Proposal for the Danish Microsatellite Program

μ-BALLERINA

- an "intelligent" satellite doing exciting science

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SCIENTIFIC OBJECTIVES

i) **Determine positions of cosmic gamma ray bursts to 1 arcminute precision, suitable for follow-up in the optical and radio domains.**

ii) **Study the early evolution of the X-ray afterglow phenomenon now known to follow cosmic gamma ray bursts.**

iii) **Provide rapid and precise positions for X-ray transients. (synergy with INTEGRAL and SRG).**

iv) **Study the detailed time evolution of long duration X-ray transients.**

v) **Provide a long term monitoring capability for both galactic and extragalactic persistent X-ray sources.**

MISSION CONCEPT

The concept of this proposal is to exploit three new developments:

- The discovery of X-ray afterglows following cosmic gamma-ray bursts: This permits exciting new data to be obtained with a small X-ray telescope within the first 24 hours of a burst.
- The development of the ØRSTED autonomous Star Imager: This makes it possible to prepare for fully autonomous attitude maneuvers. We intend to maneuver the satellite within minutes of a trigger, to observe in detail the X-ray afterglows of gamma bursts coarsely located by a wide field monitor.
- The development of global satellite communications networks, such as the IRIDIUM system: This permits to maintain continous contact with a satellite in low-Earth orbit albeit at a limited data rate. We plan to exploit this to receive in near real time the accurate source positions from μ-BALLERINA. We may also uplink approximate positions obtained by other means for immediate follow-up by μ-BALLERINA.

Building on these three developments we can design an intelligent (i.e. highly autonomous) microsatellite with extraordinary capabilities within a very active area of modern astrophysics.

THE SCIENTIFIC CASE

Background:

The discovery in March 1997, by the Beppo-SAX satellite, of X-ray afterglows lasting many hours following cosmic gamma-ray bursts (Costa et al, 1997) has set an entirely new perspective for the study of these enigmatic bursts. Now we know for sure, that with X-ray telescopes we can obtain accurate positions for the GRB sources. Such positions, in turn, allow the immediate follow-up from the ground. All what is needed, is that our satellite can react sufficiently fast following the trigger. So the simple concept of this proposal is to put a wide-field monitor and a small X-ray telescope on a microsatellite with good maneuvering capabilities.

In addition to the bursts and transients detected by its own monitor instrument, the μ-BALLERINA will also make use of rough position determinations ($\sim$1°) provided by all-sky monitors on other missions[1]. The X-ray telescope will permit to obtain both the precise positions of the sources, and quantitative new data on the spectral and time evolution of the transient sources. In particular for the GRB afterglow phenomenon such spectral and timing data will be very important for improving our understanding the physics of the burst phenomenon, which is still a very open question (see f.i. Chiang & Dermer, 1997).

Cosmic Gamma Ray Bursts

The origin of the Cosmic Gamma Ray Bursts remains one of the most puzzling problems of modern astrophysics. But the year 1997 may has marked a turning point through the discovery of X-ray, optical and radio afterglows from gamma-ray bursts (Costa et al, 1997). The Italian-Dutch satellite Beppo-SAX has observed a number of bursts with the Dutch build Wide Field Camera. This camera can localize the sources to about 5 arcminute precision. Based on this information the SAX spacecraft controllers can maneuver the satellite to allow the X-ray mirror telescopes to observe the source region within about 8 hours from the burst. In three cases a fading X-ray source has been discovered and localized to about 1 arcminute from the telescope data. In two of the three cases ground based optical follow-up revealed weak ($\sim$20 mag) counterparts, and in one case also a radio counterpart was identified (van Paradijs et al, Piro et al, Bond, Frail et al, Taylor et al, 1997). These transients could be followed for a few days.

For the first time since the discovery of the gamma-burst phenomenon, do we now have reliable counterparts. The counterparts seem to confirm the suggestion that the sources are at cosmological distances, implying enormous energy releases ($\sim 10^{53}$ ergs). The faintness of the optical counterparts necessitates the use of very large telescopes for optical spectroscopy. The Keck telescopes have already been used, and the ESO VLT will undoubtedly also be involved as soon as it is operational.

Observations of the afterglow are now the key to constrain the models for GRBs; these must be able to predict the temporal and spectral behavior of the emission. One popular model is the blastwave model, where a highly relativistic ($\gamma \sim$1000) blast wave moves ahead of a fireball and is slowed down by the surrounding medium, as the energy is deposited (Mészáros & Rees, 1997, Chiang & Dermer, 1997). This model predicts the afterglow to decay as a powerlaw as function of time. The powerlaw exponent then in turn also determines the spectral shape (if $F_x \propto t^\delta$ then $\mathrm{d}N/\mathrm{d}E \propto E^\alpha$, and $\alpha = 2/3\delta - 1$, so, for instance $\delta = -1 \Rightarrow \alpha = -1.66$).

Using its X-ray telescope μ-BALLERINA will measure the energy spectra of the afterglow of the bursts in the energy range between 0.1 and 2 keV. In this energy range we may also see effects of absorbtion of the lowest energy photons by the intergalactic medium. Here it is important to realize that photoelectric absorption only occurs if the material is un-ionized. However, the burst will itself ionize all matter to great distances. The local material around the source will, therefore, not contribute to the measured column densities.

[1] In the time frame of the μ-BALLERINA mission the all-sky monitor on the Japanese Module of the International Space Station will be in operation as well as the MOXE monitors on Spectrum-XG and maybe BATSE on CGRO. A long arc-like error box coming from the Interplanetary Timing Network will also be suited for follow-up with the μ-BALLERINA using pointing sequences.

X-ray novae and other long duration transients

X-ray novae have attracted considerable interest since they were discovered by Elvis et al. in 1975. These transients seem to be associated with binary systems containing a dwarf star and a compact object. A list of the well established members of this class is given in table 1. It will be seen, that for those cases where it has been possible to determine the mass for the underlying binary system, the values are so high, that the compact object cannot be a neutron star. Consequently these transients are now considered among the best black hole candidate systems in our Galaxy. The outburst activity seem to be recurrent; among the six well documented events, two have been observed as optical novae earlier in this century (Tanaka, 1996), the recurrence times seem to be long, 50 to 200 years. The extended period of inactivity combined with the rapid rise of the outburst (rise times of two to five days) are not understood, and alternative hypotheses have been put forward by Mineshege and Wheeler (1989), and by Hameury, Lasota and King (1986). In order to come to a better understanding of the nature of the instability leading to the outburst, more detailed observations during the earliest phases of the outbursts are required (Lund, 1993). μ-BALLERINA will provide the precise position of such transients immediately after their outburst.

Two types of black hole transients distinguish themselves. The majority (8 out of the 10 listed in table 1) follow very similar time evolution patterns, exhibiting rise times of a few days and an exponential decay phase with an e-folding time of about 40 days (Tanaka, 1996). The two atypical sources (GRS 1915+105 and GRO J1640-55) have remained bright with frequent new outbursts during several years since their discovery.

The close similarity of the decay characteristics for the first type of transients tells us that the processes controlling the decay of the outburst are fundamental and independent of the details of the underlying system. The natural place to look for the causes of such standard features is in the evolution of an "isolated" accretion disk, i.e. a disk which does not receive any new material from the dwarf companion star. The recent developments of the theory of *advection dominated accretion flow*- models (Narayan & Yi, 1994; Esin, 1997) may point the way to an understanding of these common decay characteristics.

In the past a few of the X-ray novae have been observed to emit bright, but intermittent radio bursts. But radio observations have only been possible after the optical counterparts have been identified. Here again, the immediate availability of precise coordinates for the transient will allow sensitive radio observations to be initiated without delay. In particular the two transients of table 1, which do not follow the standard time evolution for X-ray novae, have displayed a phenomenon, previously only observed from giant extragalactic sources: *superluminal motion* in the radio lobes.

Table 1. X-ray Novae.

Source name	Year	X-ray peak Crab units	Peak m_V	Mass of compact object	Identification	Prev. Outb.	Galactic latitude
A 0620+00	1975	60	12	$>7\ M_\odot$	XN Mon 1975	1917	-6.5°
H 1705-25	1977	3.5	16.5		XN Oph 1977		+9.1°
GS 2000+25	1988	20	14	$>6\ M_\odot$	XN Vul 1988		-2.9°
GS 2023+33	1989	20	12	$6.3\ M_\odot$	V404 Cyg	1938	-2.6°
GRS 1124-68	1991	8	13.2	$\sim 6\ M_\odot$	XN Mus 1991		-6.7°
GRO J0422+32	1992	5	13		XN Per 1992		-11.9°
GRS 1915+105	1992	2	>24		XN Aql 1992		-0.2°
GRS 1009-45	1993	1 †	14.6 ‡		XN Vel 1993		+9.3°
GRS 1716-249	1993	1.4 †	17.1		XN Oph 1993		+7.0°
GRO J1655-40	1994	4	14.4	$7.0\ M_\odot$	XN Sco 1994		+2.2°

† X-ray energy band 8-100 keV. ‡ 2 months after outburst.

Fast Transients

The WATCH instruments on GRANAT and EURECA have established a class of X-ray transients with duration of hours to days (Brandt et al, 1992). Such transients occur particularly frequently in the inner regions of our Galaxy.

It is possible that part of these events may be connected with old isolated neutron stars accreting interstellar matter with unstable nuclear burning (Ergma and Tutukov, 1980). According to Zduenek et al (1992) the hydrogen burning triggered by electron capture becomes unstable if the accretion rate is higher than 10^{13} g/s. The mass of the accreted envelope should be $\approx 10^{23}$ g, so several hundred years are needed to accrete this amount of matter assuming an accretion rate of $\sim 10^{13}$ g/s. The number of isolated neutron stars in our galaxy accreting with such a high rate may be as high as $\approx 10^5$ ($\approx 0.5\%$ of the total number of old neutron stars in our galaxy (Blaes & Madau, 1993). So we may expect to see 10-100 fast transients of this type per year.

Galactic Persistent Sources

Several large X-ray observatories are in preparation for the end of this decade. However, it is uneconomical to allocate these very sensitive instruments for long time monitoring of bright sources. We therefore propose to use μ-BALLERINA as a monitoring observatory. We expect that even after allocation has been made for the systematic scanning of the Galactic plane, more than 50 % of the total observation time can be made available for such observation programmes.

A number of binary X-ray sources exist in our Galaxy which exhibit systematic or random pulse period variations and flares related to the binary orbital phase. One such case is GX 301-2, in which flares have been observed at unexpected positions in the binary orbit (Castro-Tirado et al, 1993), hence long term monitoring is required to determine the flaring probability as function of orbital phase.

Expected Number of Events

About 20 gamma ray bursts per year are bright enough to allow detection and localization with the wide field monitor on board μ-BALLERINA.

Due to the maneuverability of μ-BALLERINA we can avoid loss of observation time due to occultations by the Earth or due to Sun constraints. We must still expect 20 % loss due to interference from the radiation belts. In total we can therefore only expect to see about 15 bursts per year observed with the wide field camera.

Although this is a small number, it must be remembered that these are among the strongest bursts for each year. The chances of identifying quiescent counterparts, will be best for the strong bursts.

To the events localized by the wide field monitor on μ-BALLERINA we may add those events provided by other sky monitoring systems. Here we depend, however, on the response time of these systems, and at this moment we do not make assumptions about the number of such events.

We will perform repeated surveys of 80% of the sky every day to search for transients. Only a cone around the Sun will be inaccessible. About 20 X-ray transients of duration 2 to 3 days will be seen from the inner regions of the Galaxy. On the average one bright X-ray nova occurs per year, and in addition some 5 transients of other types.

With an expected sensitivity of 11 mCrabs (5σ in 1 hour) more than 200 persistent or recurrent X-ray sources are bright enough to show up in the wide field camera, and of course many hundred sources can be studied using the telescope. In particular the monitoring of the brighter extragalactic sources for variability may be of great value if the mission flies concurrently with one of the large X-ray missions planned for the year 2000 and beyond. There are at least 10 each of AGN and BL Lac sources which are bright enough in X-rays that they can be monitored for variability in 1000 s pointings with the μ-BALLERINA telescope.

RELATIONS TO OTHER PROJECTS

The following projects are relevant for the μ-BALLERINA:

- The Beppo-SAX mission is currently active, but its performance has been limited lately by gyro-failures. At this time it is therefore uncertain if this satellite will be able to provide more of the rapid follow-up observations, which have so excited the gamma-burst community during the first part of 1997.
- The MOXE all-sky monitor on the Russian Spectrum-RG satellite will probably be active in the 1999-2001 period. Spectrum-RG will only have telemetry sessions once per 24 hours. It is therefore not suited to projects requiring short response times.
- The HETE II satellite will be launched in 1999. It will have similar localizing capabilities as the wide field monitor on μ-BALLERINA. HETE-II will transmit GRB positions (accurate to a few arcminutes) to special low-cost receiving stations installed at a number of observatories. The final payload complement of HETE-II is still under consideration.
- The RIKEN Institute in Tokyo is preparing a sensitive all sky monitor for the Japanese module on the International Space Station. The design of this instrument is not yet frozen, but is primarily intended for monitoring long duration X-ray sources - not gamma-bursts.
- ESA's INTEGRAL satellite is intended for launch in 2001. It may therefore fly concurrently with μ-BALLERINA. In that case the μ-BALLERINA could become a very useful sky monitor for INTEGRAL.

SCIENCE PAYLOAD

The science payload consists of three elements: a gamma-ray detector (a simple scintillation counter) to provide the high energy trigger for gamma-ray bursts, a wide-field monitor covering about 2.5 steradian and yielding rough positions for bursts and transients, and a focusing X-ray telescope. The instrument accomodation (including the Star Imager) is shown in the figures.

Gamma-ray detector

A small scintillation detector will provide sensitivity for gamma ray bursts in the energy range from 20 keV to 1 MeV. The signals from this detector are important for defining time windows in which to search for GRB signals in the X-ray wide field monitor.

Wide Field Camera

A wide field X-ray camera is located next to the X-ray telescope. The camera will cover 20 % of the full sky. The camera will be able to locate bright gamma burst sources to 1° or better. We intend to use a pinhole camera with a position sensitive microstrip detector (Budtz-Jørgensen et al, 1992), similar to those used on our instruments on SPECTRUM-RG and INTEGRAL. We will arrange the microstrip pattern on the inside of a spherical section with the pinhole aperture at its center.

The parameters adopted for this study are: Pinhole area: 1 cm^2, radius of detector entrance sphere: 14 cm, radius of microstrip sphere: 15 cm. With these parameters the the resolution element (the pinhole angular diameter projected on the sky) is 3.8°. The energy range of the detector is 3 to 10 keV assuming an 0.3 mm beryllium entrance window and a 1 bar xenon filling. The expected background count rates are:

Cosmic Diffuse: 7 $cm^{-2}s^{-1}sr^{-1}$ (3-10 keV)
Internal: $7 * 10^{-3}$ $cm^{-2}s^{-1}$ (3-10 keV)

leading to a total expected background rate of 0.04 counts per second per resolution element (3-10 keV). The corresponding count rate for a 1 Crab source is 1.6 s^{-1}. A 1 Crab source can therefore be detected in 10 s (16 source counts on zero background). In a 4000 s observation a 20 mCrab source is detected at 10σ. We note in passing, that this is about the level at which the first X-ray nova A 0620+00 was discovered by ARIEL-V back in 1975 (Elvis et al, 1975).

To locate the centroid of a source to better than 1° (2σ) requires the detection of ≈ 70 photons – this assumes a negligible background, an assumption which is reasonable when we consider the localization of a gamma-ray burst of duration less than one minute.

The information from the wide field camera must be processed on-board in real time to provide the guidance information for the attitude control. We estimate that we can turn the satellite through 60° within about one hundred seconds. Most gamma bursts will by then have faded below visibility in the wide field camera and in the high energy scintillation monitor. However, extrapolations from the SAX low energy data indicate that the X-ray afterglow should still be very bright in the X-ray telescope at this time and for several hours thereafter.

By proper planning of the satellite pointings during quiet times it will be possible to survey 80 % of the sky every day down to a limit of 15 mCrab or better, and still leave about 50 % of the observation time free for pointed observations with the X-ray telescope.

Focusing X-Ray Telescope

Our design assume a soft X-ray grazing incidence telescope with a field of 1°, an rms angular resolution of better than 30" over the whole field, and an energy range of 0.1 to 2 keV.

The dimensions of the low energy X-ray telescope are assumed to be similar to the ones used on EXOSAT (Taylor et al, 1982), i.e. having a focal length of about 1 m and an effective area of about 90 cm^2 at 0.1 keV, about 40 cm^2 in the energy range from about 0.3 keV to 1.5 keV, and falling steeply beyond 2 keV. The point spread function for Wolter-I geometry telescopes as used on EINSTEIN, EXOSAT and ROSAT degrades very seriously off axis; in the case of EXOSAT the image blur increased from about 7" on-axis to about 130" at 45 arcminutes off axis. However, ray tracing studies have shown that it is possible to optimize the mirror shape and achieve a rms image radius less than 5" over a 1° field (Burrows et al, 1992, Werner, 1977). The fabrication technique used for the EXOSAT mirrors (replication of a gold layer from a glass mandrel on a beryllium substrate) will be ideal for μ-BALLERINA due to the very low weight of the completed mirror assembly (7 kg). However, the replication technique does not allow to obtain the most perfect mirror surface smoothness, so allowance for some X-ray scattering has been made in the quoted rms image radius.

A CCD-detector will be used in the telescope since good response can be achieved down to 0.1 keV. The CCD can provide both excellent spatial resolution and good energy resolution. Compared to the Channel Multiplier Arrays used as high resolution detectors on EXOSAT a CCD would offer a very significant improvement in efficiency particularly between 0.5 and 2 keV.

SPACECRAFT BUS REQUIREMENTS

The following systems will be needed on the spacecraft bus:

- Solar panel and Power subsystem (ØRSTED derivative).
- GPS Receiver (Low power, standard precision version).
- Star Imager subsystem (ØRSTED derivative).
- Sun Sensor subsystem (ØRSTED derivative).
- Vector Magnetometer (limited precision version, as required by ACS system)
- Magnetorquer subsystem (ØRSTED derivative).
- CDH subsystem (ØRSTED derivative (but remember lessons learnt!)).
- Momentum Wheel assembly (New development).
- IRIDIUM (or equivalent) Communications subsystem (New development).
- ACS software (new development).
- Autonomous Observation Scheduling software (New development).
- Radiative Cooler for X-ray CCD ($\simeq -80°$) (new development).

Table 2. Mass, Power and Data Rates.

Instrument	Mass (kg)	Power (Watt)	Data Rate (kbits/s)
A. PAYLOAD:			
Gamma ray detector	1	2	0.01
Wide field camera	5	6	0.5
X-Ray Telescope	20	10	1.0
Payload Total	26	18	1.5
B. SPACECRAFT:			
New w.r.t.ØRSTED:			
Solar Panel (1 m^2, 60 W), shunts	8		
Battery (5 Amp hours)	6		
Momentum wheels	9	10	
IRIDIUM communications	2	3	
ØRSTED derived elements:			
(Structure, SIM, EPS, ACS, CDU):	40	20	0.5
Spacecraft Systems Total	65	33	0.5
Margins:	9	9	-
Launch Total	100	60	2.0

MISSION REQUIREMENTS

The satellite orbit should avoid the radiation belts and the South Atlantic Anomaly as far as possible. A low inclination, low altitude orbit is therefore preferred.

A nominal mission lifetime of two years would be reasonable, this would provide a sample of about 30 well studied gamma bursts, which will suffice for making confident statements about the possible existence of host galaxies or other objects.

We assume that all command uplink and data downlink can be handled via one of the global satellite communications systems. Specifically the IRIDIUM system offers 2000 baud data interfaces to their terminals. We are confident that we can compress our downlink data to stay within this limit. Real-time downlink is essential for prompt distribution of the GRB-positions to optical- and radio-observatories worldwide for immediate follow-up. We are also keen to exploit positions provided by other all-sky monitors. These must therefore be uplinked in near-real time, and autonomous onboard software will then have to decide if and when an observation is feasible.

Although μ-BALLERINA is expected to react autonomously to bursts and bright transients, it will be important to monitor the data in near real time to react manually to the appearence of faint or slowly rising transients or interesting state changes in one of the persistent sources.

TECHNICAL DEVELOPMENTS REQUIRED

- Autonomous attitude control software. The ACS software should autonomously be able to schedule observations and attitude maneuvers considering constraints such as: Sun and Earth avoidance angles for the Star Imager, Solar illumination angle for the solar panels, Thermal Radiator deep space viewing constraints, target occultation by the Earth.
- Momentum wheel technology for microsatellites. μ-BALLERINA has demanding requirements for the speed of the attitude maneuvers: Settle within any point inside a cone of 60° half-opening angle within 100 s. Without expendables, the only way to realize this seem to be momentum wheels. The ability of the SIM to recover the attitude quickly after a rapid slew will be particularly valuable, as this may allow us to operate without gyro's.

- IRIDIUM communication unit. This may be a potential niche product for Danish industry. An IRIDIUM communication unit capable of communicating while itself orbiting, may require an advanced anti-Doppler control of the communications frequencies.

MANAGEMENT AND FUNDING

The Danish Space Research Institute is capable of managing the payload development. Technically all the payload elements, except the X-ray CCD-detector in the telescope focus are well known to the DSRI. DSRI intends to seek international collaboration regarding the payload development.

SCIENCE OPERATIONS AND ARCHIVING

It is a key point of this proposal that the satellite operations can controlled via the common telephone network. Naturally this will require considerable anti-hacker measures. But the potential cost reductions are very significant.

We foresee that all observation programmes for persistent sources shall be carried out following open competition for observation time in the astronomical community.

The data from the wide field monitor will be made available to the general astronomical community on a daily basis, in the same way as is now the case for the All-sky Monitor on NASA's RXTE mission. (see f.i. http://heasarc.gsfc.nasa.gov/docs/xte/asm_products.html). The complete mission data set will, after analysis, be left to the NASA HEASARC Archiving system.

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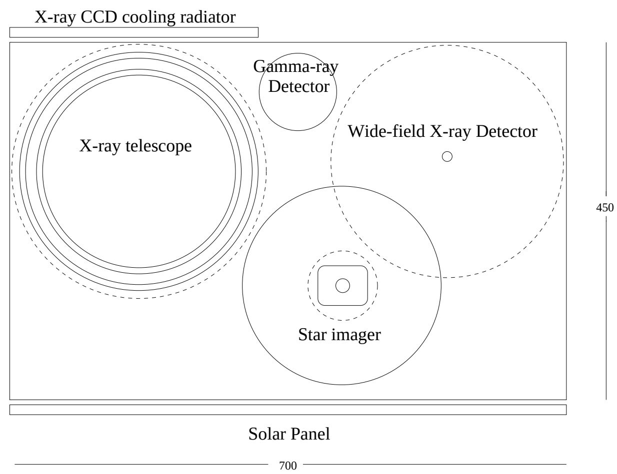
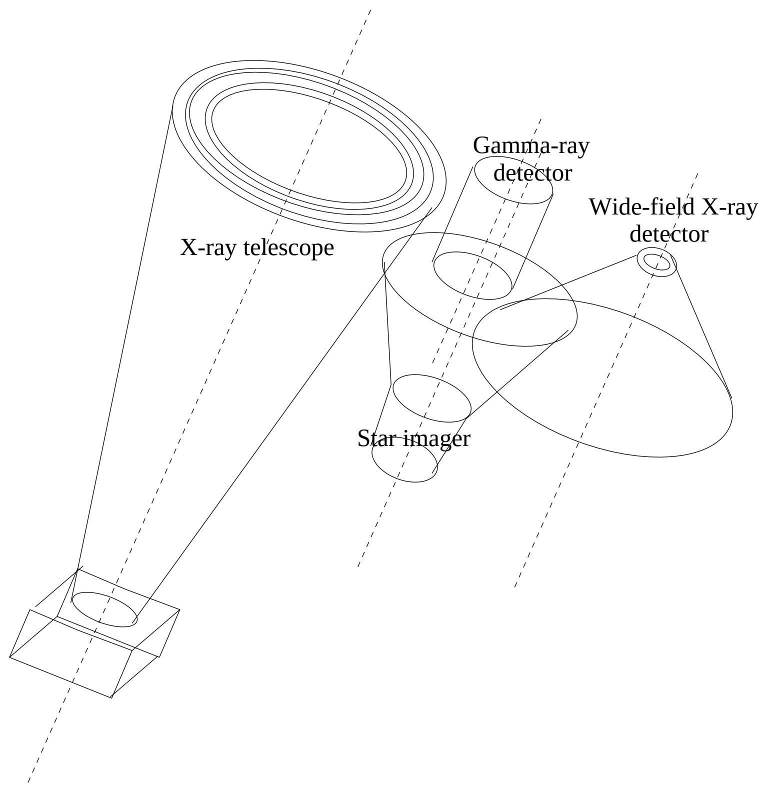


μ– BALLERINA Instrument Layout



μ–BALLERINA Payload Accomodation