SERSC 159-03: DISCOVERY OF THE BRIGHTEST SOFT X-RAY EXCESS EMITTING CLUSTER OF GALAXIES
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ABSTRACT
The soft X-ray excess emission in the southern cluster Sersic 159-03 represents hitherto the strongest effect of its kind. Emission in the ~0.2–0.4 keV passband is detected far in excess of the expected contribution from the hot phase of the intracluster medium and extends to the X-ray signal limit of the cluster. Our analysis of ROSAT PSPC observations reveal that the soft excess can be interpreted as either a thermal or nonthermal effect, and the high data quality allows us to place tight constraints on the two currently competing models. However, each model now implies that major revisions to our understanding of clusters of galaxies are needed: either “warm” gas masses in similar amounts to the hot gas or relativistic particles in or above equipartition with the hot phase appear to be unavoidable.

Subject headings: galaxies: clusters: individual (Sersic 159-03) — intergalactic medium

1. INTRODUCTION
During the 5 intervening years since the discovery of EUV and soft X-ray excess emissions in the Virgo and Coma Clusters with the Extreme Ultraviolet Explorer (EUVE) and ROSAT missions (Lieu et al. 1996a, 1996b), the original results have been cross-checked by follow-up observations of the same objects plus a larger sample of nearby galaxy clusters (Fabian 1996; Bonamente, Lieu, & Mittaz 2001a, 2001b; Bonamente et al. 2001c; Witt, Lieu, & Lockman 1998; Lieu et al. 1999b, 1999c; Lieu, Bonamente, & Mittaz 1999a, 2000; Berghöfer, Bowyer, & Korpela 2000a, 2000b; Bowyer & Berghöfer 1998; Bowyer, Korpela, & Berghöfer 2001; Bowyer, Berghöfer, & Korpela 1999; Arabadjis & Bregman 1999; Reynolds et al. 1999; Kastra et al. 1999; Dixon et al. 2001; Dixon, Harwit, & Ferguson 1996; Valinia et al. 2000; Fusco-Femiano et al. 2000; Buote 2000a, 2000b, 2001; Arnaud et al. 2001), using complementary data from the BeppoSAX, Hopkins Ultraviolet Telescope, Far Ultraviolet Spectroscopic Explorer, and Rossi X-Ray Timing Explorer missions. Recently, we have undertaken a more extensive study of soft X-ray emission in galaxy clusters of low/intermediate Nh with the aim of assessing the impact and cosmological significance of the soft excess phenomenon. Our efforts led to the discovery of soft excess emission in a sample of clusters in the Shapley concentration (Bonamente et al. 2001c), and the analysis of more sources is still under way. In this Letter we report the brightest soft X-ray (~0.2–0.4 keV) excess cluster within the ROSAT Position Sensitive Proportional Counter (PSPC) database. The excess emission reaches ~100% of the hot intracluster medium (ICM) contribution, 3–4 times higher than the same for any other PSPC targets (e.g., A1795 and Virgo; Bonamente et al. 2001b). The inverse Compton (IC) interpretation of the soft emission (see § 3) results in a nonthermal pressure that greatly exceeds that of the thermal gas: the excess of Sersic 159-03 has more demanding energetic requirements than all previously known cases (e.g., Coma, Virgo, and A1795; Lieu et al. 1999c; Bonamente et al. 2001b). Alternatively, if the origin is thermal, the mass implications of the putative “warm” gas are also extreme, with the warm-to-hot gas mass ratio ~50% (this figure is matched only by the emission seen by EUVE for A2199, however at lower statistical significance; Lieu et al. 2000).

2. X-RAY, INFRARED, AND 21 CENTIMETER OBSERVATIONS OF SERSIC 159-03
Sersic 159-03 is a rich southern galaxy cluster, also known as Abell S1101, at a redshift of z = 0.056 (Abell, Corwin, & Olowin 1989). The cluster’s X-ray luminosity (Lx = 5.35 × 1044 ergs s−1 in 0.5–2.0 keV; de Grandi et al. 1999) is typical for a cluster of its temperature (e.g., Wu, Xue, & Fang 1999), and the emission has a radial extent of ~10′ (Fig. 1). Recent XMM observations (Kastra et al. 2001) show a “cooling” of the hot ICM in the central regions and no obvious peculiarities in the X-ray morphology, consistent with our PSPC data. The cluster, moreover, has no known radio emissions associated with it.

By means of three pointed PSPC observations of this source, taken between 1992 May and 1993 May with a total exposure of about 19,000 s, we found a very bright excess emission in PSPC’s 1/4 keV band (also known as the R2 band; ~0.2–0.4 keV). Figure 2 shows how the detected emission (light blue, dark blue, and black crosses) compares with the expected emission from the hot ICM (solid lines), e.g., as described by the recent X-ray analysis of Kastra et al. (2001). The three observations were modeled simultaneously, in order to reduce statistical uncertainties.

As extragalactic soft X-ray emissions are absorbed by the interstellar medium, an accurate measurement of the line-of-sight Galactic hydrogen (H i) column density (Nh) is crucial. The Dickey & Lockman (1990) H i maps at resolutions of, respectively, 1, 4, and 9 deg2 centered at the cluster’s position indicate a region of sky free from spatial H i gradients, with an H i density at the cluster position of 1.79 × 1020 cm−2. Since Galactic infrared 100 μm emission correlates well with H i 21 cm radiation (Boulanger & Perault 1988), we further consulted IRAS 100 μm maps (Wheelock et al. 1994) at a finer resolution of 3′. The 100 μm emission is very smooth over the cluster’s region, and it confirmed our Nh-value for the cluster’s Galactic H i. This value is henceforth used in the spectral analysis. We refer to a previous paper (Bonamente et al. 2001c) for the details on PSPC data analysis techniques.

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Spectra of azimuthally averaged annular regions were modeled with a single-temperature, optically thin plasma emission. The Galactic absorption was modeled with the codes of Morrison & McCammon 1983 (hereafter MM83; “WABS” in XSPEC language) and of Wilms, Allen, & McCray 2000 (hereafter WAM00; “TBABS” in XSPEC). The He cross sections provided by WAM00 code provides the most up-to-date cross section compilation for absorption of X-rays in the interstellar medium. In the energy range of interest, 0.2–0.4 keV, the two codes are nearly indistinguishable at the resolution of the PSPC (see Fig. 4 of WAM00) and yielded statistically consistent results (see Tables 1 and 2). The emission code employed was MEKAL (Mewe, Gronenschild, & van den Oord 1985; Mewe, Lemen, & van den Oord 1986; Kaastra 1992).

When applied to the entire passband of the PSPC (0.2–2.0 keV), the fit is formally unacceptable (Fig. 3, red crosses), and a region of depleted flux (0.5–1.0 keV) appears to accompany the 0.2–0.4 keV excess. The fit is satisfactory when applied only to energies ≥0.5 keV, with the soft excess then abundantly revealed at E ≤ 0.4 keV (Fig. 3, green crosses). The best-fit parameters of the hot phase agree with the most recent X-ray XMM observation (Kaastra et al. 2001). In Table 1, we summarize the results. We emphasize that the soft excess emission is so strong that in order to be interpreted as the low-energy tail of the hot ICM emission, a Galactic column density as low as (5–8) × 10^{19} cm^{-2} would be required, which is not only severely at variance with the measured values but is even lower than that of the “Lockman Hole,” where NH achieves a global minimum. The soft emission cannot therefore be attributed to peculiarities in the Galactic H I distribution.

In Figure 4, we show the trend of the PSPC excess. The emission extends to a radius of 800 kpc (∼9°); in the 9°–12° region, where only marginal cluster emission is detected (Fig. 1), the data point is consistent with zero flux, thereby confirming the integrity of our background subtraction technique (Bonamente et al. 2001c for reference). As comparison, we note that from the XMM-European Photon Imaging Camera data of Kaastra et al. (2001), evidence for X-ray emission is apparent only 5 A Hubble constant of H_0 = 50 km s^{-1} Mpc^{-1} is assumed hereafter.

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**TABLE 1**

| REGION (arcmin) | CODE | 0.2–2.0 keV Fit | 0.2–2.0 keV Fit (Free Ni) | 0.5–2.0 keV Fit |
|----------------|------|----------------|-----------------|---------------|
|                | kT   | A              | \(\chi^2_{\text{dof}}\) | kT            | A              | \(\chi^2_{\text{dof}}\) | kT            | A              | \(\chi^2_{\text{dof}}\) |
| 0–1            | MM83 | 1.44 ±0.02     | 0.08 ±0.02      | 264/167       | 1.88 ±0.23   | 0.4 ±0.12      | 0.95 ±0.12    | 143/166       | 1.87 ±0.14 | 0.4 ±0.14     | 97/137         |
|                | WAM0 | 1.48 ±0.07     | 0.08 ±0.05      | 272/167       | 1.92 ±0.12   | 0.4 ±0.14      | 0.93 ±0.12    | 142/166       | 1.87 ±0.14 | 0.4 ±0.14     | 97/137         |
| 1–3            | MM83 | 1.38 ±0.08     | 0.03 ±0.01      | 335/162       | 2.9 ±0.09    | 0.5 ±0.14      | 0.52 ±0.13    | 154/161       | 2.9 ±0.7 | 0.5 ±0.22     | 115/132        |
|                | WAM0 | 1.38 ±0.08     | 0.03 ±0.01      | 342/162       | 3 ±0.08    | 0.5 ±0.14      | 0.51 ±0.14    | 153/161       | 2.9 ±0.65 | 0.5 ±0.28     | 115/132        |
| 3–6            | MM83 | 2.0 ±0.16      | 0.02 ±0.02      | 111/128       | 4.0 ±0.38    | 0.6 ±0.14      | 0.7 ±0.13     | 88/127        | 3.8 ±0.14 | 0.6 ±0.23     | 66/99          |
|                | WAM0 | 2 ±0.45        | 0.01 ±0.01      | 112/128       | 4.1 ±0.38    | 0.7 ±0.14      | 0.68 ±0.12    | 88/127        | 3.7 ±0.19 | 0.6 ±0.23     | 66/99          |
| 6–9            | MM83 | 2 ±0.3         | 0.7 ±0.04       | 67/84         | 2 ±0.3      | 1.3 ±0.05      | 0.8 ±0.13     | 65/83         | 2 ±0.3    | 1.3 ±0.04     | 31/55          |
|                | WAM0 | 2 ±0.3         | 0.7 ±0.04       | 67/84         | 2 ±0.3      | 1.3 ±0.05      | 0.8 ±0.13     | 66/83         | 2 ±0.3    | 1.3 ±0.04     | 31/55          |

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Note.—Here the errors are at 90% confidence levels (\(\chi^2 + 2.7\) method), and where no errors are reported, the parameters were held fixed, according to the X-ray study of Kaastra et al. 2001. A fit is performed by minimizing the \(\chi^2\) function (dof = degrees of freedom). “A” is the elemental abundance following the relative proportions of Anders & Greves 1989. The photoelectric absorption codes are from MM83 and WAM00.
out to a radial distance of about 10', in agreement with our PSPC data. The soft excess emission therefore persists to the X-ray detection limit. To illustrate the significance of the role played by the model uncertainties in our determination of the 1 keV detection limit. To illustrate the significance of the role played by the model uncertainties in our determination of the 1 keV detection limit. To illustrate the significance of the role played by the model uncertainties in our determination of the 1 keV detection limit. To illustrate the significance of the role played by the model uncertainties in our determination of the 1 keV detection limit. To illustrate the significance of the role played by the model uncertainties in our determination of the 1 keV detection limit. To illustrate the significance of the role played by the model uncertainties in our determination of the 1 keV detection limit.

3. INTERPRETATION

How do we interpret such a strong signal? A warm, optically thin phase of the ICM at sub-megakelvin temperatures can in principle account for the excess emission. Thermal conduction can be suppressed, either for the presence of tangled magnetic fields (Chandran, Cowley, & Allbright 1999) or if the warm phase is sufficiently "clumpy" (Cowie & McKee 1977; Smith & Liljequist 1979), yet the timescale for radiative losses of a warm gas is sufficiently short to necessitate rapid and continuous replenishment (such as that of the "mixing layers" scenario of Fabian 1997), if the warm phase existed in a steady state for cosmological times. In the neighborhood of $T \sim 10^6$ K, the cooling time of a gas with solar abundances is $t_{\text{cool}} \sim 3 \times 10^7 n^{-1} \text{yr}$, where $n_\text{~}$ is the gas density in units of $10^{-3} \text{cm}^{-3}$ (Landini & Monsignori-Fossi 1990), the characteristic density of the warm phase in the 1'–3' and 3'–6' regions for a volume filling factor $f \leq 1$ (0 < $f$ < 1). Our observations, however, determine the so-called emission measure of the warm phase ($EM \propto \int n^2 V$, with $V$ being the volume of the emitting gas), and $f$ remains unknown. For a given detected EM, the total warm gas mass $M$ in a given region is a function of $f$, $M \propto \sqrt{f}$; as the density increases with decreasing $f$ ($\propto 1/\sqrt{f}$), the cooling time accordingly decreases as $t_{\text{cool}} \propto \sqrt{f}$. The mass implications are very demanding: this new component will have a mass comparable to that of the hot ICM (see Table 2), and those budgets can be alleviated if $f$ is very small, although at the price of a correspondingly shorter cooling time.

Alternatively, an IC origin of the emission can be advocated (Sarazin & Lieu 1998). Diffusive shock acceleration (Axford, Leer, & Skadron 1977; Bell 1978a, 1978b; Blandford & Os- triker 1978) may be responsible for a population of relativistic electrons with a power-law spectrum in the ICM, and its IC mechanism preserves a similar power-law shape, whereby the fraction of the emission made, the agreement among the different methods of determining $N_\infty$ is unaffected by statistical uncertainties in the hot ICM modeling.$^6$

$^6$ Krick, Arabadjis, & Bregman (2000) argue that subarcminute variations of $N_\infty$ could in principle account for a 20%–30% excess. Although the relevance of this phenomenon to our Sersic 159-03 observations is uncertain, the strength of the PSPC excess reported here largely exceeds that figure. On occasions for which a comparison with stellar Ly$\alpha$ and quasar X-ray spectra could be made, the agreement among the different methods of determining $N_\infty$ would suggest an error of less than $10^{19}$ cm$^{-2}$ (see Lieu et al. 1996a and references therein).

![Figure 3](image3.png)

**Fig. 3.** —Co-added spectrum of 1'–3' region of the cluster (black crosses) overlaid on the best-fit single-temperature model obtained by fitting the whole PSPC band (left, red solid line) and by fitting only energies $\geq 0.5$ keV (right, green solid line). Residuals (red and green crosses) reveal in both cases an excess of soft photons at energies of less than 0.4 keV.

![Figure 4](image4.png)

**Fig. 4.** —Fractional excess in $\bar{\nu}$ keV PSPC band (0.2–0.4 keV) as a function of the radial distance from the cluster’s center. Fractional excess is defined as $\eta = (m - mp)/m$, where $m$ is the measured soft flux (\$ keV band) and $mp$ its prediction according to the 0.5–2.0 keV single-temperature model. The 9'–12' region was modeled with the same parameters as the 6'–9' annulus (Table 1); vertical semidiameters are $1\sigma$ statistical errors. The excess component ranges between 50% and 100% of the hot ICM gas in the soft band, the strongest observed to date in PSPC data.
two differential number distributions of electrons \( N(E) \propto E^{-\alpha} \) and emitted photons \( L(\epsilon) \propto \epsilon^{-\beta} \) are related by the equation \( \alpha = (1 + \mu)/2 \). Relativistic electrons of \( \gamma = 300–700 \), which are required to emit EUV or soft X-rays through IC scattering, straddle spectrally between low-energy Coulomb losses and high-energy radiative losses (Lieu et al. 1999c; Sarazin 1999) and may survive for a significant fraction of a cluster’s lifetime. Here we fitted the photon index \( \alpha \) to the data (Table 2), with the exception of the 3’–6’ region where \( \alpha \) is fixed at \( 1.75 \), the expected value from a cosmic-ray (CR) population of \( \mu = 2.5 \) in accordance with a Galactic CR. The modeling is formally acceptable, although with a spectral index somewhat steeper than that of a Galactic CR. However, serious problems confront the energetic requirements of the IC model: the pressure of CR electrons with \( \alpha \) in the range of 475–700 (those that emit IC radiation in the \( E = 0.2–0.4 \) keV band) exceeds that of the hot ICM by a factor of order 2–3! Moreover, this pressure estimate is necessarily a lower limit since higher and lower energy electrons may be present as well as CR ions that, although not visible, will further drive the CR budget to absurd values (Lieu et al. 1999c; see also Miniati et al. 2001).

As often happens in rich clusters of galaxies, the X-ray centroid, here coincident with the central cD galaxy ESO 291-9, is associated with a lower temperature for the hot ICM (Kaasten et al. 2001). Such a temperature decrease is also clearly visible in our PSPC data. Yet the detected soft X-ray excess cannot be directly related to it because the excess covers an area about 25 times larger than the region affected by this cooling (which has a radius of about 1’8; Kaasten et al. 2001; Allen & Fabian 1997) and, more importantly, because we already accounted for the effect in our data modeling (see the best-fit temperatures in Table 1). The behavior here is therefore analogous to, e.g., that of the Virgo and A1795 clusters, where the excess emission spreads over a much larger area than that of the central cooler region (Lieu et al. 1996b; Bonamente et al. 2001b). The central galaxy of Sersic 159-03, which also contains an IR source, is well contained within a radius of 1’ (Hansen et al. 2000): the soft excess emission must then be a genuinely cluster-wide phenomenon.

4. DISCUSSION AND CONCLUSIONS

The high statistical significance of the soft excess emission of this cluster confounds both thermal and nonthermal models (Table 2). Either model can fit the data and calls for an overhaul in our understanding of galaxy clusters.

Following the nonthermal interpretation, the large pressure budgets of Table 2 cannot easily be mitigated; on the contrary, they are strict lower limits to the relativistic particle content in the cluster. The presence of a population of relativistic particles above equipartition with the hot gas clearly has implications for a cluster’s hydrostatic balance (e.g., Berezinsky, Blasi, & Ptuskin 1997), and the role of intracluster CRs on the cluster’s evolution (e.g., heating of the ICM gas) could be much more significant than previously thought. At present, it is not known whether strong shocks, e.g., those induced by cluster mergers, may accelerate such a large amount of CRs. It is possible that the cluster experiences many such shocks throughout its lifetime; the ICM would then accumulate those CR electrons with the longest radiative lifetimes, precisely those \( \gamma \sim 300–500 \) electrons that emit in EUV and soft X-rays through IC scattering (Sarazin & Lieu 1998; Lieu et al. 1999c).

On the other hand, large warm gas masses could be sustained at the interface of cold gas clouds and the hot ICM (Fabian 1997); the presence of a “cold” (\( T \leq 10^4 \) K) phase in the ICM is in fact an interpretation of the PSPC images of the Coma and Virgo Clusters (Bonamente et al. 2001a). In the absence of such a replenishment mechanism, however, the very short radiative cooling time renders the thermal model untenable.

The bright soft excess of Sersic 159-03 reported here presents a new and unavoidable reality: whether the ultimate explanation is thermal, nonthermal, or some other origin, a major effect at work in the intergalactic medium has hitherto been completely ignored.

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REFERENCES

Abell, G. O., Corwin, H. G., & Olowin, R. P. 1989, ApJS, 70, 1
Allen, S. W., & Fabian, A. C. 1997, MNRAS, 286, 583
Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Arabadjis, J. S., & Bregman, J. N. 1999, ApJ, 514, 607
Arnaud, M., Neumann, D. M., Aghanim, N., Gastaud, R., Majorowicz, S., & Hughes, J. P. 2001, A&A, 365, L80
Axford, W. I., Leer, E., & Skadron, G. 1977, Proc. Int. Cirmst. Cosm. Ray Conf. (Plovdiv), 11, 132
Bell, A. R. 1978a, MNRAS, 182, 147
———. 1978b, MNRAS, 182, 443
Berezinsky, V. S., Blasi, P., & Ptuskin, V. S. 1997, ApJ, 487, 529
Berghöfer, T. W., Bowyer, S., & Korpela, E. J. 2000a, ApJ, 535, 615
———. 2000b, ApJ, 545, 695
Blandford, R. D., & Ostriker, J. P. 1978, ApJ, 221, L29
Bonamente, M., Lieu, R., & Mittaz, J. P. D. 2001a, ApJ, 546, 805
———. 2001b, ApJ, 547, L7
Bonamente, M., Lieu, R., Nevalainen, J., & Kastra, J. S. 2001c, ApJ, 552, L7
Boulanger, F., & Perault, M. 1988, ApJ, 330, 964
Bowyer, S., & Berghöfer, T. W. 1998, ApJ, 506, 502
Bowyer, S., Berghöfer, T. W., & Korpela, E. J. 1999, ApJ, 526, 592
Buote, D. A. 2000a, ApJ, 532, L113
———. 2000b, ApJ, 544, 242
———. 2001, ApJ, 548, 652

Chandran, B. D. G., Cowley, S. C., & Allbright, B. 1999, in Diffuse Thermal and Relativistic Plasma in Galaxy Clusters, ed. H. Böhringer, L. Feretti, & P. Schuecker (Garching: MPI), 242
Cowie, L. L., & McKee, C. F. 1977, ApJ, 211, 135
de Grandi, S., et al. 1999, ApJ, 514, 148
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Dixon, W. V., Hurwitz, M., & Ferguson, H. C. 1996, ApJ, 469, L77
Dixon, W. V., Sallmen, S., Hurwitz, M., & Lieu, R. 2001, ApJ, 550, L25
Fabian, A. C. 1996, Science, 271, 1244
———. 1997, Science, 275, 48
Fusco-Femiano, R., et al. 2000, ApJ, 534, L7
Hansen, H. E., Jørgensen, H. E., Norgaard-Nielsen, H. U., Pedersen, K., Goudfrooij, P., & Linden-Vørnle, M. J. D. 2000, A&A, 362, 133
Kaasten, J. S. 1992, in An X-Ray Spectral Code for Optically Thin Plasmas (Internal SRON-Leiden Rep., updated version 2.0)
Kaasten, J. S., Ferrigno, C., Tamura, T., Paerels, F. B. S., Peterson, J. R., & Mittaz, J. P. D. 2001, A&A, 365, L99
Kaasten, J. S., Lieu, R., Mittaz, J. P. D., Bleeker, J. A. M., Mewe, R., Colafrancesco, S., & Lockman, F. J. 1999, ApJ, 519, L119
Krick, J., Arabadjis, J. S., & Bregman, J. N. 2000, BAAS, 197, 07.11
Landini, M., & Monsignori-Fossi, B. C. 1990, A&AS, 82, 229
Lieu, R., Bonamente, M., & Mittaz, J. P. D. 1999a, ApJ, 517, L91
———. 2000, A&A, 364, 497
Lieu, R., Bonamente, M., Mittaz, J. P. D., Durret, F., Dos Santos, S., & Kastra, J. 1999b, ApJ, 527, L77
Lieu, R., Ip, W.-I., Axford, W. I., & Bonamente, M. 1999c, ApJ, 510, L25
Lieu, R., Mittaz, J. P. D., Bowyer, S., Breen, J. O., Lockman, F. J., Murphy, E. M., & Hwang, C.-Y. 1996a, Science, 274, 1335
Lieu, R., Mittaz, J. P. D., Bowyer, S., Lockman, F. J., Hwang, C.-Y., & Schmitt, J. H. M. M. 1996b, ApJ, 458, L5
Mewe, R., Gronenschild, E. H. B. M., & van den Oord, G. H. J. 1985, A&AS, 62, 197
Mewe, R., Lemen, J. R., & van den Oord, G. H. J. 1986, A&AS, 65, 511
Miniati, F., Ryu, D., Kang, H., & Jones, T. W. 2001, ApJ, 559, 59
Mittaz, J. P. D., Lieu, R., & Lockman, F. J. 1998, ApJ, 498, L17
Morrison, R., & McCammon, D. 1983, ApJ, 270, 119 (MM83)
Reynolds, A. P., Parmar, A. N., Hakala, P. J., Pollock, A. M. T., Williams, O. R., Peacock, A., & Taylor, B. G. 1999, A&AS, 134, 287
Sarazin, C. L. 1999, ApJ, 520, 529
Sarazin, C. L., & Lieu, R. 1998, ApJ, 494, L177
Smith, D. F., & Lilliequist, C. G. 1979, ApJ, 232, 582
Valinia, A., Arnaud, K., Loewenstein, M., Mushotzky, R. F., & Kelley, R. 2000, ApJ, 541, 550
Wheelock, S., et al. 1994, *IRAS Sky Survey Atlas: Explanatory Supplement* (JPL Publ. 94-11; Pasadena: JPL)
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914 (WAM00)
Wu, X.-P., Xue, Y.-J., & Fang, L.-Z. 1999, ApJ, 524, 22
Yan, M., Sadeghpour, H. R., & Dalgarno, A. 1998, ApJ, 496, 1044