The nature of the molecular gas system in the core of NGC 1275

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Accepted 2005 February 21. Received 2005 February 18; in original form 2004 August 31

ABSTRACT
We present near-infrared integral field spectroscopy of the central kiloparsec of NGC 1275 at the heart of the Perseus cluster of galaxies, obtained with the Integral Field Unit (IFU) of the United Kingdom Infrared Telescope (UKIRT) Imaging Spectrometer (UIST). The nuclear ro-vibrational H2 emission is spatially resolved and is likely to originate approximately 50 pc from the active nucleus. The Paα emission is, by contrast, spatially unresolved. The requirements for thermal excitation of the H2 by nuclear X-radiation, its kinematics on subarcsec scales and its stability against self-gravity together suggest that the observed H2 is part of a clumpy disc rotating about the radio-jet axis. The sharp jump in the H2 velocity across the nucleus implies a black hole mass of 3.4 × 10⁸ M⊙, with a systematic error of ±0.18 dex due to the uncertainty in the radio-jet inclination. This agrees well with the value implied by the empirical correlation between black hole mass and stellar velocity dispersion for nearby elliptical galaxies, and is ∼100 times the stellar mass in this region.

Key words: galaxies: active – cooling flows – galaxies: individual: NGC 1275 – infrared: galaxies.

1 INTRODUCTION
For several years, NGC 1275 at the centre of the Perseus cluster held the unique distinction of being the only galaxy in a cooling flow cluster for which CO emission from molecular gas had been detected (Inoue et al. 1996; Bridges & Irwin 1998, and references therein). The fact that it is also a well-known galaxy merger – as well as having been classified a Seyfert 1, a BL Lac and a Fanaroff–Riley type I (FR I) radio source – served to obscure any causal connection between the CO and the cooling flow. The failure to detect molecular gas in other such systems thus led to a heated debate over the validity of the cooling flow model. The latter model proposed that hot gas at the centres of relaxed clusters of galaxies was cooling out from the hot phase at rates of hundreds or thousands of solar masses per year (Fabian 1994). Recent developments on two separate fronts have however helped to bridge the impasse.

First, X-ray data from Chandra and XMM–Newton have shown that cooling rates were vastly overestimated in the past (e.g. Schmidt, Allen & Fabian 2001), and X-ray grating spectra have also revealed a deficit of line emission from gas cooling below temperatures T_vib/3 (Peterson et al. 2003). Explanations for these findings include rapid mixing of hot and cold phases, inhomogeneously distributed metals in the intracluster medium (Fabian et al. 2001, 2002), active galactic nucleus (AGN) heating by jets (Brüggen & Kaiser 2002) and sound waves (Fabian et al. 2003), thermal conduction (Voigt et al. 2002), and a significant relativistic cosmic ray component frozen into the thermal gas (Cen 2005).

Secondly, using more sensitive receivers, Edge (2001) has detected CO emission in 16 cooling flow central galaxies, consistent with 10⁷−10¹¹ M⊙ of H2 at 40 K (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 a much hotter molecular gas component in these systems has also been established, via near-infrared surveys of the ro-vibrational H2 lines. Building on some earlier work (Elston & Maloney 1992; Jaffe & Bremer 1997; Falcke et al. 1998; Jaffe, Bremer & van der Werf 2001), Edge et al. (2002) performed an H + K-band spectroscopic survey of 32 line-luminous central cluster galaxies, and showed that the H2 emission correlates in strength with the CO and Hα emission. Analysis by Wilman et al. (2002) showed that the lower-lying H2 lines are thermally excited in dense gas (n > 10⁶ cm⁻³) at T ∼ 2000 K. The inferred gas pressure (nT) thus exceeds 10⁶ cm⁻³ K, some two to three orders of magnitude higher than that in either the diffuse X-ray or optical emission-line gas. There must be a close physical connection between the H2 and optical emission-line clouds, because the H2/Hα ratio is observed to be constant over two orders of magnitude in Hα luminosity. Narrow-band Hubble Space Telescope (HST) Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) imaging of three central cluster galaxies by Donahue et al. (2000) had earlier shown that the hot H2 and hydrogen recombination emission lines have similar morphologies.
Following on from our spectroscopic survey in Edge et al. (2002), we have begun detailed studies of individual objects to analyse the relationship between the various ionized and molecular gas systems. Here we present $H$- and $K$-band area spectroscopy of the centre of NGC 1275 using the United Kingdom Infrared Telescope (UKIRT) Imaging Spectrometer (UIST) Integral Field Unit (IFU). From narrow-band $HST$ observations of this target, Donahue et al. (2000) found that the bulk of the ro-vibrational emission originates in the nuclear source, with some diffuse emission lying up to a kiloparsec away. With the UIST IFU we can map this emission, infer its excitation state and explore its possible connection to the 1.2-parsec away. With the UIST IFU we can map this emission, infer its excitation state and explore its possible connection to the 1.2-parsec away. With the UIST IFU we can map this emission, infer its excitation state and explore its possible connection to the 1.2-parsec away. With the UIST IFU we can map this emission, infer its excitation state and explore its possible connection to the 1.2-parsec away.

The observations were performed on the nights of 2003 September 24 and 26 using the UIST IFU on the UKIRT. The IFU provides a 6.5 $\times$ 3.4 arcsec$^2$ field of view and works on the image slicing principle, with the focal plane being covered by 14 ‘slits’, which are aligned parallel to the long axis of the field of view and reformatted into a single long slit at the entrance to the dispersion unit. The slits are 0.24 arcsec wide and the pixel size along the slits is 0.12 arcsec. We performed observations with two separate grisms. The first observation was taken with the short-$K$ grism spanning 2.05–2.25 $\mu$m with a spectral resolution of $\sim$3600, and we observed the target with 500-s exposures for a total of 42 min on source (with the usual object–sky–object nodding pattern). A second observation was obtained with the $HK$ grism (resolution $\sim$900), spanning 1.45–2.5 $\mu$m, with 240-s exposures for a total of 52 min on source. The long axis of the IFU was oriented in an east–west direction for both observations. The observations were taken under photometric conditions with atmospheric seeing in the range 0.3–0.4 arcsec, which is well matched to the spatial sampling provided by UIST. For convenience, the two data sets will hereafter be referred to as the ‘short-$K$’ and ‘$HK$’ data, respectively.

Data reduction was performed off-line using the UIST-specific recipes within the ORAC-DR software (Cavanagh et al. 2003) and comprised the usual steps of flat-fielding, sky-subtraction, wavelength calibration, division by an atmospheric standard and flux calibration. The resulting data cubes contain 14 $\times$ 54 spatial elements for each of the 1024 spectral channels. These were cleaned of cosmetic defects such as hot pixels and cosmic rays by use of a median filtering process, whereby a two-dimensional kernel was passed through the cube and at each point pixels deviant from the median value by more than a certain threshold were replaced by the median. The filter was applied five times, during the course of which the replacement threshold was gradually lowered from 5$\sigma$ to 2$\sigma$. Subsequent cube manipulation and spectral analysis were performed with a combination of IDL, IRAF and QDP/PGPLOT.

3 RESULTS

3.1 Emission-line morphologies

We began by deriving from the $HK$ data cube emission-line maps of $H_2 v = 1–0 S(1)$, $[\text{Fe II}] \lambda 1.644$ and Pa$\alpha$, as shown in Fig. 1. They

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Contour plots of the $H_2 v = 1–0 S(1)$, $[\text{Fe II}] \lambda 1.644$ and Pa$\alpha$ emission derived from continuum-subtracted narrow-band cuts on the data cube obtained with the $HK$ grism. The narrow-band images were smoothed with 0.48 arcsec$^2$ top-hat filters prior to contouring. The lowest contour levels are set at 2$\sigma$ of the background in the lower part of each image, and have values of $3.1 \times 10^{-20}$, $5.2 \times 10^{-20}$ and $1.1 \times 10^{-19}$ W m$^{-2}$ for $H_2 v = 1–0 S(1)$, $[\text{Fe II}] \lambda 1.644$ and Pa$\alpha$, respectively. Successive contour levels increase by $\sqrt{2}$. The boxes used for extraction of spectra for the nucleus and a filamentary structure are indicated on the $H_2 v = 1–0 S(1)$ map. The orientation on all three panels is as indicated.
were formed by taking slices through the data cube at the wavelengths of interest, then subtracting the underlying continuum by using line-free regions either side of the line and interpolating the continuum linearly across the line. The detailed spectral decomposition of the continuum by Krabbe et al. (2000) shows that there are no stellar absorption features in the vicinity of these emission lines, and that our continuum subtraction procedure is therefore reliable. The maps show that the emission in all three lines is heavily dominated by the nucleus, and although there is noticeably more extended emission to the west of it than to the east, the ‘filament’ of H\textsubscript{2} is the only feature that can be readily isolated. Its appearance in the narrow-band H\textsubscript{2} image in Donahue et al. (2000) attests to its reality. The H\textsubscript{2} \( v = 1–0 \) S(1) luminosities of this filament and the \( 2 \times 2 \) arcsec\(^2 \) nuclear region are \( 1.8 \times 10^{40} \) and \( 3.0 \times 10^{40} \) erg s\(^{-1} \), respectively. A comparison of our measurement of the H\textsubscript{2} \( v = 1–0 \) S(1) flux in the \( 2 \times 2 \) arcsec\(^2 \) nuclear region (\( 43.0 \pm 0.9 \times 10^{-15} \) erg cm\(^{-2} \) s\(^{-1} \)) with that measured in the central 3 arcsec by Krabbe et al. (2000) (\( 41.1 \pm 2.5 \times 10^{-15} \) erg cm\(^{-2} \) s\(^{-1} \)), demonstrates that there has been no variation in the 8.7 yr between the two observations.

The fine pixel scale of the UIST IFU, coupled with the excellent seeing during the observations, allows us to examine the intensity profiles of the emission within 1 arcsec of the nucleus and to constrain the spatial locations of the emitting regions. Almost 80 and 90 per cent, respectively, of the line and continuum emission in this central region fall in slits 9 and 10, the bulk of it in slit 9, which we refer to hereafter as the ‘peak slit’. In Fig. 2 we show intensity profiles along the peak slit for several emission lines, with the fluxes derived from single Gaussian fits to the profile in the central region (negative offsets to the east). The dashed lines show the contributions from two point sources of emission at \( \pm 0.12 \) arcsec, and the solid line their sum. The latter accounts for the bulk of the emission in the central 0.6 arcsec. Line fluxes were derived from double Gaussian fits to the profiles in the short-\( K \) data (see Section 3.3). The asterisks connected with the dotted line show (with arbitrary normalization) the continuum level below the H\textsubscript{2} \( v = 1–0 \) S(1) line: it is clearly less extended than the line emission and spatially unresolved. A closer look at the H\textsubscript{2} profile is shown in Fig. 3, where the fluxes were derived from double Gaussian fits to the profiles from the higher spectral resolution, short-\( K \), data cube. They show that the H\textsubscript{2} profile has a FWHM = 0.6 arcsec, corresponding to a PSF-deconvolved FWHM = 0.4 arcsec. Indeed, Fig. 3 also demonstrates (but does not of itself prove) that the bulk of the H\textsubscript{2} emission out to radii \( \geq 0.4 \) arcsec can be accounted for by a superposition of two point sources of emission, each located at a radius of approximately 0.15 arcsec from the continuum peak (i.e. the nucleus), which lies between the central two pixels. In contrast, Fig. 3 also demonstrates that the continuum beneath the line – dominated by AGN emission in this central region – is spatially unresolved. Comparison of the continuum fluxes in slits 9 and 10 (not shown) implies that the seeing disc of the unresolved point source is offset by \( \sim 0.06 \) arcsec from the centre of slit 9, towards slit 10. This reflects the precision with which a source can be acquired within the IFU aperture, and hence also limits our determination of the PSF from a single standard star observation.

To summarize our analysis of the emission-line morphologies, we adopt as a working hypothesis a model in which the bulk of the H\textsubscript{2} emission arises in an extended structure located \( \geq 0.15 \) arcsec (50 pc) either side of the nucleus along an east–west axis. Further support for this model comes from an analysis of both the excitation and kinematics of the H\textsubscript{2} emission, which we pursue below.

### 3.2 H\textsubscript{2} excitation

In Fig. 4 we show \( HK \) spectra of the nucleus and the filament referred to in Fig. 1. Also shown is the spectrum of the extended emission within the \( 2 \times 2 \) arcsec\(^2 \) nuclear box, formed by subtracting a scaled version of the spectrum of the central nine pixels (scaled using a PSF observation of a standard star to take account of light from the point source scattered into other pixels). Although it falls in a region of bad atmospheric cancellation, \( Pa\alpha \) appears to be very weak in the circumnuclear spectrum, confirming the result of Fig. 2 that it is spatially unresolved.

To examine the excitation mechanism for H\textsubscript{2}, we begin by comparing the observed H\textsubscript{2} line ratios with the predictions for thermal (collisional) excitation, which dominates in molecular gas with density \( n_T > 10^5 \) cm\(^{-3} \) (the critical density of these transitions), heated to a few thousand kelvin by ultraviolet or X-radiation, or in shocks. Under these conditions, the occupation numbers of the excited vibrational levels of the H\textsubscript{2} molecule will be in thermal equilibrium at a temperature \( T_{kk} \) equal to the kinetic temperature of the gas. Therefore, for a given object, the flux \( F_{\lambda} \) in the \( i \)th emission line will satisfy the relation \( \log(F_{\lambda}/A_{\lambda}g_i) = \text{constant} - T_i/T_{kk} \), where \( \lambda_i \) is...
the wavelength of the line, and $A_v$, $T_v$ and $g_v$ are, respectively, the spontaneous emission coefficient, energy (expressed as a temperature) and statistical weight of the upper level of the transition (the latter assumes an ortho: para H$_2$ abundance ratio of 3:1, appropriate where collisions dominate).

Such plots were constructed for the nucleus, the circumnuclear region and the filament, and are shown in Fig. 5. For the nucleus, we see that the low-lying transitions are completely thermalized, with an excitation temperature of 1360 ± 50 K, implying a gas density above $10^5$ cm$^{-3}$. The excess flux in the higher-excitation transitions may have one of three possible origins. (i) It could be from a much hotter thermalized gas with $T_{ex} = 3100 ± 500$ K (as deduced from a fit to the high-excitation lines only), close to the H$_2$ dissociation temperature of ~4000 K (fitting instead a two-temperature model with the excitation temperature of the hotter component fixed at 3100 K implies that the cooler component has a temperature of 800 ± 50 K). (ii) It could be non-thermal fluorescent emission in low-density gas. (iii) It could be non-thermal emission due to excitation of the molecule by secondary electrons deep in the cloud. We confirm the finding of Krabbe et al. (2000) that on the basis of model (i) the $v = 2$–1 $S(3)$ transition with $T_1 = 13890$ K is underluminous by a factor of ~3, explained by the fact that the upper level of this transition is depopulated by an accidental resonance with photons around the wavelength of H I Lyo at 1216 Å (Black & van Dishoeck 1987). Our excitation temperature for the low excitation lines is slightly lower than that found by Krabbe et al. (2000), who measured 1480 ± 250 K, but our determination is more precise due to our inclusion of several (1–0) Q series lines above 2.4 μm. For the higher excitation lines, Krabbe et al. determined temperatures between 2600 and 2900 K. For the circumnuclear and filament and circumnuclear spectra, we deduce excitation temperatures of 2200 K, as expected for X-ray or shock heating.

Given an excitation temperature, the $v = 1$–0 $S(1)$ fluxes can be converted to masses of hot molecular hydrogen in the following manner. For optically thin emission (which is a valid assumption for these transitions), the H$_2$ column density, $N$(H$_2$), is related to the observed intensity of the $v = 1$–0 $S(1)$ emission, $I$, by the expression $N$(H$_2$) = $4\pi f_{Ah}\nu$, where $A = 3.47 \times 10^{-7}$ s$^{-1}$, $h\nu = 9.37 \times 10^{-13}$ erg, and $f$ is the fraction of H$_2$ molecules in the $v = 1$, $J = 3$ state leading to $v = 1$–0 $S(1)$ emission. Integration over the solid angle on the sky covered by the source implies that the mass of hot H$_2$ is given by $M$(H$_2$) = $4\pi L(1$–0$S(1)) m_{H_2}/f\nu h$, where $L(1$–0$S(1))$ is the $v = 1$–0 $S(1)$ luminosity and $m_{H_2}$ is the mass of the H$_2$ molecule. Computation of the ro-vibrational H$_2$ partition function at various temperatures enables us to deduce the appropriate value of $f$, which varies as follows: 0.00031 (800 K), 0.0049 (1360 K), 0.016 (2200 K), 0.023 (3100 K). Hence, for the nucleus we deduce the following H$_2$ masses: (i) $3.9 \times 10^4 M_\odot$, if all the $v = 1$–0 $S(1)$ is thermal emission at 1360 K; (ii) $1.0 \times 10^5 M_\odot$ at 800 K and $4.5 \times 10^5 M_\odot$ at 3100 K, in the aforementioned two-temperature model. For the circumnuclear and filament spectra, the masses of hot H$_2$ at 2200 K are $3.3 \times 10^4$ and $7.3 \times 10^5 M_\odot$, respectively.

With reference to the work of Maloney, Hollenbach & Tielens (1996), we now assess the energetic requirements for X-ray heating of the molecular gas. As discussed therein, the dominant parameter controlling the physical conditions is $H_X/m$, the ratio of the X-ray energy deposition rate per particle, $H_X$, to the gas density, $n$. The former is the integral over energy of $F(E)\sigma_{pe}$, where $F(E)$ is the
local photon energy flux per unit energy interval and $\sigma_{\text{pc}}$ is the photoelectric cross-section per hydrogen atom. For an X-ray source with a power-law spectrum of photon index $\Gamma = 2$ and 1–100 keV luminosity $L_{\text{X}} = 10^{44} L_{44}$ erg s$^{-1}$ located 50$r_{50}$ pc from the gas cloud $H_X \sim 3 \times 10^{-21} L_{44} r_{50}^{-2} N_{22}^{-1}$ erg s$^{-1}$.

where $N_{\text{H}} = 10^{22} N_{22}$ cm$^{-2}$ is the equivalent neutral hydrogen column density attenuating the X-ray flux; a column of at least $10^{21}$ cm$^{-2}$ is required in order to exclude the normal ultraviolet photon-dominated region at the cloud surface. Applied to NGC 1275, we find that

$$\log H_X/n \simeq -25.3 + \log(L_{\text{X}}/L_{\text{Einstein}}) - \log(r_{50}^2 N_{22})$$

(2)

Here, $L_{\text{X}}$ is the X-ray luminosity of the source as seen by the cloud and $L_{\text{Einstein}} = 1.6 \times 10^{44}$ erg s$^{-1}$ is the X-ray luminosity of the source extrapolated (in energy) from the measurement by the Einstein satellite in 1979 (Branduardi-Raymont et al. 1981), which also suggests an obscuring column $N_{22} \sim 1$; $n_5$ is the gas density in units of $10^5$ cm$^{-3}$, which as mentioned above must be unity or higher for thermal excitation. The modelling of Maloney et al. (1996) demonstrates that the bulk of the thermally excited H$_2$ emission is produced over a fairly narrow range around $\log H_X/n = -26$, with the H$_2$ emissivity dropping by at least a factor of 3 when $\log H_X/n$ is more than $\pm 0.3$ dex from the emissivity peak. Equation (2) therefore demonstrates that X-ray heating is an energetically feasible excitation mechanism for the observed thermal H$_2$ emission. However, it is difficult to make a more precise statement because of the uncertainty over the appropriate value of $L_{\text{X}}$, because the light travel time from the nucleus to the clouds is $\sim 160$ yr, but observations of the source over just the last 30 yr show that $L_{\text{X}}$ has been far from constant. From the early 1970s to the mid-1990s the X-ray luminosity of the central source has dropped steadily by a factor of 20 (see, for example, Levinson, Laor & Vermeulen 1995 for a summary of the observational evidence). It is clear however that unless the AGN was much weaker in the past or the gas significantly denser than $n_5 \sim 1$, the hot H$_2$ could not exist much within the observed 50-pc radius. Similarly, equation (2) also dictates that, all other parameters being equal, thermally excited H$_2$ emission is produced in a fairly narrow range of radii, within $\pm 0.15$ dex of the peak radius, $\sim 35$–70 pc in this case.

In concluding this subsection, we point out that the results of Maloney et al. (1996) for X-ray heating assume an equilibrium state, which is established on a time-scale of $t_{\text{eq}} \sim 750 L_{44}^{-1} r_{50}^{-2}$ yr (set by the ionization rate of hydrogen, which has the slowest chemistry to equilibrate). Therefore, if the central X-ray source is varying significantly on time-scales of $t_{\text{eq}}$ or less – and observations over the last three decades suggest that it is – consideration of non-equilibrium chemistry may be necessary.

3.3 H$_2$ kinematics: evidence for a rotationally supported structure

We turn our attention now to the kinematics of the molecular gas in the vicinity of the nucleus, as derived from the short-$K$ data. The most striking feature, visible in the raw data, is the strong velocity

![Figure 5. Local thermodynamic equilibrium diagnostic plots for the nucleus, the filament and circumnuclear region. Clockwise from top left, the superimposed models are for single-temperature thermal excitation at temperatures of $T_{\text{ex}} = 1360 \pm 50$ K (fit just to $E_{\text{upper}} < 10000$ K lines), 3100 $\pm$ 1000 K (fit just to $E_{\text{lower}} > 10000$ K lines), 2200 $\pm$ 200 K.](https://academic.oup.com/mnras/article-abstract/359/2/755/988746)
Figure 6. Emission-line profiles of the H$_2$ $v = 1$–0 S(1) line along the peak IFU slit in the short-$K$ data, which passes east–west through the nucleus, starting from pixel (9,27) in the east to (9,32) in the west. Adjacent pixels are separated by 0.12 arcsec and the nucleus itself is assumed to lie mid-way between pixels (9,29) and (9,30) where the continuum peaks. Fits to the line with double Gaussian profiles are also shown, and note the sharp shift in the velocity of the line peak across the nucleus.

Shear in the peak position of the H$_2$ $v = 1$–0 S(1) line moving across the nucleus. To demonstrate this, we show in Fig. 6 line profiles on a pixel-by-pixel basis along the peak slit of the IFU, passing through the nucleus. The kinematics were quantified by fitting double Gaussian profiles to the lines, with the widths of the two components constrained to be the same. The fitting of such profiles does not imply that gas of both velocities is present at each physical location in the galaxy; rather, the weaker of the two components is simply scattered light from gas on the other side of the nucleus, in line with the model of Fig. 3 in which the bulk of the H$_2$ is concentrated in two approximately point-like components 0.15 arcsec either side of the nucleus. Further support for the latter model is provided by Fig. 7, which shows the fluxes of the fitted red and blue components in the peak slit (slit 9) and also in slit 10. We also show rotation curves for the central four slits (i.e. slits 8–11); for slits 9 and 10, the velocity being that of the brighter of the two Gaussians at each location. For slits 8 and 11, the lines are fainter, so only a single Gaussian can be fitted to these lines. The appearance of these rotation curves, with the sharp decrease in velocity amplitude in the slits either side of the nucleus, suggests that the molecular gas may be in a disc-like structure, rotating about an axis oriented approximately north–south, coincident with the radio jets.

What is the nature of this rotating H$_2$ structure? It is unlikely to be part of an optically thick torus of the type commonly postulated in the centres of Seyfert galaxies (e.g. Antonucci 1993), although there is evidence for such a parsec-scale torus in NGC 1275. First, the presence of a hot dust continuum in the $K$ band implies that some dust is heated to its sublimation temperature and thus lies as close as 0.05 pc to the nucleus (Krabbe et al. 2000). Secondly, gas in a parsec-scale torus perpendicular to the radio-jet axis is a plausible candidate for producing the observed free–free absorption towards the milliarcsec-scale northern radio counter-jet in NGC 1275 (Levinson et al. 1995); with reference to the latter’s models, constraints since obtained on the black hole mass in NGC 1275 (see Section 3.5) suggest that the torus is composed of individual clumps of dense gas ($n \gg 10^4$ cm$^{-3}$) and is matter-bounded in the radial direction. At larger radii, NGC 1275 has a complex dust distribution extending out to 17 kpc, in contrast to the majority of FR I radio...
sources in which the dust is settled in discs with radii <2.5 kpc (de Koff et al. 2000).

A more likely possibility is that the hot H$_2$ is part of a disc, from which we only see emission from a ring covering a narrow range of radii around 50 pc, due to the nature of the X-ray heating by the central source (see Section 3.2). Would such a disc be stable? We consider first a gas disc, in vertical hydrostatic equilibrium in the gravitational field of a central black hole of mass $M$. To ensure that the disc is stable against self-gravity we require $\Sigma < (Mh/4r^3)$, where $\Sigma$ is its surface mass density and $h$ its exponential scale-height – this is essentially the Toomre (1964) stability criterion. There are two approaches to evaluating this criterion, leading ultimately to the same conclusion. (i) Integrating vertically over the disc density profile, $n = n_0 \exp(-z^2/h^2)$, we find $\Sigma = 2\sqrt{n_0m_h\rho}$.

Hence the stability criterion becomes $r^3 < (M/8n_0m_h\sqrt{\rho})$. The mid-plane density, $n_0$, must be at least 10$^7$ cm$^{-3}$ for thermal H$_2$ excitation, and taking $M = 3.4 \times 10^8$ M$_\odot$ as the black hole mass (see Section 3.5), this translates into $r < 21$ pc, i.e. less than the observed radius of the H$_2$ distribution. (ii) Assuming that the mass of hot nuclear H$_2$ deduced in Section 3.2 ($3.9 \times 10^5$ M$_\odot$) is spread over an annulus from 35 to 70 pc we deduce $\Sigma = 0.07$ kg m$^{-2}$, so recasting the stability criterion with $r = 50$ pc we require $h/r > 10^{-3}$. However, from above $\Sigma = 2\sqrt{n_0h\rho}$, so requiring $n_0 > 10^3$ cm$^{-3}$ we deduce that $h/r < 5 \times 10^{-5}$, once again inconsistent with the stability criterion. We therefore conclude that a smooth, stable, gaseous disc of the observed radius and mass density cannot exist. The propensity for 100-pc-scale nuclear gas discs to be subject to gravitational instabilities was highlighted recently by

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**Figure 7.** Upper left: the diamonds show the fluxes of the red and blue Gaussian components fitted to the H$_2$ $v = 1$–0 S(1) lines in slit 9 (see Fig. 6), and the thick solid line their sum. The dashed lines are PSFs. Upper right: as at upper left but for slit 10 (in both these slits, the blue component is the one which dominates at positive offsets). Centre left: the velocity of the brighter of the two H$_2$ $v = 1$–0 S(1) Gaussian line components as a function of position for slit 9. Centre right: as at centre left but for slit 10. Lower panels: rotation curves for slits 8 and 11, as derived from single Gaussian fits to H$_2$ $v = 1$–0 S(1). The abscissa on all plots is the offset along the slit relative to pixel position 29.5 (see Fig. 6), with negative offsets corresponding to points east of the nucleus. All velocity error bars are 1$\sigma$. 
Tan & Blackman (2004) in the context of accretion on to the nuclei of giant elliptical galaxies. The disc can however be stabilized if the gas is located in dense clouds, as opposed to being smoothly distributed. In this case, the Toomre stability criterion can be cast as \((\sigma^2/\Omega_0) > 1.68\), where \(\sigma\) is the one-dimensional velocity dispersion of the clouds and \(\Omega_0 = \sqrt{GM/r^3}\) is the orbital angular velocity. Assuming \(\Sigma = 0.07\) kg m\(^{-2}\) as before, we hence require \(\sigma > 70\) m s\(^{-1}\) for stability, which is not at all restrictive.

From the short-\(K\) data we also investigated the kinematics of the \(H_2\) filament. With respect to the assumed velocity zero-point in Fig. 7, the \(H_2\) velocity of this gas is \(-10 \pm 14\) km s\(^{-1}\), with a deconvolved linewidth of 190 km s\(^{-1}\) FWHM. Hence, this material is unlikely to be part of the putative disc. The wavelength range of the short-\(K\) data does not contain \([Fe\, II]\) or \(Pa\alpha\) so we are unable to study the kinematics of these lines in comparable detail.

In this subsection we have demonstrated that the \(H_2\) is plausibly in a disc-like structure, composed of individual clumps of dense gas because a smooth gas disc of the observed dimensions would be gravitationally unstable. Because the points in the rotation curves are not mutually independent – the pixel separation along each slit is 0.12 arcsec whilst the seeing is 0.01 arcsec – we have not attempted to fit a full two-dimensional disc model to the data, because this would require a much better knowledge of the PSF than we have. Adaptive optics observations are needed to conclusively test the model in two dimensions. Nevertheless, in the next section we assume that the disc model is valid and we make an estimate of the black hole mass.

### 3.4 Black hole mass estimation

The computation of dynamical black hole mass estimates for galactic nuclei has reached a considerable level of complexity, requiring in general observations of the full two-dimensional velocity and velocity dispersion fields, knowledge of the distributed stellar mass and dynamical modelling. The resulting model of the gas kinematics must then be projected on to the plane of the sky, convolved with the instrumental response and fitted to the observational data. Here we circumvent all of this complexity and compute a simple estimate of the mass enclosed within the observed radius of the molecular gas. Thereafter, we use an archival \(HST\) NICMOS image of NGC 1275 to estimate the stellar mass contribution in this region. The resulting black hole mass is then found to compare favourably with other non-dynamical estimates.

From the rotation curve for the nuclear slit (slit 9) shown in Fig. 7, we see that the \(H_2\) \(v = I-0\ S(1)\) velocity jumps by approximately 240 km s\(^{-1}\) across the nucleus. If the perpendicular to the disc is inclined at an angle \(i\) to the plane of the sky, the velocity difference increases to \(\Delta V = 240/\sin i\) km s\(^{-1}\). Our best estimate of \(i\) derives from very long baseline interferometry (VLBI) radio observations of the parsec-scale jets, which suggest that the radio jets are inclined to the line of sight at an angle of 30\(^\circ\)–55\(^\circ\), with the southern jet approaching us (Walker, Romney & Benson 1994). On the assumption that the molecular gas rotation axis coincides with the radio-jet axis, we take \(i = 45^\circ\). Within the inferred molecular gas radius of \(r = 50\) pc, the dynamical mass is given by

\[
M(\text{total}) = \frac{v^2 r}{G}
\]

with \(v = \Delta V/2 = 120/\sin i\) km s\(^{-1}\). The result is \(M(\text{total}) = 3.4 \times 10^8\ M_\odot\). Taking into account the aforementioned uncertainty in the inclination of the system introduces a systematic uncertainty of \(\pm 0.18\) dex on this mass.

For the next stage of the calculation we used an image of NGC 1275 to infer the stellar mass distribution. The data in question are a 640-s exposure \(HST\) NICMOS image taken in the F160W filter (roughly corresponding to the \(H\) band) on 1998 March 16 (data set number N3ZB1R010). The standard pipeline-processed data set was obtained from the archive. Using the IRAF STSDAS task ELLIPSE, elliptical isophotes were fitted; the resulting surface brightness profile is shown in Fig. 8. Because the eccentricity of the isophotes is typically small (\(e \sim 0.2\)) we chose to fit the profile with a spherically symmetric modified Hubble law

\[
I(r) = \frac{I_0}{1 + (r/R_0)^2},
\]

which deprojects analytically to the following spatial luminosity density:

\[
j(r) = \frac{j_0}{[1 + (r/R_0)]^{3/2}}.
\]

Fitting to the data at radii \(> 0.5\) arcsec (beyond the region dominated by the AGN power law and reradiated dust emission; see Krabbe et al. 2000 for a spectral decomposition of the continuum) we deduce \(R_0 = 2.3\) arcsec and \(I_0 = 1.12 \times 10^{-16}\) erg cm\(^{-2}\) s\(^{-1}\) \(\text{Å}^{-1}\) arcsec\(^{-2}\). Although there are some systematic deviations from the model at \(R > 3\) arcsec, it is certainly good to within a factor of 2. When deprojected, the implied central stellar mass density is \(6.3(M/L)_H M_\odot\) pc\(^{-3}\), where \((M/L)_H\) is the mass-to-light ratio of the stellar population in solar units. Values of \((M/L)_H\) \(\sim 1\) are expected for stellar populations with age \(\sim 10\) Gyr for a wide range of power-law and exponential stellar initial mass functions and metallicities (Salasnich et al. 2000); also, for a given population, \((M/L)_H\) will vary in the approximate range 0.05–3 as the population evolves, and will in general increase with age. Assuming therefore that \((M/L)_H = 1\), the implied stellar mass within the 50-pc radius of the molecular gas distribution is \(3.7 \times 10^8\ M_\odot\), which is \(\pm 1\) per cent of the above figure for \(M(\text{total})\). Hence, our estimate of the black hole mass is \(M(\text{BH}) = 3.4 \times 10^8\ M_\odot\), \(\pm 0.18\) dex.

It is interesting to compare this figure with other estimates of the black hole mass in NGC 1275. Bettoni et al. (2003) used the observed central stellar velocity dispersion \((\sigma = 250\) km s\(^{-1}\)) in conjunction with the short-\(K\) data to estimate the black hole mass, but the inclination of the system introduces a systematic uncertainty of \(\pm 0.18\) dex on this mass.
3.5 Relationship between the hot H$_2$ and the large-scale distribution of CO emission

Interferometry of the CO $J = 1$–0 line by Inoue et al. (1996) suggests that some $3 \times 10^9$ M$_\odot$ of cool H$_2$ exists within the central arcmin of NGC 1275, in the form of a plume extending from the nucleus to 10 kpc west of it. Within the vicinity of the nucleus, $6 \times 10^6$ M$_\odot$ of this material is confined within a ring-like structure, which appears on the sky as two peaks: peak 1, 1.2 kpc west of the nucleus, and peak 2 the same distance to the south-east. The gas appears to be rotating about the nucleus with line-of-sight velocities $\pm 150$ km s$^{-1}$, in the same sense as the H$_2$ we have discovered on much smaller scales, suggesting a possible dynamical connection between the two gas systems. Inoue et al. (1996) suggested that the CO ring could be due to gas trapped at the inner Lindblad resonance (ILR) of the galaxy potential; from poorer spatial and spectral resolution near-infrared observations they suggested that the central peak of hot H$_2$ could be due to shock emission in a turbulent distribution of molecular clumps funnelled inwards from the CO ring. In contrast, we find that the small-scale hot H$_2$ is in a rotationally supported structure and that the nuclear radiation field is the principal source of excitation.

To further investigate the connection between the CO ring and the hot H$_2$ disc, it would be of interest to search for H$_2$ emission coincident with the former (which falls outside the UIST IFU field of view). There is no H$_2$ emission at this position in the narrow-band $HST$ NICMOS H$_2$ image of Donahue et al. (2000), suggesting that any associated emission is fainter than the H$_2$ ‘filament’ (which they do detect; see our Fig. 1). This filament may represent (possibly shocked) material being transported from the CO ring to the H$_2$ disc; it lies at the systematic velocity (see Section 3.3) and has a thermal H$_2$ excitation characteristic of shock emission (see Section 3.2). We also note that the absolute velocity of CO ‘peak 1’ 1.2 kpc west of the nucleus is virtually identical to that of the hot H$_2$ at a radius of 50 pc on the same side of the nucleus; on the slit 9 rotation curve of Fig. 7, CO ‘peak 1’ would lie at an offset of $+3.5$ arcsec with velocity $-125$ km s$^{-1}$. In the most naive of dynamical models, this would imply that $M(<r)/r$ is the same at radii of 50 pc and 1.2 kpc. Integrating equation (5), the enclosed stellar masses within these radii are $3.7 \times 10^9(M/L)_h$ and $1.5 \times 10^{10}(M/L)_h$, respectively.

Equality in $M(<r)/r$ can be achieved by adding a central black hole of mass $M(BH) = 6.5 \times 10^9(M/L)_h$ M$_\odot$. This shows that the black hole mass deduced from consideration of the hot H$_2$ dynamics alone is not inconsistent with the assumption that $(M/L)_h$ is close to unity.

4 CONCLUSIONS

For the first time, we have spatially and kinematically resolved the hot H$_2$ in the circumnuclear region of NGC 1275 and found that it could be concentrated in a rotationally supported structure in a narrow range of radius around 50 pc from the nucleus. A smaller amount of extended H$_2$ emission exists within a few hundred pc of the nucleus. X-ray heating by the active nucleus has been demonstrated to be a viable heating mechanism for the bulk of the thermally excited H$_2$ emission, and also explains why the emission is dominated by gas within a very narrow range of radii. Thanks to the fine pixel scale of the UIST IFU and excellent seeing, we were able to observe a sharp shift in the velocity of the H$_2\, 1\rightarrow 0$ (S(1) across the nucleus and to make a simple dynamical measurement of the black hole mass, of $3.4 \times 10^9$ M$_\odot$. The principal uncertainty in the mass arises from the uncertainty in the true inclination of the molecular gas disc to the plane of the sky. Nevertheless, the measured value is within 20 per cent of that inferred by Bettoni et al. (2003) from the $(M(BH)-\sigma)$ relation.

The H$_2$ structure is likely to be an extension to smaller spatial scales of the coaxial 1.2-kpc radius ring of CO emission found by Inoue et al. (1996), which is itself the terminus of a 10-kpc-long plume of CO. This suggests that we may be directly witnessing the delivery of fuel from the galactic scale to the AGN itself. As noted in Section 1, increasing numbers of cooling flow clusters appear to have large masses of CO localized in the central few tens of kpc and smaller masses of hot H$_2$ on even more compact scales. Regardless of the precise origin of the cold gas (be it from the cooling flow itself, or an interacting galaxy), the CO–H$_2$ connection found here for NGC 1275 may be universally important for fuelling AGN in the central galaxies of cooling flows, and hence for the regulation of heating and cooling in such cluster cores.

These results demonstrate the utility of the UIST IFU for high spatial and spectral resolution work of this kind, including black hole mass measurements, and promise much for the advent of similar instruments on 8-m telescopes with adaptive optics. When coupled with sensitive CO interferometry (e.g. from the Atacama Large Millimeter Array) it should be possible to extend these detailed studies to more distant clusters.

ACKNOWLEDGMENTS

The UKIRT is operated by the Joint Astronomy Centre on behalf of the United Kingdom Particle Physics and Astronomy Research Council (PPARC). RJW and ACE thank PPARC and the Royal Society, respectively, for support.

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