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SOFT X–RAY PROPERTIES OF SEYFERT GALAXIES IN THE ROSAT ALL–SKY SURVEY

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ABSTRACT

We present the results of ROSAT All–Sky Survey observations of Seyfert and IR–luminous galaxies from the Extended 12 μm Galaxy Sample and the optically–selected CfA Sample. Detections are available for 80% (44/55) of the Seyfert 1s and 34% (23/67) of the Seyfert 2s in the 12 μm sample, and for 76% (26/34) of the Seyfert 1s and 38% (6/16) of the Seyfert 2s in the CfA sample. Roughly half of the Seyferts (mostly Seyfert 1s) have been fitted to an absorbed power–law model, yielding an average photon index of Γ=2.26$\pm$0.11 for 43 Seyfert 1s and Γ=2.45$\pm$0.18 for 10 Seyfert 2s, with both types having a median value of 2.3.

The soft X–ray luminosity correlates with the 12 μm luminosity, with Seyfert 1s having relatively more soft X–ray emission than Seyfert 2s of similar mid–infrared luminosities, by a factor of 1.6 $\pm$ 0.3. Several physical interpretations of these results are discussed, including the standard unified model for Seyfert galaxies. Infrared–luminous non–Seyferts are shown to have similar distributions of soft X–ray luminosity and X–ray–to–IR slope as Seyfert 2s, suggesting that some of them may harbor obscured active nuclei (as has already been shown to be true for several objects) and/or that the soft X–rays from some Seyferts 2s may be non–nuclear.

A soft X–ray luminosity function (XLF) is calculated for the 12 μm sample, which is well described by a single power–law with a slope of –1.75. The normalization of this XLF agrees well with that of a hard X–ray selected sample. Several of our results, related to the XLF and the X–ray–to–IR relation are shown to be consistent with the hard X–ray observations of the 12 μm sample by Barcons et al.

Subject headings: galaxies: active — galaxies: luminosity function — galaxies: nuclei — galaxies: Seyfert — surveys — X–rays: galaxies

1. Introduction

The enormous interest in ROSAT's potential for the study of active galactic nuclei (AGN) is indicated by the fact that roughly one–third of pointed observation time is spent on these objects. Initial analysis of the ROSAT All–Sky Survey (hereafter RASS; Voges 1992, Brinkmann 1992) shows that ROSAT sees the vast majority of catalogued Seyfert 1 galaxies. The average power–law photon index of ROSAT AGN (QSOs and Seyferts) is $\sim 2.4 \pm 1.0$ (Bade et al. 1995), similar to that found by Hasinger et al. (1991) in their analysis of deep field observations. The values measured by ROSAT are typically much steeper than the canonical hard X–ray (2—20 keV) value of ∼1.7 measured by HEAO–1 and the Einstein SSS, and sometimes even steeper than the lower resolution, soft X–ray (0.2—4.5 keV) slopes found by the Einstein IPC (e.g., the average IPC photon index for radio–quiet quasars of 2.0 (Wilkes & Elvis 1987); also see the review by Mushotzky, Done, & Pounds 1993, for summaries of these earlier, higher–energy missions). However, certain types of Seyferts, in particular "ultra–soft" X–ray–emitting Seyferts, narrow–line Seyfert 1 galaxies (NLS1s) and previously published Seyfert 2s typically have steeper ROSAT spectra. As discussed in this paper, the X–ray photon index is a critical observational parameter, with competing physical models for AGN predicting different observed values.

In the current paper, we present of ROSAT All–Sky Survey (RASS) data for two samples of Seyfert galaxies: those in the mid–infrared selected 12–Micron sample (Rush, Malkan, & Spinoglio 1993, hereafter RMS) and the optically selected CfA Sample (Huchra & Burg 1992). As discussed in the next section, these two samples were chosen because they are large and well–defined, and, being bright and nearby, they will complement studies of higher–redshift AGN. In § 2. we discuss the selection of targets and the observations; in § 3. we present the results of the X–ray observations, and make comparisons with observations at longer wavelengths; in § 4. various physical interpretations of the results are discussed, with particular emphasis given to the unified model of Seyfert galaxies; in § 5. the Seyfert galaxy soft X–ray luminosity function is calculated from the 12 μm sample; and in § 6. we summarize the results.

2. Target Selection and Observations

2.1. Advantages of 12–Micron Selection

All of the Seyfert galaxies for which we have obtained RASS data were selected from the Extended 12 Micron Galaxy Sample (RMS) and the optically selected CfA Seyfert Galaxy Sample (Huchra & Burg 1992). These galaxies are ideally suited to expand our knowledge of the X–ray properties of Seyferts for several reasons. First, the 12 μm sample is the most complete and unbiased large sample of bright AGNs compiled to date (RMS). Spinoglio & Malkan (1989) showed that the wide range of types of Seyfert galaxies emit an approximately constant fraction of their bolometric luminosity in the mid–IR near 12 μm (and Spinoglio et al. 1995 showed the same to be true for non–Seyfert spiral galaxies with a lower constant of proportionality). Thus selecting at 12 μm is a good approximation to selecting a sample based on bolometric flux, and will therefore result in a sample which has an amount of Seyfert 1s and Seyfert 2s which accurately reflect the relative numbers of such objects in the local universe. In contrast, the more common far–IR (e.g., 60 μm) selection technique is biased towards reddened objects which emit a large fraction of their energy at long wavelengths as a result of dust–reprocessing of higher–energy photons, while optical/UV samples will be biased towards less dusty objects. The unbiased nature of the 12 μm sample will allow us to derive reliable statistical results applicable to all Seyferts as a class. Although the CfA sample was selected at optical wavelengths and is suspected of suffering from some selection affects (Persic et al. 1989; Huchra & Burg 1992), it also is better than most other samples for studying Seyfert galaxies (as has been done extensively with Einstein IPC data, by Kruper, Urry, & Canizares (1990)). This is because of the thorough and well–defined nature of this sample, as the CfA Seyfert sub–sample was defined by complete spectroscopic observations of the entire CfA sample, the latter containing every object with m_{pg} brighter than 14.5 in an area covering most of the northern hemisphere (over 2000 objects in total; Huchra & Burg 1992).

Second, the 12 μm–selected galaxies are qualitatively different from those AGN analyzed previously in the X–rays. Observing targets such as these is necessary to determine the *range* of X–ray properties among AGN, from the highest to the lowest luminosities, and across the full range of multiwavelength parameter space. For example, Moran et al. (1992) pointed out that most of the Seyfert 2s popular with previous observers have polarized broad lines, and are restricted to those with relatively strong radio luminosities and UV excesses (e.g., as found by the Markarian surveys). Compared to these Markarian Seyfert 2s (many of which were observed but not detected by Ginga—Awaki 1993), the Seyfert 2s we observed have redder optical/infrared colors, weaker and smaller radio sources, larger starlight fractions, and steeper Balmer decrements—more representative of the entire class of Seyfert 2s. Similarly, our Seyfert 1s span over 4 orders of magnitude in soft X–ray luminosity, from below 10^{42} $erg\ s^{-1}$ to above 10^{46} $erg\ s^{-1}$. This will allow us to determine whether the X-rays are relatively more dominant, in the low– and high–luminosity objects (see, for example, the discussion in § 4.). Furthermore, many previous samples of AGN studied at X–ray wavelengths have been been devoted to more distant, high–luminosity objects (often referred to as quasars, which are presumably the higher–luminosity, less–resolved counterparts to Seyferts). The two samples we discuss contain mostly nearby, bright Seyfert galaxies, which will complement higher–redshift studies.

The RASS also detected 6 of the 37 IR–luminous non–Seyferts in the 12 μm sample, and has upper limits for all but two of the others. These are objects which do not have the strong and/or broad optical emission lines usually used to identify a Seyfert, but which do have high far–infrared luminosities (integrated 8–120 μm luminosities above $6 \cdot 10^{44}$ $erg\ s^{-1}$), typical of Seyferts (RMS). In § 3.2., we compare the RASS and multiwavelength properties of these objects to those of our Seyferts. This is one way to search for galaxies which may harbor hidden active nuclei. For example, Boller et al. (1992) compared the RASS to a catalog of 14,708 extragalactic IRAS sources, finding ∼250 positional coincidences. Ten of these are spirals with non–Seyfert optical classifications, but which reach X–ray luminosities of a few 10^{43} $erg\ s^{-1}$, at least one order of magnitude higher than any non–Seyferts detected by Einstein (Boller et al. 1996a). Optical observations of these galaxies show them to have Liner or HII–region galaxy spectra. Such X–ray luminous spirals may have buried AGNs, extreme starbursts, or they may constitute a new class of X–ray emitting galaxies. Similarly, Ward et al. (1994) obtained optical spectrophotometry of several very X–ray luminous galaxies in the RASS, finding some to be AGN and others to be starburst/HII region galaxies. Bade & Schaeidt (1994) identified RASS sources on objective prism plates, finding fourteen emission–line galaxies to have the optical spectra of starburst or Seyfert 2 galaxies. Like previously known narrow–line X–ray galaxies such as NGC 2110, NGC 2992, and NGC 5506, some of these objects have Seyfert 2–like optical spectra but Seyfert 1–like soft X–ray luminosities above 10^{43} $erg\ s^{-1}$.

In addition to finding new Seyferts, comparison with IR–luminous non–Seyferts can also be used to quantify whether the soft X–ray emission in some Seyferts may be produced by the normal processes of stellar evolution, as in classic starburst nuclei like NGC 7714 (Weedman et al. 1981). This is most likely the case for those Seyferts which emit strongly in the thermal infrared, but relatively weakly in the X–rays. Even without accurate spectral fitting, the strength of the X–rays alone can be used to determine whether a non–stellar central engine is required in the Seyferts and IR–luminous non–Seyferts in our sample (e.g., as calculated in Boller et al. 1996a; see discussion in § 3.2.). However, even when an X–ray emitting central engine is not required, it may still be present if the object is heavily absorbed in the ROSAT band.

2.2. ROSAT All–Sky Survey Observations

The data presented in this work were obtained during the ROSAT All–Sky Survey in 1990—1991, using the Position Sensitive Proportional Counter (PSPC) in the 0.1–2.4 keV energy band. ROSAT was launched from Cape Canaveral on June 1, 1990 and, after a detailed calibration and verification phase, the All–Sky Survey started on July 30, 1990 (Brinkmann 1992). The survey was performed by scanning the sky along great circles in ecliptic longitude, resulting in images in the form of stripes 360° long and 2° wide, corresponding to the field of view of the XRT+PSPC. The total exposure of a target ranges from ∼500 secs for objects near the ecliptic equator to up to a few 10^4 secs for circumpolar targets. The focal plane instrumentation, developed and built at the MPE, consists of two redundant PSPCs which are operated in gas flow mode. The PSPC provides spatial and spectral resolution over the full field of view of 2° which varies slightly with photon energy E. The energy resolution is $\Delta E/E = 0.41/\sqrt{E_{keV}}$. The on–axis angular resolution is limited by the PSPC to about 25″, and the on–axis effective collecting area, including the PSPC efficiency, is about 220 cm^2 at 1 keV (Brinkmann 1992).

We have extracted nearly complete soft X–ray data (count rates or upper–limits, and in many cases spectral parameters from a power–law fit) from the RASS for the 12 μm and CfA samples of Seyfert galaxies, and for the IR–luminous non–Seyferts in the 12 μm sample. This includes 54 of the 55 Seyfert 1s, 59/68 Seyfert 2s, and 35/37 IR–luminous non–Seyferts in the 12 μm sample (RMS), as well as 47 of the the 50 Seyferts in the optically–selected CfA Galaxy Sample (Osterbrock & Martel 1993). Thus, the total number of objects with ROSAT data presented here is 173 (the brighter ∼half of the CfA Seyferts, including 22 objects reported here, are also in the 12 μm sample; this total also includes data from our pointed PSPC observations for the five objects MKN 1239, NGC 5005, NGC 5135, NGC 424, and NGC 4388—Rush & Malkan 1996). Actual ROSAT detections are available for 80% (44/55) of the Seyfert 1s and 34% (23/67) of the Seyfert 2s in the 12 μm sample, and for 76% (26/34) of the Seyfert 1s and 38% (6/16) of the Seyfert 2s in the CfA sample. This is approximately the same as the Einstein detection rates for the Seyfert 1s, and slightly higher than that for the Seyfert 2s, as estimated by detections and upper limits of objects in our sample in the literature (e.g., Kruper et al. 1990; Kriss, Canizares, & Ricker 1980).

2.3. Calculations

Applying the standard RASS processing to Photon Event Files, we extracted count rates in a 300″ circle centered on the IRAS coordinates of each of our sources (typically accurate to 10—15″), subtracting the background as determined in a concentric annulus with inner and outer radii of 500 and 1500″, respectively (with the size of the circle and/or annulus adjusted when necessary to avoid other sources). Two–sigma (or better) detections are given when the background–subtracted source count rate is greater than twice the square root of the source–plus–background count rate (most detections are above the 5σ level). Two–sigma upper limits to the count–rate are given when this is not the case. Uncertainties on the detections are quoted at 1σ. When over 50 source counts were available, we fit the spectra to an absorbed power–law function. For each object, we calculate the flux in one of three ways (as flagged in Table 1): (i) we have an unabsorbed[2], monochromatic flux at 1 keV, calculated directly from the model fit; (ii) there were not enough counts for a model fit (between 30 and 50), but only to estimate Γ from hardness ratios (assuming Galactic N_H, as described thoroughly in Bade et al. 1995). We then calculate an unabsorbed 0.1–2.4 keV flux from the RASS count rate, using the energy–to–count conversion factor, as a function of Γ and N_H (fixed at $N_{H,gal}$), as given by the XSPEC software (distributed by the NASA/Goddard Space Flight Center). These conversion factors are obtained by integrating the ROSAT XRT+PSPC effective area (convolved with the photon redistribution matrix) over frequency, and are the same as those used in the model fits in case (i); (iii) there were not enought counts for a model fit, or to estimate Γ from hardness ratios (less than 30). Thus, we used the median value of Γ=2.3 to obtain the conversion factor (which contributes errors no worse than a factor of $\sim$2 even if the actual slopes are extremely steep or flat, and usually errors of less than $\pm$50%). The conversion from count rate to unabsorbed monochromatic flux then was done in the same way as in case (ii). In either case, we calculate the unabsorbed monochromatic flux or unabsorbed integrated flux from the other using the power–law model:

$$F_{0.1\text{–}2.4\ \mathrm{keV}} = \int_{0.1}^{2.4} F_\nu \, d\nu$$

with

$$F_\nu \propto \nu^{1-\Gamma}.$$

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[2]We use the terms “unabsorbed” and “absorbed” to refer to that flux which is measured before and after passing through N_H in the Galaxy, respectively. This distinction does not consider any affects of internal absorption in the target galaxy. Later (esp. in § 4.), we use the terms “intrinsic” and “observed” to distinguish between the flux emitted from the Seyfert nucleus in the target galaxy and that which would be measured after passing through absorbing material of any type in the target galaxy, but still before it is absorbed by N_H in our Galaxy.

The luminosity in each case is calculated from the flux assuming an H_0 of 75 km s^{-1} Mpc^{-1}.

In Table 1, we give the following data: (1) object name; (2) object type and sample (12 μm and/or CfA); (3–4) the 1950 equatorial coordinates; (5) the galactic N_H value (from Heiles & Cleary [1979] for the most southern objects, and from Dickey & Lockman [1990] or Stark et al. [1992] for the rest); (6) the RASS count rate (a 2σ–or–better detection with the associated 1σ uncertainty, or a 2σ upper limit); (7) the unabsorbed, monochromatic flux, νF_ν, at 1 keV; (8) the photon index, Γ (usually from the fit; cases where this is estimated from hardness ratios are flagged); and (9) the unabsorbed, integrated 0.1—2.4 keV luminosity.

3. Results

3.1. X–Ray Properties

Figures 1*a* and 1*b* show histograms of the photon index and unabsorbed soft X–ray luminosity, respectively. The average photon index is Γ=2.26$\pm$0.11 for 43 detected Seyfert 1s and Γ=2.45$\pm$0.19 for 10 detected Seyfert 2s (uncertainties representing one standard deviation). The two classes have identical median values of Γ=2.29 and 2.28, respectively. A K–S test applied to the photon index gives only a 19.8% probability of the Seyfert 1s and 2s being drawn from different samples, implying that the slight difference in the average values is not significant. However, for our measured luminosities, the median value of 42.75 for 57 Seyfert 1s is nearly an order of magnitude higher than the value of 41.86 for 24 Seyfert 2s. A K–S test shows these two distributions to be drawn from different samples with a 99.98% probability. This could simply represent intrinsically distinct distributions of L_{SX} for the two types of Seyfert. Or, the two distributions could be intrinsically similar, but with the luminosities of the Seyfert 2s systematically suppressed, for example by scattering and/or obscuration, as discussed in § 4. In either case, this difference in luminosity is similar to that found by Barcons et al. (1995), who compared the 5 keV monochromatic luminosities of Seyfert 1s to those of Seyfert 2s, finding the former to be 7 times more luminous on the average, indicating that the luminosity difference between the two classes spans most well–observed X–ray energies.

In Figure 2, we plot Γ versus the unabsorbed 1 keV flux. We have done the fits fixing N_H to the Galactic value, which provides acceptable fits in most cases. Allowing N_H to vary as an additional free parameter yields values for N_H consistent with the Galactic value in all but a few cases, implying that most objects in this plot are not heavily absorbed. We do see, however, that four of the five flattest objects are also Seyfert 1s with very low fluxes ($\nu F_{1keV} < 10^{-11.5}$; the other one, IC 4329, is one of the objects for which the best–fit N_H was significantly larger than the Galactic value). Since the plotted fluxes are unabsorbed, i.e. not affected by N_H in the Galaxy, these few faint galaxies probably have additional *internal* absorption, which would only be obvious with broader energy coverage and many more photons per spectrum. The effect of this (unaccounted for) extra soft X–ray absorption is to make the observed spectra appear harder, giving directly the flatter values for Γ. It is also likely that these faint, flat objects are among the more dust–obscured and reddened Seyfert 1s, since NGC 3227 and NGC 4235 have been observed to be Seyfert 1.5s (Osterbrock & Martel 1993), and MKN 1040 and MKN 6 are listed as Seyfert 1.5s in NED[3], implying that these objects have relatively faint broad–line regions. Such absorption effects are likely to affect only the most internally obscured objects, however, and typically would lead to differences of only a few to a few tens of a percent in the calculated luminosity (as verified by fits to the pointed observations in Rush & Malkan 1996, which were done both

[3]the NASA–IPAC Extragalactic Database

with N_H free and with N_H set to the Galactic value, and which included a couple of heavily obscured objects). This uncertainty is much less than the range of values spanned by Figure 2. For one of the two extremely steep objects, NGC 2992, the value of Γ measured (4.10) is highly uncertain because high intrinsic absorption limited the fit to energies above 0.8 keV (see note to Table 1). The most extreme object (Γ=4.46) is 3C120. The photon index for this object is calculated from hardness ratios, and is thus less certain than that for other objects. This value for Γ also may be higher than the true slope if the value for $N_{H,gal}$ used in the hardnes–ratio–to–Γ calculation (explained in Bade et al. 1995) is higher than the actual value affecting this observation. This is quite possible, since the value assumed for N_H is $10.7 \cdot 10^{20} cm^{-2}$, the second highest of the 173 objects we observed. Because of the dependence on Γ of the unabsorbed flux in the model calculations, these two objects also have uncertain fluxes, further questioning their position on this diagram.

We also investigated any systematic effects of nuclear reddening in the entire sample, by comparing Γ to various indicators of reddening/dust content on large scales (the 25–60 μm, 12–60 μm, and 2.2–25 μm flux ratios, and the 60 μm luminosity). None of these plots showed any correlation. An inverse correlation between Γ and any of these parameters, would have indicated that those objects with flatter measured values of gamma are more intrinsically absorbed, and that the amount of soft X–ray absorption is related to general dustiness/redness in the target galaxy. However, the lack of any such correlations implies that the flat–Γ objects are not more heavily obscured on large scales and, thus, that the measured photon indices are intrinsic, *or* that any such internal absorption which may be present is not related to the large–scale reddening in the galaxy.

In addition to altering the fluxes and slopes of detected objects, absorption—in particular absorption in our Galaxy—could also affect which objects are detected by ROSAT at all. Figure 3 shows a plot of the unabsorbed 1 keV flux versus the Galactic value of N_H towards the source. For objects above $\log \nu F_{1keV} = -12.3$ there is no significant correlation, but almost all low–flux objects are detected through low values of $N_{H,gal}$. (This is show by the small box in the figure, which was positioned specifically to minimize the effect discussed here, to remove any possible binning affects caused by the position of a few objects.) This implies that faint objects observed in directions of high $N_{H,gal}$ suffer sufficient extinction to have been undetected in the RASS. Since the distribution on the sky of Seyferts as a function of brightness is independent of any Galactic properties, we can use this plot to estimate roughly the number of faint Seyferts in directions of high $N_{H,gal}$ missed by the RASS. Below $3.75 \times 10^{20}\mathrm{cm}^{-2}$, where extinction is minimal, we find 23 and 17 12 μm–sample Seyferts detected with 1 keV fluxes above and below $10^{-12.3}$, respectively. However, above $3.75 \times 10^{20}\mathrm{cm}^{-2}$, we detect 20 Seyferts brighter than $10^{-12.3}$, and only 7 less luminous, implying that there may be ∼8 X–ray–faint objects missing from the latter group. These missing Seyferts might be accounted for by the objects in our sample at high values of N_H with upper limits in the RASS.

3.2. Correlations with the Far-Infrared

Figure 4*a* shows a plot of the unabsorbed, integrated soft X–ray luminosity from the RASS versus the monochromatic IRAS 12 μm luminosity. The higher and lower solid lines represent fits to the 53 Seyfert 1s and 24 Seyfert 2s detected in either sample, respectively (nearly identical fits are obtained when fitting only the 12 μm or CfA samples alone). These fits have slopes of 1.53 and 1.66, respectively, indicating that the soft X–ray luminosity increases faster than linearly with the 12 μm luminosity, approximately as $L_{SX} \propto L_{12\mu m}^{1.5}$ (we note that the scatter is large enough that one of these luminosities can only be used to predict the other to within a factor of about ±5, if the Seyfert type is known). This trend is in the opposite direction of what one would expect if a significant Malmquist bias were present in this plot, as was shown to be the case for early reports that the X–ray luminosity scaled less than linearly with optical luminosity (Chanan 1983). Since the 12 μm luminosity is closely proportional to bolometric luminosity for both Seyfert 1s and 2s (Spinoglio & Malkan 1989; Spinoglio et al. 1995), this relation shows either (1) that more bolometrically luminous objects are less absorbed (intrinsically) in the soft X–rays (Reichert et al. 1985), or (2) that they are relatively more efficient at producing soft X–rays in the first place. Since the 12 μm luminosity represents both nuclear and galactic emission, the latter relation could simply imply that the more luminous objects are more nuclear–dominated.

However, we note that a plot of the soft X–ray flux versus the 12 μm flux does not show a significant correlation for either Seyfert type. It is well known that, when no true correlation exists, as may be indicated by pure scatter in a flux–flux diagram, the effect of redshift may introduce a spurious correlation in the luminosity–luminosity diagram. However, the reverse scenario is also possible: since luminosity is the physically meaningful parameter, it may be that the luminosity–luminosity diagram reflects the true correlation, while introducing the distance factor may smear out the correlation in a flux–flux diagram. Therefore, to determine whether there is truly a correlation, we have also fit the data in the luminosity–luminosity diagram in a way that accounts for the upper limits. This can discriminate between the two cases just mentioned, because, as Feigelson (1996) points out, "A correlation found between luminosities, when nondetections are taken into account, is a true correlation. The flux–flux diagram will reveal the intrinsic relationship between luminosities only under very limited circumstances (no censored points, linear relationship)." (Also see Feigelson & Berg 1983 and Feigelson 1992 for further discussion of statistical methods for astronomical data with nondetections.)

Because many of our soft X–ray luminosities, especially for the Seyfert 2s, are only upper limits, we analyzed these data using ASURV Rev 1.2 ("Astronomy SURVival

Analysis" software; La Valley, Isobe, & Feigelson 1992), which implements the methods presented in Feigelson & Nelson (1985) and Isobe, Feigelson, & Nelson (1986). ASURV provides statistical tests for the presence of a linear correlation between two variables when either one (in our case, the RASS luminosities) is heavily censored (e.g., mostly upper limits). In general, this is done by making certain assumptions which allow one to estimate the distribution function of the censored data (e.g., by maximum–likelihood techniques), incorporating the information supplied by the detected points. Using these methods, the generalized Kendall's tau correlation coefficient (Brown, Hollander, & Korwar 1974) indicates a 99.99% probability that a correlation is present for both the Seyfert 1s and the Seyfert 2s. The binned two–dimensional Kaplan–Meier distribution and associated linear regression coefficients of Schmitt (1985) were used to determine the linear best–fits, shown as the long–dashed lines, which have slopes of 1.46 ± 0.14 for the Seyfert 1s and for the 1.21 ± 0.07 Seyfert 2s. The Seyfert 1 fit has the same slope, and is shifted down slightly, compared to the fit for detections only. This is as expected, since only 18 of the 71 Seyfert 1s in this plot are not detected in both parameters. However, the Seyfert 2 fit is lower, as expected since most (40 of 64) points are censored in at least one variable. The ASURV fit the the Seyfert 2s is also flatter than the fit to the detections only, but still has a slope significantly greater than one. Thus, in each of these relations, L_{SX} rises greater than linearly with 12 μm luminosity, with either the same slope for Seyfert 1s and 2s, or a slightly flatter slope for the Seyfert 2s. Almost the same relation is derived by Barcons et al. (1995), who find $L_{5\ keV} \propto L_{12}^{1.3}$ for Seyferts in the 12 μm sample (both types), with the Seyfert 1s having relatively ~ 7 times the X–ray luminosity as Seyfert 2s as compared to the 12 μm luminosity.

We further note that the actual relation for Seyfert 2s (i.e. that which would be obtained if we knew the soft X–ray luminosities for all Seyfert 2s in the 12 μm sample) may fall even lower. This is because the survival–analysis routines used assume that both the detected and undetected objects were drawn from the same homogeneous sample, which can overestimate the importance of the censored data in determining the fits. This was seen, for example, in RMS, where we used ASURV to fit a line to a plot of L_{6cm} vs. $L_{60\mu m}$, for Seyferts in the 12 μm sample, including many upper limits to the 6 cm luminosity. When we later (Rush, Malkan, & Edelson 1996) obtained 6 cm detections, we found the actual fit to be parallel, but lower, i.e. 0.3 magnitudes less $\log L_{6cm}$ for a given $\log L_{60\mu m}$.

Although the slopes may be similar for each Seyfert type, we see the two fits to be clearly shifted from each other, with the soft X–ray luminosity of Seyfert 2s ranging from 1.1 to 1.3 orders of magnitude lower than that of Seyfert 1s for a given 12 μm luminosity, as the latter ranges from 42.5 to 44.5 (according to the ASURV fits). In fact, *all* objects with $\log L_{SX}/L_{12\mu m} > -1$ are Seyfert 1s, values from –2 to –1 include both 1s and 2s, while most objects below –2 are Seyfert 2s (the dotted lines indicate $\log L_{SX}/L_{12\mu m} = -1$ and –2). Similar results were obtained by Green, Anderson, & Ward (1992) who showed that galaxies with $\log L_{SX}/L_{60\mu m} > -2$ (using Einstein 0.5—4.5 keV fluxes) are almost certain to show broad–line optical emission. This is quantitatively consistent with our result, assuming typical colors for Seyferts of $\log F_{60}/F_{12} = 0.5 - 1.0$ (RMS) and assuming an Einstein photon index of 1.9 (typical for our sample, as estimated from the 20 Seyferts in our sample with measured IPC photon indices in Kruper et al. 1990).

3.3. Infrared–Luminous Non–Seyferts

The X–ray–to–IR relation of IR–luminous non–Seyfert galaxies in our sample is distinct from that of Seyfert 1s, but is distributed roughly the same as the the Seyfert 2s. This is shown in Figure 4*b* (and was also evident in Figure 1*b*), where we plot the soft X–ray versus 12 μm luminosities (the same parameters as in Figure 4*a*), showing only the detections for clarity, and also plotting the IR–luminous non–Seyferts in the 12 μm sample (as stars). In this plot, the six IR–luminous non–Seyferts detected in our sample have values of $\log L_X/L_{IR}$ between –2.8 and –1.8. This Seyfert 2–like ratio indicates that these objects may harbor active nuclei which would be obscured by dust, or, conversely, that the 12 μm and soft X–ray flux from some Seyfert 2s may be from starbursts. Boller et al. (1996a), for example, quantify this by calculating the maximum L_X that could be emitted from various stellar X–ray sources (O–stars, galactic superwinds, X–ray binaries, or SNRs). They calculate that a value of $\log L_X/L_{IR}$ of $\sim 10^{-2}$ is just around the maximum ratio which can be produced by SNRs, and therefore higher values require that additional nuclear emission must be present. Such objects would be observed as AGN (probably Seyfert 2s) only upon inspection of high–SNR, high–resolution spectroscopy, or perhaps requiring IR spectroscopy if the AGN is completely obscured by the dust in the optical. That this may indeed be the case is highlighted by the fact that three of the Seyfert 2s in this plot (individually labeled) were actually included in our IR–luminous class at the start of this project, but have since been discovered to be AGN upon inspection of optical spectra, and *each* of these objects was studied spectroscopically specifically because their high soft X–ray luminosities made them interesting Seyfert candidates. For example, realizing the power of strong X–rays as an indicator of buried AGN, we proposed a pointed ROSAT PSPC observation of the most X–ray–luminous non–Seyfert in the sample, MCG–4–2–18 ($L_X = 42.9$ and $\log L_X/L_{IR} = -1.2$). That observation was eventually awarded to Ebeling who measured a count rate and fit a power–law to the PSPC spectrum which are consistent with our RASS data, indicating no variability in the 1.5–2 years between those observations Furthermore, optical spectroscopy of that object now identifies it as a Seyfert galaxy (H. Ebeling, private comm.). Two similarly X–ray luminous galaxies (also labeled in the figure—NGC 3147 and NGC 3822) were recently identified as Seyfert 2s from their optical spectra by Moran, Halpern, & Helfand (1994), who also were interested in these galaxies because of their notable X–ray strength (as reported in Boller et al.—1992, 1993). Given these identifications, the remaining supposed non–Seyferts, especially the most X–ray–luminous ones (e.g., N6240 and ESO 286-IG19, which have $L_X = 42.3$ and 42.7, respectively), are likely candidates to have an obscured active nucleus.

4. Interpretation and the Unified Model of Seyferts

One explanation for the observed differences between Seyfert 1s and Seyfert 2s, with regards to both their soft X–ray and multiwavelength properties, is the obscuring–torus model for Seyferts (Antonucci & Miller 1985). In this model, the two types of Seyferts are intrinsically similar objects[4], with a molecular torus (or similar anisotropic obscuring material) surrounding the innermost regions. This torus shields the central engine and broad–line region gas from our direct view in edge–on objects (i.e., Seyfert 2s) but not in face–on objects (i.e., Seyfert 1s). However, the energy emitted in the inner region can be scattered into our line of sight by a cloud of electrons above and/or below the torus. Thus, if the soft X–rays originate from radii within the torus, then the amount we observe from Seyfert 2s is only the fraction which is intercepted and scattered towards our line of sight as it escapes. Since the cross–section to electron scattering is wavelength–independent, this would result in Seyfert 2s having the same distribution in Γ as Seyfert 1s, as is seen in Figures 1 and 2 above. However the scattering would only transmit a small fraction of the

[4]As mentioned in § 2.3., we use the terms "intrinsic" and "observed" to distinguish bewteen nuclear emission from the target galaxy and that which has possibly been absorbed, obscured, and/or scattered by N_H or other material in the target galaxy. Both terms are used to refer to the flux or luminosity as would be measured before being absorbed by N_H in our Galaxy.

soft X–rays (proportional to $\tau_{es} \times \frac{\Omega_c}{4\pi}$, where Ω_c is the solid angle of the scattering region seen by the nucleus—Miller, Goodrich, & Matthews 1991), so a given Seyfert 2 would also have a lower observed soft X–ray luminosity than an intrinsically similar Seyfert 1, also as seen in Figure 1*b*.

Furthermore, according to this model, if the 12 μm emission arises totally or primarily from regions at large radii from the center, i.e. mostly outside of the torus, or if the optical depth of the torus to such photons is low enough to allow them mostly to pass through, then it would be mainly isotropic and would be the same in Seyfert 1s and 2s. This is also consistent with what we see in Figures 4 above, namely that Seyfert 1s and 2s span a similar range in mid–infrared luminosity, but that for a given value of this low–frequency luminosity, the soft X–ray emission from Seyfert 2s is one and a half orders of magnitude lower. Combining these effects, we have a picture of Seyfert galaxies in which face–on objects have a certain intrinsic range in the soft X–ray and 12 μm luminosities and soft X–ray slopes, and are optically identified as Seyfert 1s. When viewed at high inclinations, the torus obscures the innermost regions, suppressing the observed soft X–ray luminosity, and shielding the broad–line region to cause the objects to be optically identified as Seyfert 2s, but without changing either the soft X–ray slope or lower–frequency luminosity. Thus, the unified model is consistent with all of our data if, as predicted by the difference between the soft X–ray luminosities of Seyfert 1s and 2s, the scattering efficiency is typically $\sim$1–5%, with not too much variation from one galaxy to another.

An alternative explanation is that the soft X–rays we are observing from Seyfert 2s are not scattered, but suffer higher amounts of internal absorption than those from Seyfert 1s (Lawrence & Elvis 1982). Either case would have the effect of lowering the observed soft X–ray flux, while not changing the lower–frequency flux (which would not be absorbed). However, we prefer the scattering explanation for two reasons: (a) there is little independent evidence for significant amounts of internal absorption in the soft X–rays (except in a few individual cases, e.g., NGC 1068) in papers which analyze ROSAT pointed observations of Seyfert 2s (e.g., Turner, Urry, & Mushotzky 1993; Rush & Malkan 1996); and (b) internal absorption would flatten the observed photon index in Seyfert 2s and thus the distribution of Γ would be significantly different between the two types of objects, contrary to what we see in Figures 1 and 2. However, we note that the results of the K–S test on Γ may be fortuitous, given the small number of Seyfert 2s used, and the possible selection effects which could result if the faint, undetected objects have a have a different distribution of Γ than does the sample as a whole. A variation of this possibility is that the nuclear soft X–rays from many (if not most) Seyfert 2s are *totally* internally absorbed, and what we observe is extended emission only, e.g., as discussed above when comparing the Seyfert 2s to IR–luminous non–Seyferts. However, this would probably also predict a different distribution of Γ between the two Seyfert types.

Another alternative to the scattering picture, which has already been used to explain some objects, is that there may be multiple components measured in the ROSAT passband in Seyferts. For example, recent studies of Einstein–selected "ultra–soft X–ray emitting AGN" (e.g., Puchnarewicz et al. 1992; Córdova et al. 1992; Thompson 1994) have identified an entire class of objects with clearly distinguishable soft X–ray components below 0.5 keV, possibly corresponding to a $\sim$ 10 eV blackbody. This sample contains a large number of narrow–line objects (e.g., Seyfert 2s, narrow–line X–ray galaxies, narrow–line Seyfert 1s) as compared to other X–ray selected samples (which they suggest may be caused by face on BLRs, or BLRs far from the central source), but is otherwise similar to such samples (e.g., in optical luminosity, and optical Fe II emission). Higher–energy components to the soft X–rays, such as iron and/or oxygen emission lines around 0.7–0.8 keV have also been suggested as a likely source for a soft excess in some individual Seyferts, particularly in Seyfert 2s (e.g., Turner et al. 1993; Rush & Malkan 1996). However, the distributions of gamma shown in Figure 1 makes this seem unlikely as a *universal* explation for the differences between 1s and 2s. For example, to account for the higher X–ray luminosities of Seyfert 1s, one might propose that their ROSAT flux is explained by an underlying power–law plus a soft or ultra–soft excess, but that we only measure the latter in Seyfert 2s (either because the power–law is component non–existent or because it is simply not observed, perhaps being obscured by the torus). But this explanation would require Seyfert 2s to have systematically steeper ROSAT spectra, which is not observed in our samples.

Finally, we note that a combination of these explanations is possible. If, for example, some objects in our sample have more internal absorption, this would tend to flatten the observed slope. On the other hand, if these same objects also have a soft or ultra–soft excess (which could originate in the same region producing the extra absorption), this factor would steepen the observed slope. These two factors could cancel each other, leaving the measured photon index roughly unchanged, as compared to the situation in which neither factor exists. This would be consistent with what we find in Figure 1, namely distributions of Γ which are not significantly different between Seyfert 1s and Seyfert 2s.

5. X–Ray Luminosity Functions

An X–ray luminosity function (XLF) has been derived for the Seyferts in the 12 μm sample (type 1 and type 2, including the few NLS1s and NLXGs). We have used the V/V_{max} method (Schmidt 1968; Schmidt & Green 1983),

$$\Phi = \frac{4\pi}{\Omega f \Delta L} \sum \frac{1}{V_{max}},$$

where Omega is the area of sky surveyed, f is the fraction of objects in our sample observed by the RASS (i.e., located in the area of sky surveyed by ROSAT, whether detected or not), and ΔL is the bin size. We have computed V_{max} individually for each galaxy in the sample. In doing so, we have followed the method of Edelson (1987) for calculating the luminosity function of a sample at a wavelength other than the wavelength at which the sample was defined (that work calculated a radio LF for an optically–selected sample). We thus use

$$V_{max} = \min(V_{max,survey} V_{max,RASS}),$$

which represents the maximum volume of space accessible by an object detected at the survey wavelength (mid–IR for the 12 μm sample) and at X–ray wavelengths. This is equivalent to deriving the XLF from the 12 μm luminosity function and from the bivariate IR–X–ray luminosity distribution function (Elvis et al. 1978; Meurs & Wilson 1984). We stress, however, that this luminosity function is only that for the 12 μm sample, with certain IR–X–ray selection effects (and can at best be considered as a lower limit to the true X–ray space density of Seyferts). In particular, the most extreme objects (i.e., those with 12 μm fluxes below the 12 μm survey limit, yet soft X–ray count rates above the RASS detection limit) will be excluded, having not been included in the sample in the first place, even though they would have been detected in the soft X–rays. (Fortunately, the IR–X–ray relation shown in Figures 4 suggests that such objects would be rare.)

The XLF for the Seyferts in the 12 μm sample is given in Table 2 and plotted in Figure 5. The errorbars represent the 90% confidence interval, based on Poisson statistics, calculated using the equations from Gehrels (1986) which are accurate for even very small numbers of data points. The solid line shows a least–square fit with a single power–law (the points are weighted by the number of objects they represent, as noted by the numbers under the solid squares, hence the line looks higher than it would if each point were weighed evenly). This fit shows the XLF to be a power–law with a well-defined slope of –1.75 and a correlation coefficient of $r = -0.98$. An F–test indicates that no significant improvement to the fit is obtained when using a broken power–law over a single power–law.

To compare our ROSAT soft X–ray XLF to that from the HEAO1 hard X–ray sample of Piccinotti et al. (1982; hereafter P82), we converted their values (both data points and fit) to the ROSAT passband. We assumed a spetrum which has a 0.1—2.0 keV photon index of 2.3 (the median from our sample), a 2.0—10.0 keV photon index of 1.7 (typical for hard X–ray samples as mentioned above), with these two components normalized to the same level at 2.0 keV. (Any reasonable variations in the slopes chosen to convert their XLF contribute negligible differences to the characteristics of this plot.) We also converted their XLF to the units of $H_0 = 75$ km s^{-1} Mpc^{-1} used in this paper. The resultant XLF from P82 is shown by the dotted line and open squares. The error bars also represent 90% confidence interval, calculated in the same way as those for the 12 μm sample (using Gehrels 1986; each of their bins includes only 3 objects, and thus all have the same sized error bars). Although the P82 XLF is steeper (slope = –2.5), the two XLFs agree within the errors over the whole range in L_X spanned by both samples, as shown by the shorter solid line, which shows the fit to our sample above $\log L_X = 42.5$ (slope = –2.12, $r = -0.96$).

The close agreement of the 12 μm–sample XLF with that calculated from the *hard–X–ray selected* sample of P82 is further support for the argument that 12 μm selection is relatively unbiased (and that our bivariate XLF is a close approximation to the purely X–ray XLF for AGN). In other words, there are few, if any, objects which are particularly X–ray–strong but weak at 12 μm. This is because the fraction of bolometric luminosity emitted at 12 μm is insensitive to the overall spectral energy distribution of a given AGN (Spinoglio & Malkan 1989; RMS; Spinoglio et al. 1995), and because the scatter in the IR–X–ray relation for a given Seyfert type is small compared to the range of luminosities spanned. This result is also confirmed in the hard X–rays by Barcons et al. (1995), who compare the 12 μm sample to a hard X–ray selected sample, and find that most of the observed 2—10 keV X–ray luminosity function over 10^{42-46} erg s^{-1} can be accounted for by 12 μm–emitting AGNs. Conversely, the 12 μm LF for Seyferts calculated from an

X–ray–selected sample would probably be too low, since such samples miss those Seyferts which are weak in X–rays. We would also expect a 60 μm–selected sample, for example, to yield a lower XLF, because objects with higher X–ray luminosities are more likely to have lower far–infrared luminosities, being low in dust content (e.g., the Markarian Seyferts).

6. Summary

We have analyzed the results of ROSAT All–Sky Survey observations of Seyfert and IR–luminous galaxies from the Extended 12 μm Galaxy Sample and the optically–selected CfA Sample. For those objects with enough counts to be fitted to an absorbed power–law model, the average photon index is Γ=2.26$\pm$0.11 for 43 Seyfert 1s and Γ=2.45$\pm$0.18 for 10 Seyfert 2s.

Any internal absorption has the affect of flattening the measured photon index and decreasing the observed luminosity, although this affect is likely significant in only the most obscured objects (we describe four Seyfert 1.5s for which this internal absorption appears to be significant). Absorption by N_H in our Galaxy has likely caused some Seyferts to go undetected by ROSAT (we estimate as many as close to 5–10 in our sample), especially where $N_{H,gal}\gtrsim 4 \times 10^{20}$cm^{-2} along our line of sight.

Although Seyfert 1s and 2s have similar distributions and median values of Γ, the median soft X–ray luminosity for Seyfert 1s is an order of magnitude higher than that for Seyfert 2s. We find correlations of L_{SX} with the 12 μm luminosity, with similar slopes for both types of Seyferts, and with Seyfert 1s having relatively more soft X–ray emission by 1—2 orders of magnitude, relative to the mid–infrared emission. These observations are consistent with the obscuring–torus model for Seyferts if the soft X–rays are scattered into our line of sight in Seyfert 2s (with a scattering efficiency typically of $\sim$1–5%), which would decrease the observed soft X–ray flux while maintaining the same photon index as compared to observing the same object face–on as a Seyfert 1. Thus, observing direct versus scattered emission could be the primary difference between Seyfert 1s and 2s, with internal absorption modifying the results slightly. Alternative explanations require fortuitous agreement of Seyfert 1 and 2 soft X–ray spectral shapes.

Infrared–luminous non–Seyferts are shown to resemble the more Seyfert 2s in their distribution of soft X–ray luminosities ($\log L_X \sim 41.4 - 42.7$) and X–ray–to–IR colors. That several of these objects may indeed harbor obscured active nuclei is implied by the fact that three similar objects in our sample were only recently identified to be Seyfert 2s based on optical spectra.

The soft X–ray luminosity function of the 12 μm sample is well described by a single power–law with a slope of –1.75. This XLF is generally consistent with that of the hard X–ray sample of Piccinotti (1982). Barcons et al. (1995) made a similar analysis of the 12 μm sample in the hard X–rays, also finding a high contribution of 12 μm–emitting AGN to the XLF, showing that 12 μm detection does not miss many hard X–ray selected AGN. They also determined values for the slope of the X–ray–to–IR relation, and the ratio of Seyfert 1 to Seyfert 2 average soft X–ray luminosities which are consistent with our results.

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TABLE 2

SEYFERT GALAXY X–RAY LUMINOSITY FUNCTION

$\log L_{SX}^{a}$ (ergs s^{-1})	$\log \Phi$ (ΔL_{44}^{-1} Mpc^{-3})	N
40.25	0.32	3
40.75	-0.62	7
41.25	-1.01	5
41.75	-2.02	10
42.25	-3.24	11
42.75	-3.33	10
43.25	-5.05	5
43.75	-4.84	7
44.25	-7.17	2
44.75	-7.71	3
45.75	-11.43	1
46.25	-9.49	1

[a] Bin center, for bins of width 0.5 in $\log L_{SX}$

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FIGURE LEGENDS

Figure 1 — Differential histograms of *a*: the Photon Index, Γ, and *b*: the soft X–ray luminosity. Densely–hatched squares are Seyfert 1s, sparsely–hatched squares are Seyfert 2s, and open squares are IR–luminous non–Seyferts. For the Seyferts: horizontal, diagonal, and vertical lines represent objects in the 12 μm sample, both samples, and the CfA sample, respectively.

Figure 2 — Γ versus the unabsorbed observed flux at 1 keV. In this and all following plots (unless otherwise noted): Filled symbols are Seyfert 1s, open symbols are Seyfert 2s, and stars are IR–luminous non–Seyferts. For the Seyferts: squares are in the 12 μm sample only, triangles are in the CfA sample only, and circles are in both samples. The two objects in the upper–right portion of this diagram have uncertain values for Γ, as explained in the text.

Figure 3 — Flux at 1 keV versus $N_{H,gal}$. The box in the lower–left indicates the region of low Galactic obscuration through which even faint Seyferts can be detected.

Figure 4 — Soft X–ray Luminosity versus the monochromatic 12 μm luminosity. *a*: Seyfert 1s and 2s. The higher and lower solid lines are fits to detected Seyfert 1s and and detected Seyfert 2s, respectively. The higher and lower long–dash lines are fits to Seyfert 1s and Seyfert 2s, respectively, accounting for upper limits using the ASURV software. Dotted lines denote $\log L_{SX}/L_{12\mu m} = -1$ and $\log L_{SX}/L_{12\mu m} = -2$. *b*: detections only, for Seyfert 1s, Seyfert 2s, and IR–luminous non–Seyferts. Three recently identified Seyfert 2s are individually labeled.

Figure 5 — X–ray luminosity function of Seyfert 1 galaxies in the 12 μm sample, fit to a straight–line power–law (long solid line and filled squares), with each point weighted by the number of galaxies it represents (as noted by the numbers under the squares). Shown for

comparison are the data and fits from Piccinotti et al. (1982; dotted line and open squares), converted to lower energies and an H_0 of 75, as described in the text. The short solid line is the fit to the 12 μm XLF in the range spanned by the Piccinotti data.