NUCLEAR INSTRUMENTATION FOR ASTROPHYSICAL APPLICATIONS

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ABSTRACT

We describe the nuclear instrumentation used in astrophysical applications developed by the Astrophysics Division of the National Institute for Space Research (INPE) in the X-ray and low energy gamma ray bands. These experiments are related to the field of High Energy Astrophysics and are dedicated to the study of cosmic sources, including the determination of their spectra, the measurement of their fluxes and imaging of the region that they encompass. These instruments must be flown at high altitude on board balloons and satellites in order to avoid photoelectric atmospheric absorption of cosmic X and gamma rays, and therefore are subjected to restrictions like weight and size of the detectors and have to operate in a hostile environment, both in terms of pressure and temperature. We present a laboratory image of a Cs^{137} source made with the MASCO imaging telescope placed 68 m away from the detector system and a simulated image of the Galactic Center that shows the scientific capabilities of the MASCO experiment.

I. INTRODUCTION

The need for information about cosmic sources demands observations of the radiation and particles emitted by these objects in all electromagnetic spectrum and in all other possible ways as well. So far, electromagnetic information is the most feasible option as technology has not advanced yet to the point where information conveyed by neutrinos and gravitons, for instance, can be obtained in an effective manner. Even the electromagnetic information is not yet fully exploited due to several technical difficulties. Astronomy and Astrophysics have long evolved with the help of optical and radio information obtained by telescopes on the ground but the high energy part of the electromagnetic spectrum remained inaccessible until recently when the space technology provided the necessary means to make observations almost free from the influence of Earth's atmosphere. This inaccessibility was due to the fact that the wavelengths in the high energy band have about the size of an atom and are strongly absorbed by the atmosphere. This means the atmosphere is essentially opaque to X-rays and gamma rays and forces all high energy telescopes to be positioned at high altitudes in the atmosphere, on board balloons, rockets and satellites.

The X-ray and gamma ray fluxes coming from astrophysical sources are very weak and this fact dictates the construction of highly sensitive instruments. The increase of sensitivity is accomplished with long observation times, since large area detectors are very difficult to be accommodated in spacecrafts. Rockets have very short flight times (of the order of minutes), limiting the experiment sensitivity, and are not much used in this field anymore. Nowadays the vast majority of the experiments are carried out on board balloons and satellites. In the past, however, rocket experiments were responsible for dramatic astronomical discoveries that helped the development of the High Energy Astrophysics. With the onset of the space era, the high energy (X and gamma ray) window could be definitely opened up for Astrophysics.

Observing in the high energy band we can examine objects whose temperatures exceed 1 million degrees Celsius and then try to understand the various physical mechanisms responsible for this emission. By and large, the experiments on board balloons and satellites measure the times, positions, and energy of the photons that hit the detectors, and these events are processed to get different types of output, like spectra, time series and images. Spectra, as in "terrestrial" spectroscopy, can reveal the existence of chemical elements in the source of radiation. Examining the high energy spectra we can determine the physical characteristics that are not revealed in other frequencies. The theory of stellar evolution benefited a lot with observations of X and gamma rays, for instance. The instruments can produce spatially-resolved spectroscopic data which can be used to make images in different energy bands . The images reveal the physical structure of an object and can be analyzed to produce a brightness profile. The astrophysical interest in the hard X-ray and low energy gamma emissions from cosmic sources is directly related to the physics of compact objects and the high energy phenomena associated with the release of gravitational energy in compact objects are, in general, characterized by several kinds of nuclear processes that can be depicted by the detection of gamma ray lines of nuclear origin and a continuum due to the degradation of the lines energy via Compton effect.

In this paper, we describe some of the nuclear instrumentation used in astrophysical applications. In particular, we describe the experiments in X and gamma ray Astronomy carried out at the Astrophysics Division of the National Institute for Space Research - INPE (Instituto Nacional de Pesquisas Espaciais). It is presented a laboratory image of a Cs^{137} source made with the MASCO imaging telescope placed 68 m away from the detector system. It is also presented a simulated image of the Galactic Center that shows the scientific capabilities of the MASCO experiment.

II. NUCLEAR INSTRUMENTATION USED IN ASTROPHYSICS

Most of the detectors used nowadays in High Energy Astrophysics are essentially the same ones used in Nuclear Physics like proportional counters, organic and inorganic scintillators, multichannel plates and CCDs [1]. The need for highly sensitive and low mass detectors pushes the development of new detectors to be used in Astrophysics. While size and mass are not limitations for laboratory experiments in Nuclear Physics, they are crucial limiting factors for High Energy Astrophysics telescopes, since the payloads have to be accommodated in relatively small volumes in order to be put in space. One of the main problems in High Energy Astrophysics is to minimize the effects of the environment in which the experiments are performed, namely the atmospheric background. The objective of an astrophysical experiment is to measure, of course, fluxes coming from celestial sources, whose intensity is low, and these effects cause a decrease in the signal-to-noise ratio. In order to solve these problems techniques known as anticoincidence detectors, in which events that are registered in both shielding and main detectors are rejected, and pulse shape discrimination, in which discrimination based on the rise-time or pulse-shape of the events are analyzed. Phoswich detectors, in which different materials are used to build the detector system, are also used.

Plastic detectors are widely employed in Astrophysics. In general, they are used as active shielding for the main detectors, since the atmospheric background is high compared to the cosmic sources fluxes. These detectors are often used to define the field of view of the telescope. Even though size is a limiting factor, for some experiments there is a need to build large volume plastic detectors. Recently, as part of a collaboration between INPE and IPEN (Instituto de Pesquisas Energéticas e Nucleares), a large volume plastic scintillator detector has been developed by IPEN laboratories [2] to be used by the MASCO telescope [3]. Fig. 1 shows pictures of one module (trapezoidal form: 1 m-long, 15 cm-thick) that will be used as active shielding for the NaI(Tl) main detector of the MASCO telescope. This active shielding is composed by 12 modules.

Figure 1: Plastic scintillators developed by IPEN to be used in the MASCO balloon-borne high energy imaging experiment.

Fast electronics, multichannel analyzers, peak detectors, preamplifiers and all the most common electronics used in nuclear applications are used in Astrophysics as well. The main difference here is the condition in which they have to operate. As said before, High Energy Astrophysics is essentially a space activity and, as such, the environment in which the instrumentation has to function is severe both in terms of temperature and pressure. Thus, several precautions have to be taken into account in order to guarantee that the experiment will gather the scientific data it was designed to. Extensive calibration and testing are mandatory before sending up an experiment to space. Satellite experiments are subject to another complicating factor: the radiation that hits the detectors coming from the Earth's radiation belts, which causes overflows in the data acquisition systems and may damage detectors and electronics.

In Astrophysics, imaging of the sky is of great interest because it can reveal the location of the emitting source. In High Energy Astrophysics this is also true but it is very difficult to be accomplished because of the high penetration power of the photons and the inherent inability to reflect and deflect them. In general, the identification of a high energy emitting source is made through the identification of its counterpart in other regions of electromagnetic spectrum, mainly in the optical region. Over the years, the capability to produce hard X-ray and gamma-ray images of the sky has been extensively searched. The research in this field has produced several improvements and the coded mask technique is a good example. Coded mask telescopes, contrariwise to conventional high energy telescopes that employ massive collimators, permit sky observations with high angular resolution in a wide field of view, allowing simultaneous measurements of several sources and background, which is an extremely important characteristic for proper background subtraction. We briefly describe below some of the imaging balloon-borne telescopes built at INPE's Astrophysics Division.

TIMAX Balloon-Borne Imaging Telescope. The TIMAX experiment [4] [5] was a balloon-borne hard X-ray coded-aperture imaging telescope designed to image 10^o x 10^o fields with approximately 2^o angular resolution. The experiment incorporated a one-piece mask-antimask system based on a 7x5 uniformly redundant array (URA) pattern [6]. The mask was placed at a distance of 1.5 m from the detector plane, which consists of 35 NaI(Tl) scintillators (31.8 mm-diameter, 2 mm-thick), with a total area of approximately 400 cm^2. The detectors operated in the 30-100 keV energy range, divided in 32 energy channels. TIMAX was a prototype of a much larger experiment (MASCO) currently under development in our laboratory [2]. The main goal of the experiment was to study the Galactic Center (GC) region, where several sources have recently been discovered and identified, demonstrating clearly that the nature and spectra of the GC sources are still far from being determined with accuracy. Imaging telescopes, which can measure both locations and spectra of the sources, subtracting background simultaneously, are very important to the further study of this region. Fig. 2 shows the detector system and coded mask employed by the TIMAX experiment and Fig. 3 shows a laboratory image obtained with this instrument.

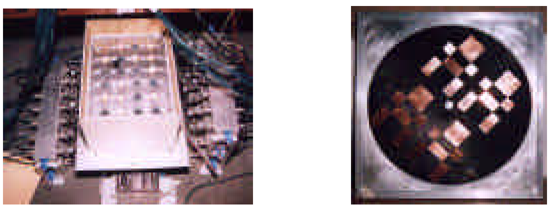

Figure 2: a) Detector system used by the TIMAX experiment composed by 35 NaI(Tl) scintillators (left); b) URA coded mask employed in the TIMAX experiment that allowed imaging with 2 degree resolution.

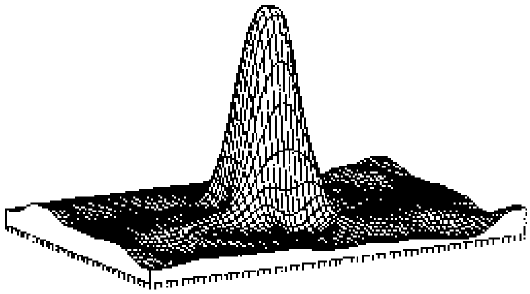

Figure 3: Laboratory image obtained by the TIMAX experiment. This reconstructed image was made using a mask-antimask correction method. The signal to noise ratio is 25.47 and the angular size is 12^o x 8.5^o.

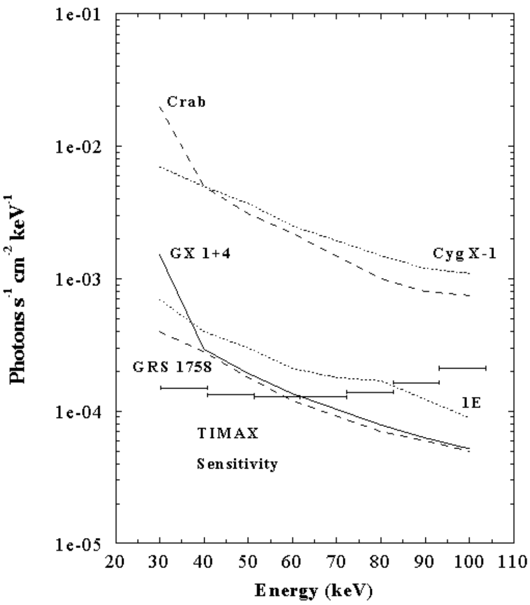

Figure 4: 3 σ sensitivity of the TIMAX experiment for an atmospheric depth of 2.1 g cm^{-2} and an integration time of 6 hours. Also shown are the spectra of several hard X-ray sources which are potential targets of the experiment: 1E 1740.7-2942 ("1E"), GRS 1758-258, GX 1+4 at "on" state, Crab and Cyg X-1 at "high" state.

The TIMAX experiment was launched from the town of Birigüi, in the state of São Paulo, Brazil (latitude: 21^o 16' 53" S; longitude: 50^o 19' 35" W), on June 8th, 1993, 21:27 UT, in a 186,000 m^3 stratospheric balloon. The balloon reached float altitude (42.4 km, 2.1 g cm^2) at 24:00 UT and remained at this altitude for approximately 8 hours. Due to a battery failure, the scientific goals of this first flight could not be achieved. The instrumental hard X-ray background spectrum measured at ceiling altitudes showed a total counting rate of approximately 40 counts/s, which is in good agreement with the estimate of 42 counts/s made in [4]. This spectrum allowed the calculation of the sensitivity of the experiment as a function of energy, for several energy bands (Fig. 4). A second flight of the TIMAX experiment was carried out on December 20, 1994, aiming the observation of precipitation electrons in the South Atlantic Anomaly (SAA). For the first time, three events of increases in the atmospheric X-ray fluxes in association with simultaneous decreases in geomagnetic H-field component in the SAA were detected [7]. Fig. 5 shows the TIMAX experiment in its flight configuration.

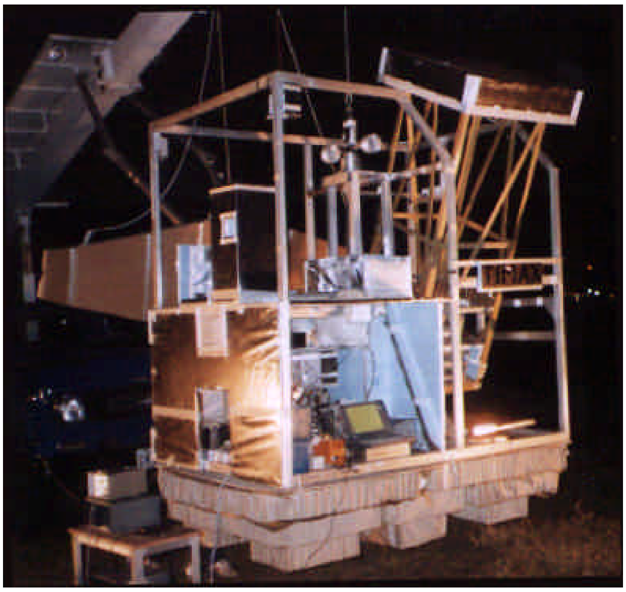

Figure 5: The TIMAX experiment in its flight configuration. The mask tower can be seen on the right side of the picture.

MASCO Balloon-Borne Imaging Telescope. The MASCO imaging telescope [2] (which stands for MÁScara COdificada - Portuguese for Coded Mask) employs the coded mask technique and has been designed to provide detailed images of the high-energy sky in the 50 keV to 1.8 MeV energy range. The MASCO experiment uses a Modified Uniformly Redundant Array (MURA) [8] [9] coded mask. The imaging device is a 19x19 element square MURA-based extended mask mounted in a single mask-antimask configuration. The mask is mounted in such a way that it becomes an antimask by 90 degrees rotation around its axis. The cell is made out of Pb and its size is 1.25 cm x 1.25 cm, with a thickness of 2 cm. The mask radius is 50 cm and the distance between the mask and the detector plane is 305 cm, defining a geometric resolution of 14 arcminutes. This is the first experiment to use such a mask pattern and configuration for astrophysical purposes [9]. Fig. 6 shows a picture of the actual mask that will be used by the MASCO experiment; its Pb cells are mounted on carbon fiber base.

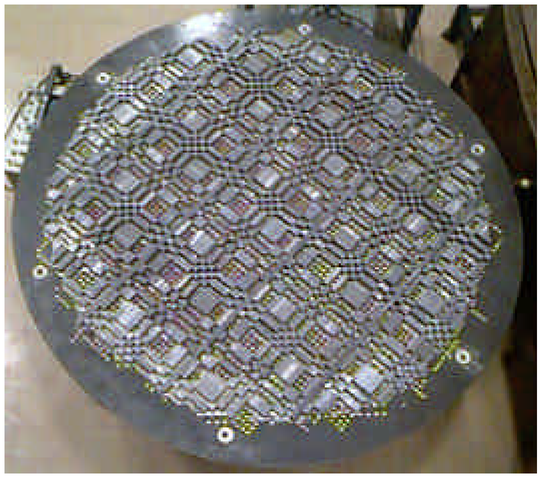

Figure 6: MURA mask of the MASCO telescope.

The detector consists in a NaI(Tl) crystal (41 cm-diameter, 5 cm-thickness) coupled to 19 photomultipliers tubes, in an Anger camera configuration, which permits approximately 10 mm of spatial resolution at 100 keV. The anticoincidence system is composed by plastic scintillators on the sides, by another 41 cm-diameter, 5 cm-thickness NaI(Tl) crystal at the bottom and by a 0.3 cm-thick plastic plate at the top to veto the unwanted photon and charged particle events. The lateral shield is divided in 12 modules and each one is viewed by one photomultiplier. The angular resolution is approximately 14 arcminutes over a 13 degree field of view. The expected 3 σ sensitivities for an on-axis source observed for 10^4 s at a residual atmosphere of 3.5 $g.cm^{-2}$ are $1{,}61 \times 10^{-5}$ $photons.cm^{-2}s^{-1}$ keV^{-1} at 50 keV, 5.46×10^{-6} $photons.cm^{-2}s^{-1}$ keV^{-1} at 300 keV and 4.99×10^{-6} photons cm^{-2} s^{-1} keV^{-1} at 1 MeV. The total geometric area is ~1300 cm^2 and the effective areas are 297 cm^2 at 50 keV, 366 cm^2 at 300 keV and 207 cm^2 at 1 MeV. The energy resolution is ~10% at 662 keV and the temporal resolution is ~20 µs. Fig. 7 presents the calculated sensitivity of the MASCO experiment. Fig. 8 shows MASCO's detector system and Fig. 9 shows MASCO's block diagram.

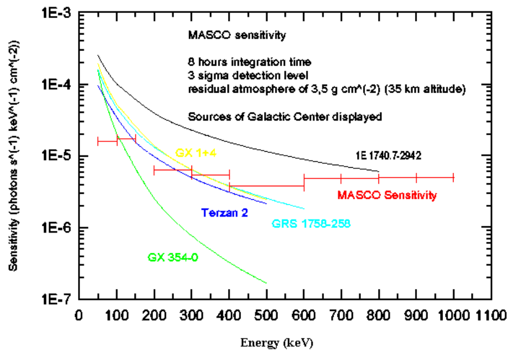

Figure 7: Sensitivity of the MASCO experiment.

Figure 8: a) MASCO detector system composed by plastic scintillators modules on the sides - 12 modules - and at the top (left); b) Back view of the Anger camera showing the 19 photomultipliers.

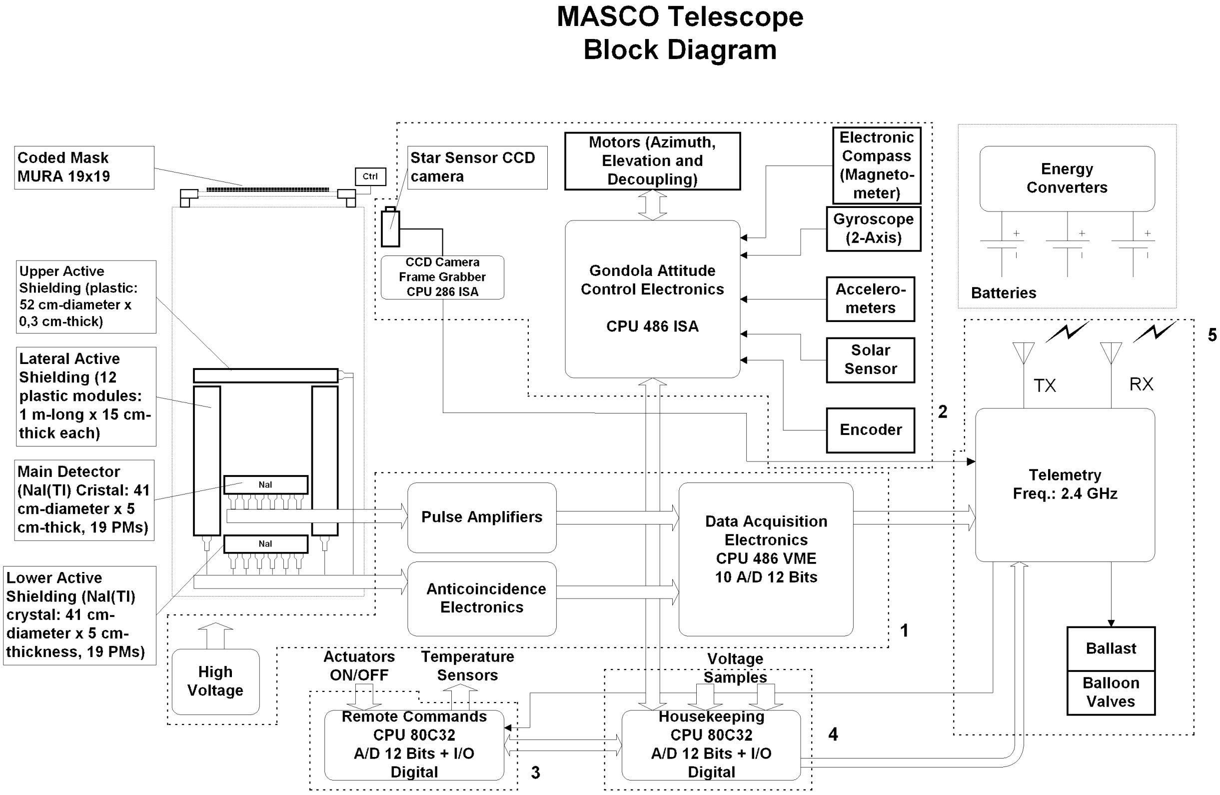

Figure 9: Block Diagram of the MASCO Telescope

Each one of the photomultiplier signals of the main NaI(Tl) detector is sent to pulse amplifiers and is individually analyzed. An on board 486 VME-bus computer gather all the information concerning the amplitude of the pulses, along with time information. Ten 12 bit analog-to-digital converters are employed to process the signals. Anticoincidence electronics is responsible for tagging the unwanted events in the main detector. A precision clock provides the time information to the computer. The data stream is sent to the on board digital data storage system and is also partially sent to the ground via real time telemetry by a PCM system. PCM command system is employed for payload maneuvers and housekeeping requirements. The MASCO telescope platform is an azimuth-elevation mount, where the azimuth motion is accomplished by moving the entire frame and the elevation by moving the inner frame to which the telescope is mounted. As a primary attitude sensor, a two-axis gyroscope is used, which is directly interfaced to the flight computer and is frequently checked for drifting via a two-axis solar sensor and a star sensor CCD camera. The star sensor uses star constellation pattern recognition to determine the experiment pointing direction. A digital compass (magnetometer) is used as a secondary azimuthal sensing element to perform coarse azimuth pointing and for fast maneuvers, and to provide realignment of the gyroscope in case of failure. Accelerometers and shaft encoders are used as elevation sensors. The servo mechanisms are a decoupling system, used to minimize the momentum transfer of the balloon to the payload, to dump angular momentum to the balloon and perform coarse azimuth positioning; a flywheel, controlled by the flight computer with a proportional, integral, differential (PID) algorithm, for fine azimuthal control; and a direct-drive on-axis motor, for elevation control. Figure 10 shows the stabilized platform where the instrument is mounted to operate at 42 km altitude.

Figure 10: MASCO telescope in its flight configuration. The 7 meter high, 2 meter x 2 meter base, gondola will be suspended by a 1 million cubic meter balloon at 42 km of altitude.

Extensive testing of the imaging system has been performed at INPE’s laboratory to verify the whole imaging system functioning. Some of these tests consisted in exposing the detector system to a 100 mCi Cs^{137} source located 68 m away from the position sensitive detector plane in order to check the capability of the MASCO experiment to produce images. The radioactive source was aligned with the center of the mask-detector system with a laser beam. The exposure time was 2 h: 1 h in the mask mode and 1 h in the antimask mode. The signal to noise ratio was ~24. Fig. 11 shows the image obtained with this procedure.

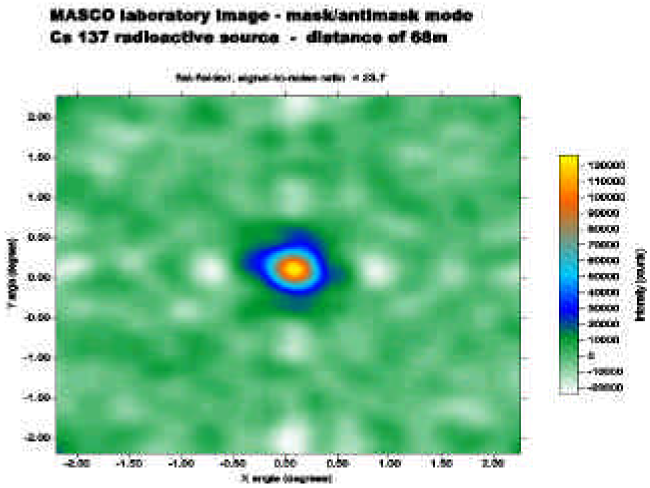

Figure 11: Laboratory image of a Cs^{137} source made with MASCO telescope.

The main scientific goal of the MASCO telescope is to produce images of the sky in the hard X-ray and low energy gamma ray bands, which will allow the study of the spectral and temporal behavior of cosmic sources. One of the main targets to be observed is the Galactic Center region, where several important sources are presented and are separated by small angular distances. These sources are highly variable and their spectra quite complex, so it is crucial to perform observations to understand the physical mechanisms responsible for the emissions. In order to simulate an observation to be performed by the MASCO telescope, we produced a sky image in the 50 to 120 keV energy interval. To do so, we estimated the background level to be detected by MASCO at balloon altitudes, in several energy bands, and then calculated the expected total number of counts for each one of the main Galactic Center sources, using the available observational data. This has been done by integrating the spectrum of each source at the corresponding energy. These spectra are well fitted by power laws in the hard X-ray band (~20 keV to 200 keV) and the source intensities (photons.cm^{-2}.s^{-1}.keV^{-1}) are given by:

$$I = I_0 \left(\frac{E}{100} \right)^{-\alpha},$$

where I_0 is source intensity at 100 keV, E is the energy in keV, and α is the spectral index. Therefore the fluxes (photons.cm^{-2}.s^{-1}) are given by:

$$F = I_0 \int_{E_1}^{E_2} \left(\frac{E}{100} \right)^{-\alpha} dE = \frac{100^{\alpha} - I_0}{1-\alpha} \left(E_2^{1-\alpha} - E_1^{1-\alpha} \right).$$

Fig. 12 shows a simulated image in the 50 to 120 keV energy band where several sources are presented: 1E1740.7-2942, which is very similar to the black hole candidate Cyg X-1 and is a potential "miniquasar" candidate; GRS 1758-258 which is a hard X-ray source; GX 354-0, which is an X-ray burster that presents transients in its emission; and GX1+4, which is an X-ray binary pulsar. All these sources are very interesting to be further studied in order to broaden our understanding of the physical mechanisms that produces their high energy fluxes. The image presented here shows the capability of the MASCO telescope to produce good quality astrophysical data.

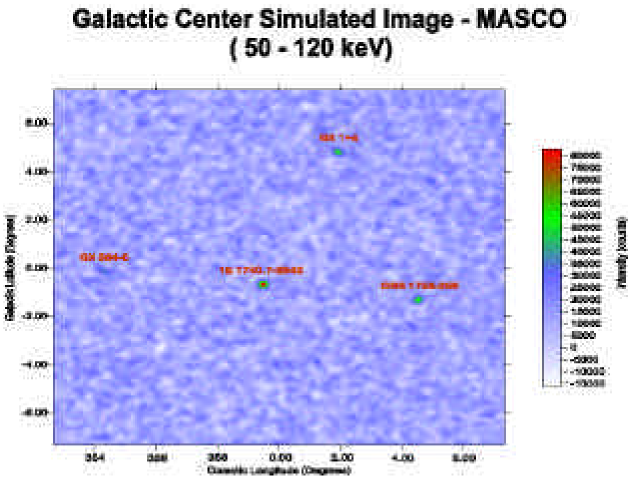

Figure 12: Simulated MASCO Telescope Galactic Center region image in the 50-120 keV energy band.

III. CONCLUSION

Observational High Energy Astrophysics is a relatively new field and has to be further developed, especially in terms of imaging. The experiments described here show advancements in some of the aspects related to the high energy imaging technique. The use of antimasks, for example, has not been widely implemented in imaging telescopes due to technical difficulties as weight restrictions. MASCO and TIMAX telescopes use antimasks in an one piece mask-antimask assembly, reducing the weight of the payload and the systematic errors involved in the image reconstruction process.

The Southern Sky, where MASCO will fly, is important for astronomy because of the high concentration of high energy sources and regions like the Galactic Center, Centaurus, Vela and the Magellanic Clouds. If we take into account MASCO's angular resolution and sensitivity, we can foresee a good contribution to be made by this experiment, namely in helping to disentangle any source confusion in the Galactic Center region and identifying possible new high-energy sources. MASCO imaging capability can also be used to further exploit the new forthcoming results of the satellite-based telescopes as well as the ongoing and future balloon-based experiments.

REFERENCES

[1] Longair, M.S., **High Energy Astrophysics (Volume 1- Particles, photons and their detection)**, Cambridge University Press, Cambridge, Second Edition, 1992.

[2] D'Amico, F.; Villela, T.; Braga, J.; Silva, E. R.; Alves, A. M. R.; Arantes, L. G.; Hamada, M.; Mesquita, C. H.; Vieira, J. M., **Fabricação e testes com detectores cintiladores orgânicos de grande volume para uso no experimento MASCO,** Boletim da Sociedade Astronômica Brasileira, vol. 16, nº 1, p. 157-158, 1996.

[3] Villela, T.; Braga, J.; D'Amico, F.; Jayanthi, U. B.; Neri, J.A., **A Balloon-Borne Imaging Telescope for High-Energy Astrophysics**, Astrophysics and Space Science, vol. 214, 161-170, 1994.

[4] Braga, J.; Villela, T.; Jayanthi, U. B.; D'Amico, F.; and Neri, J. A., **A New Mask-Antimask Coded-Aperture Telescope for Hard X-Ray Astronomy,** Experimental Astronomy, vol. 2, no. 2, p. 101-113, 1991.

[5] Braga, J.; D'Amico, F.; Villela, T., **Development of the Hard X-Ray Imaging Experiment TIMAX: Laboratory Images and First Balloon Flight**, Experimental Astronomy, vol. 5, p. 269-278, 1994.

[6] Fenimore, E. E.; Cannon, T. M., **Coded aperture imaging with uniformly redundant arrays**, Applied Optics, vol. 17, nº 1, p.337-347, 1978.

[7] Jayanthi, U.B.; Pereira, M.G.; Martin, I.M.; Stozkov; Yu.; D'Amico, F.; Villela, T., **Electron Precipitation Associated with Geomagnetic Activity: SAA Balloon Observation of X-Ray Flux**, Journal of Geophysical Research, in press, 1997.

[8] Gottesman, S.R.; Fenimore, E.E., **New family of binary arrays for coded aperture imaging**, Applied Optics, vol. 28, nº 20, p. 4344-4352, 1989.

[9] Villela, T.; Braga, J.; D'Amico, F.; Jayanthi, U.B., **A MURA-Based Coded Mask Telescope**, Advances in Space Research, vol. 15, nº 5, p. (5)95-(5)98, 1995.