MASSIM – Milli-Arc-Second Structure Imager

Submitted in response to
NNH07ZDA001N-ASMCS
Physics of the Cosmos (and Cosmic origins)

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Scientific/Technical/Management

1. Introduction

The highest energy processes in the cosmos, and those where our understanding of the underlying physics is pushed to its furthest limit, necessarily take place in very compact regions. The physics of these regions where the matter and energy densities are highest has so far been observed only by indirect methods.

We propose study of a medium class mission that will image in X-rays the structure of astrophysical objects with an angular resolution three ***orders of magnitude better than the present state of the art,*** using a new technique capable of long-term development by an additional 3+ orders of magnitude in resolution. This new scale of precision gives the Milli-Arc-Second Structure Imager (MASSIM) the capability to observe directly the geometry and dynamics of jets, black hole accretion disks, the expansion of supernovae, proto-stellar disks, stellar coronae and the interaction of binary systems. These measurements will be of unique value in understanding processes in these objects, most particularly in determining the nature and acceleration processes of astrophysical jets, whether they be emanating from young or active stars, neutron stars, stellar-mass black holes or super-massive black holes in active galactic nuclei.

MASSIM introduces to space-based X-ray astrophysical measurement a technology that is new to the field: transmissive, refractive-diffractive optics, a form of augmented Fresnel optics that is not subject to the practical limitations of grazing incidence reflection and which has a broader X-ray band-pass than pure diffractive Fresnel optics. It is these optics, which are lightweight and can be produced in large areas at moderate cost, that provide the key to the advances that MASSIM offers.

MASSIM is a medium-class mission employing formation flying of two spacecraft, an optics spacecraft carrying simple large collecting area, light weight, refractive-diffractive X-ray lenses that focus radiation in the 4.5 to 11 keV band upon detectors carried by a second spacecraft 1000 km distant. We will study use of the optics spacecraft as an occulter for possible low energy, (~keV) telescopes also situated on the 2nd spacecraft.

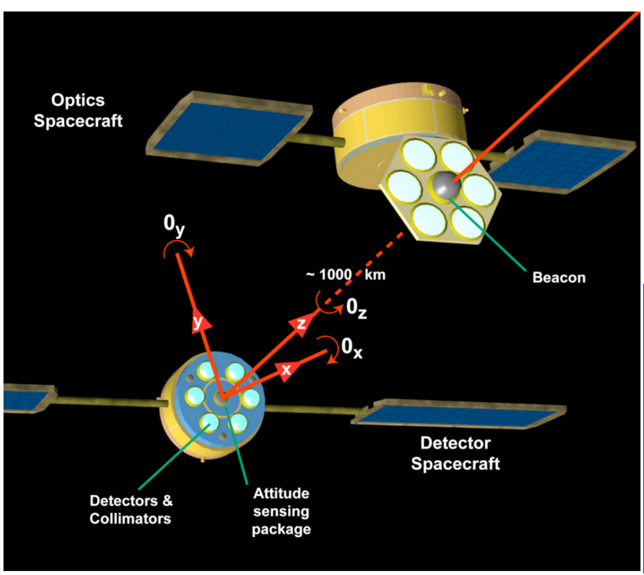


Figure 1 ***The MASSIM mission concept will use a technology new to X-ray astronomy to improve angular resolution by up to 3 orders of magnitude. An optics spacecraft carrying an array of diffractive-refractive lenses focuses X-rays onto detectors on a spacecraft 1000 km behind.***

The MASSIM mission (Figure 1) is immediately relevant to NASAs Science Mission Directorate 2007-2016 Science Plan goal: “Discover the origin, structure, evolution and destiny of the Universe …”. In particular it will address “understand phenomena near black holes”. Furthermore, the "Technology Challenges/Priorities" identified in the 2007-2016 Science Plan recognizes the need for "large, lower-cost lightweight mirrors". The optics proposed here can replace mirrors and have low cost and areal density. The precision formation flying and attitude determination that are needed for MASSIM will be required for achieving a number of other NASA objectives. The NASA capability roadmap CRM4 (Advanced Telescope and Observatories) notes the need for formation flying demonstrators; ***MASSIM with its relatively simple science instrumentation can fill this role perfectly.***

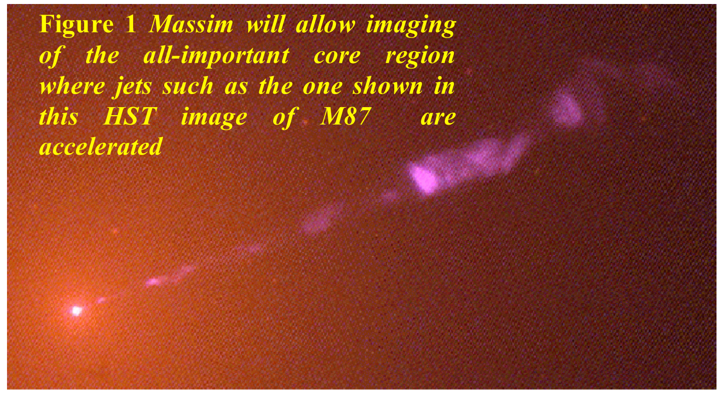


Figure 1 ***Massim will allow imaging of the all-important core region where jets such as the one shown in this HST image of M87 are accelerated***

The MASSIM mission also provides a path to a longer-term micro-arc-second mission that would actually image the event horizon of nearby supermassive black holes, thereby allowing the predictions of strong-field General Relativity to be tested in an unprecedented manner.

The proposing team includes essentially all the scientists who have performed key exploratory work on the uses of color-corrected Fresnel lenses for very high angular resolution high energy astronomy, and others who will bring to the study the heritage of analytical and experimental work relevant to interferometry and the application of physical optics to very high angular resolution X-ray and gamma-ray telescope systems.

2. Scientific Objectives

The capabilities of MASSIM are such that it can impact a wide range of important scientific topics from stars and planets to more exotic objects such as supermassive black holes (SMBHs) and quasars. Here, we briefly survey the science goals of MASSIM with an emphasis on contributions to our understanding of phenomena in the vicinity of black holes and in particular of jets (Figures 2,3).

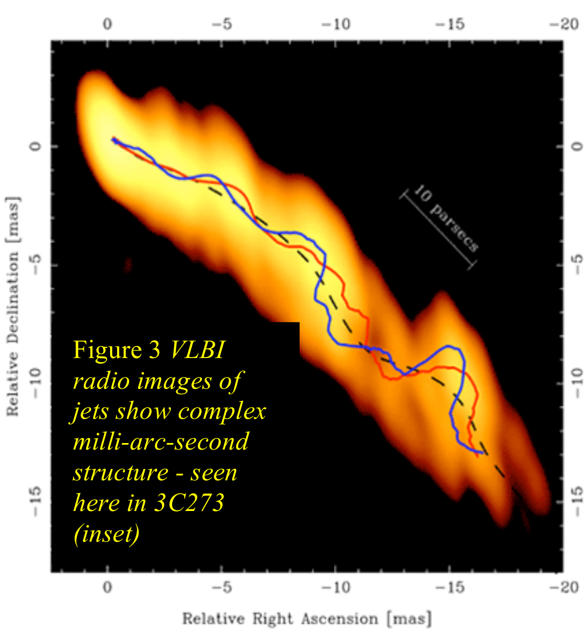


Figure 3 *VLBI radio images of jets show complex milli-arc-second structure - seen here in 3C273 (inset)*

Jets from black holes – stellar to supermassive

Jets are ubiquitous in astronomy. With improving instrumentation, jets are being discovered in more and more circumstances, from recently formed pulsars and young proto-stellar systems to old X-ray binaries and the dying stars that lead to γ-ray bursts, and from stellar mass black holes of a few solar masses ($M_{\odot}$) to active galactic nuclei (AGN) containing SMBHs of more than 10^9 $M_{\odot}$[1]. Jets are intimately linked to numerous aspects of the "origin, structure, evolution and destiny of the Universe" – the heating of the interstellar and intergalactic medium by AGN jets is widely

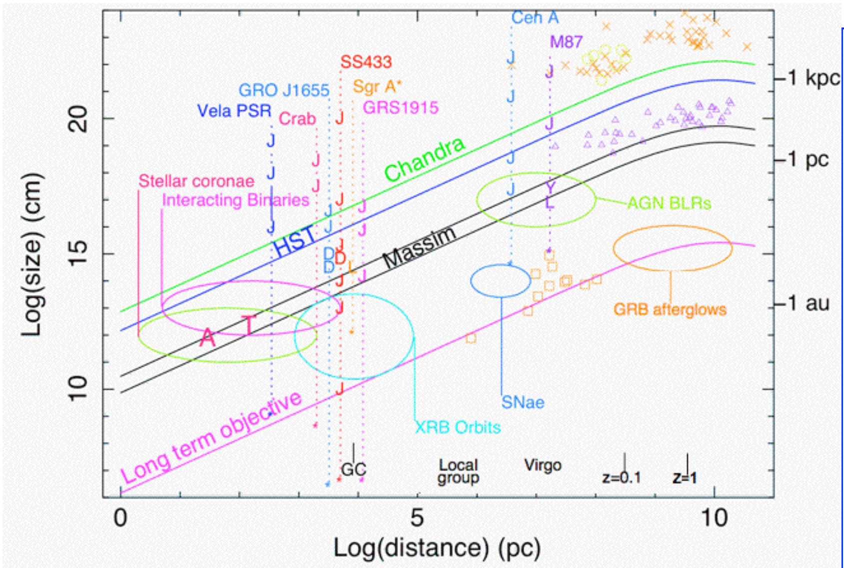


Figure 4 The angular resolution of MASSIM (black band, depending on mode) improves by about 3 orders of magnitude on that of Chandra. It is here compared with various objects and categories of object. X, O = known X-ray and optical jets. Δ = examples of compact radio VLBI jets from the Mojave survey. ☐ = Event horizons of SMBHS with well established masses[1]. A,T= Algol, T-Tauri stellar disks. Characteristic sizes of specific objects (coded by colors) are marked with *=event horizon or velocity of light cylinder, J-J=range over which jet has been observed, D,Y = expansion per day, year .

believed to be an important process in regulating galaxy growth [2].

Jets include the largest single objects in the Universe (several Mpc) but are produced in regions so compact that they are difficult to study. It is still uncertain where and how the matter in jets is accelerated – most successful models suggest gentle hydromagnetic acceleration, but there is little direct observational evidence for or against these ideas. Even the basic nature of the accelerated matter is unclear – are black hole jets electron-positron or “normal” electron-proton plasmas? It seems likely that jets are Poynting flux dominated within the acceleration region but it remains an open question where a jet becomes matter dominated [3]. And of fundamental importance is the primary energy source for these jets – are they energized by the inner accretion flow [4-6] or the magnetic extraction of spin energy from the black hole [7,8] ?

Radio VLBI (very long baseline interferometry) images with milli-arcsecond resolution have been instrumental in our understanding of black hole jets. VLBI has revealed blobs of radio-emitting plasma ejected at high speed both in the jets of AGN involving SMBHs and in those in microquasars in our own galaxy, which seem to be their stellar mass black hole analogs [9]. Often the apparent ejection speeds are superluminal, proving that these flows are highly relativistic. In nearby AGN (e.g. M87), VLBI observations track the jet down to scales $<10^2$ Schwarzschild Radii [10], demonstrating that collimation and (probably) acceleration occurs on these scales.

MASSIM’s milli-arc-second angular resolution will enable us to directly image the immediate BH environment on VLBI scales, where jets are accelerated and collimated. Its sensitivity in an energy range (4.5-11 keV), where absorption by dust and gas is negligible, will allow a direct peek into regions virtually inaccessible at other wavelengths and contains the all-important Fe K lines.

Combining X-ray images from MASSIM with VLBI maps will allow us, for the first time, to separately determine the magnetic field strengths and particle densities/energies of milli-arcsecond scale jets (via standard synchrotron theory). Measurements of these basic physical quantities are crucial if we are to test jet acceleration/collimation models (beyond the crude consistency tests possible today). Combined with secondary indicators of jet power (e.g., the power needed to inflate large scale cavities in the surrounding medium) these measurements will allow powerful tests of the particle content (pair plasma vs normal plasma) and Poynting flux content of the jets [11,12].

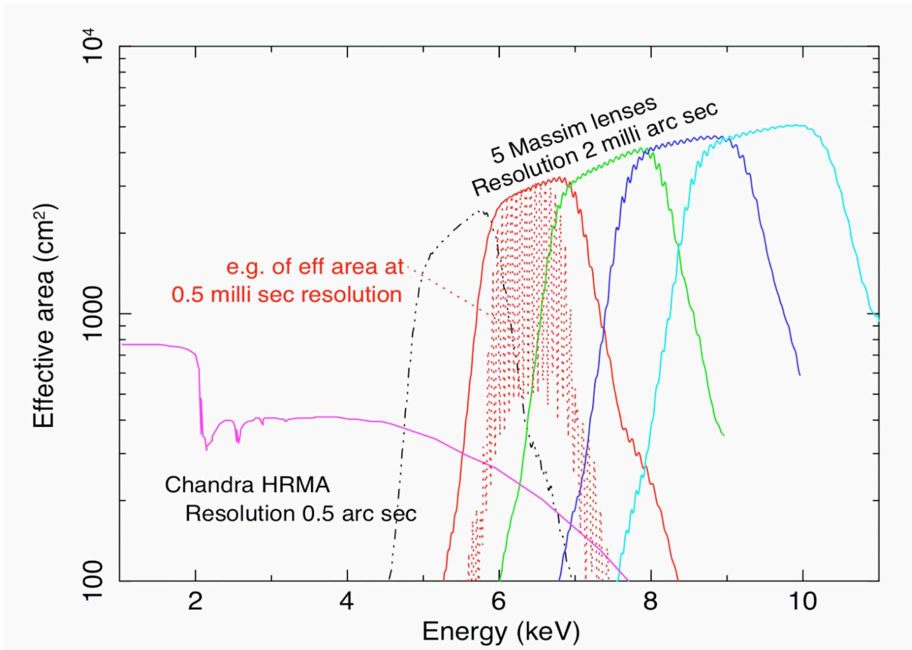
The majority of AGN are radio quiet [13], failing to display powerful jets. Milli-arcsecond jets are, however, commonly found in radio-quiet Seyfert nuclei using VLBI. The reason why jets cannot be fully fledged in Seyferts, despite the presence of accretion onto a SMBH, is still unknown. It may involve aspects of the black hole itself (e.g., its spin rate and/or the magnetic flux threading the black hole) or a foetal jet may be quenched by its environment. ***MASSIM will image the closest and best resolved radio jets in Seyferts (e.g., III Zw 2[14]) and allow us to derive quantitative information on the jet properties and environment, thus testing these scenarios.***

The closest SMBH to us is at our Galactic Center and continues to be a crucial test-bed for models of black hole accretion. The low-luminosity of this black hole despite the presence of surrounding gas (originating from stellar winds of the central star cluster) is interpreted in terms of a Radiatively-Inefficient Accretion Flow (RIAF) [15]. MASSIM will enable us to resolve X-ray emission from the accretion flow allowing unprecedented tests of the RIAF models. The importance of this is highlighted by the realization that most SMBHs in the Universe accrete in this mode.

MASSIM as a multipurpose X-ray observatory

MASSIM will be a highly capable, multi-purpose high angular resolution X-ray observatory and will have impact across astrophysics (see Figures 4,5). In addition to its study of jets, the angular resolution and the energy band of MASSIM are ideal for using the fluorescent Fe lines to explore the parsec-scale structure of AGN, including the "molecular torus" often discussed in the context of AGN unification. Closer to home, MASSIM will study pulsar wind nebulae. MASSIM observations of the Crab Pulsar will allow highly resolved images of the ultra-relativistic (Lorentz factor $\sim 10^6$) MHD wind that is believed to be accelerated by this rotating magnetized neutron star [16]. Chandra has observed the (arc-second scale) shock where

Figure 5. ***The effective area of an instrument with five 1-meter diameter diffractive-refractive lenses tuned to different energies. That of Chandra is shown for comparison. The main curves correspond to the photons collected within a spot corresponding to 2 milli-arc-seconds but the angular resolution is considerably better (down to 0.1 milli-arc-seconds) at a comb of energies within the main pass band (e.g. dotted line). The effective area is much greater than that of Chandra, so despite the larger focal spot the sensitivity is almost as good.***



this wind runs into the surrounding matter [17], but MASSIM resolution is required to study the evolution of this wind closer to the pulsar's light cylinder.

As a final example, MASSIM will resolve coronal emission in nearby stars, and the emission from interacting winds in binary star systems. This would give us our first resolved view of any stellar corona beyond the Sun, dramatically improving our understanding of magnetically active stars.

3. Technical Approach and Methodology

The key that makes possible the great step forward offered by MASSIM is the use of transmissive, diffractive-refractive optics. Current X-ray optics are based upon grazing incidence reflection, which requires large areas of mirror surface to be very well polished and precisely figured. The angular resolution is limited to little better than an arc-second.. Refractive-diffractive optics circumvent the practical limitations which stop mirror optics approaching the theoretical limit which, for a full 1 meter mirror in the X-ray band, would be more than 3 orders smaller. They rely on the fact that the refractive indices of materials that transmit X-rays differ slightly from unity. Because the wavelength is so short, despite the minuteness of the effect ($\delta = 1-\mu \sim 10^{-4} - 10^{-6}$) it is possible to use it to make lenses. And ***because δ is so small, constructional tolerances are enormously eased and diffraction-limited imaging can be achieved with low mass and at low cost. Small lenses demonstrating the principle have been made (Figure 6). Scaling to larger sizes is straightforward [§3.2.1].***

Diffractive-refractive X-ray optics do involve two specific difficulties (i) the focal lengths of such lenses tend to be very long, leading to a limited field of view for a given size detector and to the need for formation flying, and (ii) the energy bandpass is limited. Formation flying has been identified as a key technology goal of NASA and our efforts towards that end will only be part of a much more comprehensive program. The field of view issue is addressed by using as large a detector format as possible, aided by recent and expected developments in CCDs and other silicon X-ray detectors. The bandwidth problem is addressed by using multiple, achromatic systems.

We propose as a "medium class" mission an ultra-high-angular-resolution X-ray observatory based on such lenses. It will advance by some 3 orders of magnitude the precision of the imaging that is currently possible.

The achromatic lenses will consist of a thin diffractive Phase Fresnel Lens (PFL, Figure 6) on the surface of a Beryllium refractive component (Figure 7). Even the achromatic lenses have a limited bandpass and we propose a configuration with 5 or 6 lenses optimized for energies covering a band including the region of the important Fe lines 6-7 keV (Figure 5).

The lenses form real images in a focal plane at a distance of 1000 km. In this plane a second spacecraft will carry a series of large area detectors which can be based on existing technology. The performance of the CCDs used on Chandra, XMM, and Suzaku provide adequate energy resolution and a spatial resolution better than needed. The

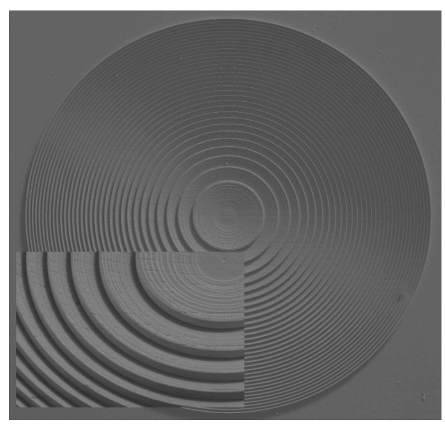


Figure 6. ***We have made and tested scaled down PFLs. The figure shows an SEM of an 8 keV, 3 mm diameter PFL; the inset shows a zoomed view. Those of flight size will actually be EASIER to manufacture***

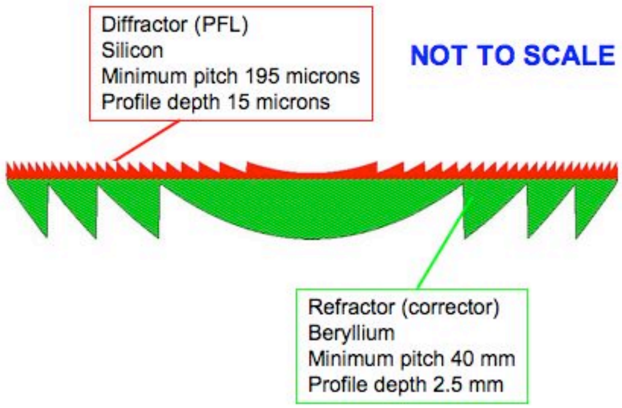


Figure 7. ***A diffractive-refractive achromat consists of a fine PFL (brown) and a refractive lens (green), which may itself be stepped on a much larger scale. The diagram is indicative and not to scale. Example materials and characteristic sizes are given for a 1 m diameter 6 keV lens with a focal length of 1000 km.***

only difference is that because of the 'plate scale' a mosaic of such detectors covering a large area is needed. To reduce the diffuse X-ray background a collimator is needed in front of each detector (§3.2.3). Metallized films will block visible/UV radiation.

The mission requires the formation flying of two spacecraft but in many respects the requirements are rather loose. For neither spacecraft is precision control of the attitude needed and the distance between the spacecraft is not critical (§3.1; Table 1)

During the study we propose considering certain options which would enhance the scientific return of the mission. One option involves simply changing the form of the lenses in one of the 'stations' in the optics spacecraft, replacing it by one in which the pitch follows a law other than the 1/r law of a Fresnel lens. This has the possibility of offering diffraction-limited performance over a much wider bandwidth and better low-energy resolution, but at the expense of effective area. Other options to be studied include a shorter focal length lens for wider field of view, intermediate resolution, studies and small low-energy X-ray telescopes on the detector spacecraft, possibly employing normal incidence multilayer optics, that would use the lens array (opaque <2 keV) as an occulter, allowing reconstruction of complementary soft X-ray images with resolution comparable to that of the main telescopes. ***Either of these would help with field of view issues, target finding and pointing verification.***

All the new science opened up by X-ray imaging in the milli-arc-second regime justifies MASSIM as a single mission. However we point out that the techniques used and demonstrated by MASSIM as a medium class mission can be extended into the (sub-) micro-arc-second regime. Thus the project may lead in the long-term to the proposal and development of a mission with even higher angular resolution. By moving to higher energies where the diffraction limit is even smaller and/or by using an array of partial lenses in a partially filled aperture, one could reach the point of being able to image space-time around the event horizon around black holes. This approach is in many respects equivalent to, and perhaps less demanding than, that developed within the MAXIM studies for the 'black hole imager' objective of the

Table 1 Baseline MASSIM characteristics

Energy Range	4.5-11 keV
Focal length	1000 km
Effective Area	2000-4000 cm^2 (inside 2 milli-arc-sec)
Angular Resolution	0.5 milli-arc-seconds (HEW 6-7 keV) 0.1 milli-arc-seconds (selected energies)
Field of view	100 milli-arc-secs (1)
Point source sensitivity	8×10^{-15} erg $cm^{-2} s^{-1}$ (2)

(1) Detector limited; 500 × 500 mm assumed + possibility of wider field of view, lower resolution, option.
(2) 5σ in 10^5s, 4.5-11 keV)

'Beyond Einstein' program. We are aware of the possibility that an outcome of the study might be that a **micro**-arc-second mission could, and should, be undertaken in a single ambitious step.

Table 1 ***Navigation and control requirements*** *(SC_1 is Optics spacecraft; SC_2 is detector spacecraft)*

Parameter (Figure 1		Nominal	Accuracy	Knowledge	Units
x, y	Transverse offset of SC_2 relative to SC_1	0	25	1	mm
z	Axial offset of SC_2 relative to SC_1	1000	10	1	km
θ_{x1} , θ_{y1}	Rotation of SC_1 about X, Y axes	0	5	1	arc min
θ_{z1}	Rotation of SC_1 about Z axis	0	5	1	arc min
θ_{x2}, θ_{y2}	Rotation of SC_2 about X, Y axes	0	10	5	arc min
θ_{z2}	Rotation of SC_2 about Z axis	0	5	1	arc min

3.1 Mission Requirements

The requirements here are those for a milli-arc-second mission but they have been evaluated based on experience from two similar but more ambitious IMDC studies. One, "FRESNEL", was a formation-flying mission with a 5 m Fresnel lens and 10^6 km spacecraft separation; the other, "FRESNEL PATHFINDER", was similar with a 1 m Fresnel lens and 10^5 km separation.

MASSIM requires two spacecraft that will be placed at L2 using a dual launch. A 'drift away' heliocentric orbit is a possible alternative. The estimated spacecraft wet masses are 500 kg (Optics spacecraft) and 1300 kg (Detector spacecraft) based on the IMDC studies.

The mid-size class launch vehicles, Delta M+(5,2) and Atlas 511 have more than adequate performance to place the two spacecraft at L2 and have available payload fairings to accommodate both spacecraft. The Atlas 511 has an existing dual manifest capability for the 5 m "Medium" fairing under consideration for the MASSIM mission.

The attitude control and formation flying requirements are given in Table 1. The key requirements for the Fresnel lenses are in red. The determination of the relative transverse position of SC_2 (optics craft) relative to SC_1 (detector craft) amounts to determining the direction of the line of sight to 0.2 milli-arc-seconds (in a celestial frame of reference). Due to the forgiving nature of low *f*-number transmissive optics, all other requirements are very lax and easily achieved. Figures in blue indicate that pointing control system requirements, for example stable imaging of a beacon on SC_2 from SC_1 , may place a tighter limit than that imposed by the X-ray imaging.

Telemetry requirements : Nominal

Thermal requirements : The preferred operating temperature for the CCDs is -90C.

Operations requirements

Mission duration: 3 yr minimum.

Typical observation duration: 1-10 days.

Available sky: Most observations can be scheduled to optimize the observing sequence; only observations of novae and supernovae are time-constrained;. Pointing at ~90° from the sun allows observation of every point in the sky within 6 months. Allowing ±30° variation in the sun angle allows half the sky at any one time.

Repointing time: should be minimized, but because observations will usually be long (many days) 1-2 days for repointing is acceptable. Analysis of a possible observing list indicates that with careful scheduling most repointings can be by less than 20°. Fifty pointings per year is a reasonable target.

3.2 Technology Readiness Levels

3.2.1 Phase Fresnel lenses {TRL 3}

Phase Fresnel Lenses (PFLs) are widely used in X-ray microscopy at synchrotron facilities, though emphasis there has been on small (sub-mm) diameter lenses and short focal lengths [*e.g.*18,19]. PFLs also offer many advantages for astronomical applications [20-34] for which angular resolution, rather than spatial resolution, is important and much larger diameters and focal lengths are needed. Members of the proposing team [20-24; 26-31] and others [32-34] have extensively studied the design and optimization of PFLs for astronomy, and in particular diffractive-refractive achromatic combinations.

With colleagues at UMd, we have successfully fabricated [35] ground-testable silicon PFLs (Figure 6) with diameters up to 4.7 mm and a focal length of 112 m at 8 keV, designed to be scaled to still larger sizes and focal lengths for astronomical applications [35,36]. These have been characterized using the 600 meter X-ray beamline at NASA/GSFC and have demonstrated efficiencies ~70% of the ideal [37], the losses being due to fabrication artifacts, now understood and being addressed in subsequent fabrications. ***Results obtained (Figure 8) show that the angular resolution is more than an order of magnitude better than that of the Chandra mirrors and close to the diffraction limit of 12 milli-arc-seconds.***

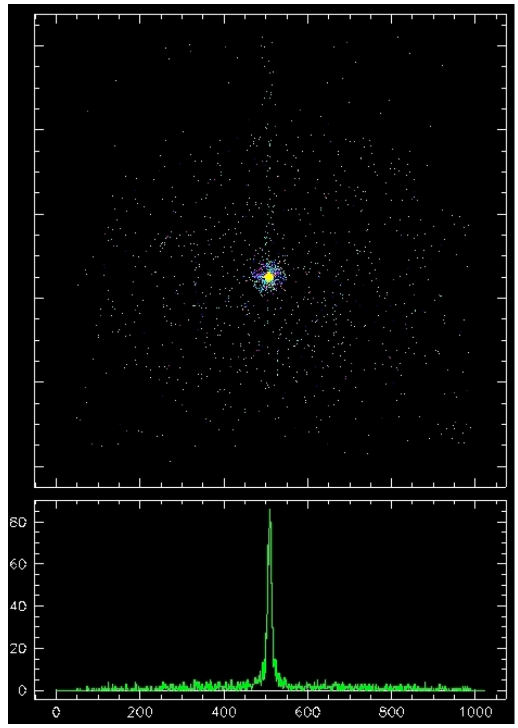
These lenses are in many respects scale models of those required for the MASSIM mission. The radial scaling changes the fine, micro-machined, profile necessary for the miniature lenses to a scale that is actually ***easier to manufacture***. The refractive X-ray lenses that complement the PFLs to make achromatic combinations are also extensively used for microscopy and beam focusing at synchrotron facilities and an extensive literature exists [*e.g. 38*]. Again the long focal length lenses that are needed for astronomy will be easier to manufacture than the high curvature, often multiple component, lenses for ground applications.

Developments needed are : (1) combination of diffractive and refractive components, to make an achromatic pair. This is work underway and demonstrations are expected next year; detailed optical analysis has already been completed [28] and no problems are anticipated; (2) studies of the engineering necessary to form a large lens by mosaicking small components already capable of being manufactured. The assembly tolerances are not extreme – 10 to 100 µm over 1 m scale – and again we do not anticipate problems; alternatively machining from one piece could be considered (3) a possible move from silicon to a less absorbing material (polymer or beryllium) and/or reduction of the substrate thickness.

3.2.2 Detectors {TRL 3-4}

Existing detectors are capable of fully exploiting the images from astronomical PFLs. The energy resolution (130 eV at 6 keV) is adequate and the spatial resolution (~50 µm) better than needed. We baseline a design based on mosaicking CCDs such as those in use on the CHANDRA, XMM and Suzaku missions. Detectors for such missions are already mosaics, but MASSIM will require ~100 CCDs per detector in place of, for example, 7-12 on XMM. Wiring problems can be alleviated because modest displacements normal to the detector plane can be

Figure 8. ***The image of a 25 µm pinhole as recorded at a distance of 460 m from a 3 mm diameter PFL at 8 keV in the GSFC long beam test facility. A Gaussian fit to the projection has σ≈60 µm (lower plot; units are pixels of 13mm). The angular resolution is more than an order of magnitude better than Chandra. Allowing for the magnification of the pinhole and other effects, we place an upper limit on the effects of lens imperfections that is within a factor of two of the diffraction limit of 12 milli-arc-seconds***



accepted. Alternative Si detector technologies [39-41] or larger format CCDs will also be considered

3.2.3 Collimators {TRL 5}

The collimators in front of the detectors, needed to reduce the diffuse X-ray background flux, can be identical in design to those currently flying on RXTE [42]. They have an open solid angle of 1 deg^2 and operate in the range 2-30 keV.

3.2.4 Formation flying

The MASSIM mission concept, while providing revolutionary scientific capability, requires only evolutionary advancement in engineering and technology. The two-spacecraft formation concept comprises formation flying capabilities which are either established from related missions or are at intermediate performance levels along the path from development paths initiated (and in some cases completed) from the Navigator Program and NASA's former Code R technology development efforts (Cross Enterprise Technology Development Program and Mission and Science Measurement Technology Program). The MASSIM study will take advantage of these broad technology developments and ground and flight demonstrations that have occurred in NASA, DoD, and associated industry and academic elements. In addition to those mentioned above, these include New Millennium Program ST-3/Starlight (ground-based developments and testbeds), ST-5, and EO-1, as well as rendezvous and proximity operations work from Orbital Express, XSS-11, and lessons learned from the DART mission. Table 2 identifies the technology capabilities required, along with the current state of the art, the requirements for the MASSIM mission concept, and what would be required to verify a technology to reach TRL 5

Resource estimates have been based on the performance of specific ion thrusters, RIT-10 and RIT-22 having TRL levels 6+, for the station-keeping and re-pointing (leading to a ~100 kg fuel requirement to perform a 3 year mission).

The determination and control of the line of sight will be a major issue for the study but solutions are available based on systems already used in space (HST FGS, GPB star sensor) combined with techniques for measuring offsets that are currently under development [44-47].

Table 2 ***Sensor Technology Capabilities Required for MASSIM***

Required Capability	Curent status	MASSIM need	Current TRL	TRL 5 Test Requirement
Measure separation	2 cm post-processed	1 km over 1000 km	9	N/A
Measure line-of-sight (direction of optics S/C, as seen from detector S/C, w.r.t stars)	N/A	0.3 milli-arc-sec	4	HW prototype integrated into high fidelity simulation, with real-time estimation and wrapped control loops
Control separation	N/A	10 km over 1000 km range	4	RF or optical channel simulator with high fidelity dynamic simulator and real-time estimation and wrapped loops
Control line-of-sight	N/A	5 milli-arc-sec	1	=25mm@1000km
Formation Commanding	Ground	On-Board	4	Distributed simulation
Autonomous collision avoidance	N	Yes	4	High-fidelity simulation

Table 3 ***MASSIM mission cost estimates*** *(FY08M$)*

Cost Element	**Phase**					**Mission Total**	**Cost Methodology**
	A	**B**	**C/D**	**A-D**	**E**		
1.0 Project Management	1.0	2.8	10.7	14.5	0.6	**15.1**	5.% of flight systems cost B- D; 7.5% of Mission Ops
2.0 Mission Sys Engr	0.8	2.5	9.6	12.9	0.0	**12.9**	90% of Project Mgmt
3.0 Mission Assurance	0.5	0.9	3.4	4.8	0.0	**4.8**	35% of System Eng
4.0 Science	1.0	3.0	6.0	10.0	13.0	**23.0**	Based on scaled numbers from Chandra & XMM
4.0 Technology Develop	17.0	12.0	5.0	34.0		**34.0**	Formation flying & optics technology
5.0 Payload	5.0	14.2	44.3	63.4	0.0	**63.4**	Estimated payload at 20% of Spacecraft mass
6.1 Lens Craft	5.0	13.8	53.9	72.8		**72.8**	500 kg (Note 1)
6.2 Detector Craft	10.0	35.4	130.4	175.8		**175.8**	1300 kg (Note 1)
7.0 Mission Ops					7.6	**7.6**	
9.0 Ground Sys			2.6	2.6	0.0	**2.6**	
10.0 System I&T		7.3	30.2	32.5	0.0	**32.5**	10% of hardware
Sub total	**40.3**	**91.9**	**296.1**	**423.2**	**21.2**	**444.4**	
Reserves		27.6	88.8	116.4	3.2	**119.5**	30% of subtotal (B/C/D/E)
With reserves	**40.3**	**119.4**	**384.9**	**544.5**	**24.3**	**563.9**	
8.0 Launcher			172.0	172.0		**172.0**	Used Medium EELV
11.0 E/PO	0.0	0.2	0.7	1.0	0.1	**1.0**	See text
Mission Total:	**40.3**	**119.7**	**557.6**	**717.5**	**24.4**	**737.9**	

Note (1) used the Advanced Mission Cost Model (Astrophysics SC; average difficulty, modified new design; launch yr 2018); verified with inflated IDC results of 2002

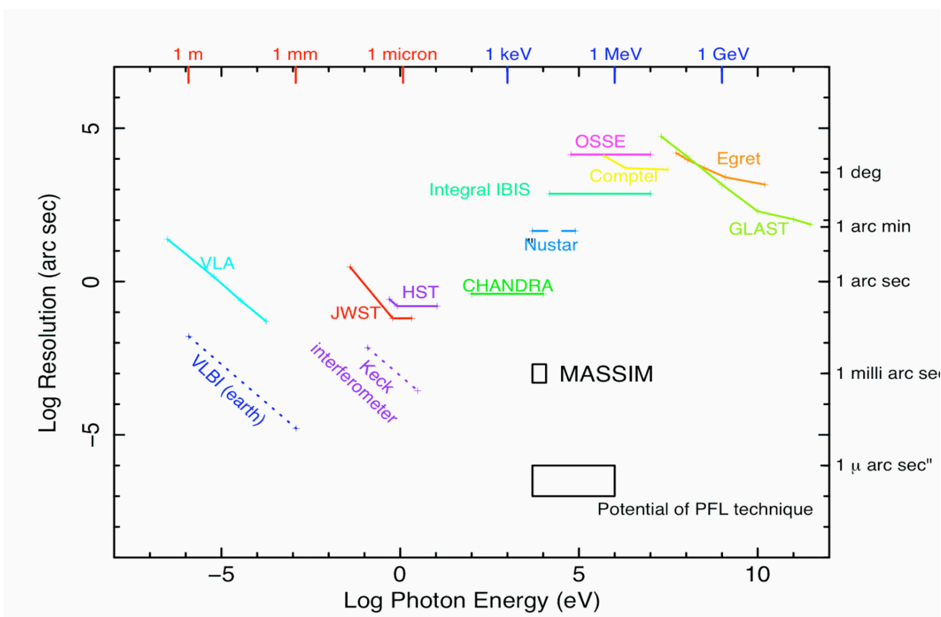
3.3 Mission costs estimate

The mission cost estimates (Table 3) were developed using a combination of parametric, grassroots and analogous cost estimating methodologies. Since we are in Pre-Phase A on this NRA activity, the estimates presented here must be viewed as preliminary. Costs were developed using a parametric estimate for the spacecraft and payload hardware cost based on the Advanced Missions Cost Model. The estimates were verified by inflating the spacecraft estimates from two 2002 IMDC Price H exercises for missions, similar to MASSIM but more ambitious. Project management, systems engineering, safety and mission assurance and system integration and testing are estimated as percentages of hardware costs based on cost averages from the extensive GSFC mission flight experience. Science costs are scaled based on Chandra and XMM costs. The ground station and mission operations costs are based on inflated IMDC estimates. Reserves are 30% of Phases B through E before launch vehicle. EPO is estimated at 0.25% of the total cost less launch vehicle and reserves. The medium launch vehicle cost was taken from the ASMC workshop webpage.

This preliminary analysis puts MASSIM at a cost that, within the uncertainties, lies within the bounds of a medium class mission. If necessary, descoping is possible by reducing the number of lenses and detectors.

Figure 9.

MASSIM and longer-term missions based on the same technology will enter a new region of parameter space. Full imaging, rather than modelling based on interferometry, will be possible and observations will be at photon energies relevent to the study of high energy processes in compact regions.



4. *Impact of Proposed Work & Present State of Knowledge*

From the far infra-red through to the γ-ray regime our current ability to form images is limited to a resolution which is ~3 orders of magnitude inferior to the capabilities of the MASSIM mission and 6 orders of magnitude worse than that of a longer-term mission using the same concept. ***For comparison, Galileo revolutionized astronomy with telescopes that improved angular resolution by about a factor of six over that of the naked eye*** [50]. In the visible and NIR, adaptive optics techniques are approaching the diffraction limit for 10m class mirrors. The only technique that can come close to the potential angular resolution of the techniques proposed here is interferometry which, with a limited number of baselines, tends to

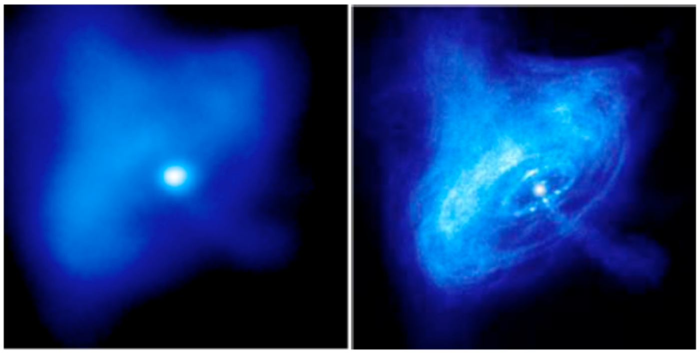


Figure 10. ***Rosat and Chandra images of the Crab pulsar and nebula, indicating the effect of an order of magnitude improvement in angular resolution. MASSIM will jump a further 3 orders of magnitude beyond the resolution of Chandra***

allow source modeling rather than producing unbiased images. ***In the X-ray and γ-ray bands, no mission currently operating or under development has performance within several orders of magnitude of MASSIM [Figure 9].*** MASSIM will allow imaging of unprecedented quality and for our key scientific objective, the study of astrophysical disks and jets, will allow a direct view of what is going on in the most critical inner regions. Figure 10 illustrates how an improvement in resolution has already led to a new understanding of another of our targets, the Crab Nebula.

Longer-term prospects

The MASSIM concept and that of longer-term follow-on missions is closely related to that of the MAXIM mission which has been extensively studied. It builds on that work but identifies a way of achieving similar objectives that is in many respects simpler and less technologically demanding

The imaging techniques proposed for MASSIM are directly extendable to the (sub-) micro-arc-second scale needed for black hole imaging. Extension to the micro-arc-second regime is possible in either of two ways. The same lens concept will work for γ-rays – in fact both imaging and efficiency improve with energy and in addition more conventional materials such as polymers or aluminum can be used in place of beryllium. A 6m lens working at 500 keV will have a diffraction limit of 0.1 micro arc seconds. Alternatively, the same angular resolution can be obtained in the region of the 6-7 keV Fe lines, using a partially filled aperture with diffractive lens components carried by multiple lens spacecraft spread over an effective lens diameter of 500m.

The X-ray optics to perform a black hole imaging mission is in principle available now; only formation flying and pointing determination issues impede a direct step to this objective.

5. Relevance to NASA and Astrophysics Division Objectives

The MASSIM mission is immediately relevant to NASA's 2007 Science Plan goal: "Discover the origin, structure, evolution and destiny of the Universe…". In particular it will address "understand phenomena near black holes". The mission is also relevant to other science objectives within this goal, such as "understand how individual stars form" (through X-ray imaging of young stars and their protostellar and protoplanetary disks) and to the question of "how did elements of the universe arise" (through supernova studies). Within the astrophysics area MASSIM, is presented in the context of "Physics of the Cosmos" but from the above it is clear that it is also relevant to "Cosmic origins" As well as the immediate scientific objectives, the precision formation flying and attitude determination that are needed for MASSIM will be needed for achieving other NASA objectives, notably IR interferometry and telescope/occulter concepts. The NASA capability roadmap [51] notes the need for formation flying demonstrators and MASSIM with its relatively simple science instrumentation would fill this role perfectly.

On another technological front, the NASA Science Plan notes the need to develop large, low cost mirrors. PFLs can be large, are low cost and low mass and can replace mirrors. The Chandra mirrors have a mass of 15-150 tons per m^2 of effective area (depending on the energy at which the effective area is evaluated); for comparison, the mass of the lenses proposed for MASSIM is about <10 kg m^{-2} (allowing 100% for support structure). Lenses also have the advantage over mirrors that small (or even modest sized) tilts do not affect the images.

The MASSIM mission provides a path to a longer-term micro-arc-second mission that would penetrate even closer to the centers of the black holes that form such a remarkable and energetically important element of the contents of the universe.

6. Plan of Work

6.1 Statement of Work: Study objectives

- Development of the science objectives and their requirements
  1. Discussion with the wider community to define fully the range of objectives that can be addressed with a milli-arc-second imager and to quantify its implications.
  2. Build an observation simulator for assessment of scientific goals
  3. Further develop science objectives, particularly to refine the mission requirements
  4. Consideration of science impact of any compromises found necessary during the study
- Optimization of the instrument design concept
  1. Detailed specification of the optics and detectors design; Trade-off field of view and detector size. Develop source-finding strategy starting from VLBI measurements
  2. Studies of lens manufacturing techniques
  3. Incorporate in the study the results from the parallel APRA-funded lens development program, including measurements on achromatic pairs
  3. Detailed quantification of implications of expected manufacturing tolerances and errors
  4. Study of options for the utilization of some of the lens stations (e.g. Talbot interferometer, photon sieve, short focal length/wide-field lenses)
  5. Study of an optional extension to low energies based on normal incidence multi-layer mirrors or other technologies and the possible use of the lens as an occulter
  6. Investigate alternative X-ray detector technologies
  7. Provide payload resource and technical requirements to spacecraft and mission studies
  8. Refinement of background and sensitivity estimates; specification of collimation needs
- Investigations of options for pointing determination and control
  1. Refinement of the baselined sensor concept
  2. Evaluation of the performance of its expected performance
  3. Review of available alternative sensor technologies
  4. Assessment of trade-offs and options
  5. Conceptual design of a sensor package to meet the mission requirements
- Refinement of formation flying design
  1. Develop low and high-fidelity dynamic models of the MASSIM spacecraft formation.
  2. Derive requirements and architectures for relative navigation, formation control, and intersatellite communications from level 1 science requirements

3. Design formation absolute and relative trajectories to best meet level 1 science requirements with minimal fuel consumption
4. Develop a testbed architecture required to reduce risk and perform trade studies on the formation flying architecture, making best use of existing facilities, and identifying any new infrastructure
5. Characterize open-loop behavior of the MASSIM formation, based on designed orbit trajectories using simulation in MATLAB, Simulink, STK, FreeFlyer, SIM42, etc.

- Develop technology validation plan
  Develop for each subsystem a validation plan leading from the current state of the art through to TRL 6/7
- Mission design optimization
  Optimize the mission concept in the light of available launchers and other capabilities to achieve the mission objectives at lowest possible cost
- Project cost estimation
  Obtain independent project lifetime costs estimates by GSFC costing office and through the GSFC IDC runs

6.2 Key Milestones

ID	Task Name	Qtr 2, 2008 – Qtr 2, 2009 (Mar – Apr)
1	IDL run to define instruments	5/9
2	Demonstration of achromatic lens	7/11
3	MDL run	9/15
4	White paper input to Strategic Plan	11/3
5	Presentation to ASMCS workshop	12/15
6	Final Report to NASA	3/16

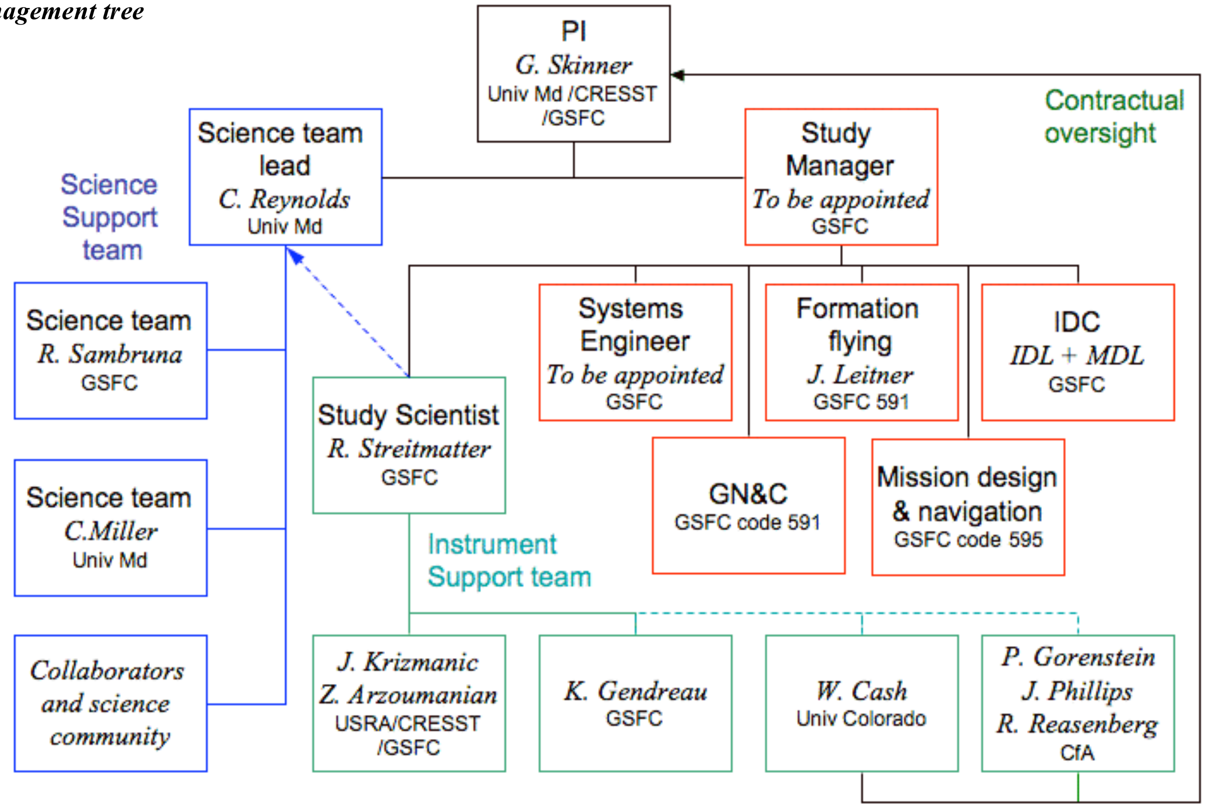
6.3 Study organization and Management Structure

Two physical consortium meetings will be held during the study, but most of the collaboration will be synchronized through telecoms held weekly or as necessary. The effort within each area will be directed toward providing input and support for two IDC runs, (IDL May 2008; MDL Sep 2008) and the preparation of final reports. A GSFC study manager will coordinate the study, in the case of the instrument team through the study scientist (Figure 11).

6.4 Cost Summary

As detailed in the budget section, the total cost of the 1-year study is \$789k. Primary costs are the reimbursement of salary and related costs for the FTEs identified in the table below. Included in GSFC's budget is the fixed \$200k cost of the IDC runs at the Center. In addition to the identified GSFC personnel, the budget also includes costs for a GSFC-provided study manager and systems engineer, as well as engineering support for the study and for the IDC runs. The travel budget is primarily for Drs. Cash and Gorenstein to attend team meetings and the IDC exercises at GSFC. Travel has also been budgeted to attend an ASMCS workshop and to present results at international meetings, using the 2008 SPIE Astronomical telescopes meeting as an example.

Figure 11. ***MASSIM study management tree***



6.5 Personnel & Institutional Responsibilities

Person	Institution	FTE	Responsibility / particular expertise
Skinner	UMd	0.25	PI (+ lens design and simulation)
Reynolds	UMd	0.1	Science Team Leader; Black Holes, general relativistic effects
Miller	UMd	*	Science Team; Accretion Disks
Krizmanic	USRA	0.25	Inst. Team; Lens prototyping, manufacture and testing
Arzoumanian	USRA	0.1	Inst. Team; X-ray interferometric measurements
Leitner	GSFC	0.33	Formation Flying
Streitmatter	GSFC	0.2	Study Scientist; Inst. Team Leader; Science integrity
Gendreau	GSFC	0.1	Inst. Team; Interferometry; MAXIM heritage; backup Instrument team leader
GSFC-provided	GSFC	0.2	Systems Engineer
GSFC-provided	GSFC	0.1	Study Manager
Gehrels	GSFC	*	Instrument and Science teams, Advisor
Sambruna	GSFC	*	Science Team. Jets and AGNs
Cash & staff	U.Col	0.38	Inst. Team; MAXIM heritage
Phillips	CfA	0.39	Inst. Team; Optical systems and precision measurement
Gorenstein	CfA	*	Inst. Team; CfA Lead; Lens design and simulation, detectors
Reasenberg	CfA	*	Inst. Team; Optical systems and precision measurement
Windt	Refl. X-ray Optics LLC	*	Inst. Team; Consultant, low energy telescope option

* Externally funded

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