Space astronomy and interplanetary exploration

P. C. Agrawal[1,]*, B. V. Sreekantan[2] and Narendra Bhandari[3]

[1]Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India
[2]National Institute of Advanced Studies, Indian Institute of Science Campus, Bangalore 560 012, India
[3]Basic Sciences Research Institute, Navrangpura, Ahmedabad 380 009, India

A brief overview of Indian contributions to space astronomy and planetary studies, mainly through the satellite-borne experiments is presented in this article. Some important results obtained in X-ray and low energy gamma-ray astronomy are summarized. Highlights of the salient results from lunar explorations are discussed. Important features of the Indian multi-wave length astronomy satellite, Astrosat and expected science from it are described. Details of the Chandrayaan-1 mission and studies initiated by the Indian Space Research Organization aimed at various aspects of lunar science are presented.

Keywords: Astrosat, Chandrayaan-1, gamma-ray burst experiment, space astronomy.

WHILE most sciences are concerned with investigations on the properties of the materials available on the earth, the physical, chemical, biological processes associated with them and explanation of the varieties of happenings in our immediate surroundings on the surface of the earth, under the ground, under the sea, and in the atmosphere around us; in contrast, astronomy is concerned with the contents of and happenings in the rest of the universe – near and far. While astronomy started with naked eye observations almost 3000 years ago with the recognition of the diurnal motions of the sun, the moon and the planets and the stellar constellations, that adorned the night sky, the advent of various technologies – telescopes, spectroscopes, particle detectors, electronics, stratospheric balloons, etc. made it possible to get a more comprehensive view of the universe – its extent, its constituents and the physico-chemical processes, etc. These observations, apart from enabling systematization and classification of the stellar objects, revealed some thoroughly unexpected aspects like the continuous expansion of universe, the existence of a universal microwave background radiation, corresponding to a temperature of 2.7 K, and also led to the discovery of strange objects like neutron stars and black holes and unimaginably powerful sources of radiations in practically all bands of the electromagnetic spectrum, the quasars and also the pulsars which gave out pulses of radiation at extremely accurate repetition rate. The sudden and spectacular explosions of stars into novae and supernovae, the remnants of which became neutron stars or black holes as identified in mid-20th century had, of course, been seen for almost a millennium, especially by the Chinese royal astronomers. Besides, observations on cosmic rays at sea level, mountain altitudes, underground and underwater and also at balloon altitudes with a variety of particle detector assemblies revealed the presence of objects in the universe, which are sources of extremely high-energy particles. Very recent developments in the field of optical astronomy have led to rather disturbing realization that with all the latest observational techniques at our command, we are able to be certain of the nature of the contents of only about 4% of the matter and radiation in the universe. The identity of the remaining 96% (named dark matter and dark energy) is still a mystery.

A new dimension was added to astronomical research with the advent of space technology, particularly, highlighted and focused by the serendipitous discovery in the first instance of powerful X-ray sources, with unusual temporal characteristics in the sky from rocket-based and satellite-based instruments. Because of the peculiar absorption properties of the earth's atmosphere, observation in the X-ray and shorter wavelength bands of radiation could be made only by going out of the earth's atmosphere. Even in the field of age-old optical astronomy, the orbiting optical telescope – the Hubble Telescope – has yielded much new information on many aspects of the cosmos.

The story regarding the discovery of the first X-ray source is fascinating. It begins with the launching of the first series of space probes by United States and satellites, immediately after the Second World War for exploring the interplanetary space. These efforts led to the discovery of a continuous outflow of solar wind particles, consisting mostly of protons, helium nuclei and also high-energy radiations. The famous cosmic ray physicist Bruno Rossi has argued that these particles and radiations impacting the moon should give rise to fluorescent X-rays. Two pairs of thin window Geiger counters, mounted with their windows horizontal were sent up on a spinning rocket by the MIT&ASE group in June 1962 to coincide with the time, when the moon was almost on the horizon. It so

*For correspondence. (e-mail: pagrawal@tifr.res.in)

happened that in those few minutes, when the spinning rocket was above the earth's atmosphere, the most powerful X-ray source ScoX-1 was next to the moon in angular direction and revealed itself[1]. Confirmation came from another similar experiment carried out by the same group a few months later. This was the beginning of X-ray astronomy in 1962. Since then, space astronomies – X-ray, gamma-ray, infrared and ultraviolet – have all become major sources of celestial information that is complementary and supplementary to what has been obtained from the ground observations in optical, radio and few windows of IR. Since 1962, American, Soviet, Japanese and European groups have flown several dozens of satellites, dedicated to the field of space astronomy and the results have been highly rewarding. This article is confined to Indian contributions to X-ray astronomy, specifically.

Indian effort in the field of high energy X-ray astronomy (>20 keV) began in 1967, with X-ray payloads flown from Hyderabad Balloon Facility by the TIFR and PRL groups. The equatorial latitudes of the Indian skies had a distinct advantage for the pursuit of high energy X-ray astronomy, because of the higher geomagnetic cut off of cosmic ray primaries and secondaries, which give rise to lower induced X-ray background at balloon altitudes[2]. Also, fortuitously, it so happened that the most prominent X-ray sources that were detected by rocket experiments, ScoX-1, CygX-1, TauX-1, Her X-1, etc. were located at rather high zenith angles in the sky of Hyderabad and its surroundings to which the balloons drifted. The series of observations by both TIFR[3] and PRL groups led to some extremely interesting results, particularly on the time variations of X-ray sources, bursting activity and spectral characteristics. The TIFR experiments were the first to detect hard X-ray, from the source HerX-1. Also, in collaboration with Japanese groups, two X-ray telescopes were flown from Hyderabad, within ten minutes of each other, during the rare event of lunar occultation of the Crab Nebula in 1975, which enabled the measurement of the size of the source in hard X-rays.

These early experiments were followed in subsequent years by flying large area high-pressure Xenon Counter assemblies and phoswich or back-to-back sodium iodide detectors from Hyderabad[4]. These experiments provided considerable amount of systematic data on the properties of X-ray sources in hard X-rays, especially on time variational and spectral aspects.

The equatorial latitude of the Indian rocket launching stations at Thumba and Sriharikota (SHAR) proved to be advantageous for rocket-based soft X-ray astronomy experiments because of low cosmic ray-induced background and minimum electron precipitation. Several large area thin window X-ray proportional counters were launched from these stations and about 40% of the sky was mapped in the energy range 0.1–2.5 keV. These early results showed that there is a patchy structure, with intensity generally increasing towards high latitudes, in the energy range 0.1–0.4 keV[5]. Limb brightening in the north polar spur was seen. Also, a hot spot in Eridanus in the southern galactic hemisphere was recorded.

Indian X-ray and gamma-ray astronomy studies with satellites

The first X-ray astronomy satellite UHURU, launched in 1970 completely transformed X-ray astronomy by discovering X-ray emission from almost all classes of galactic and extragalactic objects. A major finding of UHURU was the discovery of X-ray binaries, many of which showed X-ray pulsations. Further studies showed that these are accretion powered binary sources in which the X-ray source is either a neutron star or a black hole. Subsequent theoretical and observational investigations revealed that X-rays are produced by the release of gravitational energy due to matter siphoned off the visible companion star by the strong gravitational influence of the compact object and falling onto it. A major milestone in X-ray astronomy was the launch of Einstein X-ray observatory in 1978, which carried an imaging X-ray telescope that improved the sensitivity in X-rays by three orders of magnitude, making it possible to detect X-rays from sources at cosmological distances.

After the success of UHURU mission, it became clear that major advances in X-ray astronomy require long and detailed observations of the temporal and spectral properties of individual sources, with high sensitivity that is possible, only with the satellite-based instruments. Indian astronomers also planned development of instruments for launch on a satellite for X-ray astronomy studies. The first Indian satellite Aryabhatta launched in 1975 carried two X-ray instruments. One payload consisted of a collimated proportional counter of 60 cm^2 area, for observations in 2–20 keV range. The second instrument was a collimated sodium iodide detector of modest area, sensitive in 20–100 keV interval for hard X-ray studies. However, the observations were limited due to some power anomaly onboard the spacecraft. Two results reported from this experiment were the observation of a transition in intensity of the black hole binary Cyg X-1 and measurement of the energy spectrum of the galactic bulge source GX 17+2 (refs 6 and 7).

The next opportunity for a satellite-borne X-ray experiment came when the Indian Space Research Organization (ISRO) approved the development and launch of an X-ray astronomy instrument to be developed jointly by Tata Institute of Fundamental Research (TIFR) and ISRO Satellite Centre (ISAC), for the Indian Remote Sensing Satellite-P3 (IRS-P3), planned for launch in early 1996, as a piggyback experiment. The instrument consisted of a set of three collimated, pointed proportional counters (PPCs) with an effective area of about 1200 cm^2 and an X-ray sky monitor. The PPCs on this experiment, named as Indian X-ray Astronomy Experiment (IXAE), functioned well and provided many new results on the time variability of X-ray binaries. The success of IXAE enthused the Indian astronomy community to make a proposal to ISRO for a full-fledged astronomy observatory, aimed at multi-wavelength studies of celestial sources, over a broad spectral region, covering visible, near-ultraviolet, far-ultraviolet, soft X-ray and hard X-ray bands. This proposal was approved for development of instruments in 2001 and the Indian Government in 2004 approved the proposal for this satellite and now called, Astrosat. Details of the Astrosat mission, its principal science goals and the instruments to achieve these objectives are presented later.

Gamma-ray burst experiments

Intense bursts of gamma-rays ($E > 100$ keV) of extra-solar origin were discovered by chance in 1973 through Vela satellites, launched to detect man-made nuclear explosions. The bursts duration ranged from a fraction of a second to several tens of second and in rare cases, even longer. Several thousand gamma-ray bursts (GRBs) have been detected so far from several satellite missions, most notably, with the Burst and Transient Experiment (BATSE) on the Compton Gamma-ray Observatory. From detailed studies of the bursts and their afterglows in the X-ray and optical bands, it has now been established that GRBs are of extragalactic origin and are the most energetic explosive events in the universe.

The first GRB experiment from India was flown onboard the Indian satellite SROSS-C[8] that was launched with the ASLV on 20 May 1992. The instrument consisted of two sodium activated cesium iodide [CsI (Na)] detectors with a diameter of 76 and 37 mm and thickness of 12.5 mm. The experiment was designed to detect GRBs and measure their energy spectra and temporal profile in the energy range of 20 keV to 3 MeV. The GRB experiment had 2 ms timing capability to measure the evolution of the bursts, with high time resolution. The GRB instrument performed well throughout the life of the satellite that was unfortunately limited to about two months only, due to a lower-than-expected orbital altitude.

A total of 53 triggers were registered during the operational life of this experiment. Only three of the events appeared to be due to GRBs. One burst detected on 12 June 1992 had a duration of 2.5 s and its light curve was typical of a GRB event, with a sharp burst peak, followed by a few spikes of shorter duration. Its fluence was 5×10^{-6} erg cm^{-2}. The most interesting GRB candidate event was detected on 29 June 1992 that showed strong periodic oscillations and its light curve is shown in Figure 1 for the time T–1 s to T+8 s with a time resolution of 16 ms[9]. The period was determined to be 237.03 ± 0.5 ms that is close to the period of the well-known gamma-ray pulsar Geminga. However, at the time of occurrence of the burst, Geminga was below the horizon and hence unlikely to be the source of the burst. The possibility that this burst may also be due to repetitive precipitation of trapped electrons cannot be ruled out. Various sources for the origin of this burst have been discussed by Kasturirangan *et al.*[9].

A second GRB monitor was flown aboard the SROSS C-2 satellite launched by ASLV on 4 May 1994. The monitor worked satisfactorily throughout the life of the mission that extended over a period of more than seven years and ended in July 2001 with the reentry of the satellite. The GRB monitor consisted of a single CsI (Na) detector of 76 mm diameter and 12.7 mm thickness, covering energy interval of 20 keV to 3 MeV. Apart from having the capability of recording the timing and spectral profiles of the events, this also had capability of storing pre-trigger data unto T-65 s, using onboard memory[10].

The GRB experiment on SROSS C-2 detected 53 GRB events during its seven year life. Of these events, 26 bursts were concurrently detected by BATSE and other contemporaries. The location of these bursts was, therefore, derived by combining SROSS C-2 data with those from BATSE and other GRB experiments. A detailed analysis of these events is given by Sinha *et al.*[11]. Timing analysis of the 53 GRBs showed that some events had duration of less than 2 s, with harder spectra and the remaining bursts were longer than 2 s, with relatively softer spectra. This is consistent with bimodal distribution of burst duration obtained by BATSE, based on a very large GRB dataset. Light curves of a few GRBs detected by SROSS C-2 are shown in Figure 2 (ref. 10). A new Soft Gamma-ray Repeater (SGR) SGR 1627-41 was discovered by the BATSE experiment on 18 June 1998 and confirmed from the burst spectrometer on KONUS-Wind. The GRB monitor on SROSS C-2 detected the same burst from SGR 1627-41 on 18 June 1998 at 6151.6 s UT and another burst at 14662.08 s UT. One more burst from the same source was detected on 7 April 2000.

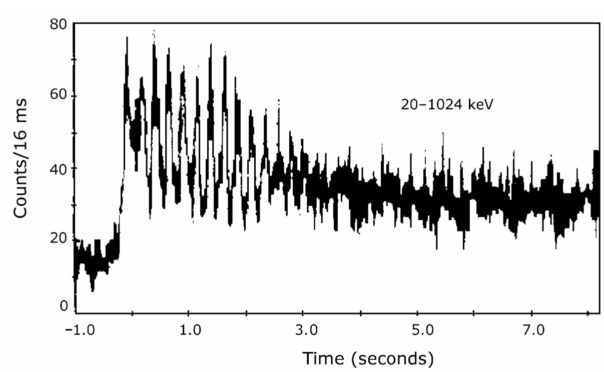

Figure 1. Light curve of a gamma-ray burst-like event, detected by SROSS-C GRB experiment on 29 June 1992. Oscillations with a period of 237 ms can be seen clearly.

The Indian X-ray astronomy experiment

The IXAE was a collaborative effort of TIFR and ISAC and its principal objective was the study of periodic and aperiodic variability of different types of X-ray binaries. This included measurement of pulsation period and its rate of change in X-ray pulsars, detection and measurement of quasi-periodic oscillations (QPOs) in black hole and neutron star binaries, study of flaring and sporadic variability, detection and study of new X-ray transients, etc. The main component of IXAE instrument was a set of three identical, co-aligned pointed proportional counters (PPCs) with a total effective area of about 1200 cm^2 and a field of view of $2.3° \times 2.3°$ defined by a honey comb-shaped passive collimator. Details of IXAE instrument are given by Agrawal *et al.*[12].

The IXAE was launched aboard the IRS-P3 satellite by the PSLV on 21 March 1996 into a 830 km circular polar orbit, with an inclination of 98º to the equatorial plane. The polar orbit of the satellite produces high and variable background in PPCs, due to high flux of electrons at latitudes of >45º. A majority of the orbits also pass through the South Atlantic Anomaly (SAA) region, which is a zone of high fluxes of charged particles. This restricted the useful observation time to typically 20 min per orbit and 6 orbits per day.

Studies of the micro-quasar GRS 1915+105: The X-ray source GRS 1915 + 105 discovered in 1992 was found to be a variable radio source that exhibited quasar-like superluminal motion and hence, termed as a micro-quasar. Not much was known about its X-ray behaviour till 1995, when RXTE and independently IXAE detected rapid erratic X-ray intensity variations and also discovered low frequency QPOs. This object was repeatedly observed with the IXAE over a 5-year period and a host of new and interesting phenomena were detected in it. Chaotic and rapid intensity variations over the time scale as small as 100 ms were detected for the first time in this source from IXAE observations made during 23–27 July 1996. A strong QPO peak at ~0.7 Hz was also detected with fractional rms amplitude of 10% in the power density spectra of all the PPCs. The QPO frequency was found to drift in the range of 0.62–0.82 Hz (ref. 13). The rapid variability, power density spectrum similar to that of the well-known black hole binary Cyg X-1, high X-ray luminosity near super-Eddington and its peculiar radio features, strongly suggested that the X-ray source in GRS 1915 + 105 is a black hole.

More detailed follow up observations of the source were made during 12–29 June 1997. It was found to be in a bright state, producing strong quasi-periodic bursts during 12–17 June and 23–26 June, with a recurrence time of ~45 s with slow rise and fast decay. A sample of these bursts is shown in Figure 3, taken from Paul *et al.*[14]. The slow rise time of the bursts has been explained as arising due to the free-fall time of the matter, ejected from the accretion disk around the black hole and fast decay due to sudden disappearance of the matter behind the event horizon.

A more detailed and thorough analysis of different types of X-ray bursts observed with the IXAE was per-

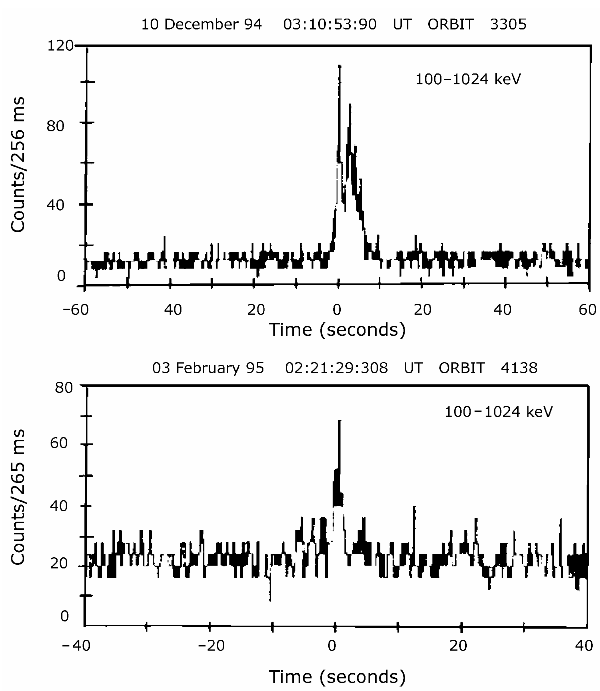

Figure 2. Two gamma-ray bursts observed with the Indian GRB experiment on the SROSS-C2 satellite.

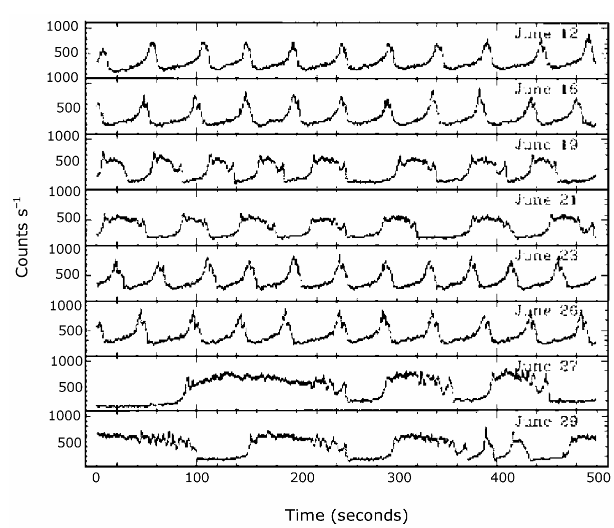

Figure 3. A series of quasi-periodic X-ray bursts, irregular and long bursts detected during 12–29 June 1997 from the micro-quasar GRS 1915+105 by the Indian X-ray astronomy experiment on the IRS-P3 satellite are shown.

formed by Yadav *et al.*[15] who found a strong correlation between the quiescent interval preceding a burst and the burst duration for the quasi-regular and irregular bursts. It was concluded that the source switched back and forth between the low-hard state and the high-soft state in a very short time, when the accretion rate was at a critical value, resulting in the production of the bursts. Another interesting discovery was the detection of X-ray 'dips' in the light curves of this source in the data of 6–17 June 1997, when the source made transition from a low-hard state to a chaotic state. The dips were detected on most of the days and their duration was in the range of 20–160 s. Onset of X-ray dips was followed by the occurrence of a huge radio flare. This led to the inference that the dips are the cause of the mass ejection, due to evacuation of matter from the accretion disk around the black hole and a superposition of a large number of the dips leads to production of radio flare and jet in the source[16]. Outside the dips ~4 Hz QPOs were detected, similar to those seen in the low-hard state, but the QPOs were absent in the dip region.

IXAE observations of some other black hole binaries: During the performance verification phase of IXAE, Cyg X-1 was observed during 1–11 May 1996 when it was in a low-hard state at a flux level of ~0.3–0.5 Crab. It was again observed in 5–8 July 1996 period, when it had moved to the bright state and was measured to have an intensity of ~0.8–1.1 Crab. The light curves in both the states show chaotic and rapid variability, with flaring activity typical of Cyg X-1. Bursts of 0.1 s and longer duration were present in both the states, but were more frequent in the hard state[17].

Cyg X-3 was another black hole object studied with the IXAE. Its intensity modulates with the binary period of 4.8 h. The evolution of the orbital period of Cyg X-3 was investigated from measurements of the binary period during 3–13 July 1999 and again during 11–14 October 1999. By combining the measurements obtained from IXAE with those from other earlier X-ray missions, the rate of change of orbital period was derived. This leads to a value of 1.05419×10^{-6}/year for the evolutionary time scale of the orbital period. Mass loss from the companion star is inferred to be the most likely cause for the orbital decay of Cyg X-3.

The IXAE also observed two X-ray transients namely XTE J1748-288 and XTE J2012 + 381 during their outbursts and monitored their intensities. Transient XTE J1748-288 was observed during its decay phase. Its brightness decayed exponentially with a decay time of 19 ± 1.6 days. There was no indication of any short-term variability and no QPOs were detected from the PDS of the source. The second transient XTE J 2012+381 underwent outburst on 24 May 1998 as reported by the All Sky Monitor on the Rossi X-ray Timing Explorer (RXTE). It was observed with the IXAE during 2–10 June 1998. Its light curve also showed exponential decay of the flux.

Studies of X-ray pulsars with the IXAE: The slow pulsar in the X-ray binary 4U 1907 + 09 with a pulsation period of 440 s and a binary period of 8.4 days was observed in August 1996 and again in June 1998. X-ray pulsations were clearly detected with a double-peak pulse profile. The primary pulse had an asymmetric shape and was separated from a weaker and broad secondary pulse by a dip. From accurate measurements of the pulsation period for the two observations, the spin-down rate of the neutron star was measured to be 0.23 ± 0.01 s per year consistent with the earlier measurements, indicating that the pulsar has been monotonically spinning-down, since its discovery. During August 1996 observation, IXAE detected a flare from 4U 1907 + 09 at a peak flux level of 88 mCrab shown in Figure 4 (ref. 18). Analysis of the outburst data revealed transient oscillations with a period of 14.4 s, similar to the 18.2 s oscillations reported from the RXTE observations during a flare that occurred in February 1996.

Transient pulsar Cepheus X-4 was observed with the IXAE during the decay phase for three days. Pulsations were detected at the known period of 66 s and the pulse profile showed luminosity-dependent changes. During the declining phase, the main-pulse dominated double pulse profile changed to inter-pulse dominated profile, when the X-ray luminosity fell to a value of 6×10^{35} ergs s^{-1}.

Another transient X-ray pulsar XTE J1946+274, which is a Be X-ray binary with an orbital period of ~80 days, was also observed with the IXAE in September 1999 and in June–July 2000. Strong pulsations with 15.8 s period were detected in both the observations with a double-peak profile and pulse fraction of ~30%. By combining data from the IXAE and those from BATSE and other satellites, the period derivative value was found to be -1.27×10^{-9} s s^{-1} consistent with constant spin-up of the neutron star.

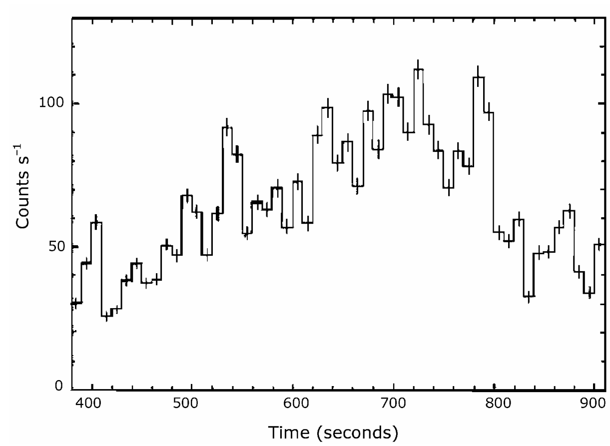

Figure 4. Light curve of the X-ray flare in the X-ray binary 4U 1907+09 detected by the Indian X-ray astronomy experiment on IRS-P3 satellite in August 1996.

Table 1. Astrosat instruments summary

	UVIT	LAXPC	SXT	CZT	SSM
Detector	Photon counting, CPM + CCD-based UV and optical detectors	Multilayer proportional counters	X-ray CCD (at the focal plane) of Wolter-1 conical foil mirrors	CdZnTe detector array	Position-sensitive proportional counter
Optics	Twin Ritchey–Chretian optics with 38 cm aperture primary	Honey-combed collimator	Conical foil mirrors (~Wolter-1)	2-D coded mask	1-D coded mask
Bandwidth	128–180 nm 180–300 nm 350–650 nm	3–80 keV	0.3–8 keV	15–100 keV	2–10 keV
Effective area (cm^2)	About 25 in 120–300 nm (depends on filter) 50 in 350–650 nm	6000 @ 5–30 keV 5000 @ 50 keV	125 @ 0.5 keV, 200 @ 1–2 keV, 25 @ 6 keV	500 (E>15 keV)	~40 @ 2 keV 90 @ 5 keV (Xe gas)
Field of view	0.50° diameter	1° × 1°	0.35° (FWHM)	17° × 17°	6° × 90°
Energy resolution (FWHM)	<100 nm (depends on choice of filters)	10% @ 22 keV	About 2–3% at 6 keV	5% at 60 keV (aiming at 3%)	19% @ 6 keV
Angular resolution	1 arsec	~1 to 5 arcmin (in scan mode only)	3–4 arcmin (HPD)	8 arcmin	~5–10 arcmin
Time resolution	1 s	10 microsec	2.6 s, 0.3 s, 1 ms	1 ms	1 ms
Sensitivity (obs. time in ks)	20 magnitude (4σ) in 50 nm band	0.1 mCrab ($3\ \sigma$) (1 K)	10 mCrab (5σ) (10 K)	0.5 mCrab (5σ) (10 K)	~30 mCrab (3σ) (0.3 K)

Indian multi-wavelength astronomy satellite 'Astrosat'

Astrosat is conceived to be a multi-wavelength astronomy mission that will cover soft X-rays (0.3–8 keV), hard X-rays (10–100 keV), near and far ultraviolet bands (120–300 nm) and visible band. The primary goal of the Astrosat is defined to be multi-wavelength studies to be realized by making simultaneous observations, with a set of co-aligned X-ray and UV instruments. The other main objectives of Astrosat are high time resolution X-ray variability studies, low and medium resolution measurement of continuum and spectral features, medium resolution X-ray imaging studies and simultaneous imaging and photometric observations in the visible, near-UV and far-UV bands for different classes of X-ray and UV sources. Astrosat has been designed for studies of time variability phenomena, like pulsations, high frequency QPOs, flaring activity, etc. in X-ray binaries and other variable sources, spectral measurement of all types of X-ray sources and obtaining energy spectra of these sources over five decades, in energy extending from visible to hard X-ray region through simultaneous observations. Astrosat will have improved sensitivity in the hard X-ray band that will facilitate detection and study of cyclotron lines, detection of non-thermal component in the spectra of black hole binaries, supernova remnants, clusters of galaxies, etc. It has been designed to have better sensitivity for detection of QPOs above 10 keV in X-ray binaries.

Astrosat is a national project, with international contributions, in which, a large number of Indian institutions like TIFR, ISAC, IIA, RRI, IUCAA, etc., are participating and contributing to the development of hardware. There are also two foreign partners, the Canadian Space Agency (CSA) and Leicester University (LU), UK facilitating the development of two important parts of the Astrosat instruments, namely, the photon counting detectors for the Ultraviolet Imaging Telescope (UVIT) by CSA and the X-ray CCD camera for the Soft X-ray Imaging Telescope (SXT) by LU. Several other centres of ISRO are designing and fabricating various components and sub-systems of the Astrosat instruments.

Astrosat instruments

The instruments planned for launch onboard Astrosat (Table 1) are: (i) Large Area X-ray Proportional Counters (LAXPCs); (ii) Cadmium-Zinc–Telluride Imager (CZTI); (iii) Soft X-ray Imaging Telescope (SXT); (iv) Scanning X-ray Sky Monitor (SSM); (v) Ultraviolet Imaging Telescope (UVIT). A description of the Astrosat instruments and their characteristics is given by Agrawal[19].

Astrosat mission details

The Astrosat will be a three-axis stabilized satellite, with a capability for orientation manoeuvres and attitude control, using reaction wheels and magnetic torquers, which get input from 3 gyros and 2 star sensors. It will have a pointing accuracy of about one arcsecond. A solid-state recorder with 120 Gb storage capacity will be used for on board storage of data. Two carriers, at a rate of 105 Mb/s, will transmit the payload data. The total mass of Astrosat observatory is estimated to be 1600 kg, including 868 kg mass of the scientific instruments. It will be launched into a 650 km altitude circular orbit, with an orbital inclination of 8° by the well-proven Polar Satellite Launch Vehicle (PSLV) from Satish Dhawan Space Centre (SDSC), Shriharikota by the end of the year 2008. The Astrosat will have a minimum mission life of five years.

Science expected from Astrosat

Multi-wavelength studies will be a unique capability of Astrosat that will improve the understanding of the radiation processes and the environment in the vicinity of the central compact objects in the AGNs. Observations of X-ray binaries will lead to understanding of the nature, environment, site and geometry of X-ray and UV emission of the compact objects. Variability studies over a wide spectral and time domain will probe the nature of the sources and the cause of variability. Detection and detailed studies of kHz QPOs in hard X-rays is an important object of Astrosat that is the key to probe the accretion flows closest to the compact source. One will be able to successfully search kHz QPOs from the X-ray sources with LAXPC, if the source intensity is above 50 mCrab.

The X-ray spectral measurements of the continuum and lines in 0.5–100 keV interval, from simultaneous observations will reveal origin of the different components of the spectra and parameters of the radiation processes. With an exposure of 1 day, LAXPCs will provide spectrum with good statistical significance for a 0.1 mCrab intensity X-ray source. The CZT imager will be able to detect a source of 0.5 mCrab in 1000 s and obtain a good spectrum in one day of observation. The sensitivity of the LAXPCs and the CZT array for measurement of magnetic field of neutron stars will be superior to that of any other existing experiment. A simulation of the expected signal in the LAXPC array for the cyclotron line fluxes detected from the X-ray pulsar 4U0115+63 with RXTE and comparison with the observed spectra from RXTE-PCA and BeppoSAX PDS[20] shows that the cyclotron lines will stand out very clearly in the LAXPC spectrum. Spectroscopy of hot thin collisional plasmas in galaxies, clusters of galaxies, supernova remnants and stellar coronae, and photo-ionized matter in accreting white dwarfs, neutron stars, black holes and AGNs would be carried out with SXT. With an energy resolution that is 10–50 times better than that of the proportional counters, SXT will separate the line emission and absorption components from the continuum in all known varieties of objects.

The imaging UVIT observations with ~2 arcsec angular resolution will measure the morphology and energy distribution of galaxies in the local region. It will also study star bursts in distant galaxies and map the ionized gas in them. It will map the Galactic H II regions, planetary nebulae and supernova remnants in our Galaxy as well as those in the nearby galaxies in various emission lines, e.g. CII (235 nm), CIII (190.9 nm), CIV (155 nm), O II (247 nm), etc. to map the elemental distribution and the physical condition of the gas. By studying early type hot OB stars in our Galaxy and their distribution in nearby galaxies, one will be able to obtain the star formation histories and enrichment of gas.

Planetary exploration

The planets in the solar system can be divided into three major groups, viz. the inner rocky planets (Mercury, Venus, Earth and Mars), the giant gaseous planets (Jupiter and Saturn) and the outer icy planets (Uranus and Neptune), besides the enigmatic Pluto, milliards of small bodies forming the asteroidal and Kuiper belts and the mysterious tenuous comets, which extend to the farthest reaches of the solar system, going out to about 100,000 AU. The past half a century of planetary exploration is considered to be extremely successful during which all the planets, their important satellites, comets and asteroids have been observed by the American, USSR, European and Japanese space missions from close distances. Samples of Moon and a comet have been brought back for laboratory analysis and meteorites originating in different asteroids and planetary bodies have been identified, giving us information about constituents of small bodies left from accretion of planets during earliest stages of the formation of planetary system.

There are two main goals of planetary exploration: (i) understanding the formation of planetary system from the solar nebula, various stages of chemical and geological evolution and their time scales and (ii) Assessment and exploitation of planetary resources. ISRO has recently initiated an ambitious programme of planetary exploration and some of these missions will be discussed later.

Pioneering survey of all the planets from Mercury to Pluto and their important satellites have been made by various space missions during the past half century and in many cases a detailed exploration has been carried out. All the planets and many of their satellites have been imaged in various wavelengths and examined using remote sensing techniques by Fly-by and Orbiter missions. Sample return missions have been given high priority because they complement the information obtained by remote sensing, provide ground truth and trace element and isotopic composition, which is crucial for identification of the source material and stages of chemical evolution, can only be determined in a well-equipped laboratory. Several

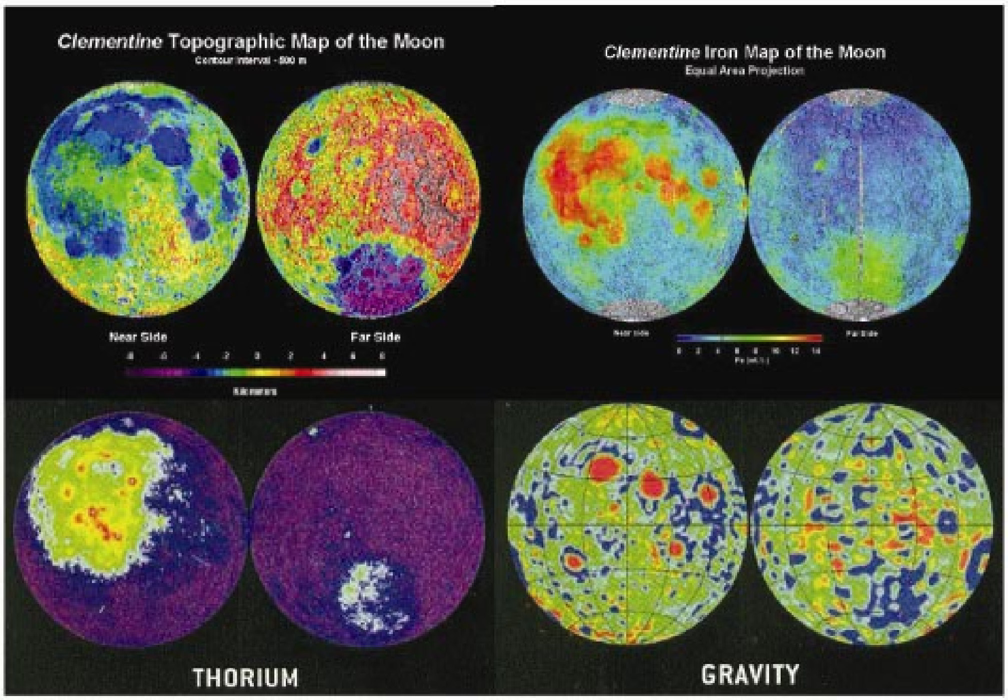

Figure 5. Clementine and Lunar Prospector data provided global maps of topography, albedo, elemental distribution (e.g. hydrogen, iron, titanium, thorium, potassium), gravity anomaly, etc. of both sides of Moon[25,29]. Some typical examples are shown above (courtesy: NASA).

hundred kilograms of samples collected from the surface of the Moon and one small sample from a comet WILD-2 have been brought back and samples of an asteroid have been collected and are currently on the way to earth.

Of all the planetary bodies in the solar system, the Moon has been studied in a most detailed manner by orbiters, landers, rovers and sample return missions, because of its proximity and the influence it has on the evolution of the Earth and life on Earth. Beginning with Surveyor landers on the Moon by NASA and six Apollo (Apollo 11, 12, 14, 15, 16 and 17) and three Luna (Luna 16, 20 and 24) sample return missions, the equatorial front side of the Moon has been studied in great detail. Samples from these nine identified locations and scores of lunar meteorites from unidentified locations of the moon which fell in Antarctica, are now available for a detailed physical, chemical, isotopic, mineralogical and geochronological study in the laboratory. The Indian effort in the study of the Moon and meteorites began in 1969 at TIFR when Apollo samples became available[21]. Subsequently, these studies continued at PRL and several aspects of lunar surface processes such as regolith dynamics, their time scales and interactions of solar flare protons and heavy nuclei were studied in Apollo and Luna samples using induced radioactivity (specifically ^{26}Al) and particle tracks, produced in lunar rocks[22–24]. During the past decade and half, Clementine, Lunar Prospector and Smart-1 have produced maps in several wavelength bands and added a wealth of information about lunar surface topography, gravity, albedo, chemical and mineral composition. Some of this information is summarized in Figure 5. Based on these studies, important stages in the early evolution of the lunar crust and its interior have been identified and a lunar calendar of major geologic events has been constructed. Some of these results have been summarized by Taylor[26] and Bhandari[27]. In spite of these studies, which included experiments conducted on the Moon as well as analysis of samples brought back from different regions and the lunar meteorites, the Moon remains the most mysterious body in the solar system; it is mysterious in the sense that its origin is not well understood. How Earth got to acquire such a large satellite, which was initially very close to Earth (~20 Earth radii), whose isotopic composition is the same as the Earth and chemistry is similar to the Earth's mantle still remains a puzzle. Is it a stray object captured by the Earth in an improbable close encounter or formed together with or around the Earth such as at one of its Lagrangian points, or by accumulation of Earth ejecta produced by large impacts or by some other more complicated process is a long-debated question. These considerations and the possibility that Moon had an important role in evolution of the Earth and evolution of life on Earth make it a special object for specific studies related to its formation, Moon–Earth interactions and orbital evolution.

Some salient features of the astronomical, chemical, mineralogical and geological aspects of the Moon have been summarized by Bhandari[27]. Based on exhaustive studies of lunar samples, some hypotheses have been proposed for the origin of the moon, the 'Giant Impact Hypothesis' being the most successful and accepted hypothesis[28]. It involves a chance collision of a large stray body (1/10th M_E) with the infant Earth and explains its chemical, isotopic and dynamical characteristics, but the composition of the impactor and formation of ancient mare on the Moon (believed to be produced due to Late Heavy Bombardment) remains partly unresolved. The question, whether the Moon was formed by such a chance event, i.e. by a fortuitous collision of a large body with the differentiated Earth, as proposed in the Giant Impact Hypothesis[28], and not as a consequence of the standard planetary formation process, by which planets form around the Sun and satellites around the planets, has important implications in understanding the formation of solar system.

Understanding the origin of Moon in the close vicinity of the Earth holds important clues to the origin and early evolution of Earth itself, as well as the evolution of life on Earth. It is for this reason that a concerted effort on exploration of the Moon is being undertaken by various space agencies. The major questions now confronting us about the Moon, besides its formation mechanism, are the internal structure, core and magma ocean formation, chemical and mineral stratigraphy. Much attention is given to the water–ice deposits at the lunar poles, because of their resource potential in establishing a human base on the Moon. However the lunar poles always remain dark, as they are located under the permanent shadow and sunlight does not reach there. Therefore lunar polar regions have not been studied so far in any detail.

The mechanism of transportation of volatiles on the moon from interior to the surface, from hot surface to cooler night side and then its deposition on the poles, is also not well understood. The database (Figure 5) is taken as the starting point for Chandrayaan-1 mission and based on the questions mentioned above, Chandrayaan-1, the orbiter mission to Moon proposed by ISRO was designed.

Although each planet in the solar system is unique and scientifically interesting, Mars has received much attention because the environment there appears to be suitable for sustaining life. Among the various new results obtained from current missions to Mars, sedimentary records and ancient flow channels of liquid water and possibility of recent water–ice deposits and its transport have been found, making it the most exciting planet for future exploration.

ISRO has now embarked on a long and sustained programme of planetary exploration, the first among these is going to be an orbiter mission to the Moon. This mission christened Chandrayaan-1 was approved in 2003 and is scheduled for launch in 2008. Simultaneously, several space agencies are planning to send missions to moon and during the next year there may be four missions orbiting the Moon. Japan's SELENE mission was launched on 14 September 2007 and China's Chang'E probe was launched on 24 October 2007. In 2008, Chandrayaan-1 will be launched which will be followed by the Lunar Reconnaissance Orbiter of USA. All these missions are orbiters equipped with remote sensing instruments, designed to study the lunar surface composition, mineral composition at high spatial resolution, lunar resources, etc.

Chandrayaan-1

Chandrayaan-1 is a lunar polar orbiter for remote sensing of the Moon from a nominal altitude of about 100 km. The primary objective of this mission is to carry out topographic, chemical, mineral and radioactive mapping of the Moon with a high spatial resolution. It will collect data for a period of two years (2008–2010) and the whole Moon will be mapped in visible, near IR and X-rays. The science goals and launch profile have been described elsewhere[27,29].

Chandrayaan-1 instruments: Chandrayaan-1 has eleven payloads, and includes a Moon impact probe. Some of the instruments onboard Chandrayaan-1 and the imaging strategy have been discussed in the Proceedings of the International Conference on Exploration and Utilization of Moon[29]. Five payloads on this mission, i.e. Terrain Mapping Camera (TMC), Lunar Laser Ranging Instrument (LLRI), Hyper-Spectral Imager (HySI), High Energy X-ray spectrometer (HEX) and Moon Impact Probe (MIP) are the Indian payloads. Several institutions are participating in developing these instruments. The imaging cameras TMC and HySI are being developed at Space Applications Centre (SAC), LLRI at Laboratory for Electro-Optics Systems (LEOS), development of HEX is a joint effort of Physical Research Laboratory (PRL) and ISRO Satellite Centre (ISAC), and VSSC is responsible for MIP. Besides, there is also a significant international participation in Chandrayaan-1. The X-ray fluorescence spectrometer (C1XS, Chandrayaan-1 X-ray Spectrometer) and Sub-keV Atom Reflecting Analyser (SARA) are joint payloads between Indian and foreign groups. Four other international payloads are: a Miniature Synthetic Aperture Radar (mini-SAR) and Moon Mineralogical Mapper (M^3), both from USA, an infra red camera (SIR-2) from Germany (European Space Agency) and a Radiation Dose Monitor (RADOM) from Bulgaria. Figure 6 shows various payloads and the impactor on the Chandrayaan-satellite. Salient features and science goals of various payloads are summarized in Table 2. The impactor has a Moon imaging system, a mass spectrometer and an altimeter and will make observations during its descent, before crash landing on the Moon.

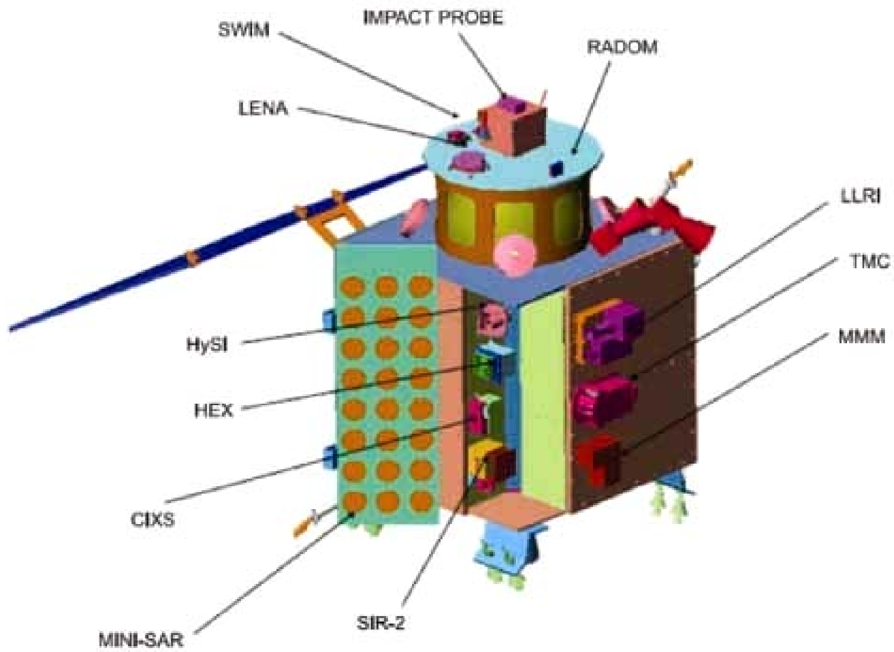

Figure 6. Sketch of Chandrayaan-1 lunar craft with ensemble of 11 payloads and the impactor.

The major elemental composition will be determined by X-ray fluorescence technique by C1XS. The characteristic fluorescence X-rays from the elements present in the lunar surface are produced by solar X-ray flares. A large number of energetic flares are expected during 2008–2010, which is the rising phase of solar activity cycle. It is expected that distribution of major elements like Mg, Al and Si will be mapped over much of the Moon and, if the solar X-ray flare energy is high enough, Ca, Ti and Fe concentrations can also be measured in segmental areas, determined by timing of solar flares and observational geometry of Chandrayaan-1. A solar X-ray monitor (XSM) onboard Chandrayaan-1 will measure the flare intensity and energy spectrum, which will be used for determining the elemental concentration. Hyper-spectral imager, infrared spectrometer (SIR-2) and moon mineralogical mapper will provide information on mineral composition. In view of the importance of mineral mapping, particularly of water and organic deposits, three spectrometers are being flown, allowing some redundancy. Together, these spectrometers will cover the spectral range from 400 to 3000 nm in continuous bands with a high resolution. The terrain-mapping camera will provide high-resolution topographic map of the whole Moon. The high energy X-ray spectrometer will map thorium and radon daughter product ^{210}Pb. The mini-SAR will provide subsurface composition, especially presence of water ice. Thus water-ice, if present, can be detected by several of these instruments, discussed above. SARA will look for neutrals in the lunar environment. Radiation dose due to solar and galactic cosmic rays will be monitored by RADOM.

Science expected from Chandrayaan-1: All these instruments are designed to provide a high-resolution distribution of several key elements, radioactive nuclides, major minerals and water–ice. It is expected that the chemical, mineral and radioactivity distribution on the Moon determined by Chandryaan-1 will be useful in determining the stratigraphic relationship of various litho units, which should provide crucial information on early evolution of the Moon. The mission should enable us to understand transport and deposition mechanism of volatiles, such as water–ice and organics from hot day-side to cool night-side and ultimately to the dark and cool lunar polar regions. These studies should also enable better appreciation of resources available on Moon. Some prime targets on the Moon for a detailed study have also been identified.

In view of the fact that four missions, SELENE, Chang'E, Chandrayaan-1 and LRO may all be there around the Moon at the same time and will have a long overlapping period of observation, possibilities exist for coordinated study by some of these missions and cooperation in carrying out some observations. Two or more of these spacecrafts may simultaneously observe the moon for several months during 2007–2010. Therefore, apart from this international collaboration on instrumentation on Chandrayaan-1 discussed above, possibility of data sharing and further

Table 2. Payloads for Chandrayaan-1 and their science goals

Payload	Sensor configuration	Wavelength/energy range	Spatial resolution	Objective
Hyperspectral Imager (HySI)	Wedge filter pixelated imager	0.4–0.92 μm with 15 nm resolution using 64 channels	80 m	Areal mapping of minerals
Infra red Spectrometer (SIR-2)	Grating spectrometer	0.93–2.4 μm	100 m	Linear mapping of minerals
Moon Mineral Mapper (M^3)	Grating spectrometer and HgCdTe detector	0.7–3.0 μm with 10 nm resolution	30 m	Areal mineral and resource (water, organics) mapping
Terrain Mapping Camera (TMC)	Three stereo cameras with pixelated detectors	Panchromatic	10 m areal 5 m elevation	Topographic mapping
Laser Ranging (LLRI)	Pulsed Nd–Yag laser with optical system	1064 nm	Elevation 10 m	Topography, Chandrayaan altimetry
X-ray Fluorescence Spectrometer (C1XS)	Swept charged CCD	1–10 keV	20 km	Chemical mapping (Mg, Al, Si, Ca, Ti, Fe)
Solar X-ray Monitor (XSM)	Si pin diode	2–10 keV	–	Solar X-ray spectrum
High Energy X-ray Spectrometer (HEX)	CdZnTe detector	20–250 keV	40 km	Th, ^{210}Pb mapping
Synthetic Aperture Radar (mini SAR)	Radar, scatterometer and altimeter	2.4 GHz	100 m	Soil properties topography, altimetery
Neutral Atom Analyser (SARA)	Mass spectrometer and solar wind monitor	10 ev–keV	100 m	Atmospheric neutrals (H–Fe) composition, magnetic anomalies
Radiation Dose Monitor (RADOM)	Si semiconductor	>8 keV	–	Radiation dose

co-operation and collaboration between some of these missions exist, so that, one mission may benefit from the data of the previous mission and suitably modify its activity, if possible. Also, there are several possibilities of in-orbit collaboration. For example, (i) Impact of a lunar craft of one mission may be observed by other missions to learn about the lunar surface characteristics and (ii) Bistatic radar observations of regions of interest, such as south polar regions using mini-SAR on Chandrayaan-1 and similar instruments on LRO can be carried out.

Lunar exploration beyond Chandrayaan-1

Moon will continue to remain an object of study because the process by which it was formed in orbit around the Earth is not fully understood and there is an element of chance involved in the various hypotheses proposed so far. In view of its importance in understanding the early evolution of the Earth, life on Earth and its ancient interplanetary environment, Chandrayaan-1 should be followed by a series of unmanned orbiters and subsequently, sample return missions. There are many options in defining future missions but, an orbiter-lander pair, with remote sensing payloads such as ultraviolet imagers, and neutron flux monitors, which are complementary to Chandrayaan-1 with an objective of focused study on specific areas of interest, determined by the Chandrayaan-1 data appears to be a good choice. A rover mission is already under consideration of ISRO. The prime samples of scientific interest are long cores through the regolith and bedrock, which will provide a wealth of information about the earliest events on the Moon. Arrhenius *et al*.[30] have shown that such cores on the Moon represent sequential deposits over time and may contain a record of the Moon's evolution from the very beginning. Site selection for cores and any surface experiments have to be done carefully. Some of the potentially interesting sites, where the lower crust or upper mantle may be exposed, such as in South Pole Aitken region have been discussed[31]. Automatic coring and sample return was demonstrated by the Soviet Luna missions in the 1970s. These cores were about a metre long, but the same technology can be modified to retrieve longer cores. This is technically a challenging proposition but could be scientifically most rewarding.

Apart from missions to Moon, ISRO is also considering missions to Mars, comets and asteroids during the next two decades. NASA, ESA and JAXA have ambitious plans of planetary missions to Mercury, Venus, Kuiper Belt and other solar system bodies, with permanent human base on Moon and thus the coming decades may turn out to be an exciting era of planetary exploration.

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ACKNOWLEDGEMENTS. P.C.A. thanks the members of the Astrosat instrument teams for providing valuable inputs used in the preparation of the Astrosat satellite-related part of this article. A part of this article related to Space Astronomy has been written by P. C. Agrawal and B. V. Sreekantan, while the part on Planetary Exploration has been written by N. Bhandari. N.B. thanks Indian National Science Academy for Honorary Scientist grant.