SAHARA

Spectral Analysis with High Angular Resolution Astronomy

A mission concept for a soft X-ray optic with
high spatial and spectral resolution over a wide field of view
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This white paper contains no sensitive or controlled material.

SUMMARY

Chandra's high spatial resolution images have shown a wealth of unexpected structure in extended sources such as cold fronts in clusters, starburst winds, shocks in supernova remnants, diffuse gas and X-ray binaries in nearby spiral and elliptical galaxies and the first direct evidence for feedback from the relationship of X-ray and radio images in clusters. Simultaneously, the high spectral resolution for point and small sources available from the Chandra and XMM gratings have energized a range of fields using high (R>200) X-ray spectra to measure winds in AGN and X-ray binaries, cooling flows in clusters, detailed structure of stellar winds, the chemical composition of stellar coronae and constraints on the interstellar media of several starburst galaxies and the intergalactic medium.

The limitations of current detectors has meant that only a few of the brightest and most-condensed sources can take advantage of both techniques, but the combination of high spatial and spectral resolution with good sensitivity promises to create a revolution in astrophysics. We therefore propose the SAHARA (Spectral Analysis with High Angular Resolution Astronomy) mission which achieves all of these goals. Combining a short focal length, low earth orbit, one instrument and simple operations, SAHARA can return a significant fraction of the IXO science case for a much lower cost.

The science case for SAHARA is based upon analysis of high quality spectra and images in the 0.2–3 keV band, which contains the H- and He-like lines of C, N, O, Ne, Mg and Si, and the L-shell lines of Fe and Ni. To reduce costs while maintaining a sizeable science return, we propose a single instrument, operating in a single mode: a high spectral resolution calorimeter with pixels matched to the angular resolution of the telescope with a fixed 4m focal length. This design optimizes the collecting area in the 0.2-3 keV band and allows for a large 8x8 sq arc min field of view (FOV). Virtually all the important diagnostics of velocity, ionization, density and chemical abundance for all but the hottest astrophysical sources can be measured in this softer band.

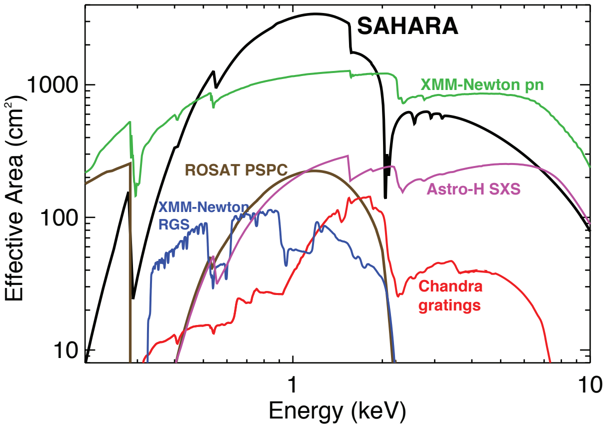

Figure 1. SAHARA's effective area between 0.5-2 keV is an order of magnitude larger than any existing or planned X-ray missions with high-resolution spectroscopy, and compares well to imaging missions.

The angular resolution goal is 3 arc sec with a 5 arc sec requirement, based on the surface brightness of sources at small scales and the need to resolve the important spatial structures seen with Chandra. The optics are based on the IXO slumped glass approach, and we believe that TRL 5 is achievable in the next two to three years for a 5 arc sec HPD mirror with ~3000 cm^2 at 1 keV with good collecting area at E<3 keV. SAHARA's effective area (see Figure 1) significantly exceeds all current missions in the key band and is not negligible in the Fe K band – enabling Astro-H Fe K band science but with much higher angular resolution and wider field of view.

The required spectral resolution derives from being able to obtain the full range of spectral diagnostics[1] in the 0.2-3 keV band, the typical clusters and galaxy dynamics of ~100 km/sec, and the need to resolve AGN wind components. These can be achieved by an X-ray microcalorimeter spectrometer (XMS), SAHARA's sole detector. The XMS will be similar to the IXO design but optimized for lower energies and can achieve higher spectral resolution with a requirement that ranges from 1.5 eV (0.5 eV goal) in the center of the array to 4 eV (2 eV goal) in outer regions. We will use position-sensitive pixels that were being developed for IXO to create a 2.5x2.5 sq arc min inner region with 2.5 arc sec pixels. A 3x3 Hydra design with 5 arc sec pixels will increase the total FOV to 8x8 sq arc min, enabling key science goals such as serendipitous source science, cluster coverage to R_{500} at z>0.1, and the ability to study large supernova remnants and nearby galaxies.

A low Earth orbit keeps launch costs low and reduces the detector background, a key to SAHARA science. SAHARA will be a general purpose observatory with a broad range of science; we have estimated costs for a three-year mission, including a Guest Observer program, to be less than $800M.

SCIENCE OVERVIEW

Although it retains a number of technical similarities, SAHARA represents a significant departure from IXO in both science focus and observatory design. The effective area and PSF requirements derive from SAHARA's concentration on imaging spectroscopy, which requires a much larger signal than imaging alone. Even the highest surface brightness sources, such as the Perseus cluster, need exposures of >500 ksec with Chandra to obtain >300 photons per 1/4 sq arc sec Chandra pixel. Accurate high resolution imaging spectroscopy requires many more photons (typically >4000 cts/spatial bin depending on effective temperature) and for an optic of moderate (~3000 cm^2) size and cost, an angular resolution bin ~100x larger than Chandra (or ~10 sq arc sec) will be adequate. This results in an angular resolution requirement of 5 arc sec, which is both technologically achievable and scientifically similar to the extremely successful ROSAT. Our low earth orbit will reduce the detector background important for diffuse emission studies. As shown by ROSAT, one can achieve very high observing efficiency (>65%) in such an orbit since the short focal length satellite can avoid Earth occultation by rapid slews and essentially loses data only to the SAA, which can be minimized by going to low inclination.

Table 1 summarizes the range of science achievable with SAHARA; each of these topics is discussed in turn in the following sections. These topics include nearly all of the IXO science combined with a range of topics described in the Astro 2010 'New Worlds, New Horizons' (NWNH) Decadal Report. In particular, we note SAHARA's wide field of view will discover serendipitous sources in each observation, enabling significant additional science.

Cosmic Feedback and the origin of Galaxies and Large Scale Structure.

As is well known the dominant baryonic component of clusters is the hot X-ray emitting gas which contains the critical information on the processes of cluster formation via hierarchical mergers, the chemical evolution of the universe and the only observable evidence for the process of feedback which is thought to control the growth of galaxies. Chandra observations of clusters have revolutionized the field showing direct evidence for mergers in surface brightness and temperature maps, the relationship between entropy and cluster properties and the interaction between the radio plasma and hot gas, indicative of AGN feedback. The small number of high-resolution XMM RGS spectra of cluster cool cores have radically changed our understanding of cluster 'cooling

Table 1: SAHARA Addresses IXO and NWNH Science

Science Question	Observation	Requirements
What happens close to a black hole?	Warm absorbers around SMBH; accretion disks in Galactic BHC	2 eV resolution in the XMS point source array
When and how did SMBH grow?	High-redshift SMBH followup of detections in other wavebands	~3000 cm^2 effective area in the 1-2 keV bandpass
How does large scale structure evolve?	Galaxy cluster survey to z<1	5 arc sec PSF, effective area at 1-2 keV, 8 arc min FOV, 4 eV FWHM energy resolution
What connects SMBH and LSS?	Low-redshift survey of cluster cavities and AGN jets	5 arc sec PSF combined with high-resolution imaging spectroscopy
How does matter behave at very high density?	Not known to be possible with SAHARA	–
Additional NWNH (Astro2010) Science Enabled by Sahara		
How do stars form & flares impact planet-hosting stars?	Surveys of star forming regions	5 arc sec PSF; broad band-pass with high-resolution imaging spectroscopy
How does gas exchange in galaxies and the IGM?	Cluster outskirts and haloes of individual galaxies	Low background over a broad band-pass with high-resolution imaging spectroscopy
How do rotation and magnetic fields affect stars?	Survey of main sequence stars	Large effective area between 0.2-3 keV with high-resolution spectroscopy
How do massive stars and Type Ia SNe explode?	Galactic and Local Group supernovae and supernova remnants	5 arc sec PSF; large FOV with high-resolution imaging spectroscopy

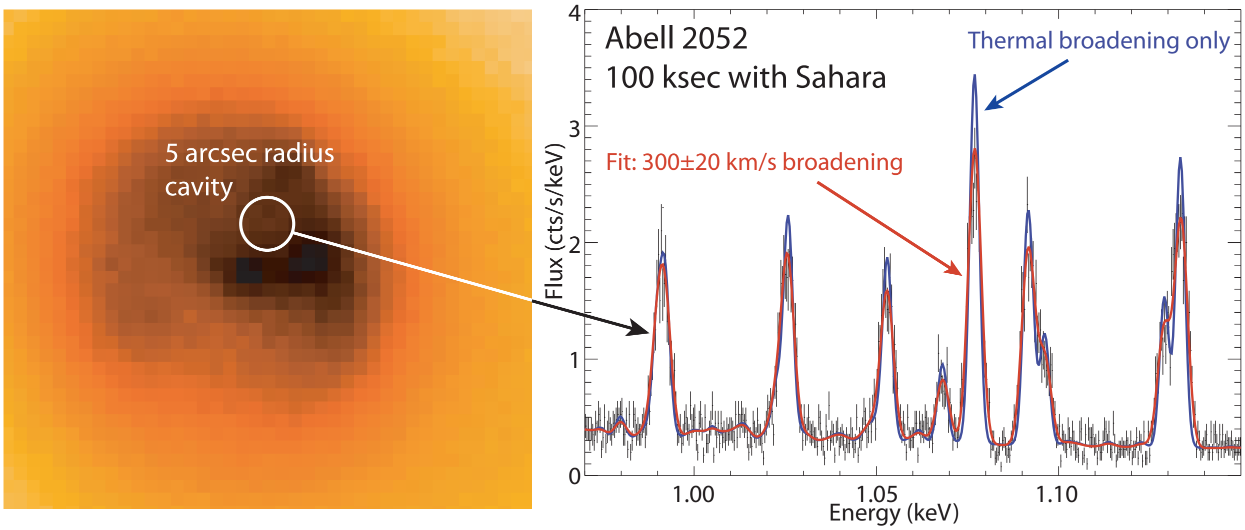

Figure 2. SAHARA will be able to both image cluster cavities such as those seen in Abell 2052 (shown left in a simulated SAHARA 100 ksec observation), and measure the turbulent broadening in the Fe L lines in both the bubble walls and the cavities themselves.

flows' and dynamics. SAHARA's combination of these capabilities will produce high-spatial resolution, high-spectral resolution maps that will enable detailed studies of cluster dynamics and turbulence, measurement of precision abundances, a search for the mechanism by which the relativistic radio emitting plasma influences the feedback mechanism and detailed analysis of cluster evolution across cosmic time (see Figure 2).

Recent analysis of X-ray cluster surveys have confirmed that they can provide precise estimates of cosmological parameters provided that the estimates of cluster mass are precise and accurate. At present the major limitations in the use of the equation of hydrostatic equilibrium for the measurement of cluster masses lies in the uncertain contribution to the pressure from turbulence, mass motion, magnetic fields and relativistic particles SAHARA's wide field of view will enable measurements of turbulence and mass motion over the full range of cluster scale sizes required to understand the magnitude of the contribution of these to the measurement of cluster mass. Significantly lessening the uncertainty in cluster mass will allow the full power of the eROSITA survey to be obtained for cosmological studies.

SAHARA's angular resolution, field of view and moderate effective area will allow detailed studies of clusters out to the highest presently known redshifts. For example the characteristic size of cool cores ~100kpc never gets smaller than 12 arc sec at any redshift which is reasonably resolved with SAHARA and the virial radius of a massive cluster at z=1 is 250 arc sec, fully encompassed within the SAHARA field of view. SAHARA will be able to measure the Fe properties of clusters via both the Fe L and Fe K bands. For a 6.5 keV plasma SAHARA gets roughly equal uncertainty in the Fe abundance from the L and K shell lines and so will be able to determine the spectral parameters of clusters over the full range of their masses, temperatures and evolution with the spatial resolution necessary to obtain the chemical abundance, turbulent structure, dynamics of mergers and the nature of feedback. The collecting area of Sahara is adequate to obtain such data in moderate exposure times of a few 10^5 sec.

What happens close to a black hole?

X-ray spectroscopy and timing have been crucial for understanding the physics of material close to the event horizon of a black hole and in measuring their spin. The X-ray band contains the only spectral features in any wavelength band originating within 30 Schwarzschild radii and the time variations in these features holds the clues to the processes happening in the regions of strong gravity.

Warm Absorbers, Reflectors and Emitters

The ubiquitous, high-velocity outflowing wind in Active Galactic Nuclei (AGN) is thought to be one of the critical components of feedback. Since most of the outflowing column density in AGN is only detected in the X-ray band, it is crucial to understand the X-ray phases of the outflow in order to account for their feedback effects Chandra grating observations of ~10 AGN have showed a suite of spectral features indicative of outflowing photoionized gas and it is thought this wind may be a major contributor to the feedback effects of AGN and are crucial features of the central regions near the black hole. However with a spectral resolution of R=500 at 1 keV and ~100cm^2 of effective area, exposures of >500ks are required to obtain the needed signal to noise for even the 10 brightest unabsorbed AGN. These features are the emission and absorption features associated with N, O, Ne, Mg and Si and thus are well matched to the SAHARA energy band.

With an order of magnitude or more collecting area and similar (at E>1 keV) spectral resolution to the Chandra and XMM gratings, SAHARA will be able to observe the ~300 objects which are 10× dimmer than the objects observed by Chandra in 10^6 sec exposures and thus obtain true samples of the wind phenomenon. Perhaps most importantly SAHARA will be able to examine the response of the absorption lines to changes in the continuum for the brightest ~30 sources and thus constrain the density of the absorbing gas and determine its distance from the central source, the total mechanical energy in the wind and the physical processes by which the wind is produced.

At E>2 keV where the important Si diagnostic lines are located the SAHARA collecting area will be 30x larger than Chandra, combined with 2-3× better spectral resolution. Si and Fe are unique in having a wide range of transitions corresponding to the full range of ionization seen in AGN winds. By covering both Fe L and Si (not possible with the XMM RGS) with 2-4× better resolution and 10x the collecting area of Astro-H SAHARA will be breaking fundamentally new ground.

Strong Gravity around Black Holes

While traditionally the physics of strong gravity in AGN has been examined by studying the 6.4 keV Fe fluorescent complex, recently[2,3] similar phenomena have been found using the Fe L shell complex at E~1 keV in a few objects, establishing a new venue for exploration of the innermost regions near the black hole. While the physics of generating this line is not as well understood as that for Fe K it is thought to be due to partially ionized reflection off the inner accretion disc. The parameters required to fit the Fe L complex are very similar to those that fit the Fe K band, solidifying the case. Because there are many more photons at Fe L than at Fe K (roughly 40× more in the case of the two best studied objects H0707 and IRAS1334) it is, for those objects which show this feature, much easier to perform reverberation and dynamical analysis in the soft band of SAHARA than in the Fe K band. The prime mission requirements here are a large collecting area near 1 keV in the rest frame to examine the time dependence of the emission. While it may seem overkill to have high spectral resolution for relativistic broad lines the existence of ionized absorbers in the line of sight to many AGN complicates the situation greatly for low resolution spectrometers and high resolution is required to confirm that the broad features are indeed due to emission and not the result of complex absorption.

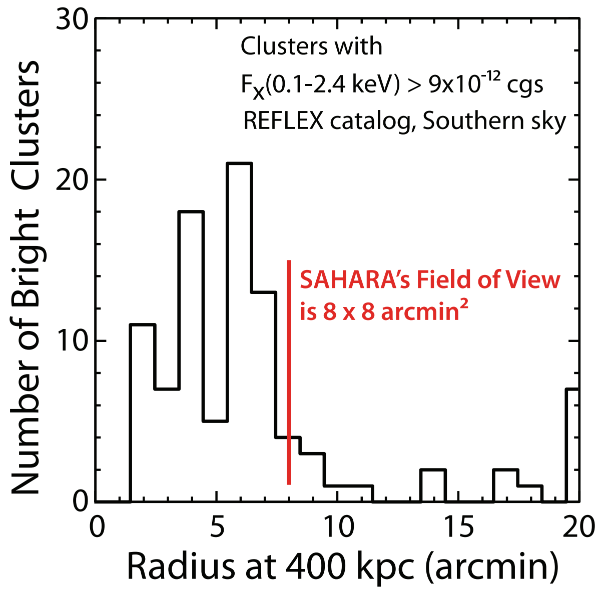

Figure 3. The radius at ~1/3 r_{500} for 100 nearby, bright clusters from the REFLEX catalog.

When and how did SMBH grow?

SAHARA's large collecting area and reasonable field of view will result in quite a few serendipitous sources in the field of view which will enable the study of the evolution of high z AGN and a search for AGN-driven winds in high redshift objects. With a requirement for ~20cts per 2 eV bin to detect absorption lines SAHARA can detect absorption line equivalent widths of ~5 eV in sources of flux 10^{-14} cgs in 10^5 sec exposures at more than 6σ. At that flux limit there are ~300 sources per sq degree or ~5 per SAHARA FOV. The 5 arc sec PSF and pixel size minimize source confusion. The median redshift at this flux is ~1.0 with some sources out to z~2. Thus during the

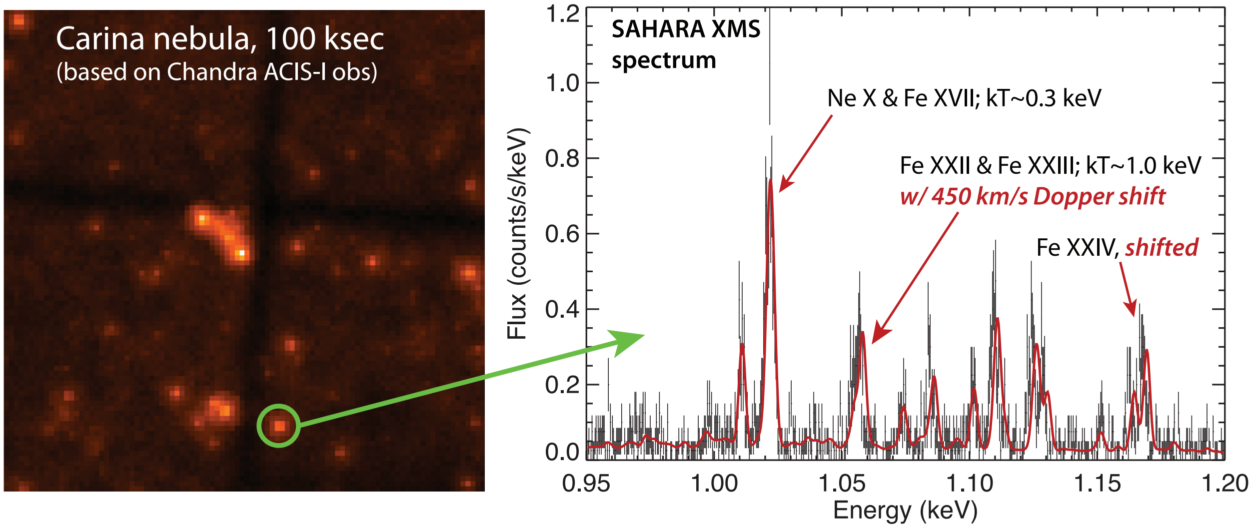

Figure 4. SAHARA XMS simulation of an 8x8 sq. arc min field from the Carina nebula, based on a Chandra ACIS-I observation (the tilted cross visible in the image is the residual of the ACIS-I detectors). Many individual stars are resolved, and a sample spectrum shows how a corona with a hot outflowing wind would be easily detected in a 100 ksec observation, even over a narrow energy range.

SAHARA mission we will obtain ~500 serendipitous source spectra per year assuming a median exposure of 2x10^5 sec. This would be the first unbiased search for AGN winds during the epoch when black holes were growing rapidly and constrain the environment of the most rapidly growing black holes. SAHARA will also be able to perform targeted searches for high-redshift black holes, with its lower effective area relative to IXO offset by an expected four times lower particle background due to the low Earth orbit, while SAHARA maintains the 5 arc sec PSF requirement. We expect to be able to observe SMBH in targeted searches out to z=6 in 1 Msec observations.

NWNH Science Enabled by SAHARA

SAHARA will be a general-purpose observatory In addition to accomplishing a significant fraction of the IXO science objectives, it will also return information about other specific topics highlighted by the NWNH report, including stellar formation and death, the creation and dispersal of elements via supernovae and stellar winds, and how stellar rotation and magnetic fields impact their coronae.

How do stars form and die?

SAHARA has the angular resolution and wide field of view necessary to resolve both star-forming regions. Figure 4 shows how SAHARA will reveal the influence of stars on their local environment via measurements of their coronal activity and stellar winds. This influence also includes their effect on habitable zones as well as on planet formation. Observations of star-forming regions have shown that X-rays from stellar flares irradiate protoplanetary disks, changing the ion-molecular chemistry as well as inducing disk turbulence. While Chandra has detected a few immense flares, the most significant impact on the protoplanetary disk is in the integrated output of the smaller flares, which can only be characterized using a mission with both substantial area and spatial resolving power.

Stellar rotation and magnetic fields

The origin of the solar corona, as well as the general problem of generating coronae in late-type stars, remains a mystery. Solar observations have shown that magnetic reconnection events rapidly vary the composition, temperature, and bulk velocities in the coronae. Chandra and XMM grating spectra have only been able to probe these processes on the brightest nearby stars. Stellar flares can quickly (in 100-1000 sec) eject significant masses, but as their bulk velocities are not known the total energy involved remains uncertain. The velocities associated with these bulk flows are of the order of 100-400 km/s, accessible with the SAHARA XMS for thousands of stellar sources observed with ROSAT with $F_X \sim 10^{-12}$ cgs.

These fainter, less active stars will have smaller magnetic field filling factors than the brighter stars observed to date, so SAHARA's observations will be sensitive to any non-linear scaling that is currently unobservable. SAHARA's large effective

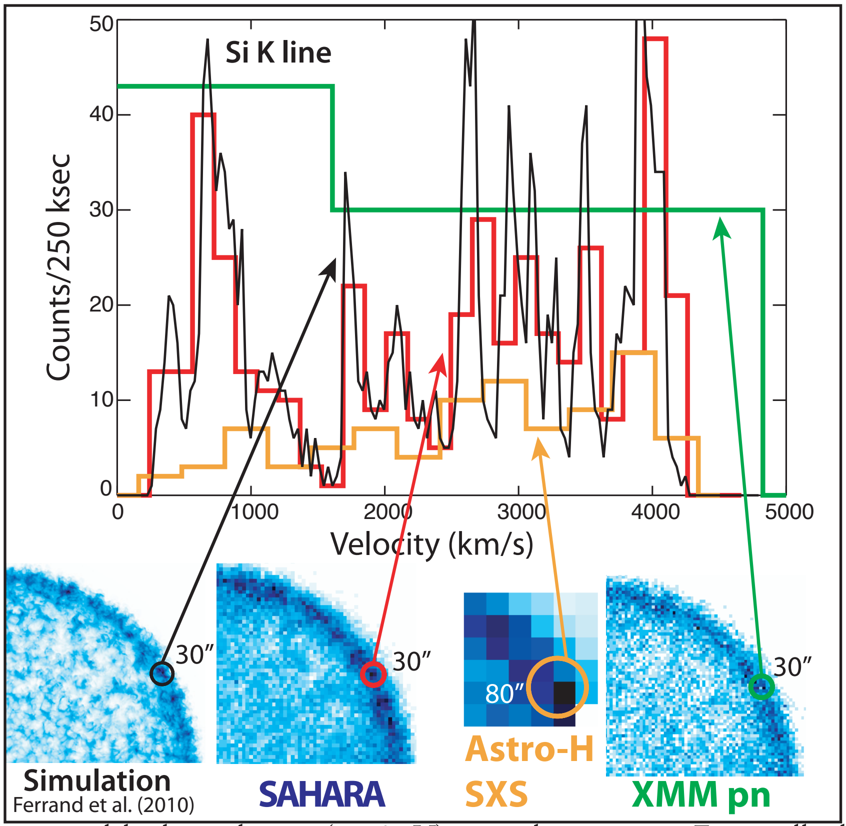

Figure 5. SAHARA XMS, XMM-Newton EPIC pn, and ASTRO-H SXS Si K images and velocity profiles based on a 3D hydrodynamical simulation[4] *of Tycho's supernova remnant (bottom left) are shown. The simulated velocity curve was extracted from the highlighted 'knot' of emission and is shown in black. Only SAHARA (red curve) has sufficient spectral resolution, sensitivity and imaging resolution to isolate the knot and retrieve the velocity information that will reveal the 3D dynamics of the supernova remnant, providing constraints on the explosion mechanism through the measurements of asymmetries. Together with accurate temperature measurements, the shock velocity will be used to quantify the supernova remnant's ability to accelerate cosmic rays.*

area and high-resolution (<1.5 eV) central array will be able to rapidly survey an unbiased sample of late-type stars with a range of rotation rates and magnetic fields, revealing how these parameters impact the creation and flaring of stellar coronae.

Supernovae and Supernova Remnants

Emission from gaseous remnants of supernovae seen with SAHARA will offer a comprehensive three-dimensional view of the ejecta composition and velocity structure, allowing detailed studies of nucleosynthesis models for individual explosions. Because the bulk of the SNR material, closely connected to the global hydrodynamics, is generally heated well above a million degrees the bulk of the emission in the X-ray band and X-ray data play a unique role in understanding the SNR. In the case of thermal emission the spectral fitting parameters, kT_e and $n_e t$, are closely related to the hydrodynamics and one can effectively constrain the kinematics. However direct observations of the spatially resolved kinematics are a key to understanding SN explosions. As shown in Figure 5, spatially resolved high resolution spectra allow a 3-D reconstruction of the shape of the SNR and provides indications of the physics involved in the formation of the detailed 2-D structure that is seen.

Essentially the complete IXO science for SNR (except the Fe K) bands can be done by SAHARA – the reduction in collecting area can be made up by longer exposures. The higher spectral resolution allowed by the smaller calorimeters will increase the level of plasma and velocity diagnostics.

SAHARA also has the ability to measure high quality spectra for the brightest 10-20 SNR in M31 and M33 as well as all of the LMC and SMC SNR extending the diagnostics achieved for 2 SNR in the LMC from Chandra and XMM.

How do galaxies and the IGM interact?

With the exception of ~5 elliptical and spiral galaxies with XMM RGS spectra there exist no high spectral resolution observations of the diffuse emission in galaxies and there are none of the point sources in nearby galaxies (except for the nuclear AGN). Even this small number of observations has shown puzzles, as some seem to show the existence of spectral features associated with charge exchange, which can only be distinguished with high spectral resolution. If correct, these features are a direct measure of mass motion and winds in these starburst galaxies and might be the signpost to galactic winds.

As an example of the power of such a mission, an Eddington-limited neutron star in M31 would produce ~1 cts/sec and thus a high quality high spectral resolution spectra can be obtained in exposures of <10^4 seconds, extending the spectroscopy of X-ray binaries to the local group.

Elliptical Galaxies The ISM in elliptical galaxies is hot, kT~1keV, and enriched in heavy elements, thus it superficially resembles the IGM in clusters. However its physical origin is thought to be very different and it represents only a fraction of the total baryonic budget of the galaxy. Because elliptical galaxies are thought to be very old and to have had very little star formation in the last 8 Gyrs, the metals in the ISM in these systems is probably dominated by stellar mass loss and type Ia supernova. Detailed X-ray spectra of these systems thus represents a unique opportunity to measure the metallicity of these old stellar systems as well as constrain the type Ia explosion and chemical production rate. In addition the ability to measure turbulence and mass motion in these systems (quite a few of which have luminous radio sources) will allow measurement of the effects of feedback on the galactic rather than cluster scale.

The X-ray bolometric luminosity of the low L_X ellipticals is dominated by point sources and the angular resolution of SAHARA is sufficient to separate the gas from the X-ray binaries, necessary to solve the mystery of why these objects have not retained their gas. Several ellipticals (e.g M84) show direct evidence for interaction between relativistic plasma and the hot X-ray emitting gas in a fashion similar to that seen in clusters, but at a vastly reduced scale and energetics. This is one of the drivers for our angular resolution.

Spiral Galaxies X-ray luminosity is dominated by X-ray binaries similar to that in the MilkyWay and their luminosity function and X-ray colors have been well studied by Chandra and XMM. For several nearby galaxies long XMM and Chandra exposures have produced CCD resolution X-ray spectra of these binaries. The brightest of the compact sources, the ultra-luminous X-ray sources have high quality CCD spectra, but so far have not shown any X-ray spectral emission or absorption features. One clear possibility is that the equivalent width of spectral features in these objects are very low and thus only visible with high resolution high S/N spectroscopy. Alternatively if the ULXs prove to be featureless they will provide excellent backlight to study the ISM of nearby galaxies in absorption. This will not be possible with Astro-H due to its relatively poor spatial resolution.

Serendipitous Galaxies & Clusters: At a flux level of 10^{-12} cgs, clusters of galaxies and normal galaxies are much less numerous, but represent ~10% of the population and thus during a 3 year SAHARA mission there will be numerous high resolution serendipitous such objects enabled by the short focal length of SAHARA.

3. MISSION REQUIREMENTS

SAHARA's well-defined and focused science objectives can be realized with a compact and small observatory. Table 2 lists the key parameters of the observatory, and Table 3 the mass, power, and data rate requirements. It consists of a spacecraft with an Optics Module containing the mirror assembly of 1.9 m in diameter with a 4 m focal length, and an Instrument Module with the calorimeter and associated electronics. The short focal length of the mirror assembly allows the entire observatory to fit inside a Taurus fairing with a fixed bench.

We have derived mission requirements from our present understanding of the spectral and spatial structures of clusters of galaxies, normal galaxies and supernova remnants, the three largest classes of extended X-ray sources. Because of their extended nature we have high spectral resolution (R>50) data for only for the cores of ~10 clusters (all from the XMM RGS). While Astro-H will be a breakthrough, its expected 90 arc sec angular resolution will not reveal any of the exciting struc-

Table 2: Essential SAHARA Performance Parameters

Parameter	Requirement (Goal)
Effective Area	3000 cm^2 @ 1.25 keV
Spectral Resolution	1.5 eV (0.5 eV) core, 3.0 eV (1.5 eV) inner array, 4 eV (2 eV) outer array
Angular Resolution	5 arc sec (3 arc sec) on axis, degrading to no worse than 10 arc sec at edge
Field of View	0.5x0.5 sq. arc min core, 2.5x2.5 sq arc min inner, 8x8 sq. arc min outer
Bandpass	0.2-3 keV; area above 3 keV desireable but not required.

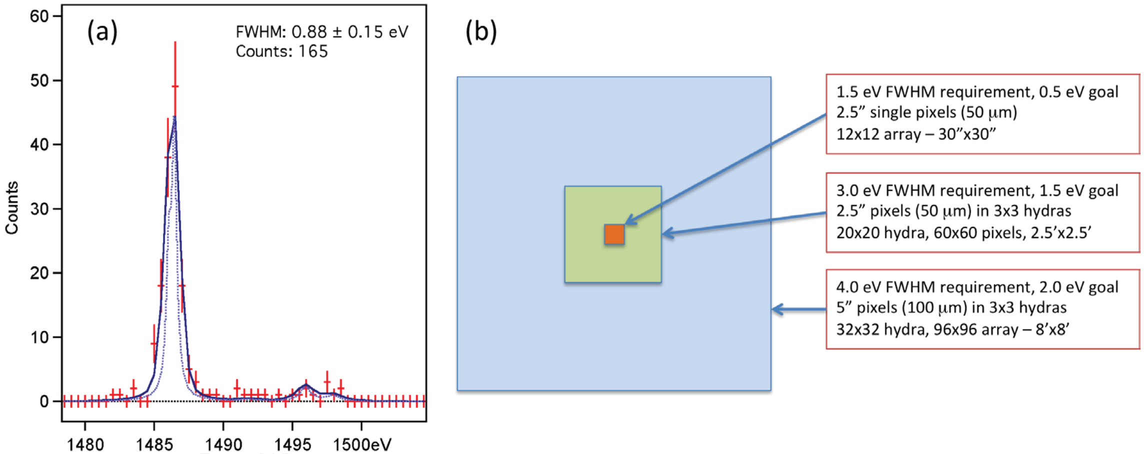

Figure 6. (a) Spectrum achieved with a 65 μm x 65 μm x 4.5 um pixel in a close-packed array measuring Al Kα X-rays. (b) The SAHARA focal plane array design and the requirements for each of the three regions.

ture seen in the Chandra images. To derive the mission properties to obtain high spectral resolution data on the required angular scales we have calculated the required exposure times to obtain more than 4000 counts/beam in the high central surface brightness central regions of ACCEPT clusters, sufficient to determine parameters such as turbulence, multi-temperature structure and abundances for thermal plasmas of kT< 3 keV.

Telescope Optics

A mirror assembly meeting the effective area, PSF, and bandpass requirements described above can be constructed using the segmented glass mirror technology that has been under development for IXO in the last decade. This mirror assembly, because of its shorter focal length (4m vs. IXO's 20m), is significantly simpler and lighter than IXO's. The simplicity manifests itself in several ways. First, in contrast to IXO's 360 shells, this assembly only has 93, reducing the number of forming mandrels required by nearly a factor of 4. Second, the inter-shell spacing is much larger than that of IXO, affording more space for more precise alignment and bonding. Third, the short focal length makes it much easier to construct vertical alignment facilities that are essential for minimizing the distortion of thin mirror segments caused by gravity.

As of October 2011, we have been able to consistently make mirror substrates at 6.5 arc sec HPD level, with the best substrates at 3.9 arc sec. The latter meet the requirements derived from the SAHARA error budget for a 5 arc sec HPD telescope. We have been able to consistently align and bond pairs of mirror segments and achieve better than 10 arc sec HPD X-ray images repeatedly. The mirror alignment and bonding work continues to improve in all aspects, such as reduction of alignment and bonding error, and achieving long term stability. We expect to be able to reach TRL-5 by the end of 2012 for building 10 arc sec telescopes and TRL-4 for building 5 arc sec telescopes. With reasonable funding, we expect this technology to reach TRL-5 for building 5 arc sec telescopes in the 2013/2014 time-frame.

X-ray Microcalorimeter Spectrometer

The scientific requirements for the SAHARA microcalorimeter instrument have led us to

Table 3: Technical Resources Summary

Component	Mass (kg)	Power (W)	Key Performance Parameters	Heritage
S/C bus, incl. optical bench	400	TBD; need MDL run	Pointing: 3" control, 0.5" post-facto reconstruction	ROSAT
XMS	259	920 avg, 947 peak, 843 standby, 488 safe-hold	2 eV @ 1keV FWHM, 2.5" pixel, 8' FOV	Astro-H
Mirror Assembly	240	300	Focal length: 4m, Diameter: 1.9m, PSF: 5" HPD, 3" HPD goal	NuSTAR

Average data rate estimated to be 68 kbps, with peak of 272 kpbs.

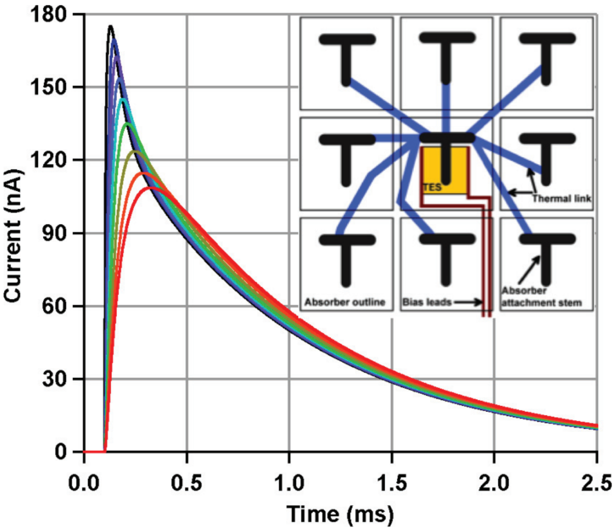

Figure 7. Simulated 9-pixel Hydra pulse shapes for a photon energy of 100eV. Inset: Schematic of the Hydra concept, showing nine absorbers each with a different thermal conductance to a single TES. Each absorber is supported above the TES and solid substrate using small stem contact regions.

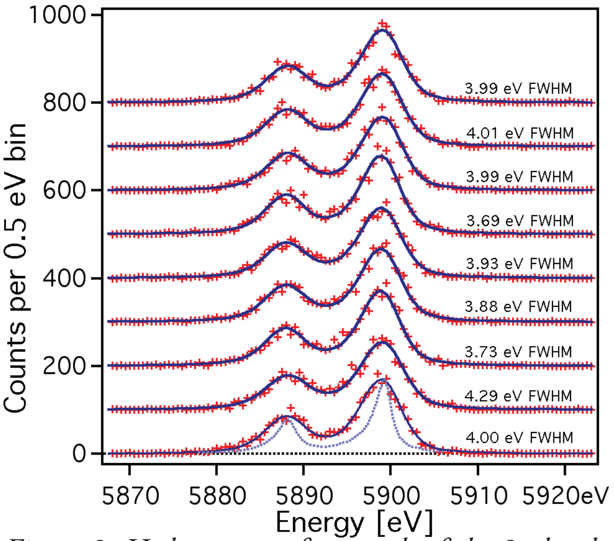

Figure 8. Hydra spectra from each of the 9 absorbers attached to a single TES from a source of MnKα X-rays. The light blue dashed line gives the intrinsic linewidth of the X-ray lines. The dark blue solid lines are fits to the data assuming Gaussian broadening consistent with the detector energy resolutions shown for each absorber.

a strawman design that has 2.5 arc sec (50 μm) pixels in its central 2.5x2.5 sq arc min core region and an extended region of 5 arc sec pixels out to an 8x8 sq arc min FOV. This plate scale is well-matched to the baseline angular resolution of the optic of 5 arc sec, and is acceptable for a 3 arc sec angular resolution optic with the use of dithering. The larger plate-scale outside of the 2.5 arc sec core is not considered detrimental because the count-rates per unit of solid angle in outer regions of the X-ray sources will require that larger pixels to have the required number of counts for the spectroscopy. The size of the field-of-view, similar to the Chandra ACIS-S3, will allow us to study most extended sources. We require excellent energy resolution of less than 2 eV (FWHM) at least in the central part of the array for energies between 0.2 and 3 keV.

Progress in small pixel transition edge sensor (TES) microcalorimeter designs originally developed for solar physics applications[5] have led to the development of 75 μm pixels with an energy resolution of 1.3 eV (FWHM) at 1.5 keV and 1.6 eV (FWHM) at 6 keV[6]. Some recent devices have been produced to take advantage of the lower count-rate requirement of SAHARA (typically less than 1 count-per-second per pixel), and preliminary results suggest that sub-eV energy resolution is achievable in the same size individual pixels. Figure 6(a) shows an Al Kα spectrum with relatively poor statistics that suggests this capability, where the baseline (theoretically achievable) energy resolution is 0.5 eV FWHM. These devices are optimized for energies below 2 keV, consistent with SAHARA requirements, but still obtain an energy resolution of ~4 eV at 6 keV. The slower pixel speed of these devices makes them easier to multiplex, and therefore allows us to baseline current state-of-the-art multiplexing capability rather than assuming improvements.

With 2.5 arc sec pixels, the field of view requirements leads us to use arrays of position sensitive microcalorimeters, known as “Hydras”[7,8]. In Hydras, a single TES is coupled to more than one discrete absorber, as depicted schematically in the insert of Figure 7. Each absorber element has a different thermal conductance to the sensor that results in position information being encoded in the pulse shape, as shown in Figure 7. This type of device has been successfully fabricated and tested in larger sizes for astrophysics. They perform as predicted and algorithms have been developed that allow identification of X-ray events down to less than 0.3 keV, with 9 absorbers attached to each TES[8].

As shown in Figure 6(b) our strawman array concept has (1) an inner core 30 arc sec region of individual 2.5 arc sec pixels in a 12x12 array. Surrounding this is (2) a 2.5 arc min region using

Table 4: Estimated WBS Costs

Description	WBS #	$M (FY12)	Notes
Management	1,2,3	72	18% wrap
Science	4	46	
Optics	5	135	
XMS	5	133	
S/C	6	130	
Ops	7	16	
LV	8	50	Taurus
GDS	9	12	
MSI&T	10	28	7% wrap
EPO	11	6	1% wrap
Total, no reserves		627	
Reserves		166	30% excl. LV, GO, EPO
Grand Total		793	
(GO Program)		(18)	
Science program includes GO and mission science and support by SOC teams.			

3x3 Hydras of 2.5 arc sec pixels in a 20x20 array of TESs. The outer region (3) extends the FOV to 8 arc min using 3x3 Hydras of 5 arc sec pixels in a 32x32 array, minus the area taken by region (2). Region (1) has a requirement 1.5 eV with a 0.5 eV goal; region (2) a requirement of 3.0 eV with a 1.5 eV goal; and region (3) a requirement of 4.0 eV with a 2 eV goal. This design is minimizes the number of read-out electronics channels to keep cost and complexity low, while still meeting all the mission requirements. With only 1344 TESs to be read out (40% lower than IXO/AXSIO), we will have approximately 12k pixels read out but much larger solid angle.

Preliminary data with spectra from a single 3x3 Hydra on a solid substrate that is close-packed in an 8x8 array of Hydras is shown in Figure 8. Each of the nine absorbers is 65 μm x 65 μm x 4.5 μm on a 75 μm pitch, and so has a heat capacity that is almost the same as those baselined for the Sahara outer array. The baseline resolution is ~ 3.0 eV, and the observed energy resolution is ~ 4.0 eV (FWHM_, and thus already meets the Sahara outer array requirements. The cause for the broadening from 3 eV to 4 eV is not fundamental and is understood.

The SAHARA microcalorimeter instrument is composed of a cryostat that houses an X-ray microcalorimeter array that it cools to 50 mK, and the electronics for the detector read-out and for controlling the cooler. Since SAHARA is being baselined as a class C mission, a cryostat design that has less cryocooler redundancy than AXSIO is considered acceptable. Only two models (one flight and one qualification) are necessary, as is the case for Astro-H. We have maintained the use of redundant cryocooler drive electronics – thus keeping a high instrument reliability. The cost of such a cryostat is 40% lower than for AXSIO. Even though our microcalorimeter array design has three distinct regions, they can all be fabricated together on the same silicon substrate. Thus the focal plane assembly is somewhat simpler (and therefore cheaper) than for AXSIO, which requires two separate detector substrates (as well as an anti-coincident detector for both SAHARA and AXSIO). We estimate that the cost of this XMS is approximately $40M less than for the AXSIO XMS design.

The TRL of the microcalorimeter components range from 3 to 5. The cooling design is based upon Astro-H and therefore is currently at TRL-5. The SQUID multiplexer read-out requirements of SAHARA are the same as for AXSIO. The detector design is currently at TRL-4, but development of this type of detector design for solar physics applications are likely to bring the TRL to 5 by the end of 2013.

Mission Cost & Development

We have not yet enlisted the help of any industry partners for SAHARA, and therefore have no detailed spacecraft or mission design. SAHARA would greatly benefit from the opportunity to use the NASA Mission Design Lab, both to better estimate costs and to understand other spacecraft issues such as pointing stability, focus requirements, the level of redundancy required, and other similar issues. We also note that many opportunities exist, not described here, for international contribution to SAHARA.

With these caveats, Table 4 shows our estimated costs by WBS. These are based on values from the optics and XMS teams, which are themselves based on substantial experience and costing exercises done for IXO. Our other cost estimates are either scaled wrap factors or are based on other similar missions. We include 30% reserves on all elements excepting the launch vehicle, EPO and funded GO science program. Our estimate of $793M, including all reserves, positions SAHARA as a medium-class mission in the context of the RFI.

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Additional references detailing the science and instrumention discussed in this response are available upon request.