NOTICE

NASA

Technical Memorandum 82010

Spectroscopy of Compact Extragalactic X-Ray Sources

S.S.Holt

(NASA-TM-82010) SPECTROSCOPY OF COMPACT EXTRAGALACTIC X-RAY SOURCES (NASA) 16 p HC A02/MF A01 CSCL 03B

N80-33332

Unclas

G3/93 34233

SEPTEMBER 1980

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

SPECTROSCOPY OF COMPACT EXTRAGALACTIC X-RAY SOURCES

Stephen S. Holt
Laboratory for High Energy Astrophysics
Goddard Space Flight Center
Greenbelt, MD 20771

Abstract

The X-ray spectra of compact extragalactic sources obtained from the HEAO-1 A-2 experiment and the Solid-State Spectrometer onboard HEAO-2 (the Einstein Observatory) are reviewed. Seyfert spectra are remarkably consistent, with characteristic power-law spectra of energy index $\alpha=0.7+.1$ over a dynamic range of almost 100 in both luminosity for the whole sample, and energy for individual members. Radio-quiet quasars have similar spectra, perhaps slightly steeper, for the limited sample available. New solid-state spectrometer results for NGC 4151 yield a consistent picture for the geometry of the broad-line clouds in both these related radio-quiet classes of galactic nuclei. Radio-loud objects, especially BL Lacs, are considerably more variable in spectrum as well as in luminosity. Direct synchrotron and synchrotron-self-Compton components are consistent with what we observe from these objects. Finally, the role of spectroscopy in addressing the extent to which compact extragalactic nuclei might contribute to the diffuse X-ray background is discussed.

The Einstein Observatory has been an important step forward in our ability to observe the whole catalog of celestial X-ray-emitting objects. Its imaging experiments are capable of interrogating the luminosity of individual sources in the .5-5 keV band with a sensitivity almost 1000 times better than that afforded by previous instrumentation, so that the sample of compact extragalactic sources which has become available for study has increased dramatically.

Spectroscopically, our capabilities have increased significantly although not quite as measurably as has the raw sensitivity of the imaging detectors. The resolving power of the dispersive Einstein spectrometers, the Focal Plane Crystal Spectrometer (FPCS) and Objective Grating Spectrometer (OGS), is largely negated by their inherently low efficiency for sources which give photon fluxes as low as do the compact extragalactic sources; these techniques must exhibit their power in the interrogation of much brighter sources contained within our galaxy. The Solid-State Spectrometer (SSS), a non-dispersive device, has the capability to do useful spectroscopy down to a level of less than 10^{-4} of the flux from the Crab nebula, with a resolving power of about 20 at energies below the Einstein telescope cutoff at 5 keV. This nicely complements the proportional counter spectra available from the HEAO-1 A-2 experiment in the energy range 2-60 keV, which have a typical resolving power about a factor of 3 worse (the resolving powers of both instruments are energy dependent: in the region of overlap, the resolving power of the SSS is about 5 times better).

The large fraction of this review will be devoted to the spectra of compact extragalactic sources obtained with both of these instruments, the A-2 and the SSS, and the consistencies which the increased dynamic range of the two, together, has allowed us to infer. I shall discuss only the most luminous classes of galactic nuclei, i.e., Seyferts, BL Lacs and quasars, and concentrate on the general spectral properties of the classes rather than the peculiarities of individual objects. Finally, I shall address the spectroscopic evidence which relates to the role that active galactic nuclei might play in explaining the diffuse X-ray background (XRB).

Seyfert galaxies are distinguished by their broad optical emission lines (of order 10^4 km/sec). The lack of broad forbidden lines indicates that the lines arise in clouds or filaments with densities in excess of 10^8 cm^{-3}, while the line species argue that the density must be less than about 10^{10} cm^{-3}. The prevailing opinion is that the broad lines originate in condensed material at a density of about 10^9 cm^{-3} (and a temperature 10^4 K) which is suspended in a much hotter medium and irradiated from a central continuum source. Davidson and Netzer (1979) have recently reviewed all the relevant pre-Einstein theoretical and experimental evidence for this consensus picture. The condensations are found at a distance from the central source which scales like the square root of the continuum luminosity (with typical value $\sim$0.1 pc), while the narrow line cores and narrow forbidden lines are created at distances of the order of 1 kpc. Invariably, Seyferts are spiral galaxies. Since quasars have virtually the same defining properties, save for the fact that they are "quasi-stellar" rather than "spiral", it would appear that the difference between the two may be more operational than real (at least with respect to quasars which are radio quiet, as Seyferts almost always are). Quasars which are radio loud, on the other hand, are much more variable, and distinguishable from BL Lac objects only in that the latter exhibit no emission lines at all.

The first correlations of Seyfert X-ray emission with optical characteristics were performed by Elvis, et al. (1978) from Ariel-5 data. While the X-ray emission did not correlate very well with optical continuum emission, it correlated extremely well with the breadth of the emission lines and the H_α intensity. The latter correlation, in particular, implied a strong connection between the X-ray emission and the central continuum source. The central power plant has long been assumed to be the manifestation of gravitational potential energy converted from infall to a black hole of mass 10^{6-8} $M_\odot$, but the details of the process and geometry are rather obscure. Recent reviews of the likely mechanisms for X-ray production illucidate the difficulties associated with attempting to infer their nature from the X-ray output spectra alone. Whether direct bremsstrahlung or synchrotron radiation, or some variety of singly or multiply Compton-scattered radiation, almost all the possible scenarios result in smooth, featureless power-law spectra over the limited dynamic range available to the X-ray detectors. In general, the individual measured spectra are as uninteresting as the qualifications above predict them to be. Nevertheless, the measurement of broader-band spectra and/or the identification of consistent similarities or differences among the classifications of compact extragalactic sources may prove to be fruitful exercises.

X-ray measurements have provided an upper limit to the size of the central source in the sense that temporal variations are assumed to be relatable to the light travel time across the entire central source. Some controversy presently exists over the reproducability of individual reports of very short timescale variations, but several active galactic nuclei have exhibited marked variability on timescales as short as about one day. The first report of such variation which was comfortably outside the realm of possible systematic uncertainties or statistical flukes was from the nearby Seyfert NGC 4151 (Mushotzky, Holt and Serlemitsos, 1978). The implications of short timescale variability have been discussed by Cavallo and Rees (1978) insofar as they can be related to the efficiency with which X-radiation can be produced. A dimension for the central source of the order of a light-day implies an efficiency for X-ray production of order 10^{-2} for the Seyfert sources.

Data from the A-2 experiment provided a surprising consistency in the spectra of Seyfert galaxies. Mushotzky, et al. (1980) found that a sample of seven, ranging over two orders of magnitude in luminosity, could all be well-fit with the same power-law index (and better fit with a power law than with a hot isothermal spectrum). The sample has since been extended to about two dozen, with a best-fit α=0.7+.1 (where the error is the rms deviation of all the individual best fits, and is smaller than the typical individual error). Data from a sample of eleven Seyferts measured with the SSS are generally consistent with the same indices, as indicated in Figure 1, but the dispersion in indices is clearly larger. All but NGC 4151 (see below) were fit with a simple power-law-plus-uniform-absorber.

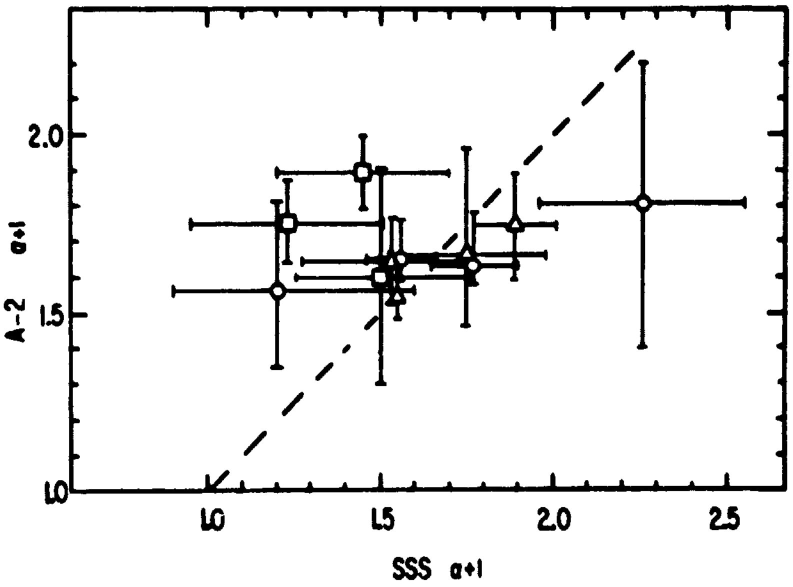

Figure 1. Best-fit power-law indices to Seyfert galaxies measured with the HEAO-1 A-2 experiment, and with the SSS. The circles are the 4 highest luminosity objects in the sample, the triangles the 4 with lower luminosity that have traditionally been labelled Seyfert I (including NGC 4151), and the squares even lower luminosity sources usually classified as emission line galaxies, but which have recently been observed to exhibit broadened wings in permitted optical lines (J. Huchra, private communication).

The typical X-ray power law index is approximately one unit flatter than the typical optical index for Seyferts, and the bright Seyfert ESO 141 was the only Seyfert measured with HEAO-1 to exhibit (occasionally) a steepening below 5 keV which might be plausibly related to an extrapolation of the optical index into the soft X-ray band. The right-most point in Figure 1 is the same source (where the HEAO-1 index on the vertical scale is that measured above 5 keV for the source). The remainder of the significant dispersion for the SSS data is due to the lowest luminosity sources, which seem to have flatter SSS than HEAO-1 spectra. This may be "explainable" in terms of the detailed interpretation of the high precision SSS data from NGC 4151.

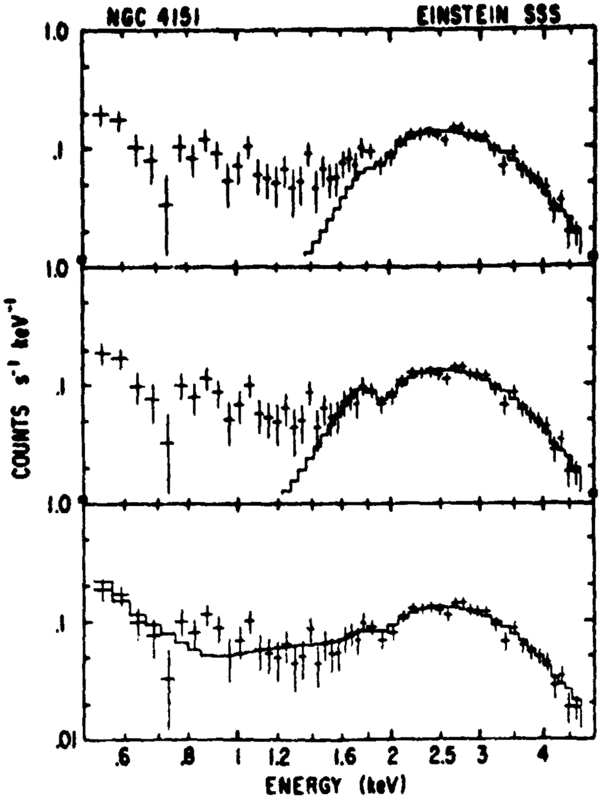

Figure 2. Raw (background-subtracted) SSS data for NGC 4151 fit with three trial spectra. The top trace represents a single power law with a uniform cold absorber in the line-of-sight. The second trace has the silicon abundance in the absorber increased by an order of magnitude, and oxygen completely ionized. The bottom trace, which is the only one of the three fits which is acceptable, has almost the same parameters as the top trace except for the fact that the absorber has "holes" over ~10% of the source.

The three traces of Figure 2 all represent the same raw (background-subtracted) data, fit with three different models. The top trace is the "standard" power-law-plus-uniform-absorber, which matches the data well above ~2 kev, but fails to reproduce the detection at lower energies. Since the higher A-2 energy range is less sensitive to absorption, and since the power-law index is apparently independent of instantaneous intensity (Mushotsky, Holt and Serlemitsos, 1978), we have fixed the index at α=0.55 in the SSS analysis, i.e., the best-fit A-2 index when Fe K-absorption and fluorescent re-emission are considered (consistent with this approach, the NGC 4151 point in Figure 1 at α=.55 has no horizontal error bars). The second trace is an unsuccessful attempt to reproduce the experimental data by allowing the uniform absorber to display peculiar elemental abundance and ionization-state parameters. Finally, the bottom trace is a successful fit to the data which arises from the assumption that the absorber has "leaks" at the 10% level. As described in detail by Holt et al. (1980), the spectroscopic analysis of NGC 4151 allows us to infer several characteristics of the source which imaging alone cannot: the approximate spherical symmetry of the broad-line region (from the ratio of fluorescent Fe K-emission to Fe K-absorption measured with the A-2 experiment), the approximate 90% "covering factor" of the broad-line clouds, and the consistency with a scenario in which the clouds are smaller than the source. Interestingly, this last point naturally explains the observed variation in apparent absorption of NGC 4151 data >2 keV taken at different times (e.g. Barr, et al. 1977) as just the Poisson statistical variations in a total of ~ 100 clouds which cover the source along our line of sight, with an average thickness of ~ 2 clouds. Remembering that the distance at which the clouds are found scales like the square root of the central source luminosity, it would not be surprising if the more luminous Seyferts (and quasars) give no hint of absorption when fit to the "standard" model, because the covered fraction would be low, while the low luminosity Seyferts would appear to have somewhat flatter spectra at low energies, because the absorption would be only partial and would not easily be recognized as such. It is conceivable, therefore, that the most straightforward extrapolation of the NGC 4151 picture revealed from the SSS data gives a natural explanation for the lack of absorption in the high luminosity sources, and the apparent flattening of the SSS spectra of the low luminosity sources. We should always bear in mind, however, the danger of generalizing too broadly from the most easily-studied class members to infer class properties. In some cases the prototypes are the most easily studied simply because they are the most closeby; in others, such as the Crab nebula as a supernova prototype, their high X-ray fluxes arise from their anomalous rather than their class properties.

In contrast to the relative uniformity in the Seyfert spectra, the BL Lac sources form, at first glance, a fairly diverse sample. Spectral components with $\alpha > 3$ and $\alpha \sim 0$ have been reported, sometimes from the same source at the same time over different energy bands. Much more variable in intensity as well as spectrum than the Seyferts, the 3 keV differential luminosity of BL Lacs can easily change by more than an order of magnitude, while a Seyfert variation of more than a factor of two is the exception rather than the rule. A detailed study of the spectra of the five BL Lacs with intensity greater than about 10^{-3} of the Crab nebula, measured with both the A-2 experiment and the SSS, has revealed that the spectra below ~ 3-5 keV can always be fit with a steep ($\alpha \gtrsim 2$) spectrum. Occasionally, in approximately 1/5 of the measurements of all BL Lac spectra we have, a harder spectrum is measured at high energies. This suggests a synchrotron origin for the low energy component, and a self-Compton origin for the more variable high energy component. A variety of consistency checks for the source PKS 2155, including an examination of the overall spectrum at all frequencies as well as the high efficiency implied by the short-term temporal variations, have been found by Urry, et al (1980) to be consistent with such a picture. The radio loudness and the violent variability of BL Lacs are quite independent reasons for expecting that a synchrotron source is more likely to be associated with BL Lacs than with Seyferts.

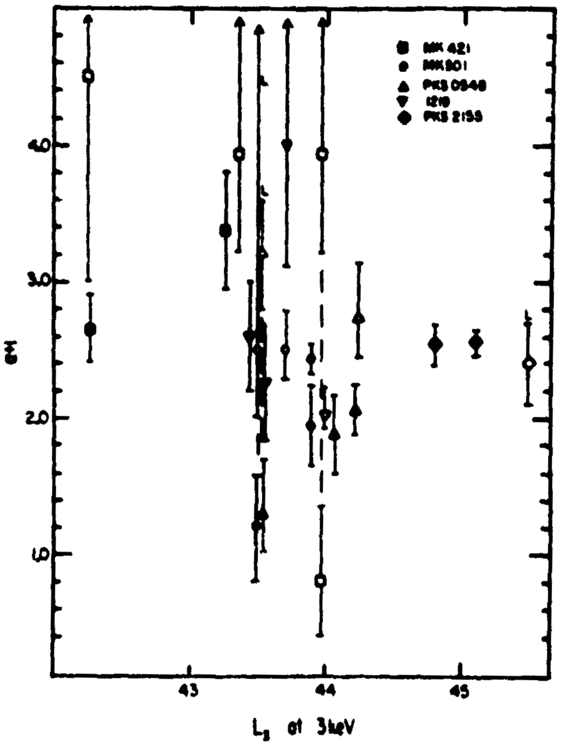

Figure 3. Best-fit spectral indices of BL Lac sources, as a function of luminosity (log base 10) in a 1 keV band at 3 keV. Each shape represents a different source, with the filled shapes representing SSS data points. The open shapes are data taken with the HEAO-1 A-2 experiment (L representing data taken with the low-energy LED detectors). The three points with $\alpha+1 \leq 1.4$ were all obtained as high energy hard components, in addition to steeper spectra measured below 5 keV concurrently, as indicated by the dashed lines.

The quasars for which we have spectral information constitute a considerably more meager sample of the detected total than do either the Seyferts or BL Lacs. More than 100 quasars have now been observed with the Einstein imaging experiments (Zamorani, et al. 1980), but most are much too weak for spectroscopic interrogation. 3C 273 has the same α=0.4 index in the SSS energy range as it does at higher energies (Worrall, et al. 1979) and QSO 0241 has an SSS index consistent with the α=1 measured by A-2 (Worrall, et al. 1980), although the heavy obscuration through the galactic plane makes the SSS spectral sensitivity less constraining for this source. Other quasars (or extreme Seyfert I or N galaxies which have sometimes been labeled quasars) for which SSS spectra have been obtained tend to be slightly steeper than the Seyfert I "universal" α=0.7 (e.g. Fairall 9, IC 4329A, III ZW2), but the total sample is too small to attempt any strong conclusions.

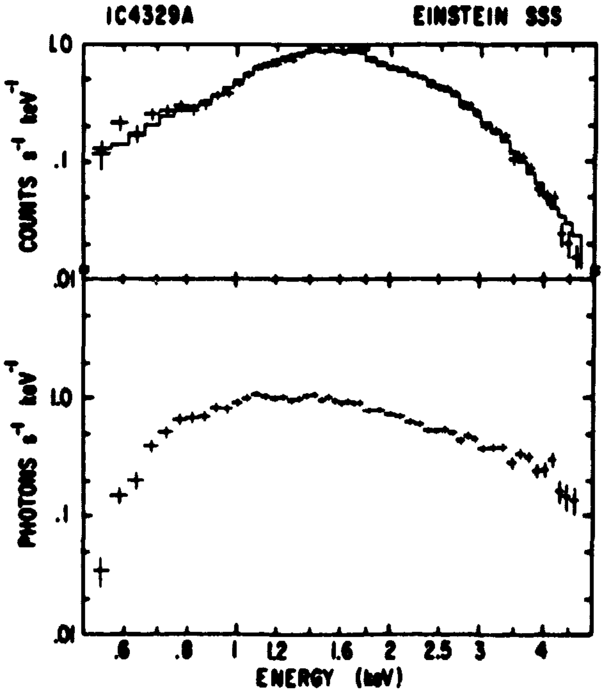

Figure 4. SSS data from the Seyfert/quasar IC 4329A. The top trace is the raw data fit with a power law of α=.86 masked by precisely the amount of cold gas (mostly in its own galaxy) inferred from the reddening. The bottom trace is the raw data of the top trace formally inverted through the SSS response function to display the incident spectrum at the detector.

Additional data which may help to suggest some initial categorization scheme is the recent result from the Einstein imaging data that the radio-loud quasars seem to exhibit an effective spectral index α_{ox} from point measurements in the optical and soft X-rays of approximately 1.3, while the radio-quiet quasars exhibit a considerably steeper index, i.e. $\alpha_{ox} \sim 1.7$. The latter represent more than 90% of quasars, and it is interesting that this α_{ox} is consistent with the average optical index for Seyferts (i.e., one unit steeper than the X-ray index). In view of the many similarities previously noted between Seyfert 1 and radio-quiet quasars, one might even make the tentative suggestion that the steep low energy component observed in ESO 141, one of the very brightest of the Seyfert I galaxies in X-rays, is a manifestation of the same effect responsible for the fact that radio-quiet QSOs seem to exhibit spectra slightly steeper than do the Seyfert I galaxies. The detailed modeling of X-ray transport out of radio-quiet quasars and Seyferts may have to accommodate this apparent slight softening in spectrum with luminosity.

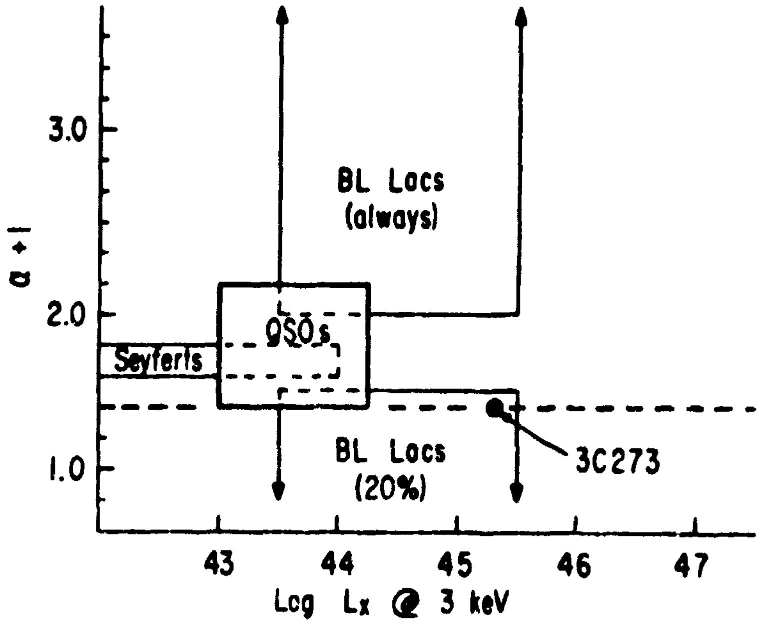

Figure 5. Summary of spectral index measurements reported here for the e classes of compact extragalactic sources.

Conversely (or similarly, depending upon your point of view), the radio-loud QSOs may be associable with the BL Lacs. In this case, the relatively flat 3C 273 spectrum may represent the Compton-scattered component, while many radio-loud quasar

X-ray spectra may be of the much steeper spectral form suggested above to arise from synchrotron emission. It should be remembered, however, that the smaller α_{ox} for the radio quasars suggests that it is their Compton components which are being observed. Further, the higher redshifts of the fainter (in apparent X-ray intensity) objects implies an X-ray sampling at higher energies at the source, which slightly complicates the interpretation given above for the radio-quiet quasar spectra. Nevertheless, the associations made here between the Seyferts and radio-quiet quasars, and the BL Lacs and radio-loud quasars, remain plausible, if not completely justified in all respects.

Finally, the extent to which the diffuse X-ray background (XRB) may be connected to X-ray emission from quasars must be addressed. There are several relevant constraints to consider, including spatial fluctuations, spectra and luminosity functions. The fluctuation analyses performed to date depend to some extent upon the evolution of the quasar population, and will not be addressed here. The optical luminosity function indicated, even before Einstein, that the XRB might easily be explainable from the superposition of individual quasars. Setti and Woltjer (1979), for example, suggested that if 3C 273 and Fairall 9 were representative quasar X-ray emitters, current estimates of the density evolution of the quasar population at high redshift would assure that the XRB would be entirely explained well before 23rd magnitude. The early Einstein imaging results seemed to bear this out, as approximately 25% of the $\sim$1 keV XRB is reconciled with quasars detectable with Einstein sensitivity (Giacconi, et al. 1979).

The spectral results may represent the most formidable obstacle to complete reconciliation. The XRB spectrum has been measured with high precision by Marshall, et al. (1980) between 3 keV and 60 keV. Below 3 keV the effects of galactic contamination (both in absorption and emission) do not allow a useful measure of the XRB spectrum, and the counter efficiency of the A-2 detectors is too low above 60 keV. The data in this energy range are remarkably well-fit by a bremsstrahlung temperature of about 40 KeV, and definitely cannot be fit with a single power-law. It is important to note several different points about this XRB spectrum. First, it indicates that the large fraction of the energy density in the XRB is $>$10 keV. Second, the aforementioned effects of the galaxy render a measure of the spectrum below 3 keV impossible, so that any attempt to reconcile a potential source with the XRB below 3 keV is faced with the necessity of assuming an extrapolation to lower energies, in addition to performing the consistency check far from where the energy density peaks. Third, measurements made at still higher energies ($>$100 keV) with other instruments indicate that the XRB measured here exceeds the extrapolation of the

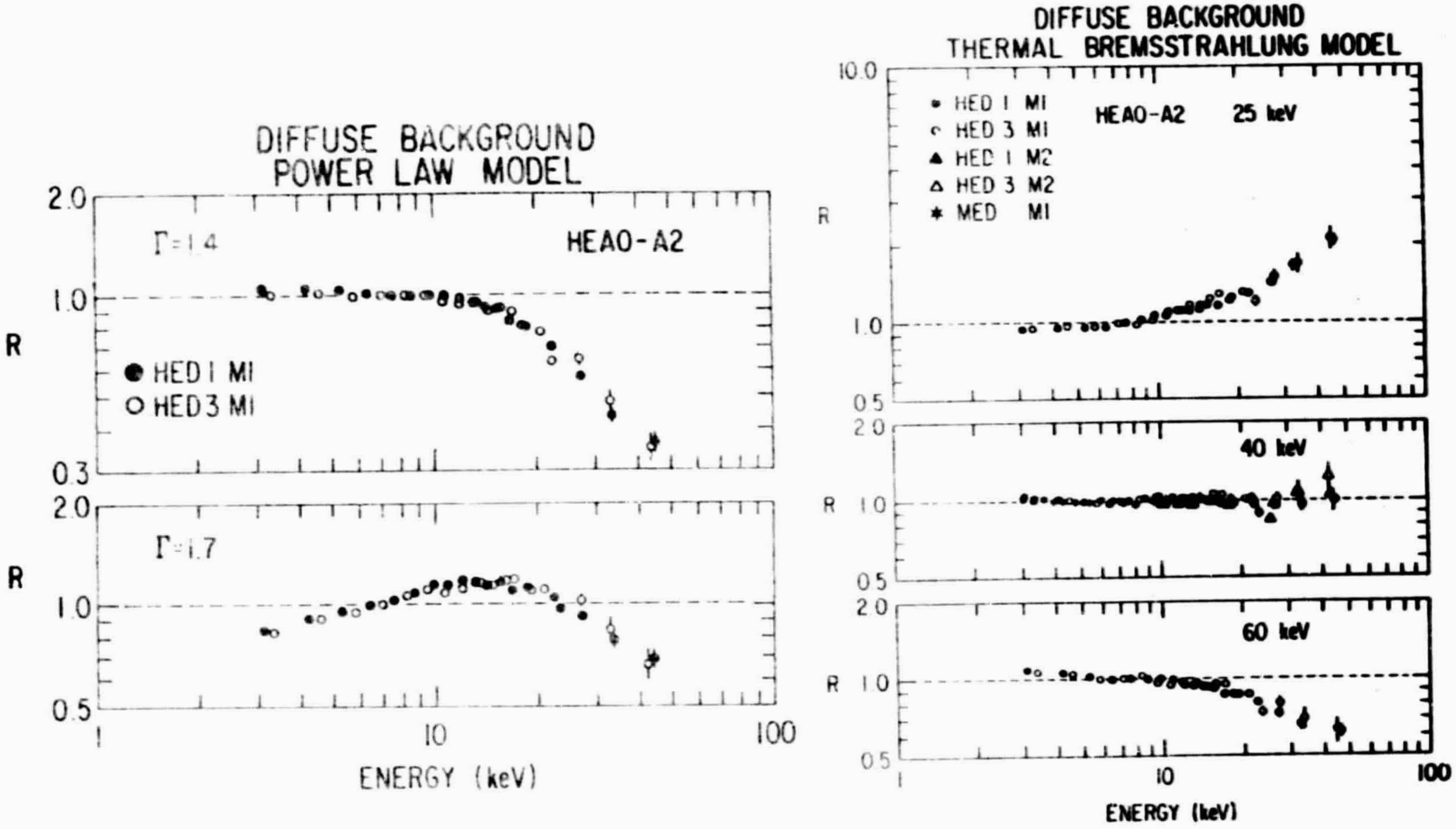

Figure 6. The ratio of the XRB spectrum measured with the A-2 experiment to trial idealized spectra. Different symbols represent independent measures with different detectors. The power-law index $\Gamma = 1 + \alpha$.

thermal spectrum. This suggests that the apparent thermal component is only one of a potentially large set of contributors to the total XRB, but that it deserves special consideration because the energy density is highest there.

The $\sim$25% contribution from quasars near 1 keV is based upon an extrapolation of this thermal spectrum to lower energies. If this fraction (or a higher one) is correct, then the reality of a true substantial thermal component to the XRB is in considerable doubt, since a large non-thermal spectral component subtracted from a thermal one will not yield a net thermal spectrum. It is important to appreciate, however, that the actual composite XRB intensity at 1 keV is not measurable, and may far exceed the extrapolation of the thermal spectrum if the quasar spectra are steep. Holt (1980) has carefully considered the effects of synthesizing an XRB spectrum from Seyfert, quasar and cluster spectra similar to those measured from individual members of these classes to determine the extent to which an apparent thermal component may still contribute; surprisingly, approximately 80% of the XRB intensity in the peak energy density range can still arise from this component. Even though the total XRB substantially exceeds it at both higher and lower energies owing to the contributons from active galactic nuclei, the apparent thermal component can still be preserved even after a large quasar contribution is removed.

This analysis suggests that the XRB near 1 keV is truly dominated by quasars, but that the XRB in the range where its energy density peaks may have a quasar contribution of no more than $\sim$10%. The origin of the apparent thermal component responsible for the large fraction of the XRB is not specified, however. Nor is the necessity of its thermal form: this analysis is meant only to demonstrate that all of the available data are not inconsistent with an apparent thermal component which can supply more than 3/4 of the XRB intensity.

It is unlikely that this component arises in a hot intergalactic medium, for theoretical reasons discussed by many authors. It is difficult to reconcile this component with quasars, based upon the tentative conclusions regarding the spectra of active galactic nuclei discussed above. Only 3C 273, a radio-loud quasar, can match the XRB spectrum, if it is redshifted to $z > 1$ (and then the consistency check can be performed over a dynamic range of only about 1/4 of the 3-60 keV interval). Figure 6 illustrates the futility of attempting to find a universal power-law component with which the XRB can be fit. More realistically, Cavaliere, et al. (1979) have attempted to determine what combination of near-power-law spectra might work. Their analysis suggests not only that $\alpha \sim 0.4$ components must sharply cutoff $<$100 keV if they dominate $>$10 keV, but also that the softer spectra reviewed here must considerably steepen the net XRB spectrum at lower energies. Unless quasars at large redshift have spectra very different than the active galactic nuclei which we can interrogate locally (e.g. if they exhibit near-bremsstrahlung spectra of 100-200 keV at the source), it will be exceedingly difficult to convincingly synthesize the XRB spectrum from them.

The postulation of quasars with X-ray spectra very different at early epochs than those of local active galactic nuclei may be the ultimate resolution of the difficulty, but a more natural explanation has recently been suggested by Bookbinder, et al. (1980). If very young galaxies are rich in supernovae and binary X-ray sources, they should give rise to intense galactic winds at temperatures of the order of 100-200 keV. Because this explanation meets the spectral constraints of the XRB with an origin which naturally arises at $z > 1$, it is a very attractive alternative to the quasar hypothesis. It will remain for the next generation of X-ray astronomical instrumentation to settle the question unambiguously.

REFERENCES

Barr, P., White, N.E., Sanford, P.W., and Ives, J.C. 1977, M.N.R.A.S. 181, pp. 43

Cavaliere, A., Danese, L., DeZotti, G., and Franceschini, A. 1979, Astron. and Ap. 79, pp. 169

Cavallo, G. and Rees, M.H. 1978, M.N.R.A.S. 183, pp. 359

Davidson, K. and Netzer, H. 1979, Rev. Mod. Phys. 51, pp. 715

Elvis, M., Maccacaro, T., Wilson, A.S., Ward, M.J., Penston, M.V., Fosbury, R.A.E., and Perola, G.C. 1978, M.N.R.A.S. 183, pp. 129

Fabian, A.C. 1979, Proc. R. Soc. London A. 366, pp. 449

Giacconi, R. et al. 1979, Ap. J. (Letters) 234, pp. L1

Holt, S.S. 1980, in X-Ray Astronomy, Giacconi, R. and Setti, G., eds, D. Reidel, Dordrecht-Holland, in press

Holt, S.S., Mushotzky, R.F., Becker, R.H., Boldt, E.A., Serlemitsos, P.J., Szymkowiak, A.E., and White, N.E. 1980, Ap. J. (Letters), in press

Marshall, F.E. et al. 1980, Ap. J. 234, pp. 4

Mushotzky, R.F., Holt, S.S., and Serlemitsos, P.J. 1980, Ap. J. (Letters) 225, pp. L115

Mushotzky, R.F., Marshall, F.E., Boldt, E.A., Holt, S.S. and Serlemitsos, P.J. 1980, Ap. J. 235, pp. 377

Setti, G. and Woltjer, L. 1979, Astron. and Ap. 76, pp. L1

Urry, M., Mushotzky, R.F., Boldt, E.A., Holt, S.S., and Serlemitsos, P.J. 1980, preprint

Worrall, D.M., Boldt, E.A., Holt, S.S., and Serlemitsos, P.J. 1980, Ap. J., in press

Worrall, D.M., Mushotzky, R.F., Boldt, E.A., Holt, S.S. and Serlemitsos, P.J., Ap. J. 232, pp. 683

Zamorani, G. et al. 1980, preprint