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Present status of hard X-ray astronomy

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Abstract. The recent observational results obtained in the energy range of 15-150 keV from balloon and satellite borne instruments are reviewed. The detection of cyclotron line features in several X-ray binaries, hard X-ray spectra and variability of black hole candidates and the hard X-ray imaging of Galactic center region are discussed. The need for developing low background, good resolution, high sensitivity hard X-ray detectors is stressed and the developments carried out in this regard at TIFR and elsewhere are briefly outlined.

Key words : X-ray astronomy—galactic center

1. Introduction

Since the serendipitous discovery of the first cosmic X-ray source Sco X-1 in the now famous rocket flight of 1962 (Giacconi *et al.* 1962), the development of X-ray astronomy in the last three decades is a truly remarkable fairy-tale success story. The advent of focussing X-ray telescopes flown on the Einstein Observatory and the recent ROSAT satellite, has tremendously improved the observational capabilities. As of today, the catalogued number of X-ray sources are in excess of 50,000 and it can be said that X-ray astronomy has come in par with the other well established optical and radio astronomies.

All these developments are, however, restricted to the low energy X-rays, below 4 keV; this threshold got extended to about 12 keV by BBXRT and the recently launched Japanese satellite ACSA. The energy range above 12 keV, the hard X-ray range, is not likely to be accessible by any focussing detectors in the near future and the developments in this field are confined to observations made with conventional X-ray detectors flown on a few satellite missions and some balloon payloads. The present review attempts to highlight the unexplored potential of the hard X-ray astronomy and indicate some instrument developments, with the focus on high sensitivity observations. For other related areas in hard X-ray astronomy the reader is referred to some recent reviews : Higdon & Lingenfelter (1990) for gamma-ray bursts; Yoshimori (1989) for solar hard X-ray bursts; Sunyaev *et al.* (1991) for hard X-ray transients. Bradt *et al.* (1992) can be referred to for information regarding X-ray astronomy missions. The eleventh COSPAR meeting (Palumbo & Vedrenne 1991) and the Toulouse International Colloquium on *The Recent Advances in High Energy Astrophysics, March, 1992* (Proceedings in A&A SS Vol 97, 1993) have very useful information on the hard X-ray techniques and observations.

The plan of this review will be as follows. The genuine difficulty in improving the sensitivity in the hard X-ray range will be highlighted in Section 2. The results obtained from the large area low energy detectors with extended response up to ~50 keV will be discussed in Section 3. Results from hard X-ray imaging and large area high sensitivity detectors are dealt in Section 4 and Section 5, respectively. Some thoughts about new detector development and the outstanding problems that can be addressed with them are discussed in Section 6.

2. Sensitivity of X-ray detectors

The X-ray detectors used in astronomy are essentially photon counting devices and the sensitivity is dictated by the Poisson variations in the count rates. The detector can be either a large area counter with some mechanical collimator to define/restrict or modulate/encode the field of view or an imaging device kept at the focal plane of a focussing mirror. For a given detector, the total number of source counts (N_s) registered in time t_s from a source with flux F photon cm^{-2} s^{-1} keV^{-1} is

$$N_s = FA\varepsilon t_s dE \qquad \ldots (1)$$

where A is the net detection area (in cm^2), ε the efficiency and dE the band width (in keV). Taking the background internal to the detector as B_i Photon cm^{-2} s^{-1} keV^{-1} and the diffuse cosmic X-ray background (CXRB) as B_D Photon cm^{-2} s^{-1} keV^{-1} str^{-1}, the total background counts (N_b) during the source observation time t_s will be

$$N_b = B_D A \Omega \varepsilon t_s dE + B_i A_d \varepsilon t_s dE \qquad \ldots (2)$$

where Ω is the solid angle, in steradians, subtended by the field of view (FOV) and A_d the total geometric area of the detector (here it is assumed that the detector internal background also scales as the detection efficiency ε). The total count during the source observation is, therefore, $N_s + N_b$. The background counts can be estimated in a separate background observation time t_b. If $t_b = t_s$, the statistical error in the source signal N_s will be $\sqrt{(N_s + 2N_b)}$.

The conventional X-ray detectors are background limited ($N_b >> N_s$) and hence the 3σ detection limit is (for $t = t_b = t_s$, and $A_d = A$)

$$F_{min} = 3\sqrt{\left(2\frac{(B_D\Omega + B_i)}{(A\varepsilon t dE)}\right)}. \qquad \ldots (3)$$

In the case of focussing X-ray detectors, the solid angle per pixel (Ω) is very small (a factor of 10,000 lower compared to the conventional detectors) and the detection area A_d is much lower compared to the effective area A. In this case $N_b << N_s$ and hence

$$F_{min} = \frac{9}{(A\varepsilon t dE)} \qquad \ldots (4)$$

and the scope for improving the sensitivity is tremendous. In figure 1 the sensitivity of soft X-ray focussing detectors are shown along with those for hard X-ray detectors. The remarkable

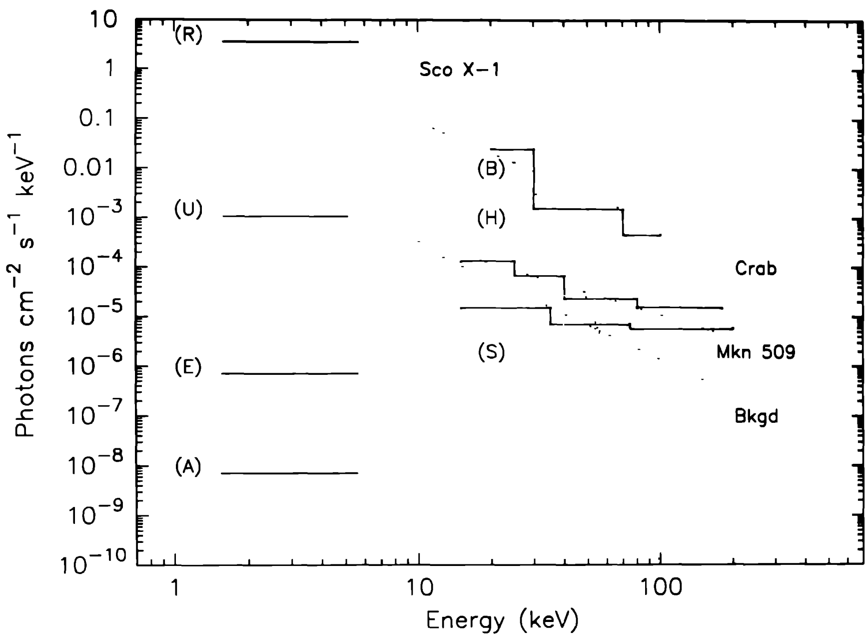

Figure 1. The sensitivity of some soft X-ray detectors (1) The rocket flight which discovered the first cosmic X-ray source Sco X-1 (R), (2) the UHURU detectors (U), (3) the Einstein Observatory (E), and (4) AXAF (A) are shown along with that of some hard X-ray detectors : (1) one of the early balloon flight detector (B), (2) HEAO A-4 (H) and (3) the SAX detector (S). The spectra of a few cosmic sources are also shown (dotted lines) along with the spectra of CXRB for a field of view of 5° (Bkgd).

improvements in the sensitivity of soft X-ray detectors are shown by a few examples (cf. Bradt *el al.* 1992) : (1) The rocket flight which discovered the first cosmic X-ray source Sco X-1 (R), (2) the 3 orders of magnitude improvement in the sensitivity by the superior background rejection techniques used in the UHURU satellite (U), (3) another 3 orders of magnitude improvement in the sensitivity brought about by the focussing X-ray detectors in the Einstein Observatory (E), and (4) the advantage of the X-ray mirrors to be further improved in the future AXAF satellite (A). An improvement of eight orders of magnitude in sensitivity has been achieved in 3 decades!

In the hard X-ray range, on the other hand, the improvement in sensitivity is only about 2 orders of magnitude. The hard X-ray spectra of some of the X-ray sources are shown in figure 1 along with the spectrum of cosmic X-ray background for an opening angle of 5 degrees. Three examples of hard X-ray sensitivity are shown : (1) one of the early balloon flights (Agrawal *et al.* 1970), (2) HEAO A-4 detector (Levine *et al.* 1984), and (3) the future SAX satellite (Butler & Scarsi 1991). The sensitivity of the early balloon payload is such that only the very bright X-ray sources are clearly detectable. The HEAO A-4 detectors (Levine *et al.* 1984) achieved one of the lowest hard X-ray background rates for a crystal detector in orbit and a complete sky survey carried out over the period of a year produced a catalog of 72 sources. The future satellite hard X-ray detectors like the SAX or the HEXTE (Bradt *et al.* 1991) will improve the sensitivity marginally. Most of the balloon-borne hard X-ray telescopes have sensitivities in the region of 10^{-5} photon cm^{-2} s^{-1} keV^{-1}.

As a comparative study, the number distribution of the UHURU (Forman *et al.* 1978) and HEAO A-4 (25-40 keV) sources are shown in figure 2. The flux is normalized to the Crab flux and the number to the total observed sources (334 for UHURU, 68 for HEAO

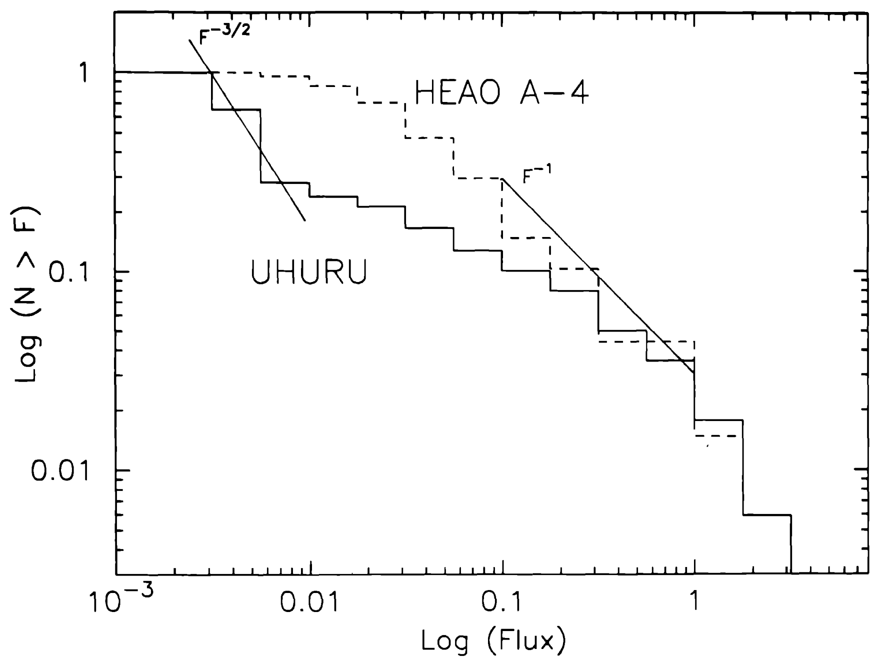

Figure 2. The number distribution (Log $N(>F)$) of the UHURU and HEAO A-4 (25-40 keV) sources. The integral number is normalized to the total number of sources in each catalog and the flux is normalized to the Crab flux. The $F^{-3/2}$ and F^{-1} distributions are also shown.

A-4). The number of soft X-ray (UHURU) sources with higher flux values show F^{-1} distribution indicating a Galactic origin of the bright sources and at lower flux values the $F^{-3/2}$ distribution indicates an extra-galactic source population. These two populations of sources are clearly separated from each other. Unlike the soft sources, the Galactic and the extragalactic source populations are not clearly separated for the HEAO A-4 sources. This is mainly because of the fact that the Galactic sources have steeper spectra compared to the extragalactic sources.

The focussing X-ray detectors are extremely inefficient at energies above 12 keV because at these energies the wavelength of X-rays (< 1 Angstrom) is comparable to the atomic dimensions. The only way to have high sensitivity hard X-ray detectors is by making large area low background collimated detectors. The basic difficulty in improving the sensitivity of hard X-ray detectors is the requirement of extremely large areas [the sensitivity improves as the inverse square root of the area—see eqn. (3)] and maintaining uniform detector characteristics over this large area. Before discussing the results obtained from the large area low-energy detectors with extended response up to 30-50 keV are discussed. These results, called here as the 'fringe results' show the potential of the hard X-ray astronomy.

3. The 'fringe' results

The X-ray detectors which were basically low energy detectors but had sufficient sensitivity up to the energy range of ~ 50 keV are HEAO A-2 (800 cm^2) (Rothschild *et al.* 1979), EXOSAT ME (1600 cm^2) (Turner *et al.* 1981) and *Ginga* (4000 cm^2) (Makino 1987). The XTE will have an area of 6250 cm^2 (Bradt *et al.* 1991) and it will improve the results obtained in this energy range.

3.1. *Cosmic X-ray background (CXRB)*

One of the most important results obtained from the HEAO A-2 detectors is the measurement of the spectrum of the cosmic X-ray background (Marshall *et al.* 1980). Combining data from two detectors having different fields of view the spectrum of CXRB is fitted as a thermal bremsstrahlung with a temperature of 40 keV. Attempts to understand CXRB as superposition of spectra of Active Galactic Nuclei (AGN) has not met with complete success and a better measurement of AGN spectra and extending the energy range of the CXRB spectrum to higher energies is very essential to understand the origin of CXRB (Setti 1992).

3.2. *X-ray binaries*

Galactic X-ray binaries are the brightest X-ray sources in the sky and a wealth of information has come from studying them at low energies. There are, however, some new important results which came about mainly from the study in the energy range above 15 keV. We concentrate on a few of them.

3.2.1. SPECTRA OF LOW MASS X-RAY BINARIES

Low Mass X-ray Binaries (LMXB) are characterized by having a neutron star with a weak magnetic field (10^8-10^9 Gauss) and a low mass companion. The X-ray emission from LMXBs is dominated by the processes in the accretion disk, which reaches quite close to the neutron star surface (Parmar & White 1988). Cygnus X-3, a binary with $4^h.8$ periodicity, is one of the brightest X-ray sources in the sky. There were indications of several continuum components in the spectra at low energies and, further, it is also one of the brightest Fe line emitters. Being extremely bright in X-rays, good signal to noise data were obtained. There is, however, no statistically acceptable model derived for the spectra and different models seem to be favoured by data from different detectors, depending on the band-width of observation. There is a lack of agreement in the derived parameters even for contemporaneously obtained data from two independent detectors. Clearly, multiple spectral components are present in the data (Rajeev *et al.* 1993).

To obtain a consistent and generalized spectral model for the X-ray emission from Cyg X-3, Rajeev *et al.* have analysed the data obtained from the three detectors of the EXOSAT observatory (ME Ar, ME Xe and GSPC). The resultant spectral model is shown in figure 3 along with the deconvolved data. The model components (blackbody, Comptonization model of Sunyaev and Titarchuk, 1980 - CompST, Fe line emission) are shown separately. It is clear that multiple components are present at any given energy range and without the inclusion of the high energy data (15-30 keV) obtained from the ME Xe detectors, it would have been difficult to separate the spectral components and fix the CompST parameters. The extension of the CompST model to higher energies also agrees with the hard X-ray (20-100 keV) measurements made at balloon altitudes (Rao *et al.* 1991).

3.2.2. CYCLOTRON LINES IN X-RAY PULSARS

The High Mass X-ray Binaries (HMXB) are characterized by neutron stars with high magnetic fields (10^{12} G) and a massive companion. The X-ray emission is mainly from physical processes in these fields and they manifest as pulsations and cyclotron lines in the spectra

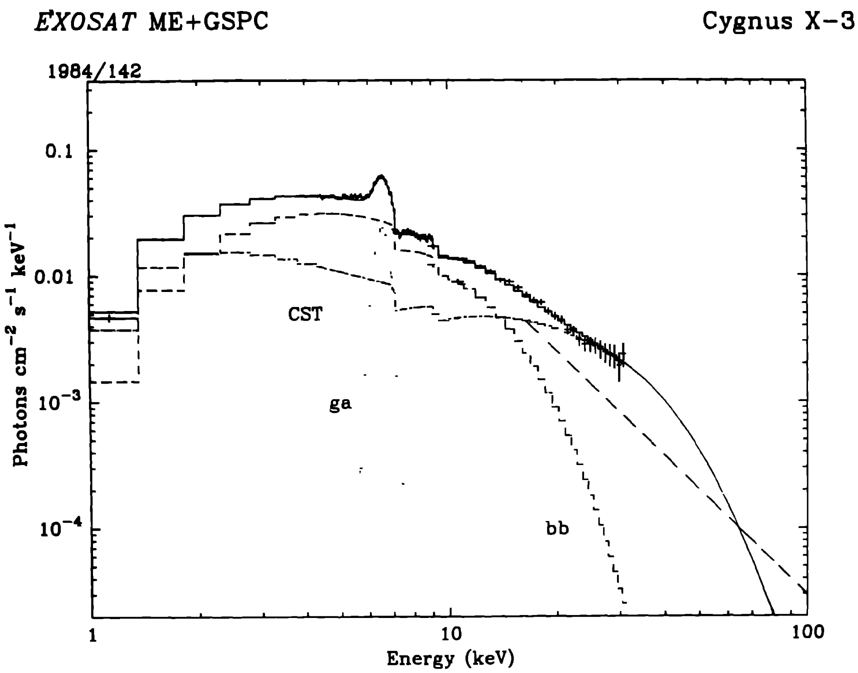

Figure 3. Deconvolved X-ray spectrum of Cyg X-3, averaged over one binary cycle, obtained from the Ar, Xe and GSPC detectors of the EXOSAT Observatory. The contribution from the individual model components, blackbody (bb), Gaussian line (ga), CompST, are also shown. The CompST spectrum is extended up to 100 keV and compared with the independent hard X-ray observations, shown as a dashed line (Rajeev *et al.* 1993).

(Nagase 1992). The classic example of the cyclotron line is from Her X-1 (Trumper *et al.* 1978). The line parameters in this source needs to be better determined and the sample extended to other sources as well.

The *Ginga* satellite, with the large area of 4000 cm^2 has discovered cyclotron lines in several of the X-ray pulsars in the energy range of 15 to 30 keV (Makishima *et al.* 1992). They have found variation of the cyclotron line energy with pulse phase and also a correlation of the cyclotron line energy and the spectral cut-off energy. A search for cyclotron lines in the energy range of 20-100 keV will vastly extend this sample and also obtain information regarding X-ray pulsars with high magnetic fields.

3.2.3. TIME VARIABILITY IN BLACK HOLE CANDIDATES

The canonical black hole candidate, Cyg X-1, is known to exhibit variability in a variety of time scales. Using the data obtained from the *Ginga* satellite Miyamoto and Kitamoto (1989), discovered a time lag between low energy X-rays (1.2 to 5.7 keV) and the hard X-rays (15.8 to 24.4 keV). These results, along with the power density spectra (PDS) at the two energies are used to derive the spot parameters and it was concluded that the accreting matters are in Keplerian orbits near the central blackhole at preferred orbits.

3.3. *Spectra of AGNs*

The active galactic nuclei (AGN) are found to be having a canonical photon spectral index of 1.7, which is used to estimate the contribution of the AGNs to the CXRB spectra. These results are, however, obtained from analyzing data obtained in the low energies only. Singh *et al.* (1990) have analysed the X-ray data (up to 30 keV) of the nearby Seyfert I galaxy Mkn 509, using the *Ginga* satellite. It was found that the spectral index obtained at 10-30 keV is significantly flatter than that obtained in the 3-10 keV range. Pounds *et al.* (1990) have combined the spectra of 12 AGNs obtained from the *Ginga* satellite and found an excess of emission above 10 keV. They have modelled this excess as a Comptonized reflection spectrum from cold slab of matter. Such spectral information at high energies has very important implications on the environment of the AGNs and also in understanding the AGN contribution to the CXRB.

4. Hard X-ray imaging detectors

As mentioned earlier, it is very difficult to make focussing X-ray telescopes for hard X-rays. There are, however, several new detectors which can obtain hard X-ray images. The most popular hard X-ray imaging device is the arrangement of a coded aperture mask in front of a position sensitive detector (Caroli *et al.* 1987). The TTM experiment onboard the *Kvant* module (Sunyaev *et al.* 1991) and the SIGMA experiment onboard the GRANAT satellite (Paul *et al.* 1991) are two of the best examples of hard X-ray imaging detectors. Though these experiments can achieve arcminute positional resolution, the sensitivity is quite inferior to even the conventional detectors with mechanical collimators and the results obtained pertain to only a few of the bright sources.

The most important result from the TTM experiment is the discovery of the hard X-ray emission from the SN 1987A (Sunyaev *et al.* 1987). The SIGMA experiment has pin-pointed the source of $e^+ e^-$ annihilation line at the Galactic centre (Sunyaev *et al.* 1992), and localized several X-ray/gamma ray transients (Sunyaev *et al.* 1991). One of the interesting discoveries is the detection of a hard X-ray source 15′ away from the AGN 3C 273 (Jourdain *et al.* 1992). This new source is highly variable and absorbed and identified as a new class of AGN.

5. Results from large area detectors

Now we turn to the results obtained from the large area high sensitive detectors in the energy range of 15 to 150 keV. Most of the results have come from the two large area scintillator detector experiments, the HEXE experiment on-board the *Kvant* module (Sunyaev *et al.* 1991) and the imaging hard X-ray detector SIGMA on GRANAT (Paul *et al.* 1991); and also from several large area balloon-borne detectors based on phoswich detectors (Damble *et al.* 1989) and xenon filled proportional counters (Rao *et al.* 1991; Baker *et al.* 1984; Sharma *et al.* 1987).

As was evident from the ‘fringe’ results, the bulk of the hard X-ray results are on X-ray binaries. Here we concentrate only on those results which could not have been obtained either from the low energy detectors or from the detectors sensitive only up to 30 keV.

5.1. *Hard X-ray pulsations and QPO*

The neutron stars in LMXBs have low magnetic field and it is also conjectured that they have high rotation speeds corresponding to millisecond periodicities. Since the low energy X-ray emission is dominated by the accretion disk emission, the pulsations from the low magnetic field pulsars will be swamped by this emission. In the hard X-rays, where the emission is expected to be coming from closer to the neutron star, it should be easier to detect pulsators, if they exist.

It is interesting to note that Damle *et al.* (1989) have found indications for the hard X-ray pulsations from the LMXB, Sco X-1. In a balloon flight carried out on 1984 December 18 from Hyderabad, India, using a set of phoswich detectors with a total area of 400 cm^2, they have discovered coherent pulsations at a period of 2.93 milliseconds. This periodicity is seen only over the first half of the observations and it is not confirmed by the low energy detectors like the EXOSAT ME. Hence this very interesting result needs to be confirmed by better sensitivity hard X-ray detectors.

Several LMXBs exhibit quasi-periodic oscillations (QPO) and a few of them like Cyg X-3 exhibit transient coherent pulsations (van der Klis & Jansen 1985). The origin of these variations is thought to be instabilities in the accretion disk and a comprehensive understanding of this phenomenon is possible by studying the time variability in the hard X-ray range. In a balloon flight carried out in 1986, Rao *et al.* (1991) discovered coherent pulsations from Cyg X-3 at a periodicity of 121 s. Considering the similarity between the pulsations obtained in the hard and soft X-rays, this periodicity was ascribed to transient oscillations of the kind detected by van der Klis & Jansen (1985).

The X-ray emission from black hole candidate binaries in the low energies is also dominated by the accretion mechanisms. Recently quasi-periodic oscillations were also seen from Cyg X-1 at a frequency of ~ 0.04 Hz (Vikhlinin *et al.* 1992). In a balloon flight carried out from Hyderabad, Chitnis *et al.* (1993) have confirmed this result by detecting a QPO from Cyg X-1 in the hard X-rays at a frequency of 0.035 Hz.

5.2. *Spectra of black hole candidates*

The hard X-ray spectra of Cyg X-1 are well fitted with the inverse Compton spectra of the simplified geometry as given by Sunyaev and Titarchuk (1980). The Sigma experiment have obtained the hard X-ray spectra of several black hole candidates and found the similarity in the hard X-ray emission from most of these sources. The hard X-ray spectrum is an independent method of classifying the black hole candidates (Grebenev *et al.* 1993).

6. Future work

As is evident from the previous discussions, most of the work reported up to now in the hard X-ray is limited to very bright sources (brighter than about 100 m Crabs). Excluding transients, there are only about a couple of dozen sources above this limiting flux. Improving the sensitivity of the hard X-ray detectors is, therefore, of prime importance for any advance in the field.

In spite of the difficulties in Section 2, there are several attempts to make very large area detectors with uniform gain and resolution. The new Xenon experiment at TIFR aims to make large area high pressure detectors with stainless-steel body along with 4π veto detectors. Sood *et al.* (1991) are attempting to make an ultra-high pressure xenon filled proportional counter array with very large area (10000 cm^2). The phoswich detectors proposed to be used in the GRISP experiment by Nikolsky *et al.* (1993) have very good energy resolution and the use of 3 detectors with different FOVs will provide a measure of the CXRB up to about 150 keV.

The major unresolved issues that can be addressed with new hard X-ray detectors are

1. *Spectra of LMXB* : The Sco X-1 has a thermal spectrum, and some evidence of a hard X-ray tail, whereas Cyg X-3 has a relatively low intensity blackbody component. It is not clear whether all LMXBs have a hard component and what is their relation vis a vis their evolution. A large sample of hard X-ray spectra of LMXBs will clarify the situation.

2. *Spectra of AGNs and CXRB* : New spectral components are seen in the spectra of AGNs up to 30 keV and the region up to 150 keV is not explored well. A systematic quantification of the spectra of different classes of AGNs is essential to understand the environment of AGNs and evaluate their contribution to CXRB. An independent measurement of the spectra of AGN over an extended band width is also highly desirable.

3. *Timing studies* : Hard X-ray QPO and other timing analyses of LMXBs and black hole candidate sources are necessary to understand the accretion mechanism.

4. *Hard X-ray studies of cataclysmic variables* : The magnetic cataclysmic variables have very hard spectrum and there are some reports of detection of high energy gamma rays (in the TeV range) from some of them (Bhat *et al.* 1991). Spectral measurement in the hard X-ray range is essential to understand the high energy phenomenon occurring in these sources.

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