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FUSE search for 10^5–10^6 K gas in the rich clusters of galaxies Abell 2029 and Abell 3112

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Abstract. Recent Chandra and XMM X-ray observations of rich clusters of galaxies have shown that the amount of hot gas which is cooling below ~1 keV is generally more modest than previous estimates. Yet, the real level of the *cooling flows*, if any, remains to be clarified by making observations sensitive to different temperature ranges. As a follow-up of the *FUSE* observations reporting a positive detection of the O VI doublet at 1032, 1038 Å in the cluster of galaxies Abell 2597, which provided the first direct evidence for $\sim 3 \times 10^5$ K gas in a cluster of galaxies, we have carried out sensitive spectroscopy of two rich clusters, Abell 2029 and Abell 3112 ($z \sim 0.07$) located behind low HI columns. In neither of these clusters could we detect the O VI doublet, yielding fairly stringent limits of $\sim 27\ M_\odot\ \mathrm{yr}^{-1}$ (Abell 2029) and $\sim 25\ M_\odot\ \mathrm{yr}^{-1}$ (Abell 3112) to the cooling flow rates using the 10^5–10^6 K gas as a tracer. The non-detections support the emerging picture that the cooling-flow rates are much more modest than deduced from earlier X-ray observations.

Key words. ISM: lines and bands – galaxies: cooling flows – galaxies: clusters: individual: Abell 2029 – galaxies: clusters: individual: Abell 3112 – ultraviolet: galaxies

1. Introduction

The concept of cooling flows, arising from simple physical considerations applied to the X-ray data, has provided an important input to the models of galaxy formation (e.g., Fabian 1994; Mathews & Brighenti 2003). On the other hand, the expected outcome, often amounting to $\geq 10^{10}\ M_\odot$ of cooled gas inside the cores of many rich clusters, has been rather elusive, despite sensitive searches made in multiple wavebands (e.g., Donahue & Voit 2003, and references therein). Evidence does exist for some such cooler gas in the form of highly extended optical nebulosities seen in the cores of several cooling-flow clusters (e.g., Hu et al. 1985; Heckman 1985), or CO emission (Edge & Frayer 2003; Salomé & Combes 2003). However, the masses involved are tiny in comparison with the simple predictions of the cooling-flow rates. The most recent addition to this intrigue comes from the high resolution spectroscopic observations of several cooling flows with XMM-Newton and Chandra which have revealed a clear deficit of gas at ≤1 keV in comparison with the prediction of simple cooling-flow models (e.g., Peterson et al. 2001, 2003; Kaastra et al. 2001; Tamura et al. 2001). In this context, spectroscopic observations to search for the UV resonance lines of O VI 1032,1038 Å emission doublet, a reliable tracer of gas in the temperature range 10^5–10^6K, can play an important role. In fact, using the Far Ultraviolet Spectroscopic Explorer (*FUSE*), Oegerle et al. (2001) have reported a convincing detection of O VI λ1032 Å line emission from the core of the rich cluster Abell 2597, and have thus estimated a rate of $\sim 40\ M_\odot\ \mathrm{yr}^{-1}$ of intra-cluster medium (ICM) in this cluster cooling through $\sim 10^6$ K. This rate is only a third of the value inferred from the analysis of ROSAT data (Sarazin et al. 1995). For the other strong cooling-flow candidate, Abell 1795, the (*FUSE*) observations by Oegerle et al. (2001) placed an upper limit of 28 $M_\odot\ \mathrm{yr}^{-1}$ within the central 28 kpc region. It may be noted that the cD galaxies in the cores of both these clusters host twin-jet radio sources extending on a 100 kpc scale and having radio luminosities typical of cluster radio sources in the nearby universe. Also, no O VI has been detected by *FUSE* in the Virgo and Coma clusters (Dixon et al. 2001a).

Motivated by the above, partly successful attempt using *FUSE*, we have carried out fairly sensitive *FUSE* spectroscopy of another two nearby ($z \sim 0.07$) BM type I clusters of richness class 2, namely, Abell 2029 and Abell 3112. For both clusters, the then available estimates of the cooling-flow rates were mostly in excess of 300 $M_\odot\ \mathrm{yr}^{-1}$, based on ROSAT and/or ASCA data (Peres et al. 1998; Sarazin et al. 1998). A crucial advantage with these two clusters is the exceptionally low H I foreground columns (Table 1), which is an essential pre-requisite for undertaking a sensitive search in the far

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Table 1. Characteristics of Abell 2029 and Abell 3112 and parameters of the *FUSE* observations.

Cluster	α (2000)	δ (2000)	l (deg)	b (deg)	z	$\lambda_{\rm OVI(1032)}$ (Å)	$\lambda_{\rm OVI(1038)}$ (Å)	Exp. time (ks)
Abell 2029	15h10m56s	5°44′42″	6°.4752	50°.5463	0.0767	1111.1	1117.2	16
Abell 3112	3h17m58s	-44°14′17″	252°.9367	−56°.0790	0.0746	1108.9	1115.0	32

ultraviolet. In the meanwhile, based on progressively new X-ray observations, the derived properties of these clusters (like many others), such as cooling-flow rates and the radial profile of the ICM temperature, have undergone a sharp "evolution" (Sect. 2), making it desirable to employ independent observational probes for addressing this issue. We report here one such attempt, based on *FUSE* observations of the two clusters.

2. The two clusters Abell 2029 and Abell 3112

2.1. Abell 2029

Abell 2029, at a redshift $z = 0.0767$, is one of the most optically regular rich clusters known, dominated by a central cD galaxy (Dressler 1978). It is one of the brightest X-ray clusters (David et al. 1993), with a luminosity $L_X(2-10 \text{ keV}) = 1.1 \times 10^{45}\ h_{70}^{-2}$ erg/s (Lewis et al. 2002), an X-ray gas temperature of 9.4 keV (Castillo-Morales & Schindler 2003) and a regular structure in X-rays as well. Recently, Chandra observations have revealed a highly regular and smooth X-ray morphology without any excess emission near the center, as well as a radial increase in the temperature from $T \sim 3$ keV within the inner ~10 kpc to $T \sim 9$ keV near $r = 250$ kpc (Lewis et al. 2002). It is noteworthy that an opposite radial dependence had been found in earlier X-ray studies of this cluster, based on ASCA/ROSAT data (Sarazin et al. 1998; Irwin et al. 1989). In another study, based on an improved analysis of ASCA observations, White (2000) found consistency with no radial variation of temperature in this cluster. Chandra observations have provided no evidence for a cooling flow in this cluster and led to an estimated mass deposition rate of $0.0 \pm 0.7\ M_\odot\,\text{yr}^{-1}$ (Lewis et al. 2002), consistent with the trend revealed by XMM-Newton spectroscopy (Kaastra et al. 2001; Boehringer et al. 2002). Note that even though the Chandra measurement only refers to the central 5″ region, the value obtained after integrating over the cooling radius would still be very modest and well within the 1σ upper limit of $\dot{M} = 175\ M_\odot\,\text{yr}^{-1}$ deduced by White (2000). On the other hand, such estimates are in marked contrast to the large mass deposition rate of $\dot{M} \simeq 400$–$600\ M_\odot\,\text{yr}^{-1}$ (Edge et al. 1992; Peres et al. 1998), and to the somewhat lower value of $162^{+30}_{-26}\ M_\odot\,\text{yr}^{-1}$ estimated by Allen & Fabian (1997) using ROSAT data. However, it is in agreement with the upper limit on molecular hydrogen derived from CO observations by Salomé & Combes (2003). The radio source associated with the ultra-luminous central cD galaxy of Abell 2029 has a very steep radio spectrum ($\alpha = -1.5$ above ~100 MHz) and has been discussed in detail by Taylor et al. (1994). The two radio lobes exhibit a pronounced "wide-angle-tail (WAT)" morphology with an overall extent of at least 80 kpc ($H_0 = 50\ \text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ used throughout this paper). The compact central core has an inverted radio spectrum ($\alpha = +0.2$); the spectrum steepens to $\alpha = -2.7$ near the edges of the radio tails. From synchrotron ageing arguments, these authors estimated an age of 1.2×10^7 years. From the extremely large rotation measure values reached within ~10 kpc of the radio nucleus (|RM| up to 8000 rad m^{-2}) and from its observed distribution, Taylor et al. have also inferred an ICM magnetic field of $>0.2\ \mu$G, ordered on a scale of 20−100 kpc. Considering that the observed ultra-steep radio spectrum and very large rotation measure are both strongly suggestive of a cooling-flow environment (e.g., Taylor et al. 1994), the non-detection of [O II] emission and the absence of blue colors in the cluster core are surprising (cf. McNamara & O'Connell 1989). It is likewise intriguing that the source exhibits a clear WAT morphology, which is usually believed to be associated with the ICM winds resulting from an ongoing cluster merger (e.g., Loken et al. 1995; Roettiger et al. 1996), which is clearly at odds with the smooth and regular X-ray surface brightness distribution of this cluster (see Lewis et al. 2002).

2.2. Abell 3112

Abell 3112 is an optically regular cluster at $z = 0.0746$ showing no evidence for substructure (Biviano et al. 2002). It appears also quite smooth and dynamically relaxed in X-rays, with some distortions near the center. This Chandra image also shows an X-ray point source coincident with the cD and with the core of a powerful radio source (Takizawa et al. 2003).

In contrast to the image analyses of EXOSAT and ROSAT data which yielded mass deposition rates of ~400 $M_\odot\,\text{yr}^{-1}$ (Edge et al. 1992; Allen & Fabian 1997; Peres et al. 1998), a much smaller value of $44^{+52}_{-32}\ M_\odot\,\text{yr}^{-1}$ has been derived from Chandra data by Takizawa et al. (2003). The distortions seen near the center in the Chandra image probably signify a dynamical interaction between the ICM and the powerful radio source hosted by the central cD galaxy. The nuclear X-ray point source with a radio counterpart is characterized as a strongly absorbed AGN (Takizawa et al. 2003). Using these data, Takizawa et al. have further deduced a radially increasing temperature from ~2 keV at the center to ~6 keV near $r = 150$ kpc, in broad agreement with the ASCA result (White 2000). However, as in the case of Abell 2029, such a temperature gradient is in conflict with the trend inferred from ROSAT/ASCA data analyses (Markevitch et al. 1998; Irwin et al. 1989).

The large negative declination of the bright radio source PKS 0316−444 associated with the cD galaxy, has adversely affected the resolution of the VLA map (Takizawa et al. 2003). Nonetheless, the map shows a strong nuclear component and two sharply bent radio tails with an overall extent approaching 100 kpc, similar to the radio galaxy in Abell 2029. The integrated spectral index of this source is −0.8 above 100 MHz.

3. Observations and data analysis

Abell 2029 was observed on April 12, 2003 with *FUSE* through the LWRS aperture (30″ × 30″) for a total time of 16 ks (Program C0880201). Abell 3112 was observed for a total time of 32 ks on November 15 and 16, 2002 (Program C0880101 and C0880102; for an overview of *FUSE*, see Moos et al. 2000 and Sahnow et al. 2000). The data of both targets were reprocessed with the version 2.2 of the CALFUSE pipeline. The output of the pipeline is a total of 13 and 6 sub-exposures for Abell 3112 and Abell 2029, respectively. The sub-exposures have been aligned and co-added resulting in a set of four independent spectra, one for each *FUSE* channel (2 LiF spectra and 2 SiC spectra).

The resulting spectra are mainly composed of numerous terrestrial emission airglow lines, and O VI solar contamination (Sect. 6). Despite a very low background, we do not detect any continuum, nor any signature of either C III or O VI emissions from the clusters, or from their central cD galaxies. Thus, we derive an upper limit of the order of a few 10^{-15} erg cm^{-2} s^{-1} Å^{-1} for the continuum of each of the central galaxies. This non-detection of the far-UV continuum is not surprising for these old ellipticals at redshift ~0.075; a detection would require a large population of several thousands of O stars and a corresponding stellar formation rate of several solar masses per year. The continuum flux of the X-ray detected AGN in A3112 (Takizawa et al. 2003) is also far below the detection limit in the far-UV.

4. Results

We do not detect any emission from the O VI $\lambda\lambda$1032-1038 Å or C III λ977 Å lines from the central ~60 kpc regions of Abell 2029 and Abell 3112 (Figs. 1 and 2). By fitting the spectra to the sum of a first-order polynomial for the background and an emission line whose wavelength is defined by the cluster redshift, we obtained the upper limits to the emission intensities. The best-fit was always obtained for zero intensity of the emission line. The emission line profile is calculated by the convolution of a Gaussian with the instrumental response to a diffuse emission filling the full LWRS aperture, which is a "top-hat" function with a width of ~100 km s^{-1}. Using various values for the Gaussian *FWHM* between 0 and 200 km s^{-1}, we found that the estimated upper limit is not very sensitive to this width. The 3σ upper limits are calculated by searching for the intensity above which the χ^2 of the fit is increased by at least 9. We thus obtained the upper limit for the O VI line emission at 1032 Å: $I_{\rm Abell\,2029} \lesssim 5 \times 10^{-16}$ erg cm^{-2} s^{-1} and $I_{\rm Abell\,3112} \lesssim 4 \times 10^{-16}$ erg cm^{-2} s^{-1} (3σ).

The O VI doublet being the main coolant at $\sim 3 \times 10^5$ K, the O VI intensity is directly related to the cooling-flow rate through this temperature regime. The upper limits given above can thus be translated into upper limits to the cooling-flow

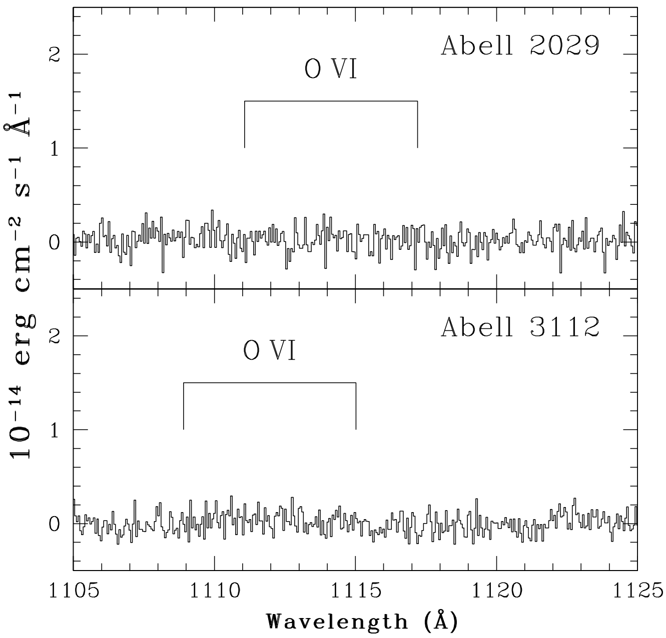

Fig. 1. The *FUSE* spectra in the region of the O VI doublet, with the expected positions of the two lines marked corresponding to the redshifts of Abell 2029 and Abell 3112 (z = 0.0767 and z = 0.0746, respectively).

rates. Using an intermediate case between isobaric and isochoric cooling, the luminosity of the line at 1032 Å is given by $L \approx 0.9 \times 10^{39}\ \dot{M}_\odot$ erg s^{-1}, where $\dot{M}_\odot$ is the mass flow rate in solar masses per year (Bregman et al. 2001; Oegerle et al. 2001). Assuming that the cooling flow is fully covered by the *FUSE* aperture, this gives the integrated line intensity within the *FUSE* aperture of $I = 2.2 \times 10^{-19}\ \dot{M}_\odot z^{-2}$ erg cm^{-2} s^{-1}, where z is the redshift of the corresponding cluster of galaxies.

Finally, the upper limit for the O VI line intensity must be corrected for interstellar extinction. This can be done using the published value of the HI column densities (Table 2). The observed upper limits for the mass deposition rates are calculated after correcting for the attenuation factor $AF \equiv I_{\rm corrected}/I_{\rm observed}$. Following the galactic extinction law as given by Savage & Mathis (1979), we assume that $AF \approx 10^{0.4A_\lambda}$, where $A_\lambda \approx 11.55\,E(B-V)$ at λ = 1110 Å and $E(B-V) \approx N({\rm H\,I})/4.8 \times 10^{21}$ cm^{-2}. This results in $(\log_{10} AF) \approx N({\rm H\,I})/10^{21}$ cm^{-2}. We thus obtain upper limits for the cooling flow rates of 27 and 25 $M_\odot$ yr^{-1} for Abell 2029 and Abell 3112, respectively (3σ upper limits).

Absorption by Galactic H_2 at the wavelengths of the O VI emission at the cluster redshifts could have been responsible for the non-detections in the two clusters. However, absorption by Galactic H_2 appears unlikely. Although at $z \sim 0.075$ O VI λ1032 Å falls within the H_2 v = 0–0 band, the closest lines are the $R(0)$ and $R(1)$ lines (λ_0 = 1108.14 Å and λ_0 = 1108.64 Å) for Abell 2029 and the $P(1)$ and $R(2)$ lines (λ_0 = 1110.07 Å and λ_0 = 1110.13 Å) for Abell 3112. Very large column densities would be required to obtain a significant absorption of the O VI emission at the cluster redshifts: $N(H_2, J = 1) \gtrsim 2 \times 10^{21}$ cm^{-2} and $N(H_2, J = 2) \gtrsim 10^{21}$ cm^{-2} for Abell 2029, and $N(H_2, J = 0) \gtrsim 10^{21}$ cm^{-2} and $N(H_2, J = 1) \gtrsim 2 \times 10^{20}$ cm^{-2} for

Table 2. Upper limits on the O VI λ1032 Å emission line and the corresponding mass flow rate.

Cluster	Size of aperture (kpc)	$N_{\rm HI}$ (10^{21} cm^{-2})	Attenuation[a] factor	I (1032 Å) (erg cm^{-2} s^{-1})	$\dot{M}$ ($M_\odot$ yr^{-1})
Abell 2029	67	0.31	2.0	$<5 \times 10^{-16}$	<27 (3σ)
Abell 3112	65	0.40	2.5	$<4 \times 10^{-16}$	<25 (3σ)

[a] Extinction at ~1100 Å.

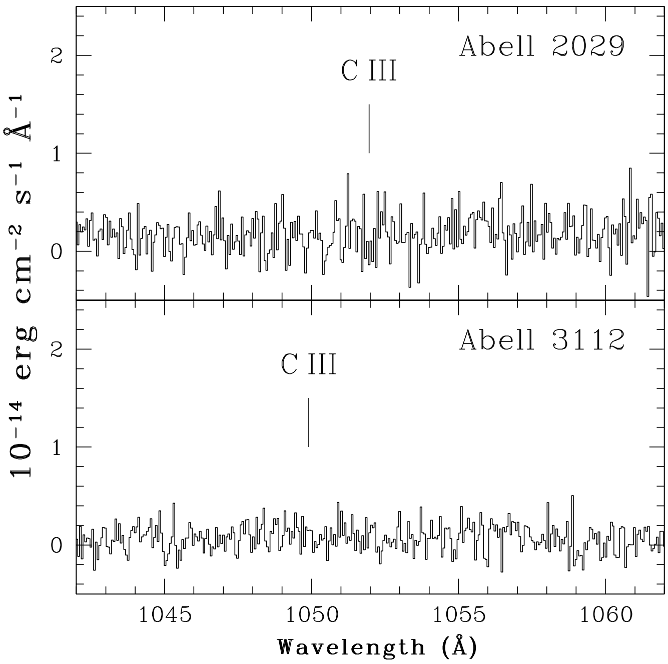

Fig. 2. Spectra of Abell 2029 and Abell 3112 in the region of the C III 977 Å line with the line position expected at the cluster redshifts. The C III line is not detected with an upper limit for the line intensity of ~10^{-15} erg cm^{-2} s^{-1}.

Abell 3112. These column densities are clearly excluded toward these directions with low H I column densities (Table 2).

In summary, we obtained an upper limit of close to ~25 $M_\odot$ yr^{-1} for the cooling-flow rates in both clusters, within their central ~60 kpc.

5. Discussion

The UV lines of the O VI $\lambda\lambda$1032–1038 Å doublet and/or of the C III λ977 Å line offer a new tool and independent method to place constraints on the cooling-flow rates in clusters of galaxies. The upper limits for the cooling flow rates in Abell 2029 and Abell 3112, derived here from the UV resonance lines of O VI $\lambda\lambda$1032–1038 Å are 10 to 20 times lower than those estimated earlier from ROSAT observations (Peres et al. 1998). The discrepancy may actually be somewhat smaller in view of the possibility that the cooling flow regions may have been covered only partially within the FUSE aperture. Moreover, the O VI lines may well be weakened due to scattering by dust within the cluster cores (see Oegerle et al. 2001). In any case, our upper limits are fully consistent with those derived recently for the mass deposition rates of the keV gas, using the Chandra and XMM-Newton observations of these clusters (Lewis et al. 2002; Takizawa et al. 2003; see Sect. 2). Thus, the present results indicate a general consistency for two separate temperature regimes of the cooling ICM in these clusters. Begelman & Fabian (1990) have discussed the possibility that the (1–3) × 10^5 K gas could be rapidly generated by turbulent mixing of the hot (10^7 K) and warm (10^4 K) phases. Thus, provided the intracluster magnetic fields do not effectively suppress the mixing process, the cooling may proceed too rapidly for a strong emission of the Fe XVII X-ray line. UV and X-ray observations therefore provide complementary information on the radiative processes within the intracluster medium.

It may also be noted that the upper limits deduced here for the O VI λ1032 Å line intensities from the two clusters are nearly half the intensity reported for Abell 2597 (Oegerle et al. 1991). Since the redshift of Abell 2597 is slightly larger than those of Abell 2029 and Abell 3112, and Galactic extinction is similar, it is clear that the O VI emission from these two clusters and their corresponding cooling rates through ~3 × 10^5 K are intrinsically lower as compared to Abell 2597.

6. O VI emission at rest-wavelength and the solar contamination

In the full spectrum of Abell 3112, obtained by combining the data from the SiC and LiF channels, we serendipitously discovered an O VI 1032–1038 Å emission doublet at zero radial velocity. Initially, we suspected this feature to originate from the interstellar medium in our Galaxy, similar to the detections reported towards a few other lines of sight (Shelton et al. 2001; Dixon et al. 2001b; Shelton 2002; Welsh et al. 2002; Otte et al. 2003). This hypothesis also seemed consistent with the levels of those detections being quite similar to the observed line intensities in our spectra: $I(\lambda1032$ Å) ~ 3460 ± 740 photons cm^{-2} s^{-1} sr^{-1} and $I(\lambda1038$ Å) ~ 2220 ± 990 photons cm^{-2} s^{-1} sr^{-1}. Moreover, the C III line at 1175.7 Å, which is often used as a signature of solar contamination, was not present in our spectra (see explanation below). However, a closer inspection of the spectra from the SiC and LiF channels revealed that the O VI doublet is only present in the SiC channels (Fig. 3). This is a clear signature of a solar contamination, rather than emission from Galactic ISM, due to the fact that the SiC mirrors are on the Sun-illuminated side of the spacecraft (Shelton et al. 2001). The absence of another known signature of solar contamination, the C III line at 1175.7 Å, can be readily understood by recalling that the SiC channels do not extend to the wavelength of this line. Clearly, this solar contamination must not be mistaken for Galactic emission. Thus, it

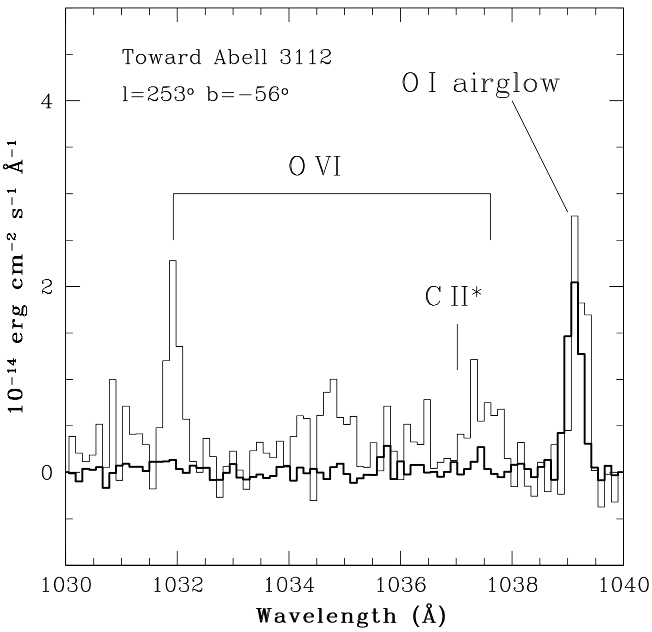

Fig. 3. Plot of the 1032−1038 Å O VI doublet, showing solar contamination (z = 0) during the observations of Abell 3112. The thin (thick) line shows the spectrum obtained by the co-addition of all SiC (LiF) data. The difference between these two spectra clearly shows that the SiC channels are affected by O VI Solar contamination.

follows that the O VI emission from the Galactic interstellar medium remains undetected in the directions of the two clusters.

7. Summary

The non-detection of the O VI $\lambda\lambda$1032−1038 Å and C III λ977 Å lines from the clusters Abell 2029 and Abell 3112, previously believed to have strong cooling-flow rates of several hundred $M_{\odot}\,\mathrm{yr}^{-1}$ adds to the growing independent evidence that the magnitude of cooling flows in the cores of clusters has been overestimated by at least an order of magnitude.

On a cautionary note we highlight the apparent detection of the O VI doublet at about zero radial velocity in the spectrum taken towards Abell 3112. The apparent emission almost perfectly mimics emission from the Galactic warm gas, similar to that already detected towards a few directions (e.g., Shelton et al. 2001). However, we argue that the O VI emission seen in the spectrum of Abell 3112, in fact, arises from Solar contamination.

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