A ROSAT HRI observation of the cooling flow cluster MS0839.9+2938

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Abstract. A ROSAT HRI observation of the cluster MS-0839.9+2938 at z=0.194 is presented. It confirms the earlier suggestion, based on the detection of extended Hα emission, that the inner regions of this cluster are dominated by a cooling flow. The surface brightness distribution within the cooling radius shows structures which can be interpreted as evidence of a highly inhomogeneous space distribution of the cooling process. We note that the brightness at the barycentre of its distribution, which falls right on top of the central giant elliptical galaxy, is lower than the peaks in the structures around: we suggest that this situation is likely to arise as a consequence of photoelectric absorption by cold gas within the cooling flow, with an equivalent column density in the order of 5×1021 cm−2 within ∼10″ from the centre.

Key words: Galaxies: clustering; cooling flows; Galaxies: clusters: individual: MS0839+2938

1. Introduction

The cluster MS0839+2938 was discovered as an extended X-ray source in the EINSTEIN Extended Medium Sensitivity Survey (Gioia et al. 1987, 1990). Subsequent optical and radio observations (Nesci et al. 1989) showed that the cluster is dominated by a giant elliptical, probably a cD type galaxy, which is characterized by an intense and extended Hα emission, and a compact, relatively weak radio emission. The redshift of this galaxy is z=0.193, and the cluster galaxy velocity dispersion along the line of sight, estimated on the basis of six redshifts, is 1500±700 km s−1. At the distance of 1200 Mpc (H0=50 km s−1 Mpc−1, q0 = 0.5), the X-ray luminosity in the 0.3-3.5 keV band was estimated to be about 4×1044 erg s−1.

Since a spatially extended optical line emission is present in several nearby cooling flow clusters, MS0839+2938 appeared to be one of the most distant candidate cooling flow cluster known at the epoch of the ROSAT launch. Strictly speaking, the identification of a cooling flow would require the detection in the X-ray emitting gas of a much lower temperature in the innermost regions than in the whole cluster. However, when this goal cannot be directly achieved, a cooling flow regime is generally regarded as proven if the central density, as derived from the cluster surface brightness distribution adopting the dominant cluster temperature, implies a cooling time definitely shorter than the Hubble time (see e.g. Arnaud 1988). The aim of our ROSAT observation was therefore to derive the density profile of MS0839+2938 and verify the existence of the cooling flow. Since the scale at the cluster distance is 4.13 kpc arcsec−1, in order to resolve the emission within the core radius we used the HRI instrument. This choice, however, implied the loss of temperature information. A detailed description of the satellite and its instruments can be found in the “ROSAT AO2 Call for Proposals” (MPE, 1991).

2. Data analysis

The pointed observation of the cluster MS0839 +2938 (image number WG800159H.N2) lasted 18879 live seconds and was performed on April 20-22, 1992. Besides the extended image of the cluster at the center of the field of view, a point source was also detected 4.7″ to the SW (32 net cts), corresponding to the star HD74076; this allowed us to check the zero point of the sky coordinates of our image and to overlay the X-ray onto the optical image of the cluster with the accuracy of ∼2″.

We determined the background level by measuring the counts in 32 adjacent squares with sides of 260″ all around the cluster in the central, 1600″ side square of the frame. The average count rate is 1.150×10−6 cts arcsec−2 s−1 (0.0217 cts arcsec−2), very near to the pre-flight expected value of 1.1×10−6 and to the value (1.25×10−6) found by Sarazin et al. (1992a) in their ROSAT HRI observation of 2A 0335+098. The standard deviation of the 32 measurements is fully consistent with the Poisson statistics. We also measured the background level in a ring 200″-280″ around the cluster center finding the same result.

3. X-ray morphology of the cluster

In order to evaluate the maximum extent out to which the cluster emission is detected, after background subtraction an isophotal map was obtained by smoothing the original data, binned in 1″×1″ pixels, through a Gaussian filter with σ =
The map is shown in Fig. 1, where the lowest contour corresponds to four times the background fluctuations: at this brightness level (0.005 cts arcsec$^{-2}$) the emission is elongated in the N-S direction, as the dominant galaxy, with a major axis of $\sim 5$ arcmin ($\sim 1200$ kpc). An approximately circular type of symmetry is evident in the less smoothed Fig. 2, obtained through a Gaussian filter with $\sigma = 8''$, which shows the emission to be centrally peaked, with the peak coinciding with the dominant galaxy, thus leading to a morphological classification as an XD cluster, according to the scheme proposed by Jones and Forman (1984).

**Fig. 1.** The X-ray map at low resolution after background subtraction. The isophotes are at levels of 0.0051, 0.0076, 0.0102, 0.0127, 0.0191, 0.0254, 0.0317, 0.0381, 0.0508 net cts arcsec$^{-2}$.

The isophotal map at high resolution (unbinned and smoothed with a Gaussian filter with $\sigma = 2''$) of the very central region is shown in Fig.3 overlaid onto an optical (R) image of the cluster (Nesci et al. 1989). This map shows that the brightness distribution in the central region is not smooth, but that it contains structures with sizes in the range of a few tens of kpc. The brightness contrast and the length scale of these structures are consistent, taking into account the blurring due the difference in distance, with those discovered with the ROSAT HRI in two relatively nearby cooling flow clusters, 2A0335+096 ($z=0.035$) and A2029 ($z=0.0767$) by Sarazin et al. (1992a, b). Given the limited count statistics, the details in the observed structures, such as their exact brightness excess, can be determined only with marginal significance, except for the bright and resolved blob located about 12'' to the South of the giant elliptical: the peak excess brightness of this blob is approximately equal to that of the surrounding diffuse emission, and the size is about 6'', or 24 kpc, across.

Another important morphological aspect is that the brightness, at the position of the giant elliptical galaxy, is lower than the peaks in the surrounding structures, while the radio position of the galaxy centre ($8^h 42^m 55.9^s$; $+29^\circ 27' 27''$ (Eq. 2000)) coincides within about 2'' with the barycentre of the overall X-ray emission. We shall return on these aspects in Sections 4 and 5.

As a side issue, we note that no X-rays were detected from the emission line galaxy (G27 in Nesci et al. 1989) with a very blue colour (V-R=0.42), located 68'' West of the dominant cluster galaxy and at a similar redshift ($z=0.186$).
4. Physical parameters

The radial profile of the brightness distribution, azimuthally averaged in steps of $10^\circ$, is given in Fig. 4. The profile beyond $50''$ ($\sim$200 kpc) can be well fitted with a power law of slope $s=-2.12\pm0.42$ at the 95% confidence level. This slope corresponds to a value for the $\beta$ parameter of the hydrostatic isothermal model (Cavaliere and Fusco-Femiano 1976) of $0.52\pm0.07$, similar to those found by Sarazin et al. (1992a,b) using the ROSAT HRI for 2A 0335+096 (0.55) and A2029 (0.61).

Fig. 4. The profile of the surface brightness $S$ azimuthally averaged in rings of $10^\circ$, as a function of radius $r$. The best fitting power-law profile beyond of $50''$ is shown as a solid line. Error bars represent the 68% confidence level in Poisson statistics.

The conversion from observed counts to physical flux requires an assumption for the X-ray emission spectrum of the cluster and an estimate of the absorption along the line of sight. For the plasma thermal spectrum we adopted the code by Mewe et al. (1985) with 0.3 solar abundance, a typical value for intracluster gas (Edge et al. 1991a), and folded it with the effective area of the ROSAT HRI. A correction was also applied to take into account the energy band shift due to the cluster redshift (k-correction), but this correction is very small with respect to that due to the galactic absorption. For the latter a hydrogen column density of $\log(N_H)=20.6$ was adopted, as in Nesci et al. (1989).

The gas temperature $T$ can be evaluated using the empirical correlation (Edge and Stewart 1991b) between $T$ and the radial velocity dispersion of the cluster galaxies. However, given the small number (6) of redshifts available, the dispersion estimate is subject to a large uncertainty related to projection, and possibly even contamination effects. We therefore preferred to adopt two rather different values of $kT$ (3 and 7 keV) and to check ‘a posteriori’ whether the derived bolometric cluster luminosity fits in the empirical luminosity-temperature relation (Edge and Stewart 1991a).

The absorption corrected flux within $120''$ from the cluster centre, in the band 0.1-2.4 keV, is $(2.45\pm0.11)\times10^{-12}$ erg cm$^{-2}$ s$^{-1}$ for $kT=7$ keV, and $(2.50\pm0.11)\times10^{-12}$ for $kT=3$ keV; these values are consistent with the estimate based on the EINSTEIN Observatory observation within the same radius. $(2.23\pm0.24)\times10^{-12}$ erg cm$^{-2}$ s$^{-1}$ rescaled to the ROSAT band. Within a radius of $200''$, which encircles the lowest contour of Fig. 1, and contains 948 net counts, the total flux is $(2.83\pm0.14)\times10^{-12}$ erg cm$^{-2}$ s$^{-1}$ for $kT=7$ keV, and $2.86\times10^{-12}$ for $kT=3$ keV. This corresponds to a luminosity in the ROSAT band of $4.8\times10^{44}$ erg s$^{-1}$ for the temperature range considered; the bolometric luminosity then is $1.25\times10^{45}$ erg s$^{-1}$ if kT=7 keV, or $7.5\times10^{44}$ erg s$^{-1}$ if kT=3 keV.

Edge and Stewart (1991a, their Fig. 11), showed that there exists a correlation between the temperature and the bolometric luminosity, whose normalization however depends on the value of the central density. As we shall presently see, the central density derived from the X-ray data is rather insensitive to which one of the two temperature values is adopted, and our cluster would belong to their subsample of objects with central density $>9\times10^{-3}$ cm$^{-3}$. With respect to their best fitting correlation line in the $kT$-$L_{bol}$ plane, this cluster falls to the right (its luminosity is too low) if $kT=7$ keV, to the left (its luminosity is too high) if $kT=3$ keV. The actual cluster temperature is therefore likely to be in this range. In the following we shall derive the relevant parameters for both cases.

The cluster one dimensional velocity dispersion expected from the derived value of $\beta$ is $\sim800$ km s$^{-1}$ for $kT=7$ keV and $\sim520$ km s$^{-1}$ for $kT=3$ keV. The estimate based on six redshifts and reported in Section 1 is marginally consistent with the first value, but it could be overestimated due to the contamination by a non-member object. After removing the most discrepant redshift we obtain a dispersion of $850$ ($\pm400$) km s$^{-1}$, quite consistent with either of the two values derived above.

From the observed surface brightness profile, assuming spherical symmetry and a constant temperature, it is possible to derive the density profile with a deprojection technique (see e.g. Arnaud 1988). To overcome numerical problems arising from the poor statistics on the points at large radii, we deprojected an analytical fit of the brightness profile. The most relevant resulting parameters, namely the central density $n_0$, the central cooling time $t_{co}$, the cooling radius $r_c$ (defined as the radius where the cooling time equals the Hubble time minus the look back time, that is $10^{10}$ years), are given in Table 1 for the two temperatures; the density profile is illustrated in Fig. 5.

| $kT$ (keV) | $n_0$ (cm$^{-3}$) | $t_{co}$ (Gyrs) | $r_c$ (kpc) | $M_{\mu,s}$ ($\leq0.5$ Mpc) |
|------------|-----------------|-----------------|------------|-----------------------------|
| 7          | 0.0170          | 3.96            | 70         | $1.1\times10^{13}$          |
| 3          | 0.0156          | 2.57            | 110        | $1.2\times10^{13}$          |

From this table it can be seen that the derived central density depends very weakly on the adopted temperature. Furthermore, no matter which one of the two temperature values is adopted, the central cooling time of MS0839+2938 is definitely lower than the Hubble time, so this cluster certainly contains a cooling flow. The mass flow rate within the cooling radius can be estimated from the relation $M = 0.4\mu m_H L_{bol}/(kT)$, where $\mu$ is the mean molecular gas weight, $L_{bol}$ is the bolometric X-ray luminosity within the cooling radius and $m_H$ is the
hydrogen mass. We derive \( \dot{M} = 130 \, M_\odot \, \text{y}^{-1} \) for \( kT=7 \, \text{keV} \) and \( \dot{M} = 280 \, M_\odot \, \text{y}^{-1} \) for \( kT=3 \, \text{keV} \).

It is noteworthy that the map in Fig. 3 is dominated by emission from the cooling flow region, hence the structures visible in the map lie within the cooling radius and are likely to be the result of inhomogeneities where the cooling process goes on more rapidly. By assuming that these structures are in pressure equilibrium with the surrounding medium, one can estimate their temperature and therefore their proper cooling time. Let us for instance consider the bright blob to the South of the central galaxy, and assume that it has a spherical configuration with radius 12 kpc and a filling factor equal one. By adopting a distance from the centre equal to the projected distance, from Fig. 5 one obtains the pressure term \( nT \); for an external temperature of 7 keV, it turns out that the observed excess counts in the blob require that the internal temperature be about 3.5 keV, and the internal density therefore be twice the external value. The cooling time in the blob is then about \( 2 \times 10^9 \) years, a factor of four shorter than that of the surrounding gas. The temperature would be lower, and the cooling time shorter, if the filling factor were less than unity.

![Fig. 5. The proton density profile \( n_p \) for \( kT=7 \, \text{keV} \). The position of the cooling radius \( r_c \) is marked. For \( kT=3 \, \text{keV} \) the density is lower by 0.04 dex.](image)

The last column in Table 1 gives the estimate of the gas mass within 0.5 Mpc, which is about \( 1.2 \times 10^{13} \, M_\odot \): in the Lbol-Mass plane (Edge and Stewart 1991a, their fig.7) this cluster falls close to the average cluster relation.

The total gravitational mass of the cluster within 0.5 Mpc, computed under the assumption of hydrostatic equilibrium (Fabricant et al. 1984), is \( 1.8 \times 10^{14} \, M_\odot \) for \( kT=7 \, \text{keV} \) and \( 7.5 \times 10^{13} \, M_\odot \) for \( kT=3 \, \text{keV} \).

5. Discussion

The ROSAT observation described in this paper demonstrates that the inner regions of the distant cluster MS0839.9+2938 are dominated by a cooling flow, and that, very much like what is observed in two relatively nearby clusters (Sarazin et al. 1992a, b), the space distribution of the cooling process is highly inhomogeneous.

Here we would like to address the question whether photoelectric absorption by cool gas within the cooling flow might be affecting the observed surface brightness distribution. White et al. (1992) present spectral evidence, based on EINSTEIN Observatory SSS data, that cold, X-ray absorbing gas is often present in cooling flows, with an equivalent \( N_\text{H} \) up to a few times \( 10^{21} \, \text{cm}^{-2} \): such a column density would significantly affect the ROSAT HRI counts. They argue on physical grounds that this gas is likely to be in the form of dense and small clouds. If these clouds are regarded as remnants of a cooling process which went on for \( 10^{10} \) years, even if the space distribution of their place of origin were highly inhomogeneous, it is quite conceivable that their present, cumulative distribution is a regular function of the radial distance from the centre. Therefore the associated absorption can hardly be responsible for the structures in the surface brightness observed within the cooling radius. On the other hand, as it was noted in Section 3, the brightness level at the barycentre of its distribution, where the central giant elliptical is located, is lower than the peaks in the surrounding structures. We suggest that this situation could be due to photoelectric absorption. In fact, a column density of \( 5 \times 10^{21} \, \text{cm}^{-2} \) would reduce the brightness in the ROSAT band by a factor of about 2 for \( kT \geq 2 \, \text{keV} \). A simple calculation shows that, if \( \dot{M} \) had remained constant over \( 10^{10} \) years, and all the cooled gas went into X-ray absorbing clouds, the \( N_\text{H} \) that one obtains if the clouds were uniformly distributed within the cooling radius, and with a covering factor of unity, is \( 7 \times 10^{21} \, \text{cm}^{-2} \). This value is a lower limit to that which would be obtained if the clouds were more realistically assumed to concentrate towards the centre. We conclude that a spectral imaging of the cluster will most probably reveal the presence of a strong absorption within \( 10^\circ \) or so from the centre, a goal achievable in the near future with the angular resolution of the AXAF satellite.

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