

SuperMon & Black Hole Tracker

Response to the Request for Information: NNH11ZDA018L

Concepts for the Next NASA X-ray Astronomy Mission

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Submitter:

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Category of response:

Mission concept: A collection of three micro-satellites and a medium class satellite in low-earth equatorial orbit.

Instrument concept: A sandwich of X-ray detector systems for the simultaneous measurement of spectral, variability, and polarization of X-ray sources.

Enabling technologies: Developing the lowest mass to area ratio X-ray detectors and large area 'semiwich' detectors with excellent energy resolution.

Other: To use the leadership of NASA and participation from developing countries to make quick breakthrough in new areas.

Answers to specific questions:

Will you be willing to participate and present your concept ?: **Yes**

Does your organization have any sensitive information that might be useful for this exercise?: **No**

Executive Summary

This proposal advocates the simultaneous measurement of the spectral, timing, and polarization properties of X-ray sources to understand the continuum spectrum. This will enable the direct measurement of the fundamental properties of compact objects and provide answers to several basic and pressing questions in high energy astrophysics like black hole growth, jet emission, central engines of gamma-ray bursts, nature of dark energy, and possibly the identification of dark matter.

This will be achieved by the following enabling technologies:

- **Low Energy Proportional Counter:** The ‘rugged’ proportional counters would be re-designed to obtain the lowest mass to area ratio of ~ 10 kg per m^2 , compared to the >100 kg per m^2 of RXTE/PCA. Though Silicon detectors can be fabricated at this mass budget, proportional counters are rugged, cheap, and easy to fabricate.
- **‘Semiwich’ detectors:** A sandwich of Silicon and CZT detectors would be developed, with all the associated cooling and packaging techniques to achieve a) ~ 200 eV resolution at 6 keV and sub-keV resolution up to 60 keV b) $>90\%$ efficiency in 2 – 60 keV region c) background reduction d) modest position resolution (a few mm^2), and e) scalability to large area.

These detectors would be configured as:

- **SuperMon:** This is a series of three micro-satellites (~ 150 kg, each) of identical configuration, making uninterrupted observations of bright X-ray sources. The low weight proportional counters will act as a shallow all-sky monitors (in BATSE-type open configuration) and the ‘semiwich’ detectors of area ~ 400 cm^2 positioned below a helium filled position sensitive proportional counters will have the spectral, timing, and polarization capabilities to study bright X-ray sources. Fast maneuverability and robust onboard intelligence will make this an unique system to study GRBs, X-ray flashes, X-ray binaries and bright Seyfert galaxies.
- **Black Hole Tracker:** This is a medium class satellite (~ 2000 kg) with 5 m^2 proportional counters in all-sky as well as pointing operational mode, 5000 cm^2 ‘semiwich’ detectors with He proportional counters to have spectro-polarimetric capabilities and 500 cm^2 focusing detector with Silicon Drift Detectors operating in 0.5 – 30.0 keV region. This will enable the detailed spectral, timing, and polarization studies of a large number of X-ray sources.

It is estimated that this configuration will satisfy most of the primary IXO objectives at a very low cost (450 million USD) and short time span (4 – 5 years). Further, it is envisaged that a judicious harnessing of the vast expertise of NASA with the enormous young man-power available in the developing countries, along with a progressive mind set of using existing technologies (primarily using computational technologies) in novel ways and having a net-enabled collaboration, can push new ideas into fruition in a very optimum way. This methodology has the potential of making space exploration fast, cheap, and diverse.

Science motivation and objectives

X-ray astronomy is a mature and powerful tool to study the cosmos. The mind-boggling advances in the sensitivity of X-ray telescopes, from *Einstein* to *Chandra* Observatories, has ensured that X-rays are detected from practically every type of cosmic objects, ranging from solar system objects (moon and the planets) to distant quasars.

Though powerful, X-ray astronomy has remained a blunt tool.

Broadly speaking, X-ray photons carry two types of messages from the cosmos. The low energy X-rays, below a few keV, have wavelengths corresponding to atomic dimensions, and they tell the tale of atoms at various ionization states. By and large they tell the tale of hot thermal plasmas, the relics of some violent phenomena which has already taken place. X-rays of higher energies (above a few keV), on the other hand, are the by-products of all impulsive particle acceleration sites: planetary atmospheres, solar and stellar active regions, accretion disc around compact objects, magnetic quakes in magnetars; also when compact objects coalesce and release humongous amount of energy at cosmological distances, which are observed as Gamma-Ray Bursts or X-ray Flashes.

X-ray astronomy has remained blunt in its ability to decipher the clues available in the continuum spectra to find out more about the accelerating sites.

Let me amplify this statement with a parallel example: the advances in stellar structure and evolution theory in the last century was stupendous. White dwarves were discovered in 1910; by 1930 their complete structure was figured out. It was done by essentially applying the emerging tools of modern physics to understand the structure. But, crucially, stellar spectroscopy provided a robust check-point for every theoretical calculations.

Compared to this, the first stellar X-ray source was discovered in 1962. Though within a few years it was figured out that compact objects had something to do about it, a quantitative description still eludes us. For example, in the case of black hole transients, observers can define a “small number of states and their association with jets providing a good frame work to base theoretical studies” (Belloni et al, 2011, arxiv1109.3388), while, theorists, claiming that there is remarkable success in the study of black hole accretion disks, lament that the most pressing problem of the day is to match “our theretical knowledge to actual observed phenomena” (Abramowicz & Fragile, arxiv1104.5400).

For example, whether the source of jet power is the spin of the black hole or the stored magnetic field is still a matter of conjecture. Further, the connection between X-ray binaries and other objects in the universe whose source of energy is thought to be accretion, like Active Galactic Nuclei and the beacons of the universe, Gamma-ray Bursts, are generally quite nebulous, and at best phenomenological.

Essentially, good quality continuum spectra of cosmic X-ray sources are lacking, primarily because high energy observation is technically extremely challenging. As discussed in Rao et al. (2006; SuperMon proposal - see page 9), “apart from the usual technical difficulty of having to conduct these experiments from space, lack of effective focusing techniques in higher energies, low number of incident photons necessitating the use of very large area detectors and the high background caused by the ubiquitous high energy cosmic rays are

some of the serious problems affecting this critical but challenging observational field in astrophysics. In particular, one of the major problems in making precise hard X-ray spectral measurements is the effect of Compton scattering. Its effect is two-fold. First the ubiquitous Cosmic Diffuse X-ray Background in the energy range above 100 keV deposit part of their energy through Compton scattering, hence generating high background in < 100 keV band. Second, source photons above 100 keV too can undergo Compton scattering, thus making the detector response uncertain. To achieve good spectroscopic capabilities in the hard X-ray band, it is necessary to have good background measurement, energy bandwidth, and sufficient counts in a large number of energy channels.”

One other aspect of non-thermal astrophysical phenomena is that the inherent nature of energy generation is highly time variable. Hence, to decipher the source emission mechanism and structure, one needs time variability characterisation, spectral information, and, to further reduce the possible degeneracies in the source structure, to have polarization information. Hence, the baseline requirement for a future X-ray astronomy mission would be:

- Good bandwidth: 2 – 60 keV to cover the various emission mechanisms like reflection, cyclotron lines, thermal/ non-thermal components etc.
- Good energy resolution: at least sub-keV resolution throughout the energy range.
- Good sensitivity: detection area large enough for making spectro-temporal measurements.
- Good background reduction: having multiple layered detectors.
- Good response and polarization sensitivity: the ubiquitous Compton scattering can be used to measure the polarization (upto 1% MDP for sources brighter than 100 mCrab).

It is envisaged that by using the enabling technologies of developing ‘semiwich’ detectors and low energy proportional counters, most of the above requirements would be satisfied. Further, a series of micro-satellites (SuperMon) would be used for bright sources and large area detectors in a small satellite, Black Hole Tracker, would be used to study several thousand X-ray sources.

Enabling technologies: ‘semiwich’ and LEPC detectors

New hard X-ray ‘semiwich’ detector: To have a good hard X-ray detector operating in the energy range of 2 – 60 keV, with good energy resolution and good background reduction technique, we can use a phoswich type background reduction technique along with a solid state detector type energy resolution. Small area Silicon detectors, with excellent energy resolution, operating in 0.5 – 15 keV range, are commercially available. Using such detectors, in a large area format, in conjunction with a CZT detector in phoswich mode is a good solution. This requires some technical innovation like using strips of Si detectors and using low noise FET based cooled amplifiers, developing quick readout system, careful packaging with a CZT detector, and an appropriate mechanical design for efficient cooling.

The technology needed for the above is available and some amount of R&D work is needed to realize such detectors in a large area format.

Low Energy proportional counters (LEPC): : Proportional counters, the work-horses of X-ray astronomy, are extremely well understood and it is possible to build these detectors in a large area format. Some innovative designs in pressure vessels are required to make them with an extremely low mass-to-area ratio of $<10 \text{ kg m}^{-2}$.

SuperMon

The continuum X-ray spectro-photometry with polarimetric ability in the 2 – 60 keV region will yield unprecedented information on the non-thermal astrophysical sites like accretion disks and jets. Particularly in the field of Gamma-ray bursts, where it is difficult to make good spectro-polarimetric observations, it is expected to yield a rich harvest. Hence a nimble micro-satellite, with automatic pointing capabilities, will be able to monitor GRBs, X-ray flashes, X-ray binaries and bright AGNs. Three such satellites, called SuperMon, will help in continuously monitoring a given source, as and when required.

The basic detector is a 400 cm^2 semiwich detector located below a helium filled position sensitive proportional counter, giving spectral, timing, and polarization information of bright X-ray sources, including gamma-ray bursts (GRBs). The low-weight proportional counters are used as an all sky open detector at low energy X-rays. Since in such background dominated detectors signal to noise ratio goes as the square root of background, a low energy detector has a better sensitivity so long as $\alpha < \beta/2$, where α and β are the power-law energy indices of the source and background spectra, respectively. A set of 1000 cm^2 proportional counters could be as sensitive as BATSE. And, having a low energy detector for triggering will be more sensitive to GRBs with lower E_{peak} values, which will probably probe larger redshifts and deeper into the universe.

The BATSE concept, that is the ratio of counts in detectors mounted at large angles gives some idea of incident angle, is good enough for a few degree localisation. Since low energy X-rays are easy to block, an improvisation in the shadowing concept by arranging vertical walls can lead to localization correct to half a degree or so. Hence, using low weight proportional counters in BATSE configuration around a collimated low background ‘semiwich’ detector will lead to a small weight ($\sim 40 \text{ kg}$) and the payload can be turned at any direction in a second or two. Add a sophisticated onboard software, and you have a nice ‘dancing diva’ in the sky doing wonders for the subject of transient X-ray sky.

To optimize the diverse needs of all sky monitoring like a) need to know the occurrence of bright transients within a few hours b) high time resolution observations of bright pulsars and other interesting objects like black hole binaries and c) regular and persistent observations of AGNs, the LEPC detectors are used for shallow all sky monitoring and the ‘semiwich’ detector, in a dancing mode, distributing its time in an optimum way to the diverse needs, is used for deep monitoring.

The instrument configuration is given in Figure 1 (see page 10), along with a basic sketch of the detector mounting arrangement. The salient characteristics of the detectors are:

LEPC detectors: The Low Energy Proportional Counters (LEPC) will have an energy range of 2 – 10 keV, area ~ 1000 cm², localization capability of 0.5 degrees for GRBs of fluence $>10^{-6}$ erg cm², all sky monitoring capability of 10 mCrab per day. Four such LEPC detectors will cover a solid angle of 3π steradians and they will also act as an active anti-coincidence shield for the spectroscopic detectors.

‘Semiwich’ detectors: A sandwich of 0.5 mm Si + 2 mm CZT detectors, cooled to -35° C by active as well as passive cooling, will be having an area of 400 cm², energy range 2 – 60 keV (collimated) and upto 150 keV (for all sky), positioned below ~ 3 cm thick He filled proportional counter (HePC), with passive collimator (FOV $\sim 2^\circ$ and coded aperture mask of position resolution a few arc-minutes). This combination will have a polarization sensitivity of 1% MDP in the 5 – 60 keV range for sources brighter than 100 mCrab (in 10^5 s).

Such a detector combination will yield:

- Detection of 300 GRBs and localization of 150 of them.
- Detection of 150 XRFs and localization of 75 of them.
- Redshift measurement (by coordinated ground observations) of 100 GRBs and 50 XRFs.
- Spectral evolution of new X-ray transients and their localization which will lead to the measurement of their black holes mass.
- Tracking of a dozen Galactic black hole sources on a continuous basis to measure their state transition, class transition and correlation with other wavelength emission.
- Tracking of a dozen bright X-ray pulsars to measure their pulse and binary period variation.
- The X-ray spectra & variability of 100 X-ray sources on a continuous basis.
- Detection of X-ray bursts from a dozen X-ray binaries and quantifying the neutron star parameters.
- Tracking of a dozen AGNs to identify X-ray QPOs in them.

A combination of three SuperMon satellites in a low earth orbit will allow uninterrupted observation of a source, if required. With this superior spectro-photometric capabilities along with polarization, this set of satellites will provide a rich harvest of observations to precisely pin down the emission mechanism in all the bright sources. A clear understanding of the emission mechanism of GRBs will help to use these beacons of the universe as standard candles (all the way upto a redshift of 8) which will help in a precise measurement of GRB Hubble diagram and thus helping us to understand the dark energy. Further, a precise knowledge of the GRB emission mechanism will also help us to use them as sources shining from the background and understanding all the intervening objects, including dark matter.

Black Hole Tracker

The enabling technology of LEPC detector can be used to design and manufacture a 50,000 cm² detector with a weight less than 50 kg. It can be fabricated in a deployable envelop and the collimators can be designed (using MEMS technology) to enable automatic pointing of any source. Apart from high time

resolution observations of bright X-ray sources such a detector can also act as an omni-directional GRB/ XRF identifier. The auto-collimators could be programmed to localize the newly detected GRBs / XRFs and tracking of multiple sources in an optimum way could be established. Similarly, the ‘semiwich’ detectors with HePCs for polarization studies can be built with an area about 5,000 cm² in less than 300 kg weight. This will allow for the detection of precise X-ray spectra of a large number of faint X-ray sources. Focusing hard X-ray detectors of modest area can complement these measurements. Hence the comprehensive X-ray Astronomy mission will have the following characteristics: a deployable LEPC detectors with auto-collimators to make high-time resolution observations of X-ray sources and to detect the faintest GRBs/ XRFs; a large area SiCZT detectors to make precise spectroscopic observations in 2 – 60 keV region; four focusing X-ray detectors to make precise Fe line spectroscopy and continuum spectroscopy upto 30 keV.

The instrument configuration is given in Figure 2 (see page 10).

Methodology

The technology scenario, worldwide, is making a remarkable transformation. Incremental, widely spread, software driven technological transformation with quick turn over is the order of the day. Space astronomy must seize this opportunity and adapt itself: instead of long drawn out mega projects, it may be worthwhile to try out quick multi-faceted projects with specific ‘niche’ technologies. The technological advances advocated in this proposal are quick and topical and can be realized in the time-frame of one to two years.

Further, the final science product crucially depends on careful analysis and modelling. Getting highly sensitive continuum spectroscopic data is only one part of the story. One needs a large number of interested theoretician and model builders to get to the bottom of the problems like what happens close to a black hole and how black holes grow. Instead of the money driven science push (*“get guest observations accepted, then get 1 dollar per second”*), it is worthwhile to try out science-driven methods: put high quality data in the web and let the best brains in the world work on them.

Well, the best brains in the world could be busy elsewhere ! But there exists a vast pool of interested young minds, particularly in the developing world, still stars in their eyes and hungry for the best data in the world. A judicious use of these resources can easily complete the proposed project in about four to five years.

Hence a possible methodology to realize this project could be as follows:

Step 1: Complete a critical evaluation of the science aspects of this proposal.

Step 2: Under NASA leadership, sub-divide this project in some half a dozen independent projects (like, say, developing the ‘semiwich’ detectors, developing the LEPC detectors, etc.).

step 3: For each sub-division, strike tripartite agreement between a) NASA for its leadership b) an established US research center for technical abilities c) an emerging learning center for student base.

step 4: Realise all the sub-parts and the complete entity in quick time, in the spirit of community partnership.

I am sure, this methodology has the potential of evolving into a robust futuristic trend for realizing many interesting science problems, particularly in space astronomy.

Science Objectives: comparison with IXO

Science Question	IXO Measurement	Present proposal: measurement	Fraction of IXO objectives satisfied
What happens close to a black hole ?	Time resolved high resolution spectroscopy of ... stellar mass and supermassive black holes.	Joint spectral, timing & polarization measurement of stellar mass and supermassive black holes.	Almost as good, if not better.
When and how did supermassive black holes grow ?	Measure the spin distribution of supermassive black holes.	Measure the spin AND accretion rate of bright AGNs	Almost as good, if not better.
How does large scale structure evolve ?	(i). High resolution spectra using AGN as illuminating sources. (ii.) High resolution spectra of clusters to measure mass and composition.	Use GRBs as illuminating sources.	A long shot. Maybe possible
Cosmic feedback	Measure metallicity and velocity structure of hot gas in galaxies and clusters.	Only wide band spectra of nearby clusters.	Cannot be satisfied
How does matter behave at very high density ?	Equation of state of neutron stars through spectroscopy & timing.	Spectroscopy, timing & polarimetry of neutron stars.	Almost as good, if not better.

Science Objectives: New results

Science Question	Present proposal: measurements	Comments
What is the nature of Dark Energy ?	Make precise spectral and polarization measurements of GRBs and use them as standard candles	A distinct possibility
What is the nature of Dark Matter ?	Study the behaviour of GRBs and study the intervening objects	A long shot.

Rough order of magnitude cost

Cost of the Project (in Million US Dollars (MUSD)): 450

Enabling technology: ‘semiwich’ detectors: 15 MUSD

Small area Si/ CZT detectors are commercially available for a few thousand dollars. With a NRE cost of 5 MUSD, large area (16 cm^2) ‘semiwich’ detectors could be built for similar costs. Another 5 MUSD can be used for manufacturing these detectors in large quantities (1000 numbers) and testing them.

Enabling technology: LEPC detectors: 10 MUSD

SuperMon satellites: 75 MUSD

SuperMon are micro-satellites and can be built and launched at a cost of 25 MUSD each.

Black hole tracker: 200 MUSD

This is a medium class satellite (600 – 800 kg payload; 1500 – 2000 kg satellite) and it can be fabricated and launched in about 200 MUSD.

Other expenditures: 150 MUSD

This includes management cost, data analysis cost, observatory running cost etc.

Conclusions

It is argued here that a spectro-polarimeter will satisfy most of the science objectives of IXO. A preliminary version of this proposal was submitted to ISRO:

Rao, A. R., K.P. Singh, S.K. Ghosh, M.N. Vahia, J.S. Yadav, D.K. Ojha, M.R. Shah, S.K. Chakrabarti, A. Nandi, D. Bhattacharya, S. Seetha, Ram Sagar, P. Vivekananda Rao, 2006, *A super Monitor for GRBs, X-ray Flashes and Black Holes (SuperMon) (A proposal submitted to ISRO)*,

Available at: ftp://deli.tifr.res.in/pub/ARRao_projects/ARRao_supermon.pdf

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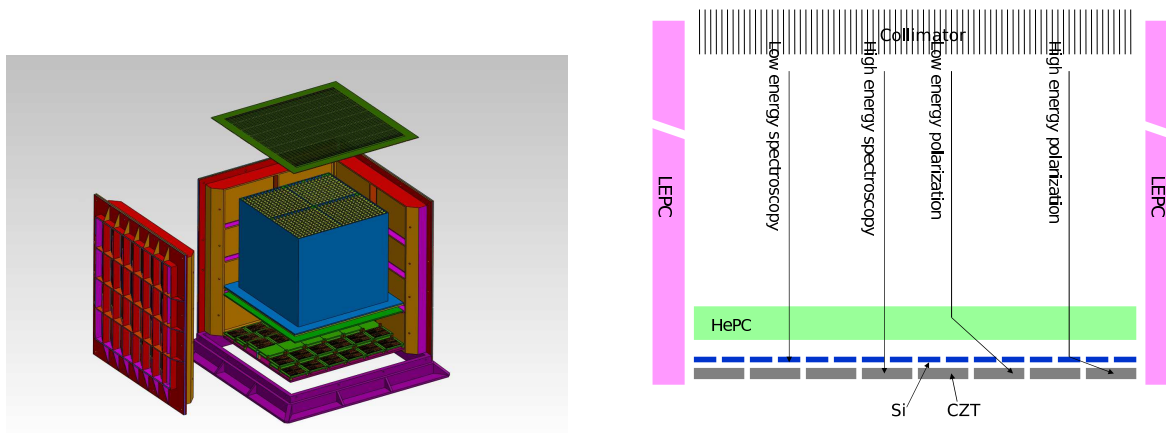


Fig. 1.— *Left*: SuperMon satellite. Four Low Energy Proportional Counters (LEPC) surrounding, in the center, (from bottom to top) a Si+CZT combination detector, He filled Proportional Counter (HePC), collimator ($2^\circ \times 2^\circ$) and a Coded Aperture Mask. *Right*: The detector configuration for spectro-polarimetric observations is shown.

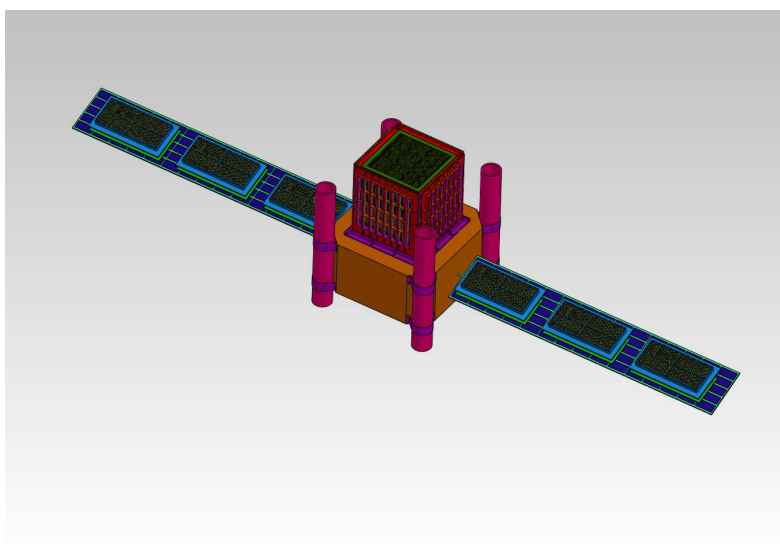


Fig. 2.— Black Hole Tracker: A scaled up version of SuperMon, along with a very large area deployable LEPC of total area 5 m^2 and four focusing soft X-ray detectors in the four corners.