The *MIRAX* X-Ray Astronomy Transient Mission

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Abstract

The *Monitor e Imageador de Raios-X* (MIRAX) is a small (~250 kg) X-ray astronomy satellite mission designed to monitor the central Galactic plane for transient phenomena. With a field-of-view of ~1000 square degrees and an angular resolution of ~6 arcmin, MIRAX will provide an unprecedented discovery-space coverage to study X-ray variability in detail, from fast X-ray novae to long-term (~several months) variable phenomena. Chiefly among MIRAX science objectives is its capability of providing simultaneous complete temporal coverage of the evolution of a large number of accreting black holes, including a detailed characterization of the spectral state transitions in these systems. MIRAX's instruments will include a soft X-ray (2-18 keV) and two hard X-ray (10-200 keV) coded-aperture imagers, with sensitivities of ~5 and ~2.6 mCrab/day, respectively. The hard X-ray imagers will be built at the *Instituto Nacional de Pesquisas Espaciais* (INPE), Brazil, in close collaboration with the Center for Astrophysics & Space Sciences (CASS) of the University of California, San Diego (UCSD) and the *Institut für Astronomie und Astrophysik* of the University of Tübingen (IAAT) in Germany; UCSD will provide the crossed-strip position-sensitive (0.5-mm spatial resolution) CdZnTe (CZT) hard X-ray detectors. The soft X-ray camera, provided by the Space Research Organization Netherlands (SRON), will be the spare flight unit of the Wide Field Cameras that flew on the Italian-Dutch satellite *BeppoSAX*. MIRAX is an approved mission of the Brazilian Space Agency (Agência Espacial Brasileira – AEB) and is scheduled to be launched in 2011 in a low-altitude (~550 km) circular equatorial orbit. In this paper we present recent developments in the mission planning and design, as well as Monte Carlo simulations performed on the GEANT-based package MGGPOD environment (Weidenspointner et al. 2004) and new algorithms for image digital processing. Simulated images of the central Galactic plane as it would be seen by MIRAX are shown.

INTRODUCTION AND SCIENCE OBJECTIVES

The "Monitor e Imageador de Raios-X" (MIRAX) is a high-energy astrophysics satellite mission which is part of the Scientific Satellite Program at the National Institute for Space Research (INPE) in Brazil. MIRAX has been selected to be the astrophysics mission within this program and has been approved for development by the Brazilian Space Agency (AEB). Since the Brazilian astronomical community is mostly devoted to the fields of optical and radio astronomy, the development and operation of MIRAX is expected to have a major impact on Brazilian science through the opening of a new observation window for astrophysical research.

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The MIRAX project has strong international partnership. The University of California in San Diego (UCSD) will provide the hard X-ray detectors and participate in the design of the hard X-ray cameras; the Space Research Organization Netherlands (SRON) will provide the soft X-ray imager; the Institut für Astronomie und Astrophysik of the University of Tübingen (IAAT) will provide the on-board computer and participate in software development; and the Massachusetts Institute of Technology (MIT) will participate in software development for data acquisition, analysis, storage and distribution.

The main scientific goal of MIRAX is the nearly continuous (9 months per year) , broad-band (2 to 200 keV), high-resolution (~5-7 arcminutes) monitoring of a specific large region of the sky that is particularly rich of X-ray sources (a 76^o x 44^o total field centered on the Galactic center and oriented along the Galactic plane). This will not only provide an unprecedented monitoring of the X-ray sky through simultaneous spectral observations of a large number of sources, but will also allow the detection, localization, possible identification, and spectral/temporal study of the entire history of transient phenomena to be carried out in one single mission. During the ~3 months/year when the Sun will be crossing the central Galactic plane, MIRAX will be pointed to other rich fields such as the Magellanic Clouds and the Cygnus and Vela/Centaurus regions. MIRAX will be able to contribute to the study of a variety of phenomena and objects in high energy astrophysics, especially in the so far poorly explored non-thermal domain of hard X-ray observations. With the planned continuous monitoring approach, MIRAX will address key issues in the field of X-ray variability such as black hole state transitions and early evolution, accretion torques on neutron stars (especially through monitoring of X-ray pulsars), relativistic ejections on microquasars and fast X-ray novae. MIRAX will also be able to contribute to Gamma-Ray Burst (GRB) astronomy, since it is expected that ~1 GRB will be detected per month in MIRAX's field-of-view (FOV). MIRAX will not only provide positions of GRBs with an accuracy a few arcminutes but will also obtain broadband X-ray spectra of the bursts and possibly their X-ray afterglows. MIRAX instruments are expected to be assembled in a dedicated small (~200 kg) satellite to be launched in a low altitude, equatorial circular orbit around 2009. Table 1 shows the baseline parameters of MIRAX. In comparison with the Burst Alert Telescope (BAT) on the Swift mission, launched in 2004, MIRAX has a smaller detector area in the hard X-ray range (factor of ~7) but a higher angular resolution (factor of 2.3). The main advantage of MIRAX over BAT is the continuous viewing approach for the study of transient phenomena and variability.

MIRAX INSTRUMENTS

In the current planned configuration, the payload will consist of a set of two hard X-ray cameras (CXD – "Câmera de Raios-X Duros") and one soft X-ray camera (CXM – "Câmera de Raios-X Moles"). Both imagers will employ the technique of coded-aperture imaging (Dicke, 1968; Skinner, 1984; Caroli et al., 1987; Braga, 1990), which has been highly successful on X-ray satellite instruments such as Spacelab 2/XRT (Willmore et al., 1984), GRANAT/ART-P (Sunyaev et al., 1990), RXTE/ASM (Levine et al., 1996), BeppoSAX/WFC (Jager et al., 1997), Kvant/COMIS-TTM (In 't Zand, 1992), and especially GRANAT/SIGMA (Roques et al., 1990; Paul et al., 1991; Bouchet et al., 2001), as well as on balloon experiments such as GRIP-2 (Schindler et al., 1997) and EXITE (Garcia et al., 1986; Braga, Covault and Grindlay, 1989).

Table 1. MIRAX baseline parameters

Mission and spacecraft parameters		
Mass	~250 kg (total), ~125 kg (payload)	
Power	~240 W (total), ~90 W (payload)	
Orbit	equatorial, circular, ~550 km	
Telemetry	S-band (2200-2290 MHz), ~1.5 Mbps downlink	
Launch	2011 by AEB selected launcher	
Instrument parameters	**Hard X-ray Imager (CXD)**	**Soft X-ray Imager (CXM)**
Energy range	10-200 keV	2-28 keV
Angular resolution	7.5 arcmin	5 arcmin
Localization	< 1 arcmin (10σ source)	< 1 arcmin (10σ source)
field-of-view	58^o x 26^o FWHM along the GP	20^o x 20^o FWHM
Spectral resolution	< 5 keV @ 60 keV	1.2 keV @ 6 keV
time resolution	< 10 μs	122 μs
Sensitivity	< 2.6 mCrab (1 day, 5 σ)	< 5 mCrab (1 day, 5 σ)
Detector area	2 x 360 cm^2	650 cm^2

The Hard X-Ray Cameras

The CXDs will be built in collaboration with the Center for Astrophysics and Space Science (CASS) of UCSD and will operate from 10 to 200 keV. The detector plane will be a 3 x 3 array of state-of-the-art CdZnTe crossed-strip detector modules with 0.5 mm spatial resolution developed at CASS, with a total area of 360 cm^2. Each detector module is a 2 x 2 array of 32 mm x 32 mm x 2mm thick CZT detectors. The detectors will be surrounded by an active plastic scintillator shield – to be developed in collaboration with the *Instituto de Pesquisas Energéticas e Nucleares* (IPEN), Brazil – and by a passive Pb-Sn-Cu graded shield. A 315 mm x 275 mm Tungsten coded-mask with 1.3 mm-side square cells (0.5 mm-thick) will be placed 600 mm away from the detector to provide images with 7'30" angular resolution. The basic pattern of the mask will be a 139 x 139 Modified Uniformly Redundant Array (MURA - Gottesman and Fenimore, 1989; Braga et al., 2002), which will allow for full shadowgrams to be cast on the position-sensitive detector area and will provide no source ambiguity problems in the fully-coded field-of-view (FCFOV). A sketch of the CXD is shown in Figure 1.

The pointing axes of the two CXDs will be offset by an angle of 29^o in order to provide a uniform sensitivity over a 39^o FCFOV in one direction; the perpendicular direction will have a $6^o12'$ FCFOV. In such a configuration the FWHM FOV is 58^o x 26^o. During the observations of central Galactic Plane, the wider direction of the FOV will be aligned with the GP. Figure 2 shows the fractional coded-area (considering the two cameras) as a function of angle, for the direction aligned with the GP.

The Soft X-Ray Camera

The CXM, provided by SRON, is the spare flight unit of the Wide Field Cameras (WFCs – Jager et al. 1997) of the *BeppoSAX* mission (Boella et al. 1997), and will operate from 1.8 to 28 keV. The CXM will have a 5' angular resolution in a 20^o x 20^o FWHM FOV. The addition of the WFC to the MIRAX payload will provide soft X-ray spectral coverage which will be extremely important for the study of the several classes of sources in the MIRAX FOV. Furthermore, the excellent perfomance of the WFCs on *BeppoSAX* brings to MIRAX an instrument that has already been tested and used successfully in orbit with very little degradation on a time scale of several years.

A preliminary design of the MIRAX spacecraft is show on Figure 3. The CXM is mounted on top of the two CXDs, which are offset by 29^o. A star camera with an Active Pixel Sensor (APS), currently being developed at INPE, is placed in the space between the two CXDs.

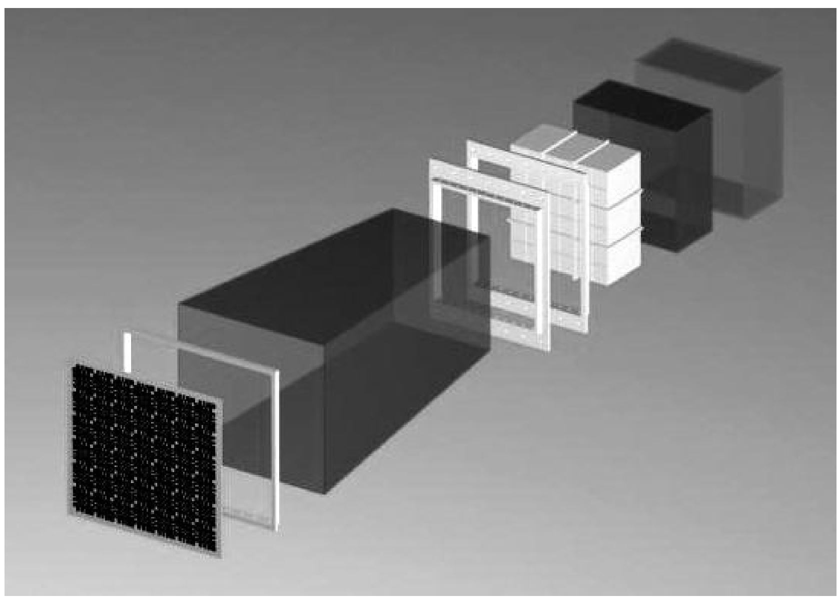

Fig. 1. Exploded diagram of the MIRAX hard X-ray camera. From left to right, the elements are: coded-mask, coded-mask support structure, Pb-Sn-Cu passive-shield walls, two structural flanges, detector modules, plastic scintillator and Pb-Sn-Cu passive shield.

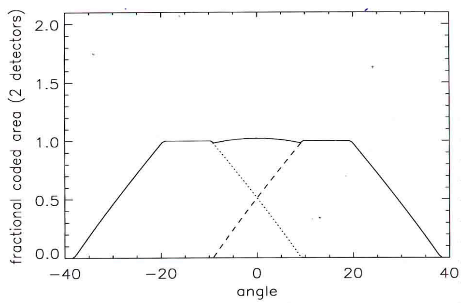

Fig. 2. The fractional coded area of the two hard X-ray cameras of MIRAX with the main axes offset by 29°. This angle provides a nearly uniform FCFOV of 39° along the GP.

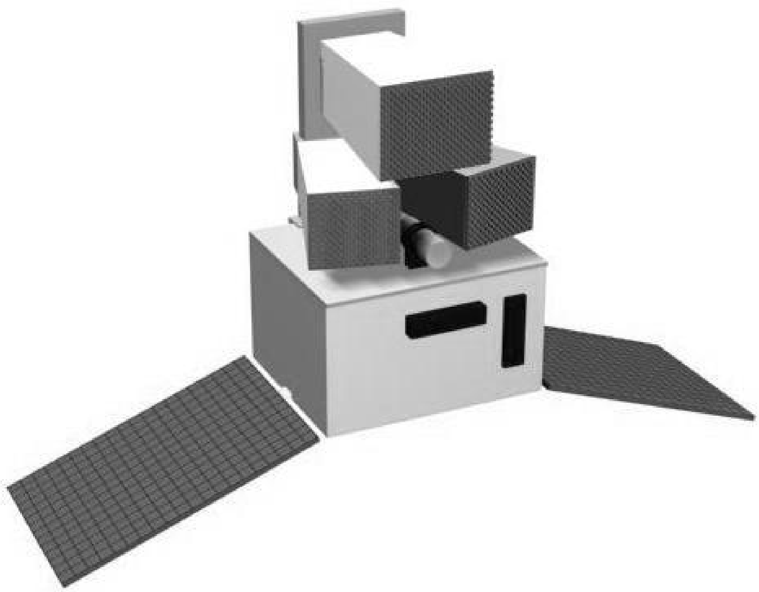

Fig. 3. A preliminary view of the MIRAX spacecraft. The two cameras mounted over the satellite bus are the hard X-ray cameras (CXDs), whereas the soft X-ray camera is on top of the CXDs. The APS optical star camera is placed in between the CXDs. The external dimensions are approximately 1.5 m x 0.7 m x 0.7 m (with the solar panels folded over the spacecraft).

The Flight Computer

The instruments on the payload of MIRAX will send data to a Central Electronis Unit (CEU), which will be the data and command interface between the imagers and the spacecraft. The CEU will receive and process data from the three cameras, select the "good" events according to a variety of criteria (thresholds, shield vetoes, calibration source events, etc.) and build the telemetry packets. The processing at the CEU will include determination of position, energy and depth of the

X-ray interactions in the CZT detectors, as well as time tagging. The data packets will then be sent to the MIRAX spacecraft computer for transmission to the ground. The CEU will be developed by the IAAT with collaboration from INPE. The IATT has extensive experience on space missions and a strong heritage in flight computers.

MIRAX SENSITIVITY

The MIRAX hard X-ray sensitivity can be estimated based on the expected background level in the low-orbit environment, which is about 200 cts/s for a single imager. The internal component is calculated from balloon flights of prototype CZT detectors launched from Fort Sumner, NM. The Crab nebula plus pulsar photon count rate will be ~120 cts/s. Taken the approximate total contribution of sources in the primary MIRAX FOV (central GP) to be about 1 Crab, the MIRAX sensitivity is expected to better than 2×10^{-5} photons cm^{-2} s^{-1} keV^{-1} at 100 keV (5 σ) , or ~2.6 mCrab/day in the 10-100 keV range (approximately 40 times better than the Earth Occultation technique of the Burst and Transient Source Experiment on *CGRO*). Techniques for background reduction for CZT strip detectors are being developed, especially involving vetoing of multiple, non-contiguous events (expected to come from particle-induced showers within the surrounding material) and low-energy interactions deep in the detector, which are produced by photons incident from the bottom of the detector plane. The CXDs will have a one-year "survey" sensitivity, considering a conservative systematics limit of 0.1% of background, of about 10^{-11} erg cm^{-2} s^{-1} in the 10-50 keV band. This is ~20 times better than what was achieved by the HEAO 1 A-4 instrument, which carried out the only hard X-ray survey to date (Levine et al., 1984).

For the low energy range, the soft X-ray imager will have approximately the sensitivity of the WFCs on BeppoSAX, which is better than 5 mCrab/day in the 2-10 keV band (approximately 2 times better than the All Sky Monitor on *RXTE*).

SPACECRAFT AND MISSION OPERATIONS

The MIRAX spacecraft will be based on the satellite bus developed at INPE for the small scientific satellite program. The platform employs a 3-axis attitude stabilization system with 2 star trackers, a sun sensor and a magnetometer. Torque rods and reaction wheels will be used as attitude controlers. The MIRAX payload will have no moving parts and a mass of ~100 kg, while the total spacecraft mass is expected to be under 200 kg. There will be no propulsion and the pointing will be inertial. The pointing precision will be 0.5^{o}, with 36"/hr stability (1/10 of the image pixel) and 20" attitude knowledge. The power consumption of the payload will be between 88 and 96 W, depending on the final configuration and the CEU requirements, and the total power of the satellite will be around 240 W.

The MIRAX mission duration is required to be 2 years, with a possible extension to 5 years. A ground station at Alcântara, Brazil, operated by INPE, will be utilized. Possibly, a second ground station in Kenya will be available. The space operation S-band (2200 – 2290 MHz) will be used for downlink and command uplink. It is expected that downlink data rates up to ~2 Mbits/s will be possible to reach, depending on the modulation and on coordination with other satellites. Our current estimates indicate that a rate of 1.5 Mbits/s will be enough to dump all the data with no compression if we use one station.

MIRAX is expected to be launched in 2009 by the Brazilian satellite launcher VLS, in case it is tested successfully and is officially considered a reliable launcher by the Brazilian Space Agency. In case a VLS is not available, other possibilities will be considered, such as a Pegasus launch or as a piggy-back payload on larger launchers. MIRAX data will be 100% available to the community immediately. Databases will be setup at the missions centers in Brazil (INPE) and at UCSD. The database will also be available at HEASARC (Goddard Space Flight Center). Specific webpages with several data products will be available.

BACKGROUND AND IMAGE SIMULATIONS

Simulations of the hard X-ray imager instrumental background in orbit are currently being carried out and will be presented at the meeting. The MGGPOD Monte Carlo simulation code (Weidenspointner et al., 2004), a user-friendly suite built around the widely used GEANT package, is being used for calculating the result of the interactions of the various radiation fields within the instruments and spacecraft materials. With the knowledge of the instrumental background and the diffuse aperture X-ray flux, we can perform detailed image simulations of the central Galactic plane as seen by MIRAX, for several instrument configurations and integration times. Preliminary results indicate that MIRAX will be able to detect a variety of systems, both transient and persistent.

CONCLUSION

Over the last decades, X and gamma-ray astronomy observations by space-borne instruments have made possible the discovery of very energetic and explosive phenomena and also new classes of astrophysical objects, changing significantly the field of astrophysics. The MIRAX satellite mission, the first Brazilian astronomical spacecraft, is expected to make a very important contribution to Brazilian astronomy and astrophysics by opening a new observational window in the high-energy domain. Furthermore, MIRAX will be able to make very unique contributions to the study of energetic transient phenomena in astrophysics by virtue of its observing strategy, which departs significantly from traditional pointed programs and scanning monitors. MIRAX will detect, localize, identify and study unpredictable phenomena which last on the timescales of minutes to days, which would otherwise be missed by traditional observing strategies. In addition, MIRAX will be able to study longer-lived phenomena in exquisite detail from 2-200 keV.

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