OPTIMAL CHANDRA AND XMM-NEWTON BANDPASSES FOR DETECTING LOW-TEMPERATURE GROUPS AND CLUSTERS OF GALAXIES

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Received 2001 November 21; accepted 2002 February 19

ABSTRACT

In this short paper I present the results of a calculation that seeks the maximum, or optimal, signal-to-noise energy band for galaxy group or cluster X-ray emission detected by the Chandra and XMM-Newton observatories. Using a background spectrum derived from observations and a grid of models, I show that the "classical" 0.5–2 keV band is indeed close to optimal for clusters with gas temperatures greater than 2 keV and redshifts z < 1. For cooler systems, however, this band is generally far from optimal. Sub-keV plasmas can suffer 20%–60% signal-to-noise loss, compared to an optimal band, and worse for z > 0. The implication is that current and forthcoming surveys should be carefully constructed in order to minimize bias against the low-mass, low-temperature end of the cluster/group population.

Subject headings: methods: data analysis — X-rays: galaxies: clusters

1. INTRODUCTION

The X-ray emission from 10^6 to 10^8 K plasma in the gravitational potentials of massive clusters and groups of galaxies has proved to be an invaluable means by which these systems can be robustly detected and quantified, e.g., Gioia et al. (1990). The use of all- or partial-sky X-ray data (Ebeling et al. 1997; Henry et al. 1992; Gioia et al. 1990) and archival pointed data (Rosati et al. 1995; Scharf et al. 1997; Vikhlinin et al. 1998) in constructing statistically complete catalogs of clusters and groups has dramatically filled in our picture of their evolution, from low redshifts to z ~ 1 (Borgani et al. 2001). The new Chandra and XMM-Newton observatories promise to further extend this early work and, in combination with measurements of the Sunyaev Zeldovich (S-Z) CMB decrement, will allow us to refine and extend our use of clusters as tools for cosmology (Haiman, Mohr, & Holder 2001). At the lower end of the mass scale, Chandra and XMM-Newton will permit the poorer, lower luminosity clusters and groups (systems with temperatures of less than 2 keV) to be systematically detected for the first time to redshifts of a few tenths. Previous surveys for these systems have often had to rely on prior optical catalogs, complicating the estimation of statistical completeness and bias (Mulchaey & Zabludoff 1998).

A common aspect of X-ray group and cluster surveys has been the frequent (although not universal) choice of a passband from 0.5 to 2 keV. Such a band typically helps minimize the contribution of soft Galactic emission and harder particle background while maximizing sensitivity to general cluster emission (McHardy et al. 1998; Rosati et al. 1995). Previous imaging X-ray observatories have also not had the good spectral resolution of Chandra or XMM-Newton, so the choice of band was less controllable.

In this short paper I present a set of simple calculations aimed at determining a set of optimal passbands for thermal plasmas over a range of temperatures and redshifts. I also demonstrate the relationship to the commonly used 0.5–2 keV band and argue that future surveys of cooler systems must take the bandpass explicitly into account or risk seriously biasing their estimates of the space density of such systems.

2. OPTIMAL ENERGY BANDS

The signal-to-noise criterion I use here is S/√N, where S is the source photon count and N is the appropriate background count. This is chosen as a decent approximation to the various forms of detection significance criteria used in X-ray surveys for extended sources. Typically, a mean background count per sky area is estimated, and the deviation of the count rate in a given area, minus the background, is compared to the statistical (usually Poisson) fluctuation in the background over that area.

2.1. The Calculations

A typical background spectrum is derived across the full instrument bandpass by combining high Galactic latitude data (less than \( < \theta_{	ext{HI}} \sim 1 \times 10^2 \)), in which bright sources and periods of high particle background (flares) have been removed. For Chandra, the data were culled by combining archival fields and the on-line background data. Similarly, for XMM, archival performance verification data and on-line background data were utilized. The background spectrum is derived by binning photons from the entire field of view and performing a simple, linear, sliding window smoothing over five pulse-invariant channels. The spectra so derived are still somewhat noisy, but not at a level that alters the results presented here.

A grid of models is generated across a range of temperatures and redshifts using XSPEC, with a MEKAL plasma, one-third solar abundances, \( < \theta_{	ext{HI}} \) is set to a high Galactic latitude maximum of \( 1 \times 10^2 \) cm^2, and the results are robust to reasonable variations in these quantities; \( \Delta T \) is set to 0.1, and \( kT \) is actually set over a range from 0.1 to 12.9 keV in steps of 0.1 keV, although only temperatures of 0.2, 0.5, 1.0, 2.0, 4.0, and 6.0 keV are presented here. The spectra are then forward-folded through the on-axis response matrix files and aperture response functions for the respective
instruments. In the case of the Chandra front-illuminated CCD device (ACIS-I), off-axis responses are also used in an effort to evaluate the effect of radiation damage–induced charge transfer inefficiencies (CTI; see § 2.2 and § 3). All Chandra responses used here assume that basic CTI corrections have been applied to the data (e.g., Townsley et al. 2000). The corrections reduce the position dependence (on the chips) of the gain and grade distributions (which distort the inferred photon energies), but an energy- and position-dependent degradation of spectral resolution remains.

An unrestricted search is then made for the maximal signal to noise by varying the lower ($E_1$) and upper ($E_2$) energy bands independently as a function of $z$.

2.2. The Results

Figures 1, 2, 3, and 4 present the optimal band search results for, respectively, the Chandra ACIS-I, ACIS-S, XMM-Newton MOS, and PN instruments.

Some of the energy band limits show clear features as a function of redshift; however, these all correspond to small variations in actual signal-to-noise ratio (S/N), as is reflected by the smoothness of the 0.5–2 keV to optimal ratio curves. The features are due to the combination of the shape of the instrumental response and features in the background and source spectra. For example, in Figure 2, the upper limit bandpass curve for $kT = 6$ keV (heaviest line) exhibits a sharp drop as the spectrum redshifts from $z = 0.6$ to 0.7. This is entirely due to the location of a fluorescent Si Kα line (at $\sim 1.7$ keV) in the background, from reflection in the Chandra mirror assembly. As the redshift of the source increases, a critical point is reached at which the optimal band edge crosses this background line, and the optimum jumps to a lower energy.

The key results may be summarized as follows: For all instruments, plasmas with $kT < 2$ keV have optimal bands that differ significantly from the 0.5 to 2 keV bandpass. For the coolest plasma considered here (0.2 keV, $2 \times 10^6$ K) at $z = 0.1$, the 0.5–2 keV band suffers a 55%–65% S/N loss with Chandra and an $\sim 45$% S/N loss with XMM, compared to the optimal bandpass. The optimal band in this case has a

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Fig. 1.—Results of an optimal band search for the Chandra ACIS-I FI chip array. Left panel: Upper (solid) and lower (dashed) energy band limits ($E_1$ and $E_2$) are plotted as a function of redshift ($z$). Plasma temperatures are 0.2 keV (light curves), 0.5, 1, 2, 4, and 6 keV (heavy curves). Right panel: The ratio of signal to noise in the classical 0.5–2 keV band to that in the optimal band is plotted (as a percentage) vs. redshift for the six plasma temperatures.

Fig. 2.—As for Fig. 1, for the Chandra ACIS-S BI chips.

Fig. 3.—As for Figs. 1 and 2, but for the XMM-Newton MOS instrument with a thin optical blocking filter.
maximum range from 0.4 to 0.7 keV for Chandra and 0.4–0.8 keV for XMM, both of which are very narrow. At higher redshifts, the S/N loss for the 0.5–2 keV band increases significantly. As the plasma temperature increases, the optimal band rapidly widens. For a 1 keV plasma at $z = 0.1$, the optimal bands are in the range of 0.6–1.2 keV and have a S/N only 10% better than 0.5–2 keV, although this typically increases with redshift. The results for a 6' off-axis response function for the Chandra ACIS-I instrument, with a lower CCD row number and hence smaller CTI, are very similar to the high row number, on-axis calculations. Variations in band limits between the two are ≤5% and therefore negligible.

In a survey in which the space density is to be recovered, the effective volume in which a source of a given intrinsic luminosity can be detected is calculated based on the maximum redshift of detectability. A 10% drop in S/N, compared to that expected, propagates into an ~10% error in volume; consequently, the band corrections suggested here are critical.

3. CONCLUSION

With luminosities of $10^{41}$–$10^{43}$ erg s$^{-1}$, low-mass, cool $(kT < 2$ keV) groups and clusters of galaxies will form a significant fraction of the extended emission X-ray systems detectable to $z \sim 0.5$ in medium-deep Chandra and XMM exposures. Probing this population of collapsed systems is vital for improving our understanding of both the overall cluster mass function and the regime in which gravitational collapse and astrophysical energies are comparable (Lloyd-Davies, Ponman, & Cannon 2000).

I have demonstrated here that the choice of bandpass is critical both in maximizing the detection sensitivity for clusters and in its correct quantification in order to recover the true space density of poor cluster systems. The optimal bands presented here can serve as a reference point for Chandra and XMM surveys.

For the radiation-damaged ACIS-I on Chandra, once the data are processed to correct for much of the CTI effect (e.g., Townsley et al. 2000), the impact of the reduced spectral resolution on the optimal band limits is minimal (similarly for the inherent CTI in the back-illuminated chips) and ≤5% in amplitude at all energies. It appears that it can therefore be safely ignored in this situation.

It has been assumed here that cluster emission is isothermal. In reality, this is often not the case, and significant temperature structure or gradients are present in massive clusters and are also likely in lower mass systems. This will not only further complicate the absolute detection of a cluster but also bias the estimation of flux in a single band. In a future work (C. A. Scharf 2002, in preparation), I will discuss the more complex issues involved with X-ray and S-Z detection biases for clusters in the context of their use as cosmological probes.

C. A. S gratefully acknowledges helpful discussions with D. Helfand and F. Paerels and the generous support of the Columbia Astrophysics Laboratory for this work.

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