NASA/TM-1998-207905

INSTRUMENTATION FOR X-RAY ASTRONOMY FROM HIGH-ALTITUDE BALLOONS: RECENT DEVELOPMENTS AND FUTURE PLANS.

B.D. RAMSEY, V. PESKOV
NASA/Marshall Space Flight Center, Alabama 35812, USA
P. FONTE
LIP, Coimbra University, Portugal P 3000
E. PODOLIAK
Institute for Physical Problems Russian Academy of Sciences, Moscow 117334, Russia.

ABSTRACT

We describe our current effort and future plans to develop new detectors and methods for studying hard x-ray emission from the Universe during balloon flights.

1. Introduction

Hard x-ray astronomy studies the Universe in the energy region 10-100 keV. The radiation from most of the interesting objects in this region has non-thermal origins and this gives important information about exotic physical processes occurring, for example, near black holes or other sources. This energy region is relatively unexplored due to low source fluxes and the difficulty of developing high-sensitivity instruments. While over 10^5 sources have been discovered at lower energies (below 10 keV), fewer than 100 have been observed in the hard x-ray region. This makes this branch of experimental astrophysics particularly challenging and potentially very rewarding.

Since radiation in the 10-100 keV region is heavily absorbed by the atmosphere, observations must be carried out with instruments flown at high altitudes. A relatively low-cost method of doing this is to use stratospheric balloons, which can carry payloads of 1 - 2 tonnes to float altitudes of around 40 km. From this vantage point greater than 2/3 of the incident flux above 30 keV enters the detector unscattered by the atmosphere.

While current balloon-flight durations cannot compete with the extended observations available on satellites, they do offer moderate observing times (a few days) and a fast and cheap way of testing and demonstrating new technology. In addition, super-pressure balloons are under development that will eventually permit flights of more than 100 days.

The Marshall Space Flight Center has a program to develop and fly x-ray instruments on high-altitude balloons. The Marshall Imaging X-ray Experiment (MIXE2) is the latest such 'telescope', consisting of a large-area MicroStrip Gas Counter (MSGC) mounted 2 m below a coded aperture mask. It provides few-arc-minute angular resolution over an energy range from the atmospheric cut-off at 20 keV up to around 100 keV, and an energy resolution of around 7.5% at 22 keV. Full details of the instrument are given in Table 1.

Table 1 : MIXE2 Characteristics

Total area	300 mm x 300 mm
anticoincidence border	10 mm
imaging region	280 mm × 280 mm
depth of absorption and drift region	200 mm
microstrip	Chrome on 7740 glass, 1 mm thick
anode width	10 μm
anode pitch	2 mm
cathode width	660 μm
cathode pitch	2 mm
rear electrodes	1.95 mm on 2 mm pitch
gas mixture	Xenon/Isobutylene (98:2)
gas pressure	2.10^5 Pa
coded mask to detector separation	2 m
mask element size	4 mm
field of view	1.8 degrees (FWHM)
angular resolution	6.8'

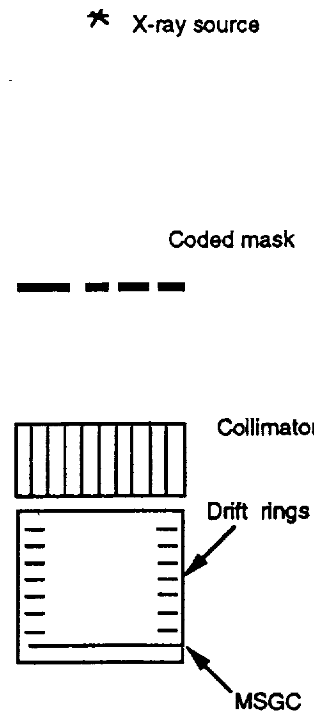

Fig. 1. MIXE2 schematic.

The development of a large-area MSGC was prompted by the encouraging performance of earlier small-format devices. Of particular interest were the high-degree of uniformity, which translated in improved energy resolution, the fine anode diameters and pitches, which resulted in low operating voltages and improved spatial resolution, and the relatively robust construction in which individual wires could not break and short the whole counter.

A drawback immediately encountered was the low gains achievable in large-area devices before breakdown would occur. This severely hampered the imaging properties as the second co-ordinate was derived from the relatively low amplitude rear signal. As a consequence, we were forced to study, in detail, breakdown mechanisms in MSGC's and ways of achieving high gains ($>10^4$) in practical devices. The results of these studies are presented here together with future plans for higher sensitivity balloon-borne instruments.

2. Development of High-Gain MSGC's for the MIXE Program

In order to develop MSGC's for the MIXE program, studies were done to identify the limiting factors in achievable gains. The detailed description of these results can be found elsewhere[1,2] and here we will present only the main conclusions, which are useful for understanding our design improvements, which in turn are described in section 3.

These conclusions are:

1) Breakdown in MSGC's occurs through a surface streamer mechanism.

2) Due to their attachment to the surface, these streamers are unquenched and rapidly transit to gliding discharges[3]. The substrate surface, therefore, represents the weak link in the breakdown chain.

3) A key to reaching high gains before breakdown occurs is to create conditions that ensure a fast reduction of the electric field, and hence the Townsend coefficient, with distance from the anode strips along the substrate surface.

We demonstrated experimentally[1,2], that (3) above could be achieved by using narrow anodes (<10 microns), large pitches, and fill gases having a strong dependence of gas gain (M) on the applied voltage (V). The latter can be accomplished using Penning mixtures, such as Xenon with a small percentage of TMA (Trimethylamine) or Isobutylene. These have very large values of dM/dV and, due to the low concentration of the quencher, the mean free pass of the U.V. photons emitted from the primary electron cloud or from the resulting avalanches is large. This effectively lowers the charge density and, since streamers are created at some critical charge density[2], it raises the threshold for breakdown.

Another important parameter is the cleanliness and smoothness of the substrate and electrode surfaces. It was demonstrated that in high electric fields, especially under intense ion bombardment, defects or inclusions on solid surfaces could emit bursts of electrons. On Dielectric surfaces, the emitting spots are usually sharp points, for example dust[4]. On Metallic surfaces the emitting spots are not only sharp points, but also dielectric inclusions[5]. These emitting points may, under special circumstances, as for example in the case of thin conductive coatings, trigger breakdowns in MSGC's[6] . We discovered that chemical cleaning alone of the MSGC surfaces was not sufficient to remove all residual contaminants. Additional baking at a temperature 80°C for 24 hours after the chemical cleaning was found necessary to give good gain stability and a high degree of uniformity over the whole surface.

One final note is that one should avoid, whenever possible, thin, low-resistivity coatings. Such coatings change the field line distribution and make the field along the surface stronger and more uniform[1]. These factors favor streamer development and render the MSGC unstable at higher gains.

As a direct result of these studies a high-gain, large-area MSGC was developed for the NASA/MSFC program[7] (detailed in Table.1). MIXE2 has an active area of 30 x 30 cm^2, features narrow anodes (10 microns) on a relatively large pitch (2mm) and uses a Penning-type mixture of Xe+2% isobutylene at a pressure of 2.10^5 Pa. It has good energy resolution (7,5% at 22keV) and gain and energy resolution uniformity of a few percent over the entire active area. After baking, the detector can work without any breakdowns at a gain $\sim 10^4$. According to our knowledge these are the best characteristics achieved so far for large area MSGC detectors.

3. New Designs of MSGC's

As a further step in developing higher-gain MSGC's, we built and tested devices with specially shaped cathodes. As was pointed out before, the weakest place in the MSGC, where breakdowns are most likely to occur, is the substrate surface between the anode and cathodes. In these new designs we tried to minimize any surface contributions and to provide a rapid field drop-off with distance from the anodes. Some of these designs are presented in fig.2, with their gain performance, measured in P10 at 10^5 Pa, presented in fig.3. The use of P10 facilitates comparisons with earlier measurements in conventional MSGC's[1]. By comparing fig.3 with fig. 19 from ref.[1], one can see that considerably higher gains were achieved with such improved designs. As discussed earlier, the maximum achievable gain also depends on the fill gas. However, the limited space of this paper does not permit us to present all these data. We note only that even higher gains were achieved in gases where the primary ionization cloud has a low ion density as for example in He-based mixtures or pure CH_4 [2].

The rate characteristics of our designs were also better that for conventional MSGC's (see ref.[6] for more details). This improvement in rate can be connected to the fact that in these designs the bulk of the ions move to cathode through the gas gap, not along the substrate surface. This situation can also be achieved, to some degree, in conventional MSGC's when a large positive bias is applied to the back plane or when a strong drift field is applied which results in a considerable portion of the ions moving to the drift electrode.

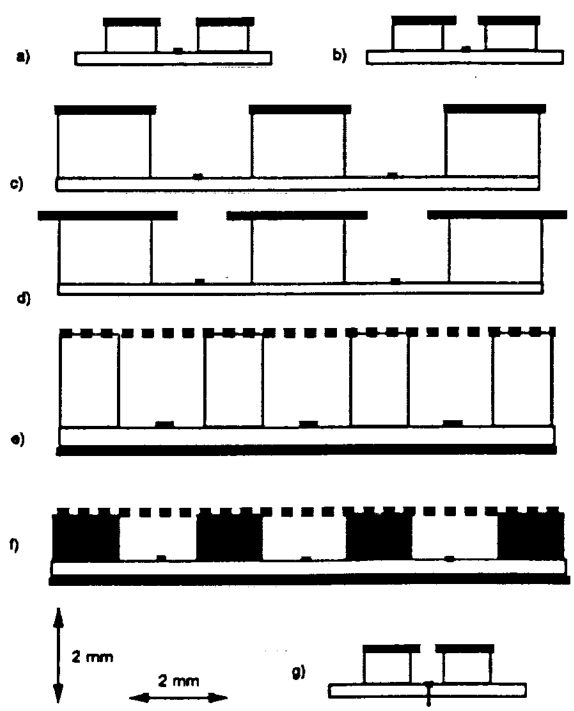

Fig. 2. Various high-gain MSGC designs.

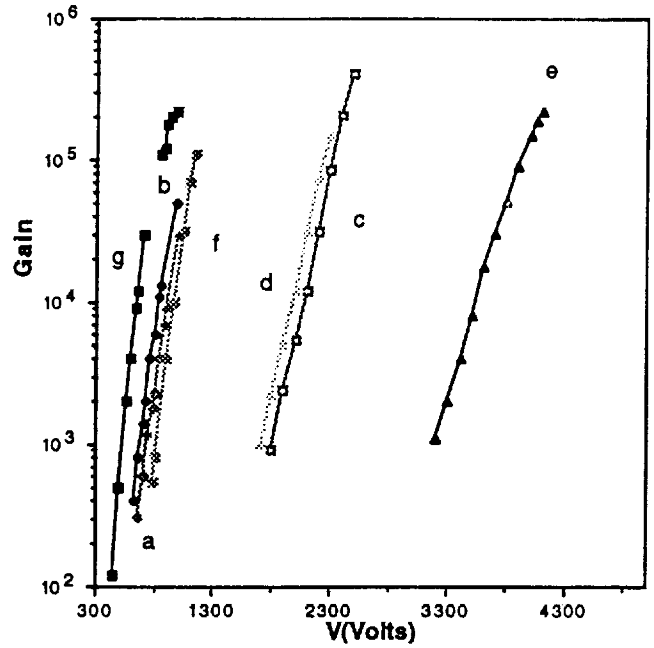

Fig. 3. Gain characteristics of the microstrip designs in Fig. 2, in P 10 gas @ 1.05 atm.

4. Test Launch of a Large-Area MSGC

After detailed calibration tests in the Laboratory, the MIXE2 instrument was launched from Fort Sumner, New Mexico, in the Spring of 1997. The flight lasted for approximately 12 hours at a float altitude of ~38km. During this time, observations were made of the Crab Nebula, Cygnus X-1 and several other bright Galactic and extra-Galactic sources, and the data from these are currently under analysis.

For future more detailed observations, further increases in sensitivity must be achieved. As all observations are limited by the very high backgrounds generated by cosmic ray charged particles, a constant challenge is to reduce this unwanted radiation component.

For the short term, we can explore new techniques of background reduction in our large-area gas detectors. For the longer term, we can develop hard-x-ray mirrors, which would focus the source flux to a small spot in the focal plane over which the background would be almost negligibly small. In this way an enormous increase in sensitivity would be achieved. Both these near and far-term programs will now be briefly described.

5. Multilayer Detector Geometries

Typically, gas detectors are designed to provide adequate absorption efficiency at the top of the energy range under investigation, and this frequently means that the detector is much thicker than it needs to be at lower energies. This in turn leads to increased background at lower energies, as the isotropic charged-particle-induced background is a volume effect.

One method to reduce this is to segment the detector into layers, and accept only photons exhibiting the appropriate depth dependence for normal incidence. This segmentation has an additional benefit in that it enables the energy resolution of the detector to be improved upon. Fig. 4 shows such a layered/segmented detector where each detector layer measures with high accuracy the X and Y coordinate of the photon (necessary for image reconstruction) and also its Z position with the obvious accuracy of Z/n, where n is the number of detector layers (or individual detectors.). As was shown in ref[8], by measuring the number of counts from each layer, Ni, one can restore the initial spectrum with a energy resolution

$$\Delta E/E = k / \sqrt{(\Sigma_i N_i)},$$

where k is a coefficient dependent upon the total number of layers.

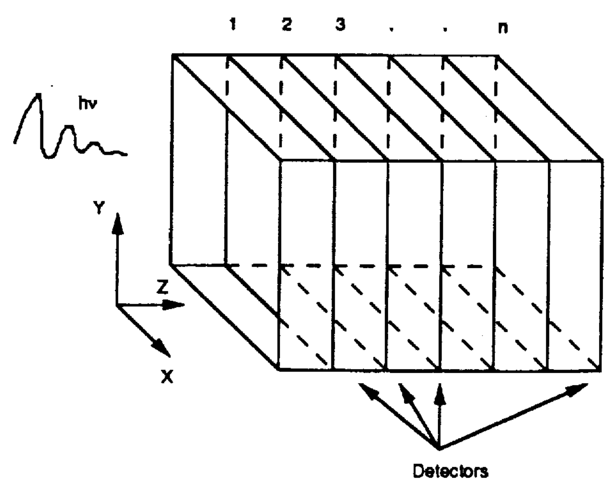

Fig. 4. Segmented detector concept.

Since the energy resolution depends on the total number of recorded photons (counts) it may become quite high. For example, with a total of 10^6 recorded counts, the energy resolution would be a few %, independent of energy for a 10 layer detector. Note that in such a method of spectrum reconstruction, no information about the individual pulse amplitudes is needed. Similar mathematical techniques can be used to reconstruct the input spectrum from amplitude measurements if the detector response function is known[9].

In the present work can combine both methods in one. Each layer of the detector measures not only the X,Y and Z coordinates of the photons adsorbed in each drift region , but also their energy. This greatly improves the energy resolution and the background rejection power. For example, simulations show that energy resolution better than 1 keV at 60 keV can be achievable in a MIXE2-type detector with 5.10^5 Pa of xenon and 5 detection layers.

5.1. *Technical Realization*

The attraction of the multilayer approach is that it can build on the current (MIXE2) detector design. The main problem is to find a rigid design for each detector plane that is transparent to the unabsorbed source photons. Two options were investigated experimentally:

a) MICROMEGAS
b) MSGC's with preamplification structures

5.1.a. MICROMEGAS

According to ref [10], MICROMEGAS is a rigid position-sensitive detector capable of operating at rather high gains (~10^5) which can be fabricated on a substrate transparent to x-rays.

Consequently, we obtained a device for test from France for evaluation [Elyssys Mesure], having an active area of 10 x 10 cm^2 and a discharge gap of 0.1 mm. By testing this device in various gases we confirmed that MICROMEGAS could operate at gains close to 10^5 when irradiated with soft x-rays (~6 keV). However, our tests also showed that the maximum achievable gain in MICROMEGAS was strongly dependent on the level of primary ionization. It was found that sparks almost always appear at some critical charge in the avalanche (~3-5.10^7 electrons), similar to the usual behavior of Parallel-Plate Avalanche Chambers (PPAC)[11]. For this reason, to avoid sparking one should strongly reduce the gain when recording heavily ionizing particles such as alphas. In fact, under alpha irradiation, a safe working gain was found to be no more than 10^3. In this regard, MICROMEGAS is very different from MSGC's where the maximum gain is much less dependent on primary ionization, and where alphas can be tolerated at gains of 10^4 (ref[12]). As heavily ionizing particles are present at balloon altitudes, and as we wish to avoid sparking, we elected to pursue MSGC's only.

5.1.b. MSGC's With Preamplification Structures

MSGC's fabricated on thin glass (0.1-0.2 mm) are sufficiently transparent to hard x-rays to make this a feasible approach to a layered detector. However, these designs were rather fragile and required a lot of precautions in their handling. For this reason we also considered an option where the MSGC was fabricated on a Kapton substrate. Measurements showed that 0.1-0.2 mm thick Kapton was fully transparent for hard x-rays. Unfortunately, prototype MSGC's on Kapton substrates, which were produced in the USA [Max Levy Inc.] were unstable above gains of 10^3. In an effort to improve their maximum achievable gains, we tested various preamplification structures placed in front of the MSGC's. The results of these studies are described in detail in our recent paper[13]. The main conclusion is that by using a PPAC as a preamplification structure one can reach both high gains and simultaneously achieve good energy resolution (fig.5) The opens the possibility of utilizing such a Kapton + PPAC combination for multilayer detector development.

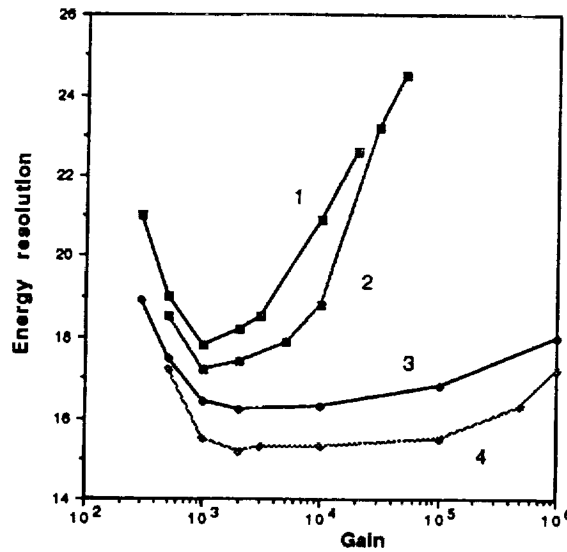

Fig. 5. Effect of preamplification. MSGC detector with (3) and without (1) preamplification in P10 fill gas. (4) and (2), the same respectively, in Xenon + Isobutylene (3%). All at 1.05 atm. For details see[13].

6. Mirrors

Focusing optics can provide enormous increases in sensitivity, by effectively reducing the background to almost zero. At low energies, below around 10 keV, arrays of nested x-ray mirrors have revolutionized the field of x-ray astronomy (see fig.6). Modern large x-ray telescopes, such as the AXAF observatory[14], have sensitivities 5 orders of magnitude greater than earlier, yet similar collecting area, non-focusing instruments. However, the critical angle, above which x-rays cannot be reflected, scales inversely with energy, and this means that at high energies it is extremely difficult to obtain useful collecting areas.

Two approaches can be used to build useful hard-x-ray mirrors. The first is to use multilayer coatings to give first order Bragg reflection at angles above the critical angle. These necessitate putting down hundreds of precisely controlled layers of alternating high/low density materials on to high-quality substrates with roughness at the few Angstrom level. The process is difficult and expensive, although many groups are actively involved in this type of development[15].

A second approach, and one being pursued at MSFC, is to accept the very shallow grazing angles and to develop a series of very small diameter, heavily nested mirrors, arranged in assemblies above an array of detectors. The MSFC mirror payload, currently under construction, will consist of 16 mirror assemblies each with approximately 11 mirrors, concentrically nested, to give a total collecting area of over 100 cm^2 up to 60 keV. Each mirror is fabricated using an electroformed nickel replication process, in which multiple copies are produced from a single super-polished mandrel[15]. This avoids the lengthy and expensive figuring and polishing of individual mirror shells, and makes possible payloads of 100's mirrors on manageable budgets. The MSFC payload, with just under 200 mirrors, will take approximately 3-4 years to complete. On a long duration balloon flight (10 days) the resulting sensitivity of this mirror assembly, when combined

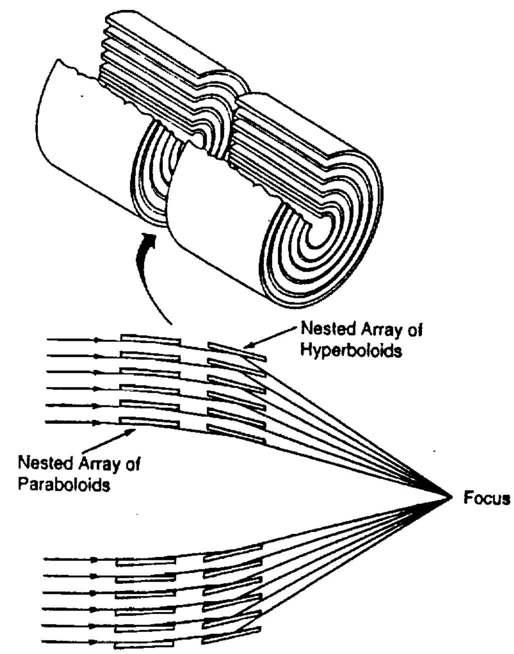

Fig. 6. Nested array of x-ray mirrors in a Wolter 1 configuration[15]

with suitable focal plane detectors, will be 10 times greater than the non-focusing MIXE2 instrument (equivalent to 100 MIXE2 units.)

The choice of a suitable focal plane detector, of which 16 will be needed, each with sub-mm spatial resolution, will depend upon the maturity of certain technologies when the mirrors are nearing completion (in approximately 3 years). Two options are under evaluation: Cadmium-Zinc-Telluride (CZT) semiconductor detectors and Gas Scintillation Proportional Counters (GSPC's).

6.1. CZT Detectors

Cadmium-Zinc-Telluride detectors are an attractive new development for focal plane detectors in the hard-x-ray region. They combine high absorption efficiency with excellent energy resolution potential, and can operate at room temperature. In addition, they can be pixellated on a fine scale to provide 2-dimensional position sensitivity matched to the focusing optics.

In practice, though, while two-electrode single-pixel devices have achieved good energy resolution (typically a few percent FWHM at 60 keV), imaging CZT's with sub-mm pixels still lag far behind in performance (by a factor of 3 to 4). One reason for this strong degradation of energy resolution is the pixel-size-dependent sharing of induced signal between adjacent pixels, and the noise caused by leakage currents and the many individual amplifiers necessary for reading out the shared signals. We are planning to develop a matrix of "three-electrode" pixels (fig. 7) which theoretically should have enhanced energy resolution (see[16] for more details.) This geometry provides a sharp potential drop near the point-like anodes and this permits collection of a maximum amount of induced signal, and minimizes the sharing of signals between adjacent cells. Additionally we are planning to apply the method of signal analysis briefly mentioned in section 6 which may further improve the energy resolution. This would necessitate using the signal risetime as a measure of the penetration depth of the incident radiation.

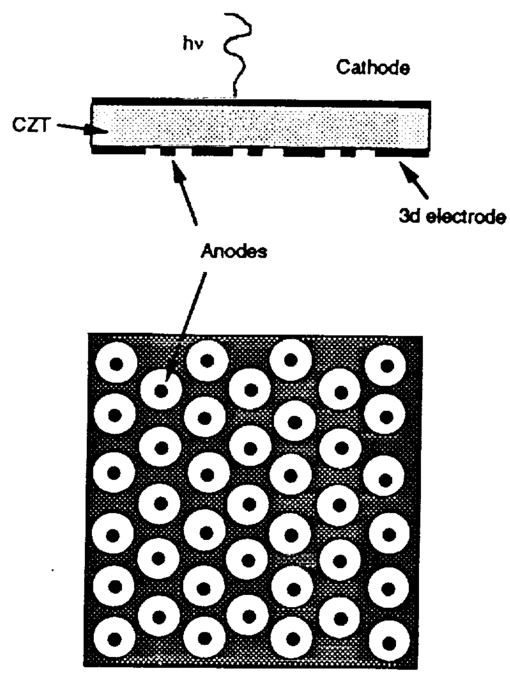

Fig. 7. Three-electrode geometry for pixellated Cadmium-Zinc-Telluride detector.

6.2. GSPC

It is by no means obvious at this time that the CZT detector can deliver on its promise of semiconductor-level energy resolution plus fine spatial imaging. As a backup solution for the focal plane of our optics, we are considering the Gas Scintillation Proportional Counter (GSPC), which, when filled to 10 atm, can deliver both sub-mm spatial resolution plus an energy resolution of around 3.5 - 4 % at 60 keV [17]. The small format requirement (2 cm x 2 cm) for the focal plane of a narrow-field-of-view set of optics means that the x-ray entrance and UV exit windows are easy to fabricate even for the high fill-gas pressure. Further, by using the drift-less approach[18], which gives a depth co-ordinate, we could easily implement the amplitude analysis reconstruction approach and discriminate against background by the absorption depth. The net result would be an instrument close to the target performance of pixellated CZT detectors, but with much more established technology.

7. Conclusion

We have presented an overview of our development efforts for instrumentation for hard x-ray astronomy. For the short term we are concentrating on large-area microstrip gas detectors for background-limited observations. We included details of our efforts to improve MSGC design and possible ways to enhance energy resolution and sensitivity. For the longer term, we described our x-ray mirror payload development, which we believe will improve sensitivities by an order of magnitude over existing large-area, non-focusing payloads. On long-duration balloon flights, this instrument will directly compete, at a small fraction of the cost, with satellite-borne payloads.

8. References

1. V.Peskov et al., *Nucl. Instr.and Meth. in Physics Res.* A397 (1997) 243.
2. P. Fonte et al., *ICFA Instrum Bulletin*, 1997, http://www.slac.stanford. edu.pubs/icfa/.
3. K. Uhlig, *Surface discharges in High Magnetic Fields,* (Hartung-Gorre Verlag), 1991.
4. P. Fonte et al., *Extremely High Counting Rate RPC* , a report submitted to the Vienna Wire Chamber Conference, Vienna, 1989.
5. R. Latham, *High Voltage Vacuum Insulation* (Academic press, New York.1995.)
6. Peskov at al., *Breakdown features of various Microstrip-Type Gas Counters designs and their Improvements,* submitted to IEEE Trans. Nucl. Sci, 1997.
7. B. D. Ramsey et al., *Nucl.Instr.and Meth. in Physics Res.,* **A383** (1996) 424.
8. E.L. Kosarev et al., *Nucl. Instr.and Meth.,* **208** (1983) 637.
9. G.F. Karabadjak et al., *Nucl. Instr.and Meth.,* **217** (1983) 56.
10. I. Giomataris, private communication.
11. P. Fonte et al., *Nucl. Instr. and Meth. in Phys. Res.,* **A305** (1991) 91.
12. B. Boimska et al., *Investigation of Discharge Limits in Diamond Coated MSGC,* Internal report CERN-PPE GDD, 1996.
13. P. Fonte et al., *A study of Breakdown Limits in MSGC's with Preamplification structures,* Preprint NASA,1997, submitted to Nucl. Instr.and Meth. in Physics Res.
14. M.C. Weisskopf et al., *SPIE* **2805** (1996) 2.
15. B.D. Ramsey, R.A.Austin and R.Decher, *Space Sci. Rev.* **69** (1994) 139.
16. C. L. Lingren et al., *Achieving Good Energy resolution with High Sensitivity in Room-Temperature Gamma-ray Detectors,* report at the IEEE Nucl. Sci Symposium, Alberquerque, 1997, USA.
17. H. Brauning et. al., *Nucl. Instr.and Meth. in Physics Res,* **A348** (1994) 223.
    A. Bolozdynya et al., *Nucl. Instr.and Meth. in Physics Res*, **A385** (1997) 225.
18. D.G. Simons et al., *SPIE* **597** (1985) 190.