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DETECTION OF X-RAY EMISSION FROM GALAXIES INSIDE THE BOOTES VOID

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ABSTRACT

We report the X-ray properties of Bootes void galaxies detected by the *ROSAT* All-Sky Survey (RASS). By searching the fields of 26 radio and 27 emission-line–selected void galaxies, we have detected nine X-ray–emitting void galaxies at greater than 2.7 σ confidence level. Five of these nine galaxies are in the *IRAS* subsample. Two of the *IRAS* galaxies were previously identified in positional cross-correlation studies of the RASS and *IRAS* Point Source Catalogue sources. Three of the X-ray–emitting galaxies are active galactic nuclei (AGNs; IRAS 14288+5255, Mrk 845, and IRAS 15195+5050), three are emission-line galaxies (PC 1357+4641, CG 547, and CG 922), and the remaining three are of unknown spectral type (IRAS 14500+4804, CG 637, and IRAS 15092+3940). The far-infrared flux levels of the AGN sources imply that most of the observed X-ray emissivity is from starburst activity. We have carried out timing and spectral analysis for the Seyfert 1 galaxy Mrk 845. Poor statistics prevents detailed analysis of the remaining sources. Only two galaxies in our sample, BHI 1514+3819 and FSS 1515+3823, were observed during *ROSAT* pointed observations resulting in a nondetection at the 1 σ level.

Subject headings: galaxies: active — galaxies: Seyfert — galaxies: statistics — galaxies: structure — X-rays: galaxies

1. INTRODUCTION

The study of galaxies within voids is important in understanding the formation and evolution of galaxies in low-density environments. Morphological trends, star formation rates, and luminosity distributions among galaxies may depend strongly on local density. This is the case within relatively high density galaxy clusters (Dressler 1980; Postman & Geller 1984), but observational evidence of this nature is difficult to obtain for voids because of the intrinsic scarcity of void galaxies. Indeed, void galaxies are often identified by peculiarities such as strong optical emission lines or strong infrared emission, so that defining an unbiased sample for study is difficult.

The Bootes void (Kirshner et al. 1981, 1987) is a 3.1×10^5 Mpc^3 volume of space at $z \sim 0.05$ (adopting $q_0 = 0.5$ and $H_0 = 75$ km s^{-1} Mpc^{-1}) in the direction of the north Galactic cap. Since its discovery, only a few dozen galaxies have been detected within this vast region. Some were identified in objective prism surveys (Sanduleak & Pesch 1982; Moody 1986; Tifft et al. 1986; Moody et al. 1987; Weistrop 1987; Weistrop & Downes 1988) or from follow-up spectroscopy to these surveys (Sanduleak & Pesch 1987, 1989; Pesch & Sanduleak 1989), others from spectroscopic observations of *IRAS*-identified galaxies (Strauss & Huchra 1988; Dey, Strauss, & Huchra 1990), and some from H I surveys of the region (Szomoru et al. 1994; Szomoru 1994; Szomoru, van Gorkom, & Gregg 1996). Low-dispersion spectroscopic surveys tend to select galaxies with strong emission lines. Similarly, *IRAS*-selected galaxies tend to be emission-line galaxies and are likely to be sources of recent star formation activity or nuclear activity.

Multiwavelength observations of Bootes void galaxies confirm they are more luminous on average than emission-line galaxies at similar redshift and that ∼40% of Bootes void galaxies exhibit unusual or disturbed morphologies (Cruzen et al. 1996; Cruzen, Weistrop, & Hoopes 1997, hereafter CWH). The most active star formation rates in void galaxies are almost 3 times the rate observed in normal field disk galaxies (Weistrop et al. 1995). The distribution of Hα equivalent widths indicates a higher fraction of emission-line systems in low-density void regions than in normal- and high-density environments and that the morphologies of galaxies at the lowest densities in voids typically favor irregular and peculiar galaxy types (Grogin & Geller 2000).

This is consistent with hierarchical galaxy formation theory, which suggests (Kauffmann 1996) that the luminous galaxies in higher density regions formed earlier than the galaxies formed in voids. By this argument, the recently formed present-epoch void galaxies should be richer in the gas and dust necessary for active star formation once this activity has been triggered by interactions and mergers. The results of Grogin & Geller (2000) support this scenario, which they further explain as a lack of small-scale primordial density perturbations needed to form massive, early-type, absorption-line galaxies in voids and by the observed low-velocity dispersions of void galaxies that make galaxy encounters more effective.

The nuclear starburst–active galactic nucleus (AGN) connection has been studied for galaxies in the high-density regions, and it has been suggested that AGNs may be the end products in the evolution of a nuclear starburst (Colina & Arribas 1999). However, no such studies have been carried out for void galaxies. The connection between starburst and nuclear activities in void galaxies may also play a role in explaining the enhanced luminosities of void galaxies and for the large fraction of void galaxies with unusual or disturbed morphologies. This connection can best be addressed through X-ray observations. To date, no X-ray studies have been carried out specifically for void galaxies. Only Mrk 845 has been detected by *HEAO 1* (Della Ceca et al. 1990).

The X-ray properties of galaxies inside the Bootes void are

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TABLE 1
RASS-detected X-Ray Galaxies in the Bootes Void

Source Name	R.A. (2000)	Decl. (2000)	Magnitude (V)	Redshift	Galaxy Type[a]	RASS Count Rate[b] (counts s^{-1})	Exposure Time (s)
PC 1357+4641	13 59 53.3	46 27 19	18.48	0.05414	ELG	0.010	724
IRAS 14288+5255	14 30 31.2	52 42 26	15.10	0.04446	Sy2	0.012–0.025	752
CG 0547	14 48 14.0	44 44 33	16.0	0.04411	ELG	0.011	667
IRAS F14500+4804	14 51 44.3	47 51 50	16.9	0.04982	?	0.010	857
CG 0922	15 00 03.1	49 32 52	16.7	0.04836	ELG	0.014	878
Mrk 845	15 07 45.0	51 27 10	15.6	0.04605	Sy1	0.02–0.58	1858
CG 0637	15 08 13.4	37 33 03	16.0	0.05257	?	0.013	676
IRAS F15092+3940	15 11 06.5	39 27 52	17.7	0.05740	?	0.016	706
CG 692/CG 693	15 21 07.4	50 40 20	16.0	0.05601	Sy1	0.033–0.051	668

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] ELG: emission-line galaxy; Sy1: Seyfert 1; Sy2: Seyfert 2; ?: unknown spectral type.
[b] Ranges denote minimum to maximum observed count rates.

described in § 2. Data were obtained from the recently released *ROSAT* All-Sky Survey (RASS) by searching for X-ray signatures at the locations of 53 previously identified void galaxies. This study produced nine detections at greater than a 2.7 σ confidence level. Five of these nine galaxies are *IRAS* galaxies. Only three of these galaxies, optically classified as AGNs, produced enough counts for further analysis. It is found that there is evidence for rapid X-ray variability in Mrk 845. *IRAS* and X-ray data of these three AGNs suggest that the X-ray emissions from these objects are largely dominated by the star formation activities. These results are summarized and prospects for future observations are discussed in § 3.

2. SEARCH WITH THE *ROSAT* ALL-SKY SURVEY

A sample of 53 Bootes void galaxies were chosen from the published literature. They are the 26 galaxies in the Very Large Array H I survey of Szomoru et al. (1996) and the 27 emission-line galaxies detected by *IRAS* or by low-dispersion spectroscopic surveys and described by CWH. A search of the *ROSAT* pointed observations log indicates only two galaxies, BHI 1514+3819 and FSS 1515+3823, were located in the field of view of a *ROSAT* pointing (200905P during 1993 February 11, with a 10,327 s exposure). No X-ray emission was detected from either of these galaxies at the 1 σ confidence level.

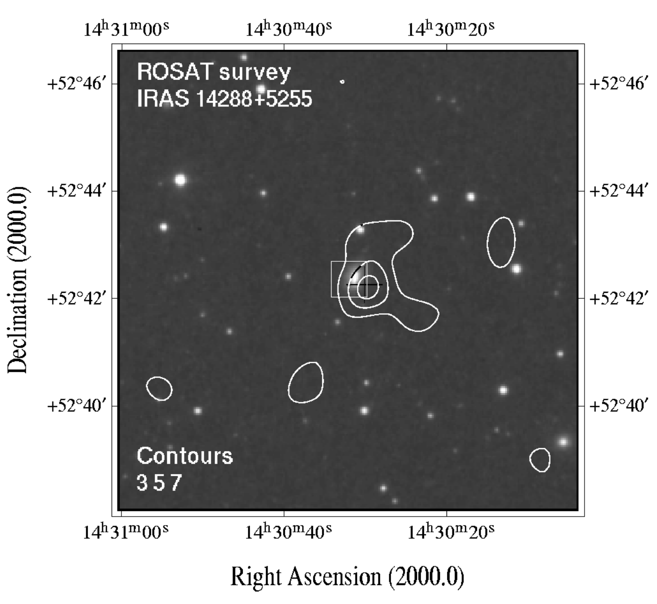

Fig. 1.—RASS X-ray contour plots of IRAS 14288+5255 overlaid on an optical DSS image. Contour levels indicate σ confidence levels above the background. The cross indicates the NASA/IPAC Extragalactic Database optical position, and the square denotes the *ROSAT* position error box centered using an automated object-finding algorithm.

A search of the RASS $12' \times 12'$ fields (Voges, Boller, & Dennerl 1996) at the positions of these 53 galaxies was then conducted. The RASS observations were carried out between 1990 July and 1991 January with the Position Sensitive Proportional Counter (PSPC) in the 0.1–2.4 keV energy band (Pfeffermann et al. 1986). We limit our analysis to those events detected when the source is within 5′ of the center of the PSPC field of view. The X-ray source counts are derived from photon event tables covering a circular area centered on the source, and the background counts are similarly taken from a source-free annulus centered on the object's position in the scan direction. Where adequate data exists, the flux variability amplitude is computed using the average count rates obtained from at least three orbits (with typical exposure times of 24 s $orbit^{-1}$).

X-rays were detected at the locations of nine of the 53 galaxies, as listed in Table 1. Six of the nine have very weak X-ray emission. The X-ray properties of the remaining three sources are discussed below. The weakest detected sources have a count rate of 0.010 counts s^{-1}. The remaining 44 galaxies fall below the $\sim 10^{-13}$ ergs cm^{-2} s^{-1} detection limit of the RASS.

2.1. *IRAS 14288+5255*

IRAS 14288+5255 has been detected in X-rays from the cross-correlation analysis between the *IRAS* Point Source Catalogue and the RASS sources (Boller et al. 1992). It is an irregular spiral galaxy with a very bright nucleus and a large, elongated disk (visual magnitude 15.1 mag, redshift = 0.04446; CWH). The irregular appearance in optical (CWH) and radio (Szomoru 1994) of this *IRAS* galaxy may be due to interaction with an unseen companion. Optical spectra suggest that it is a Seyfert 2 galaxy (Moran, Halpern, & Helfand 1996).

A digitized sky survey (DSS) optical image of IRAS 14288+5255 overlaid with X-ray confidence level contours is shown in Figure 1. The RASS detected 14 source photons in a total of 752 s from this galaxy centered at R.A. (2000) = $14^h30^m31^s.8$, decl. (2000) = $52°42'36''$.

The mean observed count rate, 0.0186 ± 0.0067 counts s^{-1}, corresponds to an X-ray flux in the 0.1–2.4 keV *ROSAT* band of 2.57×10^{-13} ergs cm^{-2} s^{-1} assuming a typical Seyfert 2 power-law photon index of $\Gamma = 2.3$ and the Galactic absorbing column $N(H_{gal}) = 1.62 \times 10^{20}$ cm^{-2}. This corresponds to a

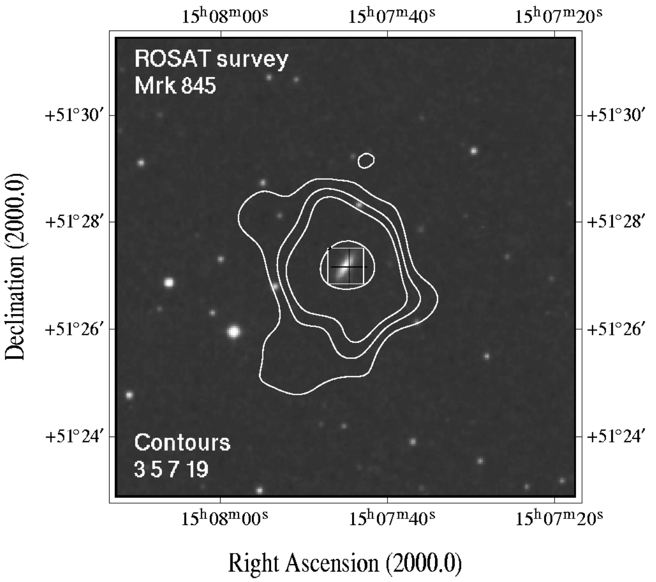

FIG. 2.—Same as Fig. 1, but for Mrk 845

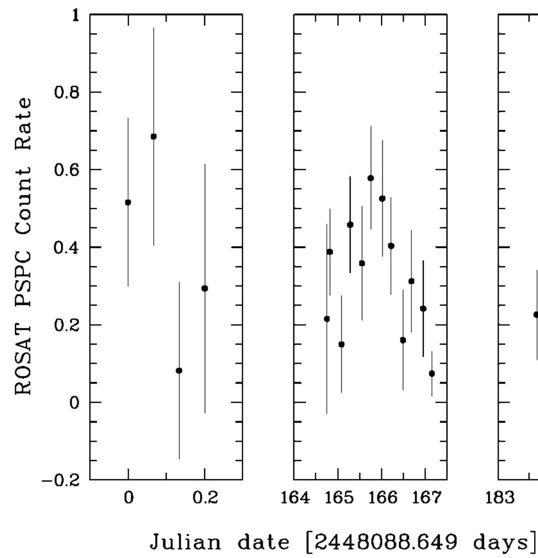

FIG. 3.—RASS light curve of Mrk 845. Time is in units of days since the initial observation on 1990 July 16. The *ROSAT* PSPC (0.1–2.4 keV) count rate is given in units of counts per second. Data are binned in intervals between 24 and 100 s. Error bars denote 1 σ uncertainties.

luminosity of 2.45×10^{42} ergs s^{-1}. The low photon statistics allows neither flux variability studies nor spectral fitting of the X-ray emission.

2.2. *IRAS 15061+5138* (*Mrk 845*)

Mrk 845 is the only galaxy in the sample for which adequate RASS data exists to construct a light curve and sample spectrum. Mrk 845 is a Seyfert 1 galaxy (Osterbrock & Dahari 1983; Sandueleak & Pesch 1987). The optical image shows a bright circular nucleus with an elongated disk but no spiral features (CWH). The asymmetric radio emission appears to coincide with the compact optical nucleus of this galaxy (Burns, Moody, & Gregory 1988; Szomoru 1994).

The DSS optical image of Mrk 845 with X-ray contours overlaid is shown in Figure 2. The RASS position is R.A. (2000) = $15^{h}07^{m}44\overset{s}{.}6$, decl. (2000) = 51°27′09″.5, and that for the optical is R.A. (2000) = $15^{h}07^{m}45\overset{s}{.}0$, decl. (2000) = 51°27′10″.0, well within the *ROSAT* pointing error limit.

Mrk 845 was observed during three epochs spanning a fraction of a day to several days: 1990 July 16 (JD 2,448,088.649), 1990 December 27 (JD 2,448,253.404), and 1991 January 15 (JD 2,448,272.270). The total exposure time on this source was 1858 s. The background-subtracted RASS light curve is shown in Figure 3. The middle panel of the light curve shows that Mrk 845 varied considerably between day 164 (JD 2,448,253.404) and day 167 (JD 2,448,255.840) after the initial observation on 1990 July 16. The lowest and highest, three-orbit–averaged, count rates during this interval are 0.07 ± 0.05 counts s^{-1} on day 167.191 (JD 2,448,255.840) and 0.58 ± 0.13 counts s^{-1} on 165.752 (JD 2,448,254.404), respectively. Fitting a constant to this section of the light curve gave a reduced χ^2 of 2.76 for 12 data points. This result indicates that Mrk 845 was variable during this period.

The spectrum of Mrk 845 from the RASS data was extracted using the EXSAS data analysis package of MPE Garching (Zimmermann et al. 1994). Source counts were collected in a disk of 260″ radius around the source position and background counts from an annular region of inner radius 700″ and outer radius 800″ around the object position in the scan direction of the satellite and free of contaminating sources. This spectrum was fitted with a simple power law plus absorption model. The photon index is 1.98 ± 0.62, and the column density of neutral hydrogen along the line of sight is 1.61×10^{20} cm^{-2}. The normalization at 1 keV is 5.2×10^{-4} photons cm^{-2} s^{-1} keV^{-1}. From this an unabsorbed flux of 1.79×10^{-12} ergs cm^{-2} s^{-1} is derived. A more realistic model (e.g., a combination of thermal and nonthermal components) was not attempted because of the rather low signal-to-noise ratio of the spectral data. If we assume a power-law model with the photon index of 2.3 and the Galactic neutral hydrogen column density 1.8×10^{20} cm^{-2}, the mean count rate given above implies an absorption-corrected flux value of 4.95×10^{-12} ergs cm^{-2} s^{-1}. Using the relation of Schmidt & Green (1986), we derive luminosities of 1.62×10^{43} and 4.56×10^{43} ergs s^{-1} for these two models, respectively.

2.3. *IRAS 15195+5050* (*CG 692/CG 693*)

The CG 692/CG 693 system was reported as the first pair of interacting spiral galaxies in the Bootes void by Weistrop et al. (1992). This system was also identified as the *IRAS* source IRAS 15195+5050 by Dey et al. (1990). CG 692 is the larger of the pair and has a single, large spiral arm. CG 693 is also a spiral galaxy (CWH). Based on the observed strong, broad hydrogen emission lines, it has been classified as a Seyfert 1 galaxy (Weistrop et al. 1992). Szomoru (1994) reported that these two interacting galaxies are within a common H I envelope. X-ray emissions from this system were first discovered using the cross-correlation analysis between the *IRAS* Point Source Catalogue and the RASS sources (Boller et al. 1992). Figure 4 shows the RASS X-ray contours overlaid on the optical image of the CG 692/CG 693 system. The X-ray contours are centered around CG 693, at R.A. (2000) = $15^{h}21^{m}11\overset{s}{.}0$, decl. (2000) = 50°40′30″, which coincides, within errors, with the optical position of CG 693. The computed mean X-ray

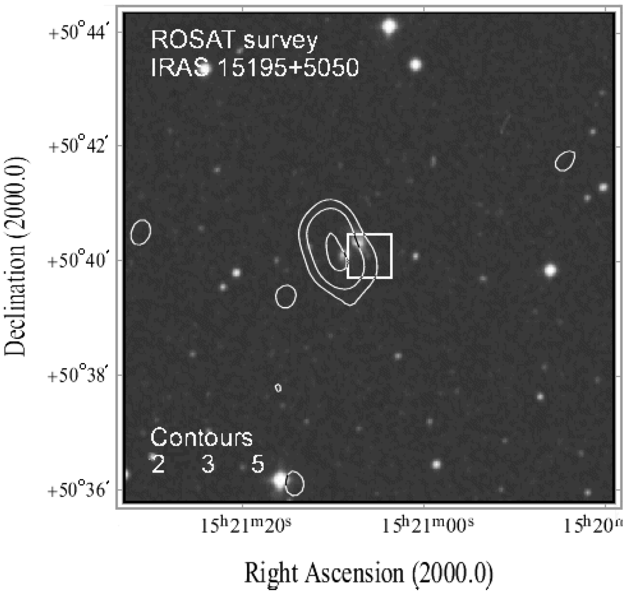

FIG. 4.—Same as Fig. 1, but for IRAS 15195+5050

count rate is 0.042 ± 0.009 counts s^{-1} for the RASS exposure time of 668 s.

Only 28 photons were detected from this source, and the low photon statistics does not allow flux variability studies and spectral fitting. Assuming a typical Seyfert 1 photon index of $\Gamma = 2.3$ for a power-law model with Galactic absorption $[N(H_{gal}) = 1.65 \times 10^{20}\ cm^{-2}]$, the RASS flux is 5.9×10^{-13} ergs cm^{-2} s^{-1}, corresponding to a 0.1–2.4 keV X-ray luminosity of 8.4×10^{42} ergs s^{-1}.

3. SUMMARY AND DISCUSSION

We have searched for X-ray emissions from 53 galaxies detected in the Bootes void using the RASS database. Nine galaxies have significant X-ray emission as listed in Table 1. Among these, the three brightest have previously been identified as AGNs (IRAS 14288+5255 is a Seyfert 2, Mrk 845 and IRAS 15195+5050 are Seyfert 1), three have been identified as emission-line galaxies, and the other three are most likely also emission-line galaxies, as the majority of known Bootes void galaxies are of this type (CWH). I Zw 81 is a Bootes void AGN (Weistrop et al. 1992) but was not detected in the RASS.

We have performed both X-ray timing and spectral analysis for Mrk 845. Mrk 845 displayed rapid and large-amplitude X-ray flux variations. This type of large-amplitude X-ray flux variability has also been detected in the narrow-line Seyfert 1 galaxy PKS 0558−504 (Boller, Brandt, & Fabian 1997; Forster & Halpern 1996; Brandt et al. 1999). It has been suggested that relativistic motions of the X-ray source may be the cause for the giant-amplitude X-ray flux variability of the narrow-line Seyfert 1 galaxies (Boller et al. 1997; Brandt et al. 1999). A similar mechanism may be the cause for the observed flux variability of Mrk 845. Low photon statistics did not allow flux variability studies nor X-ray spectral fitting of the other galaxies detected in our sample.

Since the sample of Bootes void galaxies are biased toward emission-line galaxies and *IRAS* sources, a statistical comparison of the X-ray–detected void galaxies with a population of field galaxies is inappropriate. We can, however, compare the *IRAS*-selected subsample of our galaxies to expectations. In a homogeneous universe, we expect 54 *IRAS* galaxies at the redshift and within the volume of the Bootes void (Dey et al. 1990). However, only 19 of the 53 Bootes void galaxies positionally coincide with *IRAS* galaxies, corresponding to about one-third of the homogeneous density. Second, we expect ∼4% of *IRAS* galaxies within the Bootes void to be detectable in the RASS assuming homogeneity (Boller et al. 1992). In contrast, five *IRAS* galaxies (IRAS 14288+5255, IRAS 14500+4804, IRAS 15061+5138, IRAS 15092+3940, and IRAS 15195+5050), or 26%, have been detected by RASS, as listed in Table 1. This indicates that the fraction of X-ray–emitting galaxies in the Bootes void is much higher than in average-density environments. The higher density of X-ray–emitting galaxies may be due to a higher rate of star formation and nuclear activities in the void galaxies. These activities may be due to interaction or merging of galaxies in this void. Future observations with *Chandra* or *XMM* will help us to better understand these results.

The correlation between far-infrared and X-ray luminosities of normal and starburst galaxies, deduced from analysis of *Einstein* imaging proportional counter data (David, Jones, & Forman 1992), provides a powerful tool for estimating the starburst contribution to the 0.5–4.5 keV X-ray luminosity from far-infrared flux measurements. This estimate can then be compared to the observed X-ray luminosity. The observed 0.5–4.5 keV luminosities were determined for the three brightest X-ray sources in our sample, from the observed count rates and known distances, assuming a Galactic hydrogen column density and a power-law spectrum of photon index 2.3. Comparison to the predicted luminosities implies an 84% (IRAS 14288+5255), 58% (Mrk 845), and 77% (IRAS 15195+5050) maximum contribution to the total X-ray luminosity from starburst activity. Although indicative, this conclusion depends upon the observed RASS count rates of these weak, and possibly variable, sources.

Future X-ray observations of these objects with *Chandra* and *XMM* will allow us to study these objects in detail, which will enable us to compare the properties of void galaxies with the field population.

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