Molecular Hydrogen and Paschen-alpha Emission in Cooling Flow Galaxies

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ABSTRACT

We present near-infrared spectra obtained to search for Paα and molecular hydrogen lines in edge-darkened (FR I-type) radio galaxies with bright Hα emission in the redshift range $0.0535 < z < 0.15$. We find that all three galaxies in our sample (PKS 0745-191, PKS 1346+26, & PKS2322-12) which are associated with strong cooling flows also have strong Paα and H_2 1–0 S(1) through S(5) emission, while other radio galaxies do not. Together with earlier observations this confirms claims that cooling flow galaxies are copious emitters of molecular hydrogen with large H_2 1–0 S(3)/Paα ratios in the range 0.5 to 2. The emission is centrally concentrated within the inner few kiloparsec and could come from warm (T$\simeq$1000-1500 K) molecular material which is being deposited by the cooling flow. We speculate that the H_2 emission could be related to the interaction between the jets and this molecular gas.

Subject headings: galaxies: clusters: general – cooling flows – galaxies: ISM – galaxies: jets – galaxies: ISM – galaxies: elliptical and lenticular, cD

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1. Introduction

Cooling flows (hereafter CFs) are usually invoked to explain the huge, extended X-ray luminosity seen in many massive elliptical galaxies and clusters. They are thought to represent a massive, more or less spherical, subsonic inflow of hot gas due to radiative cooling in the central regions of the galaxy (e.g. Fabian 1994). The typical inflow rates are of the order of several tens to several hundreds of solar masses per year. However, it has been a puzzle where the huge amount of inflowing matter is actually deposited after it has cooled, since there was little direct evidence in any other waveband for this material (e.g. CO or H I, O'Dea et al. 1994, 1995).

Elston & Maloney (1994) presented a brief report that strong 1–0 S(1) $\lambda 2.1213\mu$m molecular hydrogen emission occurs in CF galaxies, however no individual detections are presented in that paper. Jaffe & Bremer (1997, hereafter JB97) also have detected strong H_2 1–0 S(1) emission in three CF galaxies (Abell 478, Hydra-A, PKS0745-19) and none in a control sample of five galaxies, suggesting that such emission may be characteristic of CF galaxies. JB97 suggested that the molecular hydrogen emission lines, which usually probe shocked or X-ray heated gas with a temperature of 1000–2000 K, trace some of this missing matter.

In this letter we report near-infrared spectroscopy of more CF and control galaxies which for the first time also include transitions from S(2) to S(5). The galaxies were observed in a program to search for hidden, broad Paα lines in FR I radio galaxies, to test the idea that the optical and radio properties of FR I and FR II radio galaxies differ not because of a different central engine, but because of a 'closed' obscuring torus in FR I's (Falcke, Gopal-Krishna, & Biermann 1994). For this program, we selected a number of bright radio galaxies with FR I or amorphous radio structure and luminous Hα emission in the redshift range $0.0535 < z < 0.15$, so Paα would be redshifted into the K-band window. The galaxies were selected from the samples of Morganti, Ulrich, & Tadhunter (1992) and Owen et al. (1995). Since CF galaxies tend to be overluminous in emission lines compared to normal radio galaxies (e.g. Baum 1992), our sample had a number of such objects. However, since the sample was selected with another objective, it also includes suitable control galaxies with similar properties to those with CFs.

2. Observations

Our spectra were obtained during two observing runs in April and December, 1996, at the Multiple-Mirror-Telescope (MMT) (operated jointly by the Smithsonian Astrophysical Observatory and the Steward Observatory) with the FSPEC near-infrared long-slit spectrometer (Williams et al. 1993). Most of the time the weather was not photometric. The galaxies in our sample were observed in the K-band with either a 75 l/mm (2nd order) or a 300 l/mm (1st order) grating. The slit-width was ~ 2.5 pixels ($0\farcs43\,\mathrm{pixel}^{-1}$), and guiding utilized an infrared camera viewing the spectrometer slit. The low-resolution grating covered the whole K-band range, while the wavelength range for the high-resolution grating was chosen such that it covered the range between Paα and H_2 1–0 S(2). PKS 0745−191 was observed at two different central wavelengths to obtain a broader spectral coverage.

During the observation, sets of four exposures of the galaxies were taken, each of which was offset by $\sim 7''$ along the slit. Every 60–90 mins we observed a nearby calibration star in the same manner. The spectra were sampled on the chip by 2–3 pixels per resolution element along the spatial and the dispersion axes. The loci of the spatial and dispersion axes in each dataset were determined by tracing the OH airglow lines and the continuum of the calibration star in each of its four positions along the slit. The exposures were then geometrically transformed so that the spatial and dispersion axes became parallel with the axes of the array.

The data were first reduced following standard procedures for FSPEC (e.g. Engelbracht et al. 1996). We then re-reduced the data with a set of newly written IRAF routines which allow an almost fully automated data reduction and guarantee that all data sets, and specifically the OH airglow subtraction, are handled in an identical manner. The general approach was first to subtract the combined preceding and subsequent frames from the raw-image, which effectively removes the dark current and most of the OH airglow lines. Each background subtracted exposure was then flatfielded, median smoothed with a box size comparable to the instrumental resolution to correct for cosmic rays, and geometrically corrected. We then centered the continuum in a given aperture and extracted a spectrum of the object and of the residual OH airglow $\sim 14''$ offset from the galaxy in the same frame. Finally, the residual-subtracted spectra were co-added with appropriate scales and weights, divided by the calibration star (normalized to a black body spectrum) and wavelength calibrated using the OH airglow spectrum. We found that the automated procedure yields spectra similar to those from the standard procedures. Comparison of the two independent reductions gives assurance that the spectra are free of severe artifacts.

3. Results

The resulting spectra of three of our seven galaxies are shown in Figure 1. Due to the weather conditions during our observations and the resulting lack of good photometric data, we did not attempt a flux calibration and the flux densities are given in detector units. For each spectrum we fitted the continuum with a polynomial and added/subtracted the one sigma error per pixel derived from the variations seen in the individual exposures during the co-adding process (dotted lines in Fig. 1). This procedure gives a robust estimate of the noise level in our spectra which, due to atmospheric absorption troughs and strong OH airglow lines, can be a function of wavelength. The pixel-by-pixel error estimates allow one to distinguish artifacts due to improper sky-subtraction from real spectral features. Parameters of the line identifications are given in Table 1. Where line strengths are poorly measured, either due to terrestrial atmospheric interference or because the line fell near the end of the spectrum, the results are placed in parentheses in the table.

In three cases (PKS 0745−191, PKS 1346+26, & PKS 2322−12), all strong CF galaxies, we have discovered strong Paα and molecular hydrogen lines. We did not find any evidence for either Paα or H_2 in Abell 610, B2 0836+29, or B2 0915+32. Although these galaxies have relatively luminous Hα emission, they are not known to have strong CFs.

The most extreme emitter of molecular hydrogen is PKS 2322−12, where the H_2 1–0 S(3) line has twice the flux of Paα and we also detected H_2 1–0 S(4). In the other two CF galaxies, PKS 0745−191 and PKS 1346+26, the H_2 1–0 S(3)/Paα ratio is roughly one half. PKS 0745−191 also shows emission from the H_2 1–0 S(5) line at the end of the spectrum. With the exception of this line, whose flux is very uncertain due to poor determination of the continuum, all the line ratios we observe are consistent with thermal excitation being the dominant process, with a temperature $T = 1000$–$1500\,$K. This temperature is similar to that found by Mouri (1994) for NGC 1275, another CF galaxy.

It is known that CFs result in a detectable level of Hα emission, thought to be excited by shocks or photoionization (Heckman et al. 1989). However, since the differential extinction between Paα and the H_2 lines is negligible, this ratio is a more reliable indicator of excitation and the relative strength of molecular hydrogen emission than H_2/Hα. Nevertheless, here we estimate the H_2 1-0 S(1)/Hα ratios for our objects in order to facilitate a comparison with JB97. Assuming Hα/Paα = 5 (Hill, Goodrich & DePoy 1996) and a typical ratio 1-0 S(3)/1-0 S(1) = 0.5, we determine H_2 1-0 S(1)/H$\alpha \approx 0.2$ (up to 0.8 for the extreme case), in agreement with JB97.

From the width of the OH airglow lines, we determined that our final spectral resolution (FWHM) in the 300 l/mm grating spectra is $\sim 30\,$Å ($410\,\mathrm{km\,s^{-1}}$ at 2.2μm). The line widths we measure are clearly broadened with an observed FWHM of 40–50 Å, which implies an intrinsic line width of several hundred $\mathrm{km\,s^{-1}}$ (after subtraction of the instrumental resolution in quadrature).

For the 75 l/mm grating we achieved a resolution (FWHM) of $\sim 60\,$Å ($820\,\mathrm{km\,s^{-1}}$ at 2.2μm) and the lines in PKS 1346+26 are only barely resolved. Only the width of Paα seems to be large; however, this is probably an artifact due to the combination of a strong OH line and a deep atmospheric absorption trough around 2.0μm as indicated by a sudden increase of the noise in the red wing of the line. Also in PKS 0745−191 we find a suspicious, extremely broad base to the Paα line; however, there is a very good chance that this is due to a conspiracy of noise peaks.

The lines in PKS 2322−12 and PKS 0745−191 seem to be concentrated in the inner 2–3″ of the galaxy (FWHM), while the emission in PKS 1346+26 seems to be more extended ($\sim$ 4–5″). Due to the limited signal-to-noise ratio of the spectrum of the low surface brightness emission in this galaxy and the small stepping increments, which lead to a spatial cutoff, it is difficult to specify the extent more precisely. We also do not see a variation of the H_2 1–0 S(3)/Paα ratio within the inner 3–4″ of our galaxies exceeding 15 per cent, which may indicate that the lines are co-spatial.

4. Summary & Discussion

Our detection of molecular hydrogen in two new CF galaxies and of additional strong H_2 lines in a third, confirm the claims by Elston & Maloney (1994) and JB97 that CF galaxies are copious emitters of near-infrared molecular hydrogen lines. Moreover, this claim is further strengthened by additions to the list of control galaxies without CFs where H_2 was not detected.

There are now seven CF galaxies (NGC 1275, Abell 478, PKS 0745−191, Hydra A, PKS 1346+26, Cygnus A, & PKS 2322−12) which share the same properties: they have a) high estimated inflow rates of several $100\,M_\odot\,yr^{-1}$, b) relatively strong radio sources, c) luminous Hα emission, and d) luminous H_2 emission (Table 2). The last property makes these galaxies outstanding — no other class of radio galaxies has been found to have such a strong molecular hydrogen emission. In particular, of a total of eight (JB97 and this paper) galaxies without CFs but similar in other respects, none exhibit H_2 emission when observed to similar detection limits. On the other hand Table 2 demonstrates that for a complete subset of Fabian's (1994) list of brightest cooling flow galaxies all CF galaxies with radio and optical emission have been deteced in H_2.

In the detected galaxies the molecular gas is concentrated within the central few kpc of the galaxy and on those scales is most likely co-spatial with the Hα-emitting gas. Since the close link between optical emission lines has already been established (Heckman et al. 1989), indicating that perhaps shocks may play an important role, and even correlated x-ray and optical filaments have been found in CFs (Sarazin et al. 1992), it is conceivable that also the H_2 emission is directly related to the CFs. Molecular line ratios are consistent with thermal excitation around $T \sim 1500$K.

The theoretical interpretation for the connection between the cooling flow and the molecular hydrogen is discussed in greater detail in JB97. These authors find that the molecular masses cooling through T$\simeq$ 2000 K in the CF are a factor $\sim$100 too low to account for the H_2 emission and suggest that continuous reheating of the gas by shocks or photoionization must take place. In this case only a small fraction of the total gas deposited by the CF is enough to account for the emission. However, the high H_2-to-Hα ratios we and JB97 find in the CF galaxies are difficult to explain with current models. JB97 suggest that this requires H_2 excitation by either slow shocks or suprathermal secondary electrons produced by X-ray photoionization of cold clouds.

It is attractive to associate this excitation solely with the action of the CFs. However, all the galaxies detected in H_2 have powerful radio jets that might be another ingredient underlying these observations. For example, Seyfert galaxies too have narrow emission lines with $v \simeq 400\,\mathrm{km\,s^{-1}}$ and sometimes strong molecular hydrogen emission. As shown by *HST* observations (e.g. Capetti et al. 1996; Falcke et al. 1998), their emission line regions are often concentrated in distinct features (filaments and bow-shocks) indicative of a strong interaction between their radio jets and the interstellar medium.

Ruiz, Rieke, & Shields (1997) claim that jet-powered photoionizing shocks are the most likely source of excitation for the H_2 emission in Seyfert galaxies. Two Seyferts (in addition to the CF galaxy NGC 1275) in a sample of 28 showed ratios typical of CF galaxies: MCG 8-11-11 and Mrk 6. Ruiz et al. explain these observations by attributing the luminous H_2 emission to excitation by jet-powered shocks as they interact with molecular material. The kpc-scale radio jets in Seyferts are often confined to the disk of the host galaxy, and so in some extreme cases may encounter a region rich in gas which provides an ideal working surface for the jet to excite molecular hydrogen. It is therefore tempting to speculate that ellipticals, with their larger-scale jets and relative dearth of gas, require an external process such as a CF to transport large amounts of molecular material to a location where it can interact with the jet. This jet interaction scenario has been discussed in more detail already for PKS 1346+26 to explain the radio-optical alignment in this galaxy (McNamara et al. 1996).

As an alternative one could imagine that the enhanced H_2 emission seen so far is a consequence of ongoing mergers in the cD galaxies rather than of the CFs. Further NIR spectroscopy of cD galaxies with and without CFs and high-resolution imaging with NICMOS will therefore be crucial to identify the origin of the strong molecular hydrogen emission in these galaxies.

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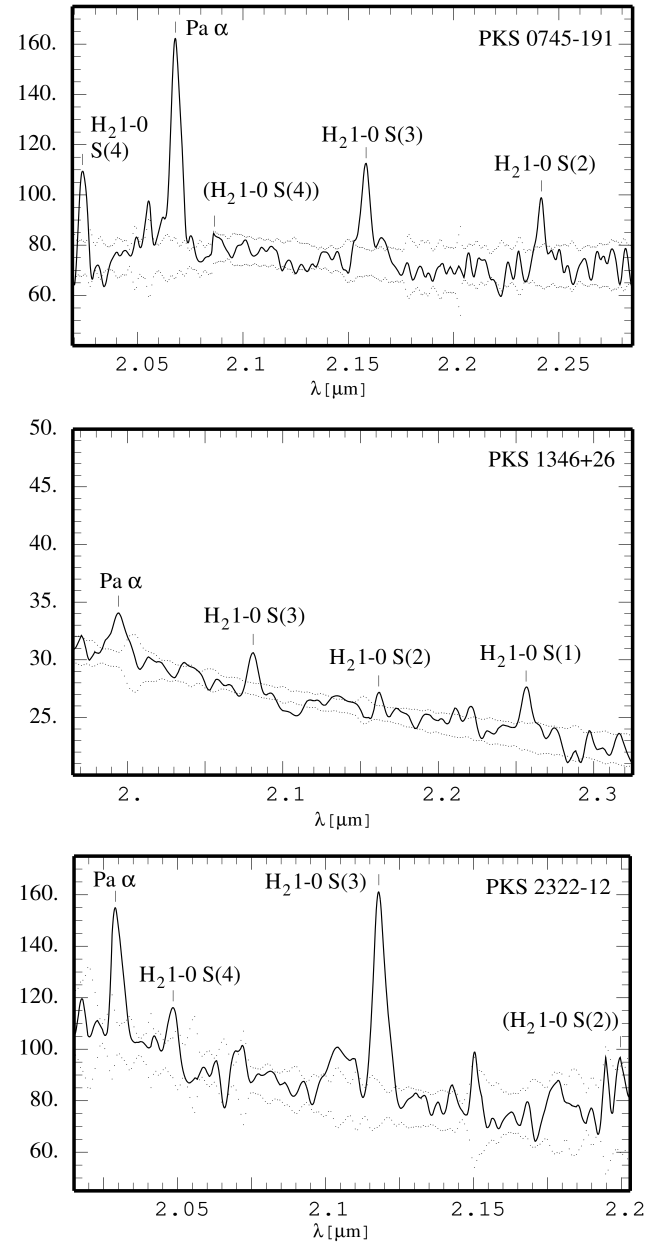

Fig. 1.— NIR spectra of galaxies with detected H_2 lines in our sample plotted as F_λ vs. λ. The flux values are in detector units. Dotted lines give the estimated error derived from co-adding the individual spectra for each galaxy.

TABLE 1
EMISSION LINE PARAMETERS

Name	z	grating [l/mm]	λ [μm]	flux	EW [Å]	FWHM [Å]	Identification
PKS 0745−191	0.1028	300	2.024	(0.46)	(31)	(42)	H_2 1-0 S(5) ($\lambda 1.8353\mu$m)
[CF]			2.068	1.00	55	52	Paα
			2.086	$\lesssim$0.06	$\lesssim$3.5	53	H_2 1-0 S(4) ($\lambda 1.8914\mu$m)^a
			2.158	0.50	31	55	H_2 1-0 S(3) ($\lambda 1.9570\mu$m)
			2.166	0.12	8	46	Brγ^b (or [SI VI])
			2.241	0.29	19	47	H_2 1-0 S(2) ($\lambda 2.0332\mu$m)
Abell 610	0.0991	300	2.061	–	<4		Paα
B2 0836+29	0.0643	75	1.996	–	<7		Paα
B2 0915+32	0.062	75	1.991	–	<5		Paα
PKS 1346+26	0.06326	75	1.995	1.00	17	(129^c)	Paα
(Abell 1795)			2.014	$\lesssim$0.18	$\lesssim$3	67	H_2 1-0 S(4) ($\lambda 1.8914\mu$m)^a
[CF]			2.081	0.56	11	72	H_2 1-0 S(3) ($\lambda 1.9570\mu$m)
			2.162	(0.24)	(5)	(52)	H_2 1-0 S(2) ($\lambda 2.0332\mu$m)^d
			2.257	0.66	15	81	H_2 1-0 S(1) ($\lambda 2.1213\mu$m)
PKS 2322−12	0.0822	300	2.029	1.00	19	39	Paα
(Abell 2597)			2.048	0.32	7	32	H_2 1-0 S(4) ($\lambda 1.8914\mu$m)
[CF]			2.118	2.02	51	50	H_2 1-0 S(3) ($\lambda 1.9570\mu$m)
			2.200	(0.63)	(18)	(46)	H_2 1-0 S(2) ($\lambda 2.0332\mu$m)^a

NOTE.— (1) – Name ([CF] marks cooling flow galaxies), (2) – redshift, (3) grating used in observation, (4) – observed wavelength of line, (5) – flux relative to Paα, (6) – equivalent width in Ångstrom, (7) – line width (FWHM) in Ångstrom (not corrected for instrumental resolution), (8) – line identification. Notes: ^{a}marginal detection, ^{b}insufficiently corrected Brγ absorption in the calibration star, ^{c}broad line width is most likely an artifact as indicated by the sudden increase of the noise in the spectrum, ^{d}after subtraction of Brγ in the calibration star.

Table 2

Brightest Cooling Flow Galaxies with Radio and Hα Emission

Name	z	L_x [10^{43} erg/sec]	$\dot{M}$ [$M_\odot$/yr]	lg P_{408MHz} [erg/sec/Hz]	$L(H\alpha)$ [10^{40} erg/sec]	H_2 1-0
Abell 478	0.0861	241	570	31.4	19[a]	S(1)[d]
PKS 0745−191	0.1028	280	702	33.7	490[b]	S(1)[d],S(2)-S(5)[e]
Hydra A	0.0538	35	315	34.2	34[c]	S(1)[d]
PKS 1346+26	0.06326	89	478	32.6	184[c]	S(1)-S(4)[e]
Cygnus A	0.05654	69	187	35.7	2612[c]	S(1)&S(3)[f]
PKS 2322−127	0.0822	64	480	33.3	65[b]	S(2)-S(4)[e]

Note.—Table of properties for galaxies from Fabian's (1994) list of brightest cooling flow galaxies, for which we have applied our original selection criterion ($z > 0.0535$, as well as radio and optical line emission) in hindsight. With the exception of NGC 1275 (redshift too low), this comprises the complete list of cooling flows with H_2 detections published so far. The columns description is: (1) – name, (2) – redshift, (3) – 2-10 keV luminosity, (4) – mass inflow rate, (5) – log of monochromatic radio power at 408 MHz (from NED database), (6) – Hα luminosity, (7) – H_2 (1-0) lines detected so far. Additional notes: Columns 3 and 4 are taken from Fabian (1994), columns 6 and 7 were taken from: [a] White et al. (1994), [b] Zirbel & Baum (1995), [c] Godon et al. (1994), [d] JB97, [e] this paper, [f] Ward et al. (1991). We use $H_0 = 50$ km sec^{-1} Mpc^{-1}.