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The H I gas content of galaxies around Abell 370, a galaxy cluster at z = 0.37

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Presented here are our measurements of the neutral atomic hydrogen gas content of 324 galaxies around Abell 370, a galaxy cluster at a redshift of z = 0.37 (a look-back time of ∼4 billion years). These measurements were made using Giant Metrewave Radio Telescope observations by coadding the H I 21-cm emission signal from the galaxies with known optical positions and redshifts. The gas content of these galaxies is significantly higher than that found in nearby clusters, providing evidence for galaxy evolution within dense environments. Despite this fact, galaxies in regions of higher density within Abell 370 have less gas than galaxies located in regions of lower density surrounding the cluster, following the same trend seen in nearby clusters.

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1. Introduction

Galaxy properties, such as morphology and star formation rate, are known to depend on environmental density (e.g. Dressler 1980; De Propris et al. 2004; Kauffmann et al. 2004). These effects probably originate from a density-dependent quenching of star formation which can come about via the consumption or removal of the available gas supply in the galaxies. As such, the amount of HI gas available to galaxies to fuel further star formation is likely to be a fundamental parameter in understanding the effect of environment. Galaxies in nearby (z $\sim$0) clusters and their surroundings show strong evidence for environmental influences on their gas content. However, at higher redshifts the gas content of clusters has not been studied in detail. Consequently, our understanding of the effect of environment on galaxy evolution has been incomplete.

Neutral atomic hydrogen gas (HI) is a large component of the gas content of galaxies and can be directly quantified from HI 21-cm emission. In the central regions of nearby clusters, late-type galaxies are found to be HI deficient compared to similar galaxies in the field (Haynes, Giovanelli, & Chincarini 1984). This effect continues well outside the cluster cores with a gradual change in the HI content of galaxies with galaxy density (Solanes et al. 2001).

Observing HI 21-cm emission from galaxies at cosmological distances ($z > 0.1$) is difficult due to the weak flux of the line. To quantify the HI gas content of large numbers of galaxies at cosmologically interesting redshifts, we have been coadding the HI 21-cm emission from multiple galaxies using their observed optical positions and redshifts. The coadding technique for measuring neutral atomic hydrogen gas has been used previously in galaxy cluster Abell 2218 at $z = 0.18$ (Zwaan 2000) and in Abell 3128 at $z = 0.06$ (Chengalur, Braun, & Wieringa 2001). We expanded this technique to field galaxies with active star formation at z = 0.24 (Lah et al. 2007).

The goal of this work is to quantify the evolution of the HI gas in galaxies in a variety of environments. At moderate redshifts the angular extent of galaxy clusters is sufficiently small that galaxy environments from the dense cluster core to almost field galaxy densities can be observed in a single radio telescope pointing.

2. The galaxy cluster Abell 370

In this work we are applying the HI coadding technique to galaxies surrounding Abell 370, a galaxy cluster at z = 0.37 (a look-back time of $\sim$4.0 billion years). Abell 370 is a large galaxy cluster, similar in size and mass to the nearby Coma cluster. The HI gas content of galaxies at different distances from the Abell 370 cluster core are examined, in particular that of galaxies inside and outside the extent of the hot, X-ray emitting, intracluster gas as well as that of galaxies inside and outside the cluster R_{200} radius (the radius at which the galaxy density is 200 times the general field).

To make the measurements, we observed the Abell 370 field for 63 hours with the Giant Metrewave Radio Telescope (GMRT) to obtain radio spectroscopic data, 7 nights with the Australian National University 40 inch to obtain optical imaging and 4 nights with the Anglo-Australian Telescope (AAT) to obtain optical spectroscopy. The histogram of the optical redshifts obtained for the cluster are shown in left panel of Fig. 1 along with the HI 21-cm frequency limits of the GMRT observations. 324 galaxies lie with the GMRT frequency limits and are otherwise usable for HI

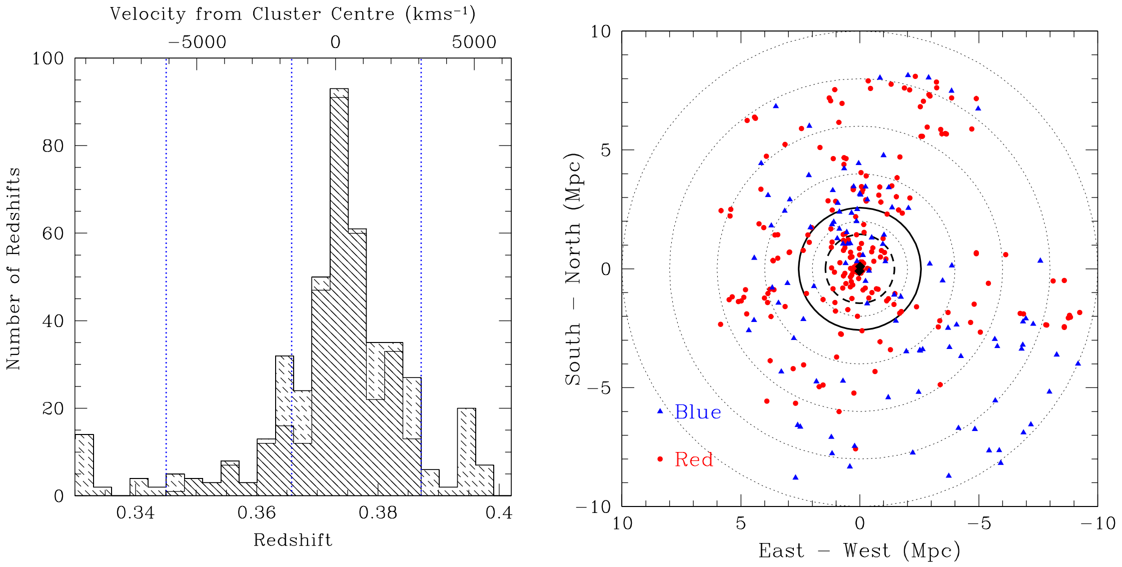

Figure 1: Left panel: This panel shows the distribution of the redshifts around the galaxy cluster Abell 370. The vertical dotted lines are the GMRT frequency limits converted to their HI redshift; the central dotted line is the boundary between the upper and lower sidebands of the GMRT radio data. The histogram shaded with the unbroken line is the distribution of the 324 redshifts used in HI coadding. The counts shaded with the broken line is the distribution of the unusable redshifts. The top x-axis shows the velocity from the cluster centre, giving an indication of the peculiar motion of the galaxies within the cluster. The cluster centre is at z_{cl} = 0.373. **Right panel:** This panel shows the 324 galaxies used in the HI coadding plotted as projected distance in Mpc from the galaxy cluster centre. The triangular points are the blue galaxies and the circular points are the red galaxies. The two diamond points near the centre are the two cD galaxies. The dashed circle is the 3σ extent of the X-ray gas and is at a radius of 1.45 Mpc (Ota & Mitsuda 2004). The solid circle is the R_{200} radius of 2.57 Mpc. The faint, dotted circles are at radii of 2, 4, 6, 8 & 10 Mpc from the cluster centre.

spectral coaddition. The right panel of Fig. 1 shows these 324 galaxies plotted as projected distance in Mpc from the galaxy cluster centre and split into optically blue and red galaxies. The definition of a blue galaxy is the Butcher-Omeler condition i.e. the blue galaxies are those at least 0.2 magnitudes bluer than the cluster ridge-line (Butcher & Oemler 1984). The dividing line between the blue and red galaxies for our data was $B-V$ = 0.57.

3. HI gas measurements

Directly detecting the HI 21-cm emission from even the most gas rich galaxy in the observed radio data for Abell 370 is unlikely. A search of the radio data cube for HI direct detections was made and nothing of significance was found. Instead of direct detection, the HI 21-cm emission signal from multiple galaxies has been coadded to increase the signal to noise of the measurement. This stacked signal can then be used to quantify the total HI gas content of the galaxies. The galaxies are located within the radio data using their measured optical positions and precise optical redshifts. Variance weighting was used when coadding the separate HI spectra, primarily to take

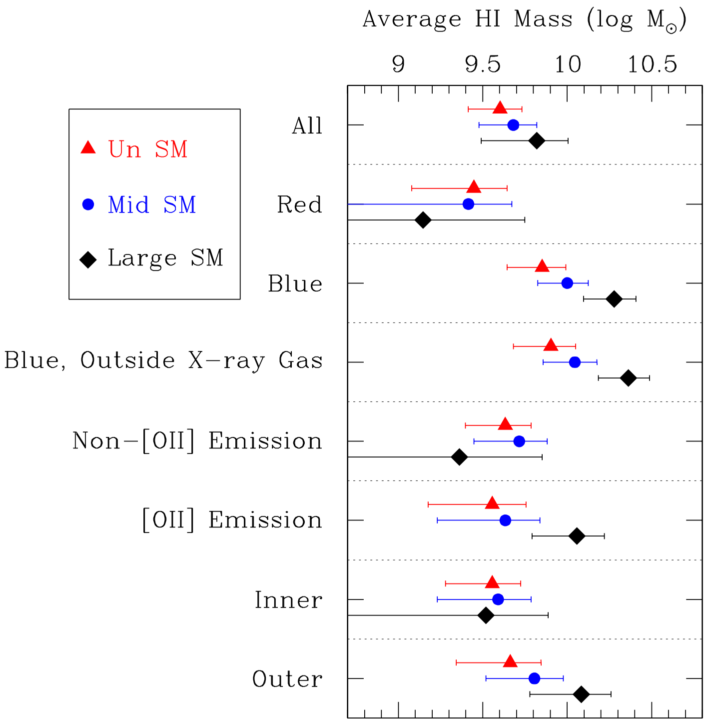

Figure 2: This figure displays the average galaxy HI mass for the different subsamples of galaxies measured using the different smoothed data combinations (see text). The 'Un SM' are the Unsmoothed values, 'Mid SM' the Mid-Smoothing values and the 'Large SM' are the Large Smoothing values.

into account the different RMS in each galaxies spectra caused by the different primary beam corrections.

The GMRT synthesised beam has a FWHM ∼3.3 arcsec at 1040 MHz which corresponds to ∼17 kpc at z = 0.37. Unfortunately all but the very smallest of the galaxies in our sample are likely to be resolved by this synthesised beam size. So the radio data was smoothed to larger synthesised beam sizes until the galaxies were unresolved and their HI signal was then measured. One can make an estimate of the projected size of the HI gas in a galaxy using the correlation found between the optical *B* band magnitude and the HI size of spiral and irregular galaxies in the field at low redshift (Broeils & Rhee 1997). However the galaxies in our sample are a mixture of early and late-type galaxies that span a wide range of environments from the high density of the cluster core to almost field galaxy densities at the edges of the cluster. Instead of using one measurement based on this estimate, three different measurements of the average HI gas mass were made to reflect the uncertainty in the HI extent of the galaxies as projected on the sky. The first coadded HI mass measurement was made by measuring the specific intensity at the optical positions of the galaxy in the original unsmoothed GMRT radio data (synthesised beam size of 17 kpc, ∼3.3 arcsec). The second coadded HI mass measurement was made by smoothing the synthesised beam to the same extent as the estimate HI size. A third measurement was made similarly, except the data is smoothed to twice the estimated HI size. This large smoothing measurement should give an accurate reflection of the total HI gas mass for galaxies that have similar HI extents to the field spiral and irregular galaxies observed by Broeils & Rhee (1997).

The coadded HI mass measurements for various subsamples of the Abell 370 galaxies can be seen in Fig. 2. The first measurement is the “All” measurement which includes all 324 galaxies for which HI 21-cm emission could be measured. There is some indication of an increase in the HI signal as one moves to the larger smoothing measurements. This is a sign that the HI gas is not contained only in the very centre of the galaxies but extends to their outer regions.

Of greater interest is examining subsamples of the galaxies, notably subsamples containing the 219 red galaxies and the 105 blue galaxies. The measurements for these subsamples can be seen in Fig. 2. The red galaxies may or may not contain HI gas at the lowest smoothing level but it is clear that the higher smoothings measurements add only noise. The blue galaxies show the opposite pattern; there is a strong signal at the lowest smoothing which increases significantly in the higher smoothing measurements. This indicates that the blue galaxies have some HI gas in their central regions but have the bulk of their HI gas located around their outskirts. This is similar to the trend seen in HI rich galaxies in the local universe, which contain large amounts of HI gas that extend beyond their visible stellar components (Broeils & Rhee 1997).

In the central regions of nearby clusters, late-type galaxies are found to be HI deficient compared to similar galaxies in the field (Haynes, Giovanelli, & Chincarini 1984). One would like to see if this trend is seen in the late-type galaxies inside the hot intracluster medium of the cluster core of Abell 370 at z = 0.37. Assuming that blue galaxies are a representative sample of the late-type galaxies, then there are 11 such galaxies within the 3σ extent of the X-ray gas (1.45 Mpc from the cluster centre, see the right panel of Fig. 1). Unfortunately this is an insufficient number of galaxies to coadd to make a meaningful measurement of the gas depletion of these galaxies. The best that one can do is consider the subsample of blue galaxies outside the X-ray significance radius of which there are 94. The average HI gas for these galaxies is slightly higher than for the all blue galaxies possibly indicating that the 11 galaxies in the X-ray gas are HI deficient. This difference in average HI mass for all 105 blue galaxies and the 94 blue galaxies outside the X-ray gas is not statistically significant but it does follow the expected trend of HI deficiency found in late-type galaxies within nearby clusters.

Subsamples of the Abell 370 galaxies were also made based on the measured [OII]λ3727 emission line in their optical spectra. [OII] emission was used as an indication of of star formation activity. A measured [OII] equivalent width of 5 Å was used as the cut off between the emission and non–emission subsamples. In the sample there are 156 non-[OII] emission galaxies and 168 [OII] emission galaxies. Their measured HI gas content can be seen in Fig. 2. Unlike the red and blue galaxies, these two subsamples seem to have similar average HI gas masses in their inner regions of their galaxies (the lowest smoothing). Only when considering the large smoothing measurements that trace the outer regions of the galaxies is a difference between the two subsamples seen. In the large smoothing the [OII] emission subsample shows an increase in the average HI gas content while the non-[OII] emission subsample measurement is consistent with no increase in HI gas.

Finally subsamples of the Abell 370 galaxies were made based on their location relative to the centre of the cluster. An inner subsample of 110 galaxies was formed from those galaxies that fell within a projected distance of 2.57 Mpc (the R_{200} radius) of the cluster centre and in the redshift range z = 0.356 to 0.390 around the cluster redshift centre. The 219 galaxies outside these criteria make up the outer galaxy subsample. For these subsamples H I measurements were made and the results are shown in Fig. 2. The inner subsample of galaxies have an average H I mass distribution similar to the red galaxy subsample; any H I gas content they have is located in the central regions of the galaxies. The similarity with the red galaxies is not surprising as the inner sample is dominated by red galaxies (87 out of the 110 galaxies). The H I measurements for the outer subsample are similar to that seen for the blue galaxies. There is a definite H I signal from the central regions of the galaxies with an increased H I signal when including the outskirts of the galaxies. The outer sample is made up of 132 red galaxies and 82 blue galaxies. The inner sample of galaxies have average H I gas contents significantly lower than the galaxies in the outer subsample. This is a clear environmental trend in the H I gas content similar to that seen in nearby galaxy clusters.

4. H I density measurements

It is necessary to compare the H I measurements of the galaxies in Abell 370 with local samples in order to quantify any evolution in the H I gas over the past ∼4 billion years (since z = 0.37). One way to quantify the gas evolution in Abell 370 is to compare the H I density around the cluster with values from the literature.

The H I density in the region covered by the optical imaging and spanning the GMRT observational frequency range was measured using all 324 galaxies along with the H I density in this region due to just the 105 blue galaxies. These measurements can be seen in Fig. 3. The density using only the blue galaxies almost equals that from using all the galaxies, indicating that most of the H I gas in this volume is located in the blue galaxies.

These H I density measurements only include the H I gas contained in the known galaxies; they do not take into account the many ‘missing’, optically fainter galaxies in the volume that contain H I gas. As such these measurement are only lower limits on the total H I density in this volume. These values have been scaled up to an estimate of the total H I density in the volume. This is done by assuming that the optical luminosity density of the galaxies is proportional to their H I density. A scaling can then be derived using the galaxies optical luminosity density in the *B* band. These scaled values are the ‘Ex’ values in Fig. 3.

Just below these measurements in Fig. 3 are literature measurements of the H I gas cosmic density values at a variety of redshifts. These values are at z = 0 (Zwaan et al. 2005), z = 0.24 (Lah et al. 2007) and z ∼ 0.6 (Rao, Turnshek, & Nestor 2006) (these last two are the two closets literature values to z = 0.37). The errors in the measurements make it difficult to determine if there has been any substantial evolution in the H I gas in galaxies from these values. Indeed it is probably not fair to compare the H I density found in this volume around Abell 370 to the cosmic density as we are dealing with an unusual region of the universe with a considerably higher galaxy density than the average. To do a fair test for evolution it is necessary to compare the measured H I density around Abell 370 to nearby volumes with similarly high galaxy densities.

In order to make a comparison with nearby galaxy clusters a sample of galaxies within 8 Mpc of the cluster centre of Abell 370 was selected. There are 220 galaxies in this subsample and the measured H I density for this region is shown in Fig. 3 along with the H I density for the 58 blue galaxies in this region. The H I density from the blue galaxies is comparable to that measured for

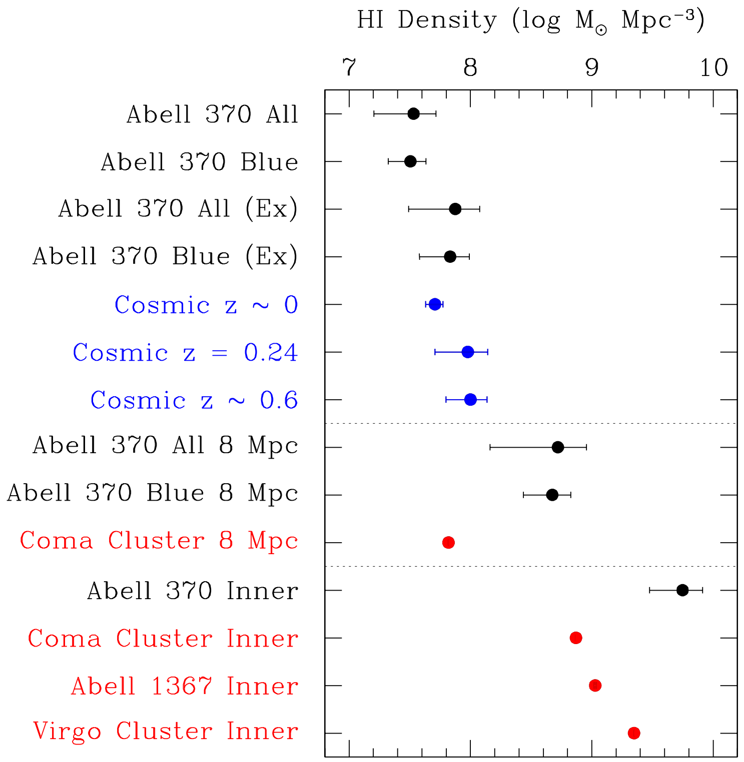

Figure 3: This figure shows the measured HI gas density around Abell 370 for various subsamples and that found in a variety of literature samples. The figure is divided into three parts by faint dashed lines. The top part shows measurements made from the total volume sampled around Abell 370 in this work. It includes the HI density measured from just the known Abell 370 galaxies as well as extrapolations to the total HI density in the volume (the 'Ex' values). Also shown in the top part are cosmic HI density values at variety of redshifts. The middle part shows the HI density within 8 Mpc of the cluster centre of Abell 370 and a similar sized volume around the nearby Coma cluster. The bottom part shows the HI density within ~2.5 Mpc of the cluster centre of Abell 370 and in similar volumes within nearby galaxy clusters.

all 220 galaxies in this 8 Mpc radius region which suggests that again it is the blue galaxies that contain the majority of the HI gas within this volume. The HI density in a similar sized volume around the Coma cluster (Gavazzi et al. 2006) is shown in Fig. 3 (Coma is the only nearby cluster of sufficient size and sufficient observations to do this comparison). The Abell 370 HI density values are ~8 times that of the similar size region around the Coma cluster. As Coma and Abell 370 are galaxy clusters of similar size, this is evidence of substantial evolution in the gas content of cluster galaxies between redshift z = 0.37 and the present.

Finally the HI density within the R_{200}= 2.57 Mpc (i.e. within the cluster core) was measured. The value due to these 110 inner galaxies is shown on Fig. 3 along with similar inner measurements for the Coma cluster (Gavazzi et al. 2005), Abell 1367 (Cortese et al. 2008) and the Virgo cluster (Gavazzi et al. 2006). A clear environmental trend in the HI density of these nearby cluster can be seen in that the smallest cluster, the Virgo cluster, has the highest density while the largest, the

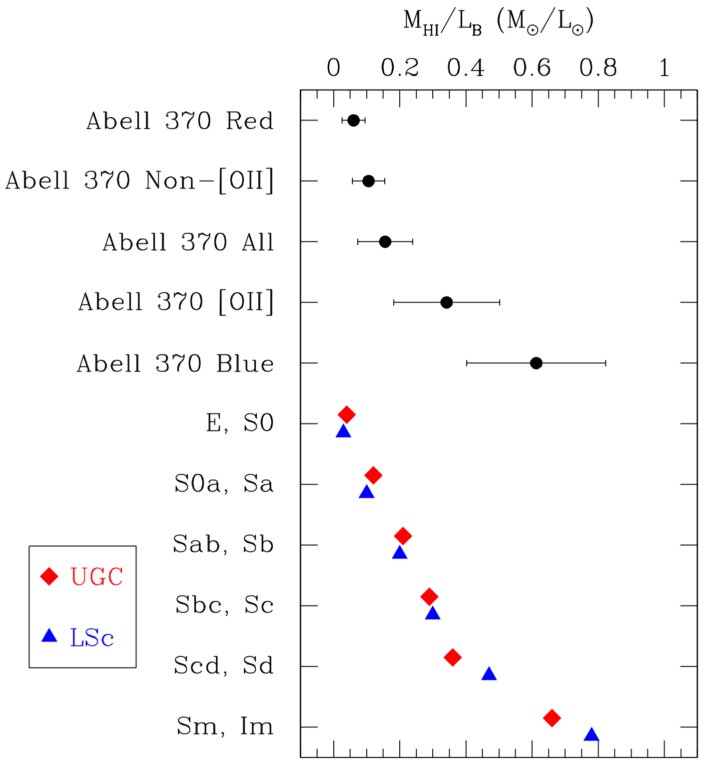

Figure 4: This figure shows the average ratio of HI mass to optical *B* band light ratio for various subsamples of the Abell 370 galaxies. Also plotted for comparison are the median HI mass to light ratios for different morphological type galaxies from the Uppsala General Catalogue (UGC) and the Local Super Cluster (LSc) (Roberts & Haynes 1994).

Coma cluster has the lowest density. However the HI density found for Abell 370 is ∼3 times higher than that found in Virgo and ∼8 times higher than that found in Coma, a similar sized cluster.

5. HI mass-to-light ratio measurements

One can compare the HI mass to optical light ratios seen for the Abell 370 galaxy subsamples to ‘normal’ galaxy values. The average ratio of HI mass to the *B* band luminosity for a variety of Abell 370 subsamples are shown in Fig. 4 along with literature values. The literature values for the HI mass to blue light ratio are for samples of galaxies with different morphological types (Roberts & Haynes 1994). The morphologies span the Hubble sequence starting with the early-type galaxies of ellipticals and S0s, moving across the variety of late-type galaxies in the direction of increasing spiral structure (moving from Sa to Sd galaxies), reaching finally the irregular galaxies. The HI mass to light ratio increases fairly regularly along this sequence.

In Fig. 4 the values for the galaxy subsamples of Abell 370 are plotted in order of increasing HI mass to light ratio. The red galaxy subsample has the lowest HI mass to light ratio while the blue

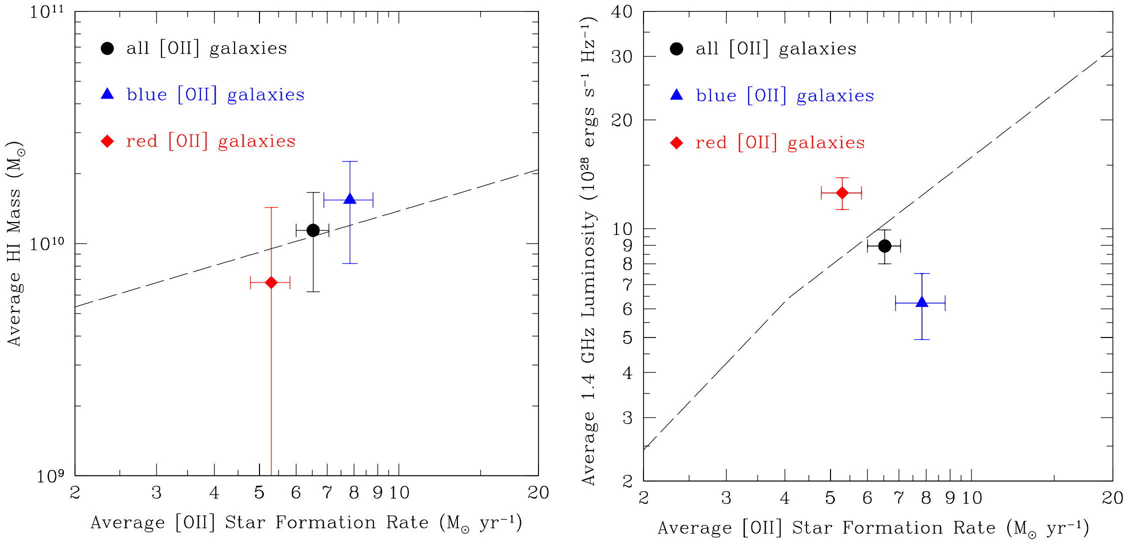

Figure 5: Left Panel: This panel shows the comparison of the average galaxy [OII] star formation rates with their average HI mass. The dashed line is the relationship seen in z ∼ 0 galaxies (Doyle & Drinkwater 2006). The large circular point is the average for all 168 galaxies with [OII] emission. The triangle point is the average for the 81 blue galaxies with [OII] emission. The diamond point is the average of the 87 red galaxies with [OII] emission. **Right Panel:** This panel shows the comparison of the average galaxy star formation rates measured from the [OII] emission line luminosity and the de-redshifted 1.4 GHz radio continuum luminosity. The dashed line is the conversion from 1.4 GHz radio continuum to star formation rate (Bell 2003). The large circular point is the average for all 168 galaxies with [OII] emission. The triangle point is the average for the 81 blue galaxies with [OII] emission. The diamond point is the average of the 87 red galaxies with [OII] emission.

galaxies have the highest. Below these are plotted the literature values. The red galaxy subsample has a HI mass to light ratio similar to that for the ellipticals and S0 galaxies of the literature samples and the blue galaxy subsample has a ratio similar to those literature galaxies either with the most spiral structure or which are irregular. Unfortunately deriving morphologies for the galaxies in Abell 370 is not possible due to the poor seeing in the optical imaging combined with the small size of galaxies at a redshift of z = 0.37. However, it is clear from this comparison that galaxies in Abell 370 seem to follow similar trends in HI mass to light ratios as nearby, ‘normal’ galaxies and even have similar HI mass to light ratios for galaxies of roughly similar types (the red and blue galaxies).

6. The SFR–HI mass correlation for the galaxies

In the local universe, a correlation between the star formation rate in a galaxy and the total mass of HI gas in that galaxy is seen Doyle & Drinkwater (2006). This correlation was examined for the galaxies around Abell 370. The star formation rate for the Abell 370 galaxies was derived from their [OII] luminosity. In the left panel of Fig. 5, the large circular point shows the comparison of the average [OII] star formation rate against the average HI gas mass for the Abell 370 galaxies with

[OII] equivalent width greater than 5 Å (the 168 galaxies of the [OII] emission subsample). Also plotted on the left panel of Fig. 5 is the linear fit to the SFR–HI correlation for the local sample of galaxies (Doyle & Drinkwater 2006). The average value for the Abell 370 [OII] emission galaxies lies almost on this line. This indicates that the galaxies around Abell 370 have normal galaxy properties, in that their higher HI gas content leads naturally to higher star formation rates.

Also shown in the left panel of Fig. 5 are the values for the average galaxy [OII] star formation rates and average galaxy HI masses for the 81 galaxies that have [OII] emission and blue colours (the triangular point) as well as for the 87 galaxies that have [OII] emission and have red colours (the diamond point). Both of these measurements agree with the Doyle & Drinkwater line. The expected trend that the blue [OII] galaxies have higher star formation rates and higher average HI masses compared to red [OII] galaxies is seen.

7. The SFR–radio continuum correlation

Synchrotron radio emission is generated in areas of active star formation from relativistic electrons accelerated in supernova remnants. The luminosity of this radiation has a good correlation with other galaxy star formation rate indicators. It is possible to directly measure the 1.4 GHz radio continuum emission from the Abell 370 galaxies and compare it to their measured [OII] star formation rate to see if the correlations found in the nearby universe hold at z = 0.37.

Despite the low RMS of 20 μJy in the GMRT radio continuum imaging, only a handful of the 168 Abell 370 galaxies with [OII] emission have radio continuum flux densities at the 5σ level. To increase the number of galaxies studied, the signal from all 168 galaxies was coadded using their known optical position to measure their average radio continuum flux density. The average 1.4 GHz radio continuum luminosity density for these 168 galaxies compared with their [OII] star formation rate is displayed as the large circular point in the right panel of Fig. 5. The dashed line in left panel of Fig. 5 is the 1.4 GHz radio continuum conversion to star formation rate (Bell 2003). The value for the [OII] emission subsample lies close to this line showing reasonable agreement.

The [OII] emission galaxies were split into the 81 blue and 87 red galaxies and the average radio continuum luminosity and average [OII] star formation rates for these subsamples measured. In the right panel of Fig. 5 the average values for the blue [OII] emission subsample is the triangular point and the average values for the red [OII] emission subsample is the diamond point. An unexpected relationship is seen, with the red galaxies showing a higher radio continuum luminosity compared to the blue galaxies even though the red galaxies have a lower [OII] star formation rate. It is not known what is causing this relationship. It is not caused by a small handful of galaxies in the red and blue subsamples; it is a general trend across both subsamples. No simple systematic effect such as AGN contamination on the radio continuum, or metallicity and/or dust extinction effects on the [OII] star formation rate are able to explain this trend. Since the [OII] star formation–HI mass correlation seems to agree with expectations, it is likely that the radio continuum is the cause of this unusual relationship.

A working hypothesis to explain this effect is the different timescale responsible for the production of the [OII] and radio continuum emission in galaxies. The weak radio continuum observed in normal galaxies is emitted by an ensemble of relativistic electrons that are produced in supernova remnants. Lifetimes of these relativistic particles can exceed the timescale associated with star burst in a galaxy. Thus we suggest that red [OII] galaxies maybe older galaxies coming out of a burst of star formation. They have some [OII] emission left behind as well as supernovae remnants that have produced a large reservoir of decaying, relativistic electrons in the galaxies. The blue [OII] galaxies are then younger systems, which are only currently seen to be building their stellar populations and their relativistic electron distributions. The hypothesis is that this difference in relativistic electron distributions between the red [OII] and blue [OII] galaxies is the cause of the difference in their radio continuum measurements.

8. Conclusion

We have measured the average HI mass for a large sample of galaxies around the galaxy cluster Abell 370 at a redshift of z = 0.37 (a look-back time of $\sim$4 billion years). The HI gas content of the galaxies is found to be markedly higher than that found in nearby clusters. Abell 370 has considerably more HI gas than Coma, a cluster of similar size. The measured HI density around the galaxy cluster Abell 370 is $\sim$8 higher than in Coma. This result shows there has been substantial evolution in the gas content of clusters over the past $\sim$4 billion years.

Despite the appreciable HI gas content in the Abell 370 galaxies, there is evidence that environmental effects reduce the gas content of galaxies, similar to what is seen in nearby clusters. The galaxies in the inner regions of the cluster (within the R_{200} radius) have average HI masses smaller by a factor of $\sim$3.5 than galaxies outside this region. The optically blue galaxies outside the hot, intracluster medium of the cluster core have a higher average HI gas mass than found from the complete sample of blue galaxies in Abell 370. This shows that the late-type galaxies close to the cluster core in Abell 370 are likely to be HI deficient similar to those seen in nearby clusters.

Although the galaxies in Abell 370 have high HI gas contents, they have similar galaxy properties to present day galaxies: the Abell 370 galaxies have normal HI mass to optical light ratios and have a similar correlation between their star formation rate and HI mass as found in nearby galaxies. The average star formation rate derived from [OII] emission and from de-redshifted 1.4 GHz radio continuum for the Abell 370 galaxies follows the correlation found in the local universe. However, there is an unexpected relationship where the red [OII] emission galaxies have a higher average radio continuum luminosity than the blue [OII] emission galaxies despite having a lower average [OII] star formation rate. This effect is the reverse of what is expected and is currently unexplained.

See the paper **Lah et al. 2009 MNRAS 399, 1447L** for more details on this work.

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