A MEDIUM SURVEY OF THE HARD X-RAY SKY WITH ASCA. II. THE SOURCE'S BROADBAND X-RAY SPECTRAL PROPERTIES

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ABSTRACT

A complete sample of 60 serendipitous hard X-ray sources with flux in the range \( \sim 1 \times 10^{-13} \) ergs cm\(^{-2}\) s\(^{-1}\) to \( \sim 4 \times 10^{-12} \) ergs cm\(^{-2}\) s\(^{-1}\) (2–10 keV), detected in 87 ASCA GIS2 images, was recently presented in the literature. Using this sample it was possible to extend the description of the 2–10 keV log N(>S)–log S down to a flux limit of \( \sim 6 \times 10^{-14} \) ergs cm\(^{-2}\) s\(^{-1}\) (the faintest detectable flux), resolving about a quarter of the cosmic X-ray background (CXB). In this paper we have combined the ASCA GIS2 and GIS3 data of these sources to investigate their X-ray spectral properties using the hardness ratios and the stacked-spectra method. Because of the sample statistical representativeness, the results presented here, which refer to the faintest hard X-ray sources that can be studied with the current instrumentation, are relevant to the understanding of the CXB and of the active galactic nucleus (AGN) unification scheme. The “stacked” spectra show that the average source’s spectrum hardens toward fainter fluxes; it changes from an energy spectral index \( \langle \nu F(\nu) \rangle = 0.87 \pm 0.08 \) for the 20 brightest sources (2–10 keV count rate \( \geq 3.9 \times 10^{-3} \) counts s\(^{-1}\), the “bright” sample) to \( \langle \nu F(\nu) \rangle = 0.36 \pm 0.14 \) for the remaining 40 fainter sources (the “faint” sample). The dividing line of \( 3.9 \times 10^{-3} \) counts s\(^{-1}\) corresponds to unabsorbed 2–10 keV fluxes in the range \( \sim 5.4 \times 10^{-15} \) to \( \sim 3.1 \times 10^{-13} \) ergs cm\(^{-2}\) s\(^{-1}\) for a source described by a power-law model with energy spectral index between 0.0 and 2.0. It thus seems that we are now beginning to detect those sources that have the “correct” spectral shape to be responsible for the 2–10 keV CXB. The hardness-ratio analyses indicate that this flattening is due to a population of sources with very hard spectra showing up in the faint sample; about half of the sources in this sample require \( \nu F(\nu) \lesssim 0.5 \), while only \( \sim 10 \% \) of the sources in the bright sample are consistent with an energy spectral index so flat. A number of sources (\( \sim 30 \% \)) in the faint sample seem to be characterized by an apparently “inverted” X-ray spectrum (i.e., \( \nu F(\nu) \lesssim 0.0 \)). These objects are probably extremely absorbed sources, as expected from the CXB synthesis models based on the AGN unification scheme, if not a new population of very hard serendipitous sources. The broadband (0.7–10 keV) spectral properties of the selected sources, as inferred from the hardness-ratios diagram, seem to be more complex than is expected from a simple absorbed power-law model. We have thus investigated more complex models, in line with the AGN unification scheme, and we find that these models seem to be able to explain the overall spectral properties of the present sample; this result also seems to be suggested by a comparison of the hardness-ratio diagram of the serendipitous ASCA sources with that obtained using a sample of nearby and well-known Seyfert 1 and Seyfert 2 galaxies observed with ASCA.

Subject headings: galaxies: active — galaxies: Seyfert — surveys — X-rays: galaxies

1. INTRODUCTION

In the last few years many efforts have been made to understand the origin of the cosmic X-ray background (CXB), discovered more than 37 yr ago by Giacconi et al. (1962). One of the competing hypotheses, the truly diffuse emission origin (see, e.g., Guilbert & Fabian 1986), has been rejected because of the small deviation of the cosmic microwave background spectrum from a blackbody shape (Mather et al. 1994). Therefore, only the alternative interpretation, the discrete sources origin, is left.

Indeed, ROSAT deep surveys, reaching a source density of \( \sim 1000 \) deg\(^{-2}\) at a limiting flux of \( 10^{-15} \) ergs cm\(^{-2}\) s\(^{-1}\) (Hasinger et al. 1998; McHardy et al. 1998), have already resolved most (70%–80%) of the soft (\( E < 2 \) keV) CXB into discrete sources. Spectroscopic observations (Shanks et al. 1991; Boyle et al. 1993, 1994; McHardy et al. 1998; Schmidt et al. 1998) of the sources with fluxes greater than \( \sim 5 \times 10^{-15} \) ergs cm\(^{-2}\) s\(^{-1}\) have shown that the majority (50%–80%) of these objects are broad-line active galactic nuclei (AGNs) at \( z \sim 1.5 \). An important minority (10%–20%) of ROSAT sources are spectroscopically identified with X-ray–luminous narrow emission line galaxies (Carballo et al. 1995; Griffiths et al. 1995, 1996; McHardy et al. 1998), whose real physical nature (obscured AGN, starburst) is at the moment being debated in the literature (see, e.g., Schmidt et al. 1998). Since their average X-ray spectrum is harder than that of the broad-line AGNs (Carballo et al. 1995; Almaini et al. 1996; Romero-Colmenero et al. 1996) and similar to that of the remaining unresolved CXB, these objects could also be substantial contributors to the CXB at higher energies. About 10% of the ROSAT sources are identified with clusters of galaxies (see, e.g., Rosati et al. 1998). Thus, it is clear that the ROSAT satellite has been successful in resolving almost all the soft CXB into discrete sources. Furthermore, optical observations of the faint ROSAT sources has lead to an understanding of the physical nature of the objects contributing to it.
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In contrast, at harder energies, closer to where the bulk of the CXB resides, the origin of the CXB is still matter of debate. Before the ASCA and BeppoSAX satellites, which carry the first long-lived imaging instruments in the 2–10 keV energy band, surveys in this energy range were made using passively collimated X-ray detectors that, because of their limited spatial resolution, allowed the identification of only the brightest X-ray sources, which represent a very small fraction (<5%) of the CXB (Piccinotti et al. 1982). The so-called “spectral paradox” further complicates the situation; none of the single classes of X-ray emitters in the Piccinotti et al. (1982) sample is characterized by an energy spectral distribution similar to that of the CXB. Due to the lack of faint, large, and complete samples of X-ray sources selected in this energy range, the contribution of the different classes of sources to the hard CXB was evaluated through population-synthesis models, and different classes of X-ray sources were proposed as the major contributors by a number of authors (e.g., starburst galaxies, absorbed AGN, and reflection-dominated AGN; see, e.g., Fabian 1989; Griffiths & Padovani 1990; Madau, Ghisellini, & Fabian 1994; Comastri et al. 1995; Zdziarski et al. 1993). Recent results from ASCA and BeppoSAX observations of individual objects and/or medium-deep survey programs (Bassani et al. 1999; Maiolino et al. 1998; Turner et al. 1998; Boyle et al. 1998a, 1998b; Akiyama et al. 1998) seem to favor the strongly absorbed AGN hypothesis, but further investigations are still needed to confirm this scenario.

At the Osservatorio Astronomico di Brera, a serendipitous search for hard (2–10 keV band) X-ray sources using data from the GIS2 instrument on board the ASCA satellite is in progress (Cagnoni, Della Ceca, & Maccacaro 1998, hereafter Paper I; Della Ceca et al., in preparation) with the aim of extending to faint fluxes the census of X-ray sources shining in the hard X-ray sky. The strategy of the survey, the image and source selection criteria, and the definition of the sky coverage are discussed in Paper I.

In Paper I, a first sample of 60 serendipitous X-ray sources detected in 87 GIS2 images at high Galactic latitude (|b| > 20°) covering ~21 deg² was presented. This sample has allowed the authors to extend the description of the number-counts relationship down to a flux limit of ~6 × 10⁻¹⁴ ergs cm⁻² s⁻¹ (the faintest detectable flux), resolving directly about 27% of the (2–10 keV) CXB.

Here we study the spectral properties of the 60 ASCA sources listed in Paper I, combining GIS2 and GIS3 data. We have carried out both an analysis of the stacked spectra of the sources, in order to investigate the variation of the source’s average spectral properties as a function of the flux, and a hardness-ratio (HR) analysis of the single sources. This latter method, which is equivalent to the “color-color” analysis largely used at optical wavelengths, is particularly appropriate when dealing with sources detected at a low signal-to-noise ratios (e.g., Maccacaro et al. 1988; Netzer, Turner, & George 1994). We have defined two independent HRs, and we have compared the position of the sources in the HR diagram with a grid of theoretical spectral models that are found to describe the X-ray properties of known classes of X-ray emitters.

The paper is organized as follows. In § 2 we present the sample and define the “faint” and “bright” subsamples. In § 3 we present the data, discuss the data analysis, and define the two HRs used. In § 4 we report the results of the stacked spectra and the HR analysis and compare them with those expected from simple spectral models and with the CXB spectra. Summary and conclusions are presented in § 5.

2. DEFINITION OF THE FAINT AND BRIGHT SUBSAMPLES

The basic data on the 60 X-ray sources used in this paper are reported in Table 2 of Paper I.

To investigate whether the spectral properties of the sources depend on their brightness, we have defined two subsamples according to the “corrected” 2–10 keV GIS2 count rate (hereafter CCR). The 20 brightest sources (CCR ≥ 3.9 × 10⁻³ counts s⁻¹) define the “bright” subsample, while the remaining 40 sources define the “faint” subsample. The dividing line of 3.9 × 10⁻³ counts s⁻¹ corresponds to an unabsorbed 2–10 keV flux of ~5.4 × 10⁻¹³ to ~3.1 × 10⁻¹³ ergs cm⁻² s⁻¹ for a source described by a power-law model with energy spectral index of 0.0 to 2.0 (absorbed by a Galactic column density of 3 × 10²⁰ cm⁻²).

We note that the numbers reported above are a very weak function of the Galactic absorbing column density along the line of sight (which ranges from 0.7 × 10²⁰ cm⁻² to 9.1 × 10²⁰ cm⁻² for the present sample).

We prefer to use the CCR instead of the flux because the CCR is (once the corrections due to the vignetting and the PSF have been applied) an observed quantity and is independent of the spectral properties of the source, while the flux is model-dependent. In first approximation, a fainter CCR corresponds to fainter sources.

3. DATA ANALYSIS

All the ASCA images used in Paper I are now in REV 2 processing status; in this paper we have used this new revision of the data. Furthermore, in order to improve the statistics, we have combined data from the GIS2 and GIS3 instruments, as explained below.

Data preparation has been done using version 1.3 of the XSELECT software package and version 4.0 of FTOOLS (supplied by the HEASARC at the Goddard Space Flight Center). Good time intervals were selected by applying the standard REV 2 screening criteria (as reported in chapter 5 of the ASCA Data Reduction Guide, revision 2.0), with the only exception of using a magnetic cutoff rigidity threshold of 6 GeV c⁻¹ (as done in Paper I). HIGH, MEDIUM, and LOW bit-rate data were combined together. Spectral analysis (see below) has been performed using version 9.0 of the XSPEC software package. We use the detector redistribution matrix files (RMF) `gis2v4_0.rmf` and `gis3v4_0.rmf`.

5 As a result of the vignetting of the X-ray telescope (XRT) and the point spread function (PSF), a source with a given flux will yield an observed count rate depending on the position of the source in the field of view. The term “corrected count rate” (CCR) means the count rate that the source would have had if observed at some reference position in the field of view and within a given extraction region. The definition of the source extraction region and of the reference position in the field of view, used to determine the CCR, are discussed in § 3.2. The CCR used here can be obtained by dividing the unabsorbed 2–10 keV flux reported in Paper I by the count rate-to-flux conversion factor of 1 count s⁻¹ (2–10 keV) = 11.46 × 10⁻¹⁴ ergs cm⁻² s⁻¹. This value is appropriate for a power-law model with an energy spectral index of 0.7, filtered by a Galactic absorbing column density of 3 × 10²⁰ cm⁻².

6 For particulars of data processing, see http://heasarc.gsfc.nasa.gov/docs/asc/ascarev2.html.

7 This combination was possible for all the sources except a0447-0627, a0506-3726, a0506-3742 and a0721+7111. For these four sources we have used only the GIS2 data.

8 The ASCA Data Reduction Guide is available electronically at: http://heasarc.gsfc.nasa.gov/docs/asc/asc/abc.html
3.1. Stacked Spectra

For each source and for the GIS2 and GIS3 data sets, total counts (source + background) were extracted from a circular extraction region of 2° radius around the source centroid. Background counts were taken from two circular uncontaminated regions of 3.5° radius, close to the source, or symmetrically located with respect to the center of the image. Source and background data were extracted in the pulse-invariant (PI) energy channels, which have been corrected for spatial and temporal variations of the detector gain. The ancillary response file (ARF) relative to each source was created with version 2.72 of the FTOOLS task ASCAARF at the location of the individual sources in the detectors.9

For each source we have then produced a combined GIS spectrum (adding GIS2 and GIS3 data) and the corresponding background and response matrix files, following the recipe given in the ASCA Data Reduction Guide (revision 2.0; see §§ 8.9.2 and 8.9.3 and reference therein). Finally, we have produced the combined spectrum of (1) the 20 sources belonging to the bright sample and (2) the 40 sources of the faint sample. We note that each object contributes to the stacked counts at most 6% in the case of the faint sample and at most 25% in the case of the bright sample.

In the spectral analysis, because we are interested in comparing these stacked spectra with that of the hard CXB, we have considered only the counts in the 2.0–10.0 keV energy range. The total net counts in the bright and faint samples are about 3400 and 2900, respectively. The stacked spectra were rebinned to give at least 50 total counts per bin.

3.2. Hardness Ratios

For each source and for the GIS2 and GIS3 data set, source + background counts were extracted in three energy bands: 0.7–2.0 keV (S band), 2.0–4.0 keV (M band) and 4.0–10.0 keV (H band). The S, M, and H spectral regions were selected so as to have similar statistics in each band for the majority of the sources. The background counts have been evaluated by using the two background regions considered above; first we have normalized the background counts to the source extraction region, and then we have averaged them. Net counts in S, M, and H have then been obtained for each source by subtracting the corresponding S, M, and H normalized background counts from the total ones.

To combine the GIS2 and GIS3 data for each source and to compare our results with those expected from simple models, the net counts obtained must be corrected for the position-dependent sensitivity of the GIS detectors (see the discussion in § 2.3 of Paper I). In particular, we must (1) define a source-extraction region and a reference position in the GIS2 or GIS3 field; (2) renormalize the S, M, and H net counts from each source to this region (since sources are detected in different locations of the GIS2 or GIS3 field of view); and (3) perform the simulations for simple models by using the effective area of this region. We will now discuss these points in turn.

As a reference region, we have used a source-extraction region of 2° radius at the position $x = 137, y = 116$ for the (XRT + GIS2) combination. Using ASCAARF, we have produced the effective area values at the position of each source detected in the GIS2 (GIS3) detector. Using these effective area values and through spectral simulations with XSPEC, we have derived the correction factors to be applied to each source in the S, M, and H bands. For each source we have then applied these correction factors to the net counts of GIS2 and GIS3 separately. Finally, we have combined the GIS2 and GIS3 corrected net counts for each source. In summary, using this procedure we have first renormalized the GIS2 and GIS3 data for each source to the reference region separately and then combined them. We note that the method applied is very similar to the flat-field procedure normally used in the analysis of optical imaging and spectroscopic data.

Using the corrected net counts in the S, M, and H bands, we have then computed for each source two hardness ratios, defined as

$$\text{HR1} = \frac{M - S}{M + S}, \quad \text{HR2} = \frac{H - M}{H + M}. $$

The 68% error bars on HR1 and HR2 have been obtained via Monte Carlo simulations using the total counts, the background counts, and the correction factors relative to each source.

Similarly, HR1 and HR2 values expected from simple spectral models (see § 4) have been obtained with XSPEC using the effective area of the reference region.

4. RESULTS

4.1. The Hard Energy Range and the CXB

In this section we discuss the hard (2–10 keV) X-ray average spectrum of the present sample and compare it with that of the CXB; to this end we use the HR2 values and the stacked spectra introduced in § 3.

In Figure 1, for all sources, we plot the HR2 value versus the GIS2 CCR; the filled squares represent the sources detected with a signal-to-noise ratio (S/N) greater than 4.0, while the open squares represent the sources detected with a S/N between 3.5 and 4.0. The HR2 values are then compared with those expected from a nonabsorbed power-law model with energy spectral index $\alpha_E (f_X \propto E^{\alpha_E})$ ranging from $-1.0$ to $2.0$.

Figure 1 clearly shows a broadening of the HR2 distribution going to fainter CCR; furthermore, a flattening of the mean spectrum with decreasing fluxes is also evident. A similar broadening and flattening of the HR2 distribution is still detected if only the 40 sources (18 bright and 22 faint) detected with a S/N greater than 4.0 are used, showing that this result is not due to the sources near the detection threshold limit.

It is worth noting the presence of many sources that seem to be characterized by a very flat 2–10 keV spectrum, with $\alpha_E \leq 0.5$, and of a number of sources with "inverted" spectra (i.e., $\alpha_E \leq 0.0$). This is particularly evident in the faint sample, where about half of the sources seem to be described by $\alpha_E \leq 0.5$ and about 30% by inverted spectra. These latter objects could represent a new population of very hard serendipitous sources or, alternatively, a population of very absorbed sources, as expected from the CXB synthesis models based on the AGN unification scheme.

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9 The task ASCAARF (which is part of the FTOOLS software package) is able to produce a position-dependent PSF-corrected effective area, $A(E, x, y, d)$, of the XRT + GIS2 or XRT + GIS3 combination. The inputs of this task are the position $(x, y)$ (in detector coordinates) and the dimension $d$ of the source's extraction region.
We have checked whether the observed hardening of the mean spectral index can be attributed to a spectral bias in the source’s selection. Since sources with the same flux but different spectra will deposit a different number of counts in the detector, it is evident that, as one approaches the flux limit of a survey, sources with a favorable spectrum will be detected (and thus included in the sample), while sources with an unfavorable spectrum will become increasingly underrepresented (see Zamorani et al. 1988 for a discussion of this effect). However, in the case of the ASCA/GIS, this selection effect favors the detection of steep sources, thus giving further support to the reality of our findings.10

We note that a population of very hard X-ray sources has also recently been suggested by Giommi et al. (1998) in order to explain the spectral properties of the faint BeppoSAX sources and to reconcile the 2–10 keV log N(>S)–log S with the 5–10 keV log N(>S)–log S obtained from BeppoSAX data.

10 As an example, in a 50,000 s observation, a source with 2–10 keV flux = 5 × 10^{-13} ergs cm^{-2} s^{-1}, characterized by an absorbed power-law spectrum with \( \alpha_E = 2.0 \) and \( N_H = 3 \times 10^{20} \), will deposit (at the reference position and inside a region of 2' radius) \( \sim 300 \) (2–10) keV counts, while a source with the same flux but a power-law spectrum with \( \alpha_E = 0.0 \) and the same \( N_H \) will deposit \( \sim 180 \) counts.

To further investigate the flattening of the source’s mean spectral index, we have used the stacked spectra introduced in § 3.1.

In Table 1 we report the results of the power-law fits to the stacked spectra of the faint and bright samples; the unfolded spectra of the two samples are shown in Figure 2 (the bright sample by open squares, the faint sample by filled squares). As can be seen from the \( \chi^2 \) values reported in Table 1 and from the spectra shown in Figure 2, a simple power-law spectral model represents a good description of the stacked spectra of the two samples in the 2–10 keV energy range. The \( N_H \) values corresponding to the mean line-of-sight Galactic absorption for the two independent samples have been used in the fits. However, given the energy range of interest (2.0–10.0 keV), the spectra are not significantly affected by the Galactic \( N_H \) value. Consistent results are obtained whether we use the lowest (0.7 \( \times \) 10^{20} cm^{-2}) or highest (9.06 \( \times \) 10^{20} cm^{-2}) Galactic \( N_H \) value sampled in the present survey.

It is worth noting that the unfolded spectra of the faint and bright samples reported in Figure 2 does not show any compelling evidence of emission lines. A strong emission line should be expected if, for example, sources with a strong iron emission line at 6.4 keV, contributing in a substantial way to the CXB, were strongly clustered at some particular redshift. This subject has already been discussed by Gilli et al. (1999), who reached the conclusion that the maximum contribution of the iron line to the CXB is less

| Sample  | Objects | Net Counts (2–10 keV) | \( \alpha_E \) | \( N_{H\text{Gal}} \) (10^{20} cm^{-2}) | \( \chi^2/V \) |
|---------|---------|----------------------|-------------|-----------------|-----------|
| Faint ....... 40 | \( \sim 2900 \) | 0.36 ± 0.14 | 2.75 | 1.09/105 |
| Bright ...... 20 | \( \sim 3400 \) | 0.87 ± 0.08 | 3.66 | 1.06/82 |
than few percent. The unfolded spectra shown in Figure 2 confirm their results.

In Figure 3 the results obtained here are compared with those obtained using data from other satellites or from other ASCA medium-deep survey programs. The best-fit energy index of the bright sample ($\langle x_b \rangle = 0.87 \pm 0.08$) is in good agreement with the mean spectral properties of the objects in the Ginga and HEAO 1 A-2 sample and is consistent (at the 2 $\sigma$ level) with the mean spectral properties of the broad-line AGNs detected by ROSAT (Carballo et al. 1995; Almaini et al. 1996; Romero-Colmenero et al. 1996). The faint sample is best described by $\langle x_f \rangle = 0.36 \pm 0.14$; this is consistent with other ASCA results (Ueda et al. 1998) and with the spectra of the CXB in the 2–10 keV energy range (Marshall et al. 1980; Gendreau et al. 1995). For Figure 3 we have used a count rate–to–flux conversion factor adequate for a power-law spectral model with $x_f = 0.36$ (faint sample) or $x_b = 0.87$ (bright sample).

We have evaluated the influence that the sources with the hardest energy distribution have on the combined spectra. If we exclude the six sources with HR2 > 0.2 (five from the faint sample and one from the bright sample), we find that the combined spectra are still significantly different, being described by a power-law model with $\langle x_b \rangle = 0.53 \pm 0.14$ and $\langle x_f \rangle = 1.04 \pm 0.10$, respectively.

Finally, in the case of the bright sample, two sources contribute about 35% of the total counts; if we exclude these two objects, the remaining stacked spectrum is described by a power-law model with $\langle x_b \rangle = 1.00 \pm 0.16$, showing that the inclusion or exclusion of these two objects do not change any of our results. Note that in the case of the faint sample, each object contributes to the stacked counts at most 6% or less.

These results clearly show that (1) we have detected a flattening of the source’s mean spectral properties toward fainter fluxes and (2) we are beginning to detect those X-ray sources that have a combined X-ray spectrum consistent with that of the 2–10 keV CXB.

4.2. The Broadband Spectral Properties and the AGN Unification Scheme

In this section we do not intend to derive specific spectral properties and/or parameters for each source; the limited statistics and the complexity of AGN broadband X-ray spectra (see Mushotzky, Done, & Pounds 1993 for a review of the subject) prevent us from doing so. Rather, we regard this sample as representative of the hard X-ray sky, and we try to investigate whether the currently popular CXB synthesis models based on the AGN unification scheme can describe the overall spectral properties of the ASCA sample as inferred from the hardness ratios. According to the AGN unification model for the synthesis of the CXB, a population of unabsorbed (type 1, $N_H \leq 10^{22}$ cm$^{-2}$) and absorbed (type 2, $N_H \gtrsim 10^{22}$ cm$^{-2}$) AGNs can reproduce the shape and intensity of the CXB from several keV to ~100 keV (see Madau et al. 1994; Comastri et al. 1995). Because ~90% of the ASCA sources in this sample$^{11}$ are expected to be AGNs (see Paper I), in the following discussion we will consider this sample as being well approximated by a population of type 1 + type 2 AGNs with flux above $\sim 1 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$.

In Figure 4 we show (open squares) the position of the sources in the HR plot for the faint (Fig. 4a) and bright (Fig. 4b) samples; in Figure 4c we show the 12 sources spectroscopically identified so far (see footnote 10). Also shown in Figures 4a, 4b, and 4c (solid lines) are the loci expected from X-ray spectra described by an absorbed power-law model. The energy index of the power law ranges from −1.0 up to 2.0, while the absorbing column densities range from $10^{20}$ cm$^{-2}$ up to $10^{24}$ cm$^{-2}$ (see Fig. 4d); the absorption has been assumed to be at zero redshift (i.e., the sources are assumed to be in the local universe).

Figure 4 clearly shows how the HR plot, combined with spectral simulations, can be used to obtain information on the sources’ X-ray spectral properties, as well as the power of using two hardness ratios to investigate the broadband spectral properties of the sources. If only one ratio is known, say, for example, HR2, a source with HR2 ~ 0–0.1 could be described by an absorbed power law with either an energy index of 0.0 and $N_H = 10^{20}$ cm$^{-2}$ or an energy index of ~2.0 and $N_H = 10^{23}$ cm$^{-2}$. The use of both HR1 and HR2 allows the ambiguity to be solved.

We note that the hardness ratios computed as described in § 3.2 have not been corrected for the different Galactic absorbing column density along the line of sight of each source. For the present sample, this ranges from $0.7 \times 10^{20}$ cm$^{-2}$ to $9.1 \times 10^{20}$ cm$^{-2}$; Figure 4 clearly show that this correction is insignificant.

One of the most striking features of Figure 4 is the large spread in HR1 and HR2 displayed by the ASCA sources and the departure from the loci of absorbed, single power law spectra. This implies that the broadband (0.7–10 keV) spectrum of the sources is more complex than the simple model of an absorbed power law. In particular, the ASCA sources located on the left side of the line, representing power laws with $N_H \sim 10^{20}$ cm$^{-2}$ (see Fig. 4d), are not explained within the absorbed power-law model. A similar

$^{11}$ Up to now, 12 sources have been spectroscopically identified. The optical breakdown is: one star, two clusters of galaxies, seven broad-line AGNs, and two narrow-line AGNs. However, we stress that this small sample of identified objects is probably not representative of the whole population.
result is obtained even if the absorbing material is assumed to be at higher redshift, e.g., $z = 1$ or 2.

We note that the object in Figure 4b (or Fig. 4c) characterized by $HR1 \sim 0.0$ and $HR2 \sim 0.71$ (a1800 + 6638; its X-ray flux is $\sim 6.5 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$) is spectroscopically identified with the Seyfert 2 galaxy NGC 6552. The X-ray spectrum of this object (Reynolds et al. 1994; Fukazawa et al. 1994) is consistent with a model composed of a narrow Gaussian line plus an empirical “leaky-absorber” continuum; the latter is composed of an absorbed power law and a nonabsorbed power law having the same photon index. Fukazawa et al. (1994) found that the NGC 6552 spectrum requires a photon index of $\sim 1.4$, an absorbing column density of $\sim 6 \times 10^{23}$ cm$^{-2}$, an uncovered fraction of $\sim 2\%$, and a narrow Gaussian line (consistent with the K$\alpha$ iron emission line at 6.4 keV) having an equivalent width of $\sim 0.9$ keV.

That the simple absorbed power law model is unable to explain the scatter in the hardness ratios is not surprising, given the observational evidence that the broadband X-ray spectra of type 1 and, even more, of type 2 AGNs are complex and affected by several parameters, such as, for instance, the viewing angle and the torus thickness (see, e.g., Turner et al. 1997, 1998; Maiolino et al. 1998; Bassani et al. 1999). In particular, for type 2 AGNs we could have, as a function of the absorbing column density, one of the following three cases:

1. $10^{22} \lesssim N_H \lesssim 5 \times 10^{23}$ cm$^{-2}$.—The hard X-ray continuum above a few keV is dominated by the directly viewed component, making the source nucleus visible to the observer and the column density measurable; the reflected/scattered component is starting to become relevant in the soft energy range. In this case, the observed spectrum is that of an absorbed type 1 AGN with some extra flux at low energies.

2. $5 \times 10^{23} \lesssim N_H \lesssim 10^{25}$ cm$^{-2}$.—In this case, both the directly viewed component and the reflected/scattered component are observed, and the resulting spectrum becomes very complex.

3. $N_H \gtrsim 10^{25}$ cm$^{-2}$.—The torus is very thick. The continuum source is blocked from direct view up to several tens of keV, and the observed spectrum is dominated by the scattered/reflected component. In this case, the observed continuum is that of a type 1 AGN (in the case of scattering by warm material near the nucleus) or of a Compton-
FIG. 5.—Open squares represent the position of the sources in the HR plot (faint + bright sample). Solid lines show the loci expected from the simplified AGN spectral model discussed in the text (see § 4.2). We have highlighted with filled dots or filled triangles the absorbing column densities of log N_H = 20, 21.5, 22, 22.5, 23, 23.5, 24, and 24.5 (left to right); the absorption has been assumed to be at zero redshift (i.e., the sources are assumed to be in the local universe). The filled triangles represent the model relative to an energy spectral index of 1.0 and scattered fraction of 1%, while the filled dots represent the model relative to an energy spectral index of 1.0 and scattered fraction of 10%. The dashed line represents the locus expected from unabsorbed power laws (N_H \sim 10^{20} \text{ cm}^{-2}) and energy spectral index ranging from −1.0 up to 2.0. We also show the input spectra for the case K = 1% and log N_H = 20, 22, 23, 24, and 24.5.
reflected spectrum (in the case of cold reflection from the torus).

Given this spectral complexity, we have tested the HR plot against the following simplified AGN spectral model, composed of:

1. An absorbed power-law spectrum. This component represents the continuum source; i.e., for an absorbing column density of about $10^{20} \text{ cm}^{-2}$, this represents the zero-order continuum of a type 1 object.

2. A nonabsorbed power-law component, characterized by the same energy spectral index of the absorbed power law and by a normalization in the range of 1%-10% of that of the absorbed power-law component. This component represents the scattered fraction (by warm material) of the nuclear emission along the line of sight; theoretical and observational evidence (see Turner et al. 1997 and reference therein) suggest that this scattered fraction is in the range 1%-10%.

3. A narrow emission line at 6.4 keV, having an equivalent width of 230 eV for low values of $N_H \sim 10^{20} \text{ cm}^{-2}$. This component represents the mean equivalent width of the Fe Kα emission line in Seyfert 1 galaxies, as determined by Nandra et al. (1997) using ASCA data.

In summary, the AGN spectral model used is

$$S(E) = E^{-\sigma_E} e^{-\sigma_E N_H} + K E^{-\sigma_E} + \text{Fe}_{6.4 \text{ keV}}$$

where $E$ is the photon energy, $\sigma_E$ is the energy spectral index, $\sigma_E$ is the energy-dependent absorbing cross section, $N_H$ is the absorbing column density along the line of sight to the nucleus, $K$ is the scattered fraction, and Fe$_{6.4 \text{ keV}}$ is the iron narrow emission line at 6.4 keV. The above simplified AGN spectral model is equivalent to the model used by Fukazawa et al. (1994) in the case of NGC 6552 and by several authors to describe the first-order X-ray spectra of Seyfert 2 galaxies (see, e.g., Turner et al. 1997).

We have tested this model as a function of $\sigma_E$, the absorbing column density $N_H$, and the scattered fraction $K$. Figure 5 shows, as an example, the results of the spectral simulations in the case of local sources ($z \sim 0.0$) with $\sigma_E = 1$ and $K = 0.01$ (filled triangles) or $K = 0.1$ (filled circles). The input spectra for the cases with $K = 0.01$ and log $N_H = 20, 22, 23, 24$, and 24.5 are also shown.

We would like to stress that using this simplified AGN spectral model we can go, in a continuous way, from a first-order type 1 spectrum to a first-order type 2 spectrum only by changing the $N_H$ parameter. In this respect, we note that the equivalent width of the iron narrow emission line at 6.4 keV (which, as we said, is fixed to 230 eV for $N_H \sim 10^{20} \text{ cm}^{-2}$) is $\sim 2$ keV when $N_H \sim 3 \times 10^{24} \text{ cm}^{-2}$; this latter value is very similar to that measured in many Seyfert 2 galaxies characterized by a similar value of the absorbing column density (Bassani et al. 1999).

As anticipated at the beginning of this section, some qualitative conclusions can be drawn from the results reported

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**Fig. 6.—Same as Fig. 4a, but for the comparison sample of Seyfert 1 and Seyfert 2 galaxies. Filled triangles, Seyfert 1 galaxies; open squares, Compton-thick Seyfert 2 galaxies; filled squares, Compton-thin Seyfert 2 galaxies (see § 4.2).**
in Figure 5. First, it appears that in the context of this simplified AGN spectral model, and for very high $N_H$ values, we are able to explain the hardness ratios of the objects located on the left side of the dashed line, representing unabsorbed power laws. Second, the results reported in Figure 5 seem to indicate that many of the latter objects could be characterized by a very high absorbing column density; if this indication is confirmed by further investigation with $\text{XMM}$ and $\text{AXAF}$, then the number of Compton-thick systems could be significantly higher than previously estimated. In the meantime, we note that this result is consistent with recent findings obtained by Maiolino et al. (1998), Bassani et al. (1999), and Risaliti, Maiolino, & Salvati (1999) by studying the fraction of Compton-thick systems in a sample of Seyfert 2 galaxies observed with $\text{BeppoSAX}$ and/or $\text{ASCA}$.

Finally, to investigate the HR plot in a model-independent way, we have used a comparison sample of nearby ($z < 1$) Seyfert 1 and Seyfert 2 galaxies pointed at with $\text{ASCA}$. This sample was selected from a data set of about 300 $\text{ASCA}$ pointings that were treated in the same manner (see §2) and that we are using to extend the survey presented in Cagnoni, Della Ceca, & Maccacaro (1998). Within this restricted $\text{ASCA}$ data set we have considered those observations pointed on nearby Seyfert 1 and Seyfert 2 galaxies; furthermore, we have considered only the Seyfert 2 galaxies also reported in Table 1 of Bassani et al. (1999), in order to have a uniform data set of their Compton thickness. The comparison sample is composed of 13 Seyfert 1, 15 Compton-thin Seyfert 2, and seven Compton-thick Seyfert 2 galaxies. The targets were analyzed in the same way as the serendipitous sources, combining the GIS2 and GIS3 data (see §3.2).

The results are shown in Figure 6. The Seyfert 1 galaxies are strongly clustered around the loci representing low $N_H$ values, while the Seyfert 2 galaxies are characterized by a very large spread in their HR1 and HR2 values. In particular, many of the Seyfert 2 galaxies are located on the left side of the line representing power laws with $N_H \sim 10^{20} \text{cm}^{-2}$; about half of these sources have been classified as Compton-thick system by Bassani et al. (1999). We are tempted to suggest that the other half are also Compton-thick objects, whose nature is still unrevealed because of the presently poor data quality. $\text{XMM}$ and/or $\text{AXAF}$ observations are needed to confirm this suggestion. However, whatever their properties (Compton thin or thick), a comparison of Figure 6 and Figures 4a and 4b strongly suggest that at least some of the serendipitous $\text{ASCA}$ sources located on the left side of the dashed line connecting the $N_H = 10^{20}$ values could be type 2 AGNs.

5. SUMMARY AND CONCLUSION

In this paper we have used $\text{ASCA}$ GIS2 and GIS3 data for a complete and well-defined sample of 60 hard (2–10 keV) selected sources to study the spectral properties of X-ray sources down to a flux limit of $\sim 10^{-13} \text{ergs cm}^{-2} \text{s}^{-1}$. To investigate whether the spectral properties of the sources depend on their brightness, we have defined two subsamples according to the “corrected” 2–10 keV GIS2 count rate; the bright sample is defined by the 20 sources with $\text{CCR} \geq 3.9 \times 10^{-3} \text{counts s}^{-1}$, while the faint sample is defined by the 40 fainter sources. The dividing line of $3.9 \times 10^{-3} \text{counts s}^{-1}$ corresponds to unabsorbed 2–10 keV fluxes in the range $\sim 5.4 \times 10^{-13}$ to $3.1 \times 10^{-13} \text{ergs cm}^{-2} \text{s}^{-1}$ for a source described by a power-law model with energy spectral index between 0.0 and 2.0.

The main results of this investigation are:

1. The average (2–10 keV) source’s spectrum hardens toward fainter fluxes. The “stacked” spectra of the sources in the bright sample is described by a power-law model with an energy spectral index of $\langle \alpha_E \rangle = 0.87 \pm 0.08$, while the stacked spectra of the sources in the faint sample require $\langle \alpha_E \rangle = 0.36 \pm 0.14$; this means that we are beginning to detect those sources that have a combined X-ray spectrum consistent with that of the 2–10 keV CXB.

2. The HR analysis shows that this flattening is due to the appearance of sources with very hard spectra in the faint sample. Above half the sources in this sample require $\alpha_E \lesssim 0.5$, while only 10% of the brighter sources are consistent with an energy spectral index so flat. Furthermore, about 30% of the sources in the faint sample seem to be characterized by “inverted” ($\alpha_E \lesssim 0.0$) 2–10 keV X-ray spectra. These objects could represent a new population of very hard serendipitous sources or, alternatively, a population of very absorbed sources, as expected from the CXB synthesis models based on the AGN unification scheme (see below).

3. A simple absorbed power-law model is unable to explain the broadband (0.7–10 keV) spectral properties of the sources, as inferred from the HR plot. X-ray spectral models based on the AGN unification scheme seem to be able to explain the overall spectral properties of this sample. This is also suggested by the comparison of our results with those obtained using a sample of nearby and well-known Seyfert 1 and Seyfert 2 galaxies observed with $\text{ASCA}$.

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