Discovery of atomic and molecular mid infra-red emission lines in off-nuclear regions of NGC 1275 and NGC 4696 with the Spitzer Space Telescope

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ABSTRACT

We present Spitzer high-resolution spectra of off-nuclear regions in the central cluster galaxies NGC 1275 and NGC 4696 in the Perseus and Centaurus clusters, respectively. Both objects are surrounded by extensive optical emission-line filamentary nebulae, bright outer parts of which are the targets of our observations. The 10–37 μm spectra show strong pure rotational lines from molecular hydrogen revealing a molecular component to the filaments which has an excitation temperature of \( \sim 300 - 400 K \). Emission is also seen from both low and high ionization fine structure lines. Cold molecular hydrogen dominates the mass of the outer filaments; the nebulae are predominantly molecular.

Key words: galaxies: clusters: general – galaxies: clusters: individual: NGC 1275 – galaxies: clusters: individual: NGC 4696 – intergalactic medium – infrared: galaxies

1 INTRODUCTION

The massive central galaxy in many clusters is often surrounded by an extensive emission-line nebulosity (e.g. Cowie et al. 1983; Johnstone et al. 1987; Heckman et al. 1989; Crawford et al. 1999). Such emission-line galaxies are always at the centre of a highly peaked X-ray emitting intracluster medium where the radiative cooling time of the intracluster gas at the centre is less than 1 Gyr (Fabian 1994; Peres et al. 1998; Bauer et al. 2005). Initially the nebulosity was studied in the optical spectral region but strong UV and IR lines have since been seen, together with dust which is inferred from the depletion of calcium, Balmer line ratios and dust lanes which are present in some cases. Recently, strong H₂ lines have been found (e.g. Jaffe & Bremer 1997; Edge et al. 2002 and refs therein) as well as emission lines from the CO molecule (e.g. Edge 2001; Salomé & Combes 2003; Salomé et al. 2006).

The ionization, excitation, origin and fate of the filaments has been a long-standing puzzle. Most obvious sources of ionization, such as an active nucleus, a radio source, shocks, young stars and conduction from the surrounding hot gas have drawbacks in one system or another.

XMM/RGS and Chandra X-ray spectra show that the intra-cluster gas in many cluster cores has a range of temperatures decreasing to about a factor of three below that of the outer hot gas, with very little X-ray emitting gas cooler than this (Peterson et al. 2001), indicating that some form of heating (e.g. from the central radio source, Churazov et al. 2002; Fabian et al. 2003a) is important and that it mostly balances the radiative cooling. Heating is unlikely to completely balance cooling over such an extended region, and so some residual cooling flow is expected to occur. Optically emitting warm gas filaments may be being dragged out from the central cluster galaxy by buoyant bubbles (Hatch et al. 2006) or may be a phase through which some gas passes in cooling out from the intracluster medium. The wider relevance of this issue is in the upper mass limit to the total stellar component of massive galaxies, which may be controlled by whatever heats cooling flows (Fabian et al. 2002b). If radiative cooling is not balanced in some way (or the cooled gas does not form stars) then the stellar component of cD galaxies should be much more massive than is observed, merely by the accretion of cooled intracluster gas. By measuring the quantity of young stars and warm/cold gas in these objects we can determine how well heating balances cooling.

The emission-line filaments are markers of feedback in massive galaxies and to use them as such we need to understand their composition, origin and lifetime. Here we study two of the brightest and most extensive emission line nebulae around central cluster...
galaxies NGC 1275 (at redshift \( z = 0.0176 \), in the Perseus Cluster) and NGC 4696 (redshift \( z = 0.00987 \) in the Centaurus cluster) using the Spitzer Infrared Spectrograph (IRS). The \( H \alpha \) filaments around NGC 1275, which extend well beyond the body of the galaxy, have warm (2000K) molecular hydrogen associated with them. This motivates us to search for much cooler (few \( \times 100K \)) molecular hydrogen in these regions using the rotational emission lines accessible to the IRS.

The central cD galaxy in the nearby Perseus cluster, NGC 1275 \(( z = 0.0176 \) ), is surrounded by spectacular \( H \alpha \) filaments which stretch over 100 kpc. These were first reported by Minkowski (1957) and imaged by Lynds (1970), McNamara et al (1996) and recently by Conselice et al (2001). The Perseus cluster is the brightest cluster of galaxies at X-ray wavelengths with the emission peaking on NGC 1275 (Fabian et al 1981, 2000, 2003a). The nucleus of NGC 1275 also powers an FRI radio source, 3C 84 (Pedlar et al 1990). Bubbles of relativistic plasma have been blown by the jets from the nucleus and have displaced the X-ray emitting intracluster gas (Bohinger et al 1993, Churazov et al 2001, Fabian et al 2000, 2002a, 2003a). It is likely that the \( H \alpha \) filaments avoid the bubbles in three dimensional space, although there is no obvious anti-correlation as seen in projection on the sky; They appear to act like streamlines showing that the flow behind the outer bubble, and thus the whole inner medium, is not turbulent and may well have been dragged out from the central region (Fabian et al 2003b, Hatch et al 2008). Molecular hydrogen \( [\text{Kr}abbe et al 2004; Jaffe et al 2004; Edge et al 2004] \) and CO (Salome et al 2006 and references therein) have been observed and mapped in the inner regions for some time.

NGC 4696 at the centre of the Centaurus cluster \(( z = 0.009867 \) ) has \( H \alpha \) filaments discovered by Fabian et al (1982) and a strong dust lane (Shobbrook 1966, Sparks et al 1989) and Crawford et al (2005) have mapped the nebulosity which appears to surround the dust lane.

The ionization state of the \( H \alpha \) filaments in central cluster galaxies is low, with \( [\text{OII}] \lambda 6300, [\text{OII}] \lambda 3727 \) and \( [\text{NI}] \lambda 6584 \) being prominent in optical spectra as well as Balmer lines. Molecular \( H_2 \) is also common (e.g. Jaffe & Bremer 1997; Donahue et al 2000, Edge et al 2004), even in the outer filaments (Hatch et al 2005). Egami et al (2004) have recently found very strong rotational \( H_2 \) lines from the brightest cluster galaxy in Zw 3146, using Spitzer IRS data. Unlike with our objects, the emission is not spatially resolved due to the high redshift of the object \(( z = 0.29 \) ). The authors remark that the \( H_2 \) lines and mass are the highest yet known. A Spitzer IRS spectrum of the centre of NGC 1275 is presented by Weedman et al (2005). Forbidden atomic lines and at least one molecular line are seen sitting on a large continuum associated with the active nucleus. Kaneda et al (2005, 2006) have taken low resolution Spitzer IRS spectra of NGC 4696 and find PAH features and \( [\text{NeII}] \) line emission.

What is ionizing and exciting the filamentary gas remains uncertain. It is not simply an active nucleus (Johnstone & Fabian 1988, Sabra et al 2000), nor do a range of alternative mechanisms provide a comprehensive explanation (e.g. Crawford & Fabian 1992; Donahue et al 2000, Sabra et al 2000, Wilman et al 2002). The UV emission from massive young stars is likely to play an important role (Johnstone et al 1987, Allen 1995, Crawford et al 1999), although this may not be the case for the outer filaments. The lifetime of the filaments is not known, although the immense size of the system around NGC 1275 (80 kpc) and the low velocity spread seen in the filaments \(( \sim 300 \text{ km s}^{-1} \) or less) indicates that they may last over \( 10^8 \) yr.

2 Observations and Data Reduction

Spitzer IRS observations of off-nuclear regions in NGC 1275 and NGC 4696, were made during two observing campaigns in 2005 July and 2006 March (IRSX005200 and IRSX006300). For each object both the Short Wavelength High Resolution (SH) and Long Wavelength High Resolution (LH) spectrographs were used, giving an effective resolving power of \( \sim 600 \) and a spectral coverage from \( \sim 10 \mu m \) to \( \sim 37 \mu m \). The entrance aperture size of the two spectrographs is rather different, being \( 4.7 \times 11.3 \) arcsec for the SH and \( 11.1 \times 22.3 \) arcsec for the LH spectrographs respectively.

Table 1 lists details of the Spitzer observations. Three off-nuclear regions were observed in NGC 1275, chosen to be coincident with particular regions identified in the \( H \alpha \) map of Conselice et al (2001), as well as a blank sky region. In NGC 1275 we covered the brightest part of the \( H \alpha \) nebula to the South West of the nucleus.

Figures 1 and 2 show the outline of the Spitzer spectrograph apertures overlaid on \( H \alpha \) images of the central cluster galaxies. There are two slightly different pointings (exposure ids) for each target position, these being the standard nod positions in the Staring Mode Astronomical Observation Template. These positions locate the target at one third and two thirds of the way along the spectrograph aperture. The SH spectrograph aperture positions are shown by the smaller rectangles whereas the LH spectrograph apertures are the larger rectangles which are approximately orthogonal to the SH spectrograph apertures. The specific pointing positions for each exposure id are given in table 1.

The observations were processed by the Spitzer Science Center through pipeline version S13.2.0. We use the ‘bcd.fits’, ‘func.fits’ and ‘bmask.fits’ files as the starting point for our reduction.

Individual Data Collection Event (DCE) files within each exposure id were first averaged together and an array of external uncertainties corresponding to the standard error on the mean was calculated. A new bmask file was also generated, this being the logical ‘or’ of all the bmask files for the input DCEs. The NGC 1275 East pointing has only one DCE in each spectrograph so in these cases the pipeline based uncertainties, which are computed from the ramp fitting of the multiple detector readouts, are used for the uncertainty arrays.
Table 1. Log of Spitzer Observations.

| Target            | Redshift | Obs date | AOR     | Mode | Exposure id | RA (2000) | Dec | Exposure time (seconds) |
|-------------------|----------|----------|---------|------|-------------|-----------|-----|------------------------|
| NGC 1275 East     | 0.0176   | 2006 Mar 14 | r14536704 | SH   | 0002        | 03:19:49.9 | +41:30:48 | 481.69 |
|                   |          |          |         |      | 0003        | 03:19:50.2 | +41:30:46 | 481.69 |
|                   |          |          |         |      | 0004        | 03:19:49.9 | +41:30:44 | 241.83 |
|                   |          |          |         |      | 0005        | 03:19:50.2 | +41:30:50 | 241.83 |
|                   |          |          |         |      | 0006        | 03:19:49.9 | +41:29:49 | 1445.07 |
|                   |          |          |         |      | 0007        | 03:19:49.9 | +41:29:50 | 1445.07 |
|                   |          |          |         |      | 0008        | 03:19:49.9 | +41:29:45 | 725.48 |
|                   |          |          |         |      | 0009        | 03:19:49.9 | +41:29:51 | 725.48 |
| NGC 1275 Position 2 | 0.0176   | 2006 Mar 14 | r14536448 | SH   | 0002        | 03:19:45.7 | +41:29:49 | 1445.07 |
|                   |          |          |         |      | 0003        | 03:19:45.7 | +41:29:47 | 1445.07 |
|                   |          |          |         |      | 0004        | 03:19:45.7 | +41:29:45 | 725.48 |
|                   |          |          |         |      | 0005        | 03:19:45.7 | +41:29:51 | 725.48 |
| NGC 1275 Position 11 | 0.0176 | 2006 Mar 14 | r14536192 | SH   | 0002        | 03:19:45.0 | +41:31:34 | 1445.07 |
|                   |          |          |         |      | 0003        | 03:19:45.0 | +41:31:32 | 1445.07 |
|                   |          |          |         |      | 0004        | 03:19:45.0 | +41:31:30 | 725.48 |
|                   |          |          |         |      | 0005        | 03:19:45.0 | +41:31:36 | 725.48 |
| NGC 1275 Blank    | 0.0176   | 2006 Mar 14 | r16754176 | SH   | 0002        | 03:19:53.6 | +41:28:35 | 963.38 |
|                   |          |          |         |      | 0003        | 03:19:53.6 | +41:28:33 | 963.38 |
|                   |          |          |         |      | 0004        | 03:19:53.6 | +41:28:31 | 483.65 |
|                   |          |          |         |      | 0005        | 03:19:53.6 | +41:28:37 | 483.65 |
| NGC 4696          | 0.009867 | 2005 Jul 9 | r14537216 | SH   | 0002        | 12:48:48.7 | -41:18:42 | 2408.44 |
|                   |          |          |         |      | 0003        | 12:48:48.9 | -41:18:45 | 2408.44 |
|                   |          |          |         |      | 0004        | 12:48:48.5 | -41:18:45 | 725.48 |
|                   |          |          |         |      | 0005        | 12:48:49.1 | -41:18:42 | 725.48 |

The NGC 1275 pointings were then background subtracted using the NGC 1275 blank field pointing, propagating the uncertainty arrays in quadrature and again creating a new bmask file that is the logical ‘or’ of the input masks.

In the case of the NGC 4696 pointing we do not have a concurrent sky-background observation. For the LH data, we used an average of background observations (scaled to the expected background level at the position of the NGC 4696 pointing using values from the Spitzer SPOT software) taken for standard star calibrations in the same observing campaign to effect sky subtraction. However, for the SH data, the analogous background observations were too short compared with the NGC 4696 data and added considerable noise when subtracted from the NGC 4696 data. We therefore leave these as not sky subtracted. One consequence of not having concurrent sky-background is that the rogue pixels in the detectors are not well corrected (or corrected at all in the case of the SH data). We therefore used the IRSclean mask software from the Spitzer contributed software site\(^1\) to interpolate over the rogue pixels for these observations.

The data from the SH and LH spectrographs are not rectilinear in either the spatial or spectral direction and therefore require software which has a knowledge of the detailed distortions in order to be able to extract one-dimesional spectra. We used the Spitzer Spice software (version 1.3beta1 and version 1.4) for this, extracting all the spectral orders over the full aperture in both spectrographs. The final step in the Spice software extraction is a ‘tuning’ that applies a flux calibration to the data. There are two possibilities at this stage because the size of the point-spread function of the Spitzer telescope is of the same order as the entrance aperture size. One option applies an extended source calibration in which it is assumed that the aperture is illuminated by a uniform surface brightness source; as much flux is scattered into the aperture as is scattered out of it. The other option is to apply the point-source calibration which corrects for the fraction of flux from a well-centered point-source that is lost from the aperture, as a function of wavelength. In figure 3, we show the magnitude of this correction derived from the Spitzer ‘slitloss’ calibration files. We plot the correction factor that the extended-source calibration needs to be multiplied by in order to obtain the point-source calibration.

To determine whether the point-source or extended source calibration is more appropriate for our data we have taken the continuum subtracted \(H\alpha\) maps and used them as proxies for the spatial distribution of the infra-red line emission since we do not know its spatial distribution. Assuming that the \(H\alpha\) emission is distributed spatially like the infra-red emission allows us to make a quantitative (but approximate) assessment of whether the emission, which

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\(^1\) [Link to the Spitzer contributed software site](http://ssc.spitzer.caltech.edu/archanaly/contributed/browse.html)

**Figure 2.** Spitzer spectrograph apertures overlaid on an \(H\alpha\) image of the central region of NGC 4696 (Crawford et al. 2005). North is up and East to the left. Small boxes show the positions of the SH spectrograph aperture while the larger boxes show the positions of the LH spectrograph aperture.
appears very clearly extended on the resolution of the optical data, is actually extended at the resolution of the Spitzer observations. We have measured the ratio of the flux in the Spitzer apertures in the raw image and in the image smoothed using a gaussian kernel of full-width half-maximum of 3.1 or 6.17 arcsec. These widths are an approximation to the size of the Spitzer point spread function as measured by fitting a one-dimensional gaussian model for the line plus a straight line to account for the local continuum. The fitting was done using the QDP program to minimize the chi-square statistic between the model and the data, subject to the propagated uncertainty in the flux at each wavelength bin. Line parameters and uncertainties are given in Tables 3, 4, 5, and 6. The uncertainties were generally calculated (for all pointings except the NGC 1275 East region) from the $\Delta \chi^2 = 1$ criterion (Lampton et al. 1976). This corresponds to a 68 per cent confidence region or a 1σ (gaussian equivalent) confidence region for one interesting parameter. In the cases where lines are not detected we set a 3σ upper limit on the line flux by fixing the position and width of the line and increasing the flux until the value of chi-square increases by 9 from the value obtained with no line present. Where no uncertainty on a parameter is listed that parameter was fixed.

The values of the minimum chi-square that were obtained when fitting the NGC 4696 short wavelength spectra were significantly above the number of degrees of freedom, whereas the values of the minimum chi-square that were obtained when fitting the NGC 1275 East spectra were significantly below the number of degrees of freedom. In both cases this indicates that the uncertainties on each bin are wrong. In the case of the NGC 4696 short wavelength data there is additional power in the spectra not accounted for in the uncertainty arrays which may be due to the presence of fringes (http://ssc.spitzer.caltech.edu/postbcd/irsfringe.html) that have not been completely removed in the pipeline software. We tried to correct for these using the irsfringe tool but were unsuccessful. In the case of the NGC 1275 East spectra there is only one DCE and the uncertainties are propagated from the ramp fitting. This leads to uncertainties which are too big.

Since using the $\Delta \chi^2 = 1$ criterion under either of these conditions leads to uncertainties on the line parameters which are either too large or too small we have adopted the ‘Ratio of Variances’ technique (Lampton et al. 1976) to rescale the critical value of delta chi-square used to calculate the line parameter uncertainties. We note in passing that the spectral extraction method used in the Spice software does introduce correlations between adjacent spectral bins but the Spitzer Science Centre advises that the degree of correlation is small because the dispersion direction in the spectral images is almost parallel with the pixel direction.

We therefore proceed using the extended source tuning option in Spice.

The final part of the reduction involves merging the individual spectral orders into one spectrum and converting the flux units to per unit wavelength. At the long wavelength end of each order the sensitivity drops significantly and so the noise increases. However, because there is an overlap in the wavelength coverage of adjacent orders we are able to use the following prescription to clean the final spectrum: In the order overlap regions we choose data from the lower order number spectrum in preference to that of the higher order number, except that we discard the 6 shortest wavelength bins in the highest order spectrum and the 4 shortest wavelength bins of all other orders. The 6 longest wavelength bins in the spectrum are also discarded. We show examples of the final spectra in Figs. 4, 5, and 6 with the expected positions of some emission lines marked. The dashed vertical lines show the boundar of adjacent spectral orders.

The emission lines in the spectra were fitted individually using a gaussian model for the line plus a straight line to account for the local continuum. The fitting was done using the QDP program to minimize the chi-square statistic between the model and the data, subject to the propagated uncertainty in the flux at each wavelength bin. Line parameters and uncertainties are given in Tables 3, 4, 5, and 6. The uncertainties were generally calculated (for all pointings except the NGC 1275 East region) from the $\Delta \chi^2 = 1$ criterion (Lampton et al. 1976). This corresponds to a 68 per cent confidence region or a 1σ (gaussian equivalent) confidence region for one interesting parameter. In the cases where lines are not detected we set a 3σ upper limit on the line flux by fixing the position and width of the line and increasing the flux until the value of chi-square increases by 9 from the value obtained with no line present. Where no uncertainty on a parameter is listed that parameter was fixed.

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| Region          | Exposure id | Spectrograph | Flux ratio |
|-----------------|-------------|--------------|------------|
| NGC 1275 East   | 0002        | SH           | 1.00       |
|                 | 0003        | SH           | 1.06       |
|                 | 0004        | LH           | 1.10       |
|                 | 0005        | LH           | 1.11       |
| NGC 1275 Position 2 | 0002       | SH           | 1.07       |
|                 | 0003        | SH           | 1.13       |
|                 | 0004        | LH           | 1.04       |
|                 | 0005        | LH           | 1.08       |
| NGC 1275 Position 11 | 0002       | SH           | 1.09       |
|                 | 0003        | SH           | 1.11       |
|                 | 0004        | LH           | 1.07       |
|                 | 0005        | LH           | 1.01       |
| Centaurus       | 0002        | SH           | 0.99       |
|                 | 0003        | SH           | 1.00       |
|                 | 0004        | LH           | 1.16       |
|                 | 0005        | LH           | 1.06       |

Figure 3. Correction factors which the Spitzer SH and LH extended source calibrations need to be multiplied by to obtain the point-source calibration.
3 ANALYSIS

The lines detected in the Spitzer mid-infrared spectra consist of emission from molecular hydrogen, from various atomic species of Neon, Sulphur and Silicon and from the 11.3 micron PAH feature.

### 3.1 Diagnostic line ratios

In order to classify the emission-line regions seen by Spitzer, we have plotted the lines of Neon/Sulphur/Silicon in Fig 8 on one of the diagnostic diagrams of Dale et al (2006). The NGC 1275 East and NGC 4696 points both lie in the Region I+II area of the diagram occupied by Seyfert and Liner nuclei. This finding is consistent with other analyses of optical emission lines in these objects which also show Liner-like spectra (e.g. Johnstone et al 1987; Crawford et al 1995).

### 3.2 [NeIII] lines

The SH spectra of the NGC 1275 East region and the NGC 4696 pointing both show strong detections of the [NeIII] $\lambda$ 15.56$\mu$m line. In the NGC 1275 East region this is a surprising discovery since most of the extended emission line gas does not show emission from the optical lines of [OIII]$\lambda\lambda$4959,5007. The ionization potential of Ne$^+$ (41.07 eV) is larger than the ionization potential of O$^+$ so if lines of [NeIII] are seen we would expect to see lines of [OIII].

There are two possible explanations for the apparent lack of the [OIII] lines when the [NeIII] lines are strong. The first possibility is that the [OIII] and [NeIII] lines are both emitted together from a spatial region which is missed in our optical long-slit spectra but sampled in the Spitzer spectra due to the much larger SH aperture ($4.7 \times 11.3$ arcsec) and the poorer point-spread function.

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Table 3. Properties of emission lines in the NGC 1275 East region Spitzer spectra. Note that the line widths are the gaussian sigma values.

| Exposure id | Line | Wavelength (microns) | Width ($\sigma$) (microns) | Flux ($\times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$) |
|-------------|------|----------------------|---------------------------|-----------------------------------------------|
| 0002        | PAH 11.3 | 11.51±0.01 | 0.11±0.01 | 1.43±0.16 |
| H$_2$ 0-0S(2) | 12.28 | 12.4906±0.0003 | 0.0087±0.0003 | 0.87±0.03 |
| [NeII] 12.81 | 13.0358±0.0006 | 0.0096±0.0003 | 1.51±0.04 |
| [NeII] 15.56 | 15.8241 | 0.0152±0.0007 | 0.54±0.03 |
| H$_2$ 0-0S(1) | 17.04 | 17.3280±0.0009 | 0.0138±0.0005 | 1.79±0.09 |
| [SIII] 18.71 | 19.04±0.003 | 0.017±0.003 | 0.39±0.07 |
| 0003        | PAH 11.3 | 11.56±0.03 | 0.14±0.03 | 1.15±0.37 |
| H$_2$ 0-0S(2) | 12.4906±0.0003 | 0.0087±0.0003 | 0.87±0.03 |
| [NeII] 12.81 | 13.0350±0.0003 | 0.0096±0.0003 | 1.51±0.04 |
| [NeII] 15.56 | 15.8236±0.0010 | 0.0129±0.0010 | 0.44±0.03 |
| H$_2$ 0-0S(1) | 17.3270±0.0010 | 0.0136±0.0005 | 1.98±0.12 |
| [SIII] 18.71 | 19.04±0.003 | 0.011±0.003 | 0.16±0.04 |
| 0004        | H$_2$ 0-0S(0) | 28.22 | 28.72 | 0.020 | <0.73 |
| [SIII] 33.48 | 34.07 | 0.024 | <1.68 |
| [SIII] 34.82 | 35.42±0.001 | 0.0242±0.0011 | 4.46±0.18 |
| 0005        | H$_2$ 0-0S(0) | 28.22 | 28.72 | 0.020 | <0.75 |
| [SIII] 33.48 | 34.07 | 0.024 | <0.75 |
| [SIII] 34.82 | 35.415±0.001 | 0.024±0.001 | 3.59±0.17 |

Table 4. Properties of emission lines in the NGC 1275 Position 2 region Spitzer spectra. Note that the line widths are the gaussian sigma values.

| Exposure id | Line | Wavelength (microns) | Width ($\sigma$) (microns) | Flux ($\times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$) |
|-------------|------|----------------------|---------------------------|-----------------------------------------------|
| 0002        | PAH 11.3 | 11.51 | 0.11 | <0.11 |
| H$_2$ 0-0S(2) | 12.28 | 12.4920±0.0008 | 0.0096±0.0009 | 0.24±0.02 |
| [NeII] 12.81 | 13.0358±0.0006 | 0.0090±0.0007 | 0.30±0.02 |
| [NeII] 15.56 | 15.8241 | 0.015 | <0.19 |
| H$_2$ 0-0S(1) | 17.04 | 17.3317±0.0004 | 0.0121±0.0004 | 0.47±0.02 |
| [SIII] 18.71 | 19.04 | 0.017 | <0.10 |
| 0003        | PAH 11.3 | 11.51 | 0.11 | <0.11 |
| H$_2$ 0-0S(2) | 12.28 | 12.4925±0.0010 | 0.0102±0.0011 | 0.27±0.03 |
| [NeII] 12.81 | 13.0382±0.0011 | 0.0079±0.0011 | 0.21±0.03 |
| [NeII] 15.56 | 15.8241 | 0.015 | <0.11 |
| H$_2$ 0-0S(1) | 17.04 | 17.3334±0.0006 | 0.0111±0.0005 | 0.42±0.02 |
| [SIII] 18.71 | 19.04 | 0.017 | 0.07 |
| 0004        | H$_2$ 0-0S(0) | 28.22 | 28.72 | 0.020 | <0.15 |
| [SIII] 33.48 | 34.07 | 0.024 | <0.27 |
| [SIII] 34.82 | 35.43 | 0.025 | <0.63 |
| 0005        | H$_2$ 0-0S(0) | 28.22 | 28.72 | 0.020 | <0.18 |
| [SIII] 33.48 | 34.07 | 0.024 | <0.36 |
| [SIII] 34.82 | 35.43 | 0.025 | <0.69 |
of Spitzer. Alternatively, since these lines are all collisionally excited and the excitation energy of the upper level in the \([\text{OIII}]\) lines is much greater than that for the upper level in the \([\text{NeIII}]\) line, if the electron temperature in the emitting gas is low enough, the infra-red \([\text{NeIII}]\) line may be produced while the optical \([\text{OIII}]\) lines are not excited.

To determine whether the first possibility is occurring we note that the \(\text{SH} \) aperture for our NGC 1275 East observations is located very close to an HII region identified by Shields & Filippenko (1990). That HII region has much stronger \([\text{OIII}]\) emission than the surrounding nebula and therefore may contribute significant \([\text{NeIII}]\) emission.

In order to assess whether the Spitzer \(\text{SH} \) apertures contain a significant amount of light from the HII region we used the Spitzer Sinytim point-spread function modelling software to generate an image of the point-spread function for the \(\text{SH} \) instrument at the observed wavelength of \([\text{NeIII}]\) (15.8\(\mu\)m). We then applied a world coordinate system to this image such that the centre of the point spread function lies at the coordinates of the HII region and the pixel scale is correct for the point-spread function image. The point spread function lies at the coordinates of the HII region and a world coordinate system to this image such that the centre of the region nebula \([\text{NeIII}]\) then we can solve for the fractional contribution of the HII region to the \([\text{NeIII}]\) flux in each exposure id. Under these two exposure ids is just 1.23, if we further assume that each exposure id has the same contribution from the extended (non-HII region) \([\text{NeIII}]\) then we can solve for the fractional contribution from the extended (non-HII region nebula) \([\text{NeIII}]\) then we can solve for the fractional contribution of the HII region to the \([\text{NeIII}]\) flux in each exposure id.

### Table 5. Properties of emission lines in the NGC 1275 Position 11 region Spitzer spectra. Note that the line widths are the gaussian sigma values.

| Exposure id | Line   | Wavelength (microns) | Width (\(\sigma\)) (microns) | Flux \((\times 10^{-14} \text{ erg cm}^{-2} \text{s}^{-1})\) |
|------------|--------|---------------------|-----------------------------|----------------------------------|
| 0002       | PAH 11.3 | 11.51              | 0.11                        | <0.27                            |
|            | \([\text{H}_{2}]\) 0-0S(2) | 12.4955±0.0013 | 0.0085±0.0014 | 0.13±0.02                       |
|            | \([\text{NeII}]\) 12.81 | 13.0402±0.0008 | 0.0086±0.0009 | 0.29±0.03                       |
|            | \([\text{NeIII}]\) 15.56 | 15.8241            | 0.015                       | <0.07                            |
| 0003       | PAH 11.3 | 11.51              | 0.11                        | <0.19                            |
|            | \([\text{H}_{2}]\) 0-0S(2) | 12.4958±0.0012 | 0.0075±0.0013 | 0.13±0.02                       |
|            | \([\text{NeII}]\) 12.81 | 13.0411±0.0011 | 0.0065±0.0010 | 0.15±0.02                       |
|            | \([\text{NeIII}]\) 15.56 | 15.8241            | 0.015                       | <0.08                            |
| 0004       | \([\text{H}_{2}]\) 0-0S(0) | 28.72              | 0.20                        | <0.07                            |
|            | \([\text{SII}]\) 33.48 | 34.07              | 0.24                        | <0.38                            |
|            | \([\text{SII}]\) 34.82 | 35.43              | 0.25                        | <0.49                            |
| 0005       | \([\text{H}_{2}]\) 0-0S(0) | 28.72              | 0.20                        | <0.14                            |
|            | \([\text{SII}]\) 33.48 | 34.07              | 0.24                        | <0.24                            |
|            | \([\text{SII}]\) 34.82 | 35.43              | 0.25                        | <0.20                            |

### Table 6. Properties of emission lines in the NGC 4696 Spitzer spectra. Note that the line widths are the gaussian sigma values.

| Exposure id | Line   | Wavelength (microns) | Width (\(\sigma\)) (microns) | Flux \((\times 10^{-14} \text{ erg cm}^{-2} \text{s}^{-1})\) |
|------------|--------|---------------------|-----------------------------|----------------------------------|
| 0002       | PAH 11.3 | 11.32±0.017        | 0.15±0.02                   | 1.44±0.2                         |
|            | \([\text{H}_{2}]\) 0-0S(2) | 12.408±0.003 | 0.009                      | 0.17±0.03                         |
|            | \([\text{NeII}]\) 12.81 | 12.9469±0.0003 | 0.0101±0.0003 | 1.13±0.03                         |
|            | \([\text{NeIII}]\) 15.56 | 15.7184±0.0005 | 0.0131±0.0006 | 0.66±0.02                         |
| 0003       | PAH 11.3 | 11.33±0.016        | 0.11±0.019                  | 1.75±0.21                         |
|            | \([\text{H}_{2}]\) 0-0S(2) | 12.411±0.004 | 0.009                      | 0.18±0.04                         |
|            | \([\text{NeII}]\) 12.81 | 12.9488±0.0003 | 0.0096±0.0004 | 0.98±0.03                         |
|            | \([\text{NeIII}]\) 15.56 | 15.7207±0.0004 | 0.0130±0.0004 | 0.58±0.02                         |
| 0004       | \([\text{H}_{2}]\) 0-0S(0) | 28.497            | 0.20                        | <0.12                            |
|            | \([\text{SII}]\) 33.48 | 33.811             | 0.24                        | <0.94                            |
| 0005       | \([\text{H}_{2}]\) 0-0S(0) | 28.497            | 0.20                        | <0.10                            |
|            | \([\text{SII}]\) 33.48 | 33.811             | 0.24                        | <1.60                            |
|            | \([\text{SII}]\) 34.82 | 35.1740±0.0021    | 0.0363±0.002 | 3.05±0.18                         |
Table 7. H$_\alpha$+[NII] emission line fluxes in Spitzer apertures measured from maps of Conselice et al (2001) (NGC 1275) and Crawford et al (2005) (NGC 4696). To account for the Spitzer point spread function, the maps were smoothed with a gaussian kernel of FWHM of 3.10 arcsec for the short wavelength aperture measurements and by gaussian with a FWHM of 6.17 arcsec for the long wavelength aperture measurements. No measurement is available for the NGC 4696 LH apertures as these cover a region of the image in which the off-line image is saturated. The NGC 1275 values have been corrected for a reddening corresponding to $A_R = 0.4$.

| Region            | Exposure id | Spectrograph | Flux $(\times 10^{-13} \text{ erg cm}^{-2} \text{s}^{-1})$ |
|-------------------|-------------|--------------|--------------------------------------------------------|
| NGC 1275 East     | 0002        | SH           | 5.8                                                   |
|                   | 0003        | SH           | 4.8                                                   |
|                   | 0004        | LH           | 16                                                    |
|                   | 0005        | LH           | 15                                                    |
| NGC 1275 Position 2 | 0002        | SH           | 1.1                                                   |
|                   | 0003        | SH           | 1.0                                                   |
|                   | 0004        | LH           | 2.7                                                   |
|                   | 0005        | LH           | 2.8                                                   |
| NGC 1275 Position 11 | 0002       | SH           | 0.83                                                  |
|                   | 0003        | SH           | 0.68                                                  |
|                   | 0004        | LH           | 1.7                                                   |
|                   | 0005        | LH           | 1.4                                                   |
| NGC 1275 Position 2 | 0002        | SH           | 1.7                                                   |
|                   | 0003        | SH           | 1.5                                                   |
|                   | 0004        | LH           | –                                                     |
|                   | 0005        | LH           | –                                                     |
| NGC 4696          | 0002        | SH           | –                                                     |
|                   | 0003        | SH           | –                                                     |
|                   | 0004        | LH           | –                                                     |
|                   | 0005        | LH           | –                                                     |

Figure 4. Upper: Spitzer SH (exposure id 0002) and Lower: Spitzer LH (exposure id 0004) spectra for the NGC 1275 East pointing. Dashed vertical lines show the boundary between adjacent spectral orders.

Figure 5. Upper: Spitzer SH (exposure id 0002) and Lower: Spitzer LH (exposure id 0004) spectra for the NGC 1275 Position 2. Dashed vertical lines show the boundary between adjacent spectral orders.
these assumptions, we find that 40 per cent of the flux in exposure id 0002 comes from the HII region while only 14 per cent of the flux in exposure id 0003 comes from the HII region. We can also solve for the contribution from the extended [NeIII] flux in the Spitzer apertures (previously assumed to be the same for exposure ids 0002 and 0003) and the total [NeIII] flux from the HII region; we obtain $3.86 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ and $7.26 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ respectively. This suggests that there is a strong [NeIII] emission component which is extended over the aperture of the NGC 1275 East region.

Gas that is photoionized by a stellar or power law continuum generally has a temperature around 10,000 K (Osterbrock & Ferland 2006). The lack of optical [O III] emission at a position where infrared [Ne III] lines are seen suggests that the electron temperature is low enough to prevent optical emission from being produced. Preliminary models using the code Cloudy (Ferland et al. 1998) show that this requires a temperature less than several thousand Kelvin. Low temperatures in a photoionized gas are produced when the abundances are at or above solar and the gas density is low enough for the infrared fine structure lines to carry the cooling (Ferland et al. 2006, Shields & Kennicutt 1995). These calculations show that metallicities in the range of solar to twice solar can produce a temperature low enough to account for the unobserved [O III] optical emission. We intend to present detailed models in support of this conclusion in a future paper.

The central region of NGC 4696 is reported to have
We note that the SIII] λ5007/Hβ ~ 0.2 in a 13.2 × 1.5 arcsec region emission at position angle 85 deg 5 arcsec south of the nucleus (Johnstone et al. 1987) and [OIII] λλ5007/Hβ < 0.4 in a region 1.8 × 1.0 arcsec centred on the nucleus Lewis et al. 2003. In contrast, the ratio in the NGC 1275 HII region is much higher at ~ 0.8. The [NeIII]/[NeII] ratio in NGC 1275 East is 0.30 compared with 0.58 in the NGC 4696 spectrum, suggesting the high metallicity explanation for the weakness of the [OIII] lines may be at work here too. We note that the inner region of the Centaurus cluster is known to have a high metallicity (eg Sanders & Fabian 2006) although the exact value derived for the very central regions is dependent on the precise model fitted.

3.3 Density diagnostic

We note that the [SIII] λ18.71/[SIII] λ33.48 line ratio is a density diagnostic. In the NGC 1275 East and NGC 4696 pointings we have detections of λ18.71 and upper limits for λ33.48. Taking the ratio of the average of the line fluxes (or upper limits), having used the Hα fluxes in the Spitzer apertures to scale the fluxes to account for the different spatial sampling as in section 3.2, gives [SIII] λ18.71/[SIII] λ33.48 > 0.6 for NGC 1275 East. Cloudy (Ferland et al. 1998) models show that this ratio corresponds to a density of > 100 cm⁻³. No constraint is placed on the density for the NGC 4696 pointing as we are unable to scale the fluxes for the aperture effects due to saturation in the Hα image.

3.4 PAH features

11.3 μm PAH features are detected in the spectra of NGC 1275 East and NGC 4696. The flux is strong and comparable to that of [NeII]. No detection is made for Perseus positions 2 and 11 which are at greater distances from the centre of the galaxy than Perseus East. The limit on this region is less than about one third of that of [NeII] indicating that either the abundance of PAHs or the excitation mechanism is much reduced there. Peeters et al. (2004) argue that PAH features are tracers of star formation, particularly of B stars. Parts of NGC 1275 have an A-type spectrum (Minkowski 1968 AJ) which indicates some, possibly sporadic, star formation; the situation in NGC 4696 is uncertain due to the obvious dust lanes. The correlation between the presence of a PAH feature and a stellar continuum in the IRS spectrum in NGC 1275 supports an excitation mechanism involving the far UV light from moderately young stars.

In a Spitzer study using IRS and Multiband Imaging Photometer (MIPS) observations of 7 nearby dusty elliptical galaxies including NGC 4696, Kaneda et al. (2006) find PAH emission from the centre and evidence for by dust emission which is more extensive than the starlight of the galaxy in the MIPS data. 

3.5 Molecular Hydrogen Lines

In figure 8 we plot the molecular hydrogen 0-0 S(1) flux against the Hα + [NII] flux for all the NGC 1275 and NGC 4696 pointings. The flux in the Spitzer 0-0 S(1) molecular line hydrogen seems to correlate well with the flux in the optical Hα + [NII] lines. The fit is a straight line constrained to go through the origin and shows that the flux in the 0-0 S(1) line is 0.03 × the flux in the Hα + [NII] complex.

To investigate the molecular hydrogen in more detail we can combine the mid-infrared pure rotational emission lines with emission lines from the 1-0 S(1) ro-vibrational states visible in the K-band.

3.5.1 Near-infrared observations and data reduction

The Spitzer apertures at positions 2 and 11 in the NGC 1275 nebula cover similar sky positions to the K-band United Kingdom Infrared Telescope (UKIRT) CGS4 long-slit observations of the ‘horseshoe knot’ and the ‘SW1’ region of Hatch et al. (2005). Noting that the entrance apertures for the Spitzer spectrographs are a different shape and size to the region extracted from the CGS4 slit we use the Hα and H2 ro-vibrational line fluxes of these two regions from Hatch et al. (2005), together with the Spitzer mid-infrared H2 rotational line fluxes of positions 2 and 11 to investigate the molecular hydrogen in these outer regions of the nebula. Full details of the observations and data reduction of the K-band data from these regions are provided in Hatch et al. (2005).

The Spitzer aperture covering the East region does not match well to the Eastern slit region of Hatch et al. (2005). Instead we have used UKIRT UIST HK-band longslit spectra of the bright radial filament that extends from a region 2.65 arcsec South of the galaxy nucleus eastward to a distance of 26.8 arcsec (9.5 kpc). The observations were obtained on 2005 January 31, and the sky conditions were photometric. The long-slit was used in a 7 pixel-wide (0.84 arcsec) configuration with a spatial scale of 0.1202 arcsec pixel⁻¹, using the HK grating which gives a spectral coverage of 1.4 – 2.5 μm at a resolution of 700 – 1260 km s⁻¹. The observations were taken in NDSTARE mode with an object-sky-object nodding pattern. Details of the observation are provided in Table 8. Sky emission features were mostly removed by the nodding pattern, flux calibration was achieved using a set of almost featureless F and G type stars of known magnitude. In each of the standards a B97 stellar feature at 2.166μm was removed by linear interpolation. The data were reduced with ORAC-DR available through the UKIRT Website, and Starlink packages.
Additionally, near-infrared Hα summing the flux across the entire region where the more northerly Spitzer aperture overlaps with the UIST aperture. This results in a total long-slit aperture of 0.84 × 6.6 arcsec². Fig. 10 shows the NGC 1275 East near-infrared spectrum over the wavelength range 1.74 – 2.48 µm. The wavelength range 1.8 – 1.88 µm is a region of poor atmospheric transmission and has been masked out of the spectrum for clarity. Errors are from Poisson statistics.

A spectrum was extracted from the UIST long-slit data by summing the flux across the entire region where the more northerly Spitzer aperture overlaps with the UIST aperture. This results in a total long-slit aperture of 0.84 × 6.6 arcsec². Fig. 10 shows the NGC 1275 East near-infrared spectrum over the wavelength range 1.74 – 2.48 µm. The wavelength range 1.8 – 1.88 µm is a region of poor atmospheric transmission and has been masked out of the spectrum for clarity of the emission-line features. The molecular hydrogen emission lines and Pα are clearly visible. Table 9 lists the surface brightnesses of all the emission lines. These intensities are lower limits because of the unknown covering factor of the excited molecular hydrogen gas.

3.5.2 Scaling the mid-infrared H₂ emission to compare with the near-infrared emission

As discussed in Section 3.2, we have assumed that the mid-infrared line emission is distributed spatially like the Hα emission. The near-infrared H₂ line emission has been shown to closely follow the Pα emission in other brightest cluster galaxies (Jaffe et al. 2005). Additionally, near-infrared H₂ emission lines are only detected in NGC 1275 in the regions of brightest Hα emission (Hatch et al. 2005). To examine the relationship between the atomic hydrogen emission and the near-infrared molecular hydrogen emission within NGC 1275 in detail, we have analysed the whole length of the NGC 1275 East HK-band long-slit data. The long-slit data were segregated into seven regions in which Pα was detected. Fig. 11 plots the Pα flux and Pα/1 – 0 S(1) line ratio against projected distance from the galaxy nucleus for all seven regions. This figure shows that the Pα/1 – 0 S(1) ratio is almost constant across a large part of Pα emission. We therefore assume that the Pα emission and near-infrared H₂ line emission are closely related spatially in NGC 1275. Therefore we can scale and combine the near-infrared and mid-infrared H₂ emission lines using the flux of the hydrogen recombination lines in the Spitzer and long-slit apertures.

We have assumed case B recombination such that Hα/Pα = 8.45 (Osterbrock & Ferland 2006), and used Table 7 with the Pα intensity of position 2 (given in Hatch et al. 2005), and the NGC 1275 East region (see Table 9) to scale the mid-infrared H₂ line fluxes given in Tables 8 and 9 to the same spatial region in which the near-infrared lines were measured. Position 11, which corresponds to the ‘horseshoe knot’ in Hatch et al. 2005, does not have a measured Pα intensity as the line was badly affected by the poor atmospheric transmission in that part of the spectrum. Therefore we have assumed that the Pα/1 – 0 S(1) ratio is 1.45 as shown in Fig. 11 and used the same scaling relations as mentioned above. There will be some extra uncertainty associated with this assumption.

Table 8. Details of the UIST long-slit observation of the NGC 1275 East region. The orientation of the nodding direction is described in the UIST manual. Position angle is measured East from North.

| Target position (J2000) | Slit angle (degrees) | Nod offset (arcsec) | Exposure time (mins) | Seeing (arcsec) |
|------------------------|----------------------|---------------------|---------------------|----------------|
| 03 19 48.16            | +70                  | +38, -23            | 144                 | 0.4            |
| 41 30 40.1             |                      |                     |                     |                |

Table 9. Near-infrared line surface brightnesses for the NGC 1275 East region together with 1σ uncertainties. The value for the 2 – 1 S(1) line is a 3σ upper limit.

| Line     | Surface Brightness x 10⁻¹⁶ erg s⁻² cm⁻² arcsec⁻² |
|----------|--------------------------------------------------|
| Pα       | 1.73 ± 0.08                                      |
| H₂ 1 – 0 S(0) | 0.24 ± 0.05                                     |
| H₂ 1 – 0 S(1) | 1.26 ± 0.08                                     |
| H₂ 1 – 0 S(2) | 0.55 ± 0.05                                     |
| H₂ 1 – 0 S(3) | 1.43 ± 0.05                                     |
| H₂ 1 – 0 S(4) | 0.23 ± 0.08                                     |
| H₂ 1 – 0 S(7) | 0.35 ± 0.03                                     |
| H₂ 1 – 0 Q(1) | 1.17 ± 0.11                                     |
| H₂ 1 – 0 Q(3) | 1.09 ± 0.11                                     |
| H₂ 2 – 1 S(1) | <0.12                                            |

Figure 10. Near-infrared spectrum of the NGC 1275 East region. The region between 1.8 – 1.88 µm has poor atmospheric transmission and has been masked out of the spectrum for clarity. Errors are from Poisson statistics.

Figure 11. Pα/1 – 0 S(1) ratio along the UIST long-slit covering the NGC 1275 East region. The solid line shows the mean Pα/1 – 0 S(1) of 1.45. Error bars are at 1σ level. The ratio of atomic-to-molecular hydrogen line emission is fairly constant across a large range of Pα emission.
As discussed above, the low $2 - 1 \ S(1)/1 - 0 \ S(1)$ line fluxes are $3\sigma$ upper limits as the line is not detected in any region.

Table 10. The intensity ratio of $H_2 \ 2 - 1 \ S(1)/1 - 0 \ S(1)$ lines in the three regions of NGC 1275. The $2 - 1 \ S(1)$ line fluxes are $3\sigma$ upper limits as the line is not detected in any region.

| Region       | $2 - 1 \ S(1)/1 - 0 \ S(1)$ |
|--------------|-------------------------------|
| NGC 1275 East| <0.097                        |
| Position 2   | <0.26                         |
| Position 11  | <0.44                         |

3.5.3 Excitation process

Molecular hydrogen can be collisionally excited, or radiatively excited by absorption of UV photons in the Lyman-Werner bands. If the density is low enough ($< 10^4 \ cm^{-3}$) the molecule will de-excite through the ground electronic ro-vibrational states by radiative de-excitations, whereas if the density is high, the populations of the rotational and vibrational states will be redistributed by collisions before de-excitation to the ground level. The form of the observed spectrum depends on the excitation source as well as the density and temperature of the gas. At high temperatures and densities the collision rate of the $H_2$ molecule with other molecules and atomic species increases. Collisional de-excitation therefore becomes more important than radiative de-excitations as the temperature and density increase. The total gas density at which collisional de-excitation rate equals the radiative de-excitation rate is known as the critical density and is a slow function of temperature (Sternberg & Dalgarno 1989; Mandy & Martin 1993). When collisional excitation or de-excitation dominates, the gas exists in local thermodynamic equilibrium (LTE) and the molecular hydrogen has an ortho-to-para ratio of three.

Mouri (1994) reports that (at least in many published models) the $H_2 \ 2 - 1 \ S(1)/1 - 0 \ S(1)$ line intensity ratio is an indicator of the realtive strengths of radiative and collisional processes. In what follows, we assume this result and also that reddening can be ignored (it is quite small in this part of the spectrum).

$3\sigma$ upper limits for the $2 - 1 \ S(1)$ emission lines were measured from the position 2, 11 and the NGC 1275 East regions and the limits on the $2 - 1 \ S(1)/1 - 0 \ S(1)$ ratios are given in Table 10. The measured ratio is significantly less than the pure radiative de-excitation value of 0.53, so the gas is predominately de-excited through collisions, perhaps with a small non-thermal component. This implies that the gas must have a density of greater than $10^4 \ cm^{-3}$.

3.5.4 Excitation temperatures, column densities and mass of warm molecular hydrogen

As discussed above, the low $2 - 1 \ S(1)/1 - 0 \ S(1)$ ratio suggests that collisional de-excitation dominates. Collisions share the energy between the particles causing the $H_2$ to be in LTE. The excited states of $H_2$ ($N(v,J)$) will be populated in a thermalised Boltzmann distribution characterised by an excitation temperature ($T_{ex}$) such that

$$N(v,J) = \frac{4\pi\lambda I}{A_{ul}h\nu_c},$$

(2)

where $\lambda$ is the rest wavelength of the line and $A_{ul}$ is the Einstein coefficient taken from Turner et al (1977). In all calculations an ortho-to-para ratio of 3 has been assumed. If the $H_2$ level populations are completely dominated by collisional excitation and de-excitation then the excitation temperature equals the kinetic temperature of the gas.

Population diagrams of $ln[N(v,J)/g_J]$ versus $E(v,J)/k_B T_{ex}$ allow investigation of whether the levels are thermalised. If the levels are thermalised the level populations will lie in a straight line with a slope inversely proportional to the excitation temperature. If a range of gas temperatures occur along the line-of-sight, the points will lie on a smooth curve with the lower energy levels lying on a steeper slope (lower temperature) than the higher energy levels (higher temperature). This is because the higher energy levels are populated at higher temperatures.

Population diagrams for the NGC 1275 East, position 2 and position 11 regions are presented in Figs. 12, 13 and 14. As the population of the states lie on a smooth-curve, these diagrams clearly show that the molecular hydrogen exists at a range of temperatures. To gain a simple picture of the structure of the molecular gas we have measured the rotational temperature from the $0 - 0 \ S(1)$ and $0 - 0 \ S(2)$ lines, and a ro-vibrational temperature from the $1 - 0 \ S(1)$ lines. In the NGC 1275 East HK-band spectrum we measured a $1 - 0 \ S(7)$ line therefore we measure two ro-vibrational excitation temperatures in this region: one from levels with an upper energy of $< 8000 \ K$ and one from levels with an upper energy of $> 8000 \ K$. These excitation temperatures are given in Table 11. The rotational temperatures of the gas are $330 - 370 \ K$ for all regions. The ro-vibrational lines reveal a layer of hotter gas at $1700 - 2000 \ K$ and in NGC 1275 East there is an additional layer of even hotter gas at $\sim 2600 \ K$.

The total $H_2$ column density of the molecular hydrogen can be calculated through rearranging equation (1) and assuming that all the molecular hydrogen exists in LTE at the excitation temperature derived from the population diagrams.

$$N_{Total} = \frac{N(v,J)Z(T)}{g_Je^{-E(v,J)/k_BT_{ex}}},$$

(3)
Table 11. Excitation temperatures, column densities and masses of molecular Hydrogen. The observed mass is calculated directly from the observed flux in the relevant aperture. The scaled mass is the mass scaled to the region in which the ro-vibrational lines were observed. Error bars are at the 1σ level.

|                    | rotational emission lines | ro-vibrational (2000 < $E_U <$ 8000 K) | ro-vibrational ($E_U >$ 8000K) |
|--------------------|---------------------------|----------------------------------------|--------------------------------|
| NGC 1275 East      |                           |                                        |                                |
| $T_{ex}$           | 330±20 K                  | 1730±210 K                             | 2580±160 K                     |
| Column density     | 4.2×10^{18} cm$^{-2}$     | 4.4×10^{18} cm$^{-2}$                  | 3.4×10^{18} cm$^{-2}$          |
| Observed mass of H$_2$ | 2.0×10$^6$ M$_\odot$     | 180 M$_\odot$                         | 73 M$_\odot$                  |
| Scaled mass of H$_2$ | 6.6×10$^6$ M$_\odot$     | 180 M$_\odot$                         | 73 M$_\odot$                  |
| NGC 1275 Position 2 |                           |                                        |                                |
| $T_{ex}$           | 370±20 K                  | 1730±310 K                             |                                 |
| Column density     | 2.6×10^{18} cm$^{-2}$     | 1.3×10^{18} cm$^{-2}$                  |                                |
| Observed mass of H$_2$ | 3.8×10$^5$ M$_\odot$     | 175 M$_\odot$                         |                                |
| Scaled mass of H$_2$ | 3.4×10$^5$ M$_\odot$     | 175 M$_\odot$                         |                                |
| NGC 1275 Position 11 |                          |                                        |                                |
| $T_{ex}$           | 370±45 K                  | 2060±950 K                             |                                 |
| Column density     | 4.5×10^{18} cm$^{-2}$     | 1.1×10^{18} cm$^{-2}$                  |                                |
| Observed mass of H$_2$ | 2.0×10$^6$ M$_\odot$     | 70 M$_\odot$                          |                                |
| Scaled mass of H$_2$ | 2.9×10$^6$ M$_\odot$     | 70 M$_\odot$                          |                                |
| NGC 4696           |                           |                                        |                                |
| $T_{ex}$           | 310±10 K                  |                                        |                                |
| Column density     | 3.5×10^{18} cm$^{-2}$     |                                        |                                |
| Observed mass of H$_2$ | 1.7×10$^5$ M$_\odot$     |                                        |                                |

Figure 13. Population diagram of NGC 1275 position 2 with 1σ error bars. The datapoints at $E = 1015$ K and 1682 K are measured by Spitzer and the error bars include the uncertainty in scaling the mid-infrared emission to the near-infrared emission using hydrogen recombination lines.

Figure 14. Population diagram of NGC 1275 position 11 with 1σ error bars. The datapoints at $E = 1015$ K and 1682 K are measured by Spitzer, but the error bars do not include any uncertainty associated with scaling the mid-infrared emission lines.

where $Z(T)$ is the partition function.

As the molecular hydrogen exists at multiple temperatures we have assumed the gas consists of two (or three in the case of NGC 1275 East) separate populations, each consisting of a Boltzmann distribution at the excitation temperatures derived from the population diagrams. A least squares fit was performed with the total column densities of each Boltzmann distribution as the two (or three) free parameters. Column densities at each excitation temperature for the three regions are given in Table 11.

The mass of warm molecular hydrogen within the Spitzer aperture can be derived from a single line luminosity and the excitation temperature. The total molecular hydrogen mass $M_{\text{Total}}$ is derived from:

$$M_{\text{Total}} = \frac{4}{3} M_{H_2} n_{\text{total}},$$

where $M_{H_2}$ is the mass of a hydrogen molecule, and $n_{\text{total}}$ is the total number of H$_2$ molecules. $n_{\text{total}}$ can be derived from the luminosity from the $(v, J)$ state through:

$$n_{\text{total}} = \frac{L(v, J) Z_{T_{\text{ex}}}}{A_{\text{ul}} h \nu g_J e^{-E(v, J)/k_B T_{\text{ex}}}},$$

where $L(v, J)$ is the luminosity in the $(v, J)$ line, $Z_{T_{\text{ex}}}$ is the partition function, $A_{\text{ul}}$ is the Einstein co-efficient, and $\nu$ is the frequency of the line. The masses of the ~350 K material in each of the Spitzer apertures were calculated from the 0-0 S(1) line. The mass derived from the 0-0S(2) line was the same as that measured from the 0-0S(1) line. The masses of the warmer gas (1700–2000 K) were...
measured using the 1-0S(1) line. A check was made using the other detected lines 1-0S(2), 1-0S(3), 1-0S(4) and the masses derived from these lines were within 10 per cent of the massess derived from the 1-0S(1) line. Finally the mass of the 2580K material seen in the NGC 1275 East region was measured from the 1-0S(7) line. The masses of molecular hydrogen derived from the different temperature lines are given in Table 3.2 as the “Observed mass of H2”. In the rows labelled “Scaled mass of H2” we list the masses of molecular hydrogen at each temperature scaled to the region in which the ro-vibrational lines were measured; the Spitzer masses were scaled down by the ratio of Hα fluxes in the relative apertures, as described in Section 3.5.2. The majority of the molecular gas exits at lower temperatures with less than 0.5 per cent of the total mass being at the higher temperatures.

3.5.5 Pressure balance between the molecular, atomic and X-ray emitting gas

There is a serious problem implied by the apparent thermal distribution of the levels in the molecular hydrogen. This is that the currently used collisional rates for the ro-vibrational states require that the density exceeds $10^{15}$ cm$^{-3}$ (Stenberg & Dalgarno 1989; Mandy & Martin 1992). If the temperature is few $\times$ 1000 K then the pressure is $10^{-5}$ cm$^{-2}$ K. This exceeds the ambient pressure, as determined from the X-ray measurements of the hot gas (Sanders et al. 2005), by an order of magnitude or more. This does not appear to be a stable situation for such thin, apparently long-lived, filaments.

Recent studies have brought the H2 collision database into question. The Orion Bar is the closest and best studied H2 / Hα / H2 interface (O’Dell 2001). Allers et al. (2005) found that H2 rotational lines implied level populations that were close to a thermal distribution. They noted that the density within the Bar is too low to thermalize the levels involved if the current H2 collision rates are correct. They suggest that current H - H2 vibrational de-excitation rates should be increased by nearly two orders of magnitude (their Table 6). If this were the case then H2 level populations could reach a thermal distribution at the low densities implied by the pressure of the hot gas. Our data are further evidence that the de-excitation rates may require a large correction.

3.5.6 Predicted 0-0 S(0) flux

We have used the temperatures and column densities of molecular hydrogen derived from the lines detected in the SH spectrograph to estimate the expected flux in the H2 0 - 0 S(0) line. However since this line is only covered by the LH spectrograph which has a larger aperture, we have scaled our predictions by the ratio of the fluxes of the Hα+[NII] lines (Table 7) in the two apertures. These predictions for the strength of the 0 - 0 S(0) lines in the NGC 1275 regions are given in Table 12 and are all below the detection limits in our spectra. We cannot carry out the scaling for the NGC 4696 pointing as the region of the Hα+[NII] map covered by the LH aperture is affected by saturation. We therefore quote the flux predicted for the SH aperture, which is $0.02 \times 10^{-14}$ erg cm$^{-2}$s$^{-1}$.

4 DISCUSSION

Using high resolution mid-infrared spectra from the Spitzer Space Telescope we have detected off-nuclear emission lines in NGC 1275 and NGC 4696. The lines arise from pure rotational transitions of the Hydrogen molecule, atomic fine-structure transitions from Ne$^+$, Ne$^{++}$, S$^{++}$ and Si$^+$ and the 11.3 micron PAH feature.

The relative intensities of the molecular hydrogen lines are consistent with collisional excitation and probe a new region of temperature space in the filaments at 300–400 K. Pressure equilibrium with the surrounding intracluster medium requires a substantial revision to H2 collision rates, as noted by Allers et al (2005). The outer filaments around NGC 1275 therefore have molecular gas at 50 K (CO, from P. Salomé et al, in preparation), 300–400 K (H2, this paper) and 2000–3000 K (H2, Hatch et al 2005), atomic gas at several 1000 K (Hα, e.g. Conselice et al 2001) and $\sim$ 10$^7$ K (Fabian et al 2003), embedded in the hot intracluster gas at about 5 x 10$^7$ K. Detection of OVI from more central regions with FUSE (Bregman et al 2004) suggests that gas at $\sim$ 3 x 10$^5$ K is also likely to be present.

The discovery of the [NIII] lines is unexpected based on the weakness of the optical [OIII] lines and suggests that the electron temperature in the filamentary medium where these lines are formed may be very low, possibly due to enhanced metalicity. The metal abundance of the central intracluster medium in cool cluster cores is enhanced by Type Ia, and possibly Type II supernova (Sanders & Fabian 2006 and references therein), so the filaments are enriched if they originate from cooling of that gas.

Collectively the mid-IR emission lines radiate about one quarter of the flux in Hα, so they play a relatively minor role in the energy flow in the filaments. However the total molecular hydrogen emission, including the near IR ro-vibrational lines is comparable to the emission from Hα. (Hα is about one tenth of the total line emission; the major emitter is expected to be Lyα.) Nevertheless they reveal more about the low temperature core to the filaments which is dominated in mass by H2. The total mass in H2 for NGC 1275, obtained from the CO emission using a standard Galactic conversion ratio, is $\sim$ 4 $\times$ 10$^7$ M$_{\odot}$ (Salomé et al 2006), most of it near the centre of the galaxy. The mass in H2 at 300 K is about 8 $\times$ 10$^7$ M$_{\odot}$, assuming that the masses found for the outer filaments in this paper scale linearly with Hα emission, and using the total Hα flux of Conselice et al (2001). The total mass of Hα emitting gas is smaller at about 3 $\times$ 10$^5$ M$_{\odot}$ and the mass of surrounding soft X-ray emitting gas, with temperature $\sim$ 7 x 10$^6$ K, is about 10$^5$ M$_{\odot}$ (Fabian et al 2006).

Further observations are required to test whether all filaments have similar composition and properties, but they do appear to be predominantly molecular.

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Table 12. The predicted flux of the 0 – 0 S(0) emission line in the LH spectrograph.

| Region         | 0 – 0 S(0) flux (10$^{-14}$ erg cm$^{-2}$s$^{-1}$) |
|----------------|---------------------------------------------------|
| NGC 1275 East  | 0.22                                              |
| NGC 1275 Position 2 | 0.04                                |
| NGC 1275 Position 11 | 0.02                                              |
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