Frontiers in space astronomy

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This article reviews the background and the current frontier in space astronomy being done at various wavebands. Space-based platforms, free from the absorption and distortions introduced by the Earth's atmosphere, are able to provide both higher resolution and sensitivity over much of the electromagnetic spectrum, and have thus become necessary tools of a professional astronomer. This area of astronomy has seen a steady growth, which is expected to continue well into the future. The space astronomy activities in India are reviewed in this global context.

Keywords: Earth's atmosphere, electromagnetic spectrum, Gamma rays, space astronomy.

Introduction

WHILE astronomy is one of the oldest branches of science, astronomy from space platforms is a very recent development, just about four decades old. In this short span of time, however, it has grown to occupy a seat at the forefront of astronomy. Astronomers have started relying on space platforms to routinely provide them crucial information regarding the nature of many celestial objects. Space missions are expensive and time consuming to realize. Despite this, their lure to astronomy continues to rise. Ambitious plans are afoot by the world community to continue this success story into the next decades.

Why space?

The primary reason for going to space to do astronomy is the access to a wider range of electromagnetic spectrum than that available at the ground level. The Earth's atmosphere is a strong absorber of electromagnetic radiation, except at the optical band, in radio waves shorter than ~10 m wavelength, and a few narrow windows in the infrared (Figure 1). In any other waveband one needs to go above the Earth's atmosphere to receive any signal from cosmic sources. In ultraviolet-soft X-ray bands the required altitude is above 150 km, and for long wavelength radio signals it is more than 400 km, i.e. above the ionospheric F layer.

Even at optical wavelengths, however, rapid fluctuations in the wavefront are introduced by refractive index variations in the turbulent atmosphere. This severely limits the image quality of large telescopes. For example, a 10 m class optical telescope has a diffraction-limited resolution of ~0.01 arcsec, but the atmosphere limits it to ~1 arcsec. This provides another motivation to situate telescopes above the atmosphere. Indeed the Hubble Space Telescope, the source of some of the most spectacular astronomical images, has amply demonstrated the success of this approach. In addition to the resolution, a space based platform also provides the advantage of very little background light, enhancing the quality and sensitivity of the images.

A third reason to go to space is to realize instrument dimensions that are not possible on the Earth's surface. For example, interferometry between telescopes separated by very long baselines are used to make the highest resolution images at radio wavelengths. For earthbound telescopes, the maximum possible length of the baseline is limited by the diameter of the earth. This limitation can be overcome by locating telescopes at large orbits around the earth. The radio telescope flown in the Japanese HALCA mission created a 30,000 km baseline when it formed an interferometer with earth-based Very Long Baseline Interferometry (VLBI) networks (Figure 2).

A similar concern arises in the context of the detection of gravitational waves from binary stellar sources. It is well known that much of the gravitational wave power is at very long wavelengths. Detection of these will require masses separated by very long distances, and accurate measurement of relative motion of such masses. Earth-bound gravitational wave detectors can do this to a limited extent – accurate laser metrology can be performed over distances of several kilometres in tunnels evacuated to keep out atmospheric disturbance – but the quest is to

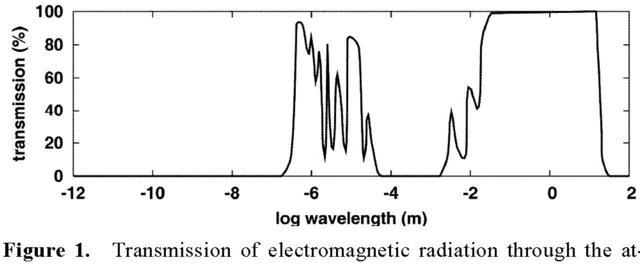

Figure 1. Transmission of electromagnetic radiation through the atmosphere as a function of wavelength. The transmission is appreciable only in optical–near IR and at radio wavelengths. Astronomy at any other band needs to be carried out from space-based platforms.

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go to much longer wavelengths. The proposed Laser Interferometric Space Antenna (LISA) mission will attempt to deploy baselines up to 5 million km, in specially designed, heliocentric earth-trailing orbits.

The origins

Early attempts at space astronomy were made using X-ray detectors flown on sounding rockets. Even the short sojourns (<10 min) of such detectors above the atmosphere were successful in detecting unexpectedly bright, new class of sources[1]. This helped build the early momentum of space-based astronomy, which has grown manifold since then. These early successes clearly indicated that the exploration of the X-ray universe would pay rich dividends, and a long-lived observation platform was required for this purpose.

The first satellite dedicated to X-ray astronomy was launched from Kenya on 12 December 1970, Kenya's independence day, and was named UHURU, the swahili word for 'freedom'. It conducted the first X-ray survey of the sky and catalogued 339 X-ray sources, including accreting binary systems, supernova remnants, active galactic nuclei and clusters of galaxies[2]. A series of X-ray astronomy satellites followed in quick succession and much new information was gathered. Highly time-variable nature of binary X-ray sources was revealed, and thermonuclear X-ray bursts on Neutron Star surface were discovered by the Dutch satellite ANS[3].

While X-ray astronomy has continued to dominate the use of space platforms, the share of other wavebands is on the rise. A beginning was made in 1968 with the OAO-2 satellite of NASA which carried 11 ultraviolet telescopes, to be followed by the very successful US–British OAO-3 (Copernicus) satellite launched in 1972 which produced high resolution UV spectra of a large number of stars that aided detailed studies of the interstellar gas[4]. The Infrared Astronomy Satellite (IRAS; launched 1983), a joint project of the USA, UK and the Netherlands, was the first major Infrared observatory in space, and serious use of space platform for optical astronomy started with NASA's Hubble Space Telescope (launched 1990). The year 1968 also saw the launch by NASA of the first Radio Astronomy Explorer (RAE) satellite which found that the earth was a strong, debilitating source of radio frequency interference. The second RAE spacecraft was launched in 1973 and was put in orbit around the moon. It carried out successful observations of the Sun and Jupiter at several radio frequencies between 25 kHz and 13.1 MHz. Shielding by the moon of the radio interference from the earth contributed to its success.

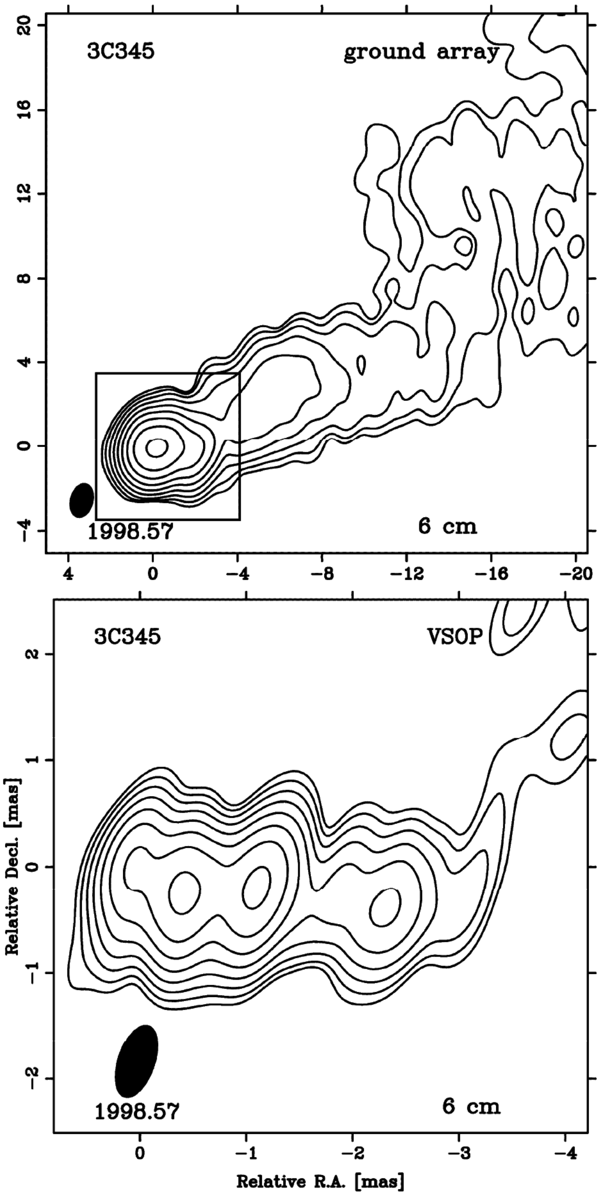

Figure 2. Example of high resolution radio imaging performed using space VLBI. The upper image is that of a quasar 3C 345 made using radio interferometric arrays on the ground. In the lower image, obtained by space interferometry with HALCA, the boxed region in the upper image is expanded and finer details are revealed (from Klare *et al.*[35]).

The present frontier

We now fast forward to the present day and review the state of the art in space astronomy in various wavebands.

Optical and ultraviolet

The Hubble Space Telescope continues to dominate the optical band. Five servicing missions since its original launch in 1990, including one in May 2009, have enhanced the telescope's capability and longevity. It is now the longest operating astronomical observatory in space. The primary mirror of the telescope is of 2.4 m diameter, and figured to work up to near ultraviolet wavelengths. The re-serviced Hubble will now contain a sensitive ultraviolet spectrograph, with resolution ($\Delta\lambda/\lambda$) up to 24,000 in the wavelength range 115–320 nm. A new high-resolution camera WFC3 will provide images with >2 arcmin field of view at better than 100 milliarcsec resolution in UV and visible bands, and at slightly lower resolution in near-infrared bands. The sensitivity of the Hubble telescope has been best demonstrated in the Hubble Ultra Deep Field exposure of 11 million sec. This deep exposure has enabled the detection of distant galaxies as faint as 30th magnitude, about 4 billion times fainter than the faintest objects visible to the naked eye in the darkest of nights[5]. A large part of our current knowledge of the early evolution of galaxies in the universe comes from this data set. The Hubble has also been a key contributor to the modern estimates of the expansion rate of the universe and its evolution, as well as the calibration of the cosmological distance scale.

A survey of the ultraviolet sky at ~5-arcsec resolution, to a depth of AB magnitude of ~20 (and deeper in selected parts) is being carried out by the CalTech-led Galaxy Evolution Explorer (GALEX) satellite[6]. The survey is now more than 96% complete, and is providing the first ultraviolet maps of the sky at this resolution and sensitivity. This will be the main source of target selection for further studies by future ultraviolet missions.

A long standing leader in ultraviolet spectroscopy has been the International Ultraviolet Explorer (IUE) satellite[7], which carried two echelle spectrographs and operated from a geosynchronous orbit for over 18 years before being shut down in 1996 due to funding constraints. It carried out over 104,000 separate observations of UV spectra with resolution up to ~10,000.

Microwaves

The main satellites for astronomy in the microwave region have been those launched to probe the Cosmic Microwave Background (CMB) radiation. The COBE satellite launched by NASA established that the spectrum of the microwave background resembles to very high accuracy that of a black body at 2.73 K (ref. 8). COBE also detected and quantified the apparent dipole anisotropy of the background caused by the Earth's motion[9]. The first estimates of the small scale anisotropy of the CMB also resulted from these measurements[10].

The immediate successor of COBE, the Wilkinson Microwave Anisotropy Probe (WMAP) is currently in orbit at the Sun–Earth second Lagrangian point. It improves significantly over COBE in both resolution and sensitivity. The CMB anisotropies have been detected by WMAP with high signal-to-noise ratio. This has enabled the estimation of cosmological parameters with precision. Thanks to these measurements we now know with some degree of confidence that 90% of the matter in the universe is 'Dark', and that 70% of the total energy density in the universe is that of 'Dark Energy' which is causing the expansion of the universe to accelerate[11].

Infrared

Sensitive measurement of far infrared signals requires the detector to be cooled to as low a temperature as possible to reduce local thermal noise. A significant fraction of the weight of an infrared space observatory is therefore contributed by coolants, and the mission life is limited by the availability of coolant (normally liquid helium) on board. The IRAS mission, the first to survey the Infrared sky, lasted just 10 months. This was followed by the Infrared Space Observatory (ISO) mission by ESA, which had a 100 times better sensitivity and 100 times better resolution than IRAS. This mission lasted for two and a half years (November 1995–May 1998) before coolant exhaustion. One of the key contributions that ISO made lies in the unravelling of interstellar chemistry in and near star forming regions[12].

The longest functioning space Infrared facility has been NASA's Spitzer mission[13]. Launched in 2003, this mission is still operating, although its coolant has just been depleted in early 2009. Following this, Spitzer is using its two near-IR bands which can continue to operate at the 31 K temperature achieved by passive cooling of the spacecraft in its earth trailing, heliocentric orbit. In its full capacity, Spitzer operated over a spectral range of 3–180 microns, and helped obtain deep, high-resolution images of regions shrouded by interstellar dust grains. The highlights of Spitzer science include detailed study of star and planet formation, discovery of organic molecules in dusty, planet-forming material and unravelling accretion processes by super massive black holes at obscured centres of dusty galaxies.

X-rays

From the early days until now, X-ray astronomy has been the main focus of space-based astronomy missions. A large number of missions have been launched and operated by the US, European, Japanese and Russian space agencies. A few small, limited capability payloads have been launched also by the Indian Space Research Organization (ISRO). The sensitivity, resolution and other capabilities of these missions have continued to increase at a rapid pace. There are several X-ray astronomy missions currently in orbit. Among them the Chandra X-ray Observatory of NASA stands out for its excellent imaging resolution and sensitivity. Four pairs of precision engineered reflecting surfaces arranged in Wolter-I geometry provide 0.5 arcsec resolution, more than an order of magnitude better than any other X-ray telescope, either past or present. The operating band is 0.1–10 keV. Two transmission grating spectrometers provide high-resolution ($\Delta E/E$ up to 2000) spectroscopic ability[14].

The Chandra X-ray Observatory has followed in the footsteps of other highly capable X-ray missions such as the Einstein[15] and ROSAT[16]. The latter performed a sensitive all-sky survey which has produced the most extensive X-ray source catalog so far (about 150,000 sources from the survey and about 100,000 serendipitous sources from pointed high resolution observations). The Chandra observatory, on the other hand, is designed for deep, pointed observations and not surveys (due to its limited field of view).

Chandra observatory has made an enormous impact in X-ray astronomy due to its high angular resolution and sensitivity (see ref. 17 for a review). Fine details of regions of high-energy interactions have been revealed, for example the core structure of the interaction zone in pulsar wind nebulae, details of matter and abundance distribution in supernova remnants, structure and energetics of jets close to their point of origin, hot gaseous envelopes around star forming regions and galaxies as well as density and temperature distribution of hot gas in clusters of galaxies.

The Chandra Observatory, Hubble Space Telescope and Spitzer together have carried out deep observations of selected common areas of the sky, under the Great Observatories Origins Deep Survey (GOODS) programme. Combination of the complementary information gathered at these different wavelength bands constitute the richest source of information about the high redshift universe available today. Science from this resource is only beginning to be explored. One example of an important result has been to confirm the presence of supermassive black holes at the centres of all types of galaxies, independent of redshift.

Another major X-ray observatory that is currently active is the XMM–Newton observatory of ESA. This uses conical approximations to reflecting surfaces to concentrate X-rays up to 10 keV. The angular resolution achieved in this process is limited to about 6 arcsec, but this thin mirror technology allows a large number of reflecting shells to be nested in the Wolter optics, providing a larger collecting area. The combined collecting area of three telescopes aboard XMM–Newton is about 5 times that of Chandra. XMM–Newton carries an imaging camera and a reflection grating spectrometer offering resolution up to $\Delta E/E \sim 800$. An on-board optical monitor helps carry out simultaneous observations in optical and X-ray bands. The large collecting area enables fast imaging of diffuse regions and sensitive spectroscopy. Science highlights of XMM include the discovery of broad spectral lines of iron from accreting black holes and neutron stars, detection of large regions of hot gas in star forming regions such as the orion nebula, discovery of a black hole inside a globular cluster, determination of luminosity and temperature of hot gas in galaxy clusters and thereby estimation of their mass, to name a few[18].

In 2005, the Japanese mission Suzaku[19] launched the first X-ray microcalorimeter array in space. Such a detector has a high quantum efficiency and an excellent spectral resolution (~6.5 eV at 6 keV). The spacecraft carries five foil-mirror X-ray telescopes, one of which is equipped with the microcalorimeter array while the others have conventional CCD detectors in the focal plane. There is also a Hard X-ray Detector instrument which extends the sensitivity to 600 keV. Unfortunately the microcalorimeter array became inoperable one month after launch due to loss of coolant from the Dewar. The rest of the instruments continue to operate and provide important science results. One of the interesting finds from this mission is the pulsar-like behaviour of a rotating magnetized white dwarf in hard X-rays[20].

In addition to imaging and spectroscopy, another aspect of X-ray astronomy that has received major attention is timing. The majority of bright X-ray sources involve accreting compact stars, and the emission from them tend to be highly variable with time. The temporal structure of the intensity variation is rich in information about the accretion flow, and indeed the compact star itself. ESA's EXOSAT mission[21] pioneered high time resolution observations of bright X-ray binaries, leading to the discovery of the Quasi-Periodic Oscillation (QPO) of a few to tens of Hz range in the luminosity of X-ray binaries containing neutron stars. The timing and the spectral properties of these binaries were seen to change in a correlated manner[22]. These observations have revealed a wealth of detail about the disk accretion process on compact objects, including the interaction of the accreting matter with the star's magnetic field. However not all features have yet been well understood, and this remains an active area of current study.

Following EXOSAT, NASA's Rossi X-ray Timing Explorer (RXTE) provided a dedicated timing platform at X-ray wavelengths. For neutron stars and stellar mass black holes the typical orbital time scales in the innermost parts of the accretion disk are in the range of milliseconds. These are also the hottest parts of the disk and are luminous in X-rays. To probe intensity variations in such short time scales, one requires a large enough collecting area to obtain sufficient photon statistics. The proportional counter array on board RXTE provided ~5000 cm^2 effective area in the 2–10 keV band. This, for the first time, allowed the study of millisecond intensity variations in bright X-ray sources. Accreting X-ray millisecond pulsars, the long-sought missing link between X-ray binaries and recycled radio pulsar were found[23]. Kilohertz QPO (Figure 3) were discovered in the X-ray intensity of a variety of low-mass X-ray binary systems[24], and during the thermonuclear X-ray burst on the surface of neutron stars, signature of periodic variability was encountered[25]. These and other detailed studies by the

RXTE have immensely enriched our knowledge of the characteristics of the compact stars and the accretion flow around them. This continues to be a very active area of research. The study of QPOs have been extended to extragalactic X-ray sources including binaries and AGNs. The majority of the Proportional Counter Units aboard RXTE have, however, stopped functioning so the available sensitivity now is much less than at launch. This mission is expected to close in September 2010. New generation of X-ray timing instruments are required to make further progress in this area.

Gamma rays

After several small scale missions, the first large observatory in the Gamma Ray band to be launched was the Compton Gamma Ray Observatory (CGRO) of NASA. It carried four experiments which covered wavebands between 30 keV and 30 GeV. The mission carried out the first all sky survey in high energy gamma rays, catalogued many new sources some of which remain unidentified at other wavelengths till today. Map of the diffuse gamma ray emission from the milky way provided strong evidence that cosmic rays in the galaxy are closely tied to the interstellar gas distribution[26]; the interaction between cosmic rays and dense molecular gas is responsible for most of the diffuse galactic gamma ray emission. Blazars (a class of active galaxies) were found to be the most prolific among all sources of gamma rays. And the brightest sources of gamma rays, albeit lasting only a few seconds, were found to be Gamma Ray Bursts (GRB), the nature of which was then unknown. CGRO observed, located and catalogued nearly 3000 GRB during its 9-year operating period[27]. The sky distribution of these bursts were found to be statistically completely uniform, giving the first hint that they may be of cosmological origin[28]. The GRB catalogue produced by CGRO remains by far the most extensive resource on burst properties till date.

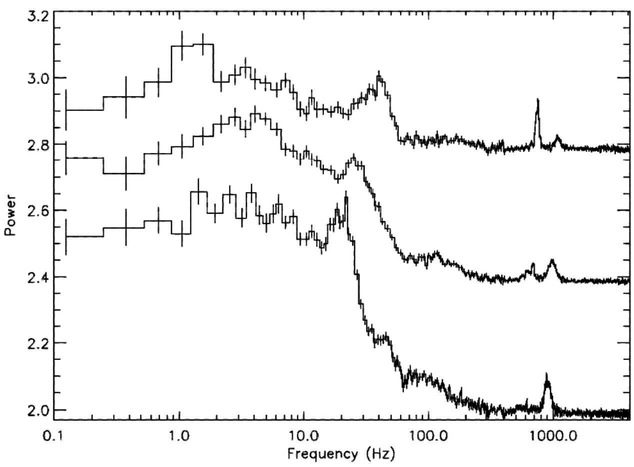

Figure 3. Power spectrum of X-ray intensity fluctuations of the accreting neutron star binary system 4U1728-34 as observed by the RXTE satellite at three different epochs. Quasi periodic oscillation peaks near 20–40 Hz as well as near a kHz are clearly visible. Such timing signatures can be used to probe the nature of the accretion flow, the spin of the neutron star as well as the space time near it. (From Strohmayer *et al.*[25].)

Major progress towards the understanding of the nature of GRB sources was made with the discovery of their X-ray afterglows[29], by the Italian-Dutch satellite mission BeppoSAX. This allowed follow-up at optical and other wavelengths, spectroscopy and redshift determination, confirming the cosmological nature of these sources. In fact GRBs constitute the most distant population of observed sources. For detailed and dedicated study of GRBs the NASA satellite mission Swift was launched in 2004. This mission is still operating. Swift has provided a wealth of multiwavelength data of the early burst phase, and has also detected some of the farthest X-ray afterglows, including the most distant astronomical source known till date, GRB 090424, at a redshift $z = 8.2$ (ref. 30).

In the hard X-ray/gamma-ray range another current mission that has made a significant impact is ESA's INTEGRAL. This satellite discovered a large population of X-ray sources in the inner parts of our galaxy, which had been hidden so far due to obscuration by dust and gas[31]. In addition, sensitive spectroscopy in the hard X-ray band has been made possible by this mission, a capability that has already discovered interesting features of several classes of sources, including highly magnetic neutron stars called magnetars.

Looking ahead

Space astronomy is in a phase of rapid development. Astronomers have deep appreciation of the precision and sensitivity that can be achieved in the space environment, so space platforms for astronomy are highly coveted. Several new missions have been recently launched or are in the process of being launched. Among them is the new major gamma ray observatory Fermi launched by NASA in 2008. This will perform an all sky survey with an order of magnitude better sensitivity and resolution than CGRO, will extend the energy band of observations to 300 GeV, and will also provide new data on the prompt emission from GRB.

ESA's Planck, the next mission to study the Cosmic Microwave Background anisotropy with higher angular resolution, and the Herschel mission, a 3.5 m telescope dedicated to sub-mm and far infrared observations, were being launched together in May 2009. Planck will extend the CMB anisotropy determination to smaller angular scales, and will be a particularly sensitive observatory for Sunyaev–Zeldovich effect: the Compton scattering of CMB by hot gas in galaxy clusters. Herschel will open a new wavelength window for astronomy, and has the potential to discover and study the formation of earliest stars and galaxies at high redshift. Objects in the early history of the universe are best observed at infrared and sub-mm wavelengths, because of the large redshifts involved (Figure 4).

NASA's next generation space telescope, called the James Webb Space Telescope (JWST), will also be dedicated to the infrared waveband. It will have a 6.5 m diameter primary mirror and sensitive near-IR imagers and spectrographs. JWST is scheduled for launch in 2014.

In the X-ray band, the next large observatory in planning is the International X-ray Observatory (IXO), a joint effort of NASA, ESA and the Japanese Space Agency JAXA. This mission will provide a very large (up to 3 m^2) collecting area for deep imaging and sensitive spectroscopy. It will also extend the high resolution imaging capability to hard X-rays, up to 40 keV. This mission is currently in development and is expected to be launched around 2020.

In the meantime, several other smaller, niche area missions will be launched. Among them is India's ASTROSAT, discussed in the next section. One area that has seen major activity of late is the search for planets outside the solar system. Various techniques are being employed by different observatories, but dedicated space missions have also been launched for this purpose. The NASA mission Kepler (launched March 2009) is designed for accurate optical photometry to detect planets as they eclipse the stars they orbit. The European Corot mission (launched December 2006) is also a precision optical photometry mission whose objectives include planet hunting and stellar variability. Darwin, a mid-infrared mission for planet search has been proposed for a 2015 launch by ESA.

The European Hipparcos mission (1989–96) was the first to carry out precision astrometry of stars. Its results

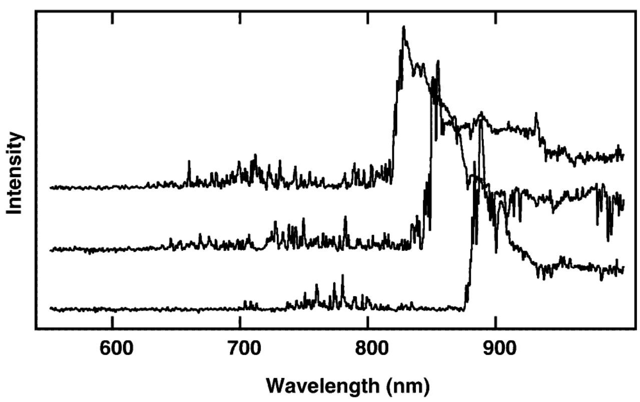

Figure 4. Keck telescope spectra of three Quasistellar objects at redshift (from top) 5.82, 5.99 and 6.28 respectively[36]. Radiation shortward of redshifted Lyman-α wavelength is strongly absorbed by the diffuse medium in the line of sight between the quasar and us. For objects at high redshifts, observations are best carried out at Infrared wavelengths.

provide the best current reference catalogue of stellar positions – accurate to 1 milliarcsec for over 100,000 stars and better than 30 milliarcsec for more than a million stars. A much more ambitious mission, Gaia, is now scheduled to follow. Gaia is designed to obtain accurate astrometry, photometry and spectrometry of a billion stars in the Galaxy. Using interferometric technique, high resolution measurements of position and proper motion of stars will be obtained. Spectral capability is included to measure the radial velocity components of the stars. Together, these results will make it possible to construct a three-dimensional map of the location and velocities of these one billion stars. Gaia is scheduled for launch in December 2011. The US mission SIMLite, currently under development, will better Gaia's resolution by a factor >25, determining stellar positions to microarcsecond accuracy.

An ultraviolet spectroscopy mission, called World Space Observatory/UV has been in the planning stage for over a decade. A joint effort of Russia, China and some European nations, this mission would provide high-resolution spectroscopic capability in near and far ultraviolet spectral bands. However, the status of this project remains uncertain at present.

One niche area to which a number of space missions have been dedicated is the study of the sun and the solar wind. Currently, at least five of them are in the operating phase: HINODE, carrying imagers and spectrometers in optical, UV and X-ray bands, RHESSI with imaging and spectral capability in X-ray and gamma-ray bands, SOHO, containing 12 instruments including coronagraphs, imagers, spectrometers and particle analysers, STEREO, a pair of spacecrafts equipped with UV imagers to take stereoscopic images of the sun and TRACE, a near-simultaneous multiwavelength imager. Together they represent the state of the art in space-based solar astronomy. Studies in unprecedented detail of the solar magnetic field, the plasma movement in active regions, coronal mass ejections and the solar wind have been possible using these spacecrafts. It is likely that a slew of spacecrafts will continue to operate in the future for solar monitoring.

Indian efforts

The Indian efforts in Space Astronomy, starting with modest beginnings, is soon to take a big leap with the launch of the Astrosat mission in 2010. An account of past efforts in Indian space astronomy can be found in the review by Kasturirangan[32]. After initial ballon and rocket-borne experiments to study hard X-ray emission from discrete X-ray sources, an X-ray payload was flown on the first Indian satellite Aryabhatta in 1975. Data obtained from this was limited because of a malfunction of the satellite power system. The next satellite Bhaskara carried an X-ray sky monitor experiment but this too had a limited lifetime. A cosmic ray experiment called Anuradha was then jointly built by TIFR, PRL and ISAC teams and launched aboard NASA's Spacelab. This payload was used to measure the abundance and ionization states of heavy ions in cosmic rays.

A GRB detector was flown aboard an Indian SROSS-C2 satellite during 1994–2001. This payload detected 53 GRB and studied their temporal and spectral properties in the gamma ray band. For 26 of these, locations were obtained by triangulation with other missions[33].

The next major astronomy experiment was the Indian X-ray Astronomy Experiment (IXAE) flown aboard a remote sensing satellite IRS P-3. This carried proportional counter detectors made at TIFR for X-ray timing. The astronomy payload operated in time sharing basis with remote sensing payloads, and therefore the available observing time was limited. Much of this time was devoted to the study of the enigmatic Black Hole source GRS1915+105. Many interesting temporal intensity variations were recorded, including some that could be interpreted as the signature of matter entering the Black Hole's event horizon[34].

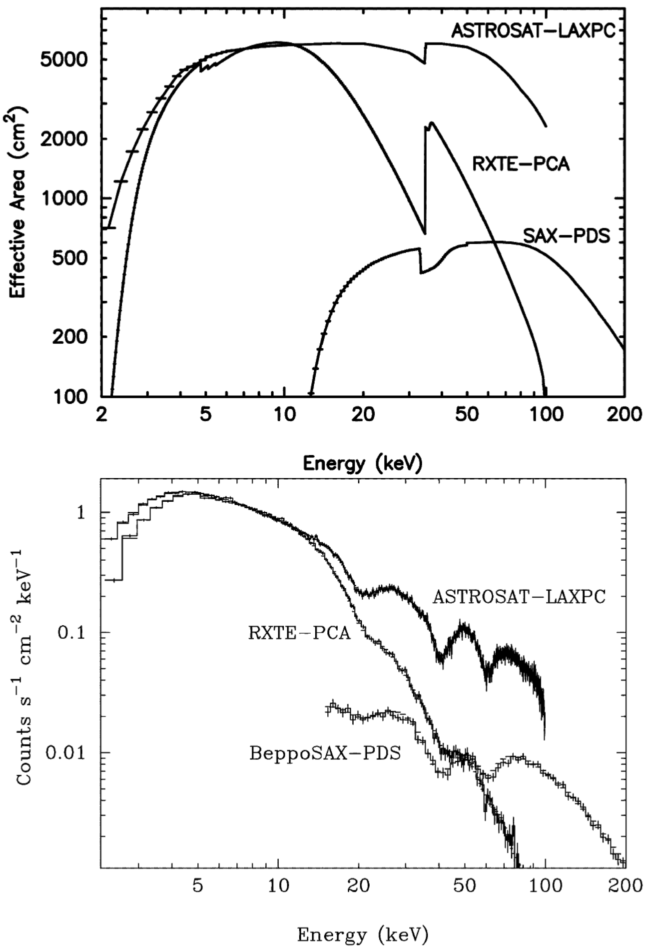

Figure 5. Upper panel: The effective area of ASTROSAT LAXPC instrument compared with that of RXTE PCA and BeppoSAX PDS. Lower panel: A simulation to compare the sensitivity to cyclotron absorption lines offered by these instruments. (From Paul[37]).

A solar X-ray spectrometer SOXS was flown aboard a geostationary satellite GSAT-2 in 2003, carrying a Silicon pin and a Cadmium Zinc Telluride (CZT) detector. Intensity, peak energy and width of iron line features in several solar bursts were observed by this payload. An imaging CZT payload RT-2 fabricated by TIFR and ISRO has recently been flown for solar studies on the Russian Coronas–Photon satellite. This experiment is currently in performance verification phase.

The experience gathered in these missions has laid the foundation for larger astronomy missions from India. In the immediate future, an Israeli-built multi-band ultraviolet imager TAUVEX is to be launched aboard an Indian geosynchronous satellite in 2009 with substantial Indian participation in science, software and operations.

India's flagship space astronomy observatory ASTROSAT has been scheduled for launch in August 2010. This will be a large 1.5-tonne spacecraft fully dedicated for astronomical observations. The mission will carry five astronomy payloads: A Large Area X-ray Proportional Counter (LAXPC) for X-ray timing; a twin Ultraviolet Imaging Telescope (UVIT); a hard X-ray CZT Imager (CZTI); a nested Wolter-I foil-mirror Soft X-ray Telescope (SXT), and an X-ray Scanning Sky Monitor (SSM). The LAXPC will be an improvement over the RXTE PCA in effective area and energy range. Precision timing and wideband spectroscopy in 2–60 keV band will be possible using this instrument. The CZTI will further extend the energy coverage up to 150 keV, and also provide a better spectral resolution. The SXT will fill in with sensitivity in the region 0.3–8 keV. The twin ultraviolet 38 cm telescopes will together operate three simultaneous observing channels in Far Ultraviolet, Near Ultraviolet and Visible bands. All these instruments will be co-aligned along the satellite pointing direction. The SSM instrument will be placed on a rotating platform pointed orthogonal to it, to survey the available sky every 6 h or so, to look for X-ray transients and large changes in the luminosities of known sources. The unique feature of this mission will be the simultaneous multi-band capability over a very large spectral range which will aid the investigation of time variable phenomena, particularly in active galaxies. The LAXPC will provide the best X-ray timing capability till date and will help extend precision timing observations to the hard X-ray region. The satellite will have excellent sensitivity for cyclotron absorption lines seen in X-ray binary systems, which carry clues regarding the local magnetic field distribution. The UVIT will be the sharpest imager flown so far in the far-UV band, with angular resolution better than 2 arcsec, and so a variety of new science areas can be addressed.

There are already plans being made for the post-ASTROSAT era. Smaller niche missions being evaluated for the intermediate term include an X-ray polarimetry mission, a Solar Coronagraph and an Infrared mission among others. In addition, the opportunity to launch the next major Indian space observatory will become available within a decade after ASTROSAT.

Concluding remarks

This article attempts to give a glimpse of the frontier areas of space astronomy being addressed now and being planned for the near future. While only a selection of examples is presented here, it is evident that the precision and sensitivity achieved by space-based astronomy instruments have fuelled a growing demand for the increase in both the quality and quantity of such missions. Space astronomy will continue to grow at a rapid pace, particularly in the wavelength bands obscured by our atmosphere. In the optical bands, the best imaging capability will return to earth with the integration of adaptive optics into the new generation optical telescopes, but space platforms will still remain lucrative for niche areas such as optical interferometry. Data from space based observatories have today become an integral part of the professional astronomer's resources. To cater to increasing demands, future observatories will need to strive for better observing efficiency and throughput by careful selection of orbits and communication links. In a relatively easily accessible near-earth orbit serious observing constraints arise due to earth occultation, sun and moon avoidance, as well as passage through regions of high charged particle density. To mitigate some of these effects, special orbits such as the second Lagrangian point (L2) of the earth–sun system are being chosen to allow long, uninterrupted observations. Several of the new generation observatories, including missions like Herschel, Planck, JWST and Darwin plan to make use of the L2 orbit.

India is one of the few nations of the world with a well-developed space programme. This presents a huge opportunity for Indian astronomers to exploit the space platform for doing astronomy at the forefront. The number of space observatories are few, so any instrument even of comparable sensitivity to other observatories, can make impact-making astronomical observations.

One of the key factors dominating the race for resolution and sensitivity in astronomy today is the study of the early universe. The design and science operation of future large observatories will be driven by similar considerations for some time to come. The required financial and technical investments in creating such large and sophisticated facilities have already gone beyond the scope of any single nation, so the major space observatories of the future will necessarily require wide international participation. For the Indian space astronomy programme, now poised for a major leap, this would open doors to more extensive international collaborations in larger programmes in the future. In addition, opportunities for targeted, niche area missions will continue to be available and it would be important for India to seize some of them.

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