Science with XMM: Overview and Comparisons with other Missions

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1. Introduction

XMM has the observational capability to push the frontiers of what we know and to explore vast new areas of science, thus a summary of its scientific capabilities is necessarily broad brush and missing many important points. In this overview I will stress what XMM is, in my opinion best at, and how it compares to the two other major missions of the next few years, AXAF and Astro-E. All three of these observatories are complementary and each has special features and properties. Of course, some of the scientific possibilities of XMM are included in the PV program − however with tens of thousands of possible targets this can only be a small fraction of what is possible.

There are six broad-brush scientific areas in which one can categorize the science possible with XMM: surveys, the nature and evolution of the AGN central engine, stellar physics, end-points of stellar evolution, supernova remnants and clusters of Galaxies. In this talk I will take two areas of science (clusters of galaxies and cosmology, active galaxies) and illustrate were XMM is best and where the other missions have superior features.

2. Top Level Summary of XMM, AXAF and ASTRO-E

XMM is optimized for large collecting area over a broad band pass ($0.1 - 14$ keV), good spatial resolution, a large FOV, good spectral resolution for both small extended and point-like sources ($0.3 - 2$ keV), simultaneous optical imaging and timing, simultaneous operation of all the instruments and long uninterrupted observations. AXAF is optimized for high spatial resolution, high spectral resolution for point sources from $0.1 - 9$ keV with moderate collecting area, long uninterrupted observations, and no X-ray stray light. Astro-E is optimized for large collecting area ($\sim \frac{3}{4}$ of XMM), broad band pass ($0.3 - 200$ keV), good spectral resolution for extended and point-like sources ($0.3 - 10$ keV), sensitive $E > 10$ keV spectroscopy, and simultaneous operation of all the instruments.

AXAF has lower collecting area than XMM or Astro-E (Figure 1), but no stray-light contamination and the point spread function (PSF) has essentially no wings. Its PSF is 10 times sharper than XMM and 100 times sharper than Astro-E but has substantially smaller collecting area than either. Because of its sharp PSF, AXAF is never confusion limited even for exposures of 10^6 s. It has a $17' \times 17'$ FOV, which is smaller than XMM but similar to Astro-E. The AXAF gratings (LETG for low energies and HETG for high energies) have a broader bandpass than

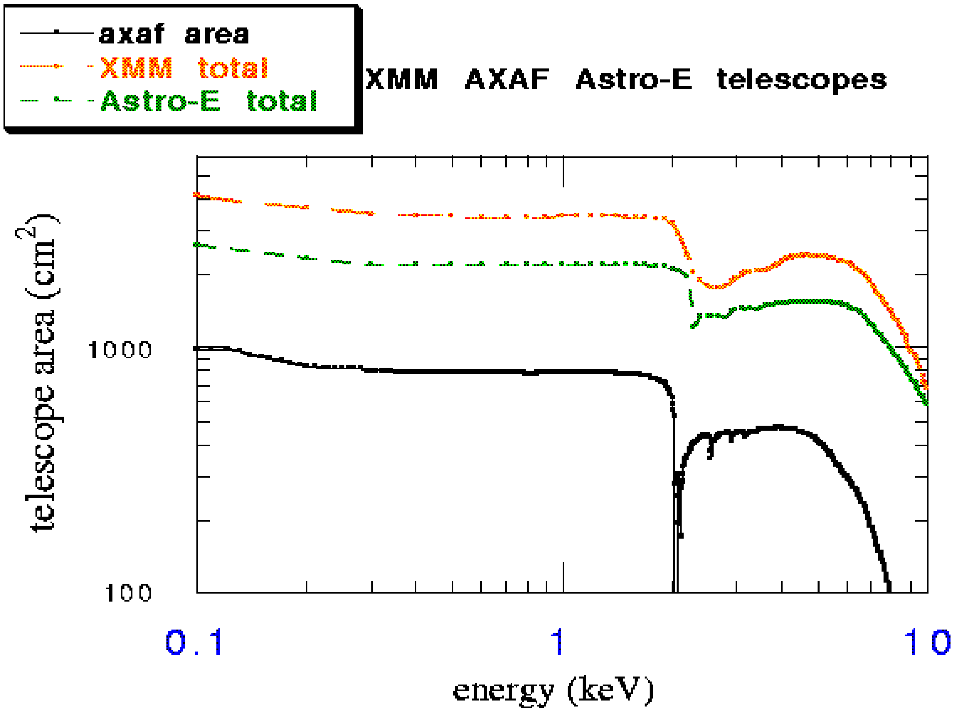

Fig. 1.— Comparison of the collecting area of the CCD telescopes for XMM, Astro-E and XMM. No correction for detector efficiency has been made.

XMM gratings but at $E < 1.5$ keV lower collecting area (Figure 2) and similar or better energy resolution (Figure 3). However because they are transmission gratings they can only observe "point-like" ($\Theta < 10''$) objects. The AXAF LETG gratings go to lower energy than the Astro-E calorimeter (XRS) or the XMM RGS. The AXAF detectors have many complex modes and only one instrument can be used at a time.

Astro-E has a large collecting area, but the poorest PSF of the three (but is still considerably better than ASCA) and a $16' \times 16'$ FOV similar to AXAF. The hard X-ray camera is expected to be considerably more sensitive than XTE or SAX in the $20 - 100$ keV band. The high spectral resolution instrument, the calorimeter, is the best of all the high resolution spectrometers (largest collecting area and resolution, Figures 2,3) at $E > 2$ keV and can observe extended sources ($\sim 4' \times 4'$ FOV) with full spectral resolution. However it has a low earth orbit and a ~ 2 year lifetime for the calorimeter. As with XMM, all three of Astro-E's instruments operate simultaneously.

XMM has the most collecting area for imaging with CCDs, but with its moderate PSF it may be confusion limited in exposures of greater than 10^5 s. Its $30'$ FOV is the largest of all three telescopes and the PSF does not degrade rapidly with off-axis angle. Because there is simultaneous operation of all the instruments, one obtains spectra and light curves from the optical monitor, CCD and grating spectrometer for all observations. As compared to AXAF, one can obtain good spectral resolution for small extended sources with the gratings. The gratings are optimized

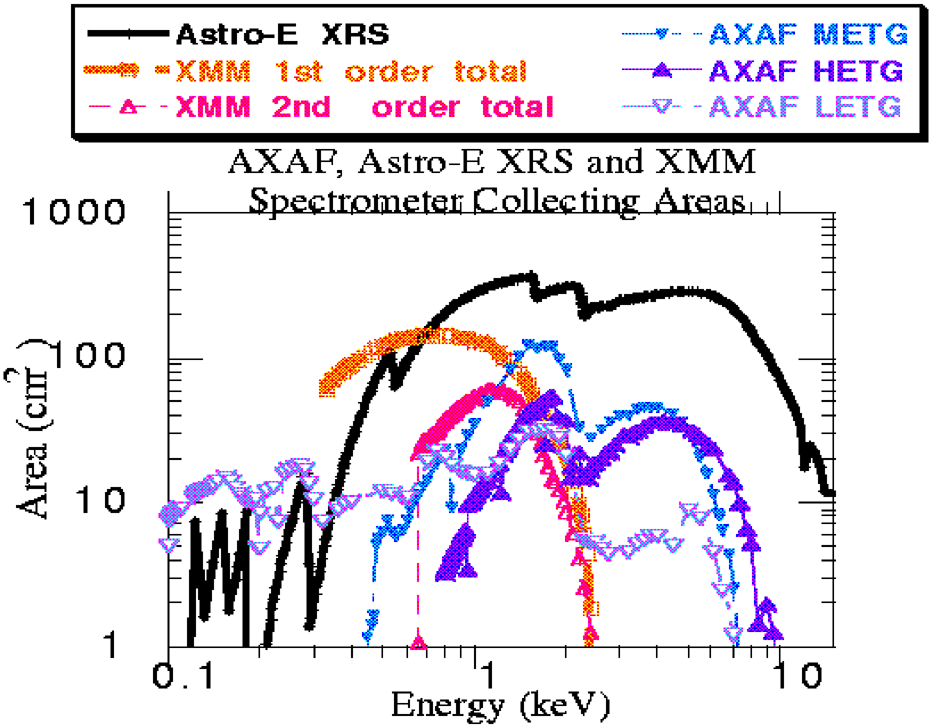

Fig. 2.— Comparison of collecting areas of the spectrometers on the three missions. On AXAF one gets the HETG and METG simultaneously while on XMM one gets the RGS first and second orders simultaneously.

for ∼ 1 keV where the spectra are very rich, primarily in Fe L lines. The combination of six instruments operating simultaneously means that there are many complex modes which have to be considered.

3. Science Background

The launch of the ASCA satellite has opened a new window on astrophysics: broad band, high throughput, moderate resolution, imaging X-ray spectroscopy. The initial results have been spectacular:

– the discovery of red shifted/blue shifted Fe, Si, S, and Ni lines in SS433,

– detailed spectral imaging diagnostics of SNR

– the determination of the shape of the Fe K line in AGN

– measurement of the abundances in clusters out to $z \sim 0.8$.

ASCA has confirmed that there are tens of thousands of objects which can be well studied

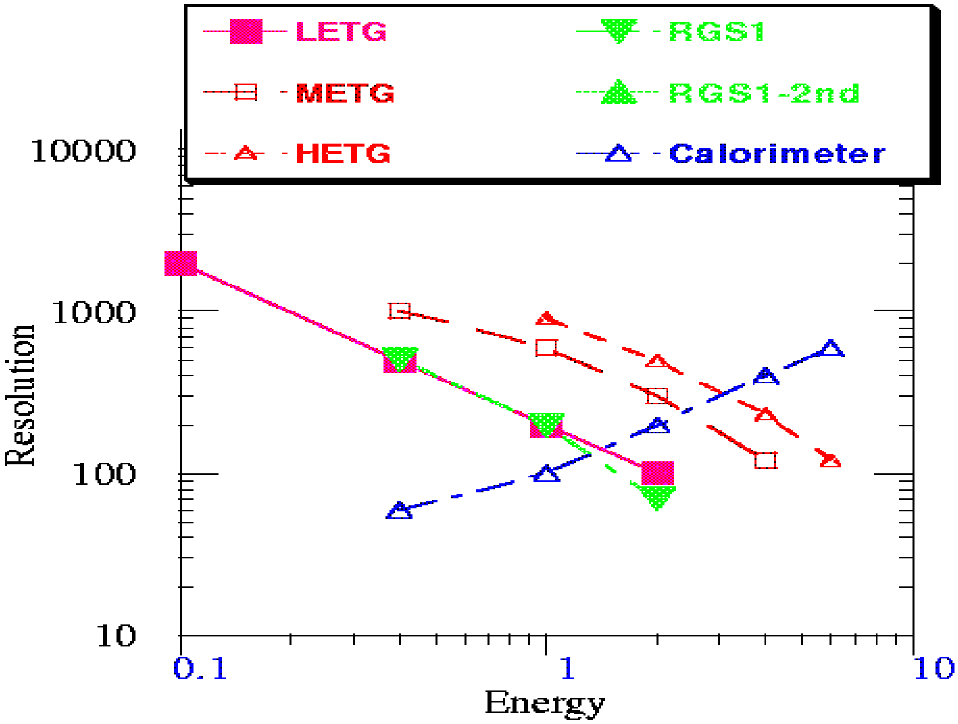

Fig. 3.— Comparison of the energy resolution of the spectrometers on XMM, AXAF and Astro-E.

spectrally with moderate spatial resolution and that large collecting area combined with good spectral resolution is the dominant requirement for further progress.

However this is a mere introduction to this extremely rich subject:

- The energy resolution of ASCA is far to low to obtain detailed ionization, temperature or mass motion diagnostics for most objects.
- The spatial resolution of 1.6′ is far too poor to obtain sufficient quality spectral images.
- The collecting area is too small to obtain good quality spectra for sources dimmer than 3×10^{-12} ergs cm^{-2} s^{-1}.

The next giant step requires high resolution, broad band, high throughput, X-ray spectroscopy combined with high throughput moderate spatial resolution X-ray imaging, which is the basic design premise behind XMM. The inclusion of the optical monitor provides a totally new window on astrophysics Multiwavelength simultaneous observations ($\lambda\lambda\lambda$) which promises to provide dramatic breakthroughs in our understanding of time variable objects.

One of the best ways to understand the different abilities of these missions is to take a limited area of science and examine the pluses and minuses of each mission in the context of a given observing program. The obvious choice in this regard is the XMM GTO program. For example for clusters of galaxies the XMM GTO program has: (in italics are the important instrumental parameters, science areas where XMM is the best mission are indicated with an "*").

Observations of "Known" science:

A. Science which primarily needs *large collecting area, broad band pass, good spatial resolution*:
1*) Derive the mass and mass distribution of all types of virialized systems with $10^{12} < M < 10^{15}$ via temperature profiles out to the virial radius.
2*) Determine the metallicity distribution of all virialized systems
3) Derive the Hubble constant via measurement of the temperature profile for a set of clusters which have radio Sunyaev-Zeldovich effect images. The relative advantage of XMM compared to AXAF is the shorter exposure time required for $z < 0.3$ clusters. The AXAF advantage is the higher angular resolution which allows higher redshift objects to be studied.
4) Observations of clusters with strong/weak lensing, Here the better AXAF spatial resolution is a major advantage because of the small angular scale of strong lensing.
5*) Measurement of the mass spectrum of clusters as a function of redshift.
6*) Measurement of the star formation rate in clusters with UV measurements with OM.

B. Science which also needs a *large FOV*:
1*) The detailed study of merging clusters at $z < 0.2$. What is required is measurement of the spatial/spectral structure and searching for the merger shock. The ability of the Astro-E calorimeter to observe velocity structure could be a major advantage here, but the small FOV is a serious disadvantage.
2*) Derive cluster parameters out to the virial radius. At $z < 0.1$, the virial radius is roughly $18'(z/0.1)(T/8 \text{ keV})^{0.5}$. Thus for clusters as hot as 8 keV at $z > 0.1$ their virial radius is contained completely in the EPIC field of view.

C. Science which primarily needs *large collecting area, broad band pass, good spectral resolution*:
1) Cooling flows. Study of the thermal structure of the cooling flow regions at moderate to high z and the "extra" absorption effect. Here the better spectral resolution of the Astro-E XRS for extended sources compared to the XMM RGS and the AXAF gratings and the better angular resolution of the AXAF are very important. However the better low energy response of the XMM EPIC is also an important consideration.
2*) Abundance and temperature profiles of high z clusters.
3*) A search for moderately high z $(1 - 1.5)$ clusters with wide field "deep" surveys
4*) Measurement of the evolution of cluster metallicity out to $z \sim 1.3$

Observation of "New" science

A. Search for clusters around high z quasars and radio sources (trade off AXAF PSF vs. XMM's collecting area and bandpass)

B.* Search for X-ray emission from superclusters and the intergalactic medium

Where will AXAF and/or Astro-E make improvements and additions? The direct AXAF CCD imaging of cooling flows at $z > 0.05$ will appreciably improve the ability to model these systems. Since a "characteristic" cooling radius for high cooling rate cooling flows is ~ 100 kpc they are fully resolved by XMM at $z > 0.25$. The Astro-E calorimeter observations of low z CFs will give high quality spectra with lots of spectral diagnostics. While it is possible that the XMM RGS can provide similar information, the deconvolution of the spatial/spectral domain will be complex. For distant cluster surveys, AXAF will always recognize an extended source at any redshift thus making identification as a cluster simple. XMM will be able to "recognize" clusters out to at least $z \sim 1.3$ and perhaps larger. For the physics of cluster mergers, Astro-E will measure the velocity field of the gas and AXAF will recognize mergers at all redshifts and be able to provide spatially resolved spectra.

As one can easily see even for a field as "simple" as cluster research, the tradeoffs and comparisons are difficult and complex.

In other areas of astrophysics, e.g., AGN (and stellar research) the main emphasis (I believe) will be on high spectral resolution studies, time resolved spectroscopy and multiwavelength campaigns. I will not talk about supernova remnants, "normal" galaxies or other extended sources, but the relative advantages and disadvantages of the missions are similar for them as for clusters.

For these point sources we have four "spectral" domains:

1) Fe K line emission and emission plus absorption of highly ionized hot plasmas ($T > 2 \times 10^7$ K): especially detailed studies of large samples, line shape and flux variations.

This is important for studies of the innermost regions of AGN. The XRS on ASTRO-E is the best instrument for these types of studies. The XMM and Astro-E CCDs with their large collecting area can do reverberation analysis for $5 - 20$ objects – that is, they can measure the response of the Fe-K line to changes in the continuum, and this provides a direct measure of the geometry of the central regions of black holes. The calorimeter on Astro-E can determine the "true" line shape and provide detailed plasma diagnostics for He-like Fe for a wide variety of sources. The AXAF gratings have small area, and poorer resolution at Fe-K but are rather useful for studies of X-ray binaries where the calorimeter suffers from pulse pile-up.

2) Plasmas of effective temperature $T \sim 0.4 - 2 \times 10^7$ K and photoionized plasmas with line rich spectra (both emission and absorption).

For objects in this temperature/ionization range, their spectra are very rich in emission/absorption lines with energies from $0.6 - 1.6$ keV, especially Fe L, O, Ne, and Mg. The XMM grating has the best figure of merit (combination of area and resolution) for plasma diagnostics in this energy range and its large collecting area will allow time resolved spectroscopy of large numbers of objects. While the calorimeter has more bandpass and area, its energy resolution is considerably poorer at the relevant energies and thus detailed plasmas diagnostics, especially of the oxygen lines, may not be possible. While the AXAF collecting area is less (except for the $1.3-2$ keV band), the energy resolution is very good. Thus, except for detailed studies of bright point-like sources (bright stars and X-ray binaries), the AXAF gratings will require long exposures. Since we do not yet know the full phase space of interesting science in this area, particularly that of photoionized plasmas, it is not year clear which is more important, energy resolution or collecting area.

3) Energies less than 0.5 keV. The main spectral features are due to photoionzation and plasmas less than $T \sim 3 \times 10^6$

In this regime the AXAF LETG has best resolution and collecting area. The XMM grating is comparable or better at $E > 0.4$ keV while the calorimeter has little or no effective area at $E < 0.3$ keV

4) The multi λ channel – only available to XMM

This is of course extremely important for variable sources (AGN, flare stars, X-ray binaries, CVs, etc.). However the ability to obtain optical/UV data for "free" is also important for serendipitous source studies, distant clusters, supernova remnants, since so far (except for HST) very little archival optical data is available for analysis.

4. Timing

The combination of fast readout and collecting area make the XMM PN the best system for timing studies. All the other CCD cameras have one problem or another. The total counting rates from Astro-E and XMM are similar to that of XTE for unabsorbed spectra but they can look at sources 1,000 times dimmer. For bright sources and very faint sources the AXAF HRC maybe best for high time resolution, depending on the details of the source. Timing with the OM provides a unique channel for AGN, X-ray binaries, flare stars, CVs, etc. Also because of the way it is read out, the XMM RGS allows timing of spectral lines. The AXAF grating read-out makes this a rather complex data analysis problem and the XRS cannot observe bright sources.

5. Broad Band Spectroscopy

Astro-E (because of its hard X-ray detector) is best at high energies ($E > 9$ keV), which is especially important for highly absorbed objects (Sey II + some X-ray binaries) and very hot/non-thermal objects (shocks in SNR, inverse Compton radiation in clusters). At low energies the XMM PN because of its soft response and thin windows is best. This is important for ultra-soft sources, the soft components in AGN and timing analysis of stars. For general "CCD" spectral analysis of isolated sources and extended objects bigger than $15''$, XMM is best over the flux range from $3 \times 10^{-15} - 5 \times 10^{-11}$ ergs cm^{-2} s^{-1} (the full range of presently known objects) in the $0.2 - 9$ keV band. At lower fluxes confusion may be an issue and AXAF is best, however long exposures are necessary to obtain reasonable signal to noise. At higher fluxes XMM may have a serious pile-up problem, the situation is not clear yet for Astro-E but because of its large PSF it should be able to handle brighter sources. However the details have not yet been worked out.

Of course, the XMM-OM provides unique UV and optical data which enhances the broad XMM X-ray bandwidth, basically the whole of the optical-X-ray observable range (except from $100 - 1800$ $\mathring{A}$) is available.

6. Serendipitous Science

Many of the major results in X-ray astronomy in the last 25 years have been serendipitous in nature. In this regard XMM is best of the future missions because of its large FOV, large collecting area, the simultaneous operation of all of its instruments and its “good enough” PSF. XMM will provide, via serendipitous observations a major increase in all types of sources: In particular spectra and time variability studies of faint sources, catalogs of rare objects (e.g., high z clusters) and instantaneous optical data for new sources. XMM goes deeper, faster over a wider energy range than any previous X-ray mission. This allows unique science to be done, not only for serendipitous surveys but also for spectral and temporal surveys of selected objects.

While AXAF’s high angular resolution opens up a new window, science at $< 10''$, it is not yet clear what will be seen. However AXAF’s ability to provide unique identification of sources with optical/radio counterparts should result in unexpected science and many of us expect exciting new discoveries in the realm of high angular resolution.

Astro-E is relatively weak in this area. The small XRS FOV and “poor” angular resolution of the CCDs preclude major advances in detecting unexpected objects. However the high throughput of the XRS will allow many unexpected discoveries in the spectral domain.

7. “High” Spectral Resolution Spectroscopy

Each of the missions has a unique niche. XMM is best in the line rich $0.6 - 1.5$ keV band for line detection and plasma diagnostics, and for spectroscopy of small extended sources (such as LMC supernova remnants). AXAF is best at $E < 0.5$ keV and in the $1.5 - 2.0$ keV band where Mg, Si, and S lines are strong. It also has the highest resolution for low temperature plasmas. Astro-E has the highest collecting areas at all energies and the best resolution at $E > 2$ keV combined with the ability to study extended sources of any size and is best for FeK, S, Ca, Ar, and Ni lines from all sources.

8. What sort of Science will come out of the XMM PV Program?

A. Surveys

There are five deep surveys that will reach the confusion level of XMM and six medium deep surveys that will be factors of $2 - 3$ more sensitive than the deepest ROSAT fields. Three of these fields also have deep AXAF pointings The combination of XMM and AXAF data will essentially solve the "problem" of the X-ray background by providing unique identifications, X-ray spectra and source counts in the energy range where the bulk of the X-ray background energy resides.

The increase in sensitivity and wide field of view of XMM are exploited in four large area surveys that will return many hundreds of faint X-ray sources with good quality spectra, providing the unique opportunity for characterizing the population of X-ray sources at moderate to large redshifts.

B. The nature and evolution of the AGN central engine

Our knowledge of X-ray and multiwavelength emission processes in AGN is based on the study of bright, nearby objects at low spectral resolution. With its large grasp, high spectral resolution and multiwavelength capability, XMM is ideally suited to extend these studies to fainter, higher redshift, higher luminosity systems and provide detailed studies of the brighter low redshift objects.

The XMM programs aim to build up a complete picture of the multiwavelength spectrum of active galaxies as a function of redshift, type and luminosity probing the evolution of quasars over the lifetime of the Universe. The structure of the central engine in Seyfert galaxies will be examined via observations of their multiwavelength spectral properties and time dependent spectral signatures. The response of the Fe K line and the warm absorber to the changes in the input spectra will map the innermost portions of the accretion disk. There are three large spectral surveys of quasars and Seyfert galaxies to examine their evolution with cosmic time and survey the X-ray spectral properties as a function of optical spectral type.

C. Stellar physics

The GTO program has observations of isolated and binary massive stars as well as time dependent monitoring of rotating and binary stars and high quality RGS spectra of a wide variety of spectral types. The large number of high quality RGS spectra of coronal sources will provide the first model independent measures of the temperature structure in a star other than the sun and robust measurements of the abundances in stellar coronae. The large XMM FOV allows detailed study of open clusters and young stellar associations which will provide vital information on the evolution of angular momentum in late-type stars, the dependence of coronal activity upon mass and age and the relationship between star formation and the heating of the ISM.

D. End-points of stellar evolution

Cataclysmic variables and X-ray binaries provide a test-bed for development of accretion models, and also provide crucial constraints on the end-points of binary evolution. The GTO program contains a major and systematic survey of cataclysmic variables designed to measure the distribution of white-dwarf masses and detailed studies of a variety of accreting X-ray binaries. High quality spectral data from XMM will allow us to probe the luminosity, spectrum, temporal variability and geometric structure of the accretion flow, accretion disk and boundary layers over a wide range of accretion rates, magnetic fields and central source masses. The combination of the RGS, EPIC and the OM will result in the first broad band, high spectral and temporal studies of these objects and allow the first detailed modeling of the radiation transfer in these systems and detailed study of photoionized plasmas. XMM will allow the first detailed spectral and temporal studies of X-ray binaries in nearby galaxies (e.g., Figure 4).

E. Supernova remnants

XMM will obtain detailed spatially resolved characterization of the physical conditions in many supernova remnants covering all the characteristic temperature components and size scales in galactic SNR.

The high throughput allows unprecedented sensitivity for mapping the spatial structure of the line emitting regions and their relation to the optical and non-thermal radio morphology (Figure 5). Also, XMM has, in contrast to AXAF, the capability of performing dispersive high-resolution spectroscopy of plasma emission features up to a few arc minutes in size. In young SNRs grating observations of a variety of shock related bright emission features will trace the evolution of the important O, Fe-L and He-like Si-emission line complexes as a function of shock radius. The high spectral-resolution capability is well matched to the typical angular sizes of a substantial number of SNRs in the LMC (and a few in the SMC), enabling the disentanglement of prominent line complexes and the measurement of ionization structure and velocities. These science goals have resulted in a major observational campaign on LMC SNR and deep RGS observations of more than ten young SNR.

9. SUMMARY

I have, very briefly, demonstrated the scientific capabilities of XMM and compared them with Astro-E and AXAF. The next five years promises to be one of startling results in every area of high energy astrophysics and I fully expect a revolution in this field. XMM will make a major contribution and I hope that the next time that we meet we will have the opportunity to see this exciting science.

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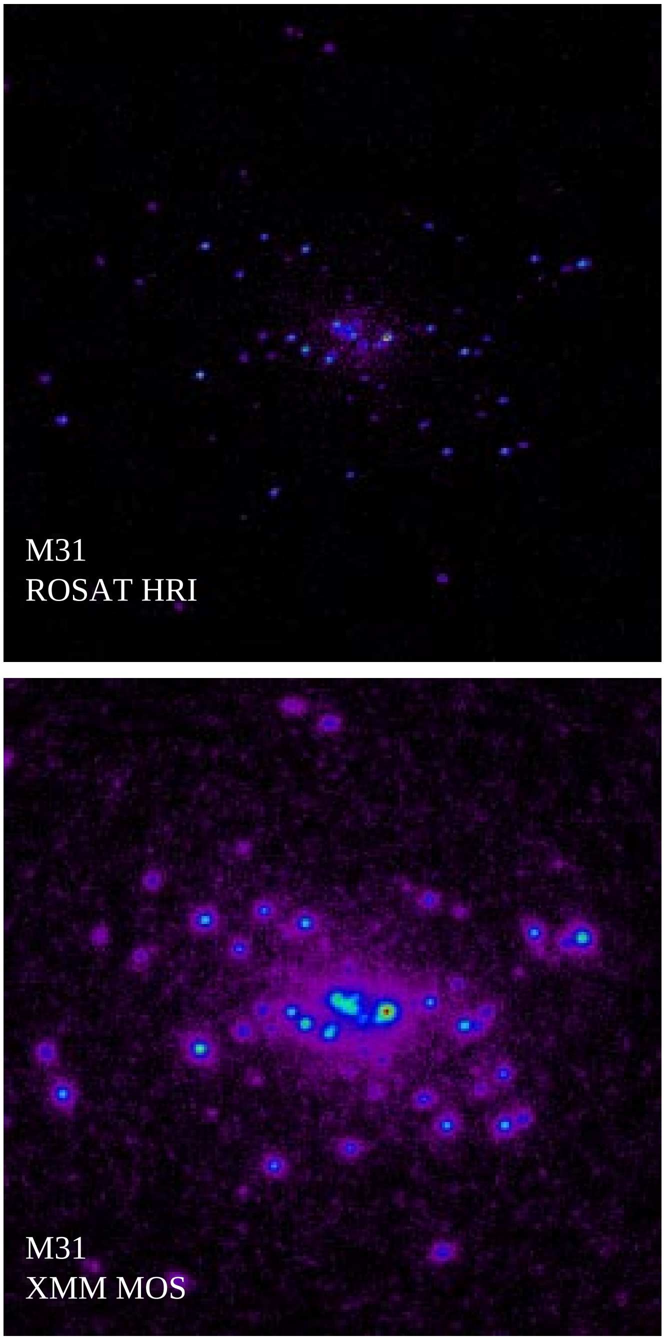

Fig. 4.— Simulation of a 30 ks XMM M31 observation based on a background subtracted 83 ks ROSAT HRI observation.

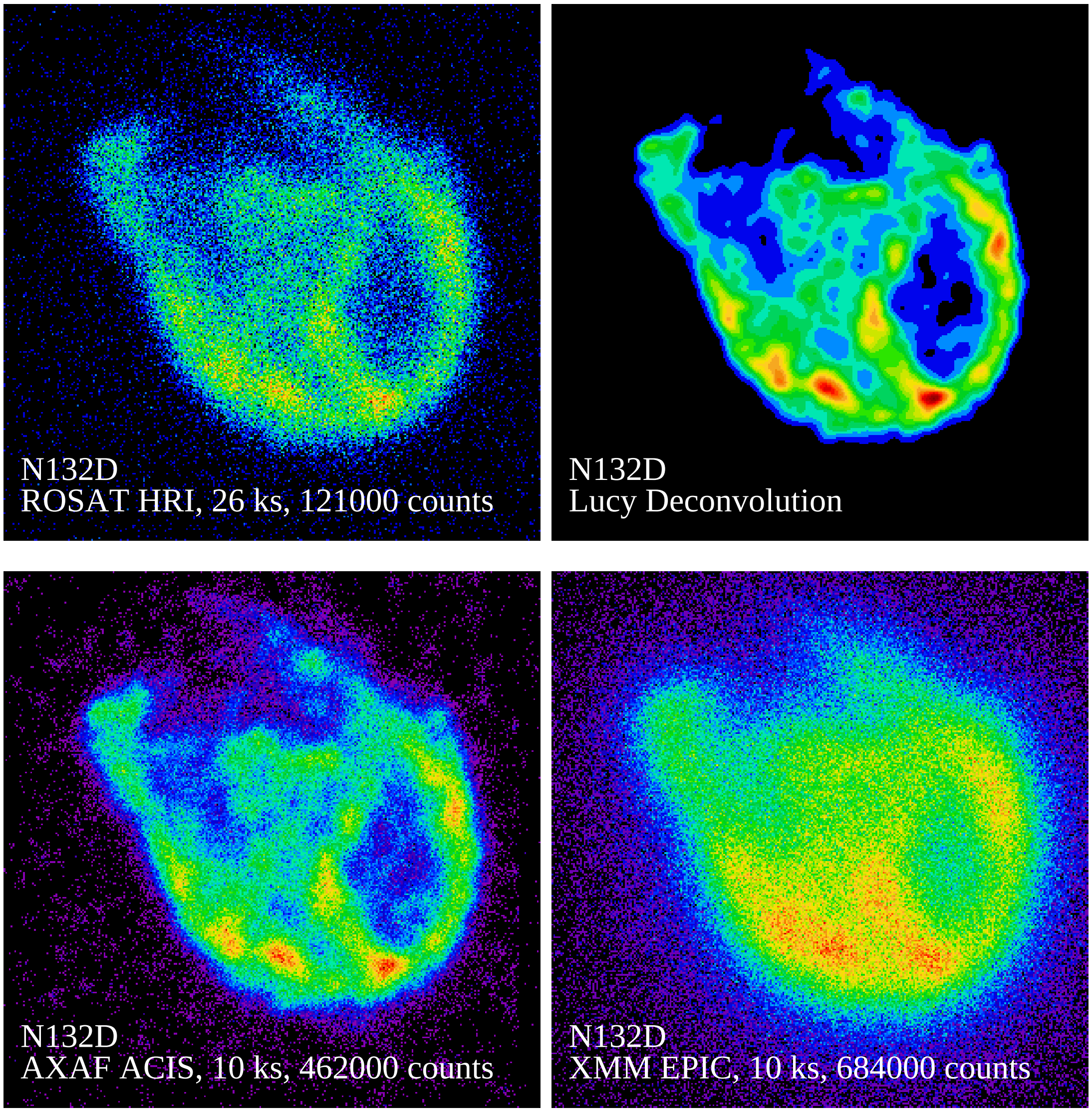

Fig. 5.— XMM and AXAF simulations of an observation of the LMC SNR N132D. The basis for the simulations is a Lucy deconvolution of a ROSAT HRI observation (courtesy of Dave Davis).