Peculiar Velocities of Wide Angle Tailed Radio Galaxies in Galaxy Clusters

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Abstract

We analyze photometry and redshifts of clusters containing WAT (Wide Angle Tailed) radio galaxies with the goal of clarifying the connection between the WATs' bent tail morphology and the dynamical state of their host cluster. We have gathered data for 18 WAT clusters from a variety of sources. We've obtained B, V, and R CCD mosaics from the Kitt Peak 0.9-m telescope, and g and r CCD images from the Sloan Digital Sky Survey (SDSS). The redshifts come from the MX multifiber spectrograph, Gemini GMOS, and SDSS. The redshifts allow us to calculate the WAT peculiar velocities (i.e. radial velocity relative to the cluster) for all 18 clusters. Significant peculiar velocities were found for 39% of the clusters before correcting for substructure, and 35% after. Our deep imaging reveals that most WAT's are associated with first ranked galaxies with extended stellar envelopes that usually show distortions. Moreover, WAT's are usually found near peaks in the galaxy surface dens ity. We conclude that most WAT's have small but non-zero speeds within their host subclusters. For some, the speeds may be high enough to bend the radio tails.

Introduction

A Wide Angle Tailed radio galaxy, or WAT, is a sub-type of the "edge-darkened" (FR-1) radio galaxies. Like other FR-1's, they tend to have a bright, unresolved radio core producing well-collimated jets which disrupt at "hot spots" and become diffuse "tails". WATs are distinguished from other FR-1's in that 1) the jets and tails show gradual bending in a "C" or "V" shape, 2) they are the most powerful of the FR-1's, and 3) they are always identified with giant elliptical galaxies, likely the brightest one in their host cluster of galaxies. In contrast, narrow angle tailed (NAT) and head tailed (HT) sources have more acutely bent back jets/tails, and tend to be associated with smaller cluster ellipticals.

These basic observations suggest that the morphologies of HTs, NATs and WATs are due to ram pressure as they move through the hot ICM (intracluster medium) of galaxy clusters; WATs have less bending because they are hosted by more massive ellipticals with slower orbital speeds. A slightly different hypothesis was developed for the prototype WAT, 3C 465, in Abell 2634 (Fig. 1): the WAT galaxy is basically at rest with respect to its cluster, but an ongoing merger with another cluster is producing a wind which shapes the tails (Pinkney et al. 1993). This merger hypothesis was bolstered by two assertions: 1) WAT's cannot both be giant cD galaxies and have large "peculiar" motions relative to their clusters (because this would tidally strip the extended stellar envelopes, and these "cD envelopes" require a central location in the cluster gravitational potential to form in the first place), and 2) large (~1000 km/s) relative motions are required to bend the tails of the WATs, and simulations (e.g, Roettiger et al. 1993) show that such flows occur in mergers.

Both of the above assertions require confirmation. Are all WAT host galaxies actually first ranked? Are they cD galaxies (giant ellipticals with extended surface brightness distributions)? If so, do they show signs of distortion due to interaction with the cluster potential or with neighboring galaxies? We will address these questions with multicolor surface photometry. Do WATs really require over 1000 km/s relative velocity for tail shaping? Papers on jet dynamics have addressed this and some say "no" (e.g., Jetha et al. 2006). With a redshift survey of the host cluster, one can measure the "peculiar velocity" of the WAT, i.e., its radial motion relative to the cluster. One cannot directly measure its tangential motion, but that is inferred by an offset of the galaxy from the cluster density peak. We have culled together redshifts for 18 WAT clusters allowing us to measure pecular velocities. If the distribution is wide enough, the bending of WATs may be due to it's motion.

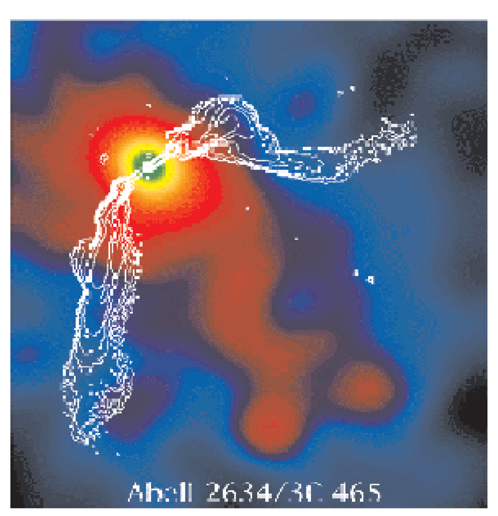


Figure 1.
Radio Contours (white) over x-ray surface brightness (colors) for the WAT in Abell 2634.

Data

CCD Imaging

- MOSA 8192x8192 mosaic KPNO 0.9-m. B, V, and R filters
- SDSS (Sloan Digital Sky Survey), g and r filters (York et al. 2000)

Spectroscopy

- MX multifiber spectrograph on 2.3-m. at Steward Obs. (Pinkney et al. 2000)
- GMOS (Gemini Multi-Object Spectrograph)
- SDSS multifiber spectrograph

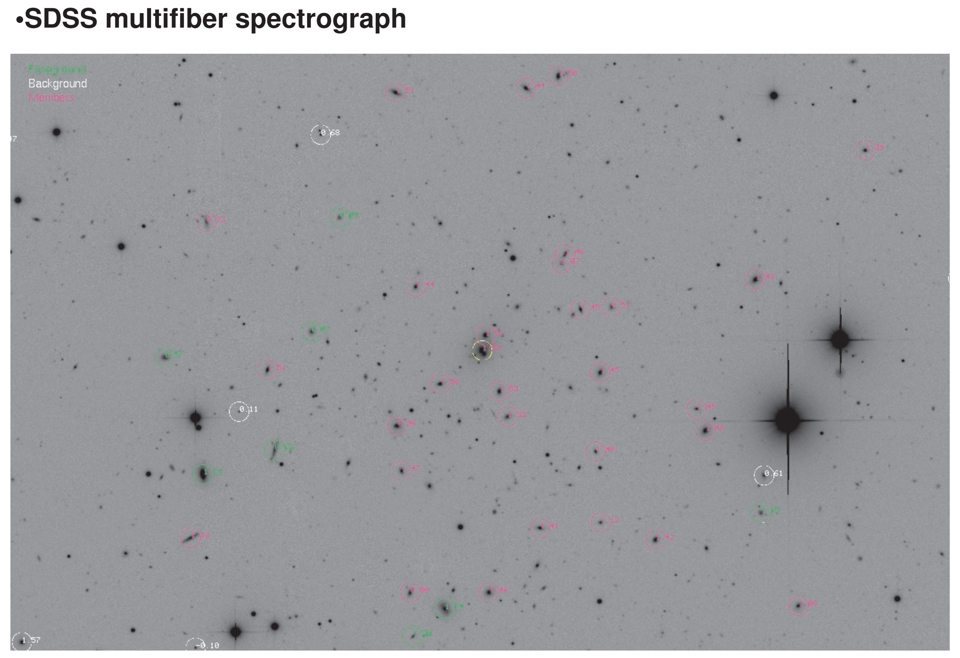
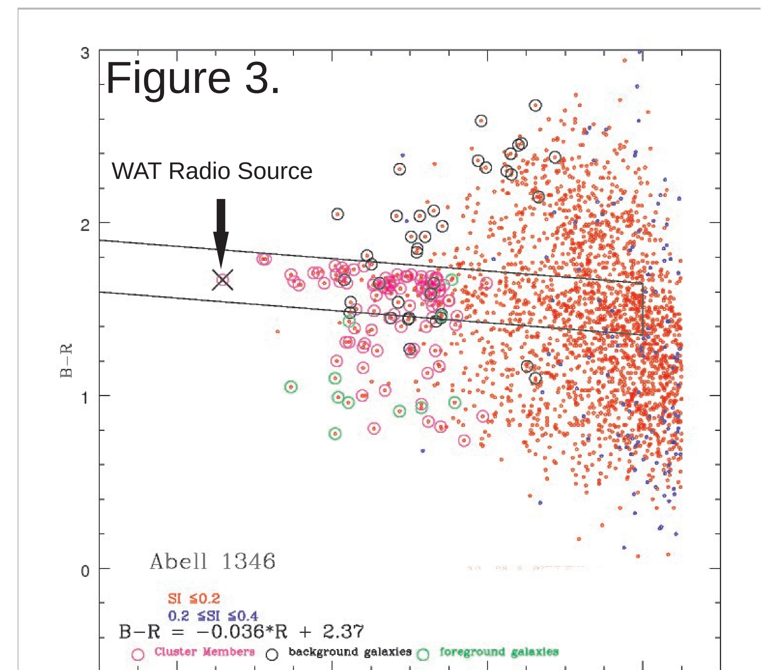


Figure 2.
This image combines data from the MOSA imager (greyscale background), the SDSS spectrograph (color coding), and SDSS photometry (g-r labels) for the cluster Abell 1446. The yellow circle marks the WAT.

Galaxy Rank

Utilizing the CMR and velocity information we were able to identify foreground, background, and member galaxies. Having matched the radio position obtained by Owen et al. (1995) to our catalog of objects, it was possible to locate the WAT on a color vs. magnitude plot (Figure 3). The point farthest to the left is the <u>first</u> <u>ranked</u> (brightest) <u>galaxy</u>. Based on SDSS redshifts, the magenta circles are members of the cluster, black circles are background galaxies, and green circles are foreground galaxies. Small red dots are non-stellar sources (galaxies) identified in our MOSA images. The tilted box encloses our color selected subsample. The top of the line was chosen by eye to lie just above the color magnitude relation (CMR). Standard widths were used for each plot (0.3 for B-R and 0.2 for V-R).

If, after creating the CMR plots, there were unidentified galaxies (sources with color information but no velocity information) that were brighter that our galaxy (either inside or outside the color selection box). We again made the CMR plot using a radially selected sample that only included objects within one Abell radius (2 h_{75}^{-1} Mpc) of the NED (NASA Extragalactic Database) centroid. In most cases, this process left the WAT as the first ranked galaxy.



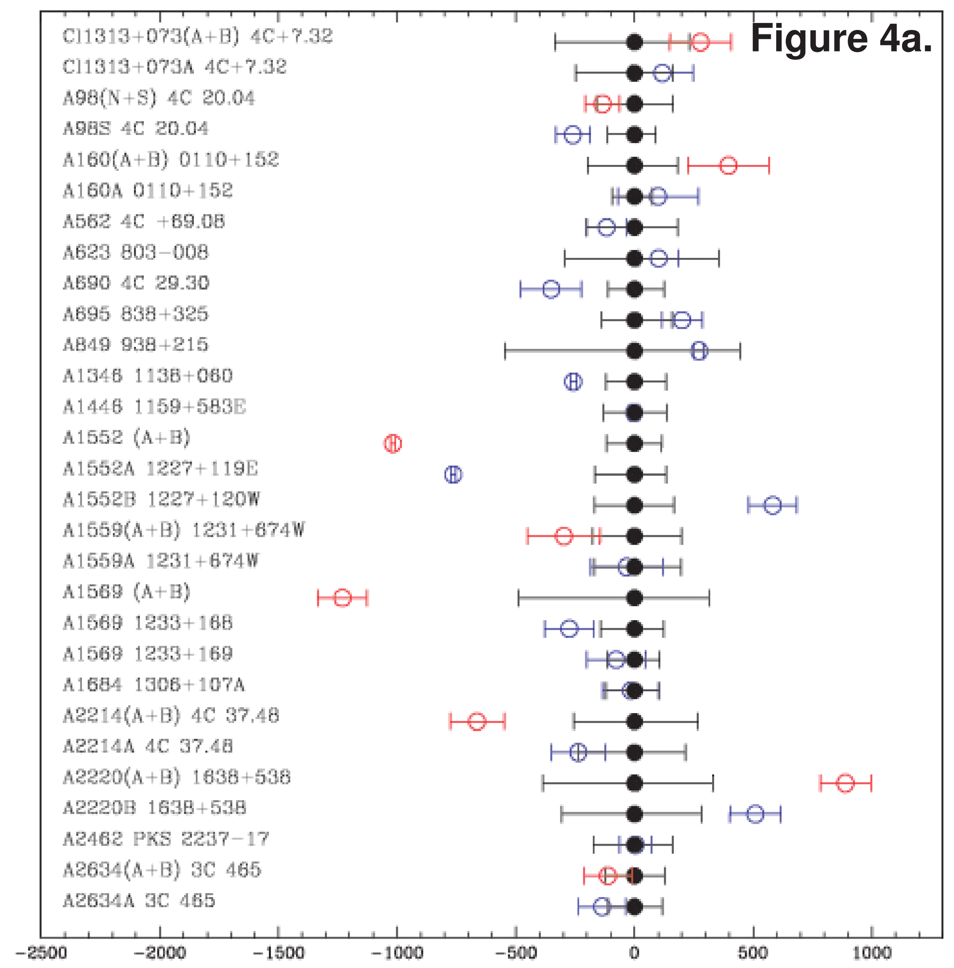
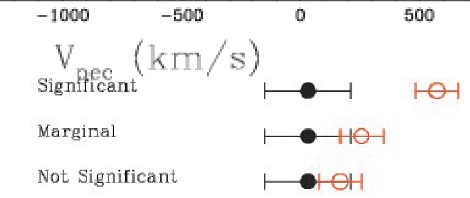


Figure 4b.



Peculiar Velocity

Figure 3a on the left shows the peculiar velocities of our WATs. The red open circles are the peculiar velocities of the WATs (with their 90% confidence intervals). The peculiar velocity is defined as

$$V_{pec} = (V_{WAT} - V_{clus})/(1+z)$$

where z is the redshift and V_{clus} is the mean of all galaxy velocities which satisfy membership criteria. We actually use C_{BI}, the biweight estimate of centroid for V_{clus}. The black dots represent C_{BI} for the cluster. The first row for each cluster defines membership as all velocities within ~3000 km/s of the WAT, but excludes the WAT. Subsequent rows are groups within the cluster which are objectively defined using Kayes Mixture Modeling (KMM, McLachlan & Basford 1988). In two clusters (A1552, A1569) there are two WAT galaxies, each allocate to its own group.

Determining Significance of Vpec

Our significance criterion is depicted graphically in Figure 4b. The dots have the same meaning as in Figure 4a. The asymetric 90% confidence intervals of C_{BI} are calculated using bootstrap resampling of the velocity distribution, including errors and cosmological correction by (1+z).

Determining Members of Subclusters

If the peculiar velocity of the WAT is significant and large, there is reason to believe that there are subclusters within the initial sample. Many times the subclusters are separated with respect to not only their spatial distribution, but also their velocity distribution. Once estimates of the right ascension, declination, and velocity means are made, we used KMM to statistically determine members of each subcluster. The program then took the given information and calculated where each galaxy belonged (either group 1 or 2 for our data, though there could be more than two subclusters in some cases). KMM gave a probability for each galaxy belonging to either subcluster as well as a percent confidence in correct members for each group overall. Figure 5 shows an example of a typical output from KMM. In all cases, after dividing a cluster into two or more subclusters the peculiar velocity of the WAT decreased and in some cases made it not significant.

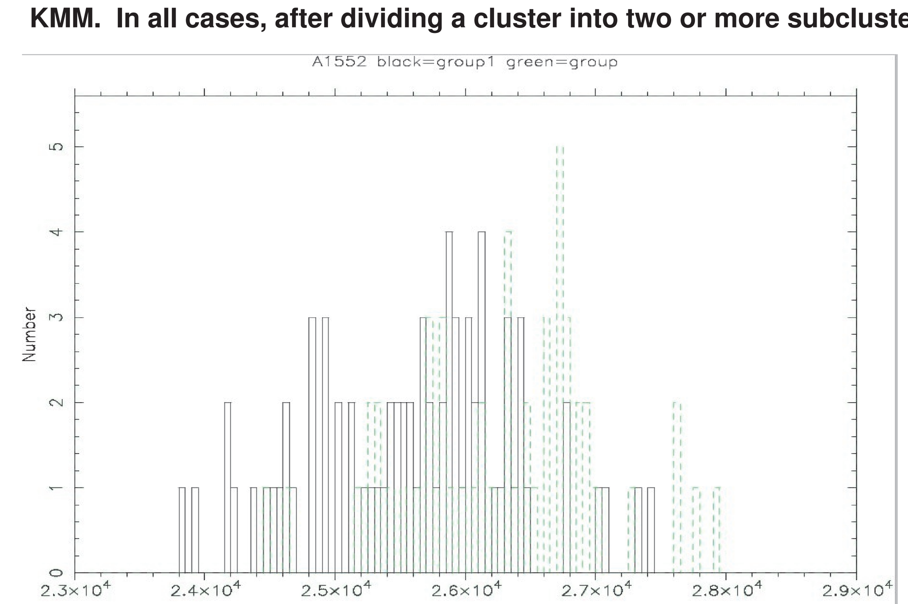
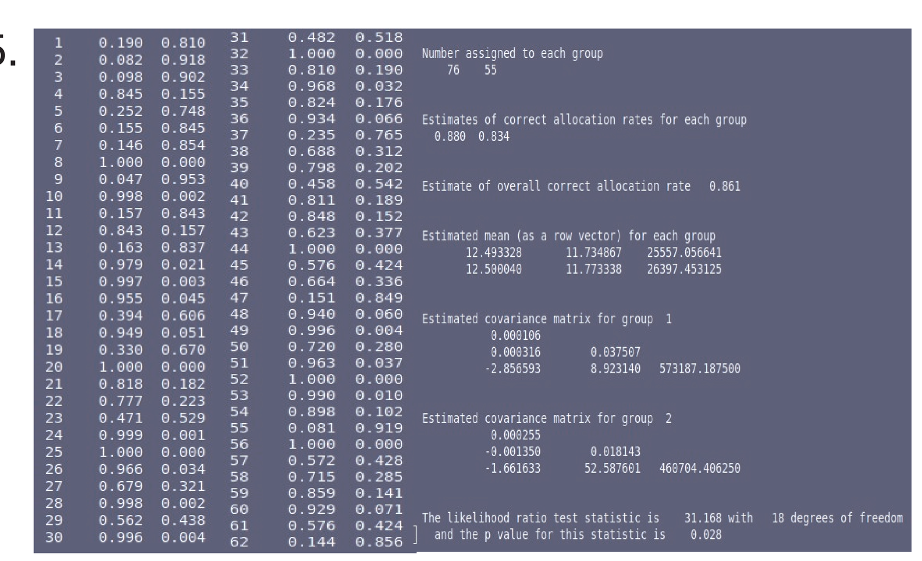


Figure 6.
To the right is a velocity histogram of Abell 1552. The black bars are members belonging to group1 and the green members, group2. Members of each group were determined from KMM (Kayes Mixture Modeling).

Figure 5.



WAT Offset From Density Peak

Most, but not all of the WAT radio galaxies were located near a peak in the galaxy density distribution, as revealed by our contour plots. Many different contour plots were inspected for each cluster corresponding to the many possible subsamples (e.g., color-selected, redshift-selected). Usually, the location of the WAT near a density peak was robust. We quantified this offset using r/R_A, where r is the offset in arcminutes and R_A is the Abell radius (1.7'/z). Most WATs had r/R_A < 0.1.

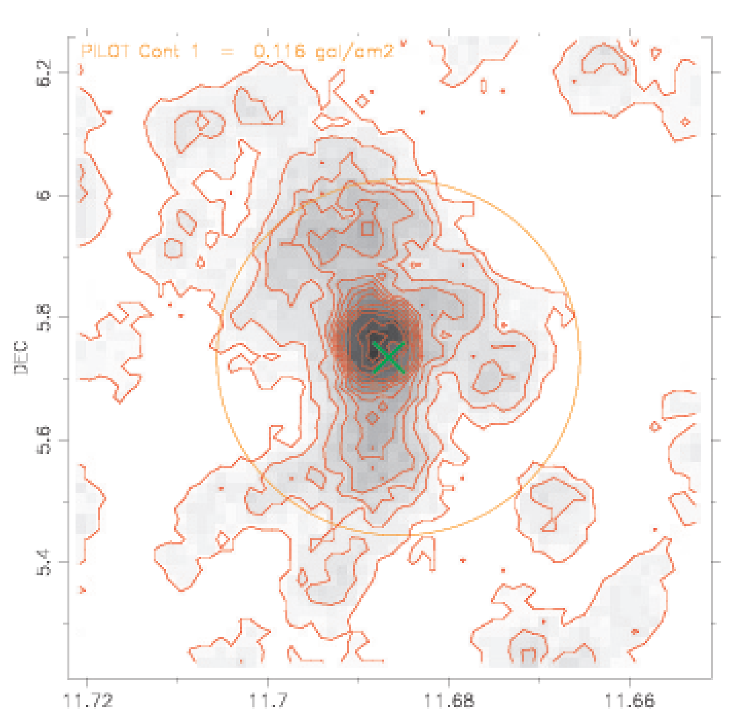


Figure 7.
The contour shows the position of the WAT in Abell 1346 relative to a galaxy density peak taken from a color selected sample of 546 galaxies. The green "X" is the WAT and the orange circle signifies the Abell radius from the center of the density peak. Abell 1346 is 0.103 Abell radii away from the peak of the density distribution.

Isophotal Distortions

The observed WATs typically are found to be large ellipticals. By studying the photometry we are able to conclude that many of the WAT's (45%) show signs of isophotal distortions. In most cases, the distortion is due to a "bridge" between the WAT and a companion galaxy. However, there were some cases that the WAT exhibited a "centroid shift" wherein the center of the contours shifts off of the galaxy's peak for fainter contours. These WAT's all have the property that they are surrounded by a large extended stellar envelope of low surface brightness.

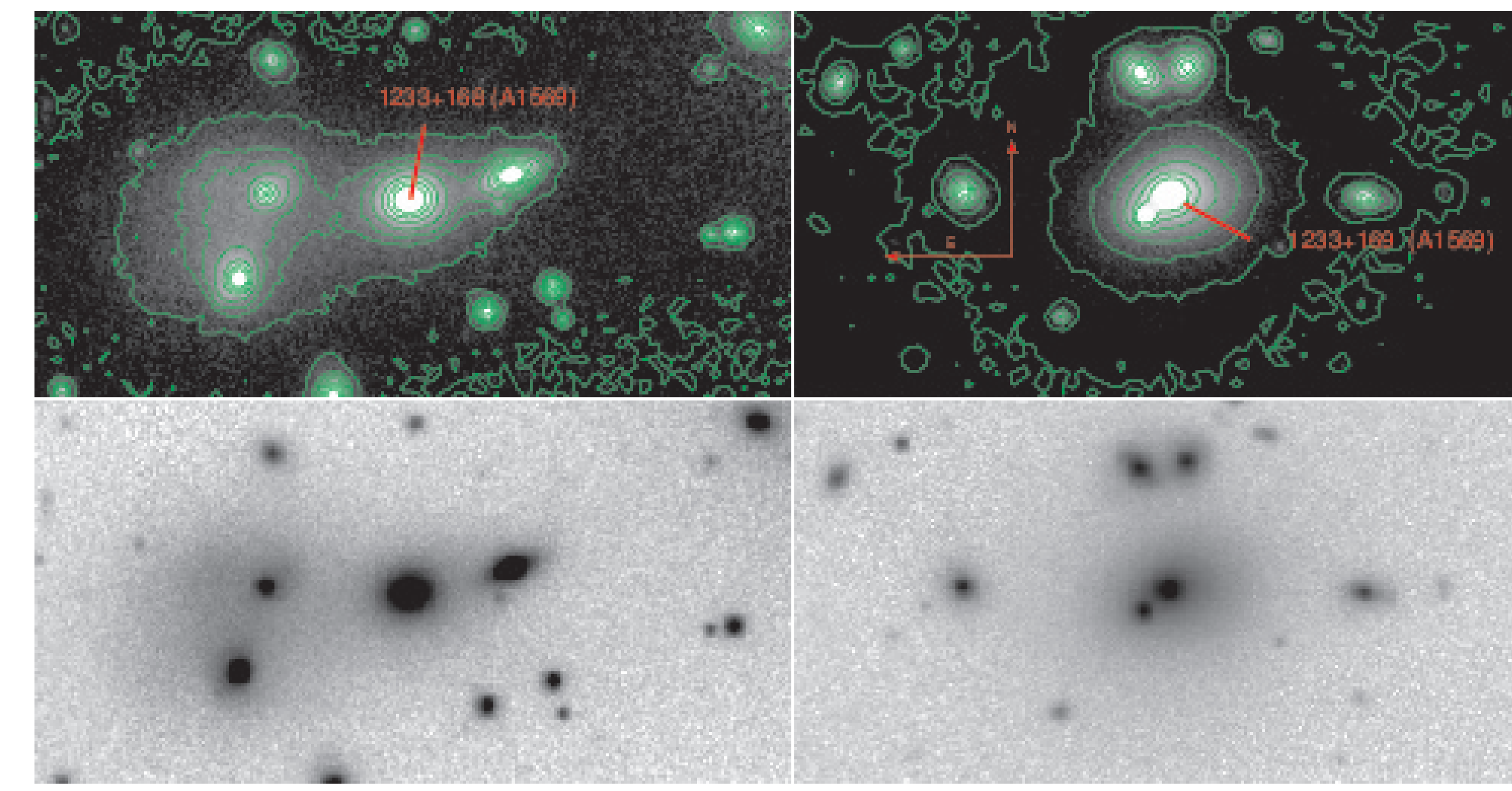


Figure 7.
The image above (Abell 1569) shows both examples and non-examples of isophotal distortion as wells as examples of extended envelopes. The green lines on the top two images are surface brightness isophotes overlaid onto an optical (R-band) images. The two bottom images are negatives of the same R-band image. The images on the LEFT show an example of a WAT with symmetric contours and only marginal evidence for a low surface brightness bridge - we said "no" to isophotal distortions. 1233+168 is, however, engulfed in a low-surface brightness envelope. The images on the RIGHT shows the nearby WAT host 1233+169. clear isophotal distortions (a "yes") in the form of an obvious centroid shift as the contour levels spread. This WAT (1233+169) displays an obvious centroid shift as the contour levels spread, so we gave it a "yes" for isophotal distortions.

Results

Average peculiar velocity ($\|V_{pec}\|$) (cosmologically corrected)	321.4 km/s	
Average normalized biweight velocity dispersion Z ($Z=\|V_{pec}\|/S_{BI}$)	0.256	
WAT's with significant peculiar velocity before substructure correction	7/18	39%
WAT's with significant peculiar velocity after substructure correction	7/20	35%
WAT's with marginally significant peculiar velocity before substructure correction	3/18	17%
WAT's with marginally significant peculiar velocity after substructure correction	4/20	20%
WAT's within 0.1 Abell radii (i.e. r<200 kpc)	10/15	67%
WAT's within 0.2 Abell radii (i.e. 400 kpc)	14/15	93%
WAT's with isophotal distortions	9/20	45%
WAT's with extended envelopes	20/20	100%
WAT's ranked 1st among cluster members	8/13	62%

Conclusions:

WAT radio galaxies tend to be located near number density peaks in galaxy spatial distribution. Some WATs are offset by an amount which is large compared to the uncertainties, but small compared to the Abell Radius. One would expect that the WAT possesses a tangential peculiar velocity in these cases. Similarly, most of the WATs have radial velocities near that of their cluster (i.e., Vpec/SBI <0.3). But ~35% of the WATs have significant radial Vpecs, even after substructure correction. Thus, even though WATs reside in extended envelopes suggesting a static location in the gravitational potential well, their radial and tangential peculiar velocities, combined with their occasional distorted isophotes, suggest that some do have motions inside their subcluster; some WAT bending may be due to its motion. In some cases, however, the Vpec may indicate subcluster contamination that could not be objectively removed, and the ongoing merger could channel winds past the WAT.

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