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Science from Astrosat

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Abstract. *ASTROSAT* is an X-ray and UV observatory that is planned to be launched in 2006 A.D. It will cover the entire X-ray spectral band from 0.3 to 150 keV in one mission, with simultaneous UV observations in the 1350 – 3000 Å. A Scanning Survey Monitor will look for transient X-ray sources in the Sky. *ASTROSAT* will thus be a unique mission in the time frame of 2006 – 2010 A.D.

Keywords : Astronomy: X-rays – UV – multiwavelength

1. Introduction

Detection and measurement of extreme states of matter – hottest, densest, in strongest gravitation and magnetic fields, is one of the most exciting areas of research in astronomy. For example, X-ray astronomy discovered the first black holes nearest to the Earth, and the very high magnetic field of neutron stars was measured directly in X-ray astronomy as cyclotron absorption features. A steady progress in X-ray astronomy, however, requires a diversity of instruments that are not usually possible to be included in a single satellite. For example, wide-band X-ray instruments with overlapping energy response and ultraviolet (UV) detectors are needed for simultaneous spectroscopic observations to identify and quantify contributions of different components (e.g. thermal, non-thermal, black body, thermal-Compton, spectral lines) in X-ray sources, and thus to understand their nature and astrophysical processes in them. UV imaging of normal, starburst and dwarf galaxies in the local and the distant universe is needed to address the evolution of stellar populations. There is, however, no X-ray & UV observatory planned in the 2006–2010 A.D. time-frame that can cover the entire X-ray spectral band from 0.3 to 150 keV and the 1350–3000 Å UV band in one mission. The *ASTROSAT* equipped with instruments in these bandwidths will thus be a unique mission to address a host of scientific issues in X-ray and UV astronomy.

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2. Astrosat Overview

ASTROSAT is an Indian multiwavelength astronomy satellite planned for launch in early 2006. The satellite is based on Indian Remote Sensing (IRS) spacecraft. The launch vehicle will be Polar Satellite Launch Vehicle (PSLV). *ASTROSAT* will be launched into a circular 600 km orbit with inclination of <15 degree. It will have a nominal lifetime of about 5 years. Operations will be with 5-6 ground station contacts per day. Equipped with magnetic torquers and 2 star trackers, *ASTROSAT* will have target acquisition accuracy of about 30 arcseconds.

2.1 Science Payload

The spacecraft will carry five scientific instruments, described elsewhere in these proceedings. A summary is given below:

- **LAXPC (Large Area Xenon Proportional Counters):** Three co-aligned units. Multilayer proportional counters with 5 layers (TIFR)
- **SXT (Soft X-ray Telescope):** Focusing telescope (2m focal length) using conical foil mirrors and CCD detector (TIFR/PSU/SAO)
- **CZTI (CdZTe Imager):** Coded aperture mask with CZT detector array (16,384 detector elements) sensitive up to 200 keV (TIFR)
- **SSM (Scanning Sky Monitor):** Similar to RXTE ASM: 3 Position-Sensitive Proportional Counters with coded aperture masks that scan the sky to detect X-ray transients and measure lightcurves of variable X-ray sources (ISAC/RRI)
- **UVIT (UV Imaging Telescopes):** Two units each of 40 cm aperture, microchannel plate detectors (IIA)

LAXPC, SXT, CZTI and UVIT will be co-aligned. SSM will be mounted on a rotating boom.

Table 2.1. Instrument Characteristics

Item	LAXPC	SXT	CZTI	SSM	UVIT
Total Area (cm^2):	6000	200	1000	180	40 cm aperture
60% QE below:	80 keV	2 keV	150 keV	10 keV	N/A
Sensitivity (cps/Crab):	12,000	2000	1000	100	22 mag
Bandwidth:	2–80 keV	0.3–8 keV	5–150 keV	2–10 keV	1350–3000 Å
$E/\Delta E$	6–12	4–50	50	3–8	Filters
Field of View:	$1^\circ \times 1^\circ$	$40' \times 40'$	$17^\circ \times 17^\circ$	$60^\circ \times 90^\circ$	$30'$
Angular Resolution:	$1^\circ \times 1^\circ$	$3' - 4'$	$8'$	$12'$	$1''$
Timing Resolution:	$10\mu s$	2 ms	1 ms	1 ms	10 ms
PI:	P.C. Agrawal	K.P. Singh	A.R. Rao	S. Seetha	N.K. Rao
Institutions:	TIFR	TIFR/ PSU/SAO	TIFR	ISAC/RRI	IIA

3. Principal Scientific Aims

Capitalizing on the unique strengths of *ASTROSAT*: namely, broad-band spectroscopy covering the entire UV and X-ray bandpasses, and timing, *ASTROSAT* will be an excellent probe to study the environs of black holes, astrophysics of accreting neutron stars and pulsars, astrophysics of accreting white dwarfs, transient X-ray sources, long-term behaviour of bright X-ray sources, hard non-thermal tails from clusters of galaxies etc. A short description of some the themes is given below.

3.1 Black-Holes and their environs

Black-Holes are believed to be the powerhouse of many bright X-ray sources. The existence of black holes of a few solar masses in *X-ray binaries* is based on strong dynamical evidence for compact objects with masses much greater than that permitted for a white dwarf or a neutron star. Luminous variable objects in the nearby galaxies have been identified with black holes of $\sim$500 $M_\odot$ (Kaaret et al. 2000), and super-massive ($10^6 M_\odot$–$10^9 M_\odot$) black holes are the best candidates to power the *Active Galactic Nuclei (AGN)* at the centre of many galaxies. X-rays are produced near black hole event horizons and accretion disks around them. The very large gravitational potential energy gained by the accreted matter leads to several interesting and exotic phenomena in the vicinity of the black holes: generation of relativistic plasma, relativistically rotating accretion disks close to the BH *(Seyfert type galaxies)*, ejection of matter in the form of jets with bulk velocity close to the velocity of light *(Blazars & Quasars)*, stochastic production of high magnetic fields, nucleosynthesis, shocks etc. Highly penetrating X-rays pierce through the gas surrounding the black holes and help us to locate and study these environments. These regions also accelerate particles to high energies, and the electrons thermalising in the ambient medium heat up the medium to very high temperatures. X-ray spectroscopy allows us to study the energy release process and acceleration mechanisms as well as determining the temperature, density and abundances of the thermal plasma. X-rays also interact with the surrounding medium, producing emission from photo-ionised regions and carrying signatures of X-ray reflection.

3.1.1 *Active Galactic Nuclei*

X-ray emission from the vicinity of a black hole is continuum dominated, except in a few cases where copious cold matter surrounds the black hole and gives rise to emission from photo-ionized plasma. For example, X-ray spectrum of a **Seyfert 1 galaxy** (see Nicastro et al. 2000; Pounds et al. 2001) contains along with a power-law the following interleaved components: (i) an excess below 0.6 keV; (ii) a deficit between 0.6 and 1.5 keV; (iii) absorption edges below 1.5 keV; (iv) narrow and broad (with red-ward bump) line-like features around 6 keV (attributed to gravitationally shifted atomic Kα line emission from almost neutral iron in inner accretion disk); (v) an excess above 10 keV (reflection component) and (v) a deficit above 100 keV. In the 0.5–10 keV (or smaller) bandpass of most previous X-ray astronomy missions, it is difficult to distinguish unambiguously between various continuum emission mechanisms (e.g., thermal bremsstrahlung vs. power-law). Understanding the X-ray spectra of AGN, therefore, requires both the hard X-ray data ($>$ 10 keV) and sub-kilovolt data to determine continuum like soft-excess from accretion disk and absorption properties. It also requires good energy resolution at low energies to study faint thermal and flourescent lines. Since these objects are highly variable the wide-band coverage must be simultaneous. *ASTROSAT* fulfills these requirements.

The present ***paradigm*** of radio-quiet AGN models for **Seyfert galaxies** inexorably links the UV and X-ray continua. The UV radiation can result either from thermal reprocessing of X-rays absorbed by gas around the black hole or as thermal output from viscous dissipation in accretion disks. Similarly the hard X-ray emission can come from the upscattering of "softer" (UV, EUV, soft X-ray) seed photons via Compton scattering by "hot" electrons and/or electron-positron pairs in a "corona". These processes may be tied together in a feedback loop directly connecting their emission mechanisms. The nature of the UV and X-ray correlations in simultaneous UV and X-ray observations will depend on which of these processes dominates. A large number of important physics questions for which answers can be sought by simultaneous UV and X-ray observations are: What proportion of UV arises via thermal reprocessing? What is the seed population for upscattering of UV photons into X-rays? What particle acceleration mechanism are responsible for producing the high energy electrons that upscatter the UV photons? What kind of feedback mechanism operates between the UV and X-rays? What are the various instabilities present in the accretion flows? What is the optical depth, temperature, and geometry of the particles responsible for producing X-rays? What is the temperature distribution and ionization state of the absorbing media around the black-holes?

There are very few examples of simultaneous UV to hard X-ray observing campaigns lasting more than a few days in duration. Only a handful of Seyfert galaxies have been studied for between 10 to 50 days (e.g., NGC 5548 by Clavel et al. 1992; NGC 4151 by Edelson et al. 1996; NGC 7469 by Nandra et al. 2000; Akn 564 by Shemmer et al. 2001). Such observations have been very difficult to achieve due to the physical location of instruments on different satellites, the lack of overlap between their orbital lifetimes, and coordination problems. The necessity of using instruments on multiple satellites with different observing constraints imposes analysis difficulties due to different sampling rates and observing windows, making comparisons and studies of correlations difficult. Furthermore, most of the previous campaigns used ground-based optical bands to compare with the X-ray observations, whereas the combination of UV and X-ray data provides better diagnostics. Long-term UV and X-ray observations with *ASTROSAT* will solve these problems and provide stringent tests of models for the structure and power source of accretion disk coronae.

Perhaps the most ***highly variable*** AGN in the X-ray sky, **Blazars**, are dominated by emission from a relativistically expanding jet pointed towards the Earth. They are among the most energetic objects in the Universe with emission extending from radio bands to GeV and TeV energies. In general, there are two types – ones with quasar-like emission lines, and others with BL Lac-type objects that are devoid of spectral features in the X-rays as well as other wavebands. The former show relatively hard X-ray spectra, while the spectra of the latter are significantly softer. The BL Lac type objects show spectral variability that is opposite to that observed in the Seyfert galaxies. The physics of the jet and the nature of the radiating particles can be constrained based on the observations of wide-band spectral variability associated with the changes in flux.

Blazars are best studied using multiwave campaigns covering radio, infra-red, optical, UV, X-ray and γ-ray bands. Most previous observations suffer from undersampling or missing of certain wavebands, except the extensive coverage of 3C279 by Hartman et al. (2001). Continuous "long look" with *ASTROSAT* will tell us more about radiation processes in these objects. For example, during the minimum state we can get a glimpse of the hot accretion disk component in a Blazar that usually cannot be seen due to the brightness of the beamed synchrotron component (Pian et al 1999).

3.1.2 *Galactic Black Hole Sources*

Galactic Black Hole Sources are bright X-ray sources that need wide-band X-ray spectroscopy. Presently, the lack of sufficient statistics and energy resolution in the hard X-ray spectral band makes it difficult to distinguish between spectral models. For example, between hybrid thermal/non-thermal Comptonisation model (Gierlinski et al. 1997) and two temperature thermal Compton model (Frontera et al. 2001). *ASTROSAT* will be able to do this properly.

Some of the stellar-mass black hole sources in our Galaxy are known as **microquasars** as they possess all the three basic ingredients of quasars : a black hole, an accretion disk heated by viscous dissipation, and collimated radio jets. Being much smaller, closer and showing faster variability than the extragalactic systems, microquasars are potential "laboratories" for the study of black hole accretion/relativistic jet systems. These jets require continuous replenishment of energetic particles. About a dozen microquasars are known today and all of these can be studied with *ASTROSAT*

3.2 Accreting Neutron Stars and White Dwarfs

Neutron stars, with a hard surface and radius only a few times the Schwarzschild radius are very efficient in converting the gravitational potential energy of in-falling matter mostly into X-rays. X-rays, therefore, provide the most suitable window to study the nature of neutron stars. Neutron stars accreting from a low mass ($\lesssim$1 $M_\odot$) companion star are known as **Low Mass X-ray Binaries** (LMXB). LMXBs are among the most luminous class of X-ray sources in the Galaxy, and based on their intensity and spectral behaviour have been classified as **bursters, dippers, accretion disk corona (ADC) sources, Z-type and Atoll sources.** Neutron stars accreting from a high mass companion star are known as **High Mass X-ray Binaries** (HMXB), and since they usually show pulsations, are also known as **X-ray binary pulsars.** Important science about the ***structure, mass, size, magnetic field strength and even evolution of neutron stars and the X-ray binaries*** can be studied by observing their temporal and spectral characteristics in a wide X-ray band. The only direct way of measuring the magnetic field strength in a neutron star is through the ***cyclotron resonance absorption feature*** in its X-ray spectrum. In the binary X-ray pulsars, the field strength is a few times 10^{12} Gauss, and in about a dozen X-ray pulsars the corresponding absorption feature has been observed in the hard

X-ray spectrum with varied degree of statistical significance (Makishima et al. 1999). *ASTROSAT* will provide a significant improvement (see below).

Magnetic Cataclysmic Variables consisting of a white dwarf accreting from a low-mass, late-type main sequence red dwarf are powerful X-ray sources requiring wide-band X-ray spectroscopy. X-rays are emitted from the optically thin plasma in the shocked regions with many zones of different temperatures, and from the white dwarf surface. There is a significant reprocessing through scattering, absorption in the accretion stream, reflection from the surface etc., thus requiring the capabilities of *ASTROSAT* from which to study these objects.

3.3 X-ray Spectral Simulations

In Figure 3.1, we show a simulated spectrum of a 40 ks observation of the *Coma cluster* of galaxies, showing the thermal and non-thermal components. The Fe abundance has been set to zero in the model to highlight the Fe lines in the lower panel showing the ratio between the observation and the model. The inset shows a blowup of the Fe line region from the SXT, showing clearly resolved 6.7 and 6.9 keV lines and providing valuable plasma diagnostics.

A simulated X-ray spectrum of a High Mass X-ray Binary (HMXB) pulsar with cyclotron absorption feature at 20 keV and its harmonics is shown in Figure 3.2. The continuum parameters, width and depth of the absorption lines are typical of HMXB pulsars (Santangelo et al. 1999).

3.4 Discovering X-ray Transients and Monitoring X-ray sources

A large number of X-ray sources, Galactic and extragalactic, are highly variable and some of them are also transient in nature. The SSM will detect and locate new transients in our Galaxy. The known transients usually consist of long period Be X-ray binaries, X-ray novae containing a black-hole, etc. Observers in other wavebands will be alerted to follow the transients as soon as these are discovered to help obtain optical identification and system parameters like mass function, binary period, mass of the compact object etc. Other sensitive instruments on *ASTROSAT* will be pointed towards them to study their variability characteristics. For example, X-ray binary sources could be studied over a large dynamic range of 10^{33} erg s^{-1} to 10^{38} erg s^{-1} and accretion rate. In addition, detailed studies of source states: ***Quiescence/off, Low hard state, High soft state, intermediate, very high*** etc. Other studies planned are: supra orbital period in HMXBs possibly related to precession period of disc/neutron star, very long term cycles and irregular variations in LMXBs possibly related to mass transfer instabilities, and spin up/down phases of pulsars.

3.5 UV Astronomy and UV Surveys

The UV sky in the 1350–3000Å looks very different from the sky in the visible light. UV samples the hot and massive stars in the galaxies and is very sensitive to dust in the stars and galaxies. UV emission is thus an excellent indicator of star formation in the galaxies. Highly ionised regions in the sky also emit strong line and continuum UV emission. Although, the Space Telescope does carry UV instruments, field of view of the

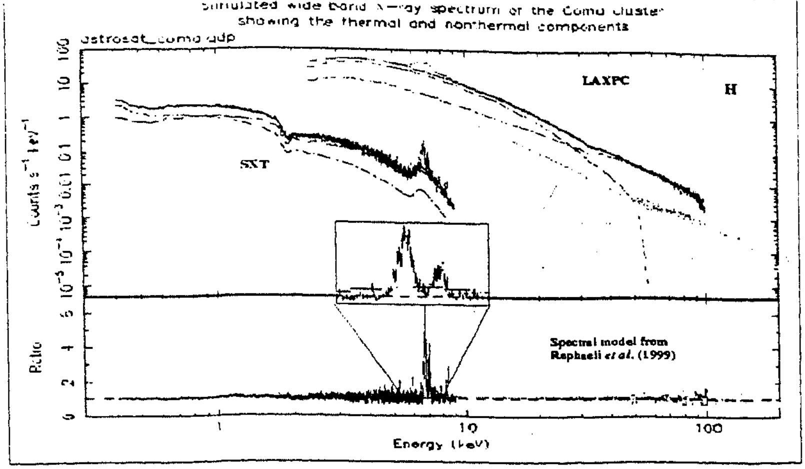

Figure 3.1. Hard X-ray tail and Fe line emission in the Coma Cluster of galaxies as expected to be seen with the Astrosat.

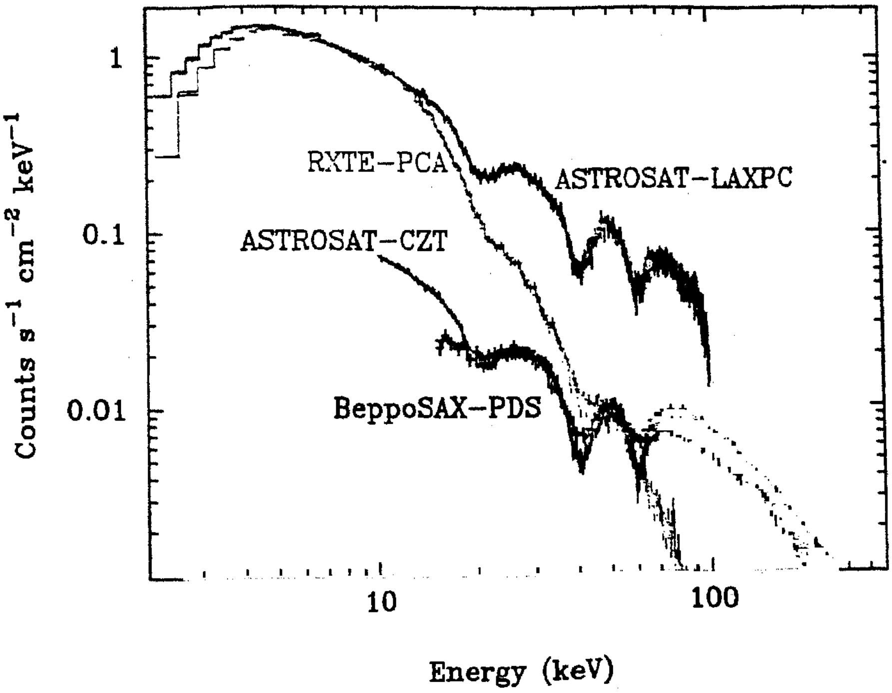

Figure 3.2. Simulated 10 ksec observations of a hard X-ray pulsar spectrum. *ASTROSAT* resolves the cyclotron lines much more clearly than Beppo-SAX or RXTE.

UVIT will be 50 times larger in diameter and the spatial resolution will also be better. A similar mission, GALEX, by NASA may be launched before *ASTROSAT* . GALEX will perform an all sky survey with somewhat poorer resolution than UVIT. UVIT will observe specific targets and carry out deep surveys of selected regions of the sky. Deep UV surveys, lasting nearly 100,000s, of the fields studied with Canada-France Hawaii Telescope (CFHT) will detect galaxies at $z \simeq 2$ assuming SFR $= 0.3$ $M_\odot$ y^{-1}, and several faint quasars and AGNs. Lyman-α surveys of nearby galaxies and clusters of galaxies in the fields chosen from Canadian Network for Observational Cosmology (CNOC) will help to calibrate the Lyman-α strengths in objects at redshits >2. Study of nearby galaxies in UV will trace the evolution of stellar populations, UV-upturn, dust properties, morphology, and their spectral energy distributions. Study of hot stars in the local group of galaxies will help in understanding the global studies of young population in more distant galaxies. In the Milky Way itself, UVIT will study the populations of subclasses of White Dwarfs (sub-dwarfs, pulsating WDs etc), WDs in the globular clusters, high mass stars and luminous blue variables which can also be used as distance calibrators, Wolf-Rayet stars showing UV variability, SEDs of O-B-A stars, the interstellar matter, Cataclysmic Variables, X-ray Binaries, and Stellar-Solar connection in cool stars via their rotation, magnetic activity, and UV flares.

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References

Clavel, J. et al., 1992, *Astrophys. J.*, **393**, 113.

Edelson, R.A. et al., 1996, *Astrophys. J.*, **470**, 364.
Frontera, F. et al. 2001, *Astrophys. J.*, **546**, 1027.
Gierlinski, M. et al. 1997, *MNRAS*, **288**, 958.
Hartman, R.C. et al., 2001, *Astrophys. J.*, **553**, 683.
Kaaret, P. et al., 2000, *MNRAS*, **321**, L29.
Makishima, K. et al., 1999, *Astrophys. J.*, **525**, 978.
Nandra, K. et al., 2000, *Astrophys. J.*, **544**, 734.
Nicastro, F. et al. 2000, *Astrophys. J.*, **536**, 718.
Pian, E. et al., 1999, *Astrophys. J.*, **521**, 112.
Pounds, K.A., 2001, *Astrophys. J.*, **559**, 181 .
Santangelo, A. et al. 1999, *Astrophys. J.*, **523**, L85.
Shemmer, O. et al., 1998, *Astrophys. J.*, **505**, 594.