Rocket-and satellite-borne X-ray and $\gamma$-ray experiments

R K Manchanda
Tata Institute of Fundamental Research, Colaba, Bombay 400 005

The spectacular progress in X-ray astronomy during the last 3 decades has followed the successful refinements and adoption of measuring techniques in the X-ray range. Various observational methods employed in the astronomical observations are similar to those used in a radiation physics laboratory. The main considerations which characterize the experiments in X-ray astronomy are: (i) the strong attenuation of the X-ray photons in the atmosphere thereby requiring observations at higher altitudes above 40 km and (ii) the photon limited regime, because the photon flux from even the strongest X-ray source is so low that individual photon counting is unavoidable. This coupled with the fact that absorption cross-sections at higher X-ray energies are quite low, makes the choice of X-ray detectors for astronomical use rather limited. This, in turn, has limited the variety of experiments being conducted in the X-ray and $\gamma$-ray regions. Presently, apart from the state-of-art detectors, many new concepts specifically applicable to X-ray bands age being explored. This paper traces the history of the rocket-and satellite-borne instruments and presents a brief summary of the current practices and future projections.

1 Overview

X-ray astronomy is relatively of a recent origin. The chance discovery of the first X-ray source was made in 1962 during a rocket-borne experiment to study the fluorescent emission from moon by Giacconi et al.1 using Geiger-Mueller (GM) counters. Soon after, a large number of groups joined in to study the X-ray emission from the extra-terrestrial objects using rockets in the low energy band and balloons in the high energy region. The period 1962-1971 can be called the 'golden era' for the rocket experiments during which many important results were obtained.3,5

The first satellite experiment on board UHURU, consisting of a 800 cm$^2$ proportional counter with the detection energy range of 2-10 keV, was launched in 1970. Since then many successful satellite experiments containing a variety of instruments have been launched. The timeline is shown in Table 1. Soon after the launch of the UHURU satellite, the emphasis of the rocket-borne experiments shifted to the ultra-soft energies below 2 keV until 1982, after which rockets are no more in use for X-ray astronomy experiments.5,6

In the case of $\gamma$-ray astronomy, the first dedicated satellite for astronomical observations in the energy range above 20 MeV was SAS-II followed by COS-B, HEAO-C and the currently operational Compton $\gamma$-ray observatory.9-10 Due to very difficult nature of the detection of high energy photons the energy space between 1 and 10 MeV is hardly explored.

In the case of rocket-and satellite-borne experiments, the high atmospheric X-ray and $\gamma$-ray backgrounds are absent. However, the presence of background produced locally by the interaction of charged particles with the detector and satellites is the limiting factor specially in the hard X-rays and low energy $\gamma$-ray region.11

Traditionally, the entire X-ray band between 100 eV and 1 MeV has been divided as: ultra-soft, soft, hard X-rays and soft $\gamma$-rays region. This

<table>
<thead>
<tr>
<th>Timeline</th>
<th>Successful X-ray/$\gamma$-ray satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td>1962</td>
<td>: Discovery</td>
</tr>
<tr>
<td>1962-1972</td>
<td>: Golden era for rocket-borne experiments</td>
</tr>
<tr>
<td>1970</td>
<td>: First X-ray astronomy satellite UHURU</td>
</tr>
<tr>
<td>Small (X)</td>
<td>: OSO-7, ANS, ARIEL-V, HAKUCHO, OSO-8, TENMA</td>
</tr>
<tr>
<td>Large (X)</td>
<td>: SAS-II, COS-B</td>
</tr>
<tr>
<td>($\gamma$)</td>
<td>: HEAO-A, Einstein, EXOSAT, GINGA, ASCA, GRANAT, ROSAT</td>
</tr>
<tr>
<td>($\gamma$)</td>
<td>: HEAO-C COMPTON</td>
</tr>
<tr>
<td>1995 onwards</td>
<td>: Expected as follows</td>
</tr>
<tr>
<td>2000 onwards</td>
<td>: Expected as follows</td>
</tr>
</tbody>
</table>
division, though arbitrary, actually came about due to different experimental methods employed in the different energy bands and the vehicle used during the early experiments. Unlike optical and radio astronomy the study of X-rays cannot be performed from ground. This is due to the strong absorption by the earth's atmosphere. Figure 1 shows the transmission of the X-ray wavelengths through the atmosphere.

It is clearly seen from Fig. 1 that apart from the optical region very limited bands are available for observation from ground. At X-ray wavelengths observation heights are above 250 km for $\lambda < 50$ Å, above 80 km for $\lambda < 6$ Å, and above 35 km for $\lambda < 0.7$ Å. As a convention various energy bands are defined as: ultra-soft X-rays (0.1-2 keV); soft X-rays (2-10 keV); hard X-rays (20-1000 keV) and soft $\gamma$-rays (above 1 MeV).

Barring the atmospheric attenuation as discussed earlier, X-ray photons can travel extremely large interstellar distances without being absorbed. This is because the opacity of interstellar medium decreases rapidly at energies above 27.0 eV corresponding to K-edge of the neutral helium which forms 20% of the interstellar matter density. The extent of the sky visible at different X-ray wavelengths with attenuation of $1/e$, $1/10$ and $1/100$ for the incident beam is shown in Fig. 2.

Below 10 keV, it is possible to concentrate the incoming flux from a large collector area onto a small detector, thereby giving both a fine angular resolution and high sensitivity. For observations above ~10 keV, the primary requirement is large-area detectors with low internal background. Despite remarkable success in the low energy X-ray astronomy, the high energy regime is relatively unexplored. This is mainly due to fundamental limitations arising from the sensitivity of the detector systems.
The detectors used in the study of charged particles measure the energy loss suffered by the particles due to ionization in the detector media. However, the process of photon detection by the detectors involves first the conversion of the incident photon energy into kinetic energy of one or more charged particles, or the excitation of the electron population leading to fluorescence emission which lies in the optical or ultraviolet range.

The main detector systems employed in the X-ray astronomy are the gas proportional counters, gas scintillation counters and the inorganic scintillators, though in some cases, solid state detectors, channel plate multipliers and more recently X-ray CCD's have been used as a focal plane detector. Also, quite often special techniques have to be employed to reduce the background and unfolding of the observed data. Recent developments in building large-area-ultrahigh-pressure proportional counters\(^{1,3,14}\) and large-area imaging detectors\(^{15}\) for hard X-ray photons above 20 keV, appear very promising for future work. The development of large aperture \(\gamma\)-ray lens using 'Laue' transmission geometry\(^{16}\) will usher the field of narrow line \(\gamma\)-ray astronomy.

**2 Necessary and sufficient criteria for X/\(\gamma\)-ray detector**

There are three basic requirements for any astronomical instrument, namely, (i) detection sensitivity, (ii) spectral sensitivity (energy resolution) and (iii) spatial sensitivity (imaging quality/position sensitivity).

Among these, first two are connected to the size of the collector and the detector, the second one to the detector alone and the third with the detector and telescope configuration. Once we discuss these properties in reference to the X-ray astronomy, requirements for the types of detector systems used in astronomical observations shall become more apparent.

**2.1 Detection sensitivity**

This parameter determines the energy dependent limit of minimum flux necessary for the determination of spectra of photon sources. There are three main modes by which a photon interacts in any neutral medium\(^{17}\). These are: photoelectric absorption, Compton scattering and the pair production process. In the X-ray region the dominant interactions to be considered are the first two, since the photon energies are restricted to below the pair threshold energy. In the \(\gamma\)-ray region pair production is the main mechanism of photon interaction.

**Photoelectric effect:**

This is the dominant mode of photon detection for energies below 200 keV. In this process, an incident photon interacts with an atom and is completely absorbed and usually a \(K\)-shell electron is ejected with a kinetic energy given by the difference of incident energy and the binding energy of the \(K\)-electron. The ejected electron may further ionize the medium, thereby giving rise to a primary charge cloud. The process is associated either by emission of a \(K\)-fluorescence photon in the form of \(K_{\alpha}, K_{\beta}\) and \(K_{\gamma}\), etc. and followed by the lower cascade or by ejection of a second electron (Auger effect) with energy close to binding energy. The photoelectric absorption process leads to complete energy conversion of the incident photons into thermal electron cloud. Since the primary mode of interaction in photoelectric process is between the photon and shell electrons, the cross-section increases as \(Z^4\), but decreases with increasing photon energy as \(-E^{-3}\). The photoelectric cross-section exhibits discontinuity corresponding to the resonance absorption at energies equal to the binding energies of different shells. The average response of such a medium can, therefore, be written as

\[
\frac{dl}{l} = -\mu dx 
\]

for a monoenergetic beam of incident photons, where \(dx\) is the material traversed in gm.cm\(^{-1}\) and \(\mu\) is the mass absorption coefficient in units of cm\(^2\).gm\(^{-1}\). For a finite thickness the relation can be integrated and written in the form \(I = I_0 e^{-\mu t}\).

**Compton scattering:**

Above 200 keV, Compton interaction between the incident photon and the shell electron is the main mode of photon absorption. In this process, an incident photon imparts a fraction of its energy to any electron during each scattering episode. Thus even the multiple scattering may or may not lead to complete absorption of the photon due to finite thickness of the detecting media. The scattering cross-section scales as \(Z\) value of the atom. Clearly, energy determination of the incoming photons in the Compton regime is highly uncertain, if these are not fully absorbed in the detector. Further, difficulty arises due to the fact that the energy lost during each interaction also depends on the angle of scattering. By considering the conservation of energy and momentum, one can write

\[
E' = \frac{E}{1 + \frac{E}{m_0c^2}(1 - \cos \theta)} \quad \ldots (2)
\]
and

\[ T = \frac{\epsilon (1 - \cos \theta)}{m_0 c^2} + \frac{1}{\epsilon} \]  \hspace{1cm} \text{(3)}

where, \( \epsilon, \epsilon' \) and \( T \) represent, respectively, the energy of the incoming and outgoing photon and the kinetic energy imparted to the electron. It is to be noted that maximum value of energy change is achieved for \( \theta = \pi \), which leads to

\[ \frac{\epsilon'}{\epsilon} = 1 + \frac{2 \epsilon}{m_0 c^2} \]

and

\[ T_{\text{max}} = \frac{2 \epsilon^2}{2 + m_0 c^2} \]  \hspace{1cm} \text{(4)}

Pair production:

In this process, the incident photon is annihilated in the presence of the Coulomb field of a nucleus with the creation of an electron-positron pair whose combined energy is equal to the photon energy.

\[ E_f = E_e + E_{\gamma} + 2m_e c^2 \]  \hspace{1cm} \text{(5)}

where, \( E_e \) and \( E_{\gamma} \) are the kinetic energies at the instant of creation. For typical energies, both the electron and the positron rapidly lose their energy to the absorbing medium. The threshold kinetic energy for the pair-production process is given by

\[ E_{\text{th}} = 2m_e c^2 (1 + m_e/M) \]  \hspace{1cm} \text{(6)}

where, \( M \) is the mass of the absorbing medium. In the case of known absorbing media \((M > m_e)\) the minimum \( \gamma \)-ray energy is 1.022 MeV, the rest mass of the electron pair. In the field of electron, the threshold is 2.044 MeV \((= 4m_e c^2)\) and the recoil energy of the electron is quite large. The probability of the pair production rapidly increases linearly above the threshold energy to about 50 MeV, after which it reaches the asymptotic value of \( 7/9 \) per radiation length \( b \). The most probable value of the opening angle at the point of creation is

\[ \theta' = \frac{90}{E_\gamma [\text{MeV}]} \]  \hspace{1cm} \text{degrees} \hspace{1cm} \text{(7)}

which gives a value of \( -9^\circ \) for \( E_\gamma = 10 \) MeV and \( -0.9^\circ \) for \( E_\gamma = 100 \) MeV and the root mean square angle between the trajectory of the pair electron and that of the parent photon at the point of creation is given by

\[ (\theta')^{1/2} = q' (E_\gamma, E_e, Z) \ln(e) \]  \hspace{1cm} \text{(8)}

where, \( q'(E_\gamma, E_e, Z) \) is a function of the order of unity. When averaged over electron energy, the calculated angle varies from \( \sim 4^\circ \) at \( E_\gamma = 30 \) MeV to \( \sim 1.5^\circ \) at \( E_\gamma = 100 \) MeV, to \( \sim 0.2^\circ \) at \( E_\gamma = 1000 \) MeV. The measurement of pair angle and the trajectory can, therefore, be used to evaluate the energy and the arrival direction of the incoming photons at \( \gamma \)-ray energies.

2.1.1 Geometrical constraints—From the above discussion, it is apparent that to achieve high detection efficiency the geometry of the X-ray detectors must have sufficient interaction depth to absorb the incident photon directly or via multiple Compton scattering and also the secondary photons or electrons produced in these processes. In case of the incomplete energy loss by the photons, the computed incident energy will give degenerate values. At \( \gamma \)-ray energies, it is important that pair angle is determined with precision, since in traversing the absorbing medium the pair electrons may suffer severe multiple Coulomb scattering which can then lead to large systematic errors in the estimation of photon energy and its arrival direction.

2.1.2 Statistical constraints—Apart from the sheer detection in the X-ray band, the aim of these measurements is to study spectral and temporal structures in the X-ray flux from variety of sources. Therefore, the choice and design of any detector system for X-ray astronomy is critically dependent on the statistical significance it can provide in a given observation band. It is due to this reason that despite a remarkable success in the low energy X-ray astronomy in the past two decades, the high energy regime is relatively unexplored and this is mainly due to low sensitivity, determined by the statistical variations in the large background of the available detector systems.

Even in the absence of an incident signal, any detector and its associated measuring system does give a background signal in the form of number of detected pulses, say, \( N \) per sec. The measure of the true signal is, therefore, in terms of probability that the increase is not due to statistical fluctuation of the background counts. In the Poisson limit for a large \( N \), the standard deviation, \( \sigma \), is written as \( \sigma = \sqrt{N} \). In the absence of any systematic effects the population of \( N \) will be ran-
domly distributed and therefore, the probability of occurrence of statistical fluctuation for $3\sigma$ is $2.7 \times 10^{-3}$ and for $5\sigma$ is $5.7 \times 10^{-7}$.

In practice, the detector background consists of (i) internal background of the detector and the unfiltered electronics noise, (ii) induced background due to interaction of cosmic rays in the detector and its surroundings, (iii) diffused cosmic X-ray flux and (iv) atmospheric X-rays in the case of measurements at balloon altitudes. Sensitivity of a given detector system having a background counting rate of $B(\text{ct}) \text{ cm}^{-2} \text{ s}^{-1}$ in the energy bands $E_1$ and $E_2$ can, therefore, be written as

$$S_{\text{min}}(E_1, E_2, t) \geq \frac{N_{\text{id}} \sqrt{B A t}}{\eta A \Delta E t} \quad \ldots (9)$$

where, $A$ is the area of the detector, $t$ the time of observation, $\Delta E$ the energy interval between $E_1$ and $E_2$, $\eta$ the average detection efficiency in the energy band and $N_{\text{id}}$ the number of $\sigma$ at which the detection is demanded.

The background counting rate $B$ itself consists of two main components, namely, $B_1$, corresponding to the internal background and $B_2$, the diffused background entering through the detector aperture and can be further written as

$$B = B_1 + \Omega \int_{E_1}^{E_2} N(\varepsilon) d\varepsilon \eta(\varepsilon) \quad \ldots (10)$$

where, $\Omega$ is the solid angle for the detector, $N(\varepsilon) d\varepsilon$ is the number spectrum of the external background flux in units of $\text{ct cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \text{ sr}^{-1}$ and $\eta(\varepsilon)$ gives the detection efficiency at energy $\varepsilon$.

From Eqs (9) and (10), it is apparent that a minimum of $3-5 \sigma$ statistical significance is a must for certainty that an observed signal is real. This, in turn, constrains the solid angle and area requirement of the detector. The minimum detectable flux can be lowered by choosing very large area detector with narrow field of view and the time of observation. The detection threshold also constrains the level of limiting temporal variations which can be studied by a given detector system.

2.1.3 Observational constraints—Further constraints on the detector area and the techniques of reducing the inherent background come from the observed spectra of the X-rays sources. Figure 3 gives a sample of the energy spectra for a variety of galactic and extra-galactic X-ray sources like, binary X-ray sources of different types, bulge sources, supernova remnants, AGNs and galactic clusters. The important point to be noted is that, in general, photon flux drops steeply with increasing energy. Therefore, the detectable source flux limit for a given detector strongly depends on the energy range of observation or conversely, a positive detection of a signal from a source in a given energy band requires tuning and optimization of various parameters for that band. The measurement of temporal variability in the X-ray source spectra as seen in Fig. 4, also depends on the detector sensitivity, inherent background and ambient photon flux. The temporal resolution of a detector is, therefore, a complex function of detector sensitivity and the time bin.

2.2 Spectral sensitivity

The spectral sensitivity of a detector determines its ability to reproduce the incident spectra which, in turn, depends on the energy resolution of the detector. The ability to detect mono-energetic line emission in the spectra of X-ray and $\gamma$-ray sources is very essential feature for any X-ray spectrometer. Scientifically, nuclear lines in the

![Fig. 3 — Sample energy spectra of various types of X-ray sources](image-url)
The 511 keV line emission in the source spectra can easily originate due to annihilation of the electrons and positrons in the relativistic plasma. The cyclotron line emission arising from the extremely high magnetic field near the neutron stars falls in the X-ray region and has been observed in the case of a few objects. Sample spectra of X-ray sources with the cyclotron line feature are shown in Fig. 5, and Figs 6 and 7 give the computed X-ray line emission from an optically thin relativistic plasma at various temperatures $10^5 < T < 10^7$ and the calculated γ-ray flux for the supernova 1987 A.

The spectral lines are produced in sources under a variety of conditions of high gravitation, radiation and magnetic fields and these may be further broadened by the Doppler effect. Thus, the line studies can provide information on densities, winds and coronae of hot and flaring stars, accretion processes around the compact objects, nuclear processes in the astrophysical plasma, temperature and pressure structures in the case of supernova remnants, radiation processes in the AGNs. The unambiguous identification of various spectral lines, their profiles and accurate determination of their emitting elements are, therefore, essential and requires high energy resolution for the photon detectors.

2.3 Spatial sensitivity
Spatial resolution of a detector defines its ability to geometrically resolve between two incident photons, or the secondary components produced.
Spatial resolution of a detector, in turn, defines the best achievable angular resolution of the X/γ-ray instrument. Imaging in X-rays has become essential for identification of the X-ray sources with other astronomical objects emitting in different wave bands like radio, infrared, etc. bands. Figure 8 gives the X-ray image of M 31 as seen with the Einstein observatory. A total of 67 sources were resolved by the focusing telescope. Figure 8 clearly demonstrates the need of imaging in X-ray and γ-ray energies. With the increase in the population of X-ray sources, angular resolution of few arc min is essential to avoid the source confusion, specially, for studying the galactic disk region. In addition, an imager allows the simultaneous measurement of background and the source, which is crucial at low flux levels. Systematic mapping of the sky with high angular resolution in the hard X-ray region, has been lacking due to limitation of the spatial resolution of the detector systems and imaging capability of the instruments. The past sky surveys in 20-200 keV range have, therefore, relied on detectors using a few square degree collimators. Imaging capability with good angular resolution is essential for localizing the hard X-ray sources.

3 Available detector systems
The commonly used detectors both as a focal plane instrument or a stand-alone large throughput detector, in the X-ray range are (i) proportional counters, (ii) scintillation counters and (iii) solid state detectors. The X-ray CCDs, X-ray bolometers and microchannel plates are still in the definition and development stages. The prime detectors used in the case of γ-ray region below 20 MeV are scintillation counters and solid state detectors. Beyond 20 MeV, the available detectors are ‘spark chambers’ and ‘drift chambers’

3.1 Proportional counters
In its basic form, a proportional counter consists of a gas-filled thin-walled tube with a coaxial anode attached to a high voltage power supply. The incident photon interacts in the gas volume creating electron-ion pairs. In the presence of an electric field, the charges drift towards the respective electrode. A large number of collisions occur
between the charges and the neutral gas atoms during the migration process. A minimum ionizing particle releases about 120 ion pairs. With a detector capacitance of 12 pf, the entire charge, if collected on the electrode, will result in a pulse height of only \( \sim 2 \mu \text{V} \).

However, depending on the applied field the electrons can easily be accelerated due to their high mobility and this, in turn, results in the ionization of more gas molecules. The detected charge however, depends on the potential difference between the anode and the cathode as seen in Fig. 9: At very low voltages, only a partial charge-collection takes place since recombination continues to be the dominant process. Collected charge increases to its full value in the ionization regime of the counter. When the applied voltage increases the threshold voltage at which the kinetic energy imparted to the electrons during the collisions is large enough for further ionization, the counter enters the proportional regime. Further increase in the voltage increases the pulse height proportionally to the applied voltage and the number of primary ion pairs, which are proportional to the incident energy of the photon. For very high electric field corresponding to G-M region, the secondary ionization increases rapidly and initiates an avalanche thus losing the signature of the number of electrons in the primary cloud.

Secondary multiplication in a coaxial proportional counter can be achieved at moderate value of anode voltage, since in a cylindrical geometry the electric field is highly non-linear and reduces as \( E(r) = \frac{V}{r \ln \left( \frac{b}{a} \right)} \), where \( r \) is the distance from the anode, \( a \) the anode radius and \( b \) the inner radius of the cathode cell. Very close to the anode wire the field strength is high enough for the development of an avalanche and the developed charge is proportional to the number of primary electrons. Far away from the anode wire, field is just sufficient for drifting of the ions. The electric field required to initiate secondary multiplication is 24 eV over a distance of \( \sim 300 \mu \text{m} \), the distance between two collisions. In the case of parallel plane geometry, the required voltage is higher by a factor of 10 due to uniform field.

Choice of filling gas in a proportional counter is determined by the energy range of its operation. In general, noble gases like argon and xenon along with a small amount of a suitable quenching gas are preferred to other polyatomic gases. The quenching gas absorbs the ultraviolet photons emitted by the excited atoms thereby giving a stable operation. Methane, iso-butane and carbon dioxide are the commonly used quenching mixtures. Argon-filled detector can be used to detect photon energy up to 20 keV, beyond which xenon is the more suitable gas.

The number density of electrons in the primary cloud in the drift region in a given counter is determined by the attachment of electrons on the electro-negative substances which result in the decrease in mobility and enhanced probability of re-combination and can be written as

\[
q_{p}(t) = \frac{\bar{N}_{e}}{\tau_{e}} \left( 1 - e^{-\frac{t}{\tau_{e}}} \right)
\]

where \( \bar{N}_{e} \) is the average number of electrons produced per incident photon of energy \( E \) and \( \tau_{e} \) the life time of the electrons and is defined as \( \tau_{e} = 1/k_{e} \), where \( k_{e} \) is the attachment coefficient and is a function of the impurity concentration, mainly \( \text{O}_{2} \). Low level of contamination up to 16 ppm in the case of 1 cm x 1 cm cell geometry at pressures up to 10 atm does not affect the detector characteristics appreciably.

The gas multiplication factor during proportional operation strongly depends on the filling gas, quenching gas, photon emission characteristics of excited gas atoms, the space charge deformations of the electric field and spread of the electrons in primary cloud. In its simplified form the gas gain \( M \) can be written as
\[ M = \int_{r_1}^{r_2} \alpha \, dr = Ke^{CV} \]  

...(12)

where, \( C \) is the capacitance of the counter and is given by \( C = 1/2 \ln(\beta a) \) and \( V \) is the anode voltage; the first Townsend coefficient of ionization, \( \alpha \), determines the degree of ionization. In practice, a maximum gain up to \( 10^5 \) can be achieved before the spark breakdown.

Classically, the energy resolution \( R_1 (= \Delta E/E = \delta \rho / \bar{\rho} \) where \( \bar{\rho} \) is the mean pulse height at energy \( E \) of a single wire proportional counter) depends on the variance of primary charge cloud and fluctuations in the gas gain. Thus, we have

\[ \left( \frac{\delta \rho}{\bar{\rho}} \right)^2 = \left( \frac{\delta \rho}{N} \right)^2 + \frac{1}{N} \left( \frac{\delta \rho}{M} \right)^2 \]  

...(13)

where, \( N \) is the mean number of primary ion pairs produced by the photon of energy \( E \), \( M \) is the mean amplification factor and \( \delta \rho \), \( \delta \gamma \) and \( \delta \phi \), are the standard deviation of the mean quantities. Following statistical theory of collisions the energy resolution can be written as\(^2\)

\[ R_1 = 236 \left( \left( F + f \right) \frac{w}{E} \right)^{1/2} \]  

...(14)

where, \( F \) is the Fano factor and \( f = (\delta \phi / M)^2 \) and \( w \) is the average energy required to produce an ion pair. The observed resolution at low pressure up to 3.5 atm can be fitted with a functional form \( R_1 = 0.46 \, E^{-1/2} \), obtained in the case of argon-filled counters. In the case of xenon-filled detectors the observed value of resolution is much worse compared to the theoretical estimates. Also, at higher energies, the long track length of the primary charge distribution due to multiple Compton scattering of a high energy photon can give rise to systematic effects arising from pulse rise time, ballistic effects, etc.\(^3\)

The useful energy range of operation of a proportional counter depends on the thickness of the entrance window which produces the low energy cut-off and the detection efficiency of the filling gas for the high energy end. A 5-mil thick beryllium window gives the low energy cut-off of 2 keV, while carbon and boron coated 1-micron thin polypropylene windows have been used to detect X-ray photons up to 150 eV. For balloon-borne detectors, aluminium window of 0.5 mm thickness suffices due to atmospheric cut-off of 15 keV at \(-40\) km altitude. The background reduction in a proportional counter can be achieved by using a charge particle detector in anti-coincidence and, in addition, pulse rise time selection for discriminating the unwanted high energy photons. In the case of multi-counter configuration, apart from the guard counter giving a veto signal, a mutual anti-coincidence between various detectors is very effective in reducing the detector background.

3.1.1 Multiwire proportional counters—In general, for uniform gas gain and resolution across the anode wire, the cell size of a proportional detector is limited to a maximum of \( 30 \times 30 \) mm. The need of a large area, therefore, necessitates a pile configuration of independent counters which is cumbersome in operation and mechanical fabrication. In contrast, a multiwire proportional counter consists of a set of thin, parallel, equally spaced unscreened anode wires, symmetrically sandwiched between two cathodes;\(^6\)\(^2\)\(^8\). For an appreciable detection efficiency for photons, it is necessary to have many such planes and, therefore, multi-layer multi-cell geometries are in common use in the area of X-ray and \( \gamma \)-ray astronomy.

Also, various cells in the detector are completely screened by cathode wire planes on all the four sides, thereby making them completely independent in the operation but sharing the common gas volume. Figure 10 shows a schematic of an MWPC along with the electric field configuration of two nearby anodes in a given plane.

3.1.2 Position sensitive proportional counters—In practical terms, the secondary ionization process in a proportional counter begins at few wire
radii (5-6) from the anode. Taking a drift velocity of the electron as \(-5 \text{ cm/}\mu\text{s}\) for an argon-methane mixture, the development of the avalanche is completed in about 1 ns. Since the shape of the avalanche is drop-like due to lateral diffusion of the electron and half of the charge is produced within the last ionization step, the avalanche is limited to a small portion of the anode wire length (about 50-100 \(\mu\text{m}\)). Many techniques have been, therefore, developed to locate the position of the avalanche along the anode wire.

The most common method of position sensing in a proportional tube is based on the charge division along the two ends of the anode wire, as shown in Fig. 11. In this arrangement anode wire is chosen to have large specific resistance per unit length. The collected charge is thus divided between the two ends in proportion to the resistance in the two arms. The signals at both ends are amplified and ratio of the two provides the position of the avalanche along the wire.

An alternative approach to the charge division method is the measurement of rise time of the pulse. Since the rise time depends on the \(RC\) time constant, different resistances on the two sides of avalanche result in different rise times. Events occurring far away from a pre-amplifier will have large rise time compared to the second pre-amplifier. A relative study can, thus, give the necessary position information. Rise time technique can also be used with a single amplifier for approximate position, provided a pre-calibrated matrix is available for comparison.

In the case of multiwire proportional counter, coarse value of the x-coordinate can be obtained by the anode number and y-coordinate from the charge ratio. Among the various techniques employed to measure both coordinates with high precision, the popular method uses induced signals in the top and bottom cathode planes which are arranged in mutually orthogonal geometry.

### 3.2 Scintillation counters

At low photon energies, gas-filled counters suffice the requirements for large area cost-effective detectors for X-ray astronomy payloads. At energies above 30 keV, the only available detector system is the scintillation counters. The use of proportional counters beyond 30 keV suffers on two counts. First, the detection efficiency is extremely small. For good sensitivity, very large volumes and high pressures are necessary and, due to finite drift mobility of the ions produced in the gas, the slow response time of such detectors results in significant dead time, thereby limiting the rate of detection. Secondly, the observed energy loss spectra does not directly map into incident photon spectrum due to large \(K\)-escape probability (85% in xenon). Monte-Carlo methods used to deconvolve the incoming spectrum critically depend on the knowledge of systematic effects. In contrast, scintillation detectors do provide high detection efficiency and very fast decay time for the scintillation photons.

In the case of scintillation detectors, incoming photon or ionizing radiation is absorbed by the material and results in the excitation of the molecules which, in turn, de-excite by prompt emission of large number of visible photons by fluorescence. If the basic material is transparent to the fluorescent wavelength, the emitted photons can be observed outside by using photomultipliers. In general, the emitting transitions also correspond to the absorption levels and hence, emitted
photons are absorbed internally. A small impurity is, therefore, added to the scintillation material which gives rise to trapping level much different from the original material and thus the resultant wavelength is different from the absorption wavelength. The organic materials fluoresce efficiently when excited but the emitted radiation lies in the near or far ultraviolet region. The addition of a small amount of impurities also act as a wavelength shifter to the visible region.

Since key performance factors of efficient conversion, linearity, transparency, fast decay time, refractive index near glass for coupling, physical and mechanical stability can not be met by any one scintillation material, choice of a scintillation detector, therefore, is the best compromise under the experimental requirements. The most widely used scintillation counters for X/γ-ray astronomy are inorganic alkali halides among which NaI(Tl), CsI(Tl) and CsI(Na) have been used extensively. In literature, NaI(Tl) has been used as the comparison standard.

The absolute conversion efficiency in the case of NaI(Tl) is 12%, the decay constant \( \lambda \sim 0.3 \) \( \mu \)s and fluorescent photon yield of 400 per keV of absorbed energy. In comparison, CsI(Na) has \( \lambda \sim 0.63 \) \( \mu \)s and for CsI(Tl) \( \lambda \sim 1.0 \) \( \mu \)s. Recently, the use of bismuth germanate (BGO) crystals as guard detectors have been considered for space borne X-ray experiments. The light output in the case of scintillation counter is fairly linear up to very high value of specific energy loss of \( dE/dx \) and can be written as

\[
\frac{dL}{dx} = A \frac{dE}{dx} \left[ a + b \frac{dE}{dx} \right]^{-1}
\]

where, \( L \) is the fluorescent light, \( E \) the energy and \( A, a, b \) are the constants. Above \( dE/dx = 4 \text{ MeV gm}^{-1} \), the conversion efficiency decreases continuously, thereby leading to a breakdown of proportionality.

Scintillation detectors continue to be used as the prime detectors in the energy range of 20 keV-10 MeV due to their availability in large area and thickness. Due to hygroscopic nature of the NaI(Tl) and CsI(Na), the detectors need to be encased in metallic containers with suitable optical window.

In a scintillation counter, the inherent background, produced in the detector material due to cosmic ray interaction and the Compton scattering of the high energy photons, dominates the aperture flux and, therefore, the flux sensitivity does not directly scale with the geometric area. The most favoured arrangement for reducing the detector background is the use of phoswich geometry using NaI(Tl) and CsI(Na) as shown in Fig. 12, which provides a shielding factor of about 4-6 in cosmic environment using pulse shape discrimination (PSD) selection criterion, since the pulse rise times differ in two crystals as seen in Fig. 12(a). However, the decay constants and the light yields of the phoswich components vary unequally with temperature. Also the decay-constant in CsI(Na) is strongly dependent on \( dE/dx \). The
PSD technique, therefore, results in a variable shielding efficiency, if the temperature varies.

In an alternative arrangement, a combination of thin and thick sodium iodide detector in a back-to-back geometry and optically decoupled by a thin aluminium foil can also provide a cheap alternative to the phoswich arrangement. The schematic arrangement is shown in Fig. 12(b). The thickness of the two components in the back-to-back geometry are carefully optimized to give better shielding with less detector volume and low dead time for the targeted energy region.

Eventhough the light produced in a scintillation counter diffuses quickly in the entire volume, it is possible to measure the position of interaction, since the scintillation light is generated along the track of ionizing particles. In the case of long scintillation bar, one-dimensional position information can be obtained by having a read-out on both ends. The pulse height versus position is typically an exponential function and, therefore, the position \( X = (1/2a) \ln (P_1/P_2) \), where \( X \) is the distance from the first tube, \( P_1 \) and \( P_2 \) are the respective pulse heights and \( a \) is the light attenuation constant. A two-dimensional position information from a scintillation counter can be achieved by using an Anger mode, in which the crystal plate is viewed by a large number of phototubes. A simultaneous analysis of the relative pulse heights from different tubes for a given event can provide the position coordinates.

3.3 Gas scintillation counters

The theory and principle of the gas scintillation counter are similar to the other scintillation detectors, except that the fluorescence medium in this case is generally a noble gas. Visible and ultraviolet photons are emitted by the excited gas molecules created by the interaction of incoming photon. Since the primary scintillation is very weak, electric field is applied to accelerate the electrons which, in turn, result in a strong secondary scintillation signal. This geometry is, therefore, termed as 'gas scintillation proportional counter' (GSPC). It differs from the proportional counter, such that electric field applied is much lower than that required for initiating the secondary ionization process. Scintillation photons are also emitted in a proportional counter but are removed by the quenching gas, as these can result in spurious pulses.

Photon emissions in noble gases are due to emissions from the diatomic molecules rather than atoms. This results in broad emission spectra with a maximum at 1280 Å for argon, 1470 Å for krypton and 1730 Å for xenon. Ultra-high purity of the gas is absolutely essential for the scintillation emission. To increase the detection efficiency of these UV photons with the conventional phototubes, wavelength shifters are used to shift the emission frequency into the blue region.

Since large gas volume is essential for any appreciable detection efficiency of X-ray photons, the constructional details of gas proportional scintillation counters are very specialized. A schematic diagram for parallel plane GSPC is shown in Fig. 13. Detector consists of large gas volume with a drift field in which the electrons produced in the primary interaction drift towards grid G1. A series of focusing rings are used to obtain a converging field for localized light production to improve the uniformity of the light collection which suffers solid-angle effect. The uniform field of 5-6 kV cm\(^{-1}\) between the G1 and G2 helps accelerate the electrons to sufficiently high energies which, in turn, results in large number of secondary fluorescence photons that are detected by the phototube. Wavelength shifter is coated on the inner sides of the gas vessel and the optical window.

Energy resolution in the case of GSPC is superior by about a factor of \( \sqrt{2} \) compared to the proportional counters, since it depends only on the fluctuation of the final number of the fluorescent photons.

3.4 Spark chambers/drift chambers

In its most basic form a spark chamber consists...
of two parallel electrodes in a gas-filled box, one of which is connected to high voltage and other is grounded. A static clearing field is always present on the electrodes to remove the ions produced by the background radiation. An extremely high voltage pulse is applied when an incoming particle meets the trigger requirement. The applied voltage must exceed the breakdown voltage and thus bright spark occurs between the plates and can be photographed through an optical window. The position of the spark indicates the point of particle passage. In practice, multi-plate spark chambers are used to obtain the complete trajectory along with suitable trigger system, as shown in Fig. 14. Typical features of a spark chamber include spark resolution, recovery time, track efficiency of the gaps and multi-track efficiency. For y-ray use, the plate material and thickness are suitably chosen to act as converter where the photons interact to produce the charged pairs. In earlier experiments, events in the spark chamber were recorded photographically from orthogonal axes by using a suitable arrangement of mirrors to fold in the image. More recently, electronic readout systems have been developed to measure the position of the spark. Digitized data ease both the data logging and the data analysis.

In wire spark chambers, one of the electrodes consists of system of closely spaced parallel wires, while the other is normal continuous electrode. The spark will, thus, occur between the continuous electrode and one wire from which the position of the spark can be inferred. A second wire plane, orthogonal with respect to the first, can provide both the x-y coordinates. A variety of techniques for reading the signal individually from each wire have been developed. Ferrite core and a constant delay line between the successive wires are the most commonly used methods. In practice, a spark fires up to three nearby wires and gravity method is used to locate the event coordinates.

Drift chambers are a variant of the wire spark chambers in which the electrons produced in the interaction drift towards the sensing electrode in a uniform field. The measurement of the drift time can thus provide the spatial coordinates of the event. For a constant drift velocity \( w \) in a one-dimensional drift chamber, track coordinates can be written as \( x = \left( t_f - t_i \right) w \). The time \( t_i \) is obtained by providing a trigger arrangement. A multiwire drift chamber is almost similar to a multiwire proportional chamber with additional field shaping wires and screening electrodes to obtain uniform drift field.

### 3.5 Solid state detectors

Solid state detectors generally consist of a volume of high purity intrinsic Ge or lithium drifted Si or Ge sandwiched between thin layer of n-type and p-type material making it a p-i-n diode configuration. The electrical contacts for a solid state detectors are blocking electrodes rather than ohmic contact to reduce the leakage current and the detector is used in reverse bias. The schematic arrangement is shown in Fig. 15. The incident photons produce electron-hole pairs in the semiconductor material which, in turn, migrate to the charge collecting electrodes under the influence of an applied electric field.

The solid state detectors have the advantage of both the high density and superior energy resolution compared to scintillation counters. Only 3 eV of incident energy is spent in generating an electron-hole pair compared with 24 eV per ionization in proportional counters and 100 eV per photoelectron in scintillation counter. In addition to superior energy resolution as seen from the comparison in Fig. 16, solid state detectors have compact size, fast time response, low voltage operation and tunable thickness for targeted use. The band gap in \( \text{HgI}_2 \) material is 2.2 eV and, hence, thermal noise is extremely small. Such detectors can be used with ordinary ohmic contacts.

![Fig. 14—Schematic for a multiplate spark chamber and a wire chamber](image-url)
Due to low resistivity of Si and Ge, the material is diffused with Li to compensate the excess charge carriers which create a region of high resistivity. Apart from the simple slab geometry for the

- REVERSE BIAS P-N JUNCTION

- CONFIGURATIONS:

- TRUE: CO-AX CLOSED: end

PLANE HPGe

n-TYPE CO-AX

Fig. 15—Sketch for a solid state detector and various configurations

Si(Li) and Ge(Li) detectors, segmented arrays of Si(Li) have also been used for background reduction and spatial information. Silicon detectors are quite suitable in the X-ray energy range, while germanium detectors are commonly used for the y-ray measurements, since due to availability of ultra-high purity material (impurity level $<10^9$ atoms/cm$^3$), large depletion depths (more than 10 mm) are possible. Both p- and n-type high purity germanium detectors are available in planar and coaxial configurations as shown in Fig. 15.

Large active volume is essential for appreciable detection efficiency at MeV energies. The maximum available size of the solid state detectors is $\sim$ 3 cm dia and, hence, mosaic configuration is essential for large area. Major disadvantage of solid state detectors is their low temperature operation at 100 K, which requires cryogenic assembly. This, in turn, limits the use of solid state detectors to moderate area throughput geometries or as the focal plane detectors.

3.6 Dispersive detectors

The resolving powers $(\lambda/d\lambda)$ for the crystal scintillators, proportional counters and solid state detectors are $\sim 3-10$, 10-20 and $\sim 40-100$, respectively. Higher resolution of $\lambda/d\lambda \sim 1000$ can be achieved by dispersing the X-ray beam similar to that at optical wavelengths. Dispersion of the X-ray photons can be achieved either by Bragg reflection from a crystal or by the use of transmission grating $^{42,43}$. In a Bragg’s crystal spectrometer, when the X-ray photon strikes the crystal, strong reflection occurs from the crystal lattice plane when

$$ n\lambda = 2d \sin \theta \quad \ldots \ (16) $$

where, $d$ is the crystal lattice spacing, $\lambda$ is the photon wavelength and $n=1,2,3,...$ is the order of reflection and $\theta$ is the angle of incident beam with the crystal plane. Since the incident wavelength is reflected over a range of angle $d\theta$ due to crystal imperfections, the resolution of the crystal spectrometer is, therefore, given by the differential equation $n\delta\lambda = 2d\cos \theta \delta \theta$. By re-arranging one gets

$$ \frac{\delta \lambda}{\lambda} = \frac{\cos \theta}{\sin \theta} \frac{\delta \theta}{\theta} = 10^2 - 10^4 \quad \ldots \ (17) $$

since $\theta$ is few arc min at X-ray wavelengths.

Similarly, in the case of transmission grating, the incident photons are coherently reflected at angle $\theta$, when

$$ n\lambda = \frac{1}{N} (\sin \theta, - \sin \theta); \quad n = 1,2,3,... \quad \ldots \ (18) $$

Fig. 16—Comparison of the energy resolution obtained by NaI(Tl) and a Ge detector
where, \( N \) is the lines \( \text{cm}^{-1} \) in the grating, \( \theta_i \) the angle of incidence and \( \theta_r \), the angle of reflection. Since \( \theta \) is very small at X-ray energies one can rewrite the above equation as

\[
\frac{1}{n \lambda} = \frac{1}{N} (\theta_r - \theta_i) \quad \ldots (19)
\]

Theoretical resolution for the grating spectrometer is given as \( \delta \lambda = \left( \frac{Ns}{1} \right) \), where \( s \) is the width of grating in cm. Due to low absolute reflection/transmission efficiency, the counting rate from the continuum of source spectra is small. To sweep the entire spectrum of a source with crystal spectrometer, it is necessary to either rotate the crystal or use a mosaic of crystals at different orientations. With the transmission grating, an imaging counter is sufficient to detect the entire range of energies.

4 X-ray and \( \gamma \)-ray instruments

Majority of the space borne instruments to-date have been dedicated to the study of continuum emission from the cosmic sources and the temporal variations in the X-ray flux. Proportional counters have been the main detectors in space borne instruments in the energy range 0.25-30 keV despite their poor energy resolution, while the data in 30-200 keV region have come with the use of scintillation counter. At \( \gamma \)-ray energies, different payloads include double Compton telescopes, spark chambers and solid state detectors. Mechanical collimators made from high Z metals in graded form can be used to limit the field of view below 300 keV. However, active collimators have also been used in space borne instruments. At higher energies, collimation of the incoming beam is not possible and hence photon arrival direction is obtained indirectly. Detector shielding and background reduction techniques are specific to each instrument and depend upon the payload configuration and the type of detector used.

4.1 Soft X-rays: 0.2-10 keV

Before the launch of Einstein observatory\(^{44} \) (HEAO-B) in 1978, measurements in ultra-soft and soft X-ray region were made using thin-window-large-area proportional counters both on rockets and satellite borne experiments. The largest size proportional counter with area of \( 1 \text{m}^2 \) was launched on board HEAO-A satellite\(^{45} \). In complete contrast, X-ray payload on board Einstein observatory consisted of a focusing optics with the use of X-ray mirrors and four different focal plane instruments, namely, imaging proportional counter, high resolution imager, solid state detector and a crystal spectrometer. Focusing optics has provided both very high angular resolution of few arc min and high detection sensitivity due to large collecting area and small size of the X-ray detector. Similar focusing optics is currently in operation on board the ROSAT satellite\(^{46} \) and will also be launched on AXAF mission\(^{47} \). The maximum detectable energy in focusing optics is about 6 keV. Two types of focusing techniques are currently in use.

Below 10 keV, a large number of X-ray sources were discovered by the first generation of small satellites\(^{48,49} \) like UHURU, OSO-7 and ARIEL-V. However, due to long operation in orbit, the sky surveys done by the focusing telescopes on board Einstein and ROSAT observatories have led to extremely crowded X-ray sky with the discovery of \( \sim 50,000 \) soft X-ray sources and have provided data on different classes of X-ray objects. Focusing telescopes on board BBXRT, ASCA and EXOSAT were mainly used for detailed pointed mode observations\(^{50,52} \).

4.1.1 Grazing incidence optics—In this method, typical X-ray optics consists of a Wolter type-I telescope as shown in Fig. 17(a), which is a complete contrast, X-ray payload on board Einstein observatory consisted of a focusing optics.
bination of thin cylindrical shells of parabolic and hyperbolic surfaces. Successive reflection from these two surfaces forms the X-ray image. Since near total reflection from a surface can only take place at grazing angles, due to extremely small wavelength of X-ray photons (\(\sim 1\) Å for \(\lambda \sim 6\) Å), an X-ray telescope has a large focal length and much reduced projected area to the incoming beam. In practice, nesting of large number of surfaces is used in order to increase the effective collecting area as shown in Fig. 18. A comparison of the various payload with Wolter geometry is given in Table 2.

Unlike optical mirrors the fabrication of optical surfaces for an X-ray telescope requires extremely accurate figuring, typically 1 Å rms and the image quality depends on the surface quality and the alignment of various segments in the mirror assembly.

The critical grazing angle \(\theta_c\) for a surface, away from the resonance absorption edges is given by

\[
\theta_c \sim 3.54 \times \frac{\lambda}{A} \times \sqrt{(r_o n)} \quad \ldots (20)
\]

where, \(\lambda\) is the X-ray wavelength, \(r_o\) is the electron radius and \(n\) is the electron density of the surface material. Equation (20) clearly shows the steep variation in grazing angle with the photon energy and the atomic number \(Z\) of the surface material. Among the various materials studied, reflectivity for nickel and gold extends up to 6 keV and are commonly used. In the Wolter type X-ray mirror assembly, it is essential to configure each surface to high accuracy and thus, is quite cumbersome. Recently, multiple replication of highly accurate surfaces from a common mandrel has become feasible. A variety of techniques have been developed using both epoxy and metallic replication. Replicated mirror assemblies were used on board EXOSAT mission and will be used in many future missions like JET-X payload on SPECTRUM X-\(\gamma\), soft X-ray detector on board SAX and the XMM satellite\(^{53-55}\).

4.1.2 Foil optics—In a Wolter type geometry, the maximum number of nested mirrors has been limited to 4 due to mechanical and fabrication constraints. As seen from the ray diagram in Fig. 17, at very small grazing angles, the geometry of the reflecting surfaces can be approximated by two conic sections. This does result in poor image quality but the conic sections can be easily made from thin metal foils by bending and thus can be packed closely. Due to large number of concentric shells, the energy range of foil mirrors extend from 0.5 keV to 12 keV. Foil mirror telescope code named BBXRT was first flown in 1990 on a space shuttle. Foil mirror telescope was also placed on board ASCA and will form the SODART telescope on board SPECTRUM X-\(\gamma\) (Ref. 56). Table 3 gives the comparative figure of merit of the foil mirror assemblies on board three missions.

<table>
<thead>
<tr>
<th>Mirror specification</th>
<th>Einstein</th>
<th>ROSAT</th>
<th>AXAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of mirrors</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>600 cm</td>
<td>800 cm</td>
<td>1200 cm</td>
</tr>
<tr>
<td>Geometrical area at 2.5 keV</td>
<td>412 cm(^2)</td>
<td>1150 cm(^2)</td>
<td>1150 cm(^2)</td>
</tr>
<tr>
<td>Grazing angle</td>
<td>40°-70°</td>
<td>65°-145°</td>
<td>27°-51°</td>
</tr>
<tr>
<td>Focal length</td>
<td>3.4 m</td>
<td>2.4 m</td>
<td>10.0 m</td>
</tr>
<tr>
<td>Surface finish</td>
<td>2.5 mm</td>
<td>0.3 mm</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>Half power dia</td>
<td>16 arc sec</td>
<td>5 arc sec</td>
<td>(\leq 1) arc sec</td>
</tr>
</tbody>
</table>

Table 3—Foil mirror assemblies (energy range 0.5-20 keV)

<table>
<thead>
<tr>
<th>Mirror specification</th>
<th>BBXRT</th>
<th>ASCA</th>
<th>SODART</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of mirrors</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Shells per mirrors</td>
<td>101</td>
<td>120</td>
<td>154</td>
</tr>
<tr>
<td>Foils</td>
<td>0.125 mm, Al</td>
<td>0.125 mm, Al</td>
<td>0.3 mm, Al</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>43 cm</td>
<td>35 cm</td>
<td>60 cm</td>
</tr>
<tr>
<td>Geometrical area at 7 keV</td>
<td>450 cm(^2)</td>
<td>600 cm(^2)</td>
<td>1200 cm(^2)</td>
</tr>
<tr>
<td>Focal length</td>
<td>3.8 m</td>
<td>3.5 m</td>
<td>8.0 m</td>
</tr>
<tr>
<td>Half power dia</td>
<td>4 arc min</td>
<td>3.5 arc min</td>
<td>4 arc min</td>
</tr>
</tbody>
</table>
4.2 Medium energies: 5-30 keV
Bulk of the spectral data from X-ray sources between 5 and 30 keV has mainly come from the HEAO-A-1, HEAO-A-2 and Ginga experiments\textsuperscript{45,57,58}, all of which used arrays of proportional counters, which differed in their detector characteristics like entrance window, gas mixture, cell configuration and the collimator design. Gas filled detectors are most suitable for measurements in this energy range due to their high detection efficiency, ease of making large area and low background detectors. Pulse-rise-time selection, 3-sided guard counters, mutual anti-coincidence of the neighbouring anodes in multi-cell geometry and fluorescent gating are quite effective in suppressing the background. Passive collimator and shielding of the detector suffice the need.

A large-area xenon-filled proportional counter with a photon detection length of 20 bar-em developed for a balloon borne payload\textsuperscript{59} is illustrated in the Fig. 19. The detector has a wall-less multi-cell configuration and is made of three layers of 4 cell each. A 48 × 48 mm cell geometry is defined by a large number of 100 μ Be-Cu cathode wires placed every 3 mm, while the anode wires consist of 50 μ gold coated stainless steel wire. End-cells in each layer and all cells in the bottom layer are connected together to form a guard counter. The signals from alternate cells in each layers are joined together internally to re-

![Diagram](https://example.com/diagram.png)

**Fig. 19**—Large-area proportional counter and its characteristics
duce the electronics volume. A $5^\circ \times 5^\circ$ collimator and thin aluminium window forms the aperture. Vital parameters, like energy resolution, detection efficiency and background reduction results are also shown in Fig. 19.

For the satellite instruments using proportional counters, it is necessary to tune various parameters like gas pressure, quenching gas, cell geometry, shielding, collimation and the background reduction methods based on the targeted energy range, satellite trajectory, the intended observation modes and the mission life.

4.2.1 Imaging detectors—Imaging detectors have a distinct advantage over the passively or actively collimated detectors in two ways. First, the background and the source flux is measured simultaneously. Therefore, it is not necessary to select a priori region of the sky for background measurements and any variation in the background during a long observation can also be properly taken care of. Second, because of high angular resolution associated with each photon, an imaging instrument can have large field of view.

At energies below 6 keV, X-ray imaging can be trivially achieved by placing a position sensitive X-ray detector at the focus of the X-ray telescope. Position information in the earlier mission was achieved mainly by the use of thin window imaging proportional counters. The detectors are classical perpendicular cathode grid read-out system with thin window consisting of lexan quoted 1 $\mu$m polypropylene material and with an on-board gas flow system. Focal plane detectors are generally small in area and hence can be built under extremely controlled conditions for accuracy and alignment. The next generation of focal plane instruments include microstrip proportional counters, X-ray CCDs, cooled bolometers, solid state detectors and micro-channel plate imagers.

4.2.2 Coded aperture masks—As discussed earlier, at energies above 10 keV, focusing of the X-ray photons is not practical. Modulation collimator techniques have been used for imaging up to 20 keV in the early experiments using rockets and satellites. Both multiple grid scanning modulation collimators and rotation modulation collimators have been developed for one-dimensional and two-dimensional imaging and were used on board OSO-7, TENMA satellites. Use of modulation collimator up to ~60 keV has been attempted in the balloon-borne experiments. Mechanical fabrication, precise alignment constraints do limit the use of modulation collimators to small area detectors.

In contrast, coded aperture masks along with a position sensitive detectors can be used for imaging from soft X-ray to $\gamma$-ray energies. A coded mask is a mosaic of equal-area open and close elements arranged in pre-determined fashion. Conceptually, coded mask technique for image reconstruction follows from the multiple pin-hole camera in which the open elements are encoded randomly and which makes the angle-dependent inherent noise in the de-convolved figure constant over all angles. A schematic arrangement of a coded mask system is shown in Fig. 20. Each segment in the recorded image consists of summa-
tion of the flux seen through shadowgram of various open elements in the aperture. In mathematical form this can be represented as

\[ I_{ij} = \sum_{k} S_{ik} M_{i+k, j} + B_{k, l} \]  

(21)

where, \( I \) is the recorded image matrix, \( S \) the input source image, \( B \) the instrumental background noise and \( M \) the mask transmission matrix and \( M=1 \) for an open element and \( M=0 \) for the opaque regions. Based on the design of the mask, \( M \) is a known parameter and hence the recorded image can be transformed into the source image using Fourier or Hadamard transform methods.

However, in practice, correlation method for image reconstruction has been used and various schemes of encoding the mask elements have been evolved to reduce the power lost into the side lobes. To completely construct the image, it is necessary to have information from all elements in the basic mask pattern for all the input angles in the field of view. Therefore, the practical masks consist of cyclic repeating basic mask pattern covering the designated field of view of detector. Uniformly redundant arrays (URA), modified uniformly redundant arrays (MURA) and hexagonal uniformly redundant arrays (HURA) have been used in the laboratory development and balloon borne observations. The first experiment using coded mask and independent crystal detector elements was launched on board SIGMA/GRANAT mission\(^{63}\). An assortment of coded mask imaging detectors in the hard X-ray and \( \gamma \)-ray region are planned for the future experiments on board SPECTRUM X\(-\gamma \) and INTEGRAL satellite missions\(^{64}\).

In principle, the angular resolution in coded mask aperture telescope is determined by the size of mask elements and the distance of the coded mask above the detector. However, the element size in the coded mask depends on the ultimate spatial resolution of the detector itself. In practice, the elements size should be at least 2 to 3 times larger than the minimum position resolution of the detector.

4.3 Hard X-rays: 20 keV-2 MeV

The energy range of photon detection in a xenon filled proportional counter with a detection length of 20 bar-cm at normal pressure does extend up to 60 keV as seen in the Fig. 19. However, the detection length of the proportional counters launched on various mission have been 5-10 bar-cm and hence the useful energy range of observation is limited to 35 keV. Large-area-high-pressure (30 bar-cm) multicell proportional counters and pile detectors using ultra-high pressure proportional counters (300 bar-cm) have been successfully developed and/or flown on balloon borne instruments\(^{13,14}\). The energy range of detection in such geometries may extends up to 600 keV. A high pressure xenon filled imaging counter code named LIME\(^{65}\) will be flown on board SPECTRUM X\(-\gamma \). Gas scintillation proportional counters launched on board various missions have generally been used for high resolution spectral studies\(^{51,52,60}\).

The main detector used so far for the space borne observation in the 20 keV-2 MeV region is the crystal spectrometer using NaI(Tl) and/or CsI(Na) scintillators. Only difference between various experiments is the choice of field of view, detector shielding using a combination of passive and active elements and electronic suppression of the background. The energy range of operation of a scintillation counter depends on the thickness of the prime detector, while the detection sensitivity is a complex function of various parameters of the payload. On a space borne payload, the detector background consists of the aperture flux arising from the diffuse cosmic ray component, shield leakage, characteristic photons excited by the electron capture by \( ^{127}I \) isotope produced due to spallation effects in the detector volume, and delayed emission in the charged particle induced background.

Crystal spectrometers were flown on board OSO-8, HEAO-A-4, Kwant module on MIR station, SIGMA/GRANAT and is currently operative on Compton observatory\(^{63,65-68}\). To-date the best survey so far, in the hard X-ray region, has been performed by the HEAO-A-4 experiment. The payload used is shown in Fig. 21. The instrument consisted of an assortment of phoswich detectors using NaI(Tl) and CsI(Na) scintillation counters with their thickness optimized to different targeted energy region, e.g. two detectors with an area of 100 cm\(^2\) each for 10-20 keV, four detectors with an area of 80 cm\(^2\) each for 0.1-5 MeV and one central detector with an area of 100 cm\(^2\) operating in the energy region 2-10 MeV. Field collimation and shielding of the entire assembly was achieved by a combination of passive metals and active NaI(Tl) detectors.

Unlike soft X-ray region, the X-ray sky in the 20 keV-2 MeV appears quite different. Only about 80 sources were detected during the life time of the HEAO-A mission. This is partly due to the limitation of sensitivity of the instrument.
Also, the number of dedicated missions in the soft X-ray region have far exceeded the hard X-ray efforts. Secondly, non-imaging nature of the earlier instrument led to several observational constraints like non-availability of the simultaneous background measurements, etc.

4.4 Low energy $\gamma$-rays: 2-20 MeV

Collimation of X-ray photon above 2 MeV is nearly impossible. The amount of passive or active material required for shielding in a conventional crystal spectrometer is too large and, hence, contributes to large secondary production of local background, thereby reducing the signal-to-noise ratio. Also, the crystal thickness required is quite large, which enhances the background further due to charged particle activation while in orbit. In principle, a bare uncollimated detector does have advantage over the background, but the lack of directivity of the incoming beam makes it useless for space measurements except for the observation of objects with well defined pulsar or binary periods. The solid state detectors with their high energy resolution can be used to study line emission in the 2-20 MeV region. Collimated solid state spectrometer launched on HEAO-C satellite is shown in Fig. 22.

The instrument consisted of four cryogenically cooled Ge(Li) spectrometers each of 46 mm dia and a volume of 60 cm$^3$. The detectors were contained in CsI(Na) anti-coincidence shield-collimator giving a field of view of $\sim 30^\circ$ at 1 MeV. Larger version of solid state detectors are being planned for future missions. As explained in Sec. 3.5, solid state detectors can be gainfully employed only in the study of line emission. For achieving directionality and for continuum spectral measurements, the most useful technique in the energy range 2-20 MeV is the Compton telescope.

The basic principle of operation of a Compton telescope may be seen in Fig. 23 which illustrates the instrument built at the Max Plank Institute, and a scaled up version of which is currently operational on board Compton $\gamma$-ray observatory. The method relies on the detection of coincident signal from either two scattered photons in two layers of detectors or one scattered photon along with complete absorption of the incoming $\gamma$-ray. A primary photon suffers a Compton scattering in the first layer of detectors optimized for scattering and is later detected in the calorimeter. The scatter consist of independent cells of plastic or liquid scintillators and the collector is formed by cells made with NaI(Tl) crystals for higher efficiency of detection. A time of flight measurement for a delayed coincidence is used to reduce the unwanted background produced by the elastic scattering of neutrons. From the theory of Compton scattering as outlined in Sec. 2.1, for a given energy of the incoming photon and the position coordinates of interaction in the top and bottom layers, there is a finite cone of incident angles which will satisfy the energy and momentum conservation relations. The width
of the annulus depends on the precision of energy measurements and the angle of incidence. An angular resolution of \(<5^\circ\) is possible at energies above 5 MeV.

Eventually, the absolute efficiency of a Compton telescope is \(\sim 1\%\), the coincidence requirement, however, reduces the background counting rate enormously. Secondly, the Compton telescope inherently does have a large field of view where choice can be made by putting restriction on the maximum scattered angle.

4.5 High energy \(\gamma\)-rays: 20 MeV-30 GeV

For photon energies above 20 MeV, only available detection method is the use of spark chamber telescope, since the pair production is the dominant mode of interaction. A spark chamber telescope as seen in Fig. 24 consists of stack of digitized wire spark chambers with interspersed conversion material to materialize the incident photons and to determine the trajectory of the secondary \(e^+e^-\) pair. An “anti-coincidence shield to discriminate against the charged particles, a trigger system involving a combination of plastic scintillation counters along with either a Cerenkov detector or a time-of-flight coincidence to differentiate between the upward and downward moving particles and a total energy calorimeter form the main components of the payload. Spark chamber telescope launched on board SAS-II and COS-B and the currently operational EGRET payload on board Compton observatory are essentially the scaled up versions of each other with the effective area of 1600 cm\(^2\) for the EGRET telescope as compared to \(\sim 400\) cm\(^2\) for COS-B instrument\(^7,8,10\).

The angular as well as energy resolution of a spark chamber telescope is defined by the accuracy of the measurement of the arrival direction of the photons which, in turn, depends on the precise location of the spark image. For example, for a plate separation of 1 cm, a 0.3 mm accuracy on the spark measurement results in the angular resolution of \(\sim 3^\circ\). Various parameters of the currently operational EGRET payload\(^9,2\) are summarized in Table 4.
Table 4—EGRET parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range:</td>
<td>20 MeV-30 GeV</td>
</tr>
<tr>
<td>Energy resolution:</td>
<td>$\sim 15% (100 \text{ MeV}-2 \text{ GeV}) \text{ FWHM}$</td>
</tr>
<tr>
<td>Effective area ($\geq 200 \text{ MeV}$):</td>
<td>1600 cm$^2$</td>
</tr>
<tr>
<td>Sensitivity ($\geq 100 \text{ MeV}$):</td>
<td>$5 \times 10^{-8} \text{ cm}^{-2} \text{s}^{-1}$</td>
</tr>
<tr>
<td>Field of view:</td>
<td>$\sim 40^\circ \text{ FWHM}$</td>
</tr>
<tr>
<td>Timing:</td>
<td>0.1 ms (absolute); 8 $\mu$s (relative)</td>
</tr>
<tr>
<td>Source position location:</td>
<td>5-10 arc min</td>
</tr>
</tbody>
</table>

5 Future developments

5.1 Ultra-high pressure proportional counters

For observations at higher energies above 30 keV, the basic limitation is due to low sensitivity of the detector systems, which primarily requires large area, high detection efficiency and low internal background. Proportional counters have been extremely successful at lower energies, but use of even high pressure ($\sim 3 \text{ bar}$) gas in the counters suffers from extremely low detection efficiency above 60 keV. Traditional uses of crystal spectrometers for measurement in the 20 keV-1 MeV band, launched on various satellite missions, have obtained limited success due to large background produced due to spallation effects in the crystal and surrounding environment. Also the sizes used for the crystal spectrometers have been modest due to cumbersome background reduction techniques and active collimation used in these experiments.

Ultra-high pressure detectors filled with argon-methane gas mixture at a pressure of 400 psi and xenon-methane at 250 psi has been successfully developed recently and can provide a suitable alternative for observations up to 600 keV (Refs 13 and 14). A balloon borne payload code named AXEL consisting of xenon-filled pile detector made with 32 UHPC counting tubes having an area of 2000 cm$^2$ and active volume of 15000 cm$^3$ and 800 cm$^2$ phoswich detector will be flown for comparative study. The estimated sensitivity of the payload is $10^{-5} \text{ ph cm}^{-2} \text{s}^{-1} \text{ keV}^{-1}$ and an extended useful energy range of 10-300 keV.

Use of large area UHPC payload in future space mission will enhance sensitivity for the source detection and spectral measurements in the extended energy range poorly studied so far.

5.2 Phoswich imaging camera

The main performance factor for a high energy X-ray imagers is the low background, large area position sensitive detector with high detection efficiency and a suitable choice of imaging technique. As already described, at intermediate and high energies, imaging can be achieved by the use of coded aperture mask. However, the only available detector for use above 100 keV at present is the crystal scintillators in Anger configuration. Use of an Anger camera made with NaI(Tl) crystal is a common diagnostics tool in medical science and has also been used on balloon borne payloads. The use of a single crystal X-ray detector seriously suffers from the background produced by Compton scattered photons and hence the detection sensitivity is quite low. As described earlier, a phoswich arrangement can veto such photons.

Large-area-position-sensitive phoswich detectors using NaI(Tl) and CsI(Na) scintillators and viewed in Anger mode with a large number of...
phototubes, have been developed recently\textsuperscript{16,71}. The optimum thickness of the two scintillators in this configuration depends on the targeted energy range. Tests show that spatial accuracy of $\sim 7$ mm for the position coordinates of the incident photons is achieved even at 30 keV while the measured energy resolution is 16\% at 60 keV. A rise-time-discrimination (RTD) between the signals from NaI and CsI scintillators provides the reduction in the Compton-scattered background in the prime detector by a factor of $\sim 5$. Use of phoswich Anger camera in the space borne hard X-ray imagers will increase the sensitivity of future surveys.

5.3 \(\gamma\)-ray lens

Because of the difficulty in detecting continuum signal in the low energy \(\gamma\)-ray region of 200 keV - 2 MeV from the cosmic sources, study of lines in this energy band has remained a dream. There are many astrophysically important lines such as $^{9}$Be (478 keV), $^{22}$Na (511 keV), $^{56}$Ni (847 keV), $^{44}$Ti (1.156 MeV) and $^{22}$Na (1.275 MeV) which can give important clues to the evolutionary state of the \(\gamma\)-ray sources. Cooled germanium detectors do have the necessary resolution to study these spectral features but lack the signal-to-noise ratio when used along with active collimators and coded aperture masks for imaging. A \(\gamma\)-ray lens can provide the requisite focusing optics to study the line features in the low energy \(\gamma\)-ray spectra.

A \(\gamma\)-ray lens consist of a large number of high quality diffraction crystals arranged in concentric circular rings\textsuperscript{13,72} and is shown in Fig. 25. The crystals are used in the transmission mode in order to increase the effective area. Each crystal is individually adjusted with respect to the incoming beam of photons to produce the diffracted image on a common point. Since the diffraction angle $\theta_d$ is twice the Bragg angle given by Eq. (16), photons with energy $E + \Delta E$ will be displaced from that obtained for photons with energy $E$ by a distance $dx = 2F d\theta$, where $F$ is the focal length of the lens. Therefore, the limitations of a \(\gamma\)-ray lens are the extremely narrow energy range of operation for a given alignment of the crystal surfaces. However, a lens geometry not only increases the effective area, but also reduces the size of detector required to detect these photons. Currently \(\gamma\)-ray lens with an aperture of 30 cm has been developed successfully.

6 Space astronomy in India

In India, the experiments in X-ray and \(\gamma\)-ray astronomy have been mostly confined to hard X-ray observations using balloon-borne payload. Space borne observations using rocket and satellite have suffered partly due to unavailability of launch opportunity and the lack of long term policy even though first attempt was made as early as in 1975. Also, only survey experiments in the soft and ultra-soft X-ray bands could be conducted using spinning rockets.

6.1 Rocket borne studies

Rocket borne spectral measurements of the X-ray sources and the diffuse background in the 2-10 keV region were made by PRL/ISAC group during 1968-1980 and TIFR group during 1972-1977 using small-area proportional counters. X-ray surveys in the ultra-soft energy region of 0.15-2 keV, using large-area ultra-thin window multi-wire proportional counters, were conducted by TIFR group\textsuperscript{73} during 1979-1982.

The payload used in the TIFR experiments was for the mapping of ultra-soft component. The data were obtained in the L- and M-band for both the northern and the southern hemispheres. Spectral properties of the diffuse background and its correlation with the neutral hydrogen, radio brightness, H$_a$ and O VI measurements were studied during these experiments.

6.2 Satellite payloads

Two satellite payloads for the study of X-ray sources in the energy range 2-20 keV were launched on board Aryabhata (1975) and Bhasika (1979). An instrument for the study of \(\gamma\)-ray bursts was recently launched on SROSS-C2 mission and is currently operational.

6.2.1 Aryabhata—Among the two payloads launched on board Aryabhata satellite, X-ray instrument consisted of a combination of a proportional and a scintillation counter to detect and measure the X-ray spectra of cosmic sources in the energy range 2.5-155 keV and was developed by the group at Indian Space Research Organiza-
ion (ISRO). The proportional counter was aligned for the pointed mode observations, while the scintillation counter telescope was placed in scan mode. The second instrument developed by TIFR group was designed to study the neutron a near circular orbit at an inclination of 51°. Data from the celestial sources in the energy region of 0.2-20 MeV, using phoswich detector technique.

The satellite was launched on 19 Apr 1975 into a near circular orbit at an inclination of 51°. Data could be obtained only for few orbits after the payload was switched on, since the +9 V bus supplying power to both the payloads failed in the 42nd orbit (3 days).

6.2.2 Bhaskara—X-ray payload on board Bhaskara satellite was an all sky monitor consisting of a pin hole camera jointly developed by TIFR and ISRO group with the primary objective of studying the time variability of X-ray sources and to detect transient X-ray objects.

The detector consisted of a position sensitive proportional counter with 2 primary anodes having a sensitive area of 18 × 1 cm² each and surrounded by guard cells on both sides and bottom. A 1 × 1 cm pin hole aperture was placed at a height of 10 cm above the detector, thereby giving a fan beam of 90° × 11° and spatial resolution of 5.5° × 5.5°.

The satellite was launched on 7 June, 1979 and the X-ray payload functioned for 3 weeks, after which the detector failed due to excessive cooling of the payload beyond specified limits.

6.2.3 SROSS—The γ-ray burst payload launched recently on the SROSS-C2 satellite consists of 3° dia. and 1/2” thick Cs(Na) crystal scintillator operating in the energy range 10 keV-1 MeV (Ref. 77). The instrument was earlier launched on SROSS-C in 1992 and worked for only 2 months. The present payload was launched in 1994 and has been working well so far. It has observed a dozen of confirmed burst events which are also seen from other satellites.

6.2.4 Indian X-ray astronomy payload (IXAP)—Indian X-ray astronomy payload is the approved mission to be launched on board PSLV-D series of satellites. The payload is being developed jointly by TIFR and ISRO and consists of two instruments. First, an array of pointed-mode proportional counters is designed to study (i) periodic and aperiodic variations in the X-ray intensity of galactic X-ray sources, (ii) long term variability of the AGN and BL Lac objects and (iii) pulsation and orbital periods of the X-ray pulsars and binaries. Secondly, an X-ray pin hole camera is designed as an all sky monitor to detect transient events.

The pointed mode array consists of 3 thin-window proportional counters with an area of 450 cm² each. A passive collimator restricts the field of view of the detectors to 2° × 2°. With the detection energy range of 2-20 keV, the expected sensitivity is 10 UFU for 1 h observations. The orbit of the PSLV satellites is not ideal for X-ray astronomy due to high inclination. However, a number of bright sources will be monitored during the mission life time.

X-ray pin hole camera consists of a 1000 cm² proportional counter sensitive in the energy range of 2-6 keV band. The aperture consists of a pin hole of 1 cm² at a height of 16 cm. Position resolution of few mm along the anode wire coupled with the 32 anode configuration of the detector will provide a spatial resolution of 1° × 1° and a total FOV of 45° × 45°.

Acknowledgements

The author thanks Dr A R Rao and Dr H Adarkar for going through the manuscript.

References


77 Marar T M K, *Private communication*.