THE ASTROPHYSICAL JOURNAL, 380:L59–L62, 1991 October 20

X-RAY EMISSION FROM STARBURST GALAXIES

YOEL REPHAELI[1,2], DUANE GRUBER,[1] MASSIMO PERSIC,[3] AND DAN MACDONALD[1]
Received 1991 March 24; accepted 1991 August 1

ABSTRACT

We report the results of an investigation of X-ray emission from a sample of 53 *IRAS*-selected candidate starburst galaxies. Superposed soft and hard X-ray emission from these galaxies in the *Einstein* IPC and *HEAO 1* A-2 and A-4 energy bands, which span 0.5 to 160 keV, is detected at the 99.6% confidence level, after allowing for confusion noise in the *HEAO 1* data. Above 15 keV the confidence level is 97%. The combined spectrum is flat, with a (photon) power-law index of 1.0 ± 0.3. The contribution of the population of sources represented by this sample to the 3–50 keV residual cosmic X-ray background is estimated to be at least $\sim 4\%$ assuming no evolution. Moderate evolution, for which there is some observational evidence, increases this fractional contribution to $\sim 26\%$.

Subject headings: galaxies: X-rays — X-rays: sources

1. INTRODUCTION

Discrete sources are known to contribute significantly to the cosmic X-ray background (CXB), but probably not all classes of contributing sources have been identified. Neither do we know yet whether, when, and how any appreciable diffuse emission has been produced. Interest has traditionally been focused on the isotropic X-ray background spectrum in the energy range 3–50 keV, because of its accessibility to observation and also because its strength and hard spectrum, unlike any class of known sources, pose important theoretical challenges. The most comprehensive observational information on the CXB had been obtained by measurements made with the A-2 (Marshall et al. 1980) and A-4 (Rothschild et al. 1983; Gruber et al. 1984) experiments aboard the *HEAO 1* satellite.

It is thought that most of the discrete source contribution is due to active galactic nuclei (AGNs) whose mean power-law spectrum has an energy index $\alpha_{\rm AGN} \simeq 0.7$. Leiter & Boldt (1982) estimated that about 30% of the CXB flux in the band 3–10 keV is due to AGNs. Models in which all of the CXB is accounted for by emission from AGNs with suitable spectral properties have been proposed (Schwartz & Tucker 1988; Fabian et al. 1990) A recent *Ginga* detection of a flat component in the spectrum of Seyfert galaxies at energies $\gtrsim 10$ keV (Matsuoka et al. 1990) lends some support for a larger AGN contribution to the CXB (Morisawa et al. 1990). Clusters of galaxies contribute a few percent to the flux in the above energy band, and probably even less at higher energies (Rephaeli, Gruber, & Rothschild 1987; Rephaeli & Gruber 1988). After subtraction of the extrapolated contributions of AGNs and clusters, the residual CXB 3–50 keV spectrum is found to be surprisingly flat (see the review by Boldt 1987). A basic goal is the interpretation of the flat residual CXB spectrum.

Starburst galaxies (SBGs) constitute a major class of bright far-infrared (FIR) sources (Soifer et al. 1986), whose enhanced output is probably due to warm dust heated by hot, massive stars. Hard X-ray binaries and supernova remnants (SNRs) should also be more abundant during the starburst phase. Correspondingly, it has been suggested (Bookbinder et al. 1980; De Zotti 1987; Weedman 1987) that SBGs emit X-rays more intensely than normal galaxies and therefore may contribute appreciably to the CXB.

To estimate the contribution of SBGs to the CXB, Weedman (1987) used his 60 μm SBG luminosity function and a flux ratio of $f(60\ \mu{\rm m})/f(2\ {\rm keV}) = 2.7 \times 10^8$ based on *Einstein* measurements (Fabbiano, Feigelson, & Zamorani 1982), finding that SBG contribute at least 13% to the CXB flux at 2 keV. This estimate for the fractional contribution of SBGs to the CXB at 2 keV is interesting and points to the possibility that a major new discrete component of the CXB has been identified. Obviously, much has to be done in order to test and quantify this hypothesis: major unknowns are the characteristic X spectra and evolution of SBGs.

In this *Letter* we report the results of a first study of the largest sample yet of SBG spectra in the combined *Einstein* IPC, and *HEAO 1* A-2 and A-4 energy bands, spanning the range 0.5–160 keV. We use $H_0 = 50$ km s^{-1} Mpc^{-1} throughout.

2. THE SAMPLE

A selection of a SBG sample would have been a simple matter had we had a (e.g., flux-limited) complete sample of SBGs. This is not yet the case. We therefore use the partial knowledge of SBGs to motivate our selection. An indicative result from analyses of *IRAS* and optical observations is that the *IRAS*-selected sample of SBGs is not the same as the optically selected one (Lawrence et al. 1986; Soifer et al. 1986). The latter authors find that the FIR/blue luminosity ratio, $L_{\rm FIR}/L_B$, of galaxies in the sample increases with $L_{\rm FIR}$, but is not correlated with L_B. Soifer et al. (1986) suggest that $L_{\rm FIR}$ and L_B are independent, and that the increase of their ratio with $L_{\rm FIR}$ is due to enhanced FIR emission, not to increased visual extinction. Enhanced FIR emission indicates higher abundance of warm dust, whereas intense blue emission would be indicative of a rich population of young massive stars. If X emission in SBGs is mainly due to high SN rate, we predict their X emission to be more directly correlated with FIR, rather than with optical emission.

[1] Center for Astrophysics and Space Science, C-011, University of California, San Diego, La Jolla, CA 92093.
[2] On leave from the School of Physics and Astronomy, Tel Aviv University.
[3] SISSA, Strada Costiera 11, I-34014 Trieste, Italy; and Osservatorio Astronomico, Trieste

Motivated by this argument, we select SBGs from the *IRAS* Bright Galaxy Sample of Soifer et al. (1987). A luminosity-limited subset of this latter sample is chosen to ensure that the majority of the selected galaxies are SBGs: we select only galaxies with $L_{\rm FIR} > 10^{11}\ L_\odot$. Presumably, this is a reasonable value for the cutoff luminosity, based on analyses of the bright *IRAS* sources (B. T. Soifer 1988, private communication). Admittedly, this selection criterion is somewhat arbitrary.

This choice defines a subset of 116 galaxies of the total 324 in the *IRAS* Bright Galaxy Sample. Only eight of the 116 galaxies are in the *HEAO 1* A-1 catalog, of a total of 18 in the whole *IRAS* Bright Galaxy Sample. Of the 116 SBGs, 19 are classified as AGNs, whose CXB contribution has been accounted for separately. Therefore, the sample reduces to 97 SBGs. Only six of these 97 galaxies are in the sample selected by Persic et al. (1989) for A-2 analysis. Thus, the two samples are essentially distinct.

The 97 sources in the total sample vary significantly in distance and in $L_{\rm FIR}$. In order to first determine the mean X spectrum of a better defined sample of nearby SBGs we extract a subsample of 53 sources with recession velocities lower than 6000 km s^{-1} (including the two nearby SBGs NGC 253 and M82) for the first stage of the investigation whose results are reported in this *Letter*.

3. X-RAY DATA ANALYSIS AND RESULTS

The two full sky surveys performed by the A-2 and A-4 experiments aboard the *HEAO 1* satellite (Rothschild et al. 1979; Matteson 1978) provided remarkably homogeneous scanning data in the 2–175 keV energy range. The *HEAO 2* Slew Survey also covers much of the sky, although at variable exposure. We describe the treatment of sky, or confusion, noise in the *HEAO 1* A-4 data, because this has a strong effect on the significance of the results.

We have examined *HEAO 2* data from the Imaging Proportional Counter (IPC), where available, for these sources. The angular resolution amounts to negligible source confusion. Six sources were found listed in IPC fields, only one of which was identified. For another 41 positions, flux estimates were obtained from the Slew Survey. There is no IPC information on (only) six sources.

The *HEAO 1* A-2 data analysis was carried out according to the standard procedure described in Della Ceca et al. (1989); in particular, objects contaminated by (i.e., $<6°$ away from) bright A-2 sources were discarded. In addition, the very selection procedure of our SBG sample ensures that all the objects are at high Galactic latitude ($b \geq 20°$), so they are free from Galactic contamination. The final A-2 sample consists of 45 objects. Their statistical error-weighted, mean individual flux is 0.145 ± 0.041 *R*15.

The two Low Energy Detectors (LED) of the A-4 experiment aboard *HEAO 1* were sensitive in the 13–175 keV band, with geometric area of 103 cm^2 each, mean efficiency of 0.7, and a field of view 1°43 by 20°. A given source was scanned for a live time of the order of 1000 s at half-year intervals. For most sources three complete scans were obtained. A local background count rate was also accumulated for about 13 s or 3° of scan azimuth preceding and following each source transit. Net source minus background spectra and error estimates from counting statistics were then obtained by co-adding the data from individual transits. The pulse-height data were grouped into four broad channels with boundaries at 13, 25, 40, 80, and 160 keV.

In addition to Poisson counting noise, measurement noise arises from fluctuations of the diffuse background (or equivalently, source confusion), incomplete subtraction of detector internal background, and detector gain variations. A measurement of the sum of all these effects was obtained by binning all the scanning data into 1468 full-response pixels. About 750 of these pixels were unconfused with any of the sources in the A-4 catalog (Levine et al. 1984) or the Galactic plane. For each energy band, and rms fluctuation level for the 750 pixels was determined. These were about 0.01 counts s^{-1}, or about 1% of the mean background count rate, and also surprisingly close to the single-pixel statistical error. These values are a factor of ~ 3 above an extrapolation of the 2.3% per 26 deg^2 quoted (Shafer & Fabian 1983) for the 2–10 keV diffuse background rms; thus noise from detector systematics appears to dominate. Since these systematics can potentially be modeled, the observed nonstatistical noise can be regarded as an upper limit. The total noise levels, roughly double the statistical noise, reduce the statistical significances by a factor of ~ 2. Net significances, statistical plus measured systematic, are reported below; these should be regarded as lower limits.

We have weighted the *Einstein*, A-2, and A-4 data on the sampled sources in two different ways. First, in order to be able to characterize the X-ray properties of a typical SBG in our sample, we weighted the individual count rates by z^2, to correct for the large scatter in distance. Doing so, and assuming photoelectric absorption corresponding to $N_{\rm H} = 10^{22}$ cm^{-2} (cf. Schaaf et al. 1989), our best-fit power law spectrum in the range 0.5–80 keV is

$$\phi(E) = (9.48 \pm 3.61) \times 10^{-6}\left(\frac{E}{10\ {\rm keV}}\right)^{-(0.99 \pm 0.27)} {\rm cm^{-2}\ s^{-1}\ keV^{-1}}\,, \quad (1)$$

with a reduced χ^2 of 1.02. This spectrum is shown in Figure 1. One way to take account of the intrinsic differences in the X properties of the sampled sources is to make the reasonable (albeit unproved) assumption that the X luminosity is pro-

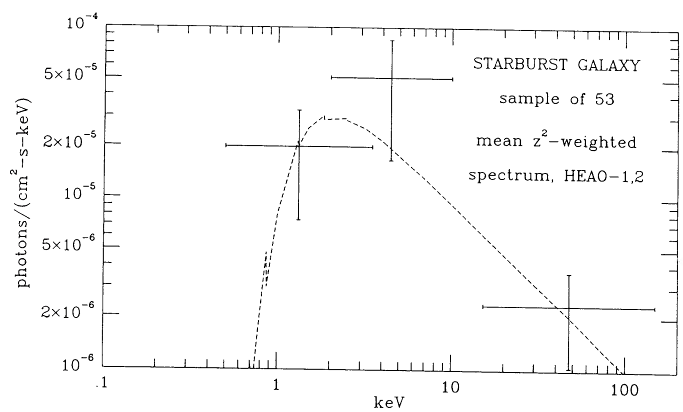

FIG. 1.—The mean X-ray spectrum of a sample of 53 *IRAS*-selected candidate SBGs with z^2 weighting. Crosses represent data from the *Einstein* IPC, *HEAO 1* A-2, and *HEAO 1* A-4 instruments, respectively, with increasing energy. The fluxes in the four A-4 channels have been combined together in the analysis. Errors shown are 1 σ. The dashed line is the best-fit power-law spectrum. Net confidences are $P = 0.996$ for all data, $P = 0.985$ for *HEAO 1* data alone, and $P = 0.963$ for data above 15 keV. Observed counting rates have been converted to photon fluxes with spectrum-dependent average efficiencies. Photoelectric absorption corresponding to $N_{\rm H} = 10^{22}$ cm^{-2} has been assumed.

portional to L_{FIR}. The mean sample spectrum, obtained by weighting individual fluxes according to L_{FIR}, is then

$$\phi(E) = (13.54 \pm 4.21) \times 10^{-6}\left(\frac{E}{10\ \text{keV}}\right)^{-(1.05\pm0.22)} \text{cm}^{-2}\ \text{s}^{-1}\ \text{keV}^{-1}\ , \quad (2)$$

with a reduced χ^2 of 0.62. In both equations (1) and (2), the quoted uncertainties include statistical and sky noise errors.

The above deduced mean SBG spectra are significantly flatter than the mean AGN spectrum, whose power-law index is 1.7 ± 0.1 (Boldt 1987). Directly integrating the flux in equation (1) over the band 2–30 keV, we compute a mean X luminosity of our fiducial SBG (located at an rms redshift of $\langle z^2 \rangle^{1/2} = 0.0133$) to be $L_{2-30} \simeq (3.3^{+1.6}_{-1.1}) \times 10^{42}$ ergs s^{-1}. Previous determinations of the X luminosity of SBGs were limited to lower energies. For example, Fabbiano (1988) calculated the luminosities of the two nearby SBGs NGC 253 and M82 to be $L_{1-10} \simeq 2.5 \times 10^{40}$ ergs s^{-1}, and $L_{1-10} \simeq 6.5 \times 10^{40}$ ergs s^{-1}, respectively, in the *Einstein* MPC 1–10 keV band. It is interesting that the luminosity of M82 is just what we would have predicted after accounting for the narrower *Einstein* band, and for the fact that the L_{FIR} of M82 is about 6 times lower than our sample mean.

4. DISCUSSION

We seem to have found that a significant fraction of the sources in the *IRAS* Bright Galaxy Sample are also intense X-ray sources. This result could constitute an important ingredient to theoretical studies of the nature of these sources, and their (likely to be related) IR and X emission mechanisms. Here, we are primarily interested in the implications arising from the identification of the sources in our sample as SBG.

The expectation that SBGs are strong X-ray sources is based on their enhanced SN activity, or on their high abundance of X-ray binaries. Bursts of SN activity can lead to enhanced X-ray emission either directly, through nonthermal emission from SNRs, or indirectly through thermal ($T \sim 10^9$ K) emission from SN-driven galactic winds (Bookbinder et al. 1980), or through Compton scattering of the FIR radiation field by SN acceleration of relativistic electrons. Our mean SBG spectrum is well fitted by a power law, so the hard–X emission could possibly be due to Compton scattering of relativistic electrons off the intense FIR radiation field (see also Schaaf et al. 1989).

Electrons of energy ~ 1 GeV are required to boost a FIR photon to ~ 10 keV. The mean FIR energy density is $\sim 2 \times 10^{-12}$ ergs, cm^{-3}, i.e. ~ 5 times more intense than the cosmic blackbody radiation. To account for the mean X luminosity of SBGs, the energy density in electrons has to be $\sim 2 \times 10^{-10}$ ergs cm^{-3}, i.e., $\sim 10^4$ times higher than in the Galaxy (roughly the SBG/Galaxy X luminosity ratio). A high density of electrons would also yield an enhanced radio emission, though by a factor lower than the above ratio because the energy loss of electrons is mainly by Compton scattering. Indeed, there exists a definite correlation between the radio (L_R) and FIR luminosities of spiral galaxies. In the FIR luminosity range relevant to SBGs, $L_R \propto L_{FIR}^{1.3}$ (Wunderlich & Klein 1988). However, the possibility that hard–X emission in SBG is mainly due to nonthermal emission is merely a conjecture, which must be carefully assessed.

The mean SBG spectra in equations (1) and (2) are considerably flatter than the mean AGN spectrum, a desirable feature if SBGs are to contribute significantly to the CXB. To compute this contribution, we need to know the local SBG density, which is not known very well. Our estimate of the density is based on the facts that the *IRAS* Bright Galaxy Sample covers only 14,500 deg^2 of the sky, and that there are 53 sources in our (analyzed) sample out to ~ 115 Mpc. Thus, the local density of SBGs is $n_0 = 2.4 \times 10^{-5}$ Mpc^{-3}. To calculate the SBG contribution to the CXB, we use equation (5.53) of Boldt (1987) for the spectral intensity of sources whose mean luminosity per (measured) energy interval is dL/dE_0, i.e.,

$$\frac{dI}{dE_0} = \left(\frac{c}{4\pi H_0}\right) n_0 \frac{dL}{dE_0} f(\alpha, z_m, \Omega_0, Q)\ , \quad (3)$$

where f is a dimensionless function which depends on α, on the maximum redshift z_m out to which these sources are found, on the cosmological density parameter, Ω_0, and on a parameter characterizing the evolution of the sources, denoted by Q in Boldt (1987). Integration of our deduced mean spectrum (cf. eq. [1]) over the energy band $[E_1, E_2]$ leads to

$$I = \left(\frac{c}{H_0}\right)^2 \langle z^2 \rangle n_0 A f(E_2^{1.01} - E_1^{1.01})\ \text{keV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ , \quad (4)$$

with $A = 9.6 \times 10^{-5}$ and E_1 and E_2 are in keV. Assuming $Q = 0$ (no evolution), $\Omega_0 = 1$ and $z_m = 4$, which give $f = 0.61$, and using an rms redshift of $\langle z^2 \rangle^{1/2} = 0.0133$, we calculated the integrated SBG intensity over the 3–10 and 3–50 keV energy bands to be $I_{3-10} \simeq 0.37$ and $I_{3-50} \simeq 2.5$ keV cm^{-2} s^{-1} sr^{-1}, respectively. Density and/or luminosity evolution would yield higher predicted SBG intensities: e.g., an evolution at the level suggested by Danese et al. (1987) for radio-selected SBG candidates, corresponding to $Q \sim 3$, would raise (see eq. [5.57] of Boldt 1987) the above intensities to $I_{3-10} \simeq 2.4$ and $I_{3-50} \simeq 16.6$ keV cm^{-2} s^{-1} sr^{-1}.

From Figure 3.6 of Boldt (1987), we then estimate the integrated intensity of the residual CXB to be $I'_{3-10} \simeq 20$ and $I'_{3-50} \simeq 65$ keV cm^{-2} s^{-1} sr^{-1}. Correspondingly, with no evolution the SBG contribution to the residual CXB is $\sim 2\%$ in the 3–10 keV band, and $\sim 4\%$ in the 3–50 keV band. Moderate evolution at the above level, $Q \sim 3$, would increase these values to $\sim 12\%$ and $\sim 26\%$, respectively. (Note that since the mean SBG spectrum is flatter than the residual CXB spectrum, the SBG contribution to the residual CXB is larger at higher energies.) As for the contribution to the *total* CXB, equation (3.1) of Boldt (1987) yields $I'_{3-10} \simeq 27$ and $I'_{3-50} \simeq 88$ keV cm^{-2} s^{-1} sr^{-1}, so the contribution of SBG to the total CXB is $\sim 1\%$ and $\sim 3\%$ with no evolution, and $\sim 9\%$ and $\sim 19\%$, if $Q \sim 3$. It should be emphasized that since we have sampled only the brightest SBGs, the total SBG contribution to the CXB may be higher than estimated here.

The above estimates confirm the earlier conjecture of Weedman (1987) and, more recently, of Griffiths & Padovani (1990) that SBGs contribute appreciably to the residual CXB. In particular, our estimate for the fractional contribution of SBGs to the CXB is in general agreement with that of Griffiths & Padovani (1990), whose (more phenomenological) analysis was, however, limited to *Einstein* data. Because our statistical study of hard-X emission from SBGs is the first of its kind, and given the fact that individual SBGs have not yet been detected at hard-X energies, our mean spectrum at energies ≥ 20 keV may be regarded as tentative, pending more sensitive observations of SBG spectra. We emphasize that since our deduced mean SBG luminosity is quite high, *Ginga* might well detect individual bright SBGs.

Assuming all the presumed 150 sources (over the full 4π sr) to be SBGs yields an upper limit to the contribution of these sources to the CXB. Among other uncertainties, it is expected that an unknown fraction of these sources are AGNs. However, that this fraction is small can be seen from an independent, previous estimate of the mean density of SBGs. The density of SBGs with $L_{\rm FIR} \geq 10^{11}\ L_{\odot}$ can be deduced from e.g., Figure 1 of Soifer et al. (1986): scaling to our adopted value of H_0, we infer a value of $\sim 2 \times 10^{-5}$ Mpc^{-3}, in good agreement with our estimate.

The angular surface density of SBGs, σ_s, can be calculated from the expression for the differential surface density of sources per unit redshift interval (which is directly related to, e.g., eq. [5.47] of Boldt 1987). Integrating to $z_m = 4$, we obtain $\sigma_s \simeq 700$ SBGs deg^{-2}. This number is smaller by a factor ~ 7 than the lower limit obtained by Hamilton & Helfand (1987) from their analysis of the isotropy of the CXB from *Einstein* IPC data. Since the IPC energy band (0.5–3.5 keV) is much below the range explored here, it is not at all clear that this limit should apply. It is reasonable that higher energy sources are rarer; correspondingly, therefore, at higher energies the CXB may be expected to be less isotropic than deduced from the IPC measurements. Indeed, although we have considered only the very bright SBGs, it is clear that lower luminosity sources also contribute, especially so at lower energies, perhaps even relatively more than the bright sources. Since such sources are more numerous (as can be seen in Fig. 1 of Soifer et al. 1986), we do expect lower CXB granularity that can be inferred from our calculated SBG surface density.

An expanded discussion of all aspects of this work will be given in a forthcoming paper (Gruber et al. 1991).

This research has been supported by NASA through grant NAG 5-1385. Y. R. and M. P. are grateful to the University of California, San Diego for hospitality. Martin Elvis assisted us with the Slew Survey. It is a pleasure to thank Elihu Boldt for many stimulating conversations. We also thank an anonymous referee for stimulating comments which helped us improve the presentation of this work.

REFERENCES

Boldt, E. 1987, Phys. Rep, 146, 215
Bookbinder, J., Cowie, L. L., Krolik, J. H., Ostriker, J. P., & Rees, M. 1980, ApJ, 237, 647
Danese, L., De Zotti, G., Franceschini, A., & Toffolatti, L. 1987, ApJ, 318, L15
Della Ceca, R., Palumbo, G. G. C., Persic, M., Boldt, E. A., De Zotti, G., & Marshall, F. E. 1990, ApJS, 72, 471
De Zotti, G. 1987, in Proc. 7th Italian Conf. General Relativity and Gravitational Physics, ed. U. Buzzo, R. Cianci, & E. Massa (Singapore: World Scientific), 331
Fabbiano, G. 1988, ApJ, 330, 672
Fabbiano, G., Feigelson, E., & Zamorani, G. 1982, ApJ, 256, 397
Fabian, A. C., George, I. M., Miyoshi, S., & Rees M. J. 1990, MNRAS, 242, 14P
Griffiths, R. E., & Padovani, P. 1990, ApJ, 360, 483
Gruber, D. E., Rothschild, R. E., Matteson, J. L., & Kinzer, R. 1984, in X-Ray and UV Emission from AGN, ed. W. Brinkman & J. Trümper (Garching: Max-Planck Institut), 129
Gruber, D., et al. 1991, in preparation
Hamilton, T. T., & Helfand, D. J. 1987, ApJ, 318, 93
Lawrence, A., Walker, D., Rowan-Robinson, M., Leech, K. J., & Penston, M. V. 1986, MNRAS, 219, 687
Leiter, D., & Boldt, E. 1982, ApJ, 260, 1
Levine, A. M., et al. 1984, ApJS, 54, 581
Marshall, E. F., Boldt, E., Holt, S. S., Miller, R., Mushotzky, R. F., Rose, R. E., Rothschild, R. E., & Serlemitsos, P. 1980, ApJ, 235, 4
Matsuoka, M., Piro, L., Yamauchi, M., & Murakami, T. 1990, ApJ, 361, 440
Matteson, J. L. 1978, AIAA Conference paper 78-35
Morisawa, K., Matsuoka, M., Takahara, F., & Piro, L. 1990, A&A, 236, 299
Persic, M., De Zotti, G., Danese, L., Palumbo, G. G. C., Franceschini, A., Boldt, E. A., & Marshall, F. E. 1989, ApJ, 344, 125
Rephaeli, Y., & Gruber, D. E. 1988, ApJ, 333, 133
Rephaeli, Y., Gruber, D. E., & Rothschild, R. E. 1987, ApJ, 320, 139
Rothschild, R. E., et al. 1979, Space Sci. Instr., 4, 269
Rothschild, R. E., Mushotzky, R. F., Baity, W. A., Gruber, D. E., Matteson, J. L., & Peterson, L. E. 1983, ApJ, 269, 423
Schaaf, R., Pietsch, W., Biermann, P. L., Kronberg, P. P., & Schmutzler, T. 1989, ApJ, 336, 722
Shafer, R. A., & Fabian, A. C. 1983, in IAU Symp. 104, Early Evolution of the Universe and its Present Structure, ed. G. O. Abell & G. Chincarini (Dordrecht: Reidel), 333
Schwartz, D. A., & Tucker, W. H. 1988, ApJ, 322, 157
Soifer, B. T., Sanders, D. B., Neugebauer, G., Danielson, G. E., Lonsdale, C. J., Madore, B. F., & Peterson, S. E. 1986, ApJ, 303, L41
Soifer, B. T. et al. 1987, ApJ, 320, 238
Weedman, D. W. 1987, in Star Formation in Galaxies, ed. C. J. Lonsdale Persson (NASA Conf. Publ. 2466), 351
Wunderlich, E., & Klein, U. 1988, A&A, 206, 47