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DETECTION OF X-RAY EMISSION FROM THE ARCHES CLUSTER NEAR THE GALACTIC CENTER

F. Yusef-Zadeh
Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208; zadeh@northwestern.edu

C. Law
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138; claw@head-cfa.harvard.edu

M. Wardle
School of Physics, University of Sydney, NSW 2006, Australia; wardle@physics.usyd.edu.au

Q. D. Wang
University of Massachusetts, Amherst, MA 01003-4517; wqd@hnr.astro.umass.edu

A. Fruscione
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138; antonell@head-cfa.harvard.edu

C. C. Lang
University of Massachusetts, Amherst, MA 01003-4517; clang@ocotillo.astro.umass.edu

and

A. Cotera
University of Arizona, Steward Observatory, Tucson, AZ 85721; cotera@as.arizona.edu
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ABSTRACT

The Arches cluster is an extraordinarily compact massive star cluster with a core radius of about 10″ (∼0.4 pc) and consisting of more than 150 O star candidates with initial stellar masses greater than 20 $M_\odot$ near G0.12-0.02. X-ray observations of the radio Arc near the Galactic center at $l \sim 0\overset{\circ}{.}2$, which contains the Arches cluster, have been carried out with the Advanced CCD Imaging Spectrometer (ACIS) on board *Chandra X-Ray Observatory*. We report the detection of two X-ray sources from the Arches cluster embedded within a bath of diffuse X-ray emission extending beyond the edge of the cluster to at least 90″ × 60″ (3.6 pc × 2.4 pc). The brightest component of the X-ray emission coincides with the core of the cluster and can be fitted with a two-temperature thermal spectrum with a soft and hard component of 0.8 and 6.4 keV, respectively. The core of the cluster coincides with several ionized stellar wind sources that have previously been detected at radio wavelengths, suggesting that the X-ray emission from the core arises from stellar wind sources. The diffuse emission beyond the boundary of the cluster is discussed in the context of combined shocked stellar winds escaping from the cluster. We argue that the expelled gas from young clusters such as the Arches cluster may be responsible for the hot and extended X-ray—emitting gas detected throughout the inner degree of the Galactic center.

Subject headings: galaxies: ISM — Galaxy: center — stars: mass loss — stars: winds, outflows — X-rays: ISM

1. INTRODUCTION

Near-IR observations of the Galactic center region have recently identified two clusters of young and massive stars embedded within the radio Arc at Galactic longitude $l \sim 0\overset{\circ}{.}2$ lying within 25 pc in projection from the Galactic center at a distance of 8.5 kpc. (Nagata et al. 1995; Cotera et al. 1996; Serabyn, Shupe, & Figer 1998; Figer et al. 1999). The two stellar clusters, which are responsible for ionizing the thermal components of the radio Arc, show similar characteristics to the IRS 16 cluster at the Galactic center (Simons, Hodapp & Becklin 1990; Allen, Hyland, & Hillier 1990; Krabbe et al. 1991).

Portegies Zwart et al. (2002) have recently predicted that the Galactic center region may contain a large of number of young and massive clusters similar to the Arches, Quintuplet, and IRS 16 clusters. Understanding their nature is an important step towards determining the rate of massive star formation in this unique region of the Galaxy.

The Arches cluster has an angular size of ∼15″ with a peak density of 3×10^5 $M_\odot$ pc^{-3} in the inner 9″ (0.36 pc; Figer et al. 1999). This cluster is one of the densest known young clusters in the local group of galaxies with densities similar to R136, the central cluster of 30 Dor in the Large Magellanic Cloud and NGC 3603; the Trapezium cluster in Orion has a density of 7×10^4 $M_\odot$ pc^{-3} (Brandl et al. 1996; Wang 1999; McCaughrean & Stauffer 1994; Brandl et al. 1999). The Arches cluster has an estimated age of 1–3 Myr and shows a flat mass function as compared to other young clusters (Figer et al. 1999). The Quintuplet cluster adjacent to the Sickle is less compact, and is 3–5 Myr old (Figer, McLean, & Morris 1999). Radio continuum emission from individual stars in both clusters has recently been detected (Lang et al. 1999, 2001). Radio spectral index and near-IR spectral type of several stars in the Arches cluster are consistent with ionized stellar winds arising from mass-losing WN and/or Of stars with mass-loss rates ≈ (1–20) × 10^{-5} $M_\odot$ yr^{-1}, and lower limits to their winds' terminal velocities range between 800 and 1200 km s^{-1} (Cotera et al. 1996).

2. OBSERVATIONS

The X-ray imaging of the inner degree of the Galactic center region dates back to *Einstein* and *SL2-XRT*, *ROSAT*,

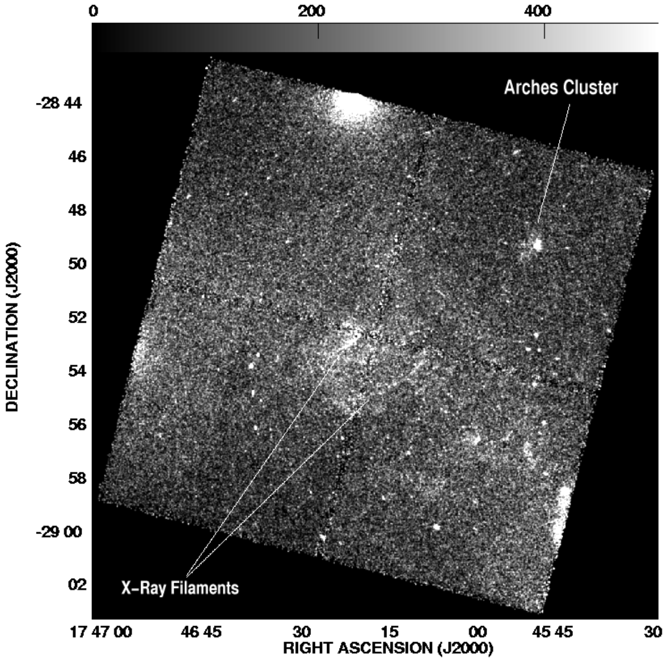

FIG. 1*a*

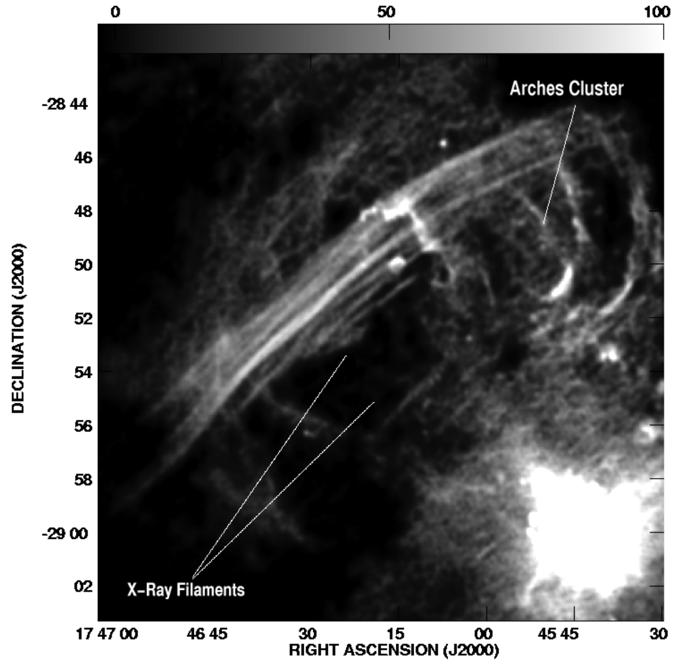

FIG. 1*b*

FIG. 1.—(*a*) Image of *Chandra*'s four ACIS-I chips for the 0.5 to 8 keV band, where diffuse emission is detected throughout this region. We note two linear X-ray structures running perpendicular to the Galactic plane. A bright source to the north at the edge of the field is identified with 1E 1743.1–2843 (Watson et al. 1981), whereas the bright feature at the bottom right corner is associated with the Sgr A complex. (*b*) Radio counterpart to an identical region of (*a*) but at λ20 cm with a spatial resolution of $10''.7 \times 10''$. The nonthermal radio filaments are seen prominently in the direction perpendicular to the Galactic plane. The northern X-ray filament is situated at the inner boundary of the nonthermal radio filaments.

ASCA observations, where a number of point sources and diffuse emission were detected (Watson et al. 1981; Skinner et al. 1987; Predehl & Trümper 1994; Koyama et al. 1996). The Advanced CCD Imaging Spectrometer (ACIS) on board the *Chandra X-Ray Observatory* (Weisskopf et al. 1996) was used to observe the radio Arc on 2000 July 7 for a total observing time 51 ks. The observation was made in the ACIS-I configuration, with a nominal aim-point toward the linear filaments of the radio Arc (epoch 2000) $\alpha = 17^{\rm h}46^{\rm m}22^{\rm s}$, $\delta = -28°51'36''.4$. In total, six of the ACIS CCDs were readout: the imaging array, I0-I3, and two of the spectroscopy array, S2 and S3. Only the data from the imaging array, particularly the I1 chip, will be presented here. The data were processed using the *Chandra* X-ray Center's CIAO software package (Noble et al. 2000). The images are effectively flat-fielded; instrument response and effective area are divided out in the form of an exposure map.

3. RESULTS

Figure 1*a* shows a flux image of X-ray emission detected in ACIS's I0 to I3 detectors with prominent sources labeled. Two sources located to the northwest of the image coincide with the Arches cluster. These sources avoid the strong diffuse X-ray emission arising from the Galactic plane of the Galactic center region. We note a prominent diffuse structure on a scale of about $2' \times 2'$ centered near (epoch 2000) $\alpha = 17^{\rm h}46^{\rm m}18^{\rm s}$, $\delta = -28°54'$. This diffuse feature shows two linear X-ray structures. Using the Very Large Array of the National Radio Astronomy Observatory,[1] a λ20 cm continuum image with a resolution of $10''.7 \times 10''$ (Yusef-Zadeh, Morris, & Chance 1984) is compared with identical region to that of Figure 1*a* and is displayed in Figure 1*b*, where the Sgr A complex is located in the southwest corner. The northern X-ray filament appears to be situated at the inner boundary of a number of nonthermal radio filaments running perpendicular to the Galactic plane.

Figure 2*a* shows contours of adaptively smoothed X-ray emission in a smaller region around the Arches cluster, with five components being identified and labeled as A1–A5. The crosses show the positions of the compact radio sources which are due to free-free emission from ionized stellar winds (Lang et al. 2001). The brightest component of X-ray emission (A1) is centered on the southwest corner of the densest part of the core of the Arches cluster, where the largest concentration of ionized stellar wind radio sources has been detected. The near-IR counterparts to radio sources are identified as either WN or Of spectral types (Nagata et al. 1995; Cotera et al. 1996).

A close-up view is displayed in Figure 2*b* where the X-ray contours have been superimposed on a gray-scale image of the stellar sources obtained with NICMOS on the *Hubble Space Telescope* (Figer et al. 1999). The brightest *radio* source, an Of/WN9 star (star 8 in Nagata et al. 1995 and Cotera et al. 1996), estimated to have a mass-loss rate of $1.7 \times 10^{-4}\ M_\odot\ {\rm yr}^{-1}$ (Lang et al. 2001), lies very close to the geometric center of A1. These facts strongly suggest that A1 is associated with the core of the Arches cluster. The second X-ray component (A2) lies about $10''$ northwest of A1 and appears to be located outside the core of the cluster but still close to the outer boundary. No radio-emitting stellar sources have been detected toward A2. The peak of A2 coincides within $1''$ with a star classified an emission line star, WN 7, WN 8, or Of 4 (Cotera et al. 1996; Blum et al. 2001). The

[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under a cooperative agreement by Associated Universities, Inc.

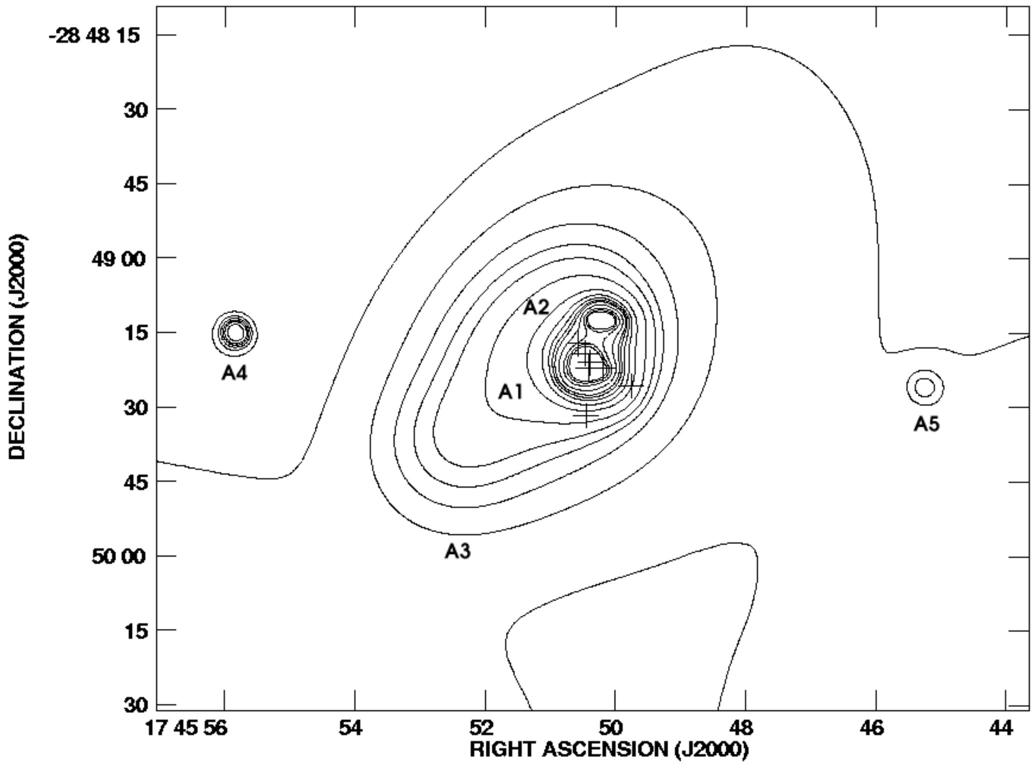

FIG. 2*a*

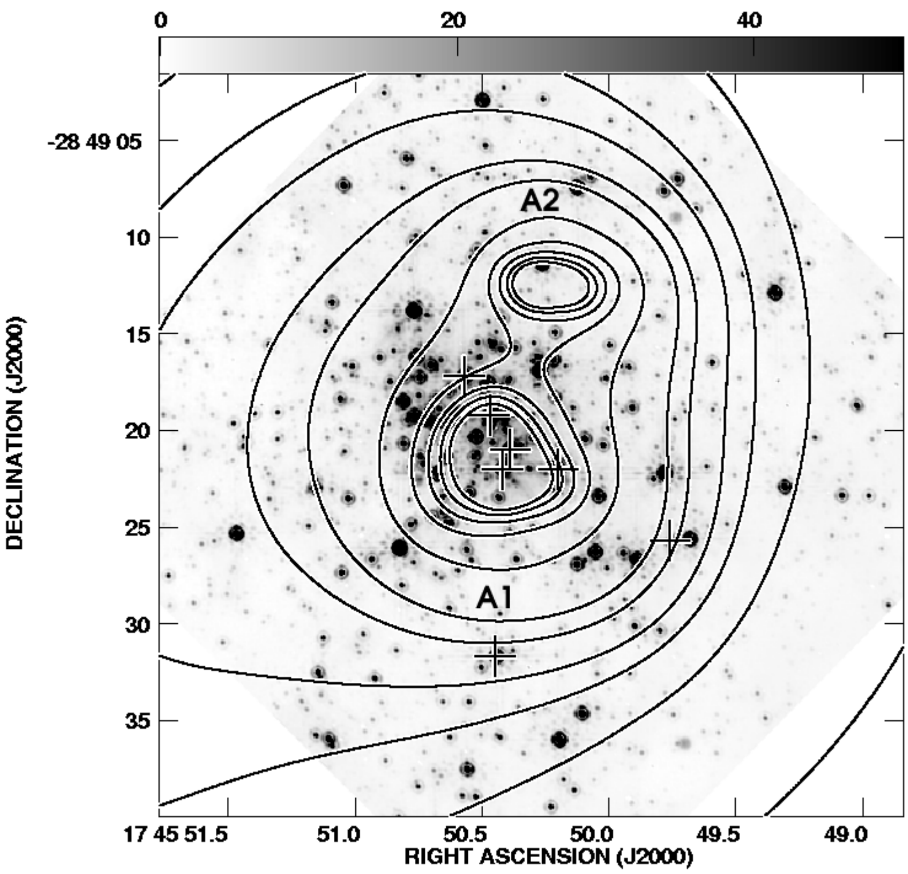

FIG. 2*b*

FIG. 2.— (*a*) Contours of adaptively smoothed X-ray emission of five components (A1–A5) of the Arches cluster. The crosses show the positions of mass-losing stellar wind sources identified in radio wavelengths. The total X-ray flux of A4 and A5 are 1.4 and 0.18×10^{-12} ergs s^{-1} cm^{-2}, respectively. (*b*) Contours of the smoothed X-ray emission from A1 and A2 with stellar radio sources as crosses superimposed on the near-IR stellar distribution of the Arches cluster.

largest scale component of X-ray emission in Figure 2*a* is a diffuse ovoid feature (A3) which envelops both A1 and A2 and is elongated at a position angle of 102° east of north from the Galactic plane. With dimensions of approximately $90'' \times 60''$(3.6 × 2.4 pc), A3 extends well beyond the edge of the cluster, which is $\lesssim 15''$ in diameter. Two pointlike A4 and A5 lie to the east and west of the cluster at (J2000) $\alpha = 17^h45^m55\overset{s}{.}84$, $\delta = -28°49'15\overset{''}{.}1$ and (J2000) $\alpha = 17^h45^m45\overset{s}{.}25$, $\delta = -28°49'26\overset{''}{.}1$. The nature of A4 and A5 as well as a number of extended and sharp features observed in high-resolution X-ray images will be discussed elsewhere.

Figures 3*a*, 3*b*, and 3*c* show the observed and modeled spectra toward the A1, A2, and A3 components. The spectra of A1 and A2 were fitted with a MEKAL model (Mewe et al. 1985) of a two-temperature thermal plasma. The two sources were permitted to have different temperatures and volume emission measures, but the abundances and absorbing column densities were constrained to be identical. Table 1 shows the parameters of the A1 and A2 model fits and one σ uncertainty and the associated 68% confidence level. The spectra are best fitted by thermal bremsstrahlung with two temperatures at 0.8 and 6.4 keV for A1 and 0.9 and 5.8 keV for A2. The respective X-ray luminosities (L_X) of A1 and A2, integrated between 0.2 and 10 keV, give 3.3 and 0.8×10^{35} ergs s^{-1} with a total $L_X \sim 4.1 \times 10^{35}$ ergs s^{-1}.

The heavy element abundances in the X-ray emitting plasma range from 1.6 to 3.8 solar, similar to other determinations in the Galactic center region (Maeda et al. 2001; Baganoff et al. 2001). The absorption column of $12.4^{+2.9}_{-2} \times 10^{22}$ H cm^{-2} toward the Arches cluster corresponds to a visual extinction of $A_V \sim 69^{+16}_{-11}$ mag, similar to that inferred from *Chandra* and *ROSAT* observations toward Sgr A East and Sgr A* at the Galactic center (Maeda et al. 2001; Baganoff et al. 2001; Predehl & Trümper 1994). There seems to be a systematic discrepancy between X-ray estimates of A_V and the value ~30 inferred from near-IR observations toward the Arches cluster and the Galactic center (Serabyn et al. 1998; Rieke & Lebofski 1985). Note that the fits to the spectra are poorer (reduced $\chi^2 \sim 1.5$) when N_H is set to 6×10^{22} H cm^{-2}, corresponding to $A_V = 30$ mag.

After the A1 and A2 components are subtracted, the spectrum of A3 is fitted by a single thermal bremsstrahlung of temperature $5.7_{4.4}$ keV, an absorbing column of $10.1^{13.5}_{7.9} \times 10^{22}$ H cm^{-2}, and an additional Gaussian contributed by fluorescent Fe Kα 6.4 keV line emission. The upper bound to the temperature is unconstrained due to the low number of counts at high energies, and the restricted energy band, although the estimated temperatures of A1, A2, and A3 are the same within errors. The total X-ray luminosity of A3 between 0.5 and 10 keV, excluding the 6.4 keV line, is $L_X \approx 1.6 \times 10^{34}$ ergs s^{-1}.

4. DISCUSSION

The Arches cluster was positioned on the I1 chip, about 7′ away from the telescope's aim point. The shape and the size of the point spread function (PSF) at this location is fitted by an elliptical Gaussian with FWHM = $4\overset{''}{.}4 \times 2\overset{''}{.}2$ and P.A. = 83°. Sources A1 and A2 are fitted by elliptical Gaussians with FWHM $8\overset{''}{.}0 \times 7\overset{''}{.}1$ (P.A. = 96°) and $7\overset{''}{.}9'' \times 5\overset{''}{.}1$ (P.A. = 90°), respectively, indicating that they are partially resolved. Further observations are needed to confirm the true extent of A1 and A2.

The resulting distortion of A1 and A2 caused by the PSF means that the present observations cannot distinguish between compact emission associated with the collisions between the ionized winds from early-type stars paired in binary systems and more extended emission arising as a result of the interaction between winds from individual stars within the cluster. Figure 2*b* suggests an association of the A1 component with the known stellar wind sources in the Arches cluster and of A2 with the bright stellar source located at (J2000) $\alpha = 17^h45^m50\overset{s}{.}27$, $\delta = -28°49'11\overset{''}{.}64$, which is identified as either a WN 8 or an Of 4 star (star 1 in Cotera et al. 1996). The X-ray emission from the collision of winds between early-type stars and early-type companions can account for the luminosity and the temperature of A1 and A2 (Stevens, Blondin, & Pollack 1992). The X-ray emission from the cluster R136 is believed to be powered by a dozen colliding wind X-ray binaries. The brightest binary system (CX 5 in Portegies Zwart et al. 2001) has an X-ray luminosity of 2×10^{35} ergs s^{-1} and a fitted temperature of 2.3 keV (Portegies Zwart, Walter, & Lewin 2001).

The A3 component is unlikely to arise from individual stellar sources or binary systems associated with the cluster as it extends far beyond the cluster boundary. Because of its low number of counts, the spectrum of A3 is uncertain. We suggest that this source could be due to shock-heated gas created by the collision of individual ~1000 km s^{-1} stellar winds in the dense cluster environment (Ozernoy, Genzel, & Usov 1997; Cantó et al. 2000). This gas is far too hot to be bound to the cluster, escaping as a supersonic wind provided the external pressure of the medium is not too high. The electron density and mass of A3 implied by our observations are 1.9 cm^{-3} and 0.4 $M_\odot$, respectively. Using the total mass-loss rate $\sim 4 \times 10^{-4}$ $M_\odot$ yr^{-1} estimated from the radio continuum sources detected in the cluster (Lang et al. 2001), we estimate that the residence time of the gas in the A3 component is about 10^3 yr. As predicted by the model (Cantó et al. 2000), the required flow velocity of the wind, about 1200 km s^{-1}, is comparable to the stellar wind speeds determined from the spectra of cluster members (Cotera et al. 1996). The elongation of the X-ray emission from A3 perpendicular to the Galactic plane may be an indication that the cluster wind flow is confined more by the ISM in the Galactic plane than normal to it. However, because of the response of the PSF, there is much uncertainty on the P. A. of A3.

The X-ray emission from the wind is dominated by the portion within the cluster boundary, thus either or both of the A1 and A2 components may be produced by the wind. The total X-ray flux between 0.2 and 10 keV from A1, A2, and A3 is $\sim 5 \times 10^{35}$ ergs s^{-1}, which is close to the X-ray luminosity of 6×10^{35} ergs s^{-1} predicted by Cantó et al. (2000). Their temperature estimate also agrees with the high-temperature component of A1 (if a mean molecular weight of 2 m_H is assumed instead of $2/3\ m_H$).

Where does the hot gas go after it escapes from the cluster? Theoretical studies predict that at any one time, the inner 200 pc of the Galaxy may harbor 50 clusters like the Arches with lifetimes of roughly 70 Myr (Portegies Zwart et al. 2001). It is possible that the gas expelled from the Arches clusters and others like it contributes to the extremely hot diffuse gas found in the inner degree of the Galactic center.

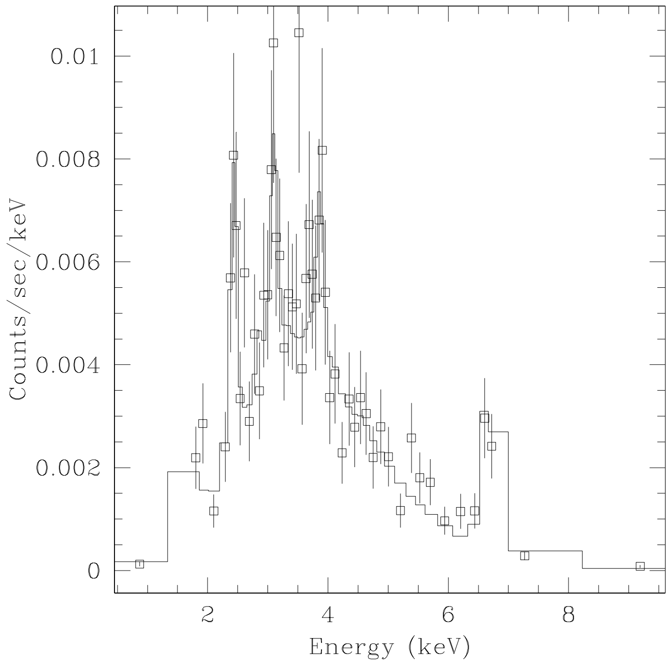

FIG. 3*a*

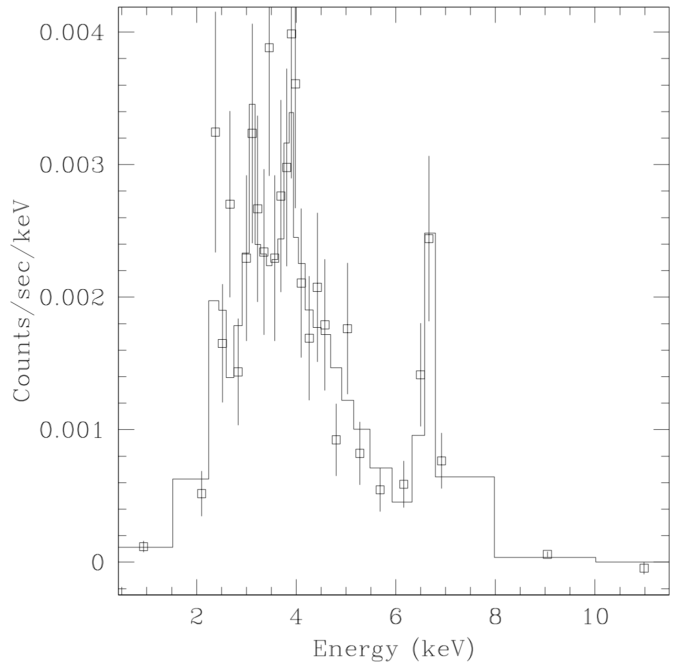

FIG. 3*b*

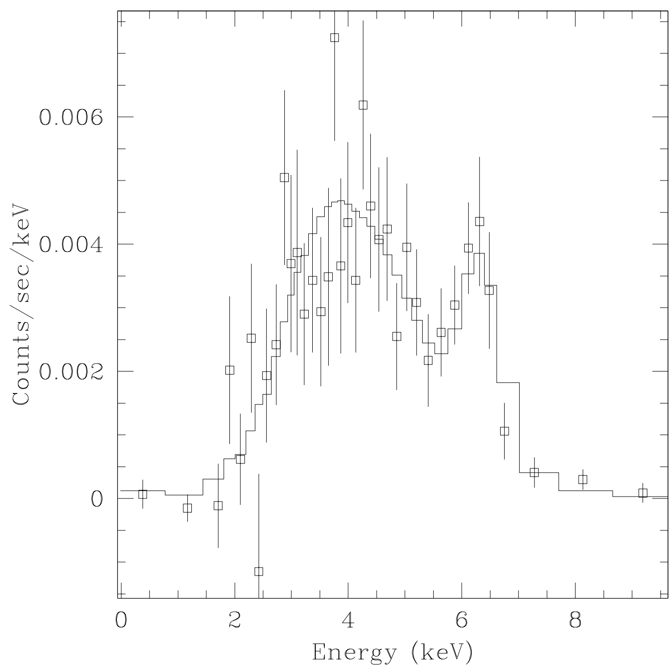

FIG. 3*c*

FIG. 3.—Spectra and fits to the A1, A2, and A3 components of the Arches cluster are shown in (*a*), (*b*), and (*c*), respectively. The A1 and A2 fits model with an absorbed, two-temperature, thermal plasma emission model, whereas the A3 fit model is an absorbed, one-temperature, thermal plasma emission model with a Gaussian at 6.4 keV corresponding to the fluorescent Fe Kα emission. The spectra of the A1 component of Arches cluster are extracted from an elliptical region with an extent of $6'' \times 11''$. The background that is subtracted is taken from the region outside of the Arches cluster, in a roughly circular region 200$''$ across. Sherpa, the fitting and modeling engine of CIAO, was used to fit the A1 and A2 spectra. We fitted the spectra with XSVMEKAL (Mewe, Groneschild, & van den Oord 1985; a.k.a. VMEKAL in XSPEC), a thermal bremsstrahlung plasma model with five emission lines of varying abundance (Si, S, Ar, Ca, Fe). The thermal model was also multiplied by an absorbing column, XSWABS. For the two-temperature fits to A1 and A2, the elemental abundances and column densities of the first and second components were linked together. The thermal flux of absorbed (absorption-corrected) spectrum when integrated between 0.2 and 10 keV give 4.8×10^{-13} (3.9×10^{-11}) ergs cm^{-2} s^{-1} for A1 and 2.7×10^{-13} (9×10^{-12}) ergs cm^{-2} s^{-1} for A2 covering a region of $5'' \times 10''$ and 5.1×10^{-13} (1.8×10^{-12}) ergs cm^{-2} s^{-1} for A3 covering a region of $74'' \times 111''$ with A1 and A2 removed.

The electron temperature of the hot gas is about 10 keV, with an electron density of 0.3–0.4 cm^{-3} and a total mass of about 2–4 $\times 10^3$ $M_\odot$ (e.g., Yamauchi et al. 1990; Koyama et al. 1996). The hot plasma at this temperature cannot be confined by the gravitational potential in the Galactic center region and, if unhindered, escapes the region on a timescale of 10^5 yr. The required replenishment rate is therefore $\sim 3 \times 10^{-2}$ $M_\odot$ yr^{-1}, which could be supplied by the gas lost from 50 clusters like the Arches cluster in the inner 200 pc. However, if the strength of the magnetic field in the inner

TABLE 1
BEST-FITTED PARAMETERS TO THE COMPONENTS OF THE ARCHES CLUSTER

Source	Parameter	Best Fit (Error Bars)
A1.............	$kT(1)$ (keV)	6.4 (−1.5, +2.8)
	Normalization	3.6×10^{-4} (-1.8×10^{-4}, $+2.2 \times 10^{-4}$)
	$kT(2)$ (keV)	0.8 (−0.2, +0.2)
	Normalization	8.3×10^{-3} (-5.5×10^{-3}, $+2.3 \times 10^{-2}$)
	χ^2 per degree of freedom	0.98
A2.............	$kT(1)$ (keV)	1.0 (−0.4, +0.6)
	Normalization	2.0×10^{-3} (-1.3×10^{-3}, $+1.0 \times 10^{-2}$)
	$kT(2)$ (keV)	5.8 (-2.3, +4.7)
	Normalization	2.3×10^{-4} (-1.4×10^{-4}, $+2.1 \times 10^{-4}$)
	χ^2 per degree of freedom	0.97
A1, A2	N_H (10^{22} cm^{-2})	12.4 (−2.0, +2.9)
	$Si/Si_\odot$	2.9 (−1.7, +3.7)
	$S/S_\odot$	1.6 (−0.6, +1.0)
	$Ar/Ar_\odot$	2.5 (−1.0, +1.3)
	$Ca/Ca_\odot$	3.9 (−1.4, +1.7)
	$Fe/Fe_\odot$	2.2 (−0.8, 1.7)

degree is about 1 mG, as a number of studies indicate (e.g., Yusef-Zadeh, Morris, & Chance 1984; Yusef-Zadeh & Morris 1987; Lang, Morris, & Echevarria 1999), then the magnetic pressure is strong enough to confine much of the hot plasma (Koyama et al. 1996; Yusef-Zadeh, Purcell, & Gothelf 1997). Under this assumption, the gas must be replenished on the cooling time of $\sim 10^8$ yr and the required input rate is 1000 times less. The confined gas can be accounted for if at any given time there is a single cluster similar to the Arches cluster within the inner degree of the Galactic center.

Searches for extended X-ray emission may prove useful in identifying young clusters near the Galactic center. It would be worthwhile to look for X-ray emission from young cluster candidates (e.g., Dutra & Bica 2000).

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