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UV observations of the galaxy cluster Abell 1795 with the optical monitor on XMM-Newton*

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Abstract. We present the results of an analysis of broad band UV observations of the central regions of Abell 1795 observed with the optical monitor on XMM-Newton. As have been found with other UV observations of the central regions of clusters of galaxies, we find evidence for star formation. However, we also find evidence for absorption in the cD galaxy on a more extended scale than has been seen with optical imaging. We also report the first UV observation of part of the filamentary structure seen in H-α, X-rays and very deep U band imaging. The part of the filament we see is very blue with UV colours consistent with a very early (O/B) stellar population. This is the first direct evidence of a dominant population of early type stars at the centre of Abell 1795 and implies very recent star formation. The relationship of this emission to emission at other wavebands is discussed.

Key words: Galaxies: clusters: individual Abell 1795; Galaxies: stellar content; Ultraviolet: galaxies

1. Introduction

The final fate of material in the centre of cooling flow clusters remains a mystery. Perhaps the most obvious end point for matter cooling out of the cooling flow is in stars, and it is indeed true that the cD galaxies in cooling flow clusters often have anomalously blue optical colours (e.g. Allen 1995), implying higher rates of star formation than normal. There is also a reported correlation between the amplitude and radial extent of the colour anomalies and the inferred mass accretion rate from X-ray measurements (McNamara & O'Connell 1992). However, much of the observations of star formation in clusters of galaxies is based on optical measurements, and so crucial information about the emission from early type, and therefore young, stars is missing. Unfortunately, UV observations of the cores of cooling flow clusters, where the emission from early type stars would be strongest, are relatively sparse (e.g. A1795 Smith et al. 1999, CL 0939+4713 Buson et al. 1998).

The cD galaxy in Abell 1795 has been extensively studied and shows a number of remarkable features, including extended nuclear emission line gas (Cowie et al 1983; Hu, Cowie & Wang 1985; Heckman et al. 1989), an unusual blue continuum (Hu 1992; Allen 1995) and filamentary structure in X-rays (Fabian et al. 2000). These properties have made it one of the best candidates for star formation arising from a cooling flow. Previous UV studies with UIT (Smith et al. 1999) have shown the presence of emission from early type stars in the cD galaxy with data that were consistent with either continuous star formation or a recent (4 Myr) burst of star formation.

Here we report on new multi-filter UV observations of the central 8 arcminutes of the cooling flow cluster Abell 1795 taken as part of an XMM-Newton PV observation. Other aspects of the XMM-Newton observations will be discussed elsewhere (Tamura et al. 2001, Arnaud et al. 2001)

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2. OM data reduction

Abell 1795 was observed in the U (3000Å- 4000Å), UVW1 (2400Å- 3600Å), UVM2 (2000Å- 2600Å) and UVW2 (1800Å- 2400Å) filters (for more details of the optical monitor see Mason et al. 2001). The observations used the default configuration where the whole field of view is sampled using five individual exposures. Most of the field of view was sampled with 1 arcsecond pixels, but a small section (110 arcseconds by 110 arcseconds) of the central region of the field was continuously monitored at higher resolution (0.5 arcsecond pixels). This means different regions of the field of view have different total exposure times. The outer regions of the detector have the lower exposure times of U: 1.5 ksec, UVW1: 2.5 ksec, UVM2: 3.0 ksec, UVW2: 3.98 ksec. The central portions of the detector have longer exposure times of U: 7.5 ksec, UVW1: 12.5 ksec, UVM2: 15.0 ksec, UVW1: 19.9 ksec.

The data were processed using the SAS (v4.1) tasks written to analyse optical monitor data. To maximise the signal-to-noise we have summed all the data in a given detector window (area on the sky). This can be important in the UV where an individual exposure does not have enough counts to enable removal of mod-8 noise (see Mason et al. 2001). The sources were then detected on each individual window (using the SAS task OMDETECT). and the output sources lists where then edited by hand to remove sources caused by straylight in the OM (for details of instrumental artifacts see Mason et al. 2001). Further, sources whose background was strongly affected by straylight were re-extracted using an annular background estimate as a more robust method. This mainly affects the central few arcminutes of the field. In total, 284 sources were detected in the full 17x17 arcmin field of view and the count rates were then converted to instrumental magnitudes. The identification of the sources via correlation with catalogs and detailed galaxy data will be presented in a follow-up paper.

3. Results

3.1. Colour-colour plots

With our final sample of 284 sources we have constructed magnitude-colour and colour-colour plots (see Figure 1). In the plots we have discriminated between point like and extended sources, extended sources being determined from the FWHM derived from the source detection algorithm. Since the source detection routine does not supply errors on the shape parameters derived for each source we have looked at the distribution of the size of the major axis of the derived source ellipse. As the measured FWHM in the UV is approximately 3 arcseconds as a rough guide we have taken anything with a FWHM greater than 4 arcseconds as extended. Point like sources are shown as crosses and extended sources are shown with a diamond, Two objects of special interest are shown by other symbols. The cD galaxy is represented by the filled diamond, and the emission feature 20 arcseconds south of the cD galaxy is represented by a square (see section 3.2 and 3.3).

	UVW1 - UVW2	UVW1 - UVM2
B	0.454	0.628
A	0.141	0.409
F	0.405	0.018
G	-2.170	-1.294
K	-3.592	-2.674

Table 1. The OM far UV colours of different stellar types

The derived detection limits determined from the background in each observation for each filter were U = 21.67, UVW1 = 21.74, UVM2 = 20.89 and UVW2 = 20.22 (instrumental magnitudes). On the magnitude-colour plots the derived detection limits are shown as dashed lines and there is good agreement between the observed detection limits of the sources and the derived detection limits, showing that we are fairly complete down to our 6 sigma detection threshold.

The colour-colour plots show the range of UV colours exhibited by the sources. The majority of the sources lie on well defined lines and the lower three panels show the position in the colour-colour plots of different stellar types (taken from Pickles (1998)) as well as a typical field galaxy spectrum. For clarity, the far UV colours for different stellar types are also listed in table 1. All the spectra have been redshifted to the cluster redshift but do not include any correction for extinction: such a correction will redden the position of the different stellar types. Most of the objects lie on or near the loci defined by the change in stellar spectral type. Most of the point sources have the colours of F and G stars, and while it is unlikely that the extended sources will have single stellar like spectra, it at least allows an estimation of the dominant stellar type in the galaxies. As might be expected with the galaxies at the centre of Abell 1795, many of the extended sources have 'red' UV colours consistent with red galaxies. There are, however, a number of very blue points including a number of extended sources. The extended source seen at the extreme right in the UVW1-UVW2 and UVW1-UVM2 plot is a very bright galaxy affected by coincidence losses which affects the observed count rates (see Mason et al. 2001). The cD galaxy and its associated UV blob also lie to the extreme right of the colour-colour plots.

3.2. The cD galaxy

Figure 2 shows an image in sky coordinates of the cD galaxy taken in each of the four filters U, UVW1, UVM2, UVW2. In the U band the source shape is consistent with the data of McNamara & O'Connell (1993), with an ellipticity of 0.6 and position angle of 17 degrees. However, in detail there are likely to be problems with the scattered

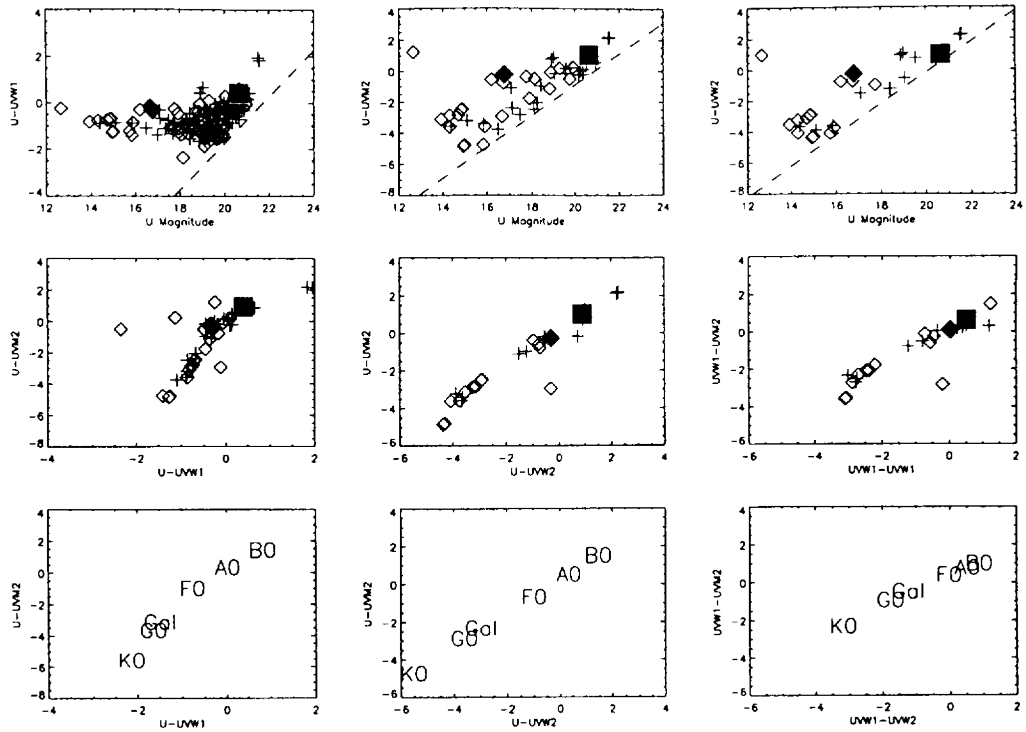

Fig. 1. The magnitude-colour plots and colour-colour plots for the Abell 1795 field. The top three panels show magnitude-colour plots together with the detection limits (dashed lines). The middle three panels show the colour-colour plots with the lower three panels showing the position of different stellar types in the colour-colour plane. Point-like sources are represented by crosses, extended sources are represented by open diamonds, and the cD galaxy and UV blob are showed as a filled diamond and square respectively.

light in OM which make the background subtraction a non trivial exercise, so direct comparisons of U band radial profiles are problematic. fortunately, the effect of this scattered light is strongly filter dependent and there are no serious background subtraction problems with the far UV filters.

Because we have colour data on the UV emission from the cD we can set limits on the dominant stellar type that may be responsible for the emission. Looking at figure 1 the filled diamond lies near the expected position of an A0 star. The emission is therefore not as blue as would be expected for emission dominated by B or O stars although if we remove the spectrum of an evolved population of stars (a spectrum of NGC 1399 normalised to the U filter) the effect on the far UV colours is small. If we make the assumption that all or most of the UVW2 emission (the bluest filter) arises from O stars (as was done by Smith et al. (1999)), then the estimated number of stars required to give the observed flux is approximately 12000. Note that the amount of contamination from an evolved stellar population in this filter is very small, less that 2%. This is in approximate agreement with the numbers of the O stars estimated by Smith et al. (1999) from UIT observations of this galaxy, where they estimated approximately 18000 O stars. However, given the fact that the colour of the cD galaxy is not that of a population of O stars, this estimate must be considered an upper limit.

One of the most striking features seen in the four filter images is a sharp discontinuity running north-source to the right of the cD galaxy centre which gets more apparent as the we go further into the UV. The only other UV image published on the central galaxy (Smith et al. 1999) also show a similar feature, although the spatial resolution of the data taken with the UIT was of the order of 6.8", about twice the nominal FWHM of OM in the UV filters ($\sim 3''$). Smith et al. explained this feature as due to the dust absorption seen in the HST data (Pinkney et al. 1996) but figure 2 shows that it appears on a larger scale than the dust lanes seen in the HST data.

There is also little evidence for the blue lobes tentatively associated with a radio jet (McNamara & O'Connell 1993), a fact which was also seen by Smith et al. (1999). However, it is likely that a more detailed analysis of the data is required to make a direct comparison, with galaxy models needing the be subtracted from the data as was done by McNamara & O'Connell (1993). It is also possible that the extinction seen in the far UV has masked the signal from the blue lobes.

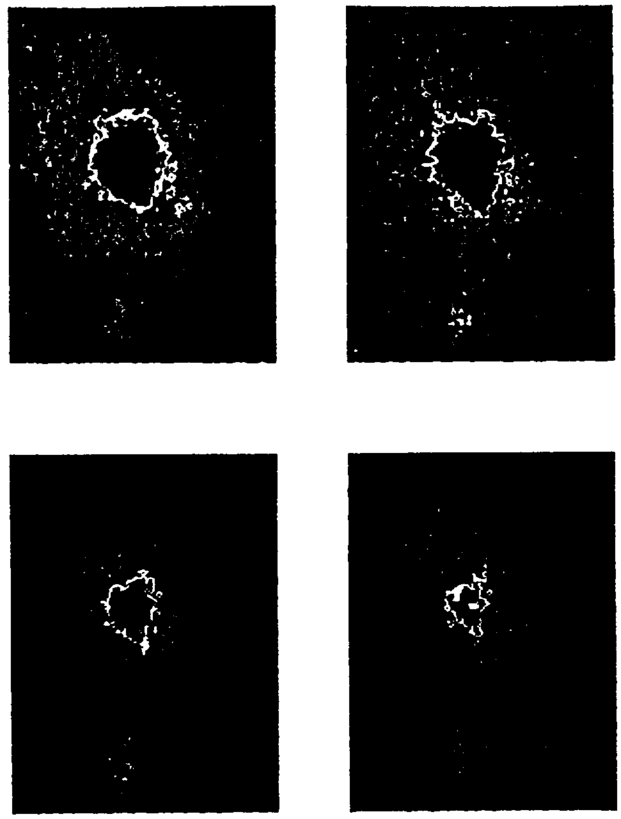

Fig. 2. The four images taken in (from top right to bottom left) U, UVW1, UVM2 and UVW2 filters of the central regions of the Abell 1795 cluster. The size of each image is 35 by 48 arcseconds. The cD galaxy is seen near the middle of each image, while the UV blob is seen 20 arcseconds to the south of the cD

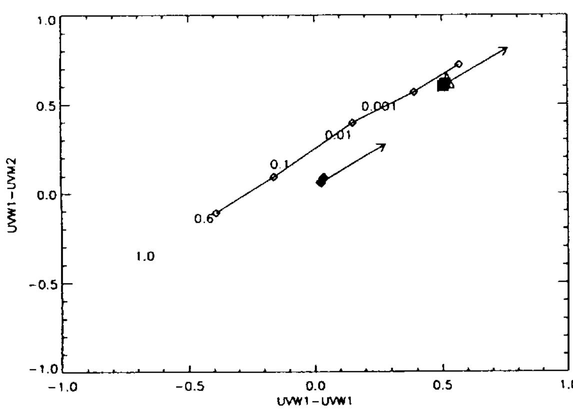

Fig. 3. Colour-colour plot showing the position of the UV blob and the cD galaxy together with the track of a single burst of star formation evolving with time and the open triangle shows where a 100 Myr continuous burst of star formation lies. The arrows show the effect of extinction up to an E(B-V) of 0.22 (Allen 1995). The UV blob is then consistent with with a burst of star formation that started between 1 and 5 million years ago, or continuous star formation.

3.3. *The UV blob*

On the colour-colour plots (Figure 1) the bluest extended source in the whole field lies just south of the cD galaxy. This object can be seen in figure 2 as a blob of very blue emission approximately 20 arcseconds south of the cD galaxy. Its approximate coordinates are R.A.: 13 48 52.8 DEC: +26 35 33 which is accurate to 2-3 arcseconds. However, the final astrometric calibrations are not yet available. This blob is almost certainly the same feature as blob E seen in McNamara et al (1996) and it is therefore likely that it is part of the same filamentary structures seen in the deep U band imaging of McNamara et al (1996). However, with the OM data we can, for the first time, get estimates of its UV colours. Unlike the case for the cD galaxy, the colours of the blob (the filled square) are much more consistent with an early star spectrum (B or O star), implying that star formation is more recent in this object. Indeed, the implication is that the blob is itself very recent, with little evidence for an evolved stellar population, and must be related to some recent occurrence or phenomena at the centre of Abell 1795.

Figure 3 shows the UVM2-UVW1, UVW2-UVW1 plan with the position of different star formation models taken from Bruzual & Charlot (1993). The models used were of a single burst of star formation with the different points on the plot corresponding to different ages after the burst of star formation. The open triangle corresponds to a constant star formation model with an age of 100 Myr and is also consistent with the data. Unfortunately on this plot variation in the timescale for constant star formation make little difference, since the data do not cover the red part of the spectrum where the difference is largest. Again we can estimate the number of O or B stars required to give the observed flux estimated as 1130 O stars or 4980 B stars. The implied UV luminosity from the O stars is then approximately 1.2×10^{43} ergs s^{-1}. Of course again this is an upper limit to the UV luminosity since it assumes only O stars contribute to the flux. From these numbers we can then estimate a star formation rate of $\sim 10 M_{\odot}$ yr^{-1} (assuming the IMF of Miller & Scalo (1979)). This is still much less than the mass deposition rate from analysis of previous X-ray data of $\sim 130 M_{\odot}$ yr^{-1} (Fabian et al. 1994, Tamura et al. 2001). However, extinction is very important in the UV. Hu (1992) estimated the intrinsic extinction to the filament as $E_{B-V} = 0.14$ but with a wide range of possible values ($0.02 < E_{B-V} < 0.22$). Allen (1995) has suggested that the value is closer to 0.22. Plotted on figure 3 are lines of extinction. However, an extinction of 0.22 would make the colour of the blob far too blue, but an E(B-V) of 0.14 will keep the colour within sensible limits. Such an extinction will increase the observed luminosities and therefore inferred star formation rates by a factor of 3, but still less than the X-ray rate.

There is a well known H-α filament to the south of the cD galaxy (e.g. Cowie, Hu, Jenkins and York 1983) which is aligned in a north south direction. This blob lies close to the peak of the H-α emission along the filament and so may be associated with it. However, comparing the relative fluxes makes it unlikely that these stars are solely responsible for the H-α emission. At the peak of the H-α emission the estimated flux was $\sim 2 \times 10^{-16}$ ergs cm^{-2} s^{-1} $arcsec^{-2}$ for the H-α + [N II] λ6568Å complex. The approximate total size of the UV blob is 20 $arcsec^2$ implying that the total H-α + [NII] emission associated with the blob is $\sim 4 \times 10^{-15}$ ergs cm^{-2} s^{-1} or a luminosity of 7×10^{40} ergs s^{-1}. Using the numbers quoted in Allen (1995) for the amount of H-α emission from a single O5 star ($\sim 6 \times 10^{36}$ ergs cm^{-2} s^{-1}) gives 5×10^{39} ergs s^{-1} for all the stars in the blob. If we include the effect of extinction we would increase the observed UV flux and therefore the estimated luminosity of H-α, which then becomes 1.5×10^{40} ergs cm^{-2} s^{-1}. This is still lower than the observed flux by a factor of four or so. Coupled with the fact that the estimation of the H-α emission can be considered to be only an upper limit, it seems unlikely that all the H-α emission can be powered by the observed UV flux seen in the OM data.

4. Discussion

4.1. The cD galaxy

As has been reported by Smith et al. (1999), UV data on the cD galaxy indicate that there is a population of young stars. However, the OM colours imply that the assumption of the far UV light being dominated by O/B stars is incorrect so any estimates of star populations and star formation rates based on UV limits quoted by Smith et al. (1999) are likely to be upper estimates, and would seem to imply that the total star formation rate in the cD galaxy is more likely to be nearer their lower limit of 8 $M_{\odot}$ yr^{-1}.

Further, in the UV, the cD galaxy appears to have quite a lot of structure with an apparent colour gradient across the galaxy together with a sharp discontinuity running north south seen in the far UV filters. The most likely explanation for the discontinuity is obscuration by dust or gas blocking out the UV emission in that area. An estimate of the E(B-V) required to remove the UVW2 emission is ~ 0.16, about twice that of the measured E(B-V) for the central portions of Abell 1795 as a whole. We therefore may be seeing obscuring material on much large scales than the reported dust lanes seen with HST data (Pinkey et al. 1996). While the resolution of OM is insufficient to make a direct link between the HST data and OM data, it is possible that the UV obscuration seen with OM is related to these dust lanes, since both the dust lanes and the UV absorption lie on the same side of the cD galaxy. The OM data may therefore be tracking dust or gas out to a larger radius than was possible with the HST data because the UV filters are uniquely sensitive to extinction.

4.2. The UV blob

The UV blob is potentially the most interesting object seen in the data. For a start it gives us the possibility of studying the star formation at the centre of a cooling flow cluster without the central cD galaxy getting in the way. The UV colours imply not only the presence of young stars, but there is no evidence of an evolved stellar population such as would be expected from an elliptical galaxy. It is therefore possible that the blob is the consequence of recent star formation alone, without a pre-existing stellar population. It is also located very close to, or within the filamentary structure seen in both H-α and deep U band imaging, although since the positions obtainable from OM at the present moment are somewhat uncertain an exact positional match is not possible. From the measurements discussed above it seem unlikely that all of the H-α emission is powered from the UV light seen in the OM data, with at least a factor of 4-5 discrepancy between the observed flux and that required for the H-α emission. However, some of the H-α emission may arise from shocked gas (e.g. Anton 1993) and it has been suggested that cooling material from the cooling flow could contribute to the ionising flux (e.g. Voit & Donahue 1990). It is also not clear from the OM data whether there is further UV emission along the tail since there is not sufficient signal-to-noise. The emission at the peak of the blob in the UVW2 filter is at about 1.8×10^{-3} counts s^{-1} $arcsec^{-1}$ or 7 σ above background so a factor of 2 decrease in flux would make it hard to see any residual emission. In the other filters, such as UVW1, the significances are greater but the scattered light component is also stronger making it impossible to be sure than any connecting emission is real.

There is also X-ray emission associated with the H-α filament which has been seen by Chandra (Fabian et al. 2000). Not only is there filamentary structure seen in X-rays but it also appears that the brightest point on the X-ray filament is coincident with the centroid of the overall X-ray emission. Comparison with the Chandra data then implies that the UV blob is also coincident with this point and so the UV blob is at or near the centre of the gravitational potential. At this location we might expect a general reservoir of matter which may be forming stars. On the other hand the cD galaxy appears offset relative to the centre gravitational well and observations have also shown that the cD galaxy does not appear to be at rest in the gravitational potential of the cluster but has a peculiar velocity of about 150 km s^{-1} (Oergle & Hill 1994). Therefore, it is likely that star formation has occurred very recently in this source (see figure 3) and that this star formation could have been triggered by the motion of the cD galaxy. If we include the effect of extinction the data implies that a single burst would have occurred only about 1 million years ago. The approximate minimum distance of the cD galaxy from the UV blob is approximately 24 kpc so the estimated average velocity is approximately 24000 km s^{-1}. However, such a high velocity is highly unlikely both dynamically and because such a high velocity is supersonic but no form of shock is seen. Therefore it would seem that a single burst of star formation triggered by the motion of the cD galaxy is unlikely.

If we were to assume as Fabian et al. (2000) have that the filament tracks the path of the cD galaxy and that it lies at an angle of 45 degrees to our line of sight, then the time since the cD galaxy was at the UV blob is of the order of 10^8 years. As shown in figure 3 constant star formation over this time can give the observed far UV colours. Therefore, while the initial burst of star formation could have be triggered by the motion of the cD galaxy, the star formation must have been maintained over a longer time. There must also be sufficient cold material to generate stars, perhaps generated by a cooling wake (e.g. David et al. 1994) or from the cooling flow itself. However, it must be kept in mind that the time it takes for material to cool out of the intercluster medium is $> 10^8$ years and with just the UV data presented here it is not possible to put constraints on the maximum timescale allowed for the continuous star formation models.

5. Conclusions

The XMM-Newton OM data have illustrated the usefulness of UV observations in studying populations of early type stars in clusters of galaxies. Such observations have allowed us to set constraints on models of star formation at the centre of Abell 1795 as well as the presence of extra extinction in the cD galaxy. We have also presented the first UV observations of emission from the filamentary structure seen in deep U band images and in H-α to the south of the cD galaxy. In particular the observations of the central regions of Abell 1795 the OM data has highlighted a population of early type stars located at or near the centre of the gravitational potential that is most likely the consequence of recent continuous star formation. There is little evidence of a dominant old stellar population, as would be expected from an elliptical galaxy. While the exact significance of this in terms of detailed models of material cooling out of the intercluster medium is not yet clear, these data should, in combination with optical/IR data, provide constraints on the timescale and rate of star formation from the intercluster medium itself.

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