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A2111: A $z = 0.23$ Butcher-Oemler Cluster with a Non-isothermal Atmosphere and Normal Metallicity

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ABSTRACT

We report results from an X-ray spectral study of the z=0.23 Abell 2111 galaxy cluster using the Advanced Satellite for Astrophysics and Cosmology (ASCA) and the *ROSAT* Position Sensitive Proportional Counter *(PSPC)*. By correcting for the energy-dependent point-spread function of the instruments, we have examined the temperature structure of the cluster. The cluster's core within 3' is found to have a temperature of 5.4±0.5 keV, significantly higher than 2.8±0.7 keV in the surrounding region of r = 3 - 6'. This radially decreasing temperature structure can be parameterized by a polytropic index of $\gamma \simeq 1.4$. Furthermore, the intracluster medium appears clumpy on scales $\lesssim 1'$. Early studies have revealed that the X-ray centroid of the cluster shifts with spatial scale and the overall optical and X-ray morphology is strongly elongated. These results together suggest that A2111 is undergoing a merger, which is likely responsible for the high fraction of blue galaxies observed in the cluster. We have further measured the abundance of the medium as 0.25±0.14 solar. This value is similar to those of nearby clusters which do not show a large blue galaxy fraction, suggesting that star formation in disk galaxies and subsequent loss to the intracluster medium do not drastically alter the average abundance of a cluster since z=0.23.

1. Introduction

Both optical (Geller and Beers 1982) and X-ray (Jones and Forman 1992) morphological studies of galaxy clusters indicate that a significant fraction of nearby clusters have substructure possibly due to mergers. Morphological studies in either wavelength bands are, however, by themselves inconclusive regarding mergers because of uncertainty due to the projection effect. Hydro-dynamical simulations of subcluster mergers show that heating of the cluster atmosphere is present in a recent post-merger system even when evidence of a merger is not visible in the X-ray surface brightness morphology (Evrard, Metzler, and Navarro 1996). Spatially resolved spectroscopy can thus help us to find hot spots similar to those seen in the simulations (Roettiger, Loken, and Burns 1997; Evrard, Metzler, and Navarro 1996). Such analysis has been carried out for a number of clusters with data from *ASCA*, which has a broad energy coverage and modest spatial resolution. The best cases for a merger in progress show both an asymmetric X-ray morphology and a temperature structure consistent with simulations of a merger. Examples are A754 (Henriksen and Markevitch 1996), the Coma cluster (Honda et al. 1997), and A1367 (Donnelly et al. 1998). In contrast, A2256 shows X-ray and optical substructures, but its temperature map obtained with *ASCA* indicates a quiescent dynamical state (Markevitch 1996).

Subcluster mergers are violent events which are expected to affect the evolution of galaxies. The relevant processes include ram-pressure (White et al. 1991), the tidal effect from the cluster potential (Henriksen and Byrd 1996), and "galaxy harassment" (Oemler, Dressler, and Butcher 1997). Thus, the evolution of cluster galaxies may be intimately connected to the formation process and changing environment of clusters (e.g., Kauffmann 1995; Oemler, Dressler, & Butcher 1997). Clusters of galaxies near the z=0.2 epoch show higher fractions of blue galaxies — the Butcher-Oemler effect. *HST* observations have shown that the effect results from a high rate of star formation in the spiral galaxy population (Dressler et al. 1994; Couch et al. 1994) and a high fraction of disturbed systems (Oemler, Dressler, and Butcher 1997). Based on a study of 10 Butcher-Oemler clusters, Wang & Ulmer (1997) have further revealed a correlation between ellipticity in the X-ray isophotes and blue galaxy fraction. A2111 is one of the clusters in the sample and shows a high fraction of blue galaxies. Based on *ROSAT* PSPC and HRI observations, Wang, Ulmer, & Lavery (1997; hereafter WUL) showed that A2111 has a highly asymmetric X-ray morphology and the X-ray centroid shifts with scale, suggesting that the cluster is undergoing a merger.

In this paper, we present a spatial-spectral analysis, using an *ASCA* observation, complemented by the *ROSAT* PSPC data of A2111. This analysis enables us to search for the spatial and spectral signature of a merger over a broad energy band and to compare the metal abundance of A2111 with nearby clusters. Throughout the paper $H_0 = 50$ km sec^{-1} Mpc^{-1} is used.

2. Observations and Analysis

A2111 was observed on January 15-16, 1997 with *ASCA* for 30,000 seconds. Data was obtained with both the Gas Imaging Spectrometer (GIS) and the Solid State Imaging Spectrometer (SIS); each has two sensors. The GIS has a higher effective area at higher energies ($>$ 5 keV) than the SIS. The data were filtered using the REV2 criteria utilized by the *ASCA* Data Processing Center in re-processing data since June 1997. Data were excluded under the following conditions: with a radiation belt monitor (RBM) count $>$ 100 cts/s, during earth occultation or at low elevation angle to the Earth ($<$ 5 degrees for the GIS and $<$ 10 degrees for the SIS), when the pointing was not stable (deviation of $>$ 0.01 degrees), during South Atlantic Anomaly passage, and when the cutoff rigidity (COR) was

> 6 GeV/c. Additionally, the SIS was required to be > 20 degrees to the bright earth and were cleaned to remove hot pixels. The resulting good exposure times are given in Table 1. The processing of the *ROSAT* PSPC observations has been discussed by WUL. Briefly, the observation had an exposure of 7511s, a spatial resolution of $\sim 0'.5$, and about seven overlapping bands over the 0.1-2 keV range.

To obtain an emission weighted spectrum for the cluster, we first conducted a joint fit to the spectra from the *ROSAT* PSPC and the *ASCA* GIS and SIS detectors. Extracted from a region within 6' from the assumed cluster centroid at $15^h39^m36^s.554; 34°25'31''.16$ (R.A.; Dec.; J2000), the spectra include essentially all of the cluster emission. Background from the PSPC is taken from source-free regions of the image. [Mark: how about the GIS background?] However, the SIS data was taken in 1-ccd mode and the cluster essentially fills the chip, precluding use of source free regions for background subtraction. We thus utilized blank sky deep *ASCA* observations taken at high Galactic latitudes for background subtraction. We adopted the Raymond & Smith thermal plasma model. The two GIS normalizations were tied to have the same emission integral, and so were the two SIS normalizations. The redshift of the cluster is fixed at 0.23. The abundance, column density, and temperature were left as free parameters giving a total of 5 free parameters. The fit is reasonably good with a reduced χ^2 of 1.11 or 345 for 311 degrees of freedom. The data and the best model fit are shown in the top panel of Figure 1 [Mark: I'd like the residuals shown instead].

While the above analysis is not sensitive to any temperature structure of A2111, we measure the ICM temperatures of the cluster in two regions, with radii 0-3' and 3-6'. Further dividing the regions is not practical due to the limited extent of the cluster compared to the XRT+GIS PSF and the limited counting statistics of the *ASCA* observation. The temperature measurement uses a PSF modeling technique described in Markevitch (1996) and Takahashi et al. (1995). The modeling technique has been successfully used in similar analyses for several relatively low redshift clusters (see references in Markevitch, Sarazin, and Henriksen 1997). Briefly, the PSPC image is used as a model surface brightness template which is convolved with the *ASCA* mirror effective area and PSF to produce model spectra in the two regions. The *ROSAT* image is flat fielded, background subtracted, and rotated to match the GIS roll angle. The PSPC energy range used is 0.5 - 2.0 keV and the emission measure is corrected to the *ASCA* energy band. The data are binned in energy to maintain a signal-to-noise ranging from $\sim$1 to $>$10. The model PSF, which is based on GIS observations of Cyg X-1 at various radii from the detector center (Takahashi et al. 1995), is increasingly uncertainty at low energies so the minimum energy used was 1.5 keV to minimize the uncertainty in the PSF. The energy bins are 1.5-2.5, 2.5-4., 4.-7. keV in the SIS and 1.5-2.5, 2.5-3., 3.-5., 5.-7., 7.-11 keV in the GIS. Markevitch (1996) discusses in detail various consistency checks performed in validating this methods for obtaining temperature maps of clusters observed with *ASCA*.

We applied the technique to our background subtracted spectra from all four *ASCA* data sets. Since the A2111 observations and the deep, blank sky observations used in the background subtraction are taken at different times, the COR values are different during each observation. Background is subtracted using blank sky images, each at a specific COR value, time weighted to the amount of source data obtained at the same COR value as the blank sky image. The SIS background image is normalized only by exposure time. A 20% systematic error in the SIS and 5% error in the GIS background normalization is included in the fitting procedure. The SIS error is estimated at 20% based on a day-to-day variation in the GIS background of 20-30% for a specific COR value. By using a composite background consisting of GIS observations with the same COR values as the data, the GIS background is better determined and the error in the normalization is estimated at 5% (Markevitch 1996 and references within). There errors are then added in quadrature with the random errors. The resulting background subtracted counts are given in Table 1.

We simultaneously fitted the four spectra from each region using the Raymond and Smith model with the abundance fixed at the best fit value obtained with the PSPC of 0.25 Solar and N_H fixed at the best fit value obtained by repeating the fit while steeping through a range of column densities, 2.5×10^{21} cm^{-2}. [why don't you fix the absorption to the measured 21 cm value?] Though this column density is much higher than the Galactic value or that obtained by adding the *ROSAT* data, it is not well constrained in the PSF modeling since we do not use data below 1.5 keV.

Confidence intervals on temperature are estimated by a Monte-Carlo simulation of the number of counts in each energy band of the spectra assuming a Poisson distribution of counts around the observed value. The spectra are then re-fit to obtain the best fit temperature. A systematic error of 5% each for the PSF and effective area are included in the error simulation. Two hundred simulated spectra are fit and the variance of the distribution of best-fitting temperatures is calculated.

[Mark: some explanation is needed here; I am not sure that I understand the procedure.] The best fit abundance and the 68% and 90% confidence range is obtained by stepping through a range of abundances, allowing the temperatures to be free parameters, while minimizing χ^2. The best fit models and GIS2 data are shown in Figures 2 and 3 for the 0-3' and 3-6' regions respectively.

3. Results and Discussion

Figs. 4 and 5 show the exposure-corrected SIS and GIS contour maps. Both maps show an overall elongation of the cluster X-ray morphology. The X-ray intensity distribution in the SIS map is very clumpy, compared to that in the GIS map. The significance of *individual* features is marginal. Some of the features also appear in the PSPC data, albeit with even lower significance. But the overall clumpiness of the X-ray distribution is real, since the SIS and GIS maps are smoothed in the exactly same way to have the same noise level. The clumpy structure appears much clearly in the SIS map because the instrument has its spatial resolution (FWHM $\sim$?) much better than the GIS (FWHM $\sim$?). The clumpy X-ray morphology may arise in the presence of multiple components of the ICM. Assuming an approximate pressure balance, the temperature inhomogeneity could naturally result in large emission measure differences in the ICM, which is manifested by the X-ray emission.

The results from our spectral modeling are summarized in Table 2. The emission weighted temperature for the cluster derived from a joint fit of the *ROSAT* and *ASCA* data is 4.9 - 5.9 keV (90% limit), which overlaps the results reported by WUL based solely on the PSPC (2.1 - 5.3 keV). The 90% confidence on the column density, 1.0 - 1.4×10^{20} cm^{-2} is slightly below that measured from 21 cm, 1.9×10^{20} cm^{-2}. With the column density fixed to the measured 21 cm value, the temperature range falls to ?-? keV, consistent with the PSPC results.

Our spatial-spectral analysis of A2111 further suggests that the average temperature of 5.4 ± 0.5 keV in the central region ($r < 1$ Mpc) of A2111 is significantly higher than 2.8 ± 0.7 keV in its surrounding, r = 3 - 6'. This temperature drop is consistent with the results from simulations after a subcluster has passed through the core of the main cluster (ref), supporting the hypothesis that A2111 is undergoing a merger (WUL). A2111 is thus the first confirmed merger for a intermediate redshift cluster that also shows a large blue galaxy fraction. The most comparable cluster with a similar redshift is A2163 (z = 0.2), for which a similar spatial-spectral study using *ASCA* data has been conducted (Markevitch 1996). The characteristic temperature of this cluster reaches about 11 keV in the central region and drops to 4 keV at 3 Mpc, indicating an ongoing merger or a post-merger. With a polytropic index (γ) 1.9, this cluster is apparently convectively unstable and can not be in an equilibrium configuration. The temperature profile for A2111 is less steep than A2163, the equivalent γ is = 1.4 (using the density parameters from WUL: $\beta = 0.54$ and core radius

= 0.21 Mpc); perhaps this cluster has pasted the stage of convective instability or involves less massive subclusters. Alternatively, a temperature drop may reflect the gravitational potential of the cluster rather than shock heating from a merger. However, the case for A2111 being a merger candidate is strengthened by the spectral and spatial results taken together.

The best fit abundance of A2111, 0.11 - 0.39 Solar (90% confidence), is typical of low z clusters and is consistent with the study by Mushotzky and Loewenstein (1997) which indicates that metallicity in galaxy clusters in essentially constant out to z $\sim$0.3. A2111 is unlike the nearby clusters which show a similar abundance because it has a high frequency of star forming galaxies, while the nearby clusters do not. The similarity in abundance argues against recent mergers having a significant effect on the overall metallicity of the cluster gas.

In conclusion, our ASCA data show that A2111 has an elongated and clumpy X-ray morphology as well as a relatively high temperature core, compared to the surrounding regions. These results, together with the apparent substructure observed in the *ROSAT* observations, strongly suggest that the cluster is undergoing a merger. This merger may explain the observed large blue galaxy fraction of the cluster, indicating the relation between cluster evolution and the Butcher-Oemler effect.

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Table 1. ASCA Data

Detector	Region	Counts	Exposure (sec)
GIS 2	0-3'	644.5	23707.
	3-6'	402.8	
GIS 3	0-3'	533.4	23370.
	3-6'	335.9	
SIS 0	0-3'	494.0	13562.
	3-6'	294.0	
SIS 1	0-3'	350.4	14314.
	3-6'	217.6	

Table 2. Spectral Modeling Results

Model	Region(s)	χ^2_ν	kT(keV)	n_H	Abundance
1 RS (0.5-11 keV)	0-6'	1.11	4.9 - 5.9	1.0 - 1.4$\times 10^{20}$ cm^{-2}	0.11 - 0.39
1 RS (PSF model)	0-3'	0.46	5.4$\pm$0.5	-	-
	3-6'	-	2.8$\pm$0.7	-	-

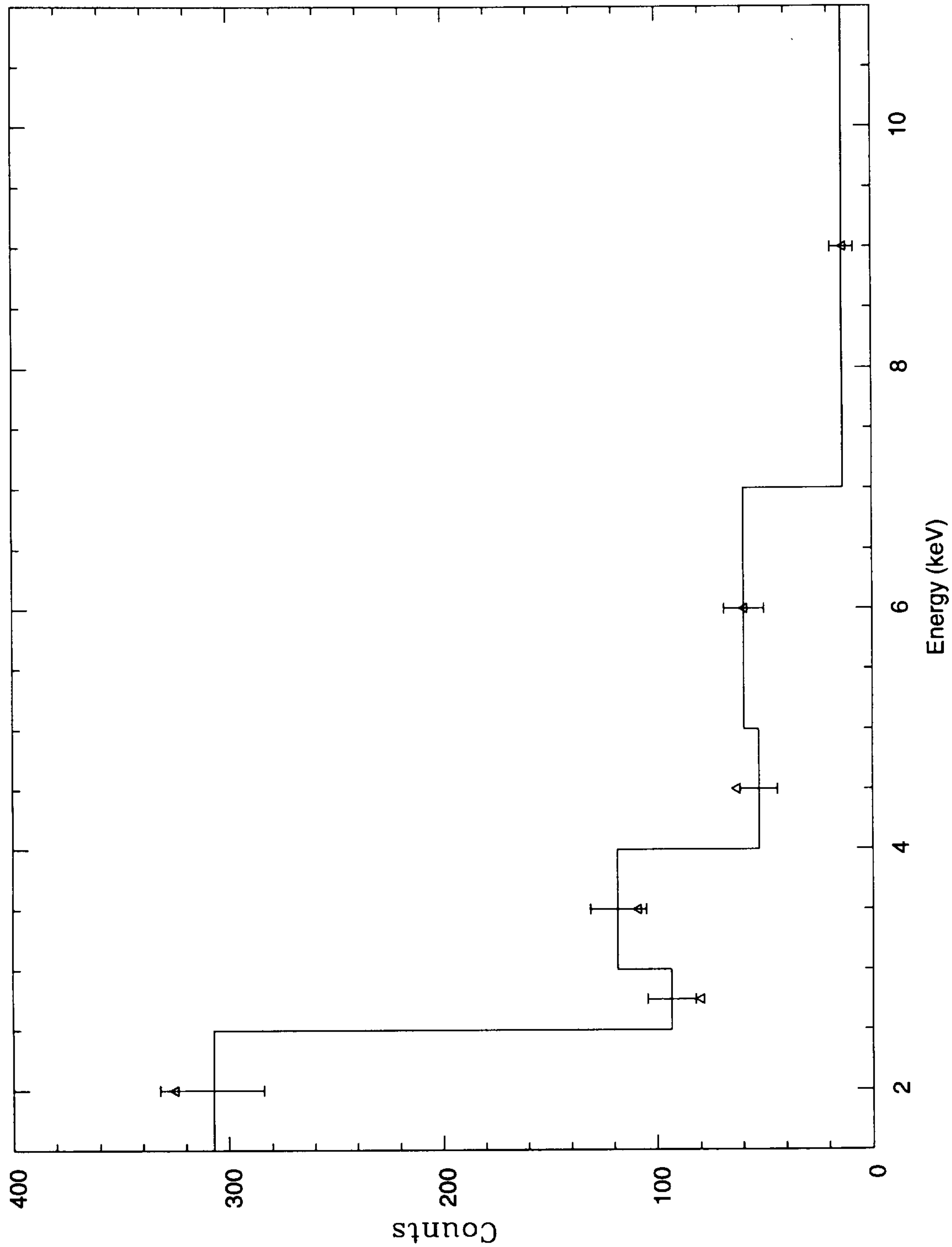
Fig. 1.— The data for the PSPC, GIS2, GIS3, SIS0, and SIS1 and best fit single component Raymond and Smith model are shown in the upper panel. The reduced χ^2 is 1.11. χ^2 vs. energy is shown in the lower panel.

Fig. 2.— The best fit model, background subtracted counts and error are shown in each of the energy bins fit for the G2 in the inner, 0-3' region of the cluster. This representative of the data quality and the goodness of fit since the spectrum from the G3, SIS0, and SIS2 were also fit but are not shown.

Fig. 3.— The same as is shown in figure 2 for the outer, 3 - 6' region of the cluster.

Fig. 4.— The exposure corrected SIS intensity map is adaptively smoothed with a Gaussian function, adjusted to achieve a uniform signal-to-noise of 6. The contour levels are 2σ higher than the next lower one and have values of: 1.6, 2.1, 2.8, 3.8, and 5.0×10^{-3} counts arcmin^{-2} sec^{-1}. The background level is 1.2×10^{-3} counts arcmin^{-2} sec^{-1}.

Fig. 5.— The GIS map is prepared similarly to the SIS map in figure 4. The contour levels have values of: 2.0, 2.7, 3.6, 4.7, 6.3, 8.4, 11.2, 14.9, and 20.0×10^{-4} counts arcmin^{-2} sec^{-1}. The background level is 1.5×10^{-4} counts arcmin^{-2} sec^{-1}.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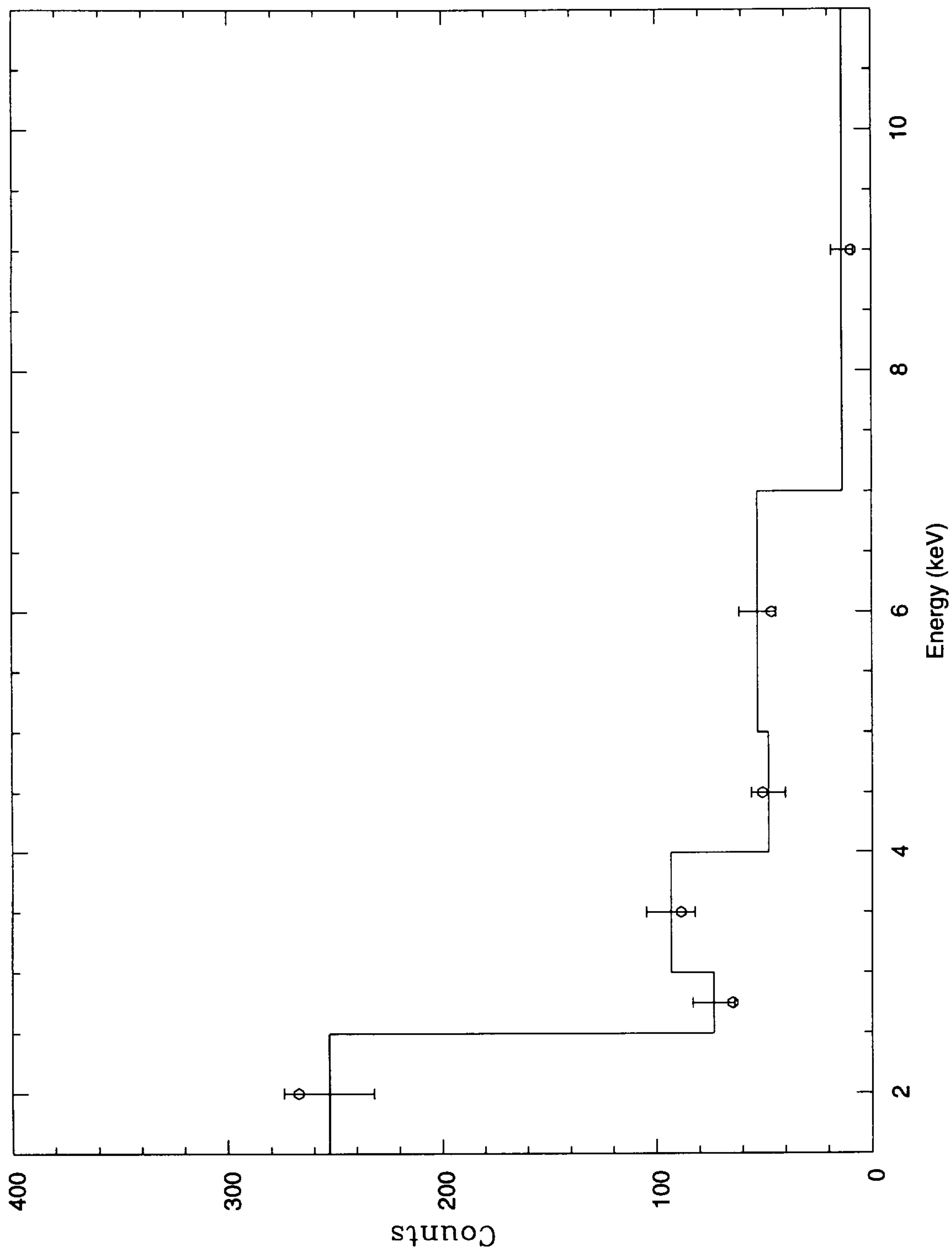

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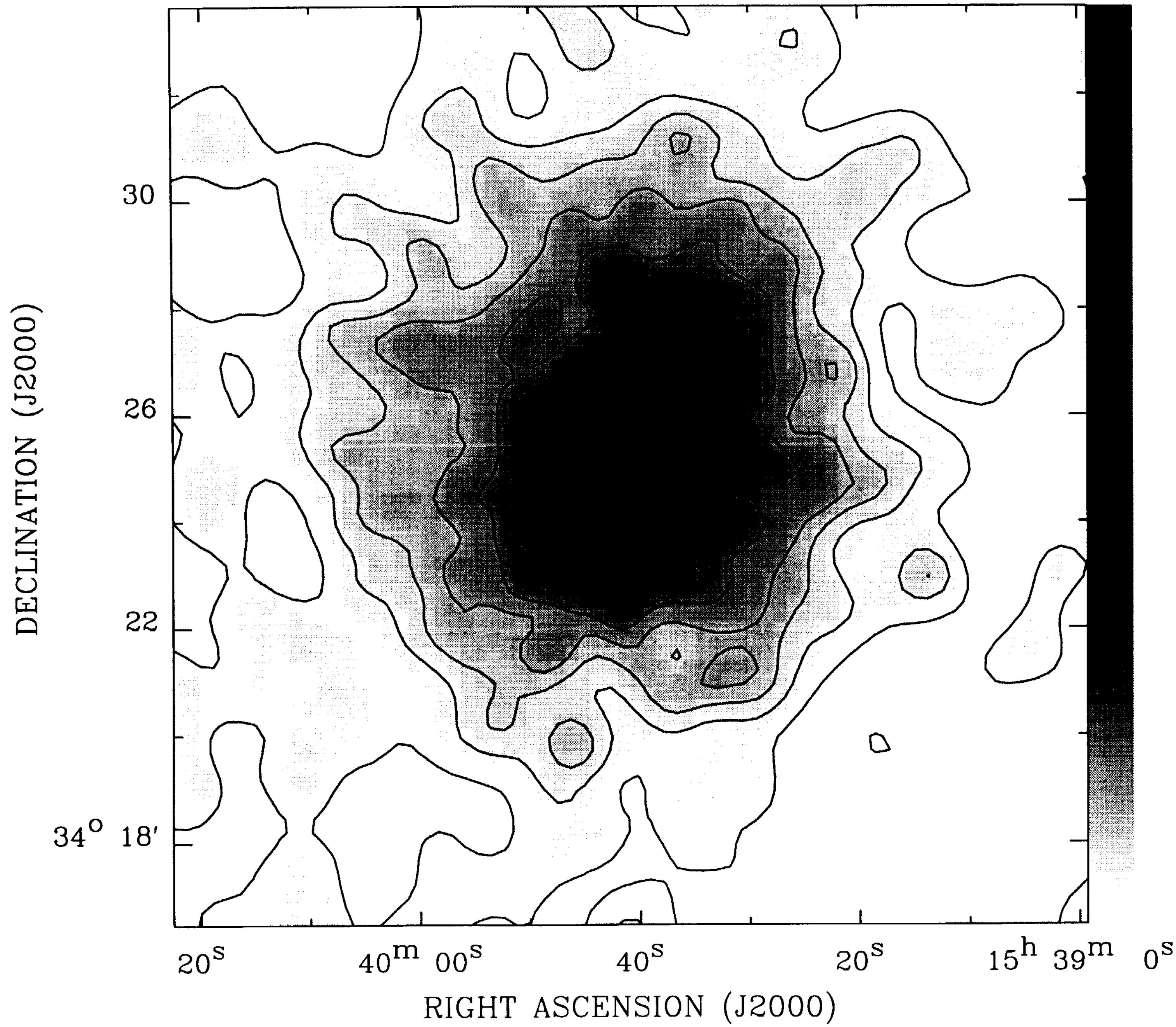
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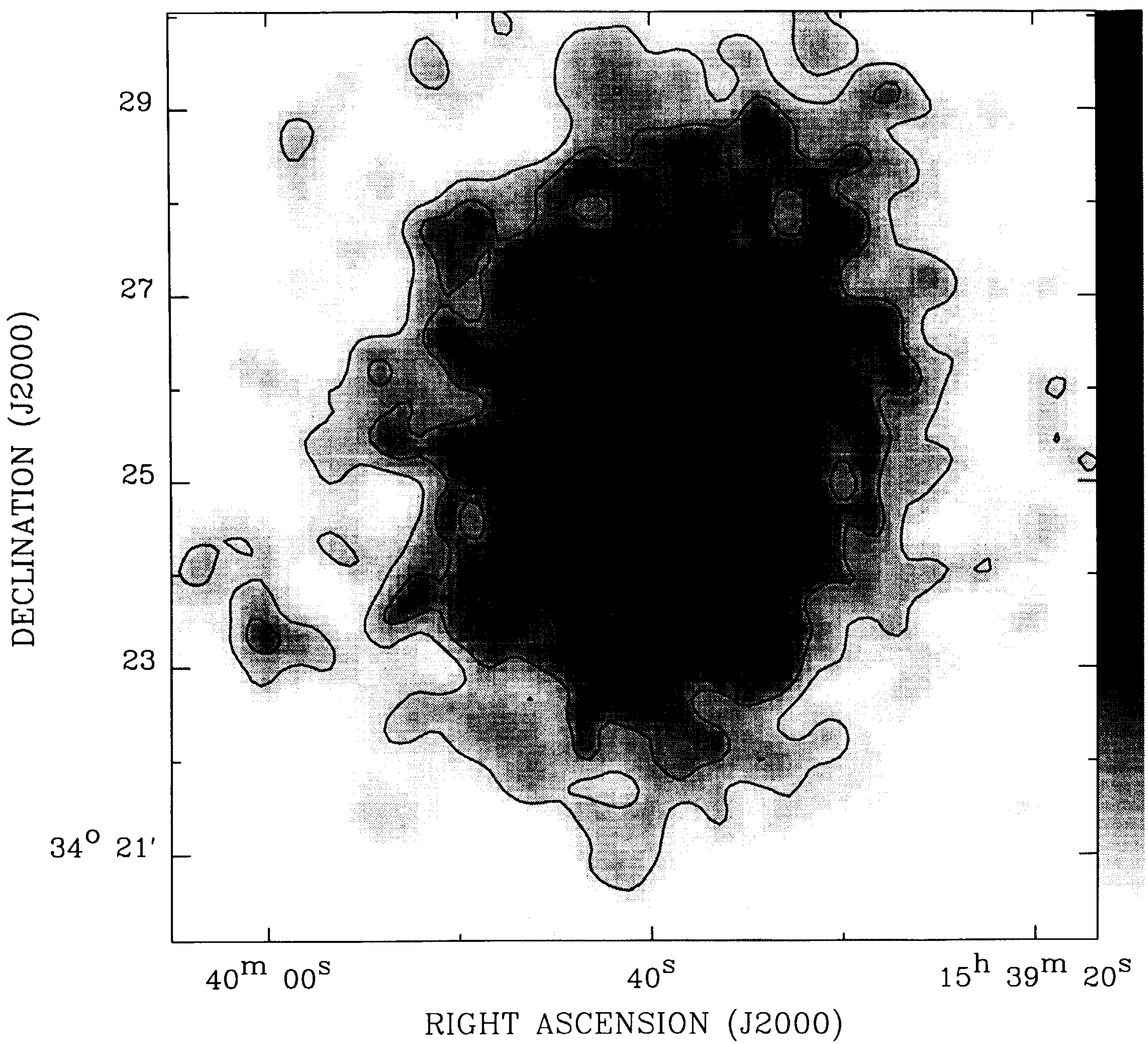

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