidates, X-ray transients, quasi-periodic oscillations, cyclotron line emission, Compton tails, superluminal X-ray sources etc. The discovery of asymmetric 6.4 keV iron fluorescence line from Seyfert galaxies have provided most compelling evidence for the existence of massive accreting black holes in the nuclei of AGNs.

Similarly there are several other new phenomena which still need to be explored by further observations, for example, in a majority of galactic binary X-ray sources, a spinning neutron star is surrounded by an accretion disk. In about 90 binaries there

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is evidence for an X-ray pulsar which produces X-ray pulsations with periods in the range of a few ms to 600s, while in about 25 objects the X-ray source is believed to be an accreting black hole. A class of binaries known as low-mass X-ray binaries (LMXBs) have low magnetic field ($< 10^{11}$ Gauss) and also do not show X-ray pulsations. Their orbital periods are in 1-10 hour range and they show X-ray eclipses and irregular dips in the light curves and exhibit irregular flickering and flaring activity on a variety of time scales. On the other hand, high-mass X-ray binaries (HMXBs) have strong magnetic field (10^{12} to 10^{13} Gauss) and usually show X-ray pulsations. The low mass X-ray binaries, SNRs, X-ray pulsars and a large majority of the extragalactic X-ray sources indicate a hard X-ray spectrum extending to few 10's of keV and even in MeV region in some cases. However, these features show a strong temporal behaviour which needs to be investigated. Similarly, the cyclotron absorption lines, whose energy is a measure of the magnetic field of the neutron star, have only been observed in a few sources. Besides, a large number of these X-ray sources have been identified with optical counterparts. In spite of 50 years of experimentation, there remain a large number of open questions which need to be answered by future experiments. Therefore, the key objective planned for the ASTROSAT mission is the simultaneous observations in UV, optical and extended X-ray energy band of 0.3 to 100 keV.

2. Scientific objectives

ASTROSAT is an IRS class satellite which will carry five major scientific payloads in a circular orbit of about 600-800 km. An artist's sketch of the bus with the location of the various payloads on the deck plate is shown in the Fig. 1. The payloads are selected to achieve a variety of scientific objectives namely;

- Broad band X-ray spectroscopic studies from 0.3-100 keV for X-ray binaries, supernova remnants, cataclysmic variables (CVs), stellar coronae, AGNs etc. with an energy resolution $E/\Delta E \sim$30, in the 0.3 to 8 keV region, $E/\Delta E \sim$6-8 in 3-100 keV band with proportional counters and $E/\Delta E \sim$10-15 using CZT detector Array.
- Detection and detailed studies of stellar and galactic black holes, non-thermal components in the X-ray spectra of SNRs and clusters of galaxies and the measurement of magnetic fields of neutron stars by detection of cyclotron lines in the X-ray spectra of X-ray pulsars.
- Detection and location of new transient X-ray sources and continuous monitoring of known X-ray sources like X-ray binaries.
- Studies of pulsations, binary light curves, QPOs and aperiodic (flaring, bursts, flickering and chaotic changes) phenomena in X-ray pulsars, X-ray binaries, coronal X-ray sources, CVs, Active Galactic Nuclei (AGNs) and clusters of

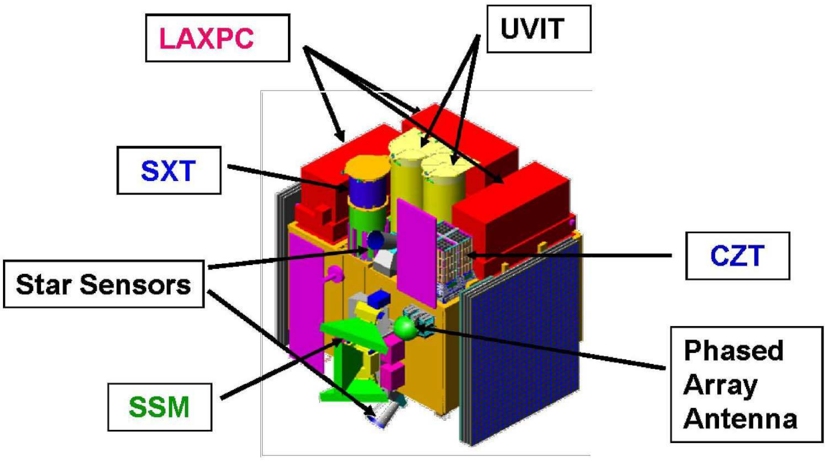

Figure 1. In orbit configuration of the ASTROSAT. The layout of different instruments on the deck plate is indicated with arrows.

galaxies with high time resolution (~10 sec) over a wide spectral band covering 0.3-100 keV

- Multiwavelength observations of a variety of cosmic sources over a wide spectral band extending over visible, UV (1300-3000 Å or ~2.3 eV to 9.5 eV), low energy X-ray (0.3 - 8 keV) and high energy X-ray (2-100 keV) bands to study correlated variations.
- Observations of interacting galaxies, star forming galaxies and globular clusters etc in the UV band.

3. Payloads and their status

Five major and one minor payload are part of the ASTROSAT mission to achieve the temporal and spectral objectives as listed in the previous section are:

1. A cluster of 3 identical Large Area X-ray Proportional Counters (LAXPC) with a combined area of 7950 cm^2 for timing and low resolution spectral studies over a broad energy band 3-80 keV.
2. An array of Cadium-Zinc-Tellueride (CZT) detectors with 1000 cm^2 area, along with a coded mask.

3. A Soft X-ray Imaging Telescope (SXT) consisting of conical foil X-ray mirrors and a CCD detector at the X-ray focus. The telescope will operate in the energy band of 0.3 to 8 keV and with a energy resolution of ($E/\Delta E \sim$ 30 to 50) for spectroscopic studies and a position resolution of about 2 to 3 arc minute.

4. An array of 3 Scanning X-ray Sky Monitor (SSM) cameras to detect new X-ray transients and to continuously monitor the light curve of the steady X-ray sources.

5. Two UV imaging telescopes each having an aperture of 38 cm and a CCD imager with a filter wheel. One of the telescopes is tuned to far UV band (1300-1800 Å) and the second one will observe both near UV region (2000-3000 Å) and the visible band (3500-6500 Å) using a beam splitter.

6. A Charge Particle monitor is included to provide ambient radiation data for safe operation of the other payloads specially, in the South Atlantic anomaly region.

4. Large Area X-ray Proportional Counters

LAXPC instrument consists of 3 co-aligned large area high pressure X-ray proportional counters to achieve high detection efficiency, good energy resolution (~ 12% at 22 keV), an extended energy band of 3-80 keV, a narrow field of view to increase sensitivity and angular resolution along with a long operational life without deterioration in resolution and general performance. Each xenon-filled proportional counter with active detection volume of 100 × 36 × 15 cm and having a multi-wire-multi-layer configuration has a narrow field of view (FOV) of $1^o \times 1^o$. The detector entrance window is 50 micron aluminized Mylar supported from outside by a window support collimator. The schematic of the LAXPC detector, internal cell geometry and the assembled unit under baking is shown in Fig. 2.

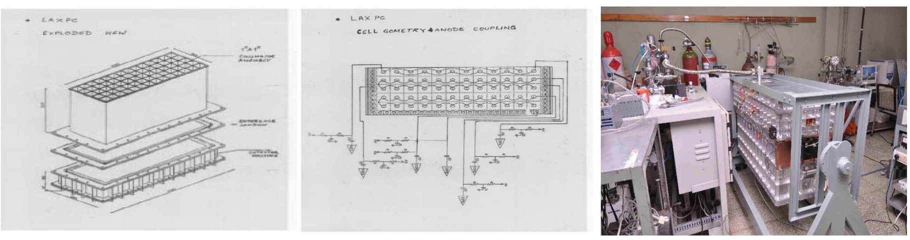

Figure 2. The schematic view of the large area proportional counters and the internal arrangements of the multi-cell multi-layer geometry and assembled detector in baking.

The detectors are filled at 1500 torr pressure with xenon+methane (90+10%) mixture. Average X-ray detection efficiency of the detector is ~ 100% below 15 keV and about 60% up to 80 keV. A sample of the energy spectrum and the calculated

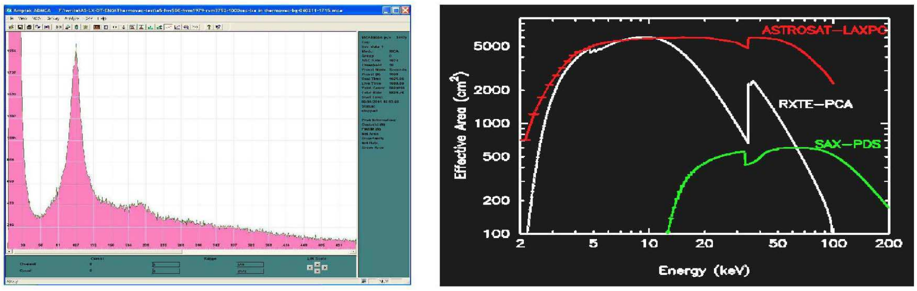

Figure 3. A sample energy resolution curve of the detector and the effective area of LAXPC payload.

effective area for the LAXPC payload is shown in Fig. 3. For long operational life an in-orbit purification system consisting of a mini-compressor coupled to a purifier cartridge has been built. The design of the on-board event processing electronics for the proportional counter is designed for the study of spectral and temporal phenomena over a wide time scale. The event processing logic ensures that only the genuine X-ray photons arriving from the target sources are processed and background events arising due to Compton scattering of the high energy photons, charged particles and shield leakage, are rejected automatically. Several modes of operations have been designed. The normal integration time for X-ray events from different layers will be 0.125 sec and will be selectable from 7.7125 ms to 1 sec range in multiple of 2. Every event is time tagged to an accuracy of 10 microsecond for high time resolution. On board pulse height data in 256 channels integrated for 8 s is also provided and an ultra-fast broadband counting with time resolution of 164 microsecond can be commanded. The total effective area of 3 LAXPCs will not be less than 6000 cm^2. Large area, high detection efficiency and low background will enable studies of fainter X-ray sources (0.1 UFU) and high time resolution (10 micro seconds) will enable studies of fast pulsations, kHz QPOs and other irregular rapid variations. The flight detectors are currently in the assembly stage and the flight electronics is being fabricated.

5. Cadmium Zinc Telluride

CZT payload uses near-room-temperature solid-state detector array which have recently become available. These detectors provide both the high detection efficiency close to 100 % up to 100 keV, as well as have a superior energy resolution (6% at 60 keV) compared to proportional counters and are more suitable for the study of line emission in X-ray spectra. Due to the constraints of thermal noise, the solid state detectors have small pixel size. For a reasonable geometrical area requirement of the detector the number of electronic channels become large and need ASIC readout, the pixilated nature of the detector however, affords imaging in hard X-rays with medium angular resolution by using an appropriate coded mask. Design specifications of the

Table 1. Design parameters of the CZT payload.

Area	1024 cm^2 (± 20%)
Pixels	16384, each 2.5 mm × 2.5 mm (5 mm thick)
Imaging method	Coded Aperture Mask (CAM)
Field of View	17×17 deg (CAM) > 100 keV 5 ×5 deg (25 - 100 keV) 1 ×1 deg (5 - 25 keV)
Angular resolution	8 arcmin (21 arcmin geometric) (5-40')
Energy resolution	3% @ 100 keV (<5%)
Energy range	5-100 keV (LLD < 15; ULD 80-120) Up to 1 MeV (Photometric)
Sensitivity	0.5 m Crab (5× 10^4 sec < 1 mCrab)

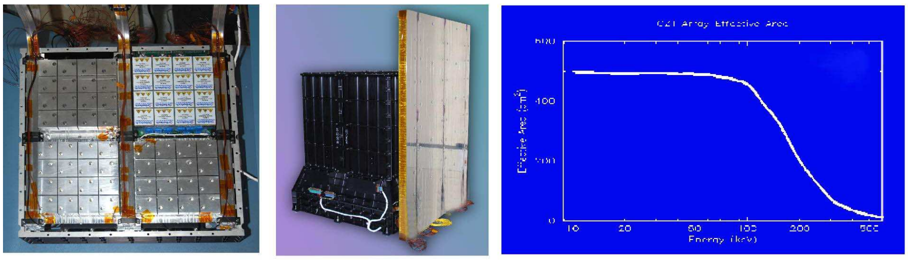

Figure 4. i. Modular detector geometry, ii. Payload Qual. model iii. Effective area of the CZT detectors.

CZT array payload on board ASTROSAT are summarized in Table 1. The pictures in Fig. 4 show the tiled layout of the CZT detectors, the qualification model which has gone through the tests and the effective-area curve versus energy.

6. Soft X-ray Imaging Telescope (SXT)

A focusing telescope can provide almost 1000 times better sensitivity compared to the non focusing instruments and also permits spatially resolved spectroscopy and variability studies by separating the confusing sources. Soft X-ray imaging telescope on board ASTROSAT mission consists of conical foil mirrors and works on the principle of grazing incidence. The telescope has a focal length of 2 meters and a cooled X-ray CCD as the detector at its focal plane. The mirror design of the telescope is optimized to have large collecting area, use of light-weight optics, ease of fabrication, highest possible energy cut-off and to fit within the envelope of a PSLV payload. The soft X-ray payload will cover an energy range of 0.3 to 8.0 keV and provide an energy

Table 2. Characteristics of SXT telescope.

Telescope length (Telescope+Camera+baffle)	2465 mm
Top Envelope Diameter	386 mm
Focal Length	2000 mm
Maximum radius of foils	130 mm
Minimum radius of foils	65 mm
Reflector Length	100 mm
Reflector thickness(Al + Epoxy 50-60+gold 1500 Å)	0.25 mm
Minimum reflector spacing	0.5 mm
Number of nested shells of foils	40×8 = 320

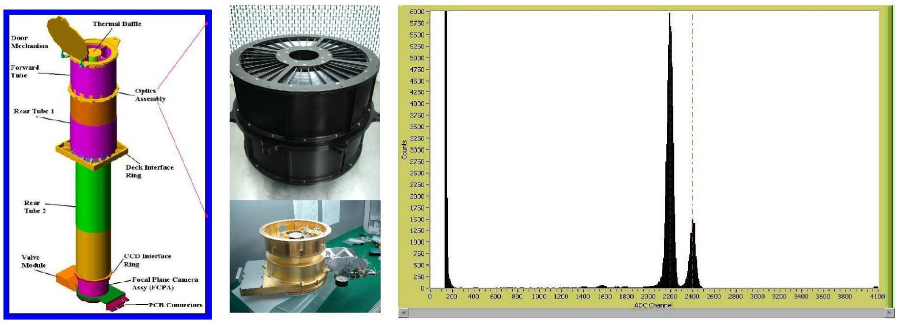

Figure 5. (i) A sketch of the SXT telescope, (ii) conical foil mirror assembly (above) and CCD housing (below), (iii) observed energy resolution for Fe55 radioactive source for an isolated pixel using engineering model.

resolution of 2% at 6 keV for good quality spectroscopy. The key parameters of the X-ray telescope are given in Table 2.

The telescope has geometrical reflecting area of 250 cm^2 for energies below 2 keV, and ~25 cm^2 at about 8 keV. The point spread function of the telescope is optimized to have half-power diameter of about 3-4 arcsec. A single large format EEV make charge coupled device (CCD) with a large depletion depth for X-ray detection has been selected as the focal plane detector and is provided by the University of Leicester, U.K. The CCD provides both imaging and spectral capability. The use of high resistivity silicon and large depletion depth provides quantum efficiency of nearly 80% at 8 keV and energy resolution of 2.5% at 6 keV and 5% at 1 keV. The readout and the control electronics have been built at TIFR. A schematic view of the X-ray telescope conical mirror assembly, the focal plane CCD housing and the observed energy resolution measured in the laboratory using engineering model CCD is shown in Fig. 5. A clear separation of 5.9 keV and 6.4 keV K_α K_β lines of Fe^{55} are clearly seen in the figure. The focusing technique used in SXT payload provides low and simultaneous background measurement leading to high sensitivity, and making it possible to study thousands of X-ray sources with intensity above ~15 micro Crab level. Both the qualification and the flight model of the optics and camera have been built. The integrated qualification model is undergoing environmental testing in ISAC Bangalore.

7. Scanning Sky Monitor

The Scanning Sky X-ray Monitor on board ASTROSAT consists of three position sensitive proportional counters with a one dimensional coded mask. The detectors are mounted on rotating platform in orthogonal positions to cover large part of the sky during each rotation. The monitor will operate in the energy range of 2-10 keV and will have a field of view of about $10^o \times 90^o$. The gas-filled proportional counter has resistive wires as anodes. The ratio of the output charge on either ends of the wire will provide the position of the X-ray interaction, providing an imaging plane at the detector.

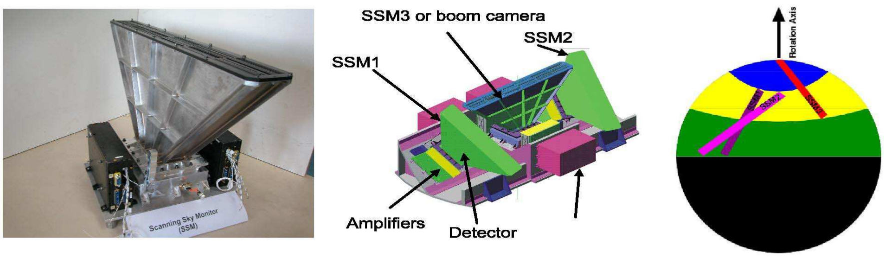

Figure 6. (i) Qualification model of the SSM payload, (ii) Mounting arrangement of the 3 SSM units on the rotation platform, (iii) The area covered by set of three rotating SSM detectors.

Each counter is attached to a 1-D coded mask as seen in Fig. 5. The coded mask will cast a shadow on the detector plane. The intensity and position of the shadow pattern will vary depending on the direction and brightness of all the X-ray sources in the field of view. A de-convolution of the image data in the detector plane will thus enable us to detect, locate and study transient sources. The sensitivity of the SSM payload for source detection is ~30 mCrab for 10 min. integration. In terms of payload readiness the SSM qualification model has successfully completed thermovac, vibration and EMI/EMC tests. The flight model is being put through individual package level testing.

8. Ultraviolet Imaging Telescope

The Ultraviolet Imaging Telescope payload has two similar and co-aligned telescopes each with 38 cm aperture primary mirror, a 14 cm secondary and photon counting imaging detectors, covering together near-UV , far-UV and visible bands. Each telescope has a 0.5^o field of view with an angular resolution of 1.5 arcsec. The optics and the detectors are optimized for the wavelength band of 1300-3000 Å in two separate channels of near UV (2000-3000 Å) and far UV (1300-1800 Å). Each channel will have an independent filter wheel to hold different filters and grism. In one of the telescope, the Cassegrain beam is split into two separate channels to cover the optical band 350-550 nm. The UVIT detectors are intensified CMOS imager with a multi channel plates (MCPs) as the electron multiplier. The choice of detector is of critical importance for the mission objectives. The main factors for consideration are: (i) the quantum efficiency in the chosen wavelength band (ii) spatial resolution to match with the designed optics (iii) noise, dynamic range and the stability characteristics (iv) susceptibility to the radiation damage in orbital environment (v) limitation in terms of cooling requirement, package size etc. While the expected resolution is < 100 nm (depends on choice of filters), the detection sensitivity is estimated as 20^{th} magnitude ($4\ \sigma$) in 50 nm band.

Table 3. Details of the Filter used in the FUV and NUV channels.

FUV				NUV		
Slot. No	Filter Type	Filter Thick-. ness mm	Pass Band nm	Filter Type	Filter Thick- ness mm	Pass Band nm
0	Block			Block		
1	CaF2	2.50	> 125	Silica	3.00	> 20
2	Barium Fluoride	2.40	> 135	NUV15	2.97	200- 230
3	Sapphire	2.00	> 142	NUV13	3.15	230 - 260
4	Grating - 1	4.52	> 125	Grating	4.52	> 200
5	Silica	2.70	> 160	NUVB4	3.33	250 - 28
6	Grating - 2	4.52	> 125	NUVN2	3.38	275 - 285
7	CaF2	2.50	> 125	Silica	3.30	> 20

Each channel will have an independent filter wheel to hold different filters and grism. In each channel, a set of filters are available, in the filter-wheels, for selecting a band. In the two ultraviolet channels, gratings are provided for low resolution (~100) slitless spectroscope. Several filters and grism are part of each focal-plane detector module. The proposed observation bands are given in Table 3.

The photon detector system and the schematic of twin telescopes are shown in Fig.7. The qualification model of the payload has been tested and the flight units are under fabrication and testing. UVIT is a powerful stand alone instrument to study the ultraviolet emission from the galactic and extragalactic sources and UV sky survey, its in-orbit operation will also be guided by the combined objective of multiwavelength

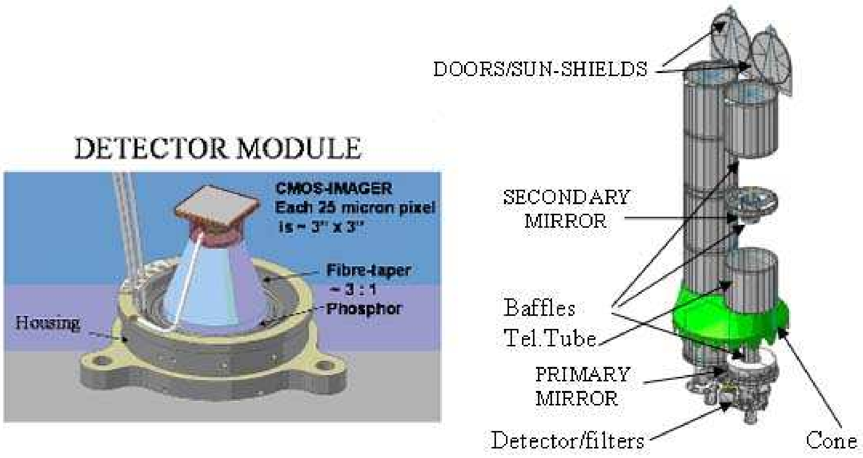

Figure 7. (i) Photon detector assembly (ii) Schematic for the Twin telescopes with Cassegrain geometry.

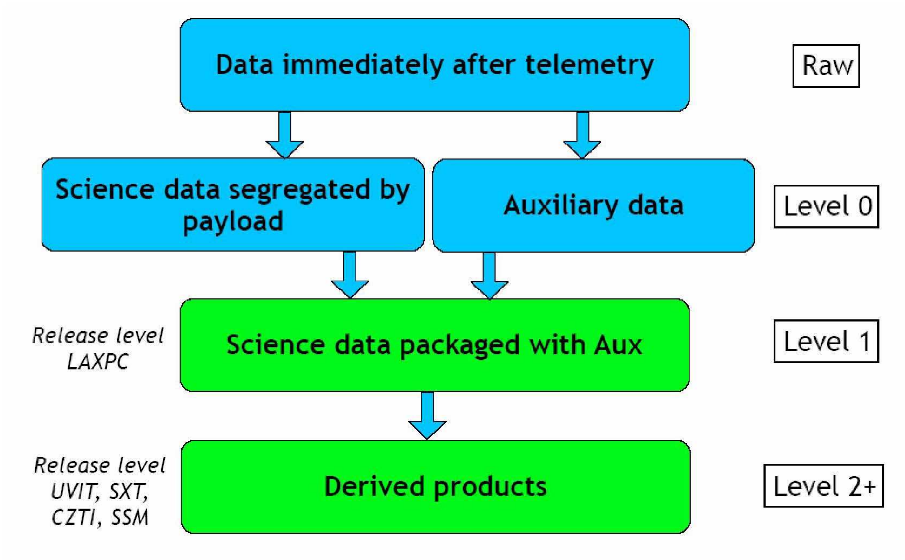

Figure 8. The Data level definition arrived for the ASTROSAT payloads.

studies with all co-aligned instruments. Simultaneous multi frequency spectra for the active galactic nuclei, Seyfert galaxies, quasar and the clusters of galaxies will lead to the understanding of the physics and the energetics of the central engine in these sources apart from the processes and the partition of the energy into various wavelength bands.

9. Data products

The operation of ASTROSAT will be along the lines of earlier major observatories, where a large amount of observation time after the payload verification phase, will be allotted to National and International proposals based upon their evaluation and selection. For this the ASTROSAT time allocation committee is being set up. Several user friendly tools for planning an observation will be available for the potential users. Several modes of data and derived products will be available for prospective analysis. The data level definition of the ASTROSAT payloads and their respective data release products are shown in the Fig. 8.

Acknowledgments

The summary presented here forms a part of input received from different payload teams which form a part of several institutes namely, TIFR, IIA, ISRO, IUCCA, RRI, Univ. of Leicester, CSA Canada. Some of the details and publication list may be found at http://meghnad.iucaa.ernet.in/~astrosat/