Integral field spectroscopy of Hα emission in cooling flow cluster cores: disturbing the molecular gas reservoir

R. J. Wilman,† A. C. Edge and A. M. Swinbank
Department of Physics, University of Durham, South Road, Durham DH1 3LE

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ABSTRACT

We present optical integral field spectroscopy of the Hα-luminous (>10^{42} erg s^{-1}) central cluster galaxies in the cores of the cooling flow clusters A1664, A1835, A2204 and Zw8193. From the [NII]+Hα complex in these moderate resolution (70–150 km s^{-1}) spectra we derive 2D views of the distribution and kinematics of the emission-line gas, and further diagnostics from the [SII] and [OI] lines.

The Hα emission shows a variety of disturbed morphologies, ranging from smooth but distorted to clumpy and filamentary, with velocity gradients and splittings of several hundred km s^{-1} on spatial scales of 20 kpc or more. Despite the small sample size, there are some generic features. The most disturbed Hα emission appears to be associated with secondary galaxies within 10–20 kpc (projected) of the central galaxy and close in velocity to the Hα.

The global Hα kinematics match those of the CO(1–0) emission in single-dish data. The [N II]/Hα, [S II]/Hα and [OI]/Hα ratios vary little with position, local Hα surface brightness or between clusters.

We propose that the Hα and CO emission arise in molecular clouds heated by a starburst, and that the latter has been triggered by interaction with a secondary galaxy. Such CO emission is known to trace massive (>10^{10} M⊙) compact (<20 kpc) reservoirs of cool molecular gas, and it is plausible that an infalling galaxy would disturb this gas, distorting the Hα morphology and initiating widespread star formation. We also examine the role of cloud–cloud collisions in the undisturbed molecular gas reservoir, and suggest that they might be an important source of excitation for the emission-line gas in the cores of lower Hα luminosity clusters with less intense star formation.

Key words: galaxies: clusters: individual: A1664 – galaxies: clusters: individual: A1835 – galaxies: clusters: individual: A2204 – galaxies: clusters: individual: ZW8193 – cooling flows – intergalactic medium.

1 INTRODUCTION

In recent years our understanding of the X-ray cooling flow phenomenon in galaxy cluster cores has been revolutionized. Throughout most of the 1980s and 1990s, X-ray observations suggested that gas in the central 100 kpc is cooling out at rates of up to several hundred solar masses per year, but the lack of evidence for a reservoir of cooled gas led to heated debate (summarized by Fabian 1994) over this interpretation of the X-ray data. Results from XMM–Newton and Chandra have since led to a sharp downward revision in X-ray cooling rates (e.g. Schmidt, Allen & Fabian 2001) and also reveal a strong deficit of line emission from gas cooling below T_{cool}/3 (Peterson et al. 2003). The implication is that X-ray cooling is quenched, for which numerous mechanisms have been proposed, including: rapid mixing of hot and cold phases, inhomogeneously distributed metals in the intracluster medium (ICM) (Fabian et al. 2001, 2002); active galactic nucleus (AGN) heating by jets (Brüggen & Kaiser 2002) and sound waves (Fabian et al. 2003); thermal conduction of heat from the hotter outer parts of the cluster into the cooler core (Voigt et al. 2002); a significant relativistic cosmic ray component frozen into the thermal gas (Cen 2005); the release of gravitational energy from blobs of gas which detach from the bulk flow and fall directly into the core (Fabian 2003).

Concurrently, significant progress has been made in identifying cool gas and dust in cluster cores. Edge (2001) detected CO emission in the centres of 16 cooling flows, consistent with 10^9–10^{11.5} M⊙..
of H$_2$ at 20–40 K for a standard CO:H$_2$ conversion (see also Salomé & Combes 2003). These are roughly the masses expected, given the revised cooling rates and likely ages. Interferometry shows further that the CO emission is localized within the central few arcsec of the cluster (Edge & Frayer 2003; Salomé & Combes 2004). The frequent occurrence of smaller masses ($\sim 10^4–10^6$ M$_\odot$) of hot H$_2$ has also been established (e.g. Jaffe, Bremer & van der Werf 2001; Edge et al. 2002), and excitation analysis suggests that this hot H$_2$ is a high pressure, transiently heated component (Wilman et al. 2002). Both CO and H$_2$ emissions correlate well with the strength of the H$\alpha$ emission from ionized gas at 10$^4$ K, whose prevalence in these environments, often in the form of spectacular filaments, has long been known (e.g. Hu et al. 1983; Crawford et al. 1999). Despite the clear association between optical line emission and short central X-ray cooling times (Peres et al. 1998; Bauer et al. 2005), their physical relationship is ill-understood. Photoionization by the observed excess population of hot massive stars can energetically account for the H$\alpha$ luminosities in the most luminous systems (Allen 1995; Crawford et al. 1999). *Spitzer* MIPS photometry of 11 central cluster galaxies (CCGs) by Egami et al. (2006) also shows that the most H$\alpha$-luminous in their sample (A1835, A2390 and Zw3146) have prominent far-infrared thermal dust emission plausibly powered by star formation, two of them with $L_{IR} > 10^{11}$ L$_\odot$. At lower H$\alpha$ luminosities the picture is less clear: the tapping of energy from the ICM through turbulence (Crawford & Fabian 1992) and heat (Sparks et al. 2004) are just two mechanisms which have been invoked to explain the optical nebulosity in such systems.

In this paper, we present integral field spectroscopy of the ionized gas in the cores of four such clusters, A1664, A1835, A2204 and Zw8193. The principal aim is to obtain a full 2D view of the distribution and kinematics of the gas through high-resolution spectroscopy of the H$\alpha$+[N ii] emission line, with additional ionization information being gleaned from the [S ii] $\lambda\lambda 6717, 6731$ and [O i] $\lambda\lambda 6300, 6363$ lines where possible. These four CCGs all have H$\alpha$ luminosities exceeding 10$^{42}$ erg s$^{-1}$, making them four of the top six most H$\alpha$-luminous systems in the extensive CCG spectroscopic survey by Crawford et al. (1999). In this regime of H$\alpha$ luminosity, photoionization by a young stellar population can account energetically for the luminosity of the H$\alpha$ nebulosity (Allen 1995; Crawford et al. 1999). In addition to an analysis of the CCGs, we also present spectroscopy of other sources within the IFU field of view, including other cluster galaxies and (in the case of A2204) a serendipitous gravitationally lensed background galaxy. We first present results for the clusters individually and then summarize and interpret their generic features. Throughout the paper we assume a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$ and $\Omega_L = 0.7$ and all physical quantities quoted from other papers have been converted accordingly.

## 2 OBSERVATIONS AND DATA REDUCTION

### 2.1 VLT-VIMOS integral field spectroscopy

The observations of A1664, A1835 and A2204 were taken in service mode on 2003 April 11 with the integral field unit (IFU) of the Visible Multi-object Spectrograph (VIMOS) on UT3 of the 8.2-m Very Large Telescope (VLT) at ESO Paranal in Chile (for further information on VIMOS see LeFevre et al. 2003). They were among the first taken with the VIMOS IFU in open time. The IFU was operated in HR-red mode, offering a $27 \times 27$-arcsec$^2$ field of view covered by 1600 optical fibres of 0.67 arcsec diameter. The fibres are coupled to a microlens array to ensure near-continuous sky coverage. The field of view in this IFU mode is split into 4 quadrants of 400 fibres, three of which disperse the light with the HR-red grism over 6250–8700 Å, while the fourth quadrant employs the HR-orange grism spanning 5500–7450 Å. The dispersion and spectral resolution are approximately 0.6 Å pixel$^{-1}$ and 1.8 Å FWHM (full width at half-maximum), respectively. For each of the three targets a pair of 1670s exposures was taken, with a pointing dither of $(\Delta\alpha, \Delta\delta) = (-6$ arcsec, $-6$ arcsec) between them. The seeing was in the range 0.5–1 arcsec throughout. Table 1 provides an observation log.

The data were reduced on site at the National Institute for Astrophysics (INAF) in Milan using the VIMOS Interactive Pipeline and Graphical Interface (VIPGI) (Scodellaro et al. 2005) developed by the VIRMOS consortium. The raw 2D frames for each quadrant were bias-subtracted, and the spectra for the individual fibres were traced, extracted and flat-fielded. The pipeline wavelength calibration was affected by instrumental flexure in the time interval between science and calibration observations. The wavelength calibration was thus performed manually in IRAF using night-sky emission features, rebinning to a common dispersion of 0.6 Å pixel$^{-1}$. Using the mapping from detector to aperture fibre position, the four quadrants were united into a single 40 $\times$ 40 fibre data cube for each pointing, covering the wavelength range 5500–8740 Å (i.e. large enough to accommodate the wavelength range of the HR-red and HR-orange grisms). The raw data format is such that the centres of adjacent fibres are separated by 5 pixels on the detector whilst the light from each fibre covers 3 pixels FWHM. There is thus a small amount of fibre-to-fibre light leakage implying that the spectra of individual fibres will not be completely independent. However, since the seeing is comparable to the fibre size and we are chiefly concerned with diffuse extended emission, the effect is not considered important and no corrections for it were made.

Subtraction of the night-sky emission background was performed by fitting Gaussian profiles to a triplet of sky features at 7316, 7329 and 7341 Å in each fibre. This intensity information was used to correct for fibre-to-fibre transmission variations across the field of view, and then to create a night-sky emission spectrum from a source-free region which was then subtracted across the whole cube. Due to the use of different grisms, sky subtraction was performed separately for quadrants 1–3 and 4, respectively. For A1664 and A2204 the two dithered sky-subtracted data cubes for each target were then combined into a single data cube 49 $\times$ 49 fibres in size (33 $\times$ 33 arcsec$^2$). For A1835, only the second of the two pointings contains significant line emission, since the target was inadvertently placed too near the edge of the field of view. Flux calibration of the spectra was not performed, but comparison with published emission line slit fluxes (Crawford et al. 1999) suggests that H$\alpha$ emission is detected down to minimum surface brightness levels in the range $0.5–1.0 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$. Following the reduction of the raw data, all subsequent cube manipulation and emission-line analysis were performed within r IRAF.

| Target | z   | IFU  | Exposure time (s) | Seeing (arcsec) | Scale (kpc arcsec$^{-1}$) |
|--------|-----|------|-------------------|----------------|--------------------------|
| A1664  | 0.1276 | VIMOS | 3340             | 0.5–1.0         | 2.3                      |
| A1835  | 0.2523 | VIMOS | 3340             | 0.5–1.0         | 3.9                      |
| A2204  | 0.1514 | VIMOS | 3340             | 0.5–1.0         | 2.6                      |
| Zw8193 | 0.1825 | OASIS | 7200             | 0.8            | 3.1                      |
2.2. WHT-OASIS integral field spectroscopy

Observations of the redshifted \( \text{H} \alpha \) emission in Zw8193 were made with the OASIS IFU on the William Herschel Telescope (WHT) on La Palma on 2005 September 2 in 0.8 arcsec seeing and photometric conditions. We used the MR 807 filter which covers a wavelength range of 7690–8460 Å at a spectral resolution of \( \lambda / \Delta \lambda = 2020 \) (2.2 Å pixel\(^{-1}\)). The 7.4 \times 10.3-arcsec\(^2\) field of view was sampled contiguously with 0.26 arcsec fibres. The total integration time was 7200 s, split into 4 \times 30 min and each dithered by one IFU lenslet to account for bad pixels. For further information about the OASIS IFU at the WHT see Benn, Talbot & Bacon (2003).

The OASIS data were reduced using the XOASIS data reduction package (Rousset 1992) developed at CRAL (Lyon). The reduction steps include bias and dark subtraction, extraction of the spectra using an instrument model, wavelength calibration, cosmic ray rejection, low-frequency flat-fielding and sky-subtraction. The individual data cubes were then mosaicked (taking into account the small offsets between exposures) and resampled on to a common grid of 0.26 \times 0.26 arcsec\(^2\) to create the final data cube. The limiting emission-line surface brightness is comparable to that reached in the VIMOS observations. Line fitting to the OASIS data was performed by binning up 3 \times 3 pixel in order to better match the seeing.

3. A 1664

3.1. \text{H} \alpha morphology and kinematics

With an extinction-corrected \( \text{H} \alpha \) slit luminosity of \( 1.6 \times 10^{42} \) erg s\(^{-1}\), the central cluster galaxy of A1664 is among the brightest \( \text{H} \alpha \) emitters in the optical spectroscopic survey of the ROSAT Brightest Cluster Sample (BCS; Crawford et al. 1999); fits to the excess blue continuum light imply a visible star formation rate of 23 \( M_\odot \) yr\(^{-1}\) (see also Allen 1995).

The complexity of the line emission in A1664 is evident in the reduced 2D frame of one of the quadrants, shown in Fig. 1. The emission spans a large range in velocity and at many spatial locations two velocity components are required to satisfactorily model the \( \text{H} \alpha/\text{[N II]} \lambda \lambda 6548, 6584 \) profiles. Within each spatial pixel, the lines were fitted with zero, one or two \( 2 \text{H} \alpha/\text{[N II]} \lambda \lambda 6548, 6584 \) Gaussian velocity components atop a flat continuum level; within each velocity component the \( \text{H} \alpha/\text{[N II]} \lambda \lambda 6548, 6584 \) double ratio was fixed at the theoretical 1:3 ratio. A simple chi-squared fitting criterion was used to decide whether one, two or zero velocity components were fitted at each position. The complex was fitted within the wavelength range 7330–7450 Å (i.e. 200 dispersion bins) and the noise level was estimated from the spectrum in the wavelength range 6490–7500 Å. Chi-squared values were evaluated for fits with zero, one or two velocity components, \( \chi^2_0, \chi^2_1 \) and \( \chi^2_2 \), respectively. For \( \chi^2_1 - \chi^2_0 > 150 \), one velocity component was fitted; for \( \chi^2_2 - \chi^2_1 > 10 \), two components were deemed necessary. All fits were examined by eye to confirm whether they were reasonable and to remove spurious fits to obvious noise spikes.

Fig. 2 shows the \( \text{H} \alpha \) and continuum maps derived from these emission-line fits. For clarity, three separate \( \text{H} \alpha \) maps are shown: the total flux (i.e. all the \( \text{H} \alpha \) emission), and the separate red and blue component fluxes for those pixels fitted with two \( \text{H} \alpha \) velocity components. The velocity and FWHM fields derived from these fits are shown in Fig. 3, and for clarity are again shown separately for the red and blue components where two components are required, and for those regions where only a single velocity component is needed. Line-profile fits are shown in Fig. 4 for selected regions of \( \text{H} \alpha \) emission in Fig. 2. From Fig. 2, we see that the \( \text{H} \alpha \) emission has a linear filamentary structure spanning approximately 13 arcsec (31 kpc) and passing through the nucleus of the central cluster galaxy along a NE–SW axis. Two velocity components are detected along its whole length: the red component peaks on the nucleus of the CCG, but the blue component exhibits two maxima (labelled B1 and B2) located approximately 1.5 arcsec from the nucleus, along an axis perpendicular to the general direction of the filament. This filament and nuclear bipolar structure are discussed further below.

3.2. The 30-kpc \text{H} \alpha filament and nuclear bipolar structure

The presence of two velocity components along the length of the filament (most clearly at its NE end where complications from the
nuclear emission of the CCG are minimal) suggests that it might be due to a disturbed secondary emission component superimposed on a quiescent background, or a stream of gas wrapped around the CCG, or possibly related to some form of outflow. It is plausibly related to the galaxy (object #1) situated just beyond the SW extremity of the filament in Fig. 2, which is confirmed to be at the cluster redshift (see Fig. 5) with a line of sight velocity of $-560 \text{ km s}^{-1}$ in the velocity system adopted in Fig. 3. This gas may have been stripped from or disturbed by object #1. Indeed, the velocity of the blue emission component at position B2 ($-450 \text{ km s}^{-1}$) is similar to that of object #1 ($-560 \text{ km s}^{-1}$).

The bipolar structure may instead be an outflow from the CCG driven by starburst activity. The line of sight velocity difference between the blue emission components at B1 and B2 is $\sim 350 \text{ km s}^{-1}$. This suggests a minimum deprojected outflow velocity of $175 \text{ km s}^{-1}$, but the symmetrical location of B1 and B2 about the nucleus suggests that the outflow may be principally directed into the plane of the sky with a much higher velocity. In the latter case, the observed radial extent of the outflow (1.5 arcsec = 3.5 kpc) can be used to constrain its age. Assuming a deprojected outflow speed of $600 \text{ km s}^{-1}$ as for the H$\alpha$ filaments in M82 (Shopbell & Bland-Hawthorn 1998), the implied age is $\sim 6 \text{ Myr}$. By contrast, the orbital time-scale of galaxy #1 responsible for the creation of the filament is $\sim 100 \text{ Myr}$ (assuming a circular orbit of radius 15 kpc traversed at $500 \text{ km s}^{-1}$). Considering the mismatch in these time-scales, it is too coincidental that an outflow from a nuclear starburst triggered by the passage of galaxy #1 should be observed to have a similar extent to the overall stream of gas. We thus favour an interpretation in which the complex H$\alpha$ structure is due to a disturbance induced by, or the stripping of gas from, galaxy #1.

### 3.3 Archival VLT-FORS1 V, R and I imaging

To shed further light on the origin of the complex H$\alpha$ distribution, we retrieved archival VLT-FORS1 imaging of A1664. The data set comprises images three 330 second exposures taken through the V, R and I filters (Bessel photometric system) on 2001 May 29 in photometric conditions and 0.8 arcsec seeing. Following bias-subtraction and flat-fielding, we merged them into a true-colour image which is displayed in Fig. 6. H$\alpha$ contours from the VIMOS IFU observations were aligned and overlaid on this image.

The main features apparent from Fig. 6 are the following: (i) the north-eastern quadrant of the CCG is redder than other parts of the CCG, suggesting dust obscuration; (ii) the south-western quadrant of the CCG is bluer than other cluster galaxies, suggesting more recent star formation; (iii) the red H$\alpha$ velocity component peaks on a nuclear dust lane which bisects the two central peaks of the blue H$\alpha$ velocity component; (iv) the southern extension of the H$\alpha$ emission (labelled B4 in Fig. 2) coincides with a blue knot of continuum emission.

$V - R$ and $R - I$ colours (expressed relative to the colours of the nearest A1664 cluster ellipticals) were extracted for regions B1, B2, B4 and object #1 in Fig. 2. These show that (i) galaxy #1 has the same colour as other cluster ellipticals at this redshift; (ii) the CCG is $\geq 0.1 \text{ mag bluer}$ in $V - R$ and $\geq 0.1 \text{ mag redder}$ in $R - I$ and that the intrinsic dust extinction increases across it from south-west to north-east. From long-slit spectra, the intrinsic extinction inferred from the Balmer decrement is in the range 0.46--0.63 mag (Allen 1995; Crawford et al. 1999). Corrected for this extinction, the same authors show that approximately 90 per cent of the (rest-frame) 4500 Å continuum is due to O5 and B5 stars giving rise...
to the $23\,M_\odot\,yr^{-1}$ starburst. The gradient of increasing dust extinction from south-west to north-east could be due to the gradient in time elapsed since the passage of galaxy #1, which may have triggered star formation and dust production. $U$- or $B$-band imaging would more clearly show the distribution of recent star formation.

3.4 Ionization properties

Although the VIMOS data contain the emission lines of [S II] $\lambda\lambda 6717, 6731$ and [O I] $\lambda\lambda 6300, 6363$ in addition to [N II]+H$\alpha$, we do not present an exhaustive study of the ionization properties of the gas. Instead, we impose the kinematics found for [N II]+H$\alpha$ and accordingly fit the [S II] and [O I] doublets with zero, one or two velocity components with only the line intensities allowed to vary, i.e. we do not search for emission in these lines where there is no [N II]+H$\alpha$ detection. In so doing, we discover that the ionization properties of the H$\alpha$ gas are quite uniform, with no notable spatial gradients. In Fig. 7 we show scatter plots of line ratios versus H$\alpha$ flux for the combined sample of lenslets. There is essentially no variation in [N II]$\lambda 6584$/H$\alpha$ and [O I]$\lambda 6300$/H$\alpha$ over more than one decade in H$\alpha$ surface brightness. These line ratios are consistent with the integrated slit values found by Crawford et al. (1999). The uniformity of the ionization state across the source supports our interpretation that all the gas (the filament and the B1/B2 nuclear structure) has the same origin. For comparison, the emission-line filaments in the kpc-scale superwind outflow in M82 have [N II]$\lambda 6584$/H$\alpha = 0.3$–$0.6$ (Shopbell & Bland-Hawthorn 1998).

3.5 Comparison with CO and H$_2$ observations

In the CO line survey of cooling flow CCGs by Edge (2001), A1664 exhibits unusually broad CO(1–0) emission spanning $620\,km\,s^{-1}$.
Figure 4. Fits to the Hα+[N II] complex in A1664 for the regions labelled in Fig. 2. The two velocity components are shown in red and blue and the green line denotes their sum. Spikes adjacent to the B3 profile are sky emission feature residuals.

Figure 5. The spectrum of continuum object #1 in Fig. 2. The absorption feature due to the Na D λ 5892.5 blend is labelled, from which a redshift of $z = 0.1255$ is determined. The feature at 6860–6880 Å is telluric absorption.

Figure 6. Left-hand panel: true-colour image of A1664 derived from archival VLT-FORS1 V, R and I imaging. Middle panel: overlaid with contours of the red Hα velocity component of Fig. 2. Right-hand panel: overlaid with contours of the blue Hα velocity component.
Figure 7. Ionization diagnostic line ratios plotted as a function of Hα flux for individual fibres in A1664. Results are shown separately for the red and blue velocity components (where fitted), and also for fibres where a single velocity component was fitted.

Figure 8. The Hα and CO(1–0) emission-line profiles integrated over comparable areas of A1664. The CO(1–0) is derived from the IRAM 30-m observation by Edge (2001) with a 23.5 arcsec beam size (the solid and dashed lines show measurements with different correlators). The Hα profile was constructed by summing over the whole source and using the multi-component Gaussian fits to the Hα+[N II] complex – the solid shows all the emission, whilst the dotted and dashed line show the contributions from fibres requiring one and two velocity components, respectively. Velocities are with respect to the nominal cluster redshift of z = 0.1276.

For comparison, in the K-band United Kingdom Infrared Telescope (UKIRT) CGS4 spectrum of Edge et al. (2002), the width of the Paα line is ∼1100 km s⁻¹ FWHM, for a N–S slit of 5.5 × 1.2 arcsec. This is consistent with the observed Hα kinematics when the VIMOS data are extracted over the same area and fitted with a single velocity component. In contrast, the H₂ v = 1–0 S(3) line is not resolved, suggesting an intrinsic width much below the instrumental broadening of 570 km s⁻¹ FWHM. This suggests that the hot H₂ is distinct from the CO and Hα-emitting gas in the case of A1664.

3.6 Cluster X-ray emission

A1664 has been observed with the ACIS-S instrument on the Chandra X-ray observatory for 10 ks. In Fig. 9 we show the smoothed 0.5–5 keV image (courtesy of A. C. Fabian). This shows that the X-ray emission is also elongated along a NE–SW axis with a possible filamentary structure, resembling the Hα emission but on a much larger spatial scale. A full analysis of the X-ray data set will be presented elsewhere. The observed similarity in Hα and X-ray morphology is analogous to that seen in the core of A1795 (Crawford, Fabian & Sanders 2005), although in that cluster the emission-line gas in the filament is very quiescent, in stark contrast to the case of A1664. As Fig. 9 demonstrates, the small neighbour galaxy of the CCG (labelled object #1 in Fig. 2) appears to coincide with a local minimum in the X-ray emission.
4 A1835

At a redshift of $z = 0.2523$, A1835 is the most distant cluster presented in this study. It is also our most luminous Hα emitter, with an extinction-corrected luminosity of $3 \times 10^{12}$ erg s$^{-1}$ and a visible star formation rate of $\sim 100$ M$_\odot$ yr$^{-1}$ (Allen 1995; Crawford et al. 1999). The Spitzer MIPS photometry of Egami et al. (2006) reveal far-infrared thermal dust emission with $L_{\text{IR}} = 7 \times 10^{11}$ L$_\odot$, plausibly powered by star formation. In the X-rays, the cluster is the most luminous in the ROSAT BCS and subsequent Chandra data are consistent with a young ($6 \times 10^8$ yr) cooling flow operating within $r = 30$ kpc (Schmidt et al. 2001).

In comparison with A1664 the kinematics are simple and relatively quiescent, requiring a single velocity component at each position. The Hα map and velocity field are shown in Fig. 10. The Hα emission has a maximum extent of 8 arcsec (31 kpc) and is elongated in a NW–SE direction; the reconstructed continuum image shows a small companion galaxy 5 arcsec (20 kpc) north-west of the CCG. The emission velocity exhibits a shear of $\sim 250$ km s$^{-1}$ along the same axis, possible due to rotation, with linewidths of $\sim 250$ km s$^{-1}$ FWHM.

As for A1664, the [N II]+Hα kinematic fits were used to search for associated emission in [S II] $\lambda\lambda 6717, 6731$. Unfortunately, the emission in [O I] $\lambda\lambda 6300, 6363$ is badly affected by night sky emission-line features and was not analysed. Line ratios as a function of local Hα flux are shown in Fig. 11, but the only firm conclusion that can be drawn is that the [N II]/Hα is once again remarkably constant with luminosity and consistent with the integrated slit value measured by Crawford et al. (1999). The [S II] $\lambda\lambda 6717/6731$ ratio shows marginal evidence for an increase with Hα surface brightness, implying higher electron density as hinted at in A1664.

A comparison with the CO emission is once again valuable. The IRAM 30-m single-dish observation of Edge (2001) shows CO(1–0) from an inferred cool molecular mass of $1.8 \pm 0.2 \times 10^{11}$ M$_\odot$. The CO emission peaks at a velocity of $-100$ km s$^{-1}$ (relative to an assumed redshift of $z = 0.2523$), identical to that of the Hα emission peak. The CO linewidth of $227 \pm 38$ km s$^{-1}$ FWHM is again a close match to the Hα. Subsequent Owen Valley Millimetre Array interferometry of the CO(1–0) emission constrains the angular extent of the CO to $<9$ arcsec (36 kpc). It thus appears that, as in A1664, the CO and Hα emission share the same kinematics and morphology.

5 A2204

Abell 2204 lies at $z = 0.1514$ and has an observed Hα slit luminosity of $10^{12}$ erg s$^{-1}$ (uncorrected for reddening), although the inferred visible star formation rate is modest ($\sim 1$ M$_\odot$ yr$^{-1}$ Crawford et al. 1999). The system is also a strong emitter of near-infrared H$_2$ vibrational emission (Edge et al. 2002), and the CO(1–0) emission from IRAM 30-m observations implies a molecular gas mass of $2.3 \pm 0.6 \times 10^{10}$ M$_\odot$ (Edge 2001). Chandra X-ray observations reveal that the cluster has a disturbed core morphology, suggestive of a recent merger, with cold fronts at radii of $\sim 28$ and 54.5 kpc, and the central radio source is also disturbed with three components within 10 arcsec, aligned roughly N–S (Sanders, Fabian & Taylor 2005).

Results from the VIMOS data in Hα and the continuum are shown in Fig. 12, along with a Hubble Space Telescope (HST) WFPC2 F606W (wide V-band) continuum image. The latter shows that the CCG is dusty and possibly interacting with galaxy #1, which lies 15 kpc away in projection at a relative velocity of 250 km s$^{-1}$ (see Jenner 1974 and Section 5.1). The Hα emission also has an irregular morphology with a number of filaments emanating from the nuclear...
5.2 The gravitationally lensed background galaxy

The HST image of the cluster in Fig. 12 exhibits a gravitationally lensed arc which terminates on a bright knot of emission which we refer to as object #4. The VIMOS data show [O ii] λ3726, 3729 emission in 11 fibres across this position which, with a redshift of z = 1.0604, we identify as the lensed background galaxy. Fig. 16 shows the portion of the calibrated 2D spectral frame in which this emission was discovered, together with the reconstructed emission-line image. The line is just at the edge of the 7600–7700 Å telluric absorption, for which we correct with the aid of the stellar continuum spectrum of object #3. Line emission is present along the full length of the arc as defined by the HST image. The total [O ii] flux from it is estimated to be 7.2 × 10^{-16} erg cm^{-2} s^{-1}, a figure obtained by comparing our Hα measurements of the CCG with the slit flux in Crawford et al. (1999). The velocity of the emission varies by less than ±20 km s^{-1}, and the linewidth is the range 100–150 km s^{-1} FWHM. This lensed arc would be suitable for a follow-up with a longer IFU observation at higher spatial resolution, possibly with adaptive optics due to the proximity of the moderately bright star #3 (R = 15.3; B = 16.5 mag).

6 ZW 8193

The core of Zw 8193 is complex in both space and velocity and initial optical spectroscopy of this cluster yielded discrepant redshifts for the emission-line (z = 0.1829 ± 0.0001) and absorption-line (z = 0.1725 ± 0.0001) components (Allen et al. 1992). Fig. 17 shows that there are three galaxies within 2–3 arcsec of the CCG; UKIRT long-slit spectroscopy revealed Paα emission in and between the CCG and its neighbour to the north, with an apparent velocity difference of 400–500 km s^{-1} (Edge et al. 2002). The benefit of higher spatial and spectral resolution OASIS IFU data now reveals the full complexity of the system. The Hα emission consists of three distinct ‘blobs’, one centred on the CCG, one on a galaxy to the north and one slightly offset from the latter to the west. The velocity ranges over ±250 km s^{-1} (relative to α = 0.1825) and reconstrcuting the placement of the 1.2 arcsec wide N–S slit used for the UKIRT observations shows the consistency of the Paα and Hα velocity fields. The [N ii]/Hα ratio varies from 0.9 on the CCG to 0.7 at the position of the northern blobs. The ratio [S ii]λ6717/Hα ≃ 0.5 and is also relatively constant across the emission. The [S ii]λ6731 line is badly affected by a night-sky emission line. The extinction-corrected Hα slit luminosity quoted by Crawford et al. (1999) is 3.1 × 10^{42} erg s^{-1} (converted to the cosmology used here).

The CO(1–0) observations of Zw 8193 have yielded seemingly inconsistent results (Edge 2001). One observation revealed a broad plateau of emission from v = −100 to v = +500 km s^{-1} but a subsequent observation failed to confirm it. As remarked by Edge (2001), the presence of a flat-spectrum radio source in Zw 8193 complicates the baseline subtraction. The quoted upper limit on the molecular gas mass is 4.3 × 10^{10} M_⊙.

As in A1664, and to a lesser extent A2204, the Hα emission morphology and kinematics appear to be influenced by the close passage of a small cluster galaxy into the core.

7 SUMMARY OF OBSERVATIONAL RESULTS

Despite the diversity and complexity of these individual clusters and the small sample size, a number of generic features are apparent. They are as follows.
A possible association between disturbed Hα emission and secondary galaxies within 10–20 kpc. In A1664, it appears plausible on both morphological and kinematic grounds that the Hα filament and complex nuclear structure in the CCG have been produced by the infall of a small cluster galaxy. This galaxy is now visible at the extremity of the filament. Since the mass of Hα-emitting ionized gas is relatively small (a few $10^7 M_\odot$, as inferred from the Hα luminosity and the measured electron density), it is possible that a significant fraction of it may have been stripped from the infalling galaxy. Our preferred interpretation, discussed in Section 8, is that the gas distribution has been disturbed by the infalling galaxy. In Zw8193, there is extended Hα emission associated with a galaxy which lies within 6 kpc (projected) of the CCG. In A2204, the irregular Hα kinematics may result from a recent interaction with a nearby galaxy (#1 in Fig. 12), or disturbance from the irregular radio source. In A1835, the Hα emission is elongated in the direction of a small companion galaxy 20 kpc away. Another well-studied CCG showing strong evidence for the influence of a nearby secondary galaxy on the Hα emission is RXJ 0820.9+0752 at $z = 0.110$ (Bayer-Kim et al. 2002).

(ii) Uniformity of the ionization state. Despite the morphological and kinematic complexity of the Hα emission, the ionization state of the gas is surprisingly uniform, as a function of position, Hα surface brightness and between clusters. The $[N\ II]/H\alpha$ and $[O\ I]/H\alpha$ ratios are particularly tight, but there may be hints of a weak increase of $[S\ II]/H\alpha$ and $[S\ II]/[S\ III]$ with Hα surface brightness. These results suggest that the same mechanism(s) excite all the optical line emission in these systems, and that they are quite independent of the processes which disturb the gas morphologically and kinematically on the kpc scales we observe, i.e. an infalling galaxy or a weak radio source may stir up the gas, but they seem not to impact on its ionization state. For this reason, it seems unlikely that large-scale shocks are involved.

The line ratios we measure are naturally consistent with the integrated slit values found by Crawford et al. (1999) and characteristic of high Hα luminosity ($>10^{41}$ erg s$^{-1}$) cooling flow CCGs. The latter show strong AGN-like $[N\ II]/H\alpha$ and $[O\ I]/H\alpha$, but weak $[S\ II]/H\alpha$ and $[O\ III]/H\beta$ similar to starbursts. As mentioned in Section 1, it was shown by Crawford et al. (1999)
that the observed Hα luminosities of such systems can be powered by photoionization by the O-star populations which explains their excess blue light. Typically, 10^5–10^6 O stars and larger populations of B, A and F stars are required in excess of the continuum expected from a cluster elliptical. However, the ro-vibrational H2:Paα line ratios of CCGs are much higher than typical starburst galaxies (Jaffe et al. 2001; Edge et al. 2002). This may require a distinct population of much denser clouds (Wilman et al. 2002) or excitation by a spectrum harder than that of O-type stars (Jaffe et al. 2005). This may also explain why the optical emission-line ratios differ from those of starburst galaxies. For the ensemble of line-emitting CCGs, Crawford et al. (1999) discovered a continuous trend of decreasing [NII]λ6584/Hα with increasing Hα luminosity, and similar weaker trends in [O III]λ5007/Hβ and [S II]λ6717/Hα. Our results show that similar trends do not extend to local Hα surface brightness within the most luminous systems.

Sparks et al. (2004) proposed that cool gas (e.g. from a galaxy merger) falling into the core of a galaxy cluster could be energized by thermal conduction from the X-ray-emitting ICM. This would lead to optical line emission from the cooler gas and a local enhancement in X-ray emission. Such a model was used to account for the close correspondence between the X-ray and Hα filaments in the Virgo and Perseus clusters (Sparks et al. 2004). It is not known whether this mechanism can reproduce the observed emission-line ratios.

(iii) CO and Hα trace the same gas, at least kinematically and probably also spatially. Two of the four clusters, A1664 and A1835, have robust detections of CO(1–0) emission in the survey of Edge (2001). In both these clusters the CO emission profile is in very good agreement with the Hα kinematics, in terms of its centroid velocity.

Figure 13. Velocity field and FWHM (in km s\(^{-1}\)) derived from fits to the Hα+[N II] complex in A2204; the Hα intensity map of Fig. 12 is reproduced here for ease of comparison. The zero-point of the velocity field is taken to be the nominal cluster redshift of \(z = 0.1514\). Line profiles for some individual fibres are also shown.

Figure 14. Ionization diagnostic line ratios plotted as a function of Hα flux for lenslets in A2204.
and linewidth, strongly suggesting that the CO and Hα emission arise from the same ensemble of clouds. Given this strong CO:Hα link, the weak (A2204) or ambiguous (Zw8193) CO detections in Edge (2001) most likely stem from a high Hα velocity width or zero-point offset (relative to the CCG redshift then assumed), respectively. In the aforementioned RXJ 0820.9+0752 at z = 0.110 (Bayer-Kim et al. 2002) the CO and extended Hα kinematics are also well matched. This is in line with the correlation between Hα luminosity and molecular gas mass discovered by Edge (2001). In contrast, the ro-vibrational H2 emission and kinematics appear to be less strongly coupled to the Hα. In A1664, the H2 has a much lower velocity width than Paα and CO, although in A2204 the match is much closer. RXJ 0820.9+0752 has weak or non-existent H2 emission and linewidth, strongly suggesting that the CO and H2 trace each other spatially and kinematically out to radii beyond 20 kpc, but A2204 is the only cluster common to our two samples.

8 INTERPRETATION: PHYSICAL PROCESSES IN THE DENSE MOLECULAR GAS RESERVOIR

We now interpret the above findings, taking as our starting point the CO observations. As reviewed in Section 1, these have revealed substantial masses of cool molecular gas (10^9–10^11.5 M⊙ at 20–40 K) in the cores of cooling flows, with a mass which correlates with the Hα luminosity (Edge 2001). Subsequent interferometry has shown that the CO emission is confined to scales <20 kpc (Edge & Frayer 2003). The lack of double-peaked CO line profiles suggests that the molecular cloud distribution is quasi-spherical, rather than disc-like. Such a dense, compact molecular gas reservoir will most likely be disturbed by the infall of a small galaxy into the cluster core, as we believe is happening most clearly in A1664, or by the onset of a nuclear radio source. We consider these possibilities in more detail below. First, we consider some physical processes in the unperturbed molecular gas reservoir and their observable consequences.

It is plausible that the CO and Hα emission arise within the same clouds, because they appear to share the same kinematics and are closely correlated in luminosity. The ionized surfaces of such clouds are likely to be in pressure equilibrium with the hot X-ray gas for which n ∼ 0.1 cm⁻³, T ∼ 10^7 K; for optical emission-line regions n ∼ 100 cm⁻³, T ∼ 10⁴ K, such that nT is the same for both phases. Pressure equality may also extend to the cool molecular gas if n ∼ 10⁵ cm⁻³, although it is possible that the cloud cores are self-gravitating. The clouds may be warmed/ionized by a combination of young stars and X-ray emission/conduction from the ICM, but the precise details do not concern us here. The ro-vibrational H2 emission may be a distinct, transiently heated high-pressure component, since line ratio analysis points to thermal excitation in dense gas with n > 10⁵ cm⁻³ and T ∼ 2000 K (Jaffe et al. 2001; Wilman...
et al. 2002). Wilman et al. (2002) proposed that shocks between a population of low-density (∼ 200 cm⁻³) Hα-emitting clouds could be used to transiently create such high-density molecular gas, although an external stellar radiation field was still used to excite the observed emission. We now modify this model and investigate collisions amongst the denser CO clouds.

8.1 Cloud–cloud collisions and external perturbations

Consider that a mass \( M \) of CO-emitting molecular gas is confined within a radius \( R_0 \) of the CCG, distributed within an ensemble of identical clouds of radius \( r \), mass \( m_c \), space density \( N(R) \) and hydrogen number density \( n \). Interferometry shows that the CO is centrally concentrated so we take \( N(R) \propto R^{-1} \), as in the inner part of an NFW profile (Navarro, Frenk & White 1997). For a typical relative cloud velocity of \( v \), the rate of cloud collisions per unit volume is \( \dot{M}_{\text{coll}} \propto \sigma v \), where \( \sigma \) is the collision cross-section, which we approximate with the geometrical cross-section \( \sigma = \pi r^2 \). It then follows that the rate at which mass is processed through such collisions is

\[
\dot{M}_{\text{coll}} = \frac{3M^2v}{2\pi^2R_0^3Nm_r}.
\]  

(1)

For \( v = 150 \text{ km s}^{-1}, R_0 = 10 \text{ kpc}, r = 1 \text{ pc} \) and \( n = 10^7 \text{ cm}^{-3} \), equation (1) evaluates to \( \dot{M}_{\text{coll}} \sim 1 - 100 \text{ M}_\odot \text{ yr}^{-1} \) for \( M = 10^{10 - 11} \text{ M}_\odot \) (\( m_p \) is the proton mass). Such supersonic collisions will shock the clouds to temperatures of several times \( 10^5 \text{ K} \). For the assumed densities the cooling time from these temperatures is very short, ∼ 1 month, so the gas will quickly return to the cool phase, i.e. collisions will merely recycle the cool gas and not deplete it. It is, however, possible the shock compression will act as a trigger for star formation. They may also create the dense molecular gas and a locally strong, hard (e.g. black body at \( T \geq 10^5 \text{ K} \)) radiation field required for the production of the ro-vibrational H\(_2\) emission. The extreme ultraviolet (EUV) luminosity produced by such shocks is \( L_{\text{coll}} = \frac{1}{2}M_{\text{coll}}v^2 \), or

\[
L_{\text{coll}} = \frac{3M^2v^3}{4\pi^2R_0^3Nm_r}.
\]  

(2)

For the same parameters as before, this amounts to \( L_{\text{coll}} = 7 \times 10^{38 - 41} \text{ erg s}^{-1} \). Although this is several orders of magnitude below the inferred luminosity of the young stellar component in these systems, the cubic dependence on \( v \) and \( R_0 \) and uncertainty over the actual values of \( r \) and \( n \) means that such shocks could make a non-negligible contribution to the excitation of the line emission in CCGs, at least locally if the gas clouds are not uniformly distributed. We note, however, that limits on the strength of the [O III] λ4363 emission line imply that shocks are unlikely to play a strong role in the production of the optical line emission in Hα-luminous CCGs (e.g. Voit & Donahue 1997). The mechanism may, however, be a relatively more important source of excitation in lower-Hα luminosity systems. Such shocks will steadily drain energy from the molecular gas reservoir, forcing the distribution to smaller radii and thus increasing the collision rate still further.

We now consider the consequences of disturbing this reservoir with the infall of a small galaxy, as appears to be happening most dramatically in A1664. From the constant excitation state of the ionized gas, it seems that this does not cause any large-scale shocks or cloud destruction. Most likely, the cloud distribution will be dynamically perturbed by the infalling galaxy, producing the observed streams and filaments. Such interactions are likely to enhance the star formation rate, either by increasing the cloud–cloud collision...
rate (as above), or via some other means. With reference to the relationship between [NII]/H\alpha and H\alpha luminosity discovered by Crawford et al. (1999), the observed uniformity of the line ratios we find in our sample may be due to the fact that, at high H\alpha luminosity, all parts of the CCG are saturated at the lowest [NII]/H\alpha values characteristic of massive star formation. In less H\alpha-luminous CCGs, we would thus predict more variations in the line ratio, with [NII]/H\alpha increasing away from the less-abundant star-forming clumps.

The possibility that galaxy interactions may trigger star formation in these molecular gas-rich environments highlights the similarities between these CCGs and luminous infrared galaxies, as discussed by Edge (2001). The Spitzer observations of Egami et al. (2006) further strengthens the connection, revealing large thermal dust luminosities $L_{IR} > 10^{11} L_{\odot}$ in two of the most H\alpha-luminous CCGs (Zw3146 and A1835).

9 CONCLUSIONS

The results presented in this paper have shed new light on the kinematic and morphological complexity of the emission-line gas in the cores of these H\alpha-luminous clusters. Our principal findings are as follows.

(i) In many cases the H\alpha emission appears to have been disturbed by interaction with a small companion galaxy to the central galaxy.

(ii) The CO and H\alpha emission share the same kinematics and by implication trace each other closely.

(iii) The emission-line ratios of the gas are uniform, showing no strong variations in [NII]/H\alpha, [SII]/H\alpha or [OIII]/H\beta, as a function of position or H\alpha surface brightness, suggesting that its excitation state is independent of the processes which disturb it in the observed kpc scales.

Our interpretation is that the H\alpha and CO emission are produced in a population of molecular clouds warmed by a starburst, which has itself been triggered by the passage of a secondary galaxy through the gas-rich cluster core. In these most luminous H\alpha CCGs, this galaxy-wide starburst leads to the saturation of the optical emission-line ratios at a uniform level characteristic of massive star formation. In the absence of such triggering, the cooled gas reservoir will be in a more quiescent state with a much lower level of H\alpha and CO emission; optical emission-line ratios will be governed by other processes, e.g. excitation through cloud–cloud collisions (as described above) or mixing layers (Crawford & Fabian 1992), to mention just two possibilities. Starting from this low H\alpha luminosity quiescent state, adding some star-forming clumps will increase the overall H\alpha and CO luminosity and give rise to spatial variations in the optical-line ratios. At the highest H\alpha luminosities, star formation will be widespread, with little spatial variation in optical emission-line ratios.

To test this interpretation, future IFU observations should be carried out on CCGs covering the [OII]3727 and [OIII]4959 emission lines and the sub-4000 A continuum in order to probe current star formation, and with near-infrared IFUs to study the H2 and Pa\alpha emission. Observations should also be performed on lower H\alpha luminosity CCGs in order to examine whether spatial variations in optical emission-line ratios are indeed larger, due to less widespread star formation. On a longer time-scale, mm-interferometers such as ALMA will reveal the spatial distribution of the CO emission (and dust) for a full comparison with the H\alpha. Our findings also highlight the need for numerical modelling of these dense CO reservoirs, with and without external perturbations.

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REFERENCES

Allen S. W., 1995, MNRAS, 276, 947
Allen S. W. et al., 1992, MNRAS, 259, 67
Bauer F., Fabian A. C., Sanders J. S., Allen S. W., Johnstone R. M., 2005, MNRAS, 359, 1481
Bayer-Kim C. M., Crawford C. S., Allen S. W., Edge A. C., Fabian A. C., 2002, MNRAS, 337, 938
Benn C., Talbot G., Bacon R., 2003, ING Newsletter, 7, 21
Br"uggen M., Kaiser C. R., 2002, Nat, 418, 301
Cen R., 2005, ApJ, 620, 191
Crawford C. S., Fabian A. C., 1992, MNRAS, 259, 265
Crawford C. S., Allen S. W., Ebeling H., Edge A. C., Fabian A. C., 1999, MNRAS, 306, 857
Crawford C. S., Fabian A. C., Sanders J. S., 2005, MNRAS, 361, 17
Edge A. C., 2001, MNRAS, 328, 762
Edge A. C., Frayer D. T., 2003, ApJ, 594, L13
Edge A. C., Wilman R. J., Johnstone R. M., Crawford, C. S., Fabian A. C., Allen S. W., 2002, MNRAS, 337, 49
Egami E. et al., 2006, ApJ, in press, preprint (astro-ph/0603656)
Fabian A. C., 1994, ARA&A, 32, 277
Fabian A. C., 2003, MNRAS, 344, L27
Fabian A. C., Mushotzky R. F., Nulsen P. E. J., Peterson J. R., 2001, MNRAS, 321, L20
Fabian A. C., Allen S. W., Crawford C. S., Johnstone R. M., Morris R. G., Sanders J. S., Schmidt R. W., 2002, MNRAS, 332, L50
Fabian A. C., Sanders J. S., Crawford C. S., Conseil C. J., Gallagher J. S., Wyse R. F. G., 2003, MNRAS, 344, L48
Hu E. M., Cowie L. L., Kaaret P., Jenkins E. B., York D. G., Roesler F. L., 1983, ApJ, 275, 27
Jaffe W., Bremer M. N., van der Werf P. P., 2001, MNRAS, 324, 443
Jaffe W., Bremer M. N., Baker K., 2005, MNRAS, 360, 748
Jennner D. C., 1974, ApJ, 191, 55
LeFevre O. et al., 2003, SPIE, 4841, 1670
Navarro J. F., Frenk C. S., White S. D. M., 1997, ApJ, 490, 493
Peres C. B., Fabian A. C., Edge A. C., Allen S. W., Johnstone R. M., White D. A., 1998, MNRAS, 298, 416
Peterson J. R., Kahn S. M., Paerels F. B. S., Kaastra J. S., Tamura T., Blinks B., J. A. M., Ferrigno C., Jernigan J. G., 2003, ApJ, 590, 207
Roussel A., 1992, PhD thesis, Univ. J. Monnet de Saint-Etienne
Sanders J. S., Fabian A. C., Taylor G. B., 2005, MNRAS, 356, 1022
Salomé P., Combes F., 2003, A&A, 412, 657
Salomé P., Combes F., 2004, A&A, 415, L1
Schmidt R. W., Allen S. W., Fabian A. C., 2001, MNRAS, 327, 1057

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Scodeggio A. et al., 2005, PASP, 117, 1284
Shopbell P. L., Bland-Hawthorn J., 1998, ApJ, 493, 129
Sparks W. B., Donahue M., Jordán A., Ferrarese L., Côté P., 2004, ApJ, 607, 294
Voigt L. M., Schmidt R. W., Fabian A. C., Allen S. W., Johnstone R. M., 2002, MNRAS, 335, L7

Voit G. M., Donahue M., 1997, ApJ, 486, 242
Wilman R. J., Edge A. C., Johnstone R. M., Fabian A. C., Allen S. W., Crawford C. S., 2002, MNRAS, 337, 63

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