Mem. S.A.It. Vol. 80, 435

Memorie della

Introduction to MAXI, the Multivariate Archive of X-ray Images

Alexis Finoguenov[1,2] and Jai Won Kim[1,3]

[1] Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, 85748 Garching, Germany
[2] University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA
[3] Astronomisches Rechen-Institut, Zentrum fur Astronomie der Universitat Heidelberg, Moenchhofstr. 12-14, D-69120 Heidelberg, Germany

Abstract. Advent of XMM-Newton and Chandra has drastically changed our understanding of clusters of galaxies. From 'round cows' clusters became picturesque objects, full of structure and interaction, caused by their hierarchical assembly.
To cope with a change in the informational content related to X-Ray cluster observation, as well as observation of extended X-ray emission in general, we have created the format of data release which will allow observers to understand and locate the cluster structure better. This information is based on the irregular grid, usually optimized to bring up the most interesting cluster features, and we adopted the use of such grids as a basic element in the data storage. Most of the information is generated on the fly, which allows to minimize the data storage requirements.
At the moment we have released the data on a recently published XMM observation of A3266 and a Chandra observation of M84 to test the performance of the site and receive the feedback on its design. The future goal is to create a user interface for data upload, available to all scientists.

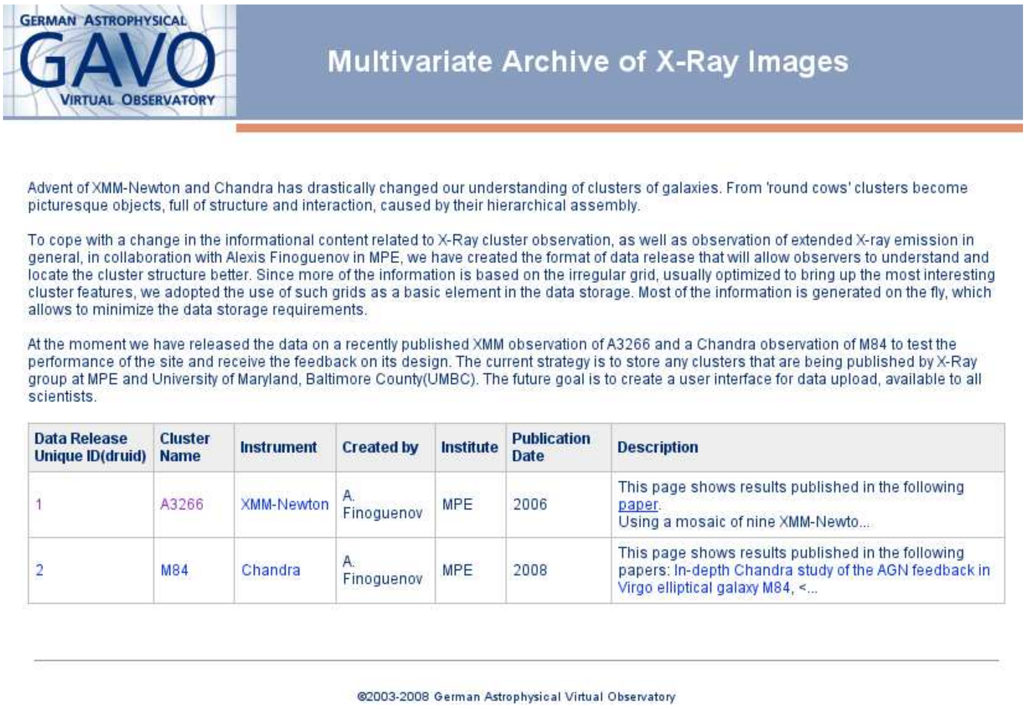
Key words. Galaxies: fundamental parameters - Virtual Observatory - theory

1. Introduction

The Virtual Observatory(VO) approach aims to allow global electronic access to the available astronomical data archives of space and ground-based observatories, as well as simulation databases. It also aims to enable data and service interoperability through common standards, and to provide state-of-the-art data analysis tools which promise interoperability. The International Virtual Observatory Alliances (IVOA) is responsible for defining standards which prescribe how to publish and to access various types of astronomical data and services, which is an essential part of interoperability.

One of the current goals in the VO is to add data from numerical simulations and provide tools allowing a comparison with observational data (Borgani, these proceedings). Taking clusters of galaxies as an example, these simulations provide 2- and 3-d information on the

Send offprint requests to: A. Finoguenov



GERMAN ASTROPHYSICAL GAVO VIRTUAL OBSERVATORY

Multivariate Archive of X-Ray Images

Advent of XMM-Newton and Chandra has drastically changed our understanding of clusters of galaxies. From 'round cows' clusters become picturesque objects, full of structure and interaction, caused by their hierarchical assembly.

To cope with a change in the informational content related to X-Ray cluster observation, as well as observation of extended X-ray emission in general, in collaboration with Alexis Finoguenov in MPE, we have created the format of data release that will allow observers to understand and locate the cluster structure better. Since more of the information is based on the irregular grid, usually optimized to bring up the most interesting cluster features, we adopted the use of such grids as a basic element in the data storage. Most of the information is generated on the fly, which allows to minimize the data storage requirements.

At the moment we have released the data on a recently published XMM observation of A3266 and a Chandra observation of M84 to test the performance of the site and receive the feedback on its design. The current strategy is to store any clusters that are being published by X-Ray group at MPE and University of Maryland, Baltimore County(UMBC). The future goal is to create a user interface for data upload, available to all scientists.

Data Release Unique ID(druid)	Cluster Name	Instrument	Created by	Institute	Publication Date	Description
1	A3266	XMM-Newton	A. Finoguenov	MPE	2006	This page shows results published in the following paper. Using a mosaic of nine XMM-Newto...
2	M84	Chandra	A. Finoguenov	MPE	2008	This page shows results published in the following papers: In-depth Chandra study of the AGN feedback in Virgo elliptical galaxy M84, <...

©2003-2008 German Astrophysical Virtual Observatory

Fig. 1. MAXI welcome page. All objects are listed together with reference to a publication, submitting astronomer, telescope.

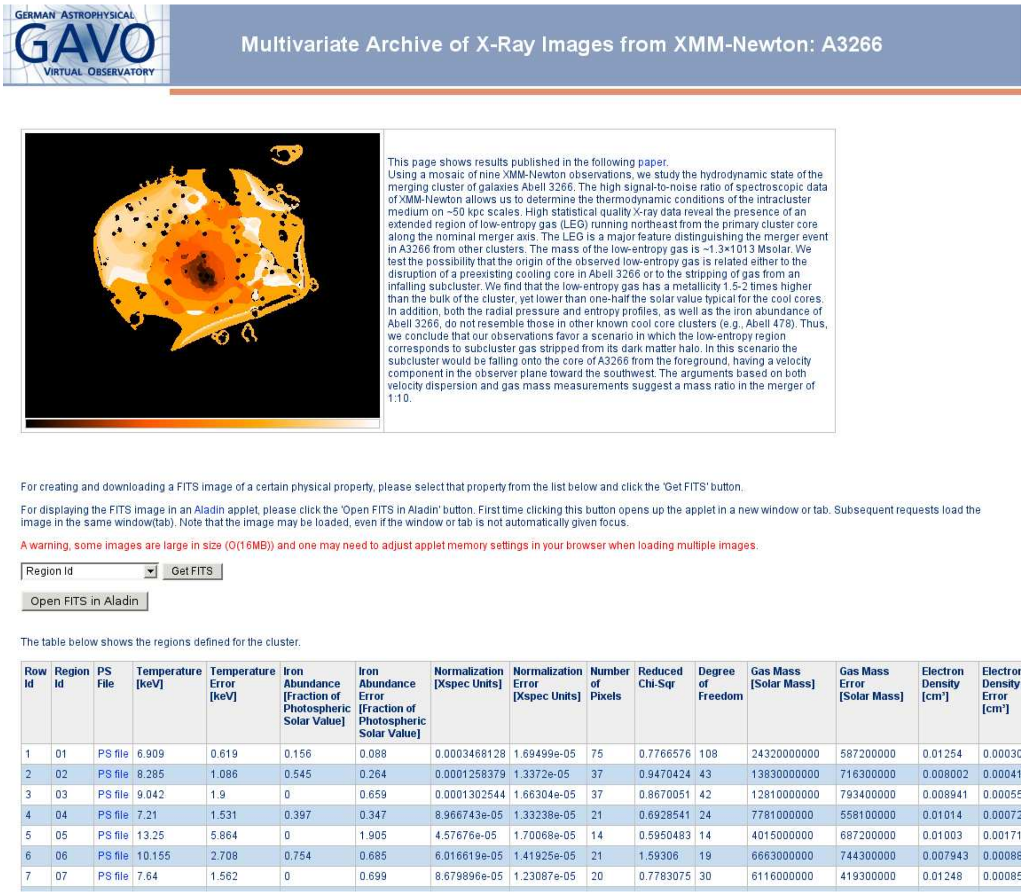
state of the gas, which can be compared to observations by X-ray satellites.

In order to make a proper comparison with real observations, one ideally requires a selection of simulated objects with similar properties, for example having similar mass and redshift, and one would like a range of techniques for making the comparison. The most comprehensive comparison scheme might involve reproduction of the two-dimensional appearance of observed clusters, with the aim of assessing the physical properties of the media, such as conduction, viscosity as well as the role of the magnetic fields.

The forward fitting approach requires the use of generalized response matrix, characterizing an ability of particular observation to characterize the properties of the object, as spatial binning of observational data removes the high-frequency signal. Moreover, real observations can not provide similar data quality on a rectangle grid, as surface density of objects in study is non-uniform. Thus a description of the way the source extraction is performed in observation is a critical component of the comparison.

The Simple Image Access Protocol (SIAP) is an IVOA standard for publishing and accessing image data. So far over 80 SIAP compliant services are registered in IVOA compliant registries. Most of these services provide standard "luminous intensity" images from surveys and pointed observations. Instead the the current project aims to publish images for a variety of physical properties of a single source derived from observations. Such "images" are currently not well describable by the SIAP metadata.

We have therefore first built a custom web service, MAXI, which publishes the cluster properties using a combination of data products. These include the mask file defining the region, X-Ray spectra derived per region represented as PS files and a table containing de-



GERMAN ASTROPHYSICAL GAVO VIRTUAL OBSERVATORY

Multivariate Archive of X-Ray Images from XMM-Newton: A3266

This page shows results published in the following paper.
Using a mosaic of nine XMM-Newton observations, we study the hydrodynamic state of the merging cluster of galaxies Abell 3266. The high signal-to-noise ratio of spectroscopic data of XMM-Newton allows us to determine the thermodynamic conditions of the intracluster medium on ~50 kpc scales. High statistical quality X-ray data reveal the presence of an extended region of low-entropy gas (LEG) running northeast from the primary cluster core along the nominal merger axis. The LEG is a major feature distinguishing the merger event in A3266 from other clusters. The mass of the low-entropy gas is ~1.3×1013 Msolar. We test the possibility that the origin of the observed low-entropy gas is related either to the disruption of a preexisting cooling core in Abell 3266 or to the stripping of gas from an infalling subcluster. We find that the low-entropy gas has a metallicity 1.5-2 times higher than the bulk of the cluster, yet lower than one-half the solar value typical for the cool cores. In addition, both the radial pressure and entropy profiles, as well as the iron abundance of Abell 3266, do not resemble those in other known cool core clusters (e.g., Abell 478). Thus, we conclude that our observations favor a scenario in which the low-entropy region corresponds to subcluster gas stripped from its dark matter halo. In this scenario the subcluster would be falling onto the core of A3266 from the foreground, having a velocity component in the observer plane toward the southwest. The arguments based on both velocity dispersion and gas mass measurements suggest a mass ratio in the merger of 1:10.

For creating and downloading a FITS image of a certain physical property, please select that property from the list below and click the 'Get FITS' button.

For displaying the FITS image in an Aladin applet, please click the 'Open FITS in Aladin' button. First time clicking this button opens up the applet in a new window or tab. Subsequent requests load the image in the same window(tab). Note that the image may be loaded, even if the window or tab is not automatically given focus.

A warning, some images are large in size (O(16MB)) and one may need to adjust applet memory settings in your browser when loading multiple images.

Region Id | Get FITS

Open FITS in Aladin

The table below shows the regions defined for the cluster.

Row Id	Region Id	PS File	Temperature [keV]	Temperature Error [keV]	Iron Abundance [Fraction of Photospheric Solar Value]	Iron Abundance Error [Fraction of Photospheric Solar Value]	Normalization [Xspec Units]	Normalization Error [Xspec Units]	Number of Pixels	Reduced Chi-Sqr	Degree of Freedom	Gas Mass [Solar Mass]	Gas Mass Error [Solar Mass]	Electron Density [cm³]	Electror Density Error [cm³]
1	01	PS file	6.909	0.619	0.156	0.088	0.0003468128	1.69499e-05	75	0.7766576	108	24320000000	587200000	0.01254	0.00030
2	02	PS file	8.285	1.086	0.545	0.264	0.0001258379	1.3372e-05	37	0.9470424	43	13830000000	716300000	0.008002	0.00041
3	03	PS file	9.042	1.9	0	0.659	0.0001302544	1.66304e-05	37	0.8670051	42	12810000000	793400000	0.008941	0.00055
4	04	PS file	7.21	1.531	0.397	0.347	8.966743e-05	1.33238e-05	21	0.6928541	24	7781000000	558100000	0.01014	0.00072
5	05	PS file	13.25	5.864	0	1.905	4.57676e-05	1.70068e-05	14	0.5950483	14	4015000000	687200000	0.01003	0.00171
6	06	PS file	10.155	2.708	0.754	0.685	6.016619e-05	1.41925e-05	21	1.59306	19	6663000000	744300000	0.007943	0.00088
7	07	PS file	7.64	1.562	0	0.699	8.679896e-05	1.23087e-05	20	0.7783075	30	6116000000	419300000	0.01248	0.00085

Fig. 2. MAXI page on XMM observation of A3266. Reference to an original publication, table content, data selector and a link to Aladin are clearly seen.

rived physical properties per region. The web site allows the creation of images for any of the properties on the fly, from this combination of table and mask file, minimizing data storage requirements.

2. Public appearance of MAXI

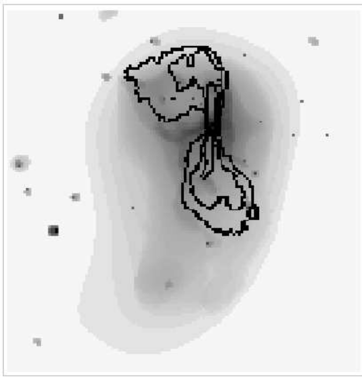
In Fig.1 we show the welcome page of the MAXI project, located at *http://www.g-vo.org/MAXI/* , which further provides links to data arranged by observatory name as well as direct link to datasets. To each data release we have assigned a unique dataset identifier, *druid* (Data Release Unique ID).

In Fig.2 a page with XMM-Newton observations of Abell 3266 (Finoguenov et al. 2006) is shown. It features a full list of X-ray cluster properties as function of extraction region, the map of extraction regions, and gives the ability to compute and display the map of any selected property. Numerous pop-up windows provide a detailed explanation to the content of each column of meta-file when a cursor is stopped on any of the column names. The quality of the analysis can be accessed by eye-balling the ps-file with spectral fit in addition to statistical measures.

In Fig.3 we show an example of a data release using data obtained by Chandra, published in Finoguenov et al. (2008). The for-

GERMAN ASTROPHYSICAL GAVO VIRTUAL OBSERVATORY

Multivariate Archive of X-Ray Images from Chandra: M84



This page shows results published in the following papers: In-depth Chandra study of the AGN feedback in Virgo elliptical galaxy M84, Chandra Observation of Low-Mass X-Ray Binaries in the Elliptical Galaxy M84, and Chandra Observation of M84, a Radio Lobe Elliptical Galaxy in the Virgo Cluster.

For creating and downloading a FITS image of a certain physical property, please select that property from the list below and click the 'Get FITS' button.

For displaying the FITS image in an Aladin applet, please click the 'Open FITS in Aladin' button. First time clicking this button opens up the applet in a new window or tab. Subsequent requests load the image in the same window(tab). Note that the image may be loaded, even if the window or tab is not automatically given focus.

A warning, some images are large in size (O(16MB)) and one may need to adjust applet memory settings in your browser when loading multiple images.

Region Id | Get FITS

Open FITS in Aladin

The table below shows the regions defined for the cluster.

Row Id	Region Id	PS File	Temperature [keV]	Temperature Error [keV]	Normalization [Xspec Units]	Normalization Error [Xspec Units]	Number of Pixels	Reduced Chi-Sqr	Degree of Freedom	Gas Mass [Solar Mass]	Gas Mass Error [Solar Mass]	Electron Density [cm³]	Electron Density Error [cm³]	Entropy [keV cm²]	Entropy Error [keV cm²]	Pressure [dyne/cm²]	Pressure Error [dyne/cm
1	001	PS file	0.593	0.044	7.313002e-06	1.14995e-06	634	1.567208	11	1917000	145200	0.01582	0.001198	9.412	0.842	1.503e-11	1.59e-12
2	002	PS file	0.502	0.054	9.174064e-06	2.07452e-06	2176	1.327256	17	5111000	548400	0.007443	0.0007987	13.175	1.697	5.99e-12	9.081e-1
3	003	PS file	0.522	0.058	8.274088e-06	1.88181e-06	1032	2.021929	13	2970000	320400	0.01155	0.001246	10.224	1.346	9.671e-12	1.492e-1
4	004	PS file	0.621	0.03	1.250245e-05	1.43114e-06	1969	1.149973	17	5050000	281200	0.01027	0.0005716	13.144	0.797	1.021e-11	7.503e-1
5	005	PS file	0.597	0.034	1.544806e-05	2.01463e-06	11069	0.9895473	39	20100000	1271000	0.003186	0.0002014	27.591	1.962	3.05e-12	2.602e-1

Fig. 3. MAXI page on Chandra observation of M84.

mat of the data release is exactly the same, as instrument-specific features have been removed during data analysis. But object-specific features are changed: due to Virgo-cluster background no reliable measurement of Fe abundance was possible on the selected grid (Finoguenov et al. 2008).

As illustrated in Fig.4, we use the Aladin (Bonnarel et al. 2000) utility to view and examine the images. The figure shows what a pressure map of the hot gas in M84 galaxy looks like when sent to this applet from the MAXI's page. By enabling loading multiple files in a single Aladin applet from any MAXI pages, a user can compare images of different clusters published in MAXI. The user has another alternative for displaying and working with images, which is to install some software on their machine, for example ds9 provides a user-friendly support for most platforms. By clicking on the "get fits file" button the user can download and open the fits file with their favorite browser.

The system requires a FITS region file and a table listing the derived physical properties per region. Optionally per region extra data sets can be provided, such as the actual spectra. Together with the data metadata must be provided. The metadata contain the basic description of an observation, and of each physical property, an example of the table metadata is shown in Tab.1. Our plan is for the site to allow upload of new data sets without intervention of software engineers. We will also implement SIAP as well as the Simple Spectral

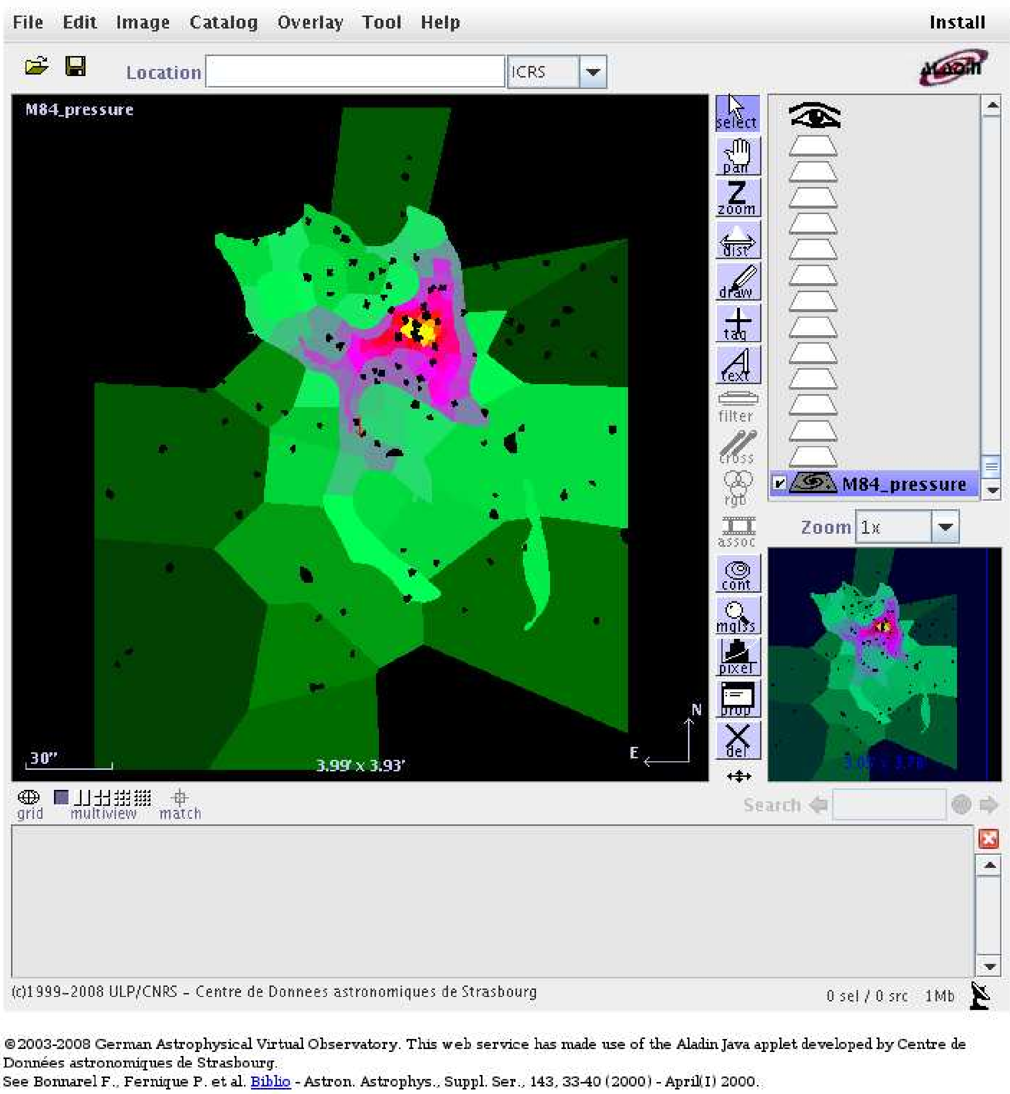


Fig. 4. Displaying the data content of MAXI page on M84 through Aladin.

Access Protocol (SSA) for the X-Ray spectra derived for each region. This is still challenging as X-Ray spectra require extra data products for their interpretation such as response matrices. In this case also the SSA metadata, in particular the characterization is an interesting problem.

3. Summary

A description of a new format of data release on extended astrophysical objects is presented. We have built tools allowing a user to select physical properties of interest and both download and examine those online. We believe that

Table 1. Data storage structure

columnName	displayName	unit	unit HTMLCode	dataType	col.Length	description	displayOrder
rowId	Row Id			int			1
regionId	Region Id			char	10	The number of the region ...	2
psFileURL	PS File			uri	200	The ps file showing the XMM spectrum ...	3
temperature	Temperature	keV	keV	DP		Best-fit temperature ...	4
temperatureError	Temperature Error	keV	keV	DP		The uncertainty in the temperature estimate ...	5
ironAbundance	Iron Abundance	f(solar)	f(solar)	DP		iron abundance, fraction of solar ...	6
ironAb.Error	Iron Abundance Error	f(solar)	f(solar)	DP		the uncertainty in the iron	7
normalization	Normalization	Xspec Units	Xspec Units	DP		$10^{-14}/(4\pi(D_A \times (1+z))^2) \int n_e n_H dV$ ...	8
norm.Error	Normalization Error	Xspec Units	Xspec Units	DP		the uncertainty in the normalization ...	9
pixelNumbers	Number of Pixels			int		number of pixels in the regions	10
reducedKaiSqr	Reduced Chi-Sqr			DP		χ^2 per degree of freedom	11
degreesOfFreedom	Degree of Freedom			int		number of degrees of freedom	12
gasMass	Gas Mass	Solar Mass	Solar Mass	DP		the total gas mass	13
gasMassError	Gas Mass Error	Solar Mass	Solar Mass	DP		the uncertainty in the gas mass	14
electronDensity	Electron Density	cm^{-3}	cm,#179	DP		the density of electrons in cm^{-3}.	15
el.DensityError	Electron Density Error	cm^{-3}	cm,#179	DP		electron density error.	16
entropy	Entropy	keV cm^2	keV cm,#178	DP		S_e electron entropy, kT_e/n_e	17
entropyError	Entropy Error	keV cm^2	keV cm,#178	DP		the uncertainty in the entropy	18
pressure	Pressure	dyne cm^{-2}	dyne/cm,#178	DP		dyne cm^{-2}.	19
pressureError	Pressure Error	dyne/cm-2	dyne/cm,#178	DP		the uncertainty in the pressure	20
minDist.ToCenter	Min Distance to Center	Mpc	Mpc	DP		the minimum distance	21
maxDist.ToCenter	Max Distance to Center	Mpc	Mpc	DP		the maximal distance	22

this archive will have an influence on both scientific exploration of the data as well as be a new way of public outreach, allowing a general public to have a closer look at mysteries of our Universe as well as include astronomical datasets into educational programs.

Acknowledgements. The authors thank Gerard Lemson for his continuous support of this project. AF is grateful to Guenther Hasinger for his constant encouragement and my coauthors on A3266 (in particular Uli Briel) and M84 (in particular Christine Jones) research topics for allowing him to present virtual observatory aspects of our joint research. AF acknowledges support from BMBF/DLR under grant 50 OR 0507. JWK works for the German Astrophysical Virtual Observatory (GAVO), which is supported by a grant of the German Federal Ministry o Education and Research (BMBF) under contract 05 AC6VHA.

References

Finoguenov, A., Henriksen, M. J., Miniati, F., Briel, U. G., & Jones, C. 2006, ApJ, 643, 790

Bonnarel F., Fernique P. et al. A&A SS, 143, 33 (2000)

Finoguenov, A., Ruszkowski, M., Jones, C., Brueggen, M., Vikhlinin, A., & Mandel, E. 2008, ApJ, 686, 911