Growing up in the city : a study of galaxy cluster progenitors at z>2

Kuiper, E.

Citation

Kuiper, E. (2012, January 24). *Growing up in the city : a study of galaxy cluster progenitors at z>2*. Retrieved from https://hdl.handle.net/1887/18394

1

INTRODUCTION

In this introduction we will present the background and framework that is necessary to better understand the work presented in this thesis. The focus of this thesis is on the progenitors of present day galaxy clusters in the early Universe. Because of this, we will give some background on the most important properties of galaxy clusters, especially in terms of the influence of environment on galaxy evolution. We will discuss several methods that are commonly used to identify galaxy clusters and we will introduce the topic of high-z radio galaxies and the link these special galaxies have with forming galaxy clusters. We will also present an outlook of what the next steps will be to further this line of research.

1.1 The beginning

Although there are many mysteries about how our Universe was born and what, if anything, came before it, we do know from many observations that it must have started with the Big Bang. The fact that everything on large scales is moving away from each other implies that the Universe must have started out in a single point.

In the first 10^{-32} seconds after the Big Bang, during the inflationary period, the Universe is thought to have expanded exponentially in volume by a factor of at least 10^{78}. After the first inflation, the Universe kept on expanding, but at a slower pace and during this expansion the temperature of the Universe dropped. After 10^{-6} seconds the temperature decreased enough for the first protons and neutrons to form, which after a few minutes produced the first deuterium and helium in the Big Bang nucleosynthesis. What is left after this is like a primordial soup, consisting mostly of protons, electrons and photons. This soup was almost homogeneously spread across the Universe, apart from some small variations in the matter density. And these small variations would shape the Universe into what we observe today.

1.2 Galaxy clusters

The variations in the matter density distribution directly after the Big Bang have shaped how our Universe currently looks. As gravity draws more matter towards the densest regions, a characteristic web-like structure emerges. Matter falls together in sheets, which in turn collapse to filaments. These filaments themselves connect and feed the nodes of highest large-scale density in the Universe: galaxy clusters.

Galaxy clusters are large structures that can contain hundreds to thousands of galaxies, they can have masses exceeding 10^{15} $M_\odot$ and have radii of the order of 1 Mpc. They were first identified as large concentrations in the projected galaxy distribution on the sky (e.g. Abell 1958). The Virgo and Coma clusters are well-known local galaxy clusters. Galaxy clusters also presented the first evidence for the existence of dark matter as the dynamical mass of the Virgo cluster seemed to significantly exceed that of the luminous matter (Smith 1936).

1.2.1 The influence of environment

One of the most striking properties of galaxy clusters is that the innermost and densest regions contain predominantly red early-type galaxies and lack blue late-type galaxies (Dressler 1980; Butcher & Oemler 1984), whereas the fraction of blue late-type galaxies increases as the density decreases. These are also known as the morphology-density and colour-density relation. These relations are a strong indication that the cluster environment must influence the galaxy evolution in some way, transforming star-forming spiral galaxies into red-and-dead ellipticals.

There are also differences between early-type galaxies in clusters and in the field. Early-type galaxies in cluster environments are typically older by 1.5 Gyr in the local Universe (Clemens et al. 2006; Sánchez-Blázquez et al. 2006). This means that elliptical galaxies in the field formed their stars 1.5 Gyr later than ellipticals in clusters. Similar studies have also been done at higher redshifts finding age differences of ~ 0.5 Gyr (van Dokkum & van der Marel 2007; Gobat et al. 2008).

Galaxy clusters are also the home of cD galaxies, the most massive galaxies known with masses exceeding 10^{12} $M_\odot$. The fact that these galaxies are exclusively located in galaxy clusters is strong evidence that the cluster environment has played a pivotal role in shaping these galaxies.

It is thus clear that the environment somehow influences galaxy evolution, but what processes cause this effect is mostly unknown. A few are proposed in the literature, such as ram-pressure stripping (Gunn & Gott 1972; Brüggen & De Lucia 2008), galaxy mergers (Barnes & Hernquist 1996; Murante et al. 2007), harrassment (i.e. rapid tidal encounters, Farouki & Shapiro 1981; Moore et al. 1998), strangulation (i.e. loss of the hot halo, Larson et al. 1980; McCarthy et al. 2008) and AGN feedback (Nesvadba et al. 2006; Bower et al. 2006), but how these processes interplay, which one is dominant and when these processes act is still unclear.

1.2.2 Galaxy clusters and cosmology

Although this will not be treated in this thesis, galaxy clusters are also important cosmological tools. The space density of galaxy clusters depends strongly on the exact cosmological parameters and the observed number of clusters at a given mass and given redshift can be used to get direct estimates of σ_8 and $\Omega_{\rm m}$ (e.g. Frenk et al. 1990; Viana & Liddle 1996; Bahcall et al. 1997; Borgani et al. 2001; Gladders et al. 2007; Sahlén et al. 2009; Mantz et al. 2010). Studying galaxy clusters thus serves as an excellent independent test for the Λ Cold Dark Matter model.

1.3 Galaxy clusters across cosmic time

Understanding galaxy formation and evolution is one of the most important tasks of present day astronomy. To achieve this it is essential to understand what the influence of environment is, what physical processes cause this environmental effect and when these processes occur. Therefore, we must study galaxy clusters across cosmic time. To be able to do this in a meaningful way it is necessary to identify a sufficiently large sample of galaxy clusters at all possible redshifts. In this section we discuss some of the methods currently used to locate galaxy clusters.

X-ray emission

Clusters contain different kinds of material. The vast majority of the matter is dark matter and the remainder is baryonic matter. The baryonic matter can be roughly divided into the galaxies and their stellar and gaseous content and the intracluster medium (ICM). The latter is gas that is not locked in galaxies and makes up approximately 15 per cent of the cluster mass. Because of the deep potential well of the cluster, it has been shock-heated to very high temperatures (10^6-10^7 K) as it entered the dark matter halo. This hot ICM is fully ionised and because of this emits X-rays through non-thermal brehmsstrahlung.

The total luminosity of the X-ray emission can be up to 10^{43}-10^{45} erg s^{-1} making it detectable even at cosmological distances. Since it also acts as a powerful diagnostic tool, the extended X-ray emission is one of the prime ways of identifying and studying galaxy clusters. The ROSAT X-ray satellite was one of the first X-ray satellites that could robustly detect large numbers of galaxy clusters up to $z < 1$ (e.g. Truemper 1993; Ebeling et al. 1998; Burenin et al. 2007). Recent works with, in particular, the XMM satellite are pushing this to higher redshifts (e.g. Mehrtens et al. 2011).

Red sequence searches

One of the most straighforward methods of identifying galaxy clusters uses the fact that clusters host a large number of more evolved, red galaxies. Observing a field with a galaxy cluster should therefore show an overdensity of red galaxies which are possibly spatially concentrated.

Several surveys have used this method to identify large numbers of galaxy clusters across the sky. A well-known survey aimed at finding galaxy clusters is the Red-sequence Cluster Survey (RCS, Gladders & Yee 2005) which found > 400 galaxy clusters in 100 deg^2, with ~ 15 per cent at $z > 0.9$.

The success of the RCS has led to multiple follow-up surveys aimed at finding both $z < 1$ and $z > 1$ galaxy clusters. One of the most ambitious surveys for $z < 1$ is RCS-2, the direct follow-up of RCS. RCS-2 is still ongoing and will use the MegaCam on the Canada-France-Hawaii Telescope to cover ~ 1000 deg^2.

To effectively select clusters at $z > 1$ the *Spitzer* Space Telescope can be used. Two surveys are currently doing this. The first is the *Spitzer* Adaptation of the Red-sequence Cluster Survey (SpARCS, Wilson et al. 2008; Muzzin et al. 2009) which is ongoing and will cover 41.9 deg^2. Another high-z cluster survey is the *Spitzer* IRAC Shallow Survey (Eisenhardt et al. 2008) which identified > 300 galaxy clusters in a field of 7.25 deg^2. Approximately 30% of these clusters are located at $z > 1$.

The Sunyaev-Zeldovich effect

With the advent of the Planck satellite in 2009 and the ground-based South Pole Telescope (SPT) and Atacama Cosmology Telescope (ACT) in 2007, recent years have seen a strong increase in the detection of galaxy clusters discovered by using the Sunyaev-Zeldovich (SZ) effect. The SZ effect is caused by inverse Compton scattering of CMB photons on high energy electrons. The hot, ionised intracluster gas contains many of such electrons, which will cause the low energy CMB photons to be upscattered. A galaxy cluster will therefore leave a distortion (a hot or cold spot) in the CMB, which can be observed.

One of the most important properties of the SZ effect is that clusters are identified by observing a difference with respect to the CMB. This makes it independent of redshift and allows for the detection of galaxy clusters in a large redshift interval. At the moment of writing, galaxy clusters have been detected with the SZ effect up to $z \sim 1.1$ (e.g. Staniszewski et al. 2009; Menanteau et al. 2010; Williamson et al. 2011; Planck Collaboration et al. 2011).

1.4 Galaxy clusters at $z > 1.5$

The problem with the methods described above is that they work very well for $z < 1.5$, but they break down for larger redshifts. This is partially due to limitations on the observations. For instance, the X-ray emission becomes too faint to be detected. However, it is likely also caused by the fact that galaxy clusters as we observe them locally are simply incredibly rare at $z > 1.5$. Instead, there are structures that are still in the process of formation, that will become galaxy clusters but are not there yet. These galaxy cluster progenitors may not be virialised or may not be massive enough to show strong X-ray emission. Similarly, the red sequence in these early galaxy clusters is not well established yet.

This has led to something of a barrier at $z = 1.5$, beyond which finding galaxy clusters, or galaxy cluster progenitors, becomes increasingly difficult. In fact, at the moment of writing only a handful of galaxy clusters at $z > 1.5$ with X-ray emission and spectroscopic confirmation are known. The first galaxy cluster above $z = 1.5$ was found at $z \sim 1.62$ independently by both Papovich et al. (2010) and

Tanaka et al. (2010). Since then a few others have been found with $1.5 < z < 1.75$ (Henry et al. 2010; Fassbender et al. 2011; Santos et al. 2011), with the current record holder being the cluster at $z = 2.07$ discovered by Gobat et al. (2011).

It is, however, important to go beyond $z = 1.5$. The cosmic star formation rate density peaks at $z \sim 2$ which heralds an important stage in galaxy evolution. Also, there is a clear relation between star formation rate and galaxy density in the local Universe as the star formation rate decreases with increasing density. Various recent studies have shown that at earlier times this relation turns around and that in the densest regions the star formation is higher (Elbaz et al. 2007; Cooper et al. 2008; Tran et al. 2010; Hilton et al. 2010; Popesso et al. 2011). This indicates that there is an important period in galaxy cluster evolution at $z > 1.5$ that we have not yet been able to observe.

1.5 HzRGs: powerhouses in the early Universe

In this thesis we use high-z radio galaxies (HzRGs, Miley & De Breuck 2008) to find galaxy cluster progenitors. As the name implies, HzRGs are galaxies located at $z > 2$ that show large radio luminosities. These large radio luminosities are caused by an active supermassive black hole at the centre of the galaxy.

The extreme nature of HzRGs makes these objects well worth investigating, but what links these objects to galaxy clusters? HzRGs have been shown to have large restframe optical luminosities. Since restframe optical light traces the bulk of the stellar mass of a galaxy, this means that HzRGs have large stellar masses. Seymour et al. (2007) have studied a large number of HzRGs with the *Spitzer* IRAC and MIPS cameras to determine their stellar masses and found in general values of $10^{11} - 10^{12}$ $M_{\odot}$.

Apart from this there are many other indications that HzRGs are forming massive galaxies. Many radio galaxies are, for instance, at the centre of Lyα halos indicating a large reservoir of ionised gas; gas that can be used for star formation. Also, the morphology of many radio galaxies is clumpy and irregular, implying active merging. Finally, the restframe UV and millimetre light indicate large SFRs of the order of 500-1000 $M_{\odot}$ yr^{-1}. All of these observations indicate that HzRGs will end up as very massive galaxies.

This is important because in the case of hierarchical galaxy formation, the smaller galaxies form first. These small galaxies then merge and coalesce to form the larger, more massive galaxies. According to this picture, a massive galaxy must have been built up from a large number of smaller galaxies. So the area around a massive galaxy should have a larger density. Since the HzRGs are very massive, it is therefore logical that they should reside in overdense regions. If the overdensity is strong enough, such a region may then evolve into a local massive galaxy cluster.

That HzRGs are possibly at the centre of forming clusters is also confirmed by the large rotation measures of the order of 1000 rad m^{-2} that are measured for some HzRGs (Carilli et al. 1994, 1997; Athreya et al. 1998). This is commonly interpreted as the HzRGs being embedded in dense hot gas. Locally, these large rotation measures are only observed in galaxy clusters and therefore this can be considered as circumstantial evidence that HzRGs are indeed at the centre of forming galaxy clusters.

Targeting the environment of HzRGs could thus lead to the discovery of galaxy cluster progenitors at $z > 2$, which could in turn significantly expand our knowledge of galaxy cluster formation and the role of the environment on galaxy evolution. Furthermore, since HzRGs are massive, they are excellent candidates for becoming cD galaxies.

Many recent studies have tried to prove that this concept of HzRGs as tracers of galaxy cluster progenitors is true (e.g. Pascarelle et al. 1996; Knopp & Chambers 1997; Pentericci et al. 2000; Kurk et al. 2004b,a; Overzier et al. 2006, 2008; Venemans et al. 2007; Matsuda et al. 2011). This is often done using using narrowband filters, which allows for the selection of emission line galaxies at the redshift of interest and has proved to be the most efficient method of finding overdensities.

The past few years have seen some interesting results in the field of protoclusters and HzRGs. For instance, Venemans et al. (2007) conducted the largest study of protoclusters to date and found that the velocity dispersion of these structures increases with decreasing redshift. This is consistent with the results of simulations of cluster formation. Furthermore, Zirm et al. (2008) and Kodama et al. (2007) have found evidence that some $z \sim 2$ protoclusters show evidence for an emerging red sequence. Finally, Hatch et al. (2011) have shown that the Hα emitters in a $z \sim 2$ protocluster are more massive than the same galaxies in the field, thereby supplying powerful evidence that the influence of environment is already apparent at $z \sim 2$.

1.6 This thesis

In this thesis we attempt to further the work done on both protoclusters and HzRGs in order to better establish a picture of galaxy cluster progenitors at $z > 2$. We have done this both in terms of the galaxies that inhabit these clusters and the structures as a whole.

Chapter 2

We begin the thesis with a study of the Spiderweb galaxy at $z \sim 2.15$. It is one of the most studied HzRGs and is known to be at the centre of a protocluster. We obtained deep SINFONI data of the radio galaxy and its immediate surroundings which harbours a large number of small galaxies.

We show that 10 of the satellite galaxies are located at the redshift of the radio galaxy and are therefore in the protocluster. This implies that the central region of the protocluster is as dense as the outskirts of local galaxy clusters. We also find a broad, bimodal velocity distribution that cannot be explained by the presence of one massive virialised halo. A merger scenario, however, is able to reproduce the observations.

Chapter 3

For this chapter we attempt to obtain a complete galaxy census for the protocluster around HzRG MRC 0316-257 at $z = 3.13$. We do this using photometry in 18 bands ranging from U band to *Spitzer* 8.5 μm. Applying different colour cuts we select blue, star forming Lyman Break Galaxies (LBGs) and red Balmer Break Galaxies (BBGs) that are approximately at the redshift of the protocluster.

We find a mild surface overdensity for the LBGs, but not for the BBGs. We also attempt to compare to literature studies in order to determine whether there are systematic differences between field and protocluster galaxies. We find no significant differences in terms of stellar mass and star formation rate. However, within the protocluster there is tentative evidence that galaxies near to the radio galaxy are more massive and form more stars.

Chapter 4

A follow-up to the work presented in Chapter 3 is presented here. In order to draw meaningful conclusions on environmental influence it is necessary to be able to distinguish between field galaxies and protocluster galaxies. This could not be done accurately with the data available in Chapter 3. Therefore, in this chapter we present spectroscopic observations of a number of the LBGs identified in Chapter 3. By obtaining spectroscopic redshifts for these galaxies we can unequivocally say which galaxies truly belong to the protocluster. This thus allows for a fully self-consistent comparison between galaxy properties in the field and in the protocluster.

Out of a sample of 20 objects we find three to be in the protocluster and five to reside in a structure directly in front of the 0316 protocluster. However, in contrast to the results presented in Chapter 2, we find that these two structures are likely unrelated. Comparing the properties of the galaxies within both structures and the field, the only difference we find is in the strength of the Lyα flux. The 0316 protocluster galaxies show larger Lyα flux than field galaxies, whereas the galaxies in the foreground structure show very little Lyα flux. The strong Lyα flux in the 0316 galaxies could possibly be attributed to a lack of dust. Why the two protocluster structures differ so strongly remains unknown for now.

Chapter 5

In this chapter we present the first results of a large observing program with the OSIRIS instrument at the Gran Telescopio Canarias, aimed to identify a large sample of protoclusters around HzRGs. By using a relatively new technique that employs tunable narrowband filters we can efficiently search for emission line galaxies at any arbitrary redshift. The pilot study focuses on the HzRG 6C0140+326 at $z \sim 4.4$.

We find a total of 27 Lyα emitters in the field. Due to the nature of the tunable filters and multiple passes at different central wavelengths we are able to obtain a rough redshift distribution and we distinguish between a foreground and protocluster field. This shows that the foreground field contains significantly fewer emitters than the protocluster field. If we compare to the literature we find that the protocluster field is a factor 9 ± 5 denser than a blank field. Also, the redshift distribution is significantly different from the expected distribution, with the Lyα emitters concentrated at $z > 4.38$. There is thus evidence for a protocluster in this field.

Chapter 6

For this chapter we focus less on the protocluster environment and more on the radio galaxies. We study two HzRGs at $z \sim 2.5$ using optical and near-infrared imaging obtained with the new WFC3 instrument aboard the Hubble Space Telescope. Both HzRGs show a complex morphology with clumps and filaments, which we attempt to explain by dissecting the light into different contributing sources.

In both cases the light from the extended structures is consistent with being scattered AGN light and nebular emission, with a possible contribution from young stars. The red population, commonly associated with older stars, is located in a single clump that shows no signs of recent disturbances. The size of the red population is consistent with that of other distant, massive galaxies. We also investigate the surrounding field and find no overdensities. Therefore, it seems that these HzRGs are very similar to other massive galaxies at $z > 2$ and the difference in appearance is mostly due to the strong AGN feedback.

Chapter 7

This chapter will act as an appendix showing some additional results obtained from the SINFONI data of the Spiderweb galaxy, but which were not included in Chapter 2. These results may lead to future research.

1.7 Outlook

Scientific research will exist as long as there are questions to be asked. This is most definitely the case for the field of protoclusters and HzRGs. One of the most important issues for protocluster research is the limited sample size. As already mentioned, the largest study of protoclusters at the moment is the work of Venemans et al. (2007) which included a total of 6 protocluster fields. This is hardly enough to conduct a meaningful statistical study. Therefore, one of the main objectives is to expand this sample. The groundwork for this is done in Chapter 5, where we conduct a pilot study employing tunable narrowband filters. A large number of at least 15 HzRG fields are still waiting to be observed and this may yield a large sample of new protoclusters to study. This may shed light on the formation history of these structures. Similarly, the South African Large Telescope with its large number of narrowband filters, could prove very worthwhile in this.

Of course, there is also a large number of new and exciting astronomical facilities that will significantly increase our knowledge of both HzRGs and protoclusters over the coming years and decades. The LOw Frequence ARray (LOFAR) will, for instance, be able to detect HzRGs out to $z \sim 8$, opening up a unique new window for studying the very early Universe. Also, the new generation of 30-m-class ground-based telescopes and the James Webb Space Telescope will further this field of research by leaps and bounds.

References

Abell G. O., 1958, ApJS, 3, 211

Athreya R. M., Kapahi V. K., McCarthy P. J., van Breugel W., 1998, A&A, 329, 809

Bahcall N. A., Fan X., Cen R., 1997, ApJ, 485, L53+

Barnes J. E., Hernquist L., 1996, ApJ, 471, 115

Borgani S. et al., 2001, ApJ, 561, 13

Bower R. G., Benson A. J., Malbon R., Helly J. C., Frenk C. S., Baugh C. M., Cole S., Lacey C. G., 2006, MNRAS, 370, 645

Brüggen M., De Lucia G., 2008, MNRAS, 383, 1336

Burenin R. A., Vikhlinin A., Hornstrup A., Ebeling H., Quintana H., Mescheryakov A., 2007, ApJS, 172, 561

Butcher H., Oemler Jr. A., 1984, ApJ, 285, 426

Carilli C. L., Owen F. N., Harris D. E., 1994, AJ, 107, 480

Carilli C. L., Roettgering H. J. A., van Ojik R., Miley G. K., van Breugel W. J. M., 1997, ApJS, 109, 1

Clemens M. S., Bressan A., Nikolic B., Alexander P., Annibali F., Rampazzo R., 2006, MNRAS, 370, 702

Cooper M. C. et al., 2008, MNRAS, 383, 1058

Dressler A., 1980, ApJ, 236, 351

Ebeling H., Edge A. C., Bohringer H., Allen S. W., Crawford C. S., Fabian A. C., Voges W., Huchra J. P., 1998, MNRAS, 301, 881

Eisenhardt P. R. M. et al., 2008, ApJ, 684, 905

Elbaz D. et al., 2007, A&A, 468, 33

Farouki R., Shapiro S. L., 1981, ApJ, 243, 32

Fassbender R. et al., 2011, A&A, 527, L10+

Frenk C. S., White S. D. M., Efstathiou G., Davis M., 1990, ApJ, 351, 10

Gladders M. D., Yee H. K. C., 2005, ApJS, 157, 1

Gladders M. D., Yee H. K. C., Majumdar S., Barrientos L. F., Hoekstra H., Hall P. B., Infante L., 2007, ApJ, 655, 128

Gobat R. et al., 2011, A&A, 526, A133+

Gobat R., Rosati P., Strazzullo V., Rettura A., Demarco R., Nonino M., 2008, A&A, 488, 853

Gunn J. E., Gott III J. R., 1972, ApJ, 176, 1

Hatch N. A., Kurk J. D., Pentericci L., Venemans B. P., Kuiper E., Miley G. K., Röttgering H. J. A., 2011, MNRAS, 415, 2993

Henry J. P. et al., 2010, ApJ, 725, 615

Hilton M. et al., 2010, ApJ, 718, 133

Knopp G. P., Chambers K. C., 1997, ApJS, 109, 367

Kodama T., Tanaka I., Kajisawa M., Kurk J., Venemans B., De Breuck C., Vernet J., Lidman C., 2007, MNRAS, 377, 1717

Kurk J. D., Pentericci L., Overzier R. A., Röttgering H. J. A., Miley G. K., 2004a, A&A, 428, 817

Kurk J. D., Pentericci L., Röttgering H. J. A., Miley G. K., 2004b, A&A, 428, 793

Larson R. B., Tinsley B. M., Caldwell C. N., 1980, ApJ, 237, 692

Mantz A., Allen S. W., Rapetti D., Ebeling H., 2010, MNRAS, 406, 1759

Matsuda Y. et al., 2011, MNRAS, 1087

McCarthy I. G., Frenk C. S., Font A. S., Lacey C. G., Bower R. G., Mitchell N. L., Balogh M. L., Theuns T., 2008, MNRAS, 383, 593

Mehrtens N. et al., 2011, ArXiv e-prints
Menanteau F. et al., 2010, ApJ, 723, 1523
Miley G., De Breuck C., 2008, A&A Rev, 15, 67
Moore B., Lake G., Katz N., 1998, ApJ, 495, 139
Murante G., Giovalli M., Gerhard O., Arnaboldi M., Borgani S., Dolag K., 2007, MNRAS, 377, 2
Muzzin A. et al., 2009, ApJ, 698, 1934
Nesvadba N. P. H., Lehnert M. D., Eisenhauer F., Gilbert A., Tecza M., Abuter R., 2006, ApJ, 650, 693
Overzier R. A. et al., 2008, ApJ, 673, 143
Overzier R. A. et al., 2006, ApJ, 637, 58
Papovich C. et al., 2010, ApJ, 716, 1503
Pascarelle S. M., Windhorst R. A., Driver S. P., Ostrander E. J., Keel W. C., 1996, ApJ, 456, L21+
Pentericci L. et al., 2000, A&A, 361, L25
Planck Collaboration, Ade P. A. R., Aghanim N., Arnaud M., Ashdown M., Aumont J., Baccigalupi C., Balbi A., Banday A. J., Barreiro R. B., et al., 2011, ArXiv e-prints
Popesso P. et al., 2011, A&A, 532, A145+
Sahlén M. et al., 2009, MNRAS, 397, 577
Sánchez-Blázquez P., Gorgas J., Cardiel N., González J. J., 2006, A&A, 457, 809
Santos J. S. et al., 2011, A&A, 531, L15+
Seymour N. et al., 2007, ApJS, 171, 353
Smith S., 1936, ApJ, 83, 23
Staniszewski Z. et al., 2009, ApJ, 701, 32
Tanaka M., Finoguenov A., Ueda Y., 2010, ApJ, 716, L152
Tran K.-V. H. et al., 2010, ApJ, 719, L126
Trümper J., 1993, Science, 260, 1769
van Dokkum P. G., van der Marel R. P., 2007, ApJ, 655, 30
Venemans B. P. et al., 2007, A&A, 461, 823
Viana P. T. P., Liddle A. R., 1996, MNRAS, 281, 323
Williamson R. et al., 2011, ApJ, 738, 139
Wilson G. et al., 2008, in Astronomical Society of the Pacific Conference Series, Vol. 381, Infrared Diagnostics of Galaxy Evolution, R.-R. Chary, H. I. Teplitz, & K. Sheth, ed., pp. 210–+
Zirm A. W. et al., 2008, ApJ, 680, 224