8. Future X-ray Observatories

COMMENTS ON THE FUTURE OBSERVATORIES AND THEIR X-RAY SPECTROSCOPY CAPABILITY

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ABSTRACT. Following a brief discussion of the possibilities offered by X-ray spectroscopy at various values of resolving power ($E/\Delta E$), the spectroscopic capabilities of a number of future missions are presented. The possible roles of Charge Coupled Devices (CCD's), Microcalorimeters, Diffraction Grating and Bragg Crystal Spectrometers are then evaluated.

1. INTRODUCTION

The power of high resolution X-ray spectroscopy has been amply demonstrated for studies of the high temperature plasma found in solar flares and active regions. For sources other than the Sun, the gas filled proportional counter detector with $E/\Delta E \sim 5$ at a photon energy of 7keV was used almost exclusively until the launch of the Einstein mission. This spacecraft included a non-dispersive solid state detector which offered high quantum efficiency and resolution some three times better than that of the proportional counter. In addition transmission grating and Bragg spectrometers, although of much lower throughput, obtained high resolution spectra of a number of important sources. These results have made it quite clear that, following the exploratory phases of the subject, it is now essential to continue high resolution spectroscopic observations.

Several missions, planned for the next decade, will include a spectroscopic capability. In the following sections, after a brief review of the role of high resolution spectroscopy in X-ray Astronomy, a number of these missions will be discussed. They include the moderate missions Spectrum-X, Astro-D and Spectrosat together with the two major observatories AXAF (NASA) and XMM (ESA). After a largely tabular presentation of the spectroscopic performance of these missions the role of non-dispersive (CCD's and microcalorimeters) and dispersive (grating and Bragg) spectrometers will be discussed.

2. X-RAY SPECTROSCOPY - POSSIBILITIES AND EXAMPLES

In this paper we will deal only with instruments having $E/\Delta E > 25$ at photon energies above 5keV. This will permit the discussion of non-dispersive systems such as solid state detectors or CCD's but will exclude a variety of gas-filled devices. This choice has been made given that with future missions, particularly those of observatory class, the subject will have passed the "discovery" phase and will require that spectroscopic techniques offer a range of diagnostic information about the sources being studied. The justification for this approach will become clear below.

2.1 Systems with $E/\Delta E < 10$

Proportional counters and, very narrowly, Gas Scintillation detectors fall in this category. While many discovery observations have been made with these systems (eg Cluster plasma, Mitchell et al, 1976),

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they offer the ability to do little more than detect the existence of emission features at E > 2keV. Such detections provide evidence for the presence of hot plasma and permit rough estimates of temperature and element abundance. Crude phase-related emission and absorption spectra have been obtained for the brighter X-ray binaries (Pravdo et al., 1979) while in addition to clusters of galaxies, emission features have been discovered in the spectra of AGN (Hayes et al., 1980) and stellar flares (White et al., 1986).

2.2 Systems with $10 < E/\Delta E < 100$

Solid state spectrometers and CCD's, together with the earlier examples of transmission grating and Bragg spectrometers can be included here. Detection and measurement of emission line intensities become possible for elements ranging from O to Ni. Temperature, emission measure and element abundances may be determined though in a model-dependent manner. Moderate resolution phase-related spectra may be obtained for binaries (McCray et al., 1982; Kahn et al., 1984) together with crude diagnostic data for extended sources such as clusters and supernova remnants (Canizares et al., 1979; Becker et al., 1979). Thus both thermal and photoionised plasma can be studied in emission and, more crudely, in absorption for a wide range of objects.

2.3 Systems with $100 < E/\Delta E < 1000$

In this energy range gratings, Bragg spectrometers and, in the future microcalorimeters, can be used to undertake model independent line ratio diagnostics. In addition the ionisation state of gas in the line of sight may be studied through both emisison and absorption spectroscopy. Thus detailed studies of both the interstellar medium and of a wide range of X-ray sources can be undertaken. A spectrum of Puppis A (Figure 1) obtained with the Einstein FPCS by Canizares et al., 1981, provides an excellent example of what can be achieved.

2.4 Systems with $E/\Delta E > 5000$

At present this kind of capability can only be provided by Bragg spectrometers and, so far, instruments with this performance have not been used to study X-ray sources other than the Sun. While all of the observations described in 2.3 could be better undertaken at this level of resolution, the available throughput will necessarily be much less than that of the microcalorimeter. However high resolution Bragg spectroscopy offers the only possiblity to measure line profiles and so to deduce both directed and turbulent plasma velocities at values less than $100 Kms^{-1}$. An example of solar flare data (Antonucci et al, 1986) is given in Figure 2.

3. FUTURE MISSIONS WITH SPECTROSCOPIC CAPABILITY

The missions may be considered under three headings and in each case a tabular summary of performance is presented. The sensitivities have been calculated for an observing time of either 10^5s or a time which would give rise to a figure five times better than the broad band confusion limited sensitivity - whichever is smaller. In all cases the sensitivity is calculated for a background limited (5σ) or photon limited (25 detected counts) situation.

3.1 Moderate Missions (see Table 1)

These include the USSR's Spectrum-X with West European X-ray telescopes, the Japanese ASTRO-D with US supplied CCD detectors and the German Spectrosat.

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TABLE 1 FUTURE MISSIONS WITH SPECTROSCOPIC CAPABILITY - MODERATE MISSIONS

MISSION/ INSTRUMENT	ANGULAR RESOLU-TION (arc sec)	FIELD OF VIEW (arc min)	SPECTRAL RESOLVING POWER (E/ΔE)	EFFECTIVE COLLECTING AREA (CM^2)	COMMENTS ON SENSITIVITY
SPECTRUM-X					
JET-X CCD (2 MODULES) (1993)	20``	20`	8 (.7 keV) 50 (7 keV)	250 (.7 keV) 130 (7 keV)	a) BROAD BAND SENS: 3.10^{-15} erg cm^{-2} s^{-1} (6.10^4s) b) MULTILAYER DIFFRACTOR: 1.10^{-5} hv cm^{-2} s^{-1} (10^5 s, 7keV, E / Δ E = 350) c) MIN DET LINE FLUX: 2.10^{-6} hv cm^{-2} s^{-1} (10^5s, 7keV)
ASTRO-D					
CCD (2 MODULES) (1993)	120``	30`	8 (.7keV) 50 (7keV)	450 (.7keV) 180 (7keV)	a) BROAD BAND SENS: 7.10^{-14} erg $cm^{-2}s^{-1}$ (2.10^3s) b) MIN DET LINE FLUX: 2.10^{-5} hv cm^{-2} s^{-1} (10^4s, 7keV)
SPECTROSAT					
LE TRANS-MISSION GRATING (WITH HRC) (1995)	2``	POINT SOURCES	50 (1keV) 160 (.28keV) 400 (.1keV)	15 (1keV) 35 (.28keV) 5 (.1keV)	a) SELECTED MIN DET LINE FLUXES: NE IX (.92keV); FE XVII (.73keV); O VII (.56keV); $1.5.10^{-5}$ hv cm^{-2} s^{-1} (10^5 s) -------------------- SI XII (.28keV); FE XVI (.25keV); FE XVI (.18keV); 7.10^{-6} hv cm^{-2} s^{-1} (10^5 s) -------------------- b) ALSO LOWER RESOLUTION SYSTEM WITH PSPC, E/ΔE ~ 1 - 100

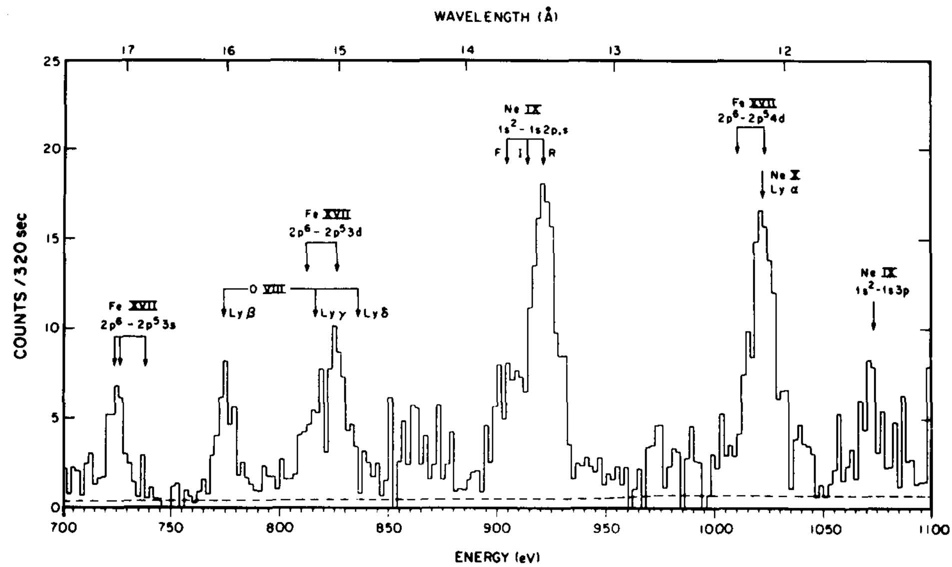

Figure 1. An emission line spectrum of the Puppis-A supernova remnant obtained with the Einstein Focal Plane Crystal Spectrometer

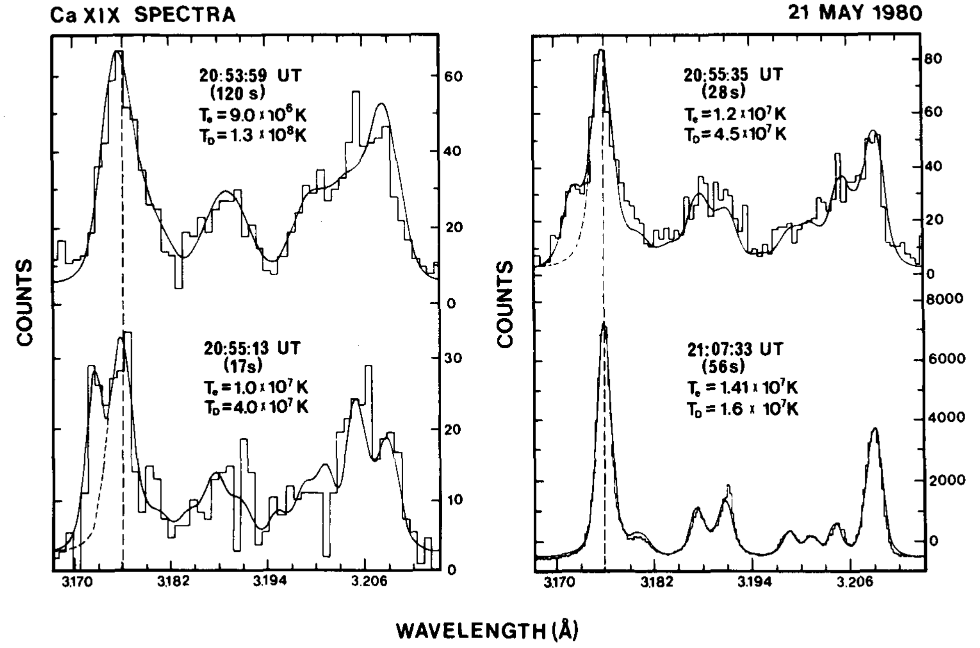

Figure 2. Spectra obtained during the impulsive and cooling phases of a solar flare with the Solar Maximum Mission X-ray Polychromator.

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3.2 X-ray Observatories - AXAF (see Table 2)

This major NASA mission is currently scheduled for launch in 1996. It carries a range of powerful spectroscopic instruments into a near earth orbit. Although the single telescope will advance the state of the art in achieving an angular resolution of better than 1``, it will have a relatively modest collecting area of $180cm^2$ at 7keV.

3.3 X-ray Observatories - XMM (see Table 3)

This ESA mission, which will include three large aperture X-ray telescopes, is scheduled for launch in 1998. It will be placed in a highly elliptical orbit (apogee - 1000Km; perigee - 70,000Km) of 60^o inclination and 24 hour period. With an overall mass of 2400kg, it will be launched on an Ariane IV rocket. Payload electrical power will be 200W out of a total of 875W. The absolute pointing accuracy will be better than 1 arc min while the spacecraft axis will drift at less than 2.5``/min. Attitude reconstruction will be to < 10`` (pitch and yaw) and < 30` (roll). The telescopes will have an angular resolution of better than 30`` (HEW) and a total collecting area of $3000cm^2$ at 7keV.

4. CHARGE COUPLED DEVICES (CCD'S)

The use of Lithium drifted Silicon detectors in X-ray spectroscopy led to significant advances when deployed at the focal plane of the Einstein telescope. Since a CCD is effectively an array of such devices which, due to its readout scheme, has the potential for even better spectral resolution than the ordinary Silicon detector, it represents a natural choice for the non-dispersive X-ray spectroscopy role in future missions.

It will be clear from tables 1 - 3 that CCD's can respond over a broad energy range (0.2keV to telescope cut-off) with high quantum efficiency thus offering a high throughput. Given recent developments towards the achievement of noise levels at the 1-2 e^- level RMS (Janesick and Elliott, 1988), the energy resolution figures listed in the tables are somewhat conservative. The small pixels (currently 20μm - 30μm) permit the ultimate angular resolution (0.5``) and sensitivity of the AXAF mission to be realised. Thus moderate resolution spectroscopy may be undertaken for both point and extended sources provided the devices are cooled to a temperature of around 180K.

In order to maintain good quantum efficiency over the whole energy range of the CCD, it is necessary to construct "back-illuminated" devices in high resistivity Silicon. The latter feature is required to permit large (~80μm) depletion depths and thus good high energy stopping power to be achieved. Deep depletion also ensures that background events can be more easily differentiated from X-ray events due to the greater energy deposited in the Silicon. Some further work is required in order to make these two features simultaneously available in flight devices.

The present restrictions on format (~< 10^3 x 10^3 pixels of up to 30μm x 30μm) mean that multiple chip arrays (~< 10 chips) must be employed to achieve adequate coverage of telescope fields of view. In this connection work in progress with fully depleted pn-CCD's (Strüder et al, 1988) offers the prospect of devices with stopping depths of up to 250μm together with pixel sizes of the same order. This latter feature is relevant for telescopes of large aperture but with somewhat poorer angular resolution.

TABLE 2 FUTURE MISSIONS WITH SPECTROSCOPIC CAPABILITY - AXAF

INSTRUMENT	ANGULAR RESOLUTION (arc sec)	FIELD OF VIEW (arc min)	SPECTRAL RESOLVING POWER (E/ΔE)	EFFECTIVE COLLECTING AREA (CM^2)	COMMENTS ON SENSITIVITY
1) CCD	0.5`` (pixel)	12` x 12` 39` x 3`	8 (0.7 keV) 50 (7 keV)	400 (.7 keV) 100 (7 keV)	BROAD BAND SENS: 2.10^{-15} erg cm^{-2} s^{-1} (10^5s) MIN DET LINE FLUX: 2.10^{-6} hv cm^{-2} s^{-1} (10^5s, 7 keV)
2) MICRO-CALOR-IMETER	~5`` - 10``	1` x 1`	50 (.7 keV) 350 (7 keV)	550 (.7 keV) 110 (7 keV)	MIN DET LINE FLUX: $4\text{-}20.10^{-7}$ hv cm^{-2} s^{-1} in 10^5 s (20.10^{-7} hv cm^{-2} s^{-1} in 10^5s, 7keV)
3) BRAGG SPECTRO-METER	20`` (1-D)	3` (1-D)	200 - 2000 (0.5-8 keV) 50 - 70 (<0.5 keV)	fA ~ 1 - 50 (0.5 - 8 keV) fA ~ 4-40 (<0.5 keV)	MIN DET LINE FLUX: $5\text{-}50.10^{-6}$ hv cm^{-2} s^{-1} in 10^5 s (50.10^{-6} hv cm^{-2} s^{-1} in 10^5 s, 7 keV)
4) LE TRANS-MISSION GRATING (WITH HRC)	< 1``	POINT SOURCES	80 - 1200 (0.1 - 2.5 keV)	10 - 40 (0.1 - 2.5 keV)	MIN DET LINE FLUX: $4\text{-}20.10^{-6}$ hv $cm^{-2}s^{-1}$ in 10^5s (8.10^{-6} hv cm^{-2} s^{-1} in 10^5 s, 0.56 keV)
5) HE TRANS-MISSION GRATINGS (WITH CCD)					
A) METG	< 1``	POINT SOURCES	100 - 1000 (0.4 - 4 keV)	10 - 200 (0.4 - 4 keV)	MIN DET LINE FLUX: $10\text{-}20.10^{-6}$ hv cm^{-2} s^{-1} in 10^5 s
B) HETG	< 1``	POINT SOURCES	100 - 1000 (1.2 - 7 keV)	15 - 50 (1.2 - 7 keV)	MIN DET LINE FLUX: $4\text{-}10.10^{-6}$ hv cm^{-2} s^{-1} in 10^5 s

TABLE 3 FUTURE MISSIONS WITH SPECTROSCOPIC CAPABILITY - XMM

INSTRUMENT	ANGULAR RESOLUTION (arc sec)	FIELD OF VIEW (arc min)	SPECTRAL RESOLVING POWER ($E/\Delta E$)	EFFECTIVE COLLECTING AREA (CM^2)	COMMENTS ON SENSITIVITY
1) CCD	< 30``	30`	8 (.7 keV)	2500 (.7 keV)	BROAD BAND SENS: 2.10^{-15} erg cm^{-2} s^{-1} (2.10^4s)
			50 (7 keV)	1200 (7 keV)	MIN DET LINE FLUX: 2.10^{-7} hv cm^{-2} s^{-1} (10^5 s, 7 keV)
2) REFLECTION GRATINGS	< 30``	POINT SOURCES	400 (.5 keV)	150 (.5 keV)	MIN DET LINE FLUX: $3\text{-}6.10^{-7}$hv cm^{-2} s^{-1} (10^5s)
			300 (1.5 keV)	440 (1.5 keV)	(5.10^{-7} hv cm^{-2} s^{-1} in 10^5s, 0.56 keV)
3) OBJECTIVE BRAGG SPECTROMETER	< 30``	POINT SOURCES	1000 (7keV)	40 (7keV)	MIN DET LINE FLUX: 3.10^{-5} hv cm^{-2} s^{-1} (10^5s, 7keV)

	ANGULAR RESOLUTION	FIELD OF VIEW	LIMITING MAGNITUDE	WAVELENGTH RANGE	$\lambda/\Delta\lambda$
4) OPTICAL MONITOR	1``	8`	24.5 (10^3s, B)	1800-6000Å	50-100 (GRISMS FOR 3000-6000Å RANGE) ALSO BROAD-BAND FILTERS

In considering the missions listed in table 1 - 3, all of them employ CCD's with the exception of the German Spectrosat. The two missions for launch in 1993 (Astro-D and Spectrum-X, table 1) have better effective apertures at 7keV than AXAF but inferior angular resolution. Nevertheless they will play a substantial role in providing an immediate spectroscopic follow-up to the ROSAT mission.

Of the two major observatory class missions, AXAF offers the better angular resolution (<1``) but a modest high energy collecting area (180cm$^2$ at 7keV). On the other hand XMM can achieve 3000cm$^2$ at 7keV but with an angular resolution of < 30``. In addition XMM offers the possibility of long continuous observation of variable sources given its highly eccentric orbit. Hence the two major missions provide highly complementary qualities in their use of focal plane CCD's.

5. THE MICROCALORIMETER

This device consists of an X-ray absorber of heat capacity C connected to a heat sink at temperature T by a link of conductivity G. If an X-ray photon of energy E is absorbed, the temperature of the absorber rises by $\Delta T = E/C$ while the subsequent decay to the equilibrium temeprature T takes place in a time $\propto C/G$. A detailed description of the version of this device being developed for AXAF is given elsewhere in these proceedings by Holt and co-workers (see also McCammon et al., 1987).

In an ideal situation, where the temperature transducer contributes only its Johnson noise, the energy resolution scales as $(kT^2C)^{1/2}$. In a practical device, the GSFC group has achieved an energy resolution of 17.3eV (FWHM) for 5.9keV photons and figures below 10eV are anticipated. Thus the microcalorimeter can combine the photon stopping power of a non-dispersive Silicon detector with the resolution of a dispersive spectrometer (see table 2). Response is also provided over a broad energy range and a useful though moderate resolving power of 50 to 70 is still available at 0.7keV.

The requirement to operate the device at T < 100mK in order to achieve the resolving powers mentioned above presents a difficult though by no means insoluble problem in the space environment. However the need to minimise heat capacity leads to a detector size of around 250µm x 250µm and so an array of such devices would be required to provide sufficient coverage of the telescope field of view. The cryogenic systems being considered include Stirling cycle coolers and/or passive radiators paired with liquid Helium dewars and with the final stage of cooling being provided by an adiabatic demagnetisation refrigerator. The liquid Helium systems sets a limit to lifetime which could be around two to three years.

The microcalorimeter has the potential to revolutionise the subject. However the difficulties mentioned above and, in particular, the limited lifetime in orbit have led to the device being considered only for inclusion in AXAF; a mission for which servicing by the shuttle is envisaged. The data in table 2 show that the microcalorimeter provides by far the best combination of energy resolution and sensitivity of any of the instruments listed.

6. DIFFRACTION GRATINGS

Among the dispersive spectroscopic instruments, transmission gratings, which were flown on the Einstein observatory, are proposed for the Spectrosat and AXAF missions while reflection gratings are part of the XMM model payload. The transmission gratings when used with either high spatial resolution microchannel plate or CCD detectors in the telescope focal plane can provide resolving powers of between 100 and 1200 (see tables 1 and 2). However they rely on high angular resolution X-ray telescopes ($\Delta\theta \sim 1``$)

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to achieve this performance. Reflection gratings can deliver resolving powers of around 400 when used with telescopes of more modest angular resolution ($\Delta\theta \sim 30''$).

Grating systems have the major advantage that they present a dispersed spectrum simultaneously for registration and analysis. However they tend to work better at lower photon energies although the high energy gratings on AXAF still give some useful performance at 7keV. Transmission gratings only offer their full resolving power for point sources and performance degrades rapidly with increasing source extent. Reflection gratings are more tolerant of source extent and so are particularly suitable for observations of distant clusters or of extragalactic supernova remnants.

From a consideration of the future missions that will use gratings it is clear that Spectrosat, which will combine transmission gratings with another version of the excellent ROSAT X-ray telescope will provide a low energy spectroscopic follow-up to the ROSAT sky survey. Of the major observatories, AXAF offers better spectral resolution while XMM offers better sensitivity.

7. BRAGG SPECTROMETERS

Although much useful data has been obtained from solar observations undertaken with Bragg spectrometers, serious use of these instruments for cosmic observations began with the flight of the Einstein observatory. Bragg spectrometers generally offer the highest resolving power of any currently available instrument but, given that many of the designs proposed operate by scanning the spectrum, they lack a multiplex advantage in addition to having an inherently low throughput.

The set of ten different crystal and multilayer diffractors being developed for the AXAF misison (see table 2) provides an impressive and comprehensive capability for high resolution spectroscopy in the 0.5 keV to 8keV energy range. Although the effective apertures in the range 1-50cm^2 are modest, resolving powers of up to 2000 are available in selected spectral ranges. The AXAF spectrometers also have some spatial resolution in one dimension. A field of view 3' in extent can be covered with a spatial resolution of around 20''.

Given the earlier stage of development, a strong candidate instrument for high resolution spectroscopy has not yet emerged for the XMM. A possible approach using an objective crystal spectrometer design is outlined in table 3. Such a system would use the prime-focus CCD camera as a detector but would have the disadvantage of observing sources in a direction orthogonal to that of the X-ray telescope axes. The use of multilayer diffractors in the focal plane in selected limited spectral ranges for high resolution observations is also a possibility which may prove easier to implement.

8. CONCLUSIONS

It will be clear from the material in the previous sections that the next decade will see the deployment in orbit of a number of very powerful spectroscopic instruments. Following the ROSAT mission, two generations of X-ray sky surveys will have been completed and thus the need for detailed spectral studies will become compelling.

The moderate missions (table 1) will provide a useful and relatively rapid follow up to ROSAT. However major advances for a very wide range of sources will follow the deployment of the two observatory spacecraft AXAF and XMM. AXAF includes a broad selection of spectroscopic instruments and, in particular, will carry the microcalorimeter, a device which for the first time combines high spectral resolution with very good quantum efficiency. However the spacecraft will be placed in near earth orbit and so it will be more difficult to arrange efficient observing strategies particularly in the case of variable sources. In addition, the mission will place a substantial emphasis on positional astronomy, spectrophotometry and on deep surveys of limited regions of the sky. Given a single, although very powerful telescope, the spectroscopic observations will have to compete for focal plane time with the other topics mentioned above.

The XMM is designed to achieve much greater collecting area than AXAF, particularly at energies above 7keV, but at the cost of degraded angular resolution. Thus XMM is more directly targeted at studies of source spectra and variability. In addition the availability of multiple focal planes and the proposed deep orbit will lead to a high degree of operational flexibility.

In fact these two major X-ray observatories are superbly complimentary and together will lead to very considerable advances in our understanding of a very large number of objects and to the solution of many pressing astrophysical problems.

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