Mon. Not. R. Astron. Soc. **317**, 105–110 (2000)

A spectroscopic study of NGC 6251 and its companion galaxies

P. N. Werner,★ D. M. Worrall and M. Birkinshaw

Department of Physics, University of Bristol, Tyndall Avenue, Bristol BS8 1TL

Accepted 2000 March 24. Received 2000 March 21; in original form 1999 November 30

ABSTRACT

Measurements of the velocities of galaxies thought to be associated with the giant radio galaxy NGC 6251 confirm the presence of a poor cluster with a systemic redshift of $\bar{z} = 0.0244 \pm 0.0004$ and a line-of-sight velocity dispersion of $\sigma_z = 283(+109, -52)\,\mathrm{km\,s^{-1}}$. This suggests a cluster atmosphere temperature of $T = 0.7(+0.6, -0.2)\,\mathrm{keV}$, which is not enough to confine the radio jet by gas pressure. The core of NGC 6251 shows strong emission lines of [O III] and Hα+[N II], but there is no evidence for line emission from the jet (detected in optical continuum by Keel).

Key words: galaxies: clusters: individual: Zw 1609.0+8212 – galaxies: distances and redshifts – galaxies: individual: NGC 6251.

1 INTRODUCTION

NGC 6251 is an $m_B = 13.6$ mag (de Vaucouleurs et al. 1991) giant E2 radio galaxy known for its remarkable radio jet, which is aligned (within a few degrees) from pc to Mpc scales (see Readhead, Cohen & Blandford 1978, Perley, Bridle & Willis 1984 and Jones et al. 1986 for pc-scale observations, kpc-scale observations, and both, respectively). Keel (1988) detected the radio jet in optical continuum emission and found that the spectrum was unusually steep. Arguments that the galaxy contains a supermassive black hole with mass $\sim 10^9\,\mathrm{M_\odot}$ (Young et al. 1979) were recently supported by *HST* observations of the nuclear gas and dust disc on a scale of a few $\times 100$ pc (Ferrarese & Ford 1999). NGC 6251 has been described as relatively isolated, but loosely associated with the Zwicky cluster Zw 1609.0+8212.

This cluster, which Zwicky (1968) described as ‘medium compact’ and ‘near’ with a population of 260, was found by Gregory & Connolly (1973) to have two main concentrations. One of them is A2247, listed as a separate cluster by Abell (1958). Like NGC 6251, it lies on the eastern boundary of Zw 1609.0+8212. Its systemic velocity is $11\,670\,\mathrm{km\,s^{-1}}$ (Sargent, Readhead & de Bruyn 1982, unpublished), and its interest lies mainly in the fact that it contains a striking chain of galaxies. The western part of the Zwicky cluster surrounds IC 1143. The three galaxies which Gregory & Connolly (1973) ascribed to this cluster segment have velocities close to $6500\,\mathrm{km\,s^{-1}}$. NGC 6251 appears to depart from this velocity by $\sim 1000\,\mathrm{km\,s^{-1}}$, and Prestage & Peacock (1988) concluded that the local galaxy density is so low that any atmosphere would more likely be associated with the galaxy than the cluster.

Birkinshaw & Worrall (1993) observed NGC 6251 with the *ROSAT* PSPC and detected a spatially unresolved X-ray concentration, containing about 90 per cent of the 0.1–2 keV flux and coincident with the radio core. The remaining ~ 10 per cent of the flux appeared to originate from an extended emission component, probably a gaseous atmosphere with a scale of ~ 3 arcmin (130 kpc)[1] FWHM. They obtained a satisfactory fit to the PSPC radial profile by superposing a point source and an isothermal β-model. The limited number of counts from the modelled extended emission did not allow a useful gas temperature measurement to be made. However, Birkinshaw & Worrall showed that for the outer parts of the kpc-scale radio jet to be confined by atmospheric pressure, a gas temperature of $T \geq 5$ keV is required. Feature A (the brightest part of the jet, only 10–40 arcsec or $\sim$7–29 kpc from the nucleus) can be confined by a gas temperature of $T \geq 2$ keV. The galaxy's internal stellar velocity dispersion of $\sigma_z = 293 \pm 20\,\mathrm{km\,s^{-1}}$ measured by Heckman, Carty & Bothun (1985a) suggests that the stellar gravitational field cannot hold an atmosphere this hot. In this paper we demonstrate the existence of a cluster associated more strongly with NGC 6251 than Zw 1609.0+8212 based on velocities for 13 galaxies including IC 1143, and we use the velocity dispersion of this cluster to estimate the temperature of the cluster atmosphere. We discuss the consequences for pressure confinement of NGC 6251's jet.

2 OBSERVATIONS AND DATA REDUCTION

Observations of the galaxies listed in Table 1 were carried out on the nights of 1992 September 22 and 23, using the Red Channel spectrograph on the Multiple Mirror Telescope (MMT). All images were obtained on a 800×800 CCD (binned 2/1) with $(15\,\mu\mathrm{m})^2$ pixels using a long slit of dimensions $180 \times 1.5\,\mathrm{arcsec^2}$. Low-resolution spectra were taken with a $300\,\mathrm{line\,mm^{-1}}$ grating, which had a useable range of 2560 Å centred on $\sim$6000 Å, and had spatial and wavelength dispersions of 0.5 arcsec and 3.2 Å per

★ E-mail: p.werner@bristol.ac.uk

[1] In this paper we adopt a Hubble constant $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

Table 1. Observational details for the low-resolution spectra.

Object	Name	Coordinates (2000) R.A.	Dec.	Exp.(s)	Date observed
1	NGC 6251	$16^{h}32^{m}34^{s}.8$	$82°32'17''$	1800	22 Sept. 1992
2	–	$16^{h}32^{m}47^{s}.7$	$82°33'25''$	900	″
3	NGC 6252	$16^{h}32^{m}43^{s}.3$	$82°34'36''$	600	″
4	Zw 367-010	$16^{h}22^{m}46^{s}.1$	$82°23'45''$	900	23 Sept. 1992
5	UGC 10581	$16^{h}43^{m}11^{s}.6$	$82°37'51''$	450	″
6a	UGC 10464a	$16^{h}28^{m}34^{s}.6$	$82°53'16''$	450	″
6b	UGC 10464b	″	″	″	″
7	Zw 367-015	$16^{h}37^{m}05^{s}.5$	$82°00'37''$	600	″
8	UGC 10431	$16^{h}25^{m}18^{s}.3$	$81°47'57''$	600	″
9	UGC 10604	$16^{h}47^{m}50^{s}.2$	$81°50'50''$	600	″
10	Zw 367-016	$16^{h}38^{m}48^{s}.5$	$81°41'28''$	600	″
11a	UGC 10471a	$16^{h}30^{m}28^{s}.5$	$81°33'44''$	600	″
11b	UGC 10471b	″	″	″	″
12	IC 1143	$15^{h}30^{m}48^{s}.5$	$82°27'34''$	300	″
13	IC 1139	$15^{h}29^{m}18^{s}.3$	$82°35'15''$	300	″

Table 2. Observational details for the high-resolution spectra of NGC 6251.

Slit Position Angle (°)	λ range (Å)	Exp. time (s)	Date observed	Comments
115.3	4874–5526	1800	22 Sept. 1992	along jet Hβ,[O III], Mg$_b$
115.3	6274–6926	1800	″	along jet Hα, [N II]
25.3	4874–5526	1800	23 Sept. 1992	perpendicular to jet Hβ,[O III], Mg$_b$
25.3	6274–6926	1800	″	perpendicular to jet Hα, [N II]

pixel, respectively. A resolution of ~10 Å (FWHM) was obtained in this instrument configuration.

The galaxies listed in Table 1 are numbered in order of increasing distance from NGC 6251 (which is object 1). Our sample (which is not complete or magnitude-limited) includes two galaxies with double cores, objects 6 and 11. Although in both cases the two nuclei are listed separately (and labelled *a* and *b*), the average redshifts were used as single measurements in subsequent cluster-related calculations, as they are clearly bound systems.

In addition, high-resolution spectra of NGC 6251 were obtained (see Table 2) with a 1200 line mm^{-1} grating, resulting in a wavelength range of 652 Å and a dispersion of 0.9 Å per pixel. Spectra centred on 5200 and 6600 Å were obtained along the radio jet (at a position angle of 115°.3) and perpendicular to it (P.A. = 25°.3). The resolution of these spectra was 2–3 Å (FWHM). The objective of these observations was to search for emission lines in the optical knots detected in continuum by Keel (1988), and to measure the rotation velocity and direction for the stars and gas in the galaxy.

The reduction and analysis of our data were carried out using the Image Reduction and Analysis Facility (IRAF). The CCD images were de-biased, trimmed and flat-fielded using the CCDPROC task. Cosmic ray hits and bad lines or columns on the CCD were removed by interpolating across the smallest dimension of the affected regions with the FIXPIX routine. For the low-resolution case, where only a nuclear one-dimensional spectrum was required, the spectra were sky-subtracted using the BACKGROUND task, then wavelength-calibrated using HeNeAr comparison spectra, traced and extracted with the APEXTRACT package.

The data reduction in the high-resolution case was somewhat

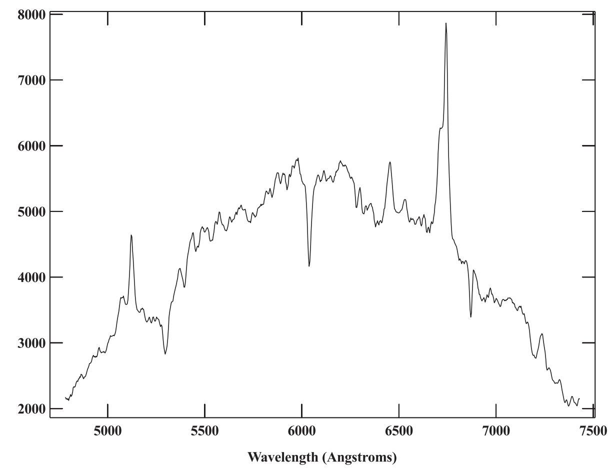

Figure 1. Raw (unfluxed) spectrum (in MMT counts) of the core of NGC 6251 in the observed frame. Note the strong [O III], [O I] and Hα + [N II] lines, as well as stellar absorption features. The resolution is ~10 Å (FWHM).

complicated by the fact that information in the spatial direction was to be preserved, so that the core spectrum could not simply be traced along the geometrically distorted two-dimensional image. A good alignment (subsequently found to be accurate to typically a few tenths of a pixel) of the dispersion axis and spatial axis with the CCD's columns and lines, respectively, was carried out using the LONGSLIT package. HeNeAr calibration lines and the trace of the galaxy nucleus were used to fit a two-dimensional geometrical rectification function to the data. This correction was then applied

Table 3. Redshifts obtained from emission lines.

Object	Emission lines used	$V^{(\mathrm{em})}$ (km s^{-1})
1	[O III] 4958, [O III] 5007, [O I] 6300 [N II] 6584	7276 ± 75
4	[O III] 4958, [O III] 5007, [N II] 6563 Hα, [N II] 6584	6930 ± 75
6a	[O III] 4958, [O III] 5007, [N II] 6563 Hα, [N II] 6584	7723 ± 47
7	[O III] 4958, [O III] 5007, Hα, [N II] 6584, [S II] 6716, [S II] 6731	4141 ± 41
8	[N II] 6563, Hα, [N II] 6584	7635 ± 63
10	Hα, [N II] 6584	16648 ± 51
11a	Hβ, Hα, [N II] 6584	7128 ± 54

Table 4. Results of the cross-correlations and peculiar velocities relative to the systemic velocity of the cluster.

Object	$V^{(\mathrm{abs})}$ (km s^{-1})	$z^{(\mathrm{abs})}$	V_{pec} (km s^{-1})	$V_{\mathrm{pec}}/\sigma_z$	Distance from NGC 6251 (arcmin)	(Mpc)
1	7459 ± 22	0.0249 ± 0.0001	260	0.67	0	0
2	6913 ± 56	0.0231 ± 0.0002	−273	−0.70	1.21	0.052
3	7240 ± 46	0.0242 ± 0.0002	46	0.11	2.33	0.101
4	7001 ± 38	0.0234 ± 0.0001	−187	−0.48	21.1	0.911
5	7223 ± 44	0.0241 ± 0.0001	30	0.08	21.3	0.919
6a	7797 ± 43	0.0260 ± 0.0001	567 [a]	1.46 [a]	22.3	0.964
6b	7748 ± 43	0.0258 ± 0.0001	" [a]	" [a]	"	"
7	4224 ± 140	0.0138 ± 0.0004	– [b]	– [b]	33.0	1.42
8	– [c]	– [c]	432 [d]	1.11 [d]	46.8	2.02
9	7554 ± 56	0.0252 ± 0.0002	353	0.91	51.8	2.24
10	– [c]	– [c]	– [b,d]	– [b,d]	52.4	2.26
11a	7158 ± 102	0.0239 ± 0.0003	−36 [a]	−0.09 [a]	58.7	2.54
11b	7154 ± 52	0.0239 ± 0.0002	" [a]	" [a]	"	"
12	6548 ± 40	0.0218 ± 0.0001	−629	−1.62	121	5.21
13	6616 ± 71	0.0221 ± 0.0002	−563	−1.45	123	5.29

[a] average velocity of bound binary system used in velocity dispersion calculation.
[b] not cluster members ($V_{\mathrm{pec}} > 3000$ km s^{-1}).
[c] The weak continuum did not allow a good cross-correlation to be carried out.
[d] The peculiar velocity is calculated from the *emission* velocity.

to the image, and one-dimensional spectra at varying offsets from the core of the galaxy were subsequently extracted.

Fig. 1 is an unfluxed spectrum of the core of NGC 6251 from our low-resolution data.

3 REDSHIFTS

3.1 Measurements

Seven of the 15 spectra showed emission lines which enabled redshifts to be determined. Table 3 shows which lines were used, and the resultant heliocentric velocities. The error bars take account of the scatter of the velocities calculated from the various lines, as well as the errors on the individual line wavelengths. Due to a slight defocusing effect which is particularly noticeable in the emission lines, an error of 10 per cent of the FWHM of the line is included in these latter errors.

We measure the absorption redshifts of the galaxies by the standard method of cross-correlating their stellar spectra with the stellar absorption-line spectrum of an object of known redshift (Tonry & Davis 1979). The cross-correlation was carried out over the wavelength ranges 5000–5450 and 5950–6200 Å (including the Mg_b and Na D features while avoiding poorly subtracted night sky lines around 5600 Å) using the IRAF task FXCOR in the RV package.

The template used for the cross-correlation was a very high signal-to-noise spectrum of NGC 7619 obtained from a 600-s exposure (with the 300 line mm^{-1} grating) during the 1992 September 22 observing run. NGC 7619 is a 12.1 mag E2 galaxy with a velocity of $V = 3747 \pm 20$ km s^{-1} (Huchra et al. 1983). More recent velocities for NGC 7619 (e.g. de Vaucouleurs et al. 1991; Huchra et al. 1995) are in reasonable agreement, so that any systematic error introduced into our results by the choice of template velocity is likely to be less than a few tens of km s^{-1}.

The cross-correlation velocities of the galaxies in our sample are shown in Table 4.

3.2 Comparison of emission and absorption redshifts

Comparing the velocities obtained from emission lines (Table 3) and absorption features (Table 4), it is evident that, although the results are all consistent within the errors, there is a systematic $V^{(\mathrm{abs})} - V^{(\mathrm{em})} = 65 \pm 9$ km s^{-1} (leaving out NGC 6251, which will be considered separately). This could be due to the slight defocusing effect described in Section 3.1. Alternatively, it could indicate that the adopted velocity of the template galaxy NGC 7619 is a slight overestimate (see Section 2). Making a correction of 65 km s^{-1} to the $V^{(\mathrm{em})}$ of object 8 (the only *emission* velocity used in the velocity dispersion calculation) has a negligible effect on the systemic velocity and on σ_z.

Part of the unusually high discrepancy between the emission and absorption redshifts for NGC 6251 can be ascribed to this systemic error. The remaining ~100 km s^{-1} difference is in agreement with the results of Ferrarese & Ford (1999), who also find the emission lines to be at a significantly lower velocity than the absorption features. Adding up the Gaussian constituents of

Table 5. Comparison of measured velocities with the literature

Object	This paper km s^{-1}	Published values km s^{-1}	Reference[a]
1	7459 ± 22	7400 ± 22	*Zcat* 95
		6900 ± 42	RC3 91
		7380 ± 100	SRdB 82
		7294 ± 60	SO 81
		6900 ± 600	MO 79
3	7240 ± 46	6510 ± 100	SRdB 82
4	7001 ± 38	6840 ± 100	SRdB 82
6	7773 ± 30[b]	7789 ± 24	SHDYFT 92
		7710 ± 100	SRdB 82
7	4224 ± 140	17010 ± 100	SRdB 82
8	7621 ± 61	1774 ± –	RH 91
9	7554 ± 56	7320 ± 100	SRdB 82
		20208 ± 184	GC 73
10	16644 ± 6	7590 ± 100[c]	SRdB 82
11	7156 ± 57[b]	6930 ± 100	SRdB 82
12	6548 ± 40	6395 ± 143	GC 73

[a] references: *Zcat* 95 Huchra et al. 1995; SHDYFT 92 Strauss et al. 1992; RC3 91 de Vaucouleurs et al. 1991; RH 91 Richter & Huchtmeier 1991; SRdB 82 Sargent et al. 1982, unpublished; SO 81 Shuder & Osterbrock 1981; MO 79 Miley & Osterbrock 1979; GC 73 Gregory & Connolly 1973.
[b] mean velocity of two core components, as previous authors did not take account of the double nucleus.
[c] This value is placed between brackets in the SRdB 82 paper, indicating that the authors are not entirely confident about it.

their fits to the Hα + [N II] system over all their (0.1-arcsec) *HST* apertures produces an emission-line spectrum which is remarkably similar in shape and position to our nuclear (1.8-arcsec aperture) spectrum.

3.3 Comparison of velocities with the literature

The redshifts of several of the galaxies observed here have also been measured by other authors. They are compared with our results in Table 5. There is considerable discord among the velocities, with the most severe disagreement arising when comparing our values to those published in the 1970s and early 1980s.

Of the five galaxies showing serious discrepancies with published values, one (source 7) has consistent absorption and emission redshifts in this paper. We have a very high-quality spectrum for object 3, and the cross-correlation with the template galaxy yielded a high Tonry & Davis 'R' factor (an indication of the reliability of the resulting redshift). The coordinates given by Richter & Huchtmeier (1991) for object 8 are 2 arcmin away from the correct position, and Sargent et al. (1982, unpublished) indicate that they are unsure of the accuracy of their velocity measurement for source 10; in both of these cases, we suspect that target misidentification in the earlier observations may be the reason for the different redshift values.

4 CLUSTER SYSTEMIC REDSHIFT AND VELOCITY DISPERSION

We used the cross-correlation results in Table 4 to compute the systemic redshift and the velocity dispersion of the cluster of galaxies using the method of Danese, De Zotti & di Tullio (1980) and as described by Werner, Worrall & Birkinshaw (1999).

The mean velocity of the cluster was found to be $c\bar{z} = 7193 \pm 128\,\mathrm{km\,s^{-1}}$, equivalent to a redshift $\bar{z} = 0.0240 \pm 0.0004$. The one-dimensional line-of-sight velocity dispersion $\sigma_z = 388(+128, -65)\,\mathrm{km\,s^{-1}}$, yields a three-dimensional physical velocity dispersion of $\sigma = 672(+239, -145)\,\mathrm{km\,s^{-1}}$.

Such a low velocity dispersion suggests that the cluster is poor. A comparison with the correlation between σ and Abell richness class R (e.g. Danese et al. 1980) indicates R $\leq$ 0, corresponding to a population $\leq$30.

As the results in Table 4 indicate, NGC 6251 has a peculiar velocity of $260 \pm 130\,\mathrm{km\,s^{-1}} = 0.67 \pm 0.33\,\sigma_z$ within the cluster. It is generally believed that giant elliptical radio galaxies dominating clusters are more or less at rest relative to the cluster's systemic velocity. Although this is consistent at the two-sigma level with the data above, there is a reason that the peculiar velocity of NGC 6251 given in Table 4 may be an overestimate. Considering the projected distances of objects 12 and 13 from the rest of the cluster (>5 Mpc), their comparatively large peculiar velocities ($\geq 1.45\sigma_z$), and their closeness to one another in position and velocity, it seems likely that they are part of the physically distinct IC 1143 group, and that they should be removed from the velocity dispersion calculations. This leads to a significantly higher systemic velocity for the cluster, $c\bar{z} = 7328 \pm 105\,\mathrm{km\,s^{-1}}$ ($\bar{z} = 0.0244 \pm 0.0004$) with $\sigma_z = 283(+109, -52)\,\mathrm{km\,s^{-1}}$. In this case, NGC 6251 is one of the slowest-moving members of the cluster, with a peculiar velocity of $128 \pm 107\,\mathrm{km\,s^{-1}}$.

5 THE DYNAMICS OF NGC 6251

Heckman et al. (1985b) measured the rotation curves of several radio-loud and radio-quiet elliptical galaxies to test theories that the rotation axis might coincide with the radio axis in powerful radio galaxies ($\log P_{178\,\mathrm{MHz}} \geq 24\,\mathrm{W\,Hz^{-1}}$). They present rotation curves for NGC 6251 in position angles of 27° and 124°, and conclude that the galaxy rotates about an axis at P.A. $\sim$85° ± 28° with a velocity of $V \sim 47 \pm 16\,\mathrm{km\,s^{-1}}$.

We measured rotation curves for two position angles, 25°.3 and 115°.3 (Table 2), the latter being aligned with the jet. The results of the slit in P.A. = 25°.3 suggest a slow rotation of the order of $50\,\mathrm{km\,s^{-1}}$ about the jet, consistent with Heckman et al.'s result in P.A. = 27°. The velocities *along* the jet were inconclusive. Deeper observations are required to obtain a sufficient signal-to-noise ratio in the outer parts of the galaxy (at a radius $\geq$8 arcsec or $\sim$6 kpc) if more precise information on the rotation axis or velocity than that found by Heckman et al. is to be obtained.

6 LINE EMISSION ALONG THE RADIO JET?

The jet of the powerful radio galaxy M87 has been detected at optical wavelengths, and many authors report imaging and spectroscopic studies (see Keel 1988, and references therein). Keel subsequently detected optical continuum emission from the NGC 6251 jet, and his *B*-, *V*- and *R*-band fluxes of feature A (10–40 arcsec or $\sim$7–29 kpc from the nucleus) imply a spectrum much steeper than M87 or other similar jets.

Our observations were not deep enough to reveal significant continuum emission from feature A, but we searched for line emission from [O III], Hα and [N II]. No emission lines in the jet were found, at an upper limit (for Hα) of 10^{-17}–$10^{-16}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ for a range of linewidths of 300–1000 Å,

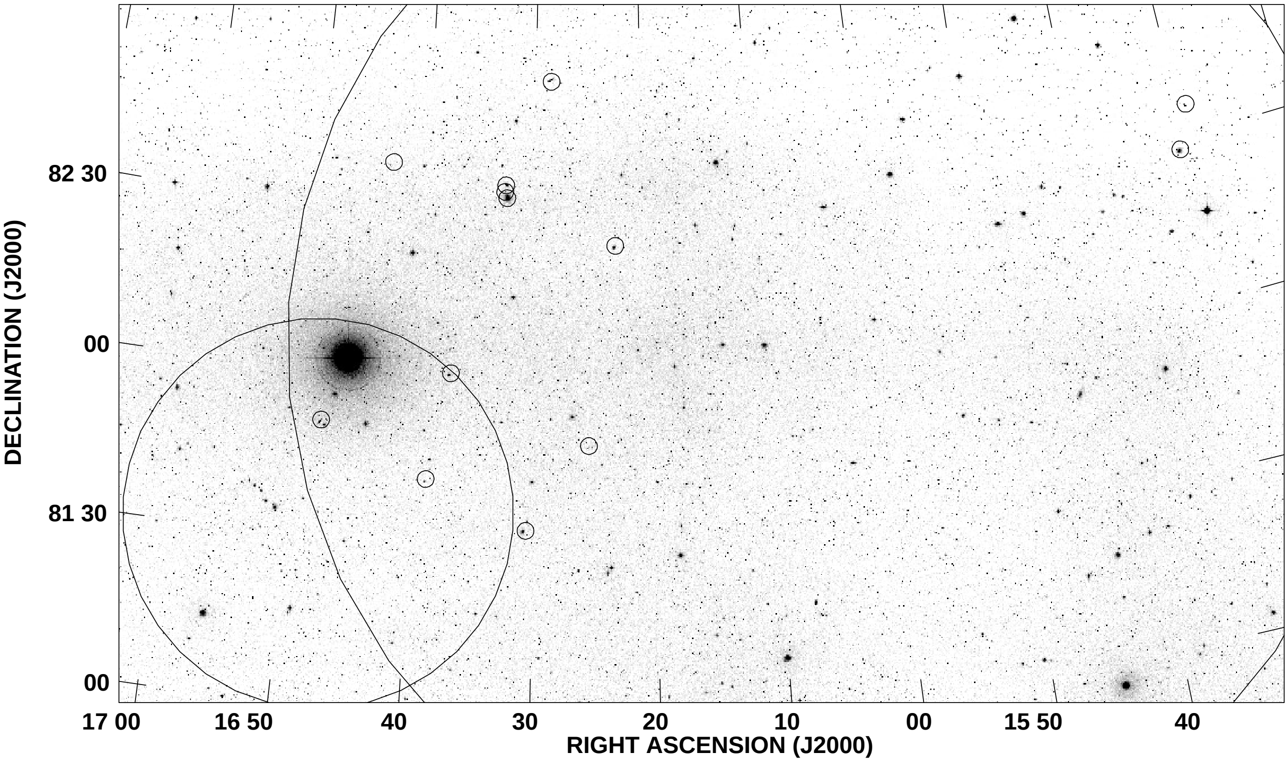

Figure 2. Second Digitized Sky Survey (DSS2) image, with our targets indicated by small circles. The ~1°-diameter circle in the south-eastern corner of the field is the outline of Abell 2247. The large circle indicates the bounds of Zwicky cluster Zw 1609.0+8212.

respectively. Poor weather prevented us from obtaining the planned, much deeper, exposures.

7 DISCUSSION

7.1 NGC 6251 and Zw 1609.0+8212

Considering our redshifts in the context of the two subsystems that make up cluster Zw 1609.0+8212 (see Section 1), it is clear that our sample does not include any members of the subcluster separately listed as A2247 ($c\bar{z} = 11\,670\,\mathrm{km\,s^{-1}}$), and situated in the eastern part of the Zwicky cluster, South-East of NGC 6251. Objects 12 and 13 appear to belong to a slightly closer group or small cluster on the western edge of Zw 1609.0+8212 and we have accordingly argued for their removal from the velocity dispersion calculations in Section 4. Objects 7 and 10 have redshifts unlike those of other objects in the sample, and appear to be more or less isolated field galaxies. This leaves us with eight companion galaxies (two with double nuclei) near the velocity of NGC 6251, and these seem to form a third subcluster within the limits of Zw 1609.0+8212. It is clear that not all the brightest galaxies within Zwicky's boundary are physically associated.

Fig. 2 shows the positions of our sources, as well as rough outlines of clusters A2247 and Zw 1609.0+8212.

7.2 Velocity dispersion and X-ray temperature

The one-dimensional velocity dispersion of a cluster of galaxies is related to the X-ray gas temperature of the cluster atmosphere (Lubin & Bahcall 1993; Bird, Mushotzky & Metzler 1995; Girardi et al. 1995). The higher velocity dispersion reported in Section 4 corresponds to an X-ray temperature of $T = 1.2(+0.8, -0.3)\,\mathrm{keV}$. The alternative velocity dispersion of $\sigma_z = 283(+109, -52)$ $\mathrm{km\,s^{-1}}$ derived for the cluster without IC 1139 and 1143 (which we argue are part of a separate group) suggests a lower gas temperature of $T = 0.7(+0.6, -0.2)\,\mathrm{keV}$.

Comparing this temperature of 0.7 keV with the extrapolated $L_\mathrm{X} - T$ relation of Arnaud & Evrard (1999), we find that it corresponds to a bolometric X-ray luminosity $L_\mathrm{X}^{(\mathrm{bol})} \simeq 2.4(+11.6, -1.5) \times 10^{42}\,\mathrm{erg\,s^{-1}}$, or $L_\mathrm{X} \simeq 2.2(+10.4, -1.4) \times 10^{42}\,\mathrm{erg\,s^{-1}}$ in the band 0.2–1.9 keV. Worrall & Birkinshaw (1994) estimate $L_\mathrm{X}^{(0.2-1.9\,\mathrm{keV})} = 8 \times 10^{41}\,\mathrm{erg\,s^{-1}}$ for gas within a 3-arcmin (130-kpc) radius. Given the parameters of their β-model fit, this corresponds to a total luminosity of $L_\mathrm{X}^{(0.2-1.9\,\mathrm{keV})} \simeq 2 \times 10^{42}\,\mathrm{erg\,s^{-1}}$ for the whole cluster, which is in good agreement with our velocity dispersion via the $\sigma_z - T$ and $L_\mathrm{X} - T$ relations.

The predicted temperature for the velocity dispersion also agrees with two-component spectral fits based on *ROSAT* PSPC data (Birkinshaw & Worrall 1993), within the rather large uncertainties. It is clear that the gas that can be confined in this cluster is too cool for static pressure confinement of the radio jet at distances between 5 and 200 kpc from the core.

8 CONCLUSIONS

In this paper we have shown that:

(i) there is a poor cluster of galaxies associated with NGC 6251; it is one of at least three distinct and not necessarily related subclusters of Zw 1609.0+8212;

(ii) the temperature of the cluster atmosphere inferred from the velocity dispersion measurement is not high enough to provide static pressure confinement of any part of the kpc-scale radio jet (at distances of 5 to 200 kpc from the core) according to the lower limits on jet pressure calculated by Birkinshaw & Worrall (1993);

(iii) a tentative rotation curve perpendicular to the direction of the jet agrees with that measured by Heckman et al. (1985b), and

(iv) there is no evidence for [O III], Hα, or [N II] line emission at feature A on the jet, where Keel (1988) found optical continuum emission.

Better optical spectra of NGC 6251 are needed to probe deeper for line emission and to confirm the tentative dynamical results presented in Section 6. Forthcoming X-ray observations should measure the temperature of the cluster atmosphere, predicted to be 0.5–2.0 keV, based on our measurements of the cluster velocity dispersion.

ACKNOWLEDGMENTS

Observations reported in this paper were obtained at the Multiple Mirror Telescope Observatory, a facility operated jointly by the University of Arizona and the Smithsonian Institution.

The Second Digitized Sky Survey (DSS2) image was obtained from the ESO/ST-ECF Archive (http://archive.eso.org/dss/dss).

REFERENCES

Abell G. O., 1958, ApJS, 3, 211
Arnaud M., Evrard A. E., 1999, MNRAS, 305, 631
Bird C. M., Mushotzky R. F., Metzler C. A., 1995, ApJ, 453, 40
Birkinshaw M., Worrall D. M., 1993, ApJ, 412, 568
Danese L., De Zotti G., di Tullio G., 1980, A&A, 82, 322
de Vaucouleurs G., de Vaucouleurs A., Corwin H. G. Jr., Buta R. J., Paturel G., Fouqué P., 1991, Third Reference Catalogue of Bright Galaxies. Springer-Verlag, New York
Ferrarese L., Ford H. C., 1999, ApJ, 515, 583
Girardi M., Fadda D., Giuricin G., Mardirossian F., Mezzetti M., Biviano A., 1996, ApJ, 457, 61
Gregory S. A., Connolly L. P., 1973, ApJ, 182, 351
Heckman T. M., Carty T. J., Bothun G. D., 1985a, ApJ, 288, 122
Heckman T. M., Illingworth G. D., Miley G. K., van Breugel W. J. M., 1985b, ApJ, 299, 41
Huchra J., Davis M., Latham D., Tonry J., 1983, ApJS, 52, 89
Huchra J., Geller M., Clemens C., Tokarz S., Michel A., 1995, The CfA Redshift Catalogue, Version June 1995, Harvard-Smithsonian Center for Astrophysics
Jones D. L. et al., 1986, ApJ, 305, 684
Keel W. C., 1988, ApJ, 329, 532
Lubin L. M., Bahcall N. A., 1993, ApJ, 415, L17
Miley G. K., Osterbrock D. E., 1979, PASP, 91, 257
Perley R. A., Bridle A. H., Willis A. G., 1984, ApJS, 54, 291
Prestage R. M., Peacock J. A., 1988, MNRAS, 230, 131
Readhead A. C. S., Cohen M. H., Blandford R. D., 1978, Nat, 272, 131
Richter O.-G., Huchtmeier W. K., 1991, A&AS, 87, 425
Shuder J. M., Osterbrock D. E., 1981, ApJ, 250, 55
Strauss M. A., Huchra J. P., Davis M., Yahil A., Fisher K. B., Tonry J., 1992, ApJS, 83, 29
Tonry J., Davis M., 1979, AJ, 84, 1511
Werner P. N., Worrall D. M., Birkinshaw M., 1999, MNRAS, 307, 722
Worrall D. M., Birkinshaw M., 1994, ApJ, 427, 134
Young P. J., Sargent W. L. W., Kristian J., Westphal J. A., 1979, ApJ, 234, 76
Zwicky F. E., 1968, Catalogue of Galaxies and of Clusters of Galaxies, Vol. VI. California Institute of Technology, Pasadena

This paper has been typeset from a TEX/LATEX file prepared by the author.