HIGH RESOLUTION X-RAY SPECTROSCOPY OF GALAXIES AND CLUSTERS WITH AXAF

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Abstract
We review the high resolution X–ray spectroscopy capabilities of the AXAF observatory focusing on the High Energy Transmission Grating (HETG). As part of the Guaranteed Time Observation (GTO) program, the HETG science team will observe both elliptical galaxies and clusters of galaxies. We discuss the problems associated with observing extended sources with the HETG and some of the potential scientific insights which AXAF’s spectroscopy capabilities can provide for these classes of objects.

1 Introduction
The High Energy Transmission Grating (HETG) onboard AXAF will provide the first opportunity since the Einstein Focal Plane Crystal Spectrometer (FPCS) to obtain high resolution X-ray spectra from the cores of galaxies and clusters. These objects are known to contain large quantities of cool gas and are rich sources of X-ray emission. With an energy resolution of $E/\Delta E \sim 1000$, the HETG will be capable of resolving individual X-ray emission lines, absorption lines, and absorption edges in galaxy and cluster spectra. Using plasma diagnostics, these spectra will provide information on source properties such as temperatures, ionization states, densities, velocities, elemental abundances, and thereby structure, dynamics, and evolution. In this paper, we briefly review the technical capabilities of the HETG and ACIS spectrometers onboard AXAF. With these capabilities in mind, we then discuss some of the scientific issues which HETG observations of galaxies and clusters will allow us to explore.

2 Overview of the HETG
The HETG is one of four scientific instruments (SIs) that will operate onboard NASA’s Advanced X-ray Astrophysics Facility (AXAF). These instruments include two imaging detectors: the AXAF CCD Imaging Spectrometer (ACIS) and the High Resolution Camera (HRC). The remaining two instruments consist of dispersive grating spectrometers: the HETG and LETG (Low Energy Transmission Grating). The preferred detector for the HETG is the ACIS-S consisting of 6 imaging CCDs in a 1x6 array. Figure [a] presents the effective areas for the primary...
science instruments onboard AXAF. By combining the AXAF mirror’s high angular resolution (∼1 arcsec) and the grating’s large diffraction angles (∼100 arcsec/Å), the HETG provides spectral resolutions up to $E/\Delta E \sim 1000$ in the AXAF energy band. The HETG consists of 336 individual grating facets of two types: High Energy Grating (HEG) facets and Medium Energy Grating (MEG) optimized for maximal efficiency above and below 2.0 keV, respectively. Table 1 summarizes the spectral capabilities of the HETG as well as the native spectroscopic abilities of the ACIS detector itself. Details of the HETG have been presented previously in SPIE proceedings and various AXAF Science Center (ASC) publications [1,2].

The HETG was designed to provide optimal spectral resolution for point sources. If the observed object has a significant spatial extent, the spectral resolving power ($E/\Delta E$) of the HETG will be degraded. Figure 1b) depicts the effects of increasing source extent on the HETG spectral resolution. For objects with core radii less than ∼5 arcsec, the spectral resolving power of the HETG can still exceed that of the ACIS imager for energies below about 2.0 keV. In the case of cooling flow clusters and ellipticals at Virgo distances, the X–ray emission is

| High Energy Transmission Grating (HETG) | MEG | HEG |
|----------------------------------------|-----|-----|
| Grating Period                         | 4001.41 ang | 2000.81 ang |
| Energy Range                           | 0.4 − 5.0 keV | 0.9 − 10.0 keV |
| Resolution                             | $E/\Delta E = 520$ 1.0 keV | (point sources) |
|                                       | $E/\Delta E = 1000$ 1.0 keV | (point sources) |

| AXAF CCD Imaging Spectrometer (ACIS)   | Imaging array | 4 CCDs (all FI) | FOV=16.9 × 16.9 arcmin |
|----------------------------------------|---------------|-----------------|------------------------|
| Spectroscopy array                     | 6 CCDs (4 FI, 2 BI) | FOV=8.3 × 50.6 arcmin |
| Resolution                             | FI: $E/\Delta E = 10, 46$ 0.5, 5.9 keV | (point sources) |
|                                       | BI: $E/\Delta E = 4.3, 31$ 0.5, 5.9 keV | (point sources) |
expected to be quite peaked (sharp surface brightness distributions are one of the signatures of cooling flows), producing even higher spectral resolution. This point is illustrated in Figure 2 which compares the intrinsic AXAF point response function (PSF) with the surface brightness distribution of the cluster PKS0745-191. Thus, the Fe L emission from the ISM in elliptical galaxies and the ICM in clusters of galaxies can still be profitably explored with the HETG.

3 Clusters of Galaxies

X–ray observations of galaxy clusters indicate that the material in the cores consists of a multiphase plasma. In many clusters, large amounts of intracluster gas appear to be cooling below X–ray emitting temperatures with typical cooling rates of $100–1000 \, M_\odot \, yr^{-1}$ [3]. Evidence for cooling in cluster cores include sharply peaked surface brightness profiles, cooling times less than the estimated age of the cluster, and the observation of low temperature, low ionization X–ray lines. This last point is of particular importance, since it represents direct evidence that cooler ($T \sim 10^6–7 \, K$) gas is present at the centers of clusters [4]. However, the fate of the cooling material in cluster cores is unknown, and indeed that the gas is actually cooling and remaining below X–ray temperatures has not been proven. The ultimate repository of this cooling gas remains one of the most important observational problems concerning galaxy clusters.

High resolution X–ray spectra of clusters with the HETG will allow us to directly probe the physical state of material in the core. Measurement of individual line fluxes will provide several independent and simultaneous determinations of the amount of cooling material in these objects. The detection of lines produced by material at several different densities and temperatures would verify that the gas in cluster cores is inhomogeneous as implied by broadband X-ray surface brightness profiles. X-ray line profiles can provide information on opacity in the core and line widths will allow us to place limits on the turbulence in the gas which is likely to dominate over broadening due to inflow velocity or thermal broadening. Finally, accumulated cold material in cluster cores should produce a number of effects (X-ray line flux reduction, absorption edges, etc.) which are potentially observable with AXAF’s high energy resolution [5]. As part of the Guaranteed Time Observation (GTO) program, the HETG science is currently planning to observe two cooling flow clusters: PKS0745-191 and Abell 1835.
4 Elliptical Galaxies

Elliptical galaxies are bright sources of X-ray emission and contain large amounts of hot, interstellar gas. For brighter X-ray galaxies, the inferred masses of hot gas are consistent with those expected given the present rates of stellar mass loss. Spectral observations of elliptical galaxies indicate that the X-rays are produced by thermal emission from diffuse gas at temperatures of $T \approx 10^7$ K ($kT \approx 1$ keV). Thus, like clusters, these objects should be rich sources of X-ray line emission. Figure 3 shows the Fe L region for a simulated 60 ksec HETG observation of the elliptical galaxy NGC1399. Bright emission lines from various elements are clearly resolved. Current models of the X-ray emission from ellipticals require a low rate of Type Ia supernova heating and chemical enrichment in the gas. HETG observations such as these will place strong constraints on the gas abundances in these objects. In addition, for the brightest X-ray galaxies, the cooling times in the gas are short, which suggests that the gas may form galactic cooling flows. If present, strong X-ray line emission from this cooling material should also be detectable with the HETG in many ellipticals.

![Figure 3: Simulated HETG 1st order MEG spectrum for a 60 ksec observation of NGC1399. The input spectral model was a 1.0 keV Raymond–Smith thermal plasma with 0.2 solar abundances. Some of the stronger X-ray lines are indicated.](image)

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