THE *XMM-NEWTON* WIDE-FIELD SURVEY IN THE COSMOS FIELD. III. OPTICAL IDENTIFICATION AND MULTIWAVELENGTH PROPERTIES OF A LARGE SAMPLE OF X-RAY-SELECTED SOURCES¹

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ABSTRACT

We present the optical identification of a sample of 695 X-ray sources detected in the first 1.3 deg² of the COSMOS *XMM-Newton* survey, down to a 0.5–2 keV (2–10 keV) limiting flux of $\sim 10^{-15}$ erg cm⁻² s⁻¹ ($\sim 5 \times 10^{-15}$ erg cm⁻² s⁻¹). In order to identify the correct optical counterparts and to assess the statistical significance of the X-ray-to-optical associations we have used the “likelihood ratio technique.” Here we present the identification method and its application to the CFHT *I*-band and photometric catalogs. We were able to associate a candidate optical counterpart to $\sim 90\%$ (626) of the X-ray sources, while for the remaining $\sim 10\%$ of the sources we were not able to provide a unique optical association due to the faintness of the possible optical counterparts ($I_{AB} > 25$) or to the presence of multiple optical sources, with similar likelihoods of being the correct identification, within the *XMM-Newton* error circles. We also cross-correlated the candidate optical counterparts with the Subaru multicolor and ACS catalogs and with the Magellan/IMACS, zCOSMOS, and literature spectroscopic data; the spectroscopic sample comprises 248 objects ($\sim 40\%$ of the full sample). Our analysis of this statistically meaningful sample of X-ray sources reveals that for $\sim 80\%$ of the counterparts there is a very good agreement between the spectroscopic classification, the morphological parameters as derived from ACS data, and the optical-to-near-infrared colors: the large majority of spectroscopically identified broad-line active galactic nuclei (BL AGNs) have a pointlike morphology on ACS data, blue optical colors in color-color diagrams, and an X-ray-to-optical flux ratio typical of optically selected quasars. Conversely, sources classified as narrow line AGNs or normal galaxies are on average associated with extended optical sources, have significantly redder optical-to-near-infrared colors, and span a larger range of X-ray-to-optical flux ratios. However, about 20% of the sources show an apparent mismatch between the morphological and spectroscopic classifications. All the “extended” BL AGNs lie at redshift < 1.5 , while the redshift distribution of the full BL AGN population peaks at $z \sim 1.5$. The most likely explanation is that in these objects the nuclear emission is not dominant with respect to the host galaxy emission in the observed ACS band. Our analysis also suggests that the type 2/type 1 ratio decreases toward high luminosities, in qualitative agreement with the results from X-ray spectral analysis and the most recent modeling of the X-ray luminosity function evolution.

Subject headings: galaxies: active — surveys — X-rays: diffuse background — X-rays: galaxies — X-rays: general

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1. INTRODUCTION

The primary goals of the Cosmic Evolution Survey (COSMOS; Scoville et al. 2007a) is to trace star formation and nuclear activity along with the mass assembly history of galaxies as a function of redshift and environment. Although there were early theoretical suggestions (e.g., Silk & Rees 1998), it was the tight relation observed in local galaxies between the mass of black holes and the velocity dispersion (the $M_{\text{BH}}-\sigma$ relation; see, e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000) and the fact that the locally inferred black hole mass density appears to be broadly consistent with the estimates of the mass accreted during the quasar phase (Fabian & Iwasawa 1999; Yu & Tremaine 2002; Elvis et al. 2002; Marconi et al. 2004; Merloni 2004) that made it clear that BH-driven nuclear activity and the assembly of bulge masses are closely linked. This realization has led to a large number of theoretical studies, suggesting feedback mechanisms to explain this fundamental link between the assembly of black holes (BH) and the formation of spheroids in galaxy halos (Di Matteo et al. 2005; Menci et al. 2004 and references therein).

In this framework, the hard X-ray band is by far the cleanest one for studying the history of accretion onto black holes in the universe, being the only band in which emission from accretion processes clearly dominates the cosmic background. The detailed study of the nature of the hard X-ray source population is being pursued by complementing deep pencil beam observations with shallower, larger area surveys (see Brandt & Hasinger 2005 for a recent review). Indeed, in recent years, large efforts have been dedicated to the optical-to-radio characterization of X-ray sources selected at different X-ray depths (see, among the most recent: the XBootes survey [Brand et al. 2006], the Serendipitous Extragalactic X-ray Source Identification [SEXSI; Eckart et al. 2006], the Extended Groth strip Survey [EGS; Georgakakis et al. 2007], and the HELLAS2XMM survey [Cocchia et al. 2007]). In particular, sizable samples of objects detected at the bright X-ray fluxes ($\geq 10^{-14}$ erg cm $^{-2}$ s $^{-1}$) over an area of the order of a few square degrees are needed to cover the high-luminosity part of the Hubble diagram and to obtain, together with samples from narrower and deeper pencil-beam observations, a well-constrained luminosity function with a similar number of sources per luminosity decade and redshift bin. The results from both deep surveys (Alexander et al. 2003; Barger et al. 2003; Giacconi et al. 2002; Szokoly et al. 2004; Hasinger et al. 2001) and shallow surveys (Fiore et al. 2003; Green et al. 2004; Steffen et al. 2004) have unambiguously unveiled a differential evolution for the low- and high-luminosity AGN population (Ueda et al. 2003; Barger et al. 2005; Silverman et al. 2005; Hasinger et al. 2005; La Franca et al. 2005). However, in these studies, the evolution of the high-luminosity tail of the obscured AGN luminosity function remains a key parameter still to be determined. The best strategy to address this issue is to increase the area covered in the hard X-ray band, and the corresponding optical-NIR photometric and spectroscopic follow-up, down to $F_{2-10 \text{ keV}} \sim 5 \times 10^{-15}$ erg cm $^{-2}$ s $^{-1}$, where the bulk of the XRB is produced.

Another important issue in AGN studies is the determination of the global spectral energy distributions (SEDs), over the widest possible frequency range, of different types of AGNs. Large samples of AGNs have been assembled using different selection criteria at different frequencies (e.g., radio, infrared, optical-UV, and X-ray); however, the lack of complete multiwavelength coverage for many of these samples makes the comparison of the properties of different classes of AGNs difficult. For example, while the average SED of optically and radio-selected bright quasars has been reasonably well known for more than a decade

(Elvis et al. 1994), little is still known about the SEDs of lower luminosity X-ray-selected AGNs and, in particular, of the obscured ones. This reflects into a significant uncertainty in the estimate of the bolometric correction (k_{bol} , i.e., the correction from the X-ray to the bolometric luminosity) to be applied to the observed luminosity of X-ray-selected AGNs and, in turn, on the estimates of the Eddington luminosities and of the masses of the central black holes (Fabian 2003). Recent results on high-redshift quasars have shown that the overall X-ray-to-optical spectral slope (α_{ox} , usually measured between 2500 Å and 2 keV, e.g., Tananbaum et al. 1979) and the corresponding k_{bol} , is a function of the AGN luminosity, with the low-luminosity objects having a lower k_{bol} (Vignali et al. 2003; Fabian 2003; Steffen et al. 2006). It is therefore clear that, in order to get a complete census of the luminosity output of AGNs, a multiwavelength project is needed: only in this way can the SEDs from radio to X-rays of a large sample of AGNs, selected at different frequencies, be compiled.

The *XMM-Newton* wide-field survey in the COSMOS field (hereafter COSMOS *XMM-Newton*) is an important step forward in addressing the topics described above. The ~ 2 deg 2 area of the *HST* ACS COSMOS Treasury program (Scoville et al. 2007b), bounded by $9^{\text{h}}57.5^{\text{m}} < \text{R.A.} < 10^{\text{h}}03.5^{\text{m}}$; $1^{\circ}27.5' < \text{decl.} < 2^{\circ}57.5'$, has been surveyed with *XMM-Newton* for a total of ~ 800 ks during AO3, and additional 600 ks have been already granted in AO4 to this project. When completed, COSMOS *XMM-Newton* will provide an unprecedentedly large sample of X-ray sources (≥ 2000), detected on a large, contiguous area, with complete ultraviolet to mid-infrared (including *Spitzer* data) and radio coverage, and almost complete spectroscopic follow-up granted through the zCOSMOS (Lilly et al. 2007) and Magellan/IMACS (Impey et al. 2007) projects.

The COSMOS *XMM-Newton* project is described in Hasinger et al. (2007). The X-ray point source counts from the first 800 ks of the *XMM-Newton* observations obtained so far are presented in Cappelluti et al. (2007), while the properties of extended and diffuse sources are described in Finoguenov et al. (2007). First results from the spectral analysis of AGNs with known redshift and high counting statistics are presented in Mainieri et al. (2007).

This paper presents the optical identification of X-ray point sources detected in this first year of the *XMM-Newton* data, and the first results on the multiwavelength properties of this large sample of X-ray-selected AGNs.

The paper is organized as follows: § 2 presents the multiwavelength data sets and describes the method used to identify the X-ray sources and its statistical reliability; the X-ray-to-optical and near-infrared properties are presented in § 3, along with preliminary results from the ongoing spectroscopic follow-up; in §§ 4 and 5 we discuss and summarize the most important results. Throughout the paper, we adopt the cosmological parameters $H_0 = 70$ km s $^{-1}$ Mpc $^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ (Spergel et al. 2003).

2. X-RAY SOURCE IDENTIFICATION

2.1. Optical and X-Ray Data Sets

The COSMOS *XMM-Newton* X-ray source catalog comprises 1390 different pointlike X-ray sources detected over an area of ~ 2 deg 2 in the first-year *XMM-Newton* observations of the COSMOS field (Hasinger et al. 2007; Cappelluti et al. 2007). In this paper, we limit our analysis to the sources detected in the first 12 COSMOS *XMM-Newton* observations (over a total of ~ 1.3 deg 2), for which both the X-ray source list and the optical catalogs were in place in 2005 June, and a substantial spectroscopic

follow-up already exists. These fields are flagged in Table 1 in Hasinger et al. (2007) and the average exposure time is of ~ 25 ks (~ 40 ks in the overlapping region, see Hasinger et al. 2007 for more details). The catalog paper with the identification from the entire COSMOS *XMM-Newton* survey is in preparation and will rely strongly on the identification procedure described here.

The 12 fields X-ray catalog (hereafter the 12F catalog) comprises 715 X-ray sources detected over a total of ~ 1.3 deg². From the 12F catalog we removed 20 sources classified as extended by the detection algorithm (see Cappelluti et al. 2007 for a description of the adopted detection algorithm). The observed X-ray emission from most of these sources is likely to be due either to groups/clusters of galaxies, or to the contribution of two or more X-ray sources close to each other. In both cases, an association with a unique optical counterpart is not possible. The total number of pointlike X-ray sources in the 12F catalog, detected in at least one of the X-ray bands, is therefore 695. Of these, 656 are detected in the soft band (0.5–2 keV), 312 in the medium band (2–4.5 keV; 38 only in the medium band), and 47 in the hard band (4.5–10 keV; 1 only in the hard). The X-ray centroids of these 695 pointlike X-ray sources have been astrometrically calibrated using the SAS task *eposcorr*, as described in Cappelluti et al. (2007); the resulting shift of $\sim 1''$ [$\Delta(\alpha) = 0.99''$; $\Delta(\delta) = 0''$] was applied to all source positions.

As a first step in the identification process, we used the *I*-band CFHT/Megacam catalog (McCracken et al. 2007), which, although slightly shallower than other available data (e.g., the Subaru *B*, *g*, *V*, *R*, *I*, and *z* photometric data, see Capak et al. 2007), has the advantage of having reliable photometry even at bright magnitudes ($I_{AB} \lesssim 19$), where the Subaru photometry starts to be significantly affected by uncertainties due to saturation.

At magnitudes brighter than $I_{AB} = 16$, only ~ 0.24 sources are expected by chance in a $3''$ error circle around all 695 X-ray sources on the basis of the background counts of the Megacam catalog; therefore we considered as secure optical identifications all 21 sources brighter than $I_{AB} = 16$ in the CFHT catalog and within $3''$ from the X-ray centroids. For all the remaining X-ray sources (674) we used the method described in § 2.2.

Then, we have cross-correlated the optical counterparts with the multicolor photoreddshift catalog (2005 June 22 release, Capak et al. 2007).²⁰ All the magnitudes are in the AB system (Oke 1970), if not otherwise stated.²¹

2.2. The Method

Typical error circles of *XMM-Newton* data ($\sim 5''$ radius at 95% confidence level²²) often contain more than one source in deep optical images, so that the identification process is not always straightforward. Obviously, this is particularly true when the candidate counterparts are faint. We therefore decided to use the “likelihood ratio” (LR) technique, in order to properly identify the optical counterparts (Sutherland & Saunders 1992; Ciliegi et al. 2003; Brusa et al. 2005). The LR is defined as the ratio between the probability that the source is the correct identification and the cor-

responding probability of being a background, unrelated object (Sutherland & Saunders 1992), i.e.,

$$LR = \frac{q(m)f(r)}{n(m)},$$

where $q(m)$ is the expected probability distribution, as a function of magnitude, of the true counterparts, $f(r)$ is the probability distribution function of the positional errors of the X-ray sources assumed to be a two-dimensional Gaussian, and $n(m)$ is the surface density of background objects with magnitude m . For the calculation of the LR parameters we followed and improved the procedure described in Brusa et al. (2005). For the $f(r)$ calculation, we used the statistical error as computed from the detection procedure and tested against the pattern of observations with extensive Monte Carlo simulations presented by Cappelluti et al. (2007). We also added in quadrature a systematic error of $0.75''$: as noticed by Loaring et al. (2005), this additional component may be due to residual uncertainties in the detector geometry and may represent a fundamental limit to the positional accuracy of *XMM-Newton*. We adopted a $3''$ radius for the estimate of $q(m)$, obtained by subtracting the expected number of background objects ($n(m)$) from the observed total number of objects listed in the catalog around the positions of the X-ray sources. Since on the basis of several results in the literature (see, e.g., Fiore et al. 2003; Della Ceca et al. 2004; Loaring et al. 2005), a large fraction of the possible counterparts are expected to be found within a $3''$ radius, this choice maximizes the statistical significance of the overdensity around the X-ray centroids, due to the presence of the optical counterparts. With this procedure, $q(m)$ is well defined up to $I_{AB} \sim 23.0$ – 23.5 . At fainter magnitudes, the number of objects in the error boxes around the X-ray sources turns out to be smaller than that expected from the field global counts $n(m)$. Formally, this would produce an unphysical negative $q(m)$, which, in turn, would not allow the application of this procedure at these magnitudes. The reason for this effect is the presence of a large number of relatively bright optical counterparts ($I_{AB} = 16$ – 23) close to the X-ray centroids. These objects, which occupy a non-negligible fraction of the total area of the X-ray error boxes, make it difficult to detect fainter background objects in the same area. As a consequence, the $n(m)$ estimated from the global field is an overestimate of the observed $n(m)$ at faint magnitudes in the X-ray error boxes. In order to estimate the correct $n(m)$ to be used at faint magnitudes in the likelihood calculation, we have randomly extracted from the Megacam catalog 1000 optical sources with the same expected magnitude distribution of the X-ray sources, and we computed the background surface density around these objects. As expected, we found that, indeed, the $n(m)$ computed in this way is consistent with the global $n(m)$ at $I_{AB} < 23.0$ but is significantly smaller than it (and smaller than the observed counts in the error boxes) at fainter magnitudes. Therefore, the input $n(m)$ in the likelihood procedure was the global one for $I_{AB} < 23$ and that derived with this analysis around sources with the same magnitude distribution as the “bright” optical counterparts for $I_{AB} > 23.0$. This allowed us to identify a few tens of very faint sources that would have been missed without this correction in the expected $n(m)$.

Figure 1 shows the observed magnitude distribution of all optical objects present in the *I*-band catalog within a radius of $3''$ around each X-ray source (*solid histogram*), together with the expected distribution of background objects in the same area, estimated using the procedure described above (*dashed histogram*). The difference between these two distributions (*dotted histogram*) is the expected magnitude distribution of the optical counterparts. The smooth curve fitted to this histogram (*dotted*

²⁰ The new version of the photometric catalog has been released at the time of the submission of this paper. The (small) differences between the two photometric catalogs do not affect the results presented in this work.

²¹ We adopted the following AB-Vega conversion: $I(\text{Vega}) = I(\text{AB}) - 0.4$, $R - K(\text{Vega}) = R - K(\text{AB}) + 1.65$.

²² Such a radius represents the radius for which $\sim 95\%$ of the *XMM-Newton* sources in the SSC catalog are associated with USNO A.2 sources (see Fig. 7.5 in The First *XMM-Newton* Serendipitous Source Catalogue: IXMM User Guide to the Catalogue 2003, Release 1.2, associated with Catalogue ver. 1.0.1, prepared by the *XMM-Newton* Survey Science Centre Consortium, <http://xmmssc-www.star.le.ac.uk/>).

FIG. 1.—Observed magnitude distribution of all the optical objects detected in the *I* band within a radius of $3''$ around each of the 674 pointlike X-ray sources fainter than $I_{AB} = 16$ (solid histogram), together with the expected distribution of background objects in the same area [$n(m)$, dashed histogram]. The difference between these two distributions (dotted histogram) is the expected magnitude distribution of the optical counterparts. The smooth curve fitted to this histogram (dotted line) has been used as input in the likelihood calculation [$q(m)$].

curve) has been used as the input in the likelihood calculation $q(m)$; the normalization of this curve has been set to 0.76, corresponding to the ratio between the integral of the $q(m)$ distribution and the total number of the X-ray sources. For the threshold value in the likelihood ratio we adopted $LR_{th} = 0.4$, which maximizes the sum of sample reliability and completeness in the present sample (Sutherland & Saunders 1992; Brusa et al. 2005).

2.3. Results

We computed the likelihood ratio for all the optical sources within $7''$ of the 674 X-ray centroids (a total of 2158 sources), finding 730 optical sources with $LR > LR_{th}$. The expected number of true identifications among these objects, computed by summing the reliability of each of them, is ~ 524 ($\sim 78\%$ of the total number of X-ray sources). The number of X-ray sources that have at least one optical source with $LR > LR_{th}$ is 587 (87% of the sample). The remaining 87 X-ray sources either are associated with $LR < LR_{th}$ counterparts (74) or do not have any optical counterpart in the catalog within $7''$ from the X-ray centroids (13). We have therefore visually checked these 87 unidentified sources. In 24 cases we found a clear, relatively bright optical source within the X-ray error circle in the *I*-band image. These objects were missing in the input CFHT catalog used to compute the likelihood ratio (mainly because close to bright objects and/or in CCD masked regions) or they were present but incorrectly associated with a much fainter magnitude. The *I*-band magnitudes of these 24 sources were therefore retrieved from the Subaru multicolor catalog and added to our list of possible counterparts. It is important to note that this problem affects only a minority of the X-ray source counterparts ($\sim 3.5\%$, most of them close to bright stars

and/or defects in the optical band images), and it can be easily solved with the adopted procedure.

We then ran the likelihood analysis again, this time using as input catalog the *K*-band (KPNO/CTIO) data extracted from the multicolor catalog (see Capak et al. 2007). The main advantage of also using this near-infrared catalog is that the X-ray to near-infrared correlation for AGNs is much tighter than the one in the optical bands (Mainieri et al. 2002; Brusa et al. 2005). Moreover, although the currently available *K*-band data are shallower than the optical ones, their use is potentially important to find the reddest optical counterparts, which are a not negligible fraction of the identifications of faint X-ray sources (see, e.g., Alexander et al. 2001).

Indeed, using this catalog and adopting the same value of $LR_{th} = 0.4$, we found likely counterparts for 46 of the 87 unidentified sources, which include all 24 discussed above and 22 additional red, faint sources with unambiguous identification in the *K* band (see also Mignoli et al. 2004).

Summarizing, on the basis of the likelihood analysis applied to the *I*-band and *K*-band catalogs, we have possible counterparts for 633 out of 674 X-ray sources (654 out of 695 when the 21 sources brighter than $I = 16$ are included). We have further tentatively divided the 654 proposed identifications into “reliable” and “ambiguous.” In the first class we include the 21 sources with $I_{AB} < 16$, the 559 sources for which either there is only one object with $LR > LR_{th}$ or the ratio between the highest and the second highest LR value in the *I* or *K* band is greater than 3, and the 46 sources identified only in the *K* band. The total number of objects in this class is therefore 626. The combined use of optical and NIR catalogs for the identification process led to a

TABLE 1
SUMMARY OF OPTICAL IDENTIFICATION OF POINTLIKE X-RAY SOURCES

Sources	All	Identified	Unidentified
Sources with $I < 16$ (I bright)	21	21	...
Sources with $I > 16$	674	587	87
Additional sources identified with K	...	46	...
Total	695	654 (626 reliable, ^a 28 ambiguous ^b)	41

^a We classified as “reliable” all 21 I -bright sources, the 46 sources identified from the K band, and 559 objects for which there is only one object with $LR > LR_{th}$ or the ratio between the highest and the second highest LR value in the I and/or in the K band is greater than 3. See § 2.3 for details.

^b We classified as “ambiguous” all the sources for which the ratio of LR values of the possible counterparts in the I band and in the K band is smaller than 3. See § 2.3 for details.

number of “reliable” counterparts larger than that inferred from the use of the optical catalog only (524). However, we note that $\sim 5\%$ of these reliable counterparts can still be misidentifications. The other 28 sources comprise all the sources for which the ratio of LR values in the I or K band of the possible counterparts is smaller than 3, and they are considered as ambiguous. In the following we tentatively identify these 28 X-ray sources with the optical counterparts with the highest LR value. Table 1 gives a summary of the identifications, while Figure 2 shows a few ex-

amples of finding charts for sources representative of the different types discussed above.

For the remaining 41 sources, the possible counterparts have on average faint or very faint optical magnitudes, none of them has $LR > LR_{th}$, and most of them lie at $\Delta(X - O) > 2''$. For a fraction of them the true counterpart of the X-ray source may indeed be very faint and/or undetected in the optical bands (see, e.g., Koekemoer et al. 2004). Another possibility is that the X-ray emission originates from a group of galaxies at high-redshift with

FIG. 2.—Upper panel: examples of I -band finding charts of sources with a unique optical counterpart or securely identified from the likelihood analysis. Middle panel: examples of I -band finding charts of sources with ambiguous counterparts. Lower panel: examples of K -band finding charts of sources identified from the K -band catalog. In all the panels, the circle is centered on the *XMM-Newton* position and has a radius of $5''$.

optically faint members: in this case, the X-ray extension of the putative group emission may be comparable to or smaller than the *XMM-Newton* PSF and the source can be classified as pointlike. Finally, a small fraction of these objects can be spurious X-ray sources, as suggested by the fact that the percentage of sources with low X-ray detection likelihood (e.g., $\text{DETML} < 9$; see Cappelluti et al. 2007 for a definition of DETML) is significantly higher for these unidentified sources ($\sim 30\%$) than for the optically identified X-ray sources ($\sim 10\%$). A detection with *Chandra* with significantly smaller error circles would definitively discriminate among these different possibilities.

2.4. Statistical Properties

The distribution of the X-ray-to-optical distances and of the *I*-band magnitudes for the X-ray sources identified as described in § 2.3 are shown in Figure 3 (*solid histograms*). For the X-ray sources with more than one optical counterpart with $\text{LR} > \text{LR}_{\text{th}}$, the X-ray-to-optical distance and the *I*-band magnitude of the optical object with the highest LR are plotted. In the lower panel the dashed histogram shows the lower limits to the I_{AB} magnitudes, corresponding to the brightest objects in the error circles, when the 41 X-ray sources without an optical identification are also added.

About 90% of the reliable optical counterparts have an X-ray-to-optical separation $[\Delta(X - O)]$ smaller than $3''$ (see Fig. 3, *inset in upper panel*), which is consistent with or even better than the $\sim 80\%$ within $3''$ found in *XMM-Newton* data of comparable depth (see, e.g., Fiore et al. 2003; Della Ceca et al. 2004; Loaring et al. 2005). The improvement is likely given by the combination of the accurate astrometry of the positions of the X-ray sources (tested with simulations in Cappelluti et al. 2007), and the full exploitation of the multiwavelength catalog (optical + *K*) for the identification process (that makes “reliable” a larger number of sources). In addition, because of the geometry of the final mosaic, most of the X-ray sources are closer than $5'$ to the center of at least one pointing, so that the corresponding PSF is not significantly deteriorated. The majority of the X-ray sources ($\sim 73\%$) have counterparts with I_{AB} magnitudes in the range $20 < I_{\text{AB}} < 24$, with two tails at fainter ($\sim 12\%$) and brighter ($\sim 15\%$) magnitudes. The median magnitude of optical counterparts is $I_{\text{AB}} = 21.65$.

These distributions do not change significantly if we make a different choice for the optical counterpart of the 28 “ambiguous” sources, i.e., the second most likely optical counterpart is considered. Therefore, from a statistical point of view the properties of these 654 X-ray sources (see Table 1) can be considered representative of the overall X-ray point source population, at the sampled X-ray fluxes.

2.5. Redshift Distribution

Spectroscopic redshifts for the proposed counterparts are available from the Magellan/IMACS observation campaign (193 objects; Impey et al. 2007; Trump et al. 2007) and the first run of zCOSMOS observations (25 objects; Lilly et al. 2007; J. P. Kneib 2006, private communication) and/or were already present in the SDSS survey catalog (48 objects; Adelman-McCarthy et al. 2006; Kauffmann et al. 2003²³), for a total of 248 independent redshifts (five of them of galactic stars). Spectroscopic information and classification is therefore available for a substantial fraction of our optical/infrared counterparts (248/654, $\sim 38\%$). The X-ray-to-optical distances and the *I*-band magnitude distributions of the

FIG. 3.—*Upper panel*: Histogram of the distances between the X-ray and optical counterparts for all 654 sources identified as discussed in § 2.3 (*solid histogram*) and the subsample of sources with spectroscopic redshift and classification (*shaded histogram*). The inset in the top right part of the plot shows the cumulative distribution of X-ray-to-optical distances for all the sources (*bold curve*) and for the subsample of sources with spectroscopic redshift (*dashed curve*). The dashed line at $3''$ marks the radius that encloses 90% of the X-ray counterparts (see discussion in § 2.2). *Lower panel*: Histogram of the *I*-band magnitudes distribution for the 633 primary identifications fainter than $I_{\text{AB}} = 16$. The solid and shaded histograms have the same meaning as in the upper panel. The dashed histogram shows the lower limit to the I_{AB} magnitudes, corresponding to the brightest objects in the error circles, for the 41 X-ray sources without an optical identification. The inset in the top right part of the plot shows the cumulative distribution of X-ray-to-optical distances for all the sources with $I > 16$ (*bold curve*) and for the subsample of sources with spectroscopic redshift (*dashed curve*).

²³ These sources have been retrieved from NASA Extragalactic Database (NED).

FIG. 4.—Redshift distribution for the sample of 243 sources with “secure” spectroscopic information from Magellan/IMACS data (Trump et al. 2007), the zCOSMOS project (Lilly et al. 2007), and from the SDSS archive (Adelman-McCarthy et al. 2006). The black filled histogram shows the contribution of spectroscopically classified BL AGNs. The redshift windows in which each broad line ($H\alpha$, $H\beta$, $Mg\ II$, $C\ III$, $C\ IV$) is visible in the IMACS/zCOSMOS spectra (wavelength range ~ 5400 – $9000\ \text{\AA}$) are also reported in the upper part of the figure.

subsample with spectroscopic redshift are shown as shaded histograms in both panels of Figure 3. The spectroscopic completeness is $\sim 50\%$ at $I_{AB} \leq 22$ and drops to $\sim 35\%$ at $22 < I_{AB} \leq 23$ and to $\sim 18\%$ at $23 < I_{AB} \leq 24$.

While a more detailed analysis of the optical spectra will be presented in future papers, based also on more data that are rapidly accumulating from the on-going projects, for the purposes of the present paper we divided the extragalactic sources (243 objects) into only two classes, following Fiore et al. (2003): objects with broad optical emission lines (BL AGNs, 126 in total) and sources without a clear, broad emission signature in the optical band, but with narrow emission or absorption lines (NOT BL AGNs, 117 in total). The latter class is therefore a mixed bag of different types of objects and comprises mainly narrow-lined AGNs, low-luminosity AGNs, starbursts, and normal galaxies. Figure 4 shows the redshift distribution for all the extragalactic sources in the spectroscopic sample (*solid open histogram*) along with the redshift distribution of the sources spectroscopically classified as BL AGNs (*filled histogram*). At low redshift ($z < 1$) the spectroscopic identifications are dominated by objects associated with NOT BL AGNs, while at high redshifts ($z > 1.5$) almost exclusively BL AGNs are detected. As already noted by Eckart et al. (2006) and Cocchia et al. (2007) the small number of narrow line objects at $z > 1.5$ is most likely due, at least in part, to selection effects: high-redshift narrow line AGNs are on average fainter in the I band than BL AGNs, and a significant fraction of them is expected to be below the optical magnitude limit for spectroscopic follow-up. This is shown in Figure 5, where the spectroscopic redshifts are plotted versus the I -band magnitudes of the optical counterparts, for both BL AGNs (*circles*) and NOT BL AGNs (*squares*): while BL AGNs show a large spread in I magnitudes over a large redshift range, the distribution of NOT BL AGNs in this plane is much narrower and shows a rapid rise in I magnitude with redshift (see also Fig. 14 in

FIG. 5.—Redshift vs. I -band magnitude for sources spectroscopically classified as BL AGNs (circles) and NOT BL AGNs (squares). [See the electronic edition of the Supplement for a color version of this figure.]

Trump et al. 2007). Conversely, the small number of BL AGNs at low z can be ascribed to several factors: (1) spectroscopic misclassification: given the wavelength range (~ 5400 – $9000\ \text{\AA}$) of both the IMACS and the VIMOS zCOSMOS data, at low redshift ($z \lesssim 1$) broad emission lines are not well sampled (e.g., $H\alpha$ is not visible at $z \gtrsim 0.4$, $H\beta$ is not visible at $z \gtrsim 0.8$, and $Mg\ II$ enters the spectral window at $z \sim 1$), while narrow lines (e.g., $[O\ II]$) and/or absorption features (e.g., Balmer break) can be more easily detected; (2) especially in the case of moderately weak Seyferts, the

FIG. 6.—Photometric redshifts vs. spectroscopic redshifts for the sources with secure redshifts in the 12F sample. Circles mark extended sources, triangles mark pointlike objects, on the basis of the ACS data. The dotted lines limit the locus for which $|z_{\text{spec}} - z_{\text{phot}}| < 0.15 \times (1 + z_{\text{spec}})$. [See the electronic edition of the Supplement for a color version of this figure.]

FIG. 7.—Full width at half-maximum (FWHM) vs. ACS I -band magnitude for all the sources (*small black symbols*) in the ACS photometric catalog. Overplotted as blue triangles (red circles) are the X-ray sources classified as pointlike (extended) from ACS. The histograms on the right part of the figure show the distribution of FWHM for the sources detected only in the soft band (*dashed histogram*) and for the sources detected only in the hard band (*solid histogram*). Both histograms are normalized to the total number of sources in each class.

relative contribution of the host galaxy and the AGN can be such that the broad lines are diluted in the stellar light and can be revealed only in high S/N spectra (Moran et al. 2002; Severgnini et al. 2003).

To obtain a complete redshift distribution for the X-ray sources, photometric redshifts should be computed for the sources without spectroscopic data. As a training sample, we used the code described in Bender et al. (2001) and tested it on the sample of objects with secure spectroscopic redshifts. For objects classified as “extended” in the ACS images (see § 3.1), we applied the same semiempirical templates of nonactive galaxies that have been used to compute the photometric redshift in the Fornax Deep Fields (see Gabasch et al. 2004 and references therein) and GOODS-South field (Salvato et al. 2007); in both applications, a $\sigma[\Delta z/(1+z)] \sim 0.05$ has been obtained. For objects that have been classified as pointlike sources, only AGN templates have been adopted (see also Mainieri et al. 2005 and references therein). In Figure 6 our best attempt so far is shown. Circles are optically extended X-ray–selected sources, while triangles represent pointlike objects. A relatively high fraction of both extended ($\sim 73\%$) and pointlike ($\sim 66\%$) sources have $|z_{\text{spec}} - z_{\text{phot}}| < 0.15(1 + z_{\text{spec}})$.

3. MULTIWAVELENGTH PROPERTIES

3.1. ACS Morphology: Stellar versus Extended Objects

The catalog of the primary optical counterparts of the X-ray sources was then cross-correlated with the 2005 June version of the ACS catalog (Leauthaud et al. 2007; Koekemoer et al. 2007), from the first *HST* cycle (Cycle 12), in order to gather some preliminary information on the morphological classification of the X-ray sources. Since the available ACS catalog does not cover the entire COSMOS *XMM-Newton* area analyzed here, we could use ACS information only for 524 optical sources, out of the total of 654. For these sources, we retrieved from the catalog the measure of the full width at half-maximum (FWHM, in image pixels), the ACS I -band magnitude and a parameter that defines the morphological classification (stellar or extended) on the basis of the analysis of the available data. Following Leauthaud et al. (2007) objects were divided into “stellar/pointlike” (hereafter pointlike) and “optically extended” (hereafter extended) on the basis of their position in the plane defined by the peak surface brightness above the background level and the total magnitude (see Fig. 6 in Leauthaud et al. 2007). The FWHM versus the I -band magnitude

FIG. 8.— $U - B$ vs. $B - V$ diagram for all the field objects with $B > 19$ (small black points) classified as pointlike in the full ACS catalog and with an error in all three optical bands smaller than <0.15 (Capak et al. 2007). The locus occupied by stars is clearly defined in this diagram, with the two densely populated regions in the blue (upper left of the black points envelope; hot subdwarf stars) and red (lower right; dwarf M stars) parts of the sequence. The horizontal solid line marks the color cut for the selection of ultraviolet excess objects. Overplotted as blue triangles are the counterparts of X-ray sources classified as pointlike from ACS, which satisfy the same selection in the photometric errors. Spectroscopically confirmed BL AGNs and NOT BL AGNs are also indicated (green and yellow symbols overplotted on the blue ones, respectively). Finally, the expected tracks of quasars from redshift 0 to ~ 3.5 in this color-color diagram is also reported (see text for further details).

is shown in Figure 7; in this figure, the blue triangles indicate sources classified as “pointlike,” and red circles indicate sources classified as “extended.” More than 50% of the primary IDs have stellar (or almost stellar; $\text{FWHM} < 3$ pixels) profile on ACS data. This is particularly true for the very soft sources (i.e., detected only in the soft band, see Fig. 7, *dashed histogram*). The situation is completely different for the really hard sources (i.e., no detection in the soft band, see Fig. 7, *solid histogram*), for which most of the counterparts ($\sim 80\%$) are associated with extended sources.

A subsample of 214 objects (108 BL AGNs, 101 NOT BL AGNs, 5 stars) has both spectroscopic information and ACS classification. In agreement with the expectations, we find a good correspondence between ACS and spectroscopic classification: the majority of BL AGNs are classified as pointlike by ACS (86/108, $\sim 80\%$), while the majority of NOT BL AGNs are classified as extended by ACS (85/101, $\sim 85\%$). A total of 38 sources show a “mismatch” between the morphological and spectroscopic classification, and we will come back to these sources later in the paper.

3.2. Optical Color-Color Diagrams for Pointlike Objects

Figure 8 shows the $U - B$ versus $B - V$ diagram for all field objects (small black points) with $B > 19$ classified as pointlike in the full ACS catalog and with an error in all three optical bands smaller than 0.15 mag (Capak et al. 2007). The locus occupied by stars is very well defined in this diagram, with the two densely populated regions in the blue (upper left of the black points envelope; hot subdwarf stars) and red (lower right; dwarf M stars) parts of the sequence. Most of the points at $U - B < 0.3$ (UVX objects) are expected to be AGNs at $z \lesssim 2.3$, while the objects on the right of the stellar sequence are likely to be compact galaxies classified as pointlike. Overplotted as blue triangles are the X-ray sources classified as pointlike from ACS that satisfy the same selection in the photometric errors. Spectroscopically confirmed BL AGNs and NOT BL AGNs are also indicated (following Fig. 5, green and yellow symbols overplotted on the blue ones, respectively). Finally, the expected track of quasars from redshift 0 to 3.5 in this color-color diagram is also reported, computed using

FIG. 9.— I -band magnitude (Vega system) vs. the soft (0.5–2 keV) flux for all the primary counterparts in the sample (all symbols), and the subsamples of objects classified as pointlike (blue circles) and extended (red circles) from ACS morphology. The shaded area represents the region typically occupied by known AGNs (e.g., quasars and Seyferts) along the correlation $\log(X/O) = 0 \pm 1$. Spectroscopically confirmed BL AGNs and NOT BL AGNs are also indicated (green and yellow symbols, respectively). Asterisks (*) mark the objects tentatively identified with stars (see §§ 3.2 and 3.3). Lower limits to the I -band magnitude correspond to the magnitude of the brightest objects in the error circles of the unidentified X-ray sources.

the SDSS AGN template from (Budavari et al. 2001; see also Capak et al. 2007 for further details).

It is quite reassuring that the majority ($\geq 80\%$) of X-ray-selected pointlike quasars occupy the classical QSO locus and would have been selected as outliers from the stellar locus in this color-color plot. A few (5–8) sources are within or close to the locus of “red” stars. So far we have spectroscopic data only for two of these objects and both of them are stars. All these sources are detected only in the soft X-ray band and show a low (< 0.1) X-ray-to-optical flux ratio²⁴ (X/O) and are therefore likely to be stars. A similar number (8–10) of X-ray sources are within or close to the locus of blue stars. The spectroscopic identifications available for these objects include three BL AGNs at $z \geq 1.4$; a fourth object is likely to be a star on the basis of the bright I -band magnitude and low X/O ratio.

3.3. X-Ray-to-Optical Flux Ratio

Another independent check on the agreement between optical identification, morphological analysis, and spectroscopic break-

down is shown in Figure 9, where the I -band magnitude (Vega system) is plotted versus the soft X-ray flux for all the X-ray sources (black open symbols), ACS-pointlike objects (blue symbols), and ACS-extended sources (red symbols).

As discussed in § 2.1, the sources brighter than $I_{AB} = 16$ are identified “a priori”: all of them have been visually inspected, and the majority of them turned out to be associated with bright stars and have pointlike morphology from ACS. A sample of 8 additional stars has been tentatively identified on the basis of the information from $U - B$ versus $B - V$ diagram, the bright optical magnitudes and the low X-ray-to-optical flux ratio. All the sources identified with stars (a total of 25) are plotted as asterisks (*) in Figure 9 and they constitute $\sim 4\%$ of the soft X-ray-selected sample. This value is similar to that reported in the *ROSAT* Deep Survey (Lehmann et al. 2001) and in the ChaMP survey (Green et al. 2004), from the optical identification of large samples (100–300) of soft X-ray-selected sources at limiting fluxes similar to that of COSMOS.

If objects associated with stars are removed, pointlike sources occupy preferentially the locus in this plane with X/O in the range 0.1–10, where most of the broad-line quasars from previous optical and soft X-ray-selected surveys lie (Fig. 9, hatched region).

²⁴ The I -band flux is computed by converting I magnitudes into monochromatic fluxes and then multiplying them by the width of the I filter (Zombeck 1990, p. 100).

FIG. 10.— $R - K$ color vs. K -band magnitude (Vega system) for the X-ray source counterparts with ACS information. Symbols as in Fig. 9. Sources spectroscopically identified with BL AGNs (green) and NOT BL AGNs (yellow) are also highlighted. The histogram on the right part of the figure shows the distribution of $R - K$ colors for the sources with $HR > -0.3$ (i.e., candidate X-ray obscured AGNs, solid histogram) and the sources detected only in the soft band ($HR = -1$, dashed histogram).

Also most of the extended sources are within the same range of X/O ratio, but with more significant tails toward both low and high values of X/O. For most of these sources, thanks to the superb ACS resolution, it will be possible to resolve the nucleus and the host galaxy. Optically bright (i.e., $X/O < 0.1$) extended sources are preferentially identified with nearby galaxies, in which the optical luminosity is mainly due to the integrated stellar light; for the majority of them, the high level of observed X-ray flux suggests that some activity is taking place in their nuclei (see, e.g., Comastri et al. 2002).

3.4. Optical-to-Near-Infrared Colors

Figure 10 shows the $R - K$ versus K -band magnitude (Vega magnitudes) for the subsample of objects with ACS morphological information (excluding spectroscopically confirmed stars). In addition, sources spectroscopically identified with BL AGNs are marked with green symbols, while sources identified with NOT BL AGNs are marked by yellow symbols. A significant difference in the $R - K$ distributions for pointlike and extended sources is present: while the widths of the two distributions are similar ($\sigma \sim 0.8$ for both of them), extended sources are significantly redder ($\langle R - K \rangle = 4.05 \pm 0.05$) than pointlike sources ($\langle R - K \rangle = 2.91 \pm 0.06$). When the spectroscopic information

is also considered, objects with red $R - K$ colors are preferentially associated with NOT BL AGNs (yellow circles), while blue objects are preferentially associated with BL AGNs (green circles).

We have then investigated the distribution of the $R - K$ colors as a function of the X-ray hardness ratio (HR), a widely used tool to study the general X-ray spectral properties of X-ray sources when the number of counts is inadequate to perform a spectral fit. Mainieri et al. (2007, Paper IV of this series) have shown that 99% of the sources with $HR > -0.3$ in their subsample can be fitted by a $\Gamma = 1.8$ – 2 power-law continuum absorbed by a column density (N_H) larger than 10^{22} cm^{-2} . Conversely, sources detected only in the soft band (i.e., $HR = -1$) are most likely unobscured.

The hardest sources ($HR > -0.3$, see Fig. 10, solid histogram on the right) are mostly associated with red and very red objects ($R - K > 4$). This indicates an excellent consistency between optical obscuration of the nucleus as inferred from ACS (extended morphology), optical-to-near-infrared colors, and the presence of X-ray obscuration as inferred from the hardness ratio (see also Alexander et al. 2001; Giacconi et al. 2002; Brusa et al. 2005; Mainieri et al. 2007). Conversely, sources detected only in the soft band (i.e., $HR = -1$, dashed histogram) have preferentially blue $R - K$ colors (>60% of the sources have $R - K < 4$), typical of

FIG. 11.—Distribution of the absolute B -band magnitude for BL AGNs (solid histogram, upper panel) and NOT BL AGNs (solid histogram, lower panel) in the subsample of objects with ACS information and spectroscopic classification. In both panels the shaded histograms give the contribution of outliers in each class, i.e., “extended” BL AGNs and “pointlike” NOT BL AGNs, respectively. The dashed line at $M_B = -23$ marks the “classic” separation between Seyfert and quasars.

those of optically selected, unobscured quasars (Barkhouse & Hall 2001). It is interesting to note, however, that the observed correspondence between hard (soft) X-ray colors and red (blue) optical-to-near-infrared colors is not a one-to-one correlation (see also, e.g., Georgantopoulos et al. 2004; Brusa et al. 2005). In fact, as shown for example by the tail toward high $R - K$ colors of the dashed histogram in Figure 10, a non-negligible fraction of red objects is associated with very soft X-ray sources.

3.5. Outliers: Mismatch between Morphological and Spectroscopic Classification

As discussed in § 3.1, there is a relatively good agreement (on the order of 80%) between the morphological and spectroscopic classifications for the subsample of sources for which these informations are available. However, there are 22 (~20%) BL AGNs classified as “extended” in ACS and 16 (~16%) NOT BL AGNs classified as pointlike by ACS.

The absolute magnitude is an obvious quantity to examine in order to try to understand why for these sources the morphological and spectroscopic classifications do not agree with each other. Figure 11 shows the distribution of rest-frame, absolute B -band magnitude for the 209 extragalactic sources that have both morphological (ACS) and spectroscopic classification, separately for BL AGNs (upper panel) and NOT BL AGNs (lower panel). The black filled histograms show the observed distribution for the “outliers,” i.e., “extended” BL AGNs and “pointlike” NOT BL AGNs, respectively. In order to minimize the uncertainties in the K -correction, the absolute B -band magnitudes have been computed from the apparent magnitude in the optical filter closest to the rest-frame B band at any given redshift.

All the “extended” BL AGNs lie at redshift < 1.5 , while the redshift distribution of the full BL AGN population peaks at $z \sim 1.5$ (see Figs. 4 and 5). The fact that ACS reveals an extended component is likely to be due to the fact that the nuclear emission in these objects is not dominant with respect to the host

galaxy emission, at least in the observed ACS band. Indeed, the average M_B of the extended BL AGN sources lies in the low tail of the M_B distribution of the entire BL AGN population and typically in the Seyfert regime, taking $M_B = -23$ as the “classical” separation between Seyferts and QSOs (Schmidt & Green 1983).

The unresolved nature of “pointlike” NOT BL AGNs is more puzzling. It can be due, at least in part, to the definition we adopted for the segregation of stellar objects: especially at high redshift, the ratio between the peak flux and the total magnitude cannot be such to define them “extended.” However, we note that most of them occupy the high-luminosity tail of the distribution of M_B of the overall population of NOT BL AGNs, and therefore can be classified as high-luminosity, type 2 quasars from the available optical spectroscopy (see also Mainieri et al. 2007 for a more detailed analysis of the rest-frame X-ray properties). Moreover, they tend to be “bluer” (i.e., less absorbed) in the optical-to-near-infrared colors (Fig. 10, yellow symbols on blue points), suggesting that we are seeing more directly the emitting nucleus.

Figure 12 shows the absolute B magnitude as a function of the 0.5–10 keV luminosity (as computed in Mainieri et al. 2007) for the subsample of sources with spectroscopic redshift and good X-ray counting statistics. Circles mark BL AGNs (blue for the pointlike and yellow for the extended sources), while triangles mark NOT BL AGNs (cyan for the pointlike and red for the extended sources). Sources with $L_X < 10^{42}$ erg s $^{-1}$ are mostly associated with bright ($I < 18$), extended objects (red triangles) at $z < 0.2$; two of them are detected only in the soft band. Among the two sources detected also at higher energies, there is the candidate Compton thick AGN discussed in Hasinger et al. (2007).

The region at luminosities higher than 10^{44} erg s $^{-1}$ is mainly populated by pointlike, BL AGNs (blue circles). Only 8 sources classified as NOT BL AGNs lie in this part of the diagram: the high X-ray luminosity classifies them as candidate type 2 QSO (Mainieri et al. 2007). Conversely, the majority of the sources in the middle part of the X-ray luminosity region are associated with extended, NOT BL AGNs (red triangles) and low-redshift BL AGNs (Seyfert 1 galaxies, yellow circles).

4. DISCUSSION

Comparing the optical color-color properties of AGNs in the COSMOS field with those of field objects (see Fig. 8), we estimate that X-ray data with a flux limit of $S_{0.5-2 \text{ keV}} \sim 10^{-15}$ erg cm $^{-2}$ s $^{-1}$ recover at least half (50%) of the AGN candidates that would be selected on the basis of their ultraviolet excess ($U - B < 0.3$) at $B \lesssim 23$ (see Zamorani et al. 1999 for a similar estimate at a somewhat brighter X-ray flux from *ROSAT* observations in the Marano field). This fraction of 50% has been obtained assuming that all objects with ultraviolet excess are AGNs. Since at these magnitudes blue stars and compact galaxies may represent ~30% of the samples of pointlike objects with ultraviolet excess (Mignoli & Zamorani 2001), we conclude that the efficiency of present X-ray data in detecting AGNs with ultraviolet excess at $B \leq 23$ is likely to be as high as 70%. We note that the large majority of the BL AGNs selected via the UV excess method have $M_B < -23$ (see Fig. 11) and are therefore classified as quasars, confirming previous results (see, e.g., Zamorani et al. 1999 and references therein). We also note, however, that the photometric catalog we use has deeper limiting magnitudes with respect to all the previous studies on optically selected UV-excess QSOs and therefore we start to explore and pick up lower luminosity (e.g., Seyfert-like) objects up to $z \sim 1.5$. On the other hand, a significant fraction (~40%) of the X-ray-selected AGNs, especially those without broad lines in their optical spectra, would have not been easily selected as AGN candidates on the basis of purely optical criteria,

FIG. 12.—Absolute rest frame B -band magnitude vs. the logarithm of the full (0.5–10 keV) X-ray luminosity (erg s^{-1}). Symbols are as follows: blue circles, spectroscopically confirmed BL AGNs classified as *pointlike* from ACS; yellow circles, spectroscopically confirmed BL AGNs classified as *extended* from ACS; cyan triangles, spectroscopically confirmed NOT BL AGNs classified as *pointlike* from ACS; red triangles, spectroscopically confirmed NOT BL AGNs classified as *extended* from ACS. The horizontal solid line marks the “classic” optical transition between Seyfert and quasars.

either because of colors similar to those of normal stars or field galaxies at $z \sim 1$ –3 or because of morphological classification not consistent with that of pointlike sources (see Fig. 10). These results highlight the need for a full multiwavelength coverage to properly study and characterize the AGN population as a whole.

With the current spectroscopic coverage ($\sim 38\%$) the observed redshift distribution and spectroscopic classification of identified X-ray sources could be biased against low-redshift BL AGNs and high-redshift NL AGNs (see § 2.5 and Trump et al. 2007 for a more detailed discussion on AGN selection effects in COSMOS; see also Treister et al. 2004). However, according to the most recent modeling of the X-ray luminosity function evolution (e.g., Ueda et al. 2003; Barger et al. 2005; Hasinger et al. 2005; La Franca et al. 2005), the paucity of low-redshift BL AGNs and high-redshift obscured NL AGNs may be at least partly real and due to a luminosity dependent evolutionary behavior of X-ray–selected sources. The space density of high-luminosity ($L_X > 10^{44} \text{ erg s}^{-1}$) quasars decreases steeply below $z \simeq 1$, while the decrease of the space density of lower luminosity objects in the same redshift range is much slower (see, e.g., Fig. 9 in Fiore et al. 2003). Moreover, there is now increasing evidence that the relative ratio between obscured and unobscured AGNs is a decreasing function of the

X-ray luminosity (Ueda et al. 2003; Hasinger 2004; La Franca et al. 2005; Akylas et al. 2006). As a consequence, at low redshifts the X-ray source population is dominated by low-luminosity, often obscured AGNs, while at higher redshifts luminous unobscured quasars take over. This is in qualitative agreement with the observed change of the type 2/ type 1 ratio (R) in the present sample when the typical Seyfert (32/33, $R \sim 1$ at $L_X \sim 10^{42}$ – $10^{44} \text{ erg s}^{-1}$) and quasar (8/44, $R \sim 0.18$ at $L_X > 10^{44} \text{ erg s}^{-1}$) luminosities are considered (see Fig. 12).

At a limiting flux of $2 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the soft band, where the sky coverage has decreased to 50% of the total 1.3 deg^2 area covered by the 12F pointings, no object at $z > 3$ is present so far in our current spectroscopic sample. On the one hand, the lack of high-redshift sources could be due, at least in part, to the still limited spectroscopic completeness, which is on the order of 50% at $I_{AB} < 22$ and about 25% at fainter magnitudes, with no spectroscopic redshifts for $I_{AB} > 24$. As a comparison, Murray et al. (2005) have 14 $z > 3$ quasars in their 9 deg^2 XBootes survey, at a limiting flux about 1 order of magnitude brighter than our survey and with a similar spectroscopic completeness. By rescaling the area and the limiting fluxes, this would translate into $\sim 3 z > 3$ quasars in the COSMOS XMM-Newton 12F area, which is still

consistent with zero being observed. On the other hand, the number of AGNs at $z > 3$ expected from population synthesis models (see also Hasinger et al. 2007; Gilli et al. 2007) is ~ 30 , and a random sampling at $\sim 25\%$ completeness, to take into account the current follow-up spectroscopy, would therefore predict about 7 quasars at $z > 3$, which are not observed. The forthcoming spectroscopic observations will increase the spectroscopic completeness, allowing to verify if a sizable number of high-redshift ($z > 3$) quasars is present among the optically faintest counterparts and among the optically unidentified X-ray sources, or if some of the model assumptions, mainly based on extrapolations of the lower redshift ($z < 3$) luminosity functions, should be refined.

5. SUMMARY

In this paper we presented the optical identifications for a large subsample (~ 700) of X-ray sources detected in the first 1.3 deg^2 of the COSMOS *XMM-Newton* observations, down to a $0.5\text{--}2 \text{ keV}$ limiting flux of $\sim 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$. The X-ray counterparts have been identified in optical (*I*-band) and near-infrared (*K*-band) catalogs, making use of the maximum-likelihood technique. The combined use of the two different catalogs allowed us to test the identification procedure and turned out to be extremely useful both for isolating input catalogs problems and for identifying optically faint counterparts. Overall, 90% (626) of the X-ray sources have been unambiguously associated with optical or near-infrared counterparts. Twenty-eight X-ray sources have 2 possible optical counterparts with comparable likelihood of being the correct identification. These sources have been classified as “ambiguous,” and we tentatively identify them with the optical counterpart with the highest LR value. The sample of proposed identifications therefore comprises 654 objects, while for the remaining 41 X-ray sources it was not possible to assign a candidate counterpart. We will use the forthcoming *Chandra* data (granted in AO8) to definitively discriminate the ambiguous and false associations and we also predict that a large fraction of these very faint, unidentified objects will be resolved with the inclusion of *Spitzer* (IRAC and MIPS) data in the source identification.

We then cross-correlated our proposed optical counterparts with the Subaru multicolor catalog (Capak et al. 2007), the *HST* ACS data (Leauthaud et al. 2007), and the first results from the massive spectroscopic campaigns in the COSMOS field (Trump et al. 2007; Lilly et al. 2007). Our analysis reveals that for $\sim 80\%$ of the X-ray source counterparts with spectroscopic redshifts (a total of 248) there is a good agreement between the spectroscopic classification, the morphological parameters, and optical-to-near-infrared colors: the large majority of spectroscopically identified BL AGNs have a pointlike morphology on ACS data (see § 3.1), blue optical colors in color-color diagrams (see § 3.2), and an X-ray-to-optical flux ratio typical of optically selected quasars (see § 3.3). Conversely, NOT BL AGNs are on average associated with extended optical sources, have significantly redder optical-to-near-infrared colors, and span a larger range of X-ray-to-optical flux ratios (see §§ 3.3 and 3.4). When the X-ray information is also considered, we found that hard X-ray sources are preferentially associated with extended sources and are “reddish” ($\sim 60\%$ with $R - K > 4$; see also Mainieri et al. 2007), while sources detected only in the soft band are mostly associated with pointlike objects and have “blue” optical-to-near-infrared colors.

Comparing the optical color-color properties of AGNs in the COSMOS field with those offield objects (see Fig. 8), we estimate that X-ray data with a flux limit of $S_{0.5-2 \text{ keV}} \sim 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ recover $\sim 70\%$ of the AGNs selected on the basis of their ultra-

violet excess at $B \lesssim 23$. This fraction will rise up to 90% – 100% at $S_{0.5-2 \text{ keV}} \sim 5 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$, the final depth of the COSMOS *XMM-Newton* survey.

About 20% of the sources show an apparent mismatch between the morphological and spectroscopic classifications. Our analysis indicates that, at least for BL AGNs, the observed differences are largely explained by the location of these objects in the redshift-luminosity plane (see § 3.5). Our analysis also suggests a change of the type 2/type 1 ratio as a function of the X-ray luminosity, in qualitative agreement with the results from X-ray spectral analysis (Mainieri et al. 2007) and the most recent modeling of the X-ray luminosity function evolution (Figs. 5 and 12).

Although the Magellan/IMACS and VIMOS/zCOSMOS spectroscopic campaigns will continue to obtain redshifts for AGNs in the COSMOS field, we expect that a fraction on the order of 30% of the sources will not have spectroscopic redshifts, due to the faintness of their optical counterparts ($\sim 15\%$) and the limitation of multi-slit spectroscopy due to mask efficiency (Impey et al. 2007). We have tested a photometric code specifically designed to obtain redshifts for X-ray-selected sources on the subsample of sources with spectroscopic data and showed that it is possible to obtain a reasonable estimate of the sources redshifts [$|z_{\text{spec}} - z_{\text{phot}}| < 0.15 \times (1 + z_{\text{spec}})$], for $\sim 70\%$ of the sources. We plan to use the same code to derive the redshifts for the faintest X-ray counterparts.

Summarizing, we were able to perform a combined multi-color, spectroscopic and morphological analysis on a statistical and meaningful sample of X-ray sources, and this work represents one of the most comprehensive multiwavelength studies to date of the sources responsible of most of the XRB (see also Eckart et al. 2006). This work is just the first phase of COSMOS AGN studies; the results presented in this paper clearly show the need for a full multiwavelength coverage to properly study and characterize the AGN population as a whole. As more data become available, the selection of COSMOS AGNs by all available means—X-ray, UV, optical, near-IR, and radio—will build up to give the first bolometric selected AGN sample, fulfilling the promise of many years of multiwavelength studies of quasars.

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