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Journal
The Astrophysical Journal, 456(2)

ISSN
0004-637X

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Publication Date
1996

DOI
10.1086/176672

Peer reviewed

THE SOFT–X–RAY SPECTRAL SHAPE OF X–RAY–WEAK SEYFERTS[1]

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ABSTRACT

We present and analyze ROSAT–PSPC observations of eight Seyfert 2 galaxies, two Seyfert 1/QSOs, and one IR–luminous non–Seyfert. These targets were selected from the Extended 12 μm Galaxy Sample and, therefore, have different multiwavelength properties from most (optically or X–ray selected) Seyferts previously observed in the soft X–rays. The targets were also selected as having atypical X–ray fluxes among their respective classes, e.g. relatively X–ray strong Seyfert 2s and X–ray weak Seyfert 1/QSOs.

Comparing our observations with those from the ROSAT All–Sky Survey, we find variability (of a factor of 1.5–2 in flux) in both of the Seyfert 1/QSOs, but in none of the Seyfert 2s. Both variable objects have steeper photon indices in the more luminous state, with the softest (< 1.0 keV) flux varying the most. The timescales indicate that the variable component arises from a region less than a parsec in size.

Fitting the spectra to an absorbed power–law model, we find that both the Seyfert 2s and the Seyfert 1/QSOs are best fit with a photon index of 3.1–3.2. This is in agreement with the average photon index of a sample of Markarian Seyfert 2s observed by Turner, Urry, & Mushotzky (1993), indicating that most Seyfert 2s, even those displaying a wide variety multiwavelength of characteristics, as well as some Seyfert 1/QSOs, have a photon index much steeper than the canonical (Seyfert 1) value of $\sim$1.7. One possible explanation is that these objects have a flatter continuum plus a soft (< 1.0 keV) excess in the form of high–EW iron and/or oxygen fluorescence lines, a black–body or even a thermal plasma. Alternatively, the underlying continuum may indeed be steep, powered by a different physical mechanism than that which produces the flat continua in other Seyfert 1s/QSOs.

We imaged one Seyfert 2 (NGC 5005) with the ROSAT HRI, finding about 13% of the soft X–rays to come from an extended source. This object also has the most evidence from spectral fitting for an extra contribution to the soft–X–ray flux in addition to a power–law component, indicating that different components to the soft X–ray spectrum of this object (and likely of other X–ray–weak Seyferts) may come from spatially distinct regions.

Subject headings: Galaxies: Active — Galaxies: Nuclei — Galaxies: Seyfert — X–Rays: Galaxies

[1] Accepted for publication in the 10 January 1996 issue of ApJ.

1. Introduction

Although Seyfert galaxies and quasars have been well studied in the X–rays, most previous observational scrutiny has been devoted to the brighter Seyfert 1/QSOs which are more easily detected. There are few observations of those Seyfert 1/QSOs which are relatively X–ray weak or of any Seyfert 2, and not all of those have been measured well enough for detailed spectral analysis. This paper discusses new ROSAT spectra of such objects, broadening the range of types of AGN observed in the soft X–rays. This can provide us with an understanding of the soft X–ray nature of (low luminosity) AGN which is more representative of this entire class of objects, and free from the biases which can result from analyzing only a small subset AGN types.

Previous X–ray missions, in the 2–10 keV energy range, found Seyfert galaxies (mostly Seyfert 1s) to be best fit by power–law spectra with a photon index of about $\Gamma \approx 1.7$—1.9 (e.g. Mushotzky 1984; Turner & Pounds 1989). However, the ROSAT spectra of Seyferts generally have steeper photon indices, of about $\Gamma \approx 2.4$ for Seyfert 1s (Turner, George, & Mushotzky 1993, hereafter TGM) and even steeper values $\Gamma \approx 3.2$, for Seyfert 2s (Turner, Urry, & Mushotzky 1993, hereafter TUM). There are several possible explanations for these steep observed indices. This could indicate a steeper intrinsic continuum slope, or alternatively adding a "soft X–ray excess" to an underlying power–law model usually improves the fit and flattens the best–fit continuum slope. The nature of this soft excess has been suggested to be one or more of the following: Fe–L and/or Oxygen–K emission lines around 0.8–1.0 keV, a low–temperature blackbody, an optically–thin thermal component, a steep second power–law, or the underlying hard continuum leaking through a partial absorber. It is not evident that a combination of a power–law and a soft excess is necessary in all objects. Perhaps a large amount of absorption ($N_H \gtrsim 10^{23}$) could harden an even softer underlying power–law to give the observed spectrum, or a strong blackbody or optically–thin thermal component could account for all of the observed soft–X–ray flux, without an underlying power–law even being necessary.

These large object–to–object differences in the observed range of L_x/L_{opt} in Seyfert 1s and QSOs of a factor of 300 (e.g., values of α_{ox} ranging from −1.0/−1.1 to −1.9—Picconotti et al. 1982; Tananbaum et al. 1986) reflect substantial fundamental differences in the structure of their central engines. A large difference in X–ray properties is also seen in the spectra of Seyfert 2s. For example, NGC 1068, the prototype of a Seyfert 2 which may be a hidden Seyfert 1, is also the brightest and best observed Seyfert 2 in the X–rays. It appears to have a very steep soft X–ray spectrum (Monier & Halpern 1987), but is more like Seyfert 1s at high energies (Koyama et al. 1989), and does not resemble the average spectrum of other Seyfert 2s observed with the IPC, or the spectrum of the Seyfert 2 Mkn 348 observed with Ginga (Warwick et al. 1989).

These differences, lead to the question of whether the usual Seyfert 1—Seyfert 2 dichotomy, usually made based on optical spectra, is a physically accurate way to classify these objects in the X–rays. Observations of a wide range of Seyfert galaxies are necessary to determine whether Seyfert 1s and Seyfert 2s represent two primarily distinct classes of objects, or if they are better described as having a continuous range of properties, and whether the observed differences are intrinsic to the nucleus, or represent varying circumnuclear properties, such as the amount and distribution of absorbing material. Our data suggest that a subset of Seyfert 1s (of which we discuss only two objects in this work, but which may include many other objects) are more intrinsically similar (with respect to the source of the soft X–ray emission) to most Seyfert 2s than to other Seyfert 1s. This is most likely explainable if different mechanisms produce the X–rays in the X–ray–quiet objects. If the standard X–ray emission mechanisms (e.g., inverse–Compton scattering of lower energy photons by relativistic electrons, direct synchrotron emission from relativistic electrons produced near the central engine or jet, and/or thermal emission from the hot inner parts of an accretion flow) are in fact virtually "turned off" in these objects, it is quite possible that weaker, more exotic mechanisms (e.g., optically thin thermal emission from the hot intercloud medium) may contribute significantly to the X–rays we actually detect.

2. Target Selection and Observations

2.1. Selection of Objects from the 12 Micron Sample

The objects for which we have obtained pointed PSPC spectra were carefully selected for several reasons. First, they are from (with the exception of

PG 1351+640) the most complete and unbiased source of bright AGNs compiled to date—the Extended 12 Micron Galaxy Sample (Rush, Malkan, & Spinoglio 1993). This sample is complete relative to a bolometric flux level, and includes those Seyferts which are the brightest at longer wavelengths, including a truly representative number of both X–ray–quiet and X–ray–loud objects. We selected the IR–brightest Seyfert 2s from this sample which had not previously been observed in any pointed X–ray mission. We also selected two typical examples of relatively X–ray–weak Seyfert 1/QSOs. Mkn 1239 has one of the lowest detected X–ray fluxes of all 55 Seyfert 1s in the 12 μm Sample (20 counts and 0.05 cts/sec in the ROSAT All–Sky Survey—Rush et al. 1996), and PG 1351+640 has the steepest α_{ox} (−1.91) of the 66 PG QSOs observed by Einstein (Tananbaum et al. 1986).

Second, the 12 μm–selected Seyferts are qualitatively different from those observed previously. Halpern & Moran (1993) pointed out that the Seyfert 2s usually observed, with polarized broad lines, are restricted to those with relatively strong UV excesses (found by the Markarian surveys; e.g. those reported in TUM) which are also relatively radio–strong. Compared to these Markarian Seyfert 2s (many of which were observed but not detected by Ginga—Awaki 1993), the targets we observed have redder optical/infrared colors, weaker and smaller radio sources, larger starlight fractions, and steeper Balmer decrements—more representative of Seyfert 2s as a general class. Similarly, Mkn 1239 and PG 1351+640 differ from those broad–line AGN usually observed, in that they are specifically chosen to have relatively weak X–ray fluxes. The one IR–luminous non-Seyfert we observed was chosen by cross–referencing the non–Seyferts in the 12 μm Sample with a large sample of IRAS galaxies detected in the ROSAT All–Sky Survey (hereafter RASS; Boller et al. 1992; Boller et al. 1995b) for those non–Seyferts with the highest IR luminosity and X–ray flux.

2.2. Pointed ROSAT PSPC Observations during AO2–AO4

The observations were carried out AO2—AO4 (from 1991 December to 1993 October) with the ROSAT X–ray telescope, with the Position Sensitive Proportional Counter (PSPC) in the focal plane. The PSPC provides spatial and spectral resolution over the full field of view of 2° which vary 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). See Table 1 for a summary of the observations and count rates for each object, where the objects are listed in decreasing order of total counts obtained.

We have also obtained ROSAT All–Sky Survey data for almost all of the Seyferts in the 12 μm and CfA samples. This will be discussed in another paper to be completed shortly after this one (Rush et al. 1996). Those data, on over 100 Seyferts spanning a wide range of characteristics, will complement this work by enabling us to address statistically the scientific issues discussed below for individual objects.

3. Data Analysis

For each step of the data analysis discussed below, only those counts in pulse invariant (PI) channels 12—200 inclusive are included. The lower limit is set by the fact that the lower level discriminator lies just below this limit, so any data taken from lower channels cannot be considered as valid events. Furthermore, analysis of the PSPC PSF has shown that the positions of very soft events cannot be accurately determined because of a ghost imaging effect (J. Turner, p.comm). The exact level at which this effect is significant is different for each observation (Hasinger & Snowden 1990), so we conservatively chose to exclude PI channels below 12. The upper PI channel included is 200, since the mirror effective area falls off rapidly at higher energies. We have also defined low, medium, and high energies to refer to PI channels 12—50, 51—100, and 101—200, respectively, and "all" energies refers to PI channels 12—200.

The spectral analysis was done by first extracting spectra from the events file using the QPSPEC command in the PROS package in IRAF. We made sure that the output of PROS were properly compatible with XSPEC, in particular with regards to the manner in which these two packages deal with binning and calculating statistical errors.[2] We then fit simple models using the XSPEC software, with the events in PI channels 12—200 binned so as to include at least 20 counts in each bin, allowing χ^2 techniques to be

[2] This simple but very important procedure is explained in detail at http://heasarc.gsfc.nasa.gov/docs/rosat/to_xspec.html.

applied.[3] We used the most recent response matrix available, released from MPE in 1993 January. We first fit the data to the standard absorbed power–law model, both with all parameters (Γ, N_H, and normalization) free and with N_H fixed at the Galactic value (see Table 2). We use the photon index, Γ, defined such that $N \propto E^{-\Gamma}$ (N = number of photons), which is output by the fitting routines in XSPEC. This relates to the spectral slope, α, defined by $F \propto \nu^{-\alpha}$, as $\alpha = 1 - \Gamma$. We also performed several other fits, either adding a thermal component to the power–law or fitting only a thermal component. These are discussed in § 4.2.

The quoted uncertainties are at the 90% confidence level, assuming one free parameter of interest (Lampton, Margon, & Bowyer 1976), when available (i.e., when the chi–square minimization to determine these uncertainties properly converged; these are denoted as separate upper and lower uncertainties). Otherwise, the 1σ uncertainty on each parameter is given (denoted as a single $\pm$ value.)

Hardness ratios provided a simple approximation to the spectral shape, even for those objects which didn't have enough counts to accurately fit a spectral model to (see Table 3). The hardness ratio is defined as HR = (A–B)/(A+B), where A = ctrt (0.12–1.00 keV) and B = ctrt (1.01–2.00 keV). Also given is the ratio A/(A+B), which we refer to as F_{soft}.

The spatial analysis was done using the SAO image display in IRAF/PROS. Each of the sources were observed at the center of the PSPC field, with the exception of NGC 1144, which was about 20′ south of the field center. This object was partially occulted by the telescope support structure and we thus corrected the exposure time accordingly. The accumulated PSPC counts for each object were calculated using the IMCNTS task in IRAF/PROS and are listed in Table 1. All counts in a circular region surrounding the source are given, after subtracting the background, as calculated in a source–free annular region just outside the circle.

Finally, using the TIMSORT and LTCURV tasks in PROS, we extracted light curves for each object. This was done individually for low, medium, and high energies and for all energies. All of the objects were observed over periods of no more than 8 days, except for NGC 3982 and PG 1351+640, which were observed in several segments, spanning 5 and 11 months, respectively, allowing us to test for variations on a half–year to year time scale.

[3] We only required 10 counts per bin both NGC 3982 and CGCG 022–021, and 5 counts per bin in NGC 1144, in order to have at least 7 bins for the fits; this makes the results extremely rough, but otherwise we would have only 3–4 bins, with which no fits could be done.

4. Results

4.1. Variability

4.1.1. Seyfert 2s

Any variation in the spectra of our Seyfert 2s would have be considered an important result, as there are only a couple reports to date of X–ray variability in Seyfert 2 galaxies (e.g., in NGC 1365—TUM and, possibly, in Mkn 78—Canizares et al. 1986), and none of these are conclusive (e.g., the variation in NGC 1365 may be due to the serendipitous sources). However, no significant short–term variation was found for any Seyfert 2 in our sample. The one object which was observed over a 5 month period, NGC 3982, showed no significant variation over this time scale either (see, for example, the count rates in Table 1).

We also compared the count rates of our pointed observations to those obtained during the ROSAT All–Sky Survey for the same objects (Rush et al. 1996), as shown in Figure 1. Point sizes in Figure 1 are proportional to the square of the total counts[4] in our pointed observation and errorbars are 1σ statistical uncertainties in the count rates. The RASS was taken during 1990 July—1991 February, thus this comparison provides timelines of 1—3 years for the various objects. As can be seen, the 5 Seyfert 2s with the most counts in our observations show no sign of variability since the RASS. That the count rates for two of the fainter Seyfert 2s and for the one IR–luminous non–Seyfert are different is probably not an indication of variability, since we have extremely low counts for those objects (in both our observations and the RASS), and it is unlikely that only the objects with the fewest observed count rates would be the only ones to vary.

[4] Several figures have point sizes proportional to counts instead of count–rate or flux. This is because the former is also an indicator of SNR and thus also of the statistically accuracy of spectral fits and other quantitative results. Also, this makes little difference since the exposure times vary only by a factor of two among our objects while the total counts vary by a factor of ~20.

4.1.2. Seyfert 1/QSOs

However, there is evidence for variation in both of our Seyfert 1/QSOs. From Table 1 and Figure 1, we can see that Mkn 1239 increased its count rate by about a factor of two between the RASS and our observation (over 21–28 months, depending on when this object was observed during the RASS). The spectral slope steepened slightly during this period, from $\Gamma = 2.69$ to $\Gamma = 2.94$ (for a power–law fit, with N_H constrained to $N_{H,gal}$, which is the only spectral parameter we have from the RASS).

We don't have RASS data for PG 1351+640, but we can see that it varied during our observations, which spanned the 11 months from 1992 November to 1993 October, increasing its total counts and flux by factors of 1.5 and 1.4, respectively (a $\sim 10\sigma$ result). The spectral shape varied, becoming steeper as this object became more luminous, as with Mkn 1239. The 0.12–1.00 keV count rate increased by $\sim 59\%$, whereas the 1.00–2.00 count rate only increased by $\sim 14\%$, as indicated by the counts and hardness ratios of Table 3. The best–fit photon index steepened slightly, from 2.54 to 2.73 (see Table 2).

That the spectra of both of these objects steepened during the more luminous state indicates that most of the variability was at the lowest energies (i.e., below 1 keV). The timescale of the variability puts an upper limit on the size of the emitting region for this soft component, of much less than a light–year for PG 1351+640, and less than two light–years for Mkn 1239, restricting the source to the area not much larger than the broad–line region.

4.2. Spectral Fitting

4.2.1. Power–Law Models

We fit each of our spectra to a simple absorbed power–law model, both with N_H held constant at the Galactic value, and allowing it to vary. As an example, we show in Figure 2 the data and folded model for our highest SNR object, PG 1351+640. Below we discuss how the spectra for the other objects differ. We also show, in Figure 3, the χ^2 contour plot which results from minimizing χ^2 as a function of N_H and Γ for this object. The contours represent the 68%, 90%, and 99% confidence limits (1σ, 1.6σ, and 2.6σ, respectively) and the plus marks the best–fit value. The contour plots for our strongest 6 objects (in terms of total counts–PG 1351+640; NGC 5005; Mkn 1239; NGC 424; NGC 4388; and NGC 5135) look roughly the same as this one, and those for the other objects look increasingly "bent", with less well–defined maxima as the total number of photons decreases.

As indicated in Table 2, when N_H is allowed to vary, the best–fit value is always higher than the Galactic value, by a factor of 2–3 (again, for the 6 well–determined spectra), the one exception being PG 1351+640 which shows no increase. The fact that χ^2_ν (reduced χ^2) decreases by $\sim$35–50% when allowing N_H to vary indicates that these values are more accurate than the Galactic ones. This indicates that there is indeed some internal absorption of one form or another in these objects, and that the underlying slope is steeper than that which is obtained when requiring $N_H = N_{H,gal}$. We illustrate this in Figure 4, where we plot the photon indices obtained with N_H free versus with N_H fixed. Most of our Seyfert 2s, as well as those from TUM, have the former steeper by ~ 1.

The average values of Γ which we obtain with N_H free are $\bar{\Gamma} = 3.13$ for our 4 Seyfert 2s with sufficient counts, and $\bar{\Gamma} = 3.20$ for our two Seyfert 1/QSOs. These values are similar to the six Seyfert 2s observed by TUM, which have $\bar{\Gamma} = 3.16$, but differ from the six Seyfert 1/QSOs observed by TGM which have $\bar{\Gamma} = 2.41$.

In Figure 5, we plot the photon index versus count rates for the pointed observations of this work, TUM, and TGM. We see that most of the objects have significantly steeper values of Γ than the old canonical value of 1.7 (dotted line). All of our well–observed Seyfert 2s (filled triangles), and most of TUM's Seyfert 2s (open triangles), and both of our Seyfert 1/QSOs have values of $\Gamma \sim 3$. The one exception is Mkn 372 which has a value of $\Gamma = 2.2$. However this object is now known to be a Seyfert 1, and, as expected lies close to the average value of the Seyfert 1/QSOs from TGM at $\bar{\Gamma} \sim 2.4$.

What these data show us is that, not only do most Seyfert 2s have a best–fit photon index around $\Gamma \sim 3$, but also that Seyfert 1s are divided between objects which have similar spectral slopes as Seyfert 2s and those which have flatter spectra with $\Gamma \sim 2.2$. Physical explanations for this are discussed further in §5. and §7.

4.2.2. Internal Absorption

For each of our targets, we looked at the best–fit hydrogen column density as compared to the Galactic value, and compared this to the photon indices and hardness ratios, to try to determine the significance of internal absorption and how this affects the observed count rates and spectral shape. Figure 5 seems to indicate that a few of the faintest objects also have the hardest spectra. This is tentative, however, since these objects are the ones with the fewest photons and the data are not very trustworthy. However, we do note that, if real, this is consistent with these faint objects being the most heavily absorbed (i.e., with low signal–to–noise, a heavily absorbed, intrinsically steep spectrum would appear similar to a relatively unabsorbed flat spectrum). We investigate this trend further by plotting the spectra of our 8 brightest objects in Figure 6 (in order of brightness, from the upper left, down to the lower right), fit to a power–law with N_H free. The general trend is for the fainter objects to have harder spectra (as also indicated by the hardness ratios in Table 3), with the 4 highest hardness ratios belonging to 4 of the 5 lowest–count objects (the exception being NGC 3982 which actually has one of the lowest hardness ratios).

To determine whether these harder–spectrum objects may be more heavily obscured by dust, we have compared their ROSAT hardness ratios to their IRAS colors (see Figure 7). Six of our objects are very dusty in the far–IR, having values of $\log F_{\nu,60}/F_{\nu,25} \approx 0.8 - 1.0$, which is among the reddest (which probably means most dust–enshrouded) third of even Seyfert 2s (Rush et al. 1993). This includes the four lowest–count objects in our sample. Conversely, both PG 1351 and Mkn 1239 have values of $\log F_{\nu,60}/F_{\nu,25} \approx 0.15$, which is among the hottest $\sim 20\%$ of even Seyfert 1s. However, there is no strong relation of the IRAS color to the hardness ratio other, other than that of the three hardest objects are also among the reddest.

Taken together, these results indicate that there is a trend for the fainter objects to have harder ROSAT spectra, indicating that absorption is partially responsible for steepening the spectra. However there is less evidence that the amount of absorption is correlated with redness/dustiness in the galaxy, as determined from IRAS colors.

4.2.3. Additional Models

We also fitted some of our spectra to other models. These include a power–law plus an emission line or thermal component (Raymond–Smith thermal plasma or blackbody), or a thermal component alone. As discussed in §6. for individual objects, there are several cases where the fits improve, indicating that more than a simple power–law may be necessary to explain the soft X–rays.

First, we added an additional component to the underlying power–law. The fits to neither of our Seyfert 1/QSOs were improved by adding another component. This is as expected, as the power–law fits to both objects were quite good (χ^2 of 0.79 and 0.67 for PG 1351+640 and MKN 1239, respectively). The fit did improve, however when we added an emission line to some of our Seyfert 2s. See, for example, Figure 8 which shows the model for a power–law plus gaussian emission line fit to NGC 5005. The best–fit energy for this line is at 0.8 keV, around the energy expected for Fe–L and/or Oxygen–K emission lines. Adding this component also has the effect of flattening the underlying power–law slope from 3.0 to 2.4. Similar results are obtained for the fits to NGC 5135 and NGC 4388, which are slightly improved by adding emission lines at 0.5, and 0.6 keV, respectively.

We also tried fitting each object to a thermal model only. Again, both Seyfert 1/QSOs were not fit at all well in this way. However, several Seyfert 2s (NGC 5005, NGC 5135, NGC 5929, and NGC 1144), were fit better (i.e., lower χ^2 for the same number of free parameters) by a ~ 0.2 keV black–body than by an absorbed power–law (see, for example Figure 9 for the black–body fit to NGC 5135). This is significant in that it prevents us from saying conclusively that the soft–X–rays from these objects are associated with the AGN at all, and that they may simply be due to stellar processes. It is not likely that ROSAT data alone will be able to finally distinguish between stellar and non–stellar explanations for the X–ray emission from Seyfert 2s, as the most definitive tests to discriminate between such models are best done in the hard X–rays (e.g., Iwasawa 1995).

4.3. Spatial Extent

4.3.1. HRI Image of NGC 5005

If multiple components are responsible for the soft–X–rays in these objects, it is quite possible that they are from spatially distinct regions, as is already known to be the case for some brighter Seyfert galaxies. For example, the brightest and best observed Seyfert 2 in the X–rays is NGC 1068, the prototype of a Seyfert 2 which may be a hidden Seyfert 1. HRI Imaging (Wilson 1994; Halpern 1992; Wilson et al. 1992) of this object reveals at least three components to the soft–X–ray emission: (a) a compact nuclear source, coincident with the optical nucleus, (b) asymmetric emission extending 10–15″ N – NE, closely correlated with the radio jet and narrow–line [O III] emission, and (c) large–scale (60″) emission with similar morphology to the starburst disk. These three components comprise 55, 23, and 22% of the X–ray flux, respectively.

To investigate whether similar structures may be responsible for part of the soft X–rays from our (much fainter) objects, we obtained a 27 ksec HRI exposure of our brightest Seyfert 2 galaxy, NGC 5005, shown in the contour plot in Figure 10 (the contour values range from 0.05 to 0.60 photons/pixel and the spatial resolution is 0.″5/pixel). The central source spans ∼20″ x 20″, and is significantly extended (FWHM ∼10″) as compared to the HRI on–axis PSF (FWHM ∼5.″5). The position of the peak of this central component agrees within error to the optical position, and is roughly 3.″7 south of the radio–interferometer position given by Vila et al. (1990).

In addition to this central component, there is an extended wing from about 10″ to 25″ to the south–west of the central source (from 0.6h^{-1} kpc to 1.4h^{-1} kpc). This feature contains about 13% as many background–subtracted counts as does the central source (31 compared to 247). The orientation of this feature is roughly parallel to the major optical axis of the galaxy (∼45° E of N), although the latter represent structure on the 1–arcminute scale. At smaller sizes, arcsecond–scale radio maps made with the VLA at 6 and 20 cm are presented in Vila et al. (1990). They find the central source to dominate the nuclear region of the galaxy (being marginally resolved — FWHM ∼0.″7), and weak extended structure over ∼2 arcsec in no particular direction.

Although this is our brightest Seyfert 2 galaxy, the spatial resolution and counts are only sufficient to tell that there definitely is some asymmetric soft–X–ray emission. Higher spatial–resolution and higher SNR data of X–ray–weak Seyferts with future X–ray missions will be necessary to determine the general significance of the contribution of extended components to the soft–X–ray spectrum of such objects.

4.3.2. PSPC Images

None of targets show extended emission in the PSPC image. (However, not being primarily an imaging instrument, the resolution of the PSPC would only show structure on much larger scales than the HRI, and cannot be used to rule out sub–arcminute–scale structure, as exemplified by the fact that our HRI image of NGC 5005 clearly shows structure not apparent in the PSPC images of the same object.) Several of the images contain field objects ∼10–20′ from the target, clearly distinguished by the resolution of the PSPC. The only exception is NGC 1144, which is not spatially separated from NGC 1143. Since the latter is a non–active galaxy the X–rays are likely to be mostly from NGC 1144, however we note the PSPC spectrum is a combination of these two sources.[5] It is interesting to note that TUM found serendipitous (optically) unidentified X–ray sources about 1′ from each of the six Seyfert 2s observed in their program. In some cases (e.g., NGC 1365) these sources are likely bright X–ray sources in the host galaxy, and in others (e.g., Mkn 78) they are likely low–luminosity AGNs. We looked for such sources in the field of our 12 μm Seyfert 2s, and found none. The number of Seyfert 2s (14) observed between these two samples makes it highly unlikely that this difference could be explained simply by chance. One possible explanation is that the objects in TUM are galaxies previously known to be relatively bright in the X–rays from Einstein IPC observations, and these serendipitous sources could have contributed to the Einstein flux.

5. Discussion

5.1. The Standard Soft X–Ray Slope for X–Ray Weak Seyferts

Considering both our data and that of TUM, it appears that a steep spectral slope, around Γ = 3, should be considered the standard slope for X–ray–weak Seyferts. This includes virtually all Seyfert 2s, as indicated by the results that have been derived for Seyfert 2s displaying a wide range in multiwavelength characteristics. As discussed in § 2.1., our objects were chosen from the 12 μm sample and thus have redder optical/infrared colors than the objects observed by TUM, which are Markarian objects se-

[5] This object has the least counts of all, primarily due to obscuration by the telescope support structure, so no strong conclusions can be drawn about its spectrum.

lected as having a strong UV–excess.

Even the prototypical Seyfert 2 galaxy, NGC 1068, resembles these objects. Monier & Halpern (1987) observed this object with Einstein, finding a 0.1–3.8 keV photon index of $\Gamma \approx 3.0$, and N_H consistent with the Galactic value. Our data from the RASS give a 0.1–2.0 keV value of $\Gamma = 2.78$ for this object (Rush et al. 1996), which is slightly harder, but consistent when considering that our RASS data was fitted with N_H constrained to $N_{H,gal}$.

This category of X–ray–steep AGN not only includes most Seyfert 2s, but some X–ray–weak Seyfert 1/QSOs, such as PG 1351+640 and Mkn 1239. That the soft X–ray source in these objects may be the same as in most Seyfert 2s is consistent with their selection as being X–ray weak for Seyferts 1/QSOs. In contrast, other Seyfert 1/QSOs, e.g. those observed by TGM, were known to be relatively strong in the soft X–rays, and thus one would expect those objects to have X–ray spectra more similar to conventional Seyfert 1s. Thus, it seems that the standard Seyfert 2–Seyfert 1 dichotomy in not the simplest way to categorize these AGN in the soft X–rays. Rather, we could refer to (relatively) steep, X–ray–weak objects and flat, X–ray–strong objects, whose soft X–rays are probably dominated by different components.

We also find steep average spectral slopes in our RASS data (to be analyzed thoroughly in Rush et al. 1996), of $\bar{\Gamma}_{Sy1} = 2.24 \pm 0.49$ and $\bar{\Gamma}_{Sy2} = 2.86 \pm 0.48$ for 39 Seyfert 1s and 5 Seyfert 2s, respectively (uncertainties quoted are 1σ individual scatter). These fits were done with N_H constrained to $N_{H,gal}$, and thus the best–fit slopes are likely a little steeper, depending mainly on the amount of internal obscuration. This could place the average slope of the Seyfert 2s over 3 and that of the Seyfert 1s around 2.4–2.5. This and the fact that there is a wide range of slopes for the Seyfert 1s, with over 1/3 being steeper than $\Gamma = 2.5$ assuming no internal absorption, makes these results consistent with those for our pointed observations—namely that all Seyfert 2s and some Seyfert 1s have slopes much closer to 3 than to 2. Similar results have been found in other works, for example Boller, Brandt, & Fink (1995a), who surveyed 46 narrow–line Seyfert 1s with ROSAT and found them all to have extremely steep spectra (some with Γ as high as 5).

5.2. Physical Interpretation

There are several competing explanations for the steep slopes observed in many X–ray–weak Seyferts, as compared to the flatter slopes observed in conventional (X–ray–strong) Seyferts. The physical models which may be able to explain all or part of the observed differences between steep–slope and flat–slope Seyferts include:

(1) A separate, hard power–law present in steep objects which is very weak, such as a scattered component. Although we see no evidence of such a component in our fits, we cannot rule out this possibility, as observations in a larger wavelength baseline of X–ray–weak Seyferts may detect such a component if it is extremely faint.

(2) Much of the soft spectrum of steep objects being produced by the same physical mechanism, located in the same place, as the soft excess observed in many flat objects. In this model, steep objects have relatively more soft excess and less of the hard power–law.

The evidence for this type of spectrum would be that fits to a power–law–only model would give a very steep slope, but that adding the soft excess would flatten the underlying slope while improving the fit. As discussed in §4.2.3. and §6., we have evidence for this in several of our objects, and even a pure black–body with no underlying power–law cannot be ruled out in some cases. This is even more evident in TUM, as most of their objects are fitted significantly better when either an emission line or Raymond–Smith plasma are added to the power–law. If we do assume that a very soft excess exists in these objects, a physical model for this excess still remains to be determined. For example, it could be thermal emission from the galaxy, hot gas near the nucleus, iron and/or oxygen emission line(s), or the UV bump shifted into the ultra–soft X–rays as suggested in Boller et al. (1995a). But, again, we stress that such evidence is not universal, as several of our objects show no definite preference for anything other than a power–law.

(3) That the soft spectrum we see in X–ray–weak Seyferts represents a component present in most or all Seyferts, but which is much weaker in X–ray strong objects and is thus suppressed by the hard spectrum in those objects. If so, is this universal component non–nuclear, i.e. similar to the soft X–rays observed in normal or starburst galaxies (from, e.g., X–ray binaries and SNRs)?

(4) That the soft spectra arise from the same physical process (and from the same location) as the flat power-laws in some Seyfert 1s, but with a higher value for Γ, caused by variance of one or more intrinsic physical parameters? For example, of several explanations Boller et al. (1995a) suggest for their steep spectra, one of the more promising ones is that the central engine in these objects is at a lower mass than other Seyfert 1s, and would thus have an accretion disk emitting at a higher temperature, shifting the UV bump into the low-energy end of the ROSAT band, steepening the X-rays. This idea is also one possible explanation for the steep spectra we found in PG 1351+640 and MKN 1239, as well as other X-ray-weak Seyfert 1/QSOs. To test this idea thoroughly, one would need to observe the spread in Γ for many X-ray-weak and X-ray-strong Seyferts and see if there is a continuous range of observed values, as opposed to a more-or-less bimodal distribution. If such a range is observed, then determining any X-ray or multiwavelength parameter which is correlated with Γ would provide information about the fundamental cause of its variance.

Finally, an important caveat in this distinction between X-ray-weak and strong Seyferts is that our X-ray-weak Seyfert 1/QSOs are not exactly like our Seyfert 2s in the soft X-rays, which is seen in several ways: (1) even though the former have the same steep slope when fitted to a power-law, they are more often fitted only by this steep power-law, as opposed to a power-law plus an additional component (and PG 1351+640 cannot be fitted at all by any model other than a pure power-law); (2) they are also more luminous in the soft X-rays than all but the very strongest Seyfert 2s; and (3) they show less indication of internal absorption (above the Galactic value): of all our objects, PG 1351+640 is the only one to not have even the slightest evidence for internal absorption in a power-law fit, and several of our Seyfert 2s show much stronger evidence for internal absorption than does MKN 1239. This last difference is of particular importance because it can affect the measured parameters in each of the models listed above. These differences imply that, although the observed soft X-ray emission from these Seyfert 1/QSOs is similar to that from Seyfert 2s, the underlying physical processes are probably at least partially different. Perhaps, for example, the X-ray-weak Seyfert 1/QSOs are best explained by one or more of the models listed above, but the Seyfert 2s by another. Thus, whereas is seems as though these relatively X-ray weak Seyfert 1/QSOs should definitely not be strictly grouped with the more luminous (flat-slope) Seyfert 1/QSOs with regards to the soft X-ray properties, they still appear somewhat distinct from even the relatively X-ray strong Seyfert 2s and perhaps represent an intermediate or mixed class.

6. Notes on Spectral Fits to Individual Objects

6.1. PG 1351+640 and Mkn 1239

These two Seyfert 1/QSOs were relatively well observed, with 990 and 595 counts obtained, respectively. Both were well fitted with a simple power-law. For our strongest object, PG 1351+640, no improvement is obtained by allowing N_H to vary, giving no indication of internal absorption. For Mkn 1239, an increase of about a factor of 1.5 in N_H over the Galactic value reduces χ^2 from 0.95 to 0.67, perhaps indicating some internal absorption.

We tried to fit each object to the other models listed in Table 2. For PG 1351+640, the parameters returned each time indicated that a single power-law was preferred (i.e., the normalization for other component was at or near zero). Mkn 1239, on the other hand, fit well to a power-law model with the addition of a gaussian emission line around 0.7 keV. This fit was not, however better than those with a Raymond-Smith plasma or black-body replacing the emission line. Thus, if there is a second component to the soft X-rays spectrum, we cannot distinguish among several possibilities for its shape.

For PG 1351+640, we also separately fit the spectra which were taken during 1992 November and 1993 October to a power-law model. A slight increase in the best-fit Γ is found in the more luminous state.

6.2. NGC 424, NGC 4388, NGC 5005, and NGC 5135

These four Seyfert 2s each yielded at least 400 counts (see table 1), sufficient for accurate spectral fitting. For these objects, an average photon index of $\bar{\Gamma} = 3.13$ (3.0, 3.2, 3.2, and 3.2, respectively) was obtained when N_H was allowed to vary, and of $\bar{\Gamma} = 2.00$ (1.7, 2.1, 1.9, and 2.3) when N_H was constricted to the Galactic value.

In all cases, we tried adding another component to the fit. In the case of NGC 5135 the fit was improved at a significance level of > 90%. This object has the hardest spectrum of these four Seyfert 2s. Considering that it is also fitted by the largest N_H, the hard spectrum and the good fit to a second component above 0.5 keV both probably indicate significant absorption of the softest X–rays below 0.5 keV. Adding emission lines also improved the fits to NGC 5005 (> 99% significance level) and NGC 4388 (> 90%). Only in the case of NGC 5005 was the emission line at the energy expected for Fe–L and/or Oxygen–K, thus identification of these components with a specific emission process is not possible. We also fit NGC 5005 and NGC 5135 to a black–body model and obtained better fits than to a power–law model, further indicating that we don't know the source of the soft X–rays— whether they are from the nonstellar active nucleus or from stellar processes such as X–ray binaries or supernova. In the latter case, we have some evidence that a small contribution of the soft–X–rays may come from an extended component, as discussed in §4.3.1. for NGC 5005.

6.3. IRAS F01475–0740 and NGC 5929

For these two objects, only 276 and 200 counts were obtained, allowing only 12 and 9 points (bins) for the spectral fitting, respectively. Interestingly, relative to the 0.5— 2.0 keV range, F01475–0740 has almost no counts below 0.5 keV, and NGC 5929 has very few. In fact, F01475–0740 has the hardest spectrum of any object we observed, indicted both by the hardness ratios in Table 3 and by the very flat value of Γ. NGC 5929 also has a harder spectrum than any of the objects discussed above, but not nearly as hard as F01475–0740. This may indicate that these objects are very heavily absorbed, which would explain both the low overall flux and the hard spectra.

When adding another component to the power–law for F01475–0740, Γ always tended towards zero (as flat as we would allow), with only a small contribution from the other component— indicating nothing more than the very hard spectrum of the simple power–law. For NGC 5929, a slight improvement in the fit was obtained by adding a second component, similar to some of the brighter four Seyfert 2s discussed above, but with much less statistical significance.

6.4. NGC 3982 and NGC 1144

These two objects yielded so few counts that can only give a very rough estimate of the best–fit photon index, which is 2.12 and 1.90 for NGC 3982 and NGC 1144, respectively with N_H fixed. Only NGC 3982 had enough photons to allow a fit with N_H variable, which yielded $\Gamma = 3.4$. Although this slope is similar to the values for our bright Seyfert 2s, the spectra do not look similar. NGC 3982 has the softest and NGC 1144 the second hardest count rates of any of our Seyfert 2s. There were not enough counts to fit to composite models, but we did try to fit these spectra to a simple black–body, to estimate whether or not a power–law is even the most descriptive of the soft X–rays. For NGC 3982 there was only marginal improvement in the fit, but for NGC 1144 χ^2 did drop by almost a factor of two for the black–body fit as compared to a power–law.

6.5. CGCG 022–021

In addition to the 10 Seyfert galaxies discussed above, we also observed one IR–luminous non–Seyfert which had been detected by the ROSAT All–Sky Survey. We would expect the ROSAT spectra of this type of object to be similar to those from Seyfert 2s (both of which emit strongly in the thermal infrared, but relatively weakly in the X–rays), if the X–ray emission in the latter are produced by the normal processes of stellar evolution, as in classic starburst nuclei like NGC 7714 (Weedman et al. 1981).

Unfortunately, the observation of CGCG 022–021 yielded only 81 ± 30 counts, and a count–rate of 0.010 ± 0.003 cts/s, which is not sufficient for a detailed spectral analysis. There may be some indication of variability, since the RASS count–rate was 0.064 ± 0.018 cts/s, indicating a $> 2\sigma$ change. However, this is very tentative as the (background–subtracted) counts obtained in the pointed and RASS observations are only 81 and 26, respectively.

We do see, though, that this non–seyfert has a hard spectrum quite similar to that several of the weaker Seyfert 2s (F01475–0740, NGC 5929, and NGC 1144). This indicates that heavy internal absorption is probably present. To describe the spectrum further, we attempted to fit simple models to the X–ray flux, although with high uncertainties. A simple power–law and a black–body model provided similarly accurate fits (χ^2 of 1.2 and 1.3, respectively), however the error bars are high.

7. Summary and Conclusions

We have analyzed pointed ROSAT PSPC spectra of 11 objects selected as having atypical soft X–ray fluxes. These include 8 Seyfert 2s and one IR–luminous non–Seyfert selected from the Extended 12 μm Galaxy Sample, which all have relatively strong detections in the ROSAT All–Sky Survey, as compared to other objects in their class. We also observed on X–ray weak Seyfert 1/QSO from this sample and a similar object selected from the PG Bright Quasar Survey.

We found both Seyfert 1/QSOs, Mkn 1239 and PG 1351+640, to vary in flux by a factors of 2 and 1.5, over periods of less than 2 and 1 year, respectively. Both objects had steeper spectra in their more luminous state, indicating that the variability was mainly due to the softest X–rays, which are confined to a size of less than a parsec.

All of our Seyfert 2s which had sufficient counts for accurate spectral fitting, as well as both Seyfert 1/QSOs, have soft X–ray photon indices of $\Gamma \approx 3$, similar to the Seyfert 2s observed by TUM. The wide–spread occurrence of such steep slopes suggests that this value of $\Gamma \approx 3$ is the norm for a wide variety of AGN, namely Seyfert 2s and many Seyfert 1/QSOs. Therefore, discussing relatively steep ($\Gamma \approx 3$), X–ray–weak objects versus flat ($\Gamma \approx 2$), X–ray–strong objects may be a more fundamental way to separate Seyferts with respect to the soft X–rays than the usual type 1–type 2 dichotomy (derived primarily from optical spectra).

There are several possible explanations for these steep slopes. One is the presence of a very soft (< 1 keV) excess in addition to a flatter underlying continuum. We see strong evidence in the spectral fits to some of our objects for such a component, but a physical model for this excess still needs to be determined—it could be strong iron and/or oxygen line emission, a black–body, or even a thermal plasma. However, several of our objects show no definite preference for anything other than a steep power–law. Alternatively, both flat and steep components could be present in some Seyferts, with one or the other dominating depending on internal physical conditions. Or the steep and flat spectra observed in different objects may have the same basic origin, but with variance of one or more parameters affecting the measured slope. Distinguishing between these and other models for the X–ray emission from Seyferts can best be done by testing multiple–component models over the entire 0.1—10 keV range, where the distinguishing spectral signatures of competing models can be most clearly identified. Thus, obtaining high—SNR spectra of X–ray weak Seyferts, with several thousand of counts both in the soft and hard X–rays, should prove a profitable pursuit of current and future X–ray missions.

Finally, we obtained a ROSAT HRI image of one Seyfert 2 (NGC 5005) and found about 13% of the flux to come from an extended component. This implies that multiple components of the soft–X–ray spectra of Seyferts may arise in spatially distinct regions, as has been previously observed primarily in brighter objects. Further, deeper images of X–ray–weak Seyferts will be necessary to determine the physical processes giving rise to these components, as well as how common such phenomena are in Seyfert galaxies.

We thank Jane Turner for much help in understanding the PROS and XSPEC software, the ROSAT data, and the specifications of the PSPC, and for providing us with the results of TUM and TGM before publication. This work was supported by NASA grants NAG 5–1358 and NAG 5–1719.

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FIGURE LEGENDS

Figure 1 — Our pointed PSPC count rates versus count rates from the ROSAT All–Sky Survey. Squares are Seyfert 1/QSOs, triangles are Seyfert 2s, and the star is our IR–luminous non–Seyfert. Point sizes $\propto \sqrt{\text{total counts}}$. Error bars are 1σ statistical uncertainties. The solid line represents $CTRT_{Pointed} = CTRT_{RASS}$.

Figure 2 — PSPC Spectrum of PG 1351+640, fit to an absorbed power–law with N_H free.

Figure 3 — χ^2 contour plot of N_H vs. Γ for the fit shown in Figure 2. Contours represent confidence limits of 68, 90, and 99% and the plus marks the best–fit value.

Figure 4 — Photon Index for power–law fits: with N_H free versus N_H constrained to $N_{H;gal}$. The solid lines represent $\Gamma_{free} = \Gamma_{gal}$ and $\Gamma_{free} = \Gamma_{gal} + 1$. Symbols are the same as in Figure 1, with open triangles representing Seyfert 2s from TUM.

Figure 5 — Photon Index for power–law fits with N_H free, versus log count rate. Symbols are the same as in Figure 1, with the addition of open squares and open triangles for the Seyfert 1/QSOs in TGM and the Seyfert 2s in TUM, respectively. Point sizes $\propto \sqrt{\text{total counts}}$. The dotted line shows the canonical value of $\Gamma = 1.7$. For the Seyfert 1/QSOs from TGM, there was little spread in Γ (5 of 6 objects between 2.11–2.50 and the other—Mkn 335—at 3.10), and thus only the average value is shown here.

Figure 6 — PSPC spectra of all of our 8 brightest objects, each fit to an absorbed power–law with N_H free. The objects are placed in order of total counts obtained, starting with PG 1351+640 in the upper left, going down each column, to NGC 1144 in the lower right.
(Figure 6 is Placed LAST among the figures.)

Figure 7 — IRAS 25–60 μm color versus hardness ratio. Symbols sizes are proportional to total counts.

Figure 8 — Model of the fit of a power–law plus emission line to our PSPC spectrum of NGC 5005, where the individual components are shown. The dot–dash line is a gaussian emission line at 0.8 keV, the long dashed line is the absorbed power–law, and the solid line is the total model.

Figure 9 — PSPC Spectrum of NGC 5135, fit to a black body model.

Figure 10 — Contour plot made from our 27 ksec HRI Image of NGC 5005. Contours range from 0.05 to 0.60 photons/pixel. The spatial resolution is 0″.5 per pixel.