J. Astrophys. Astr. (2011) **32,** 599–607

Evolutionary Map of the Universe: Tracing Clusters to High Red-shift

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Abstract. The Australian SKA Pathfinder (ASKAP) is a new radio-telescope being built in Western Australia. One of the key surveys for which it is being built is EMU (Evolutionary Map of the Universe), which will make a deep (∼10 μJy/bm rms) radio continuum survey covering the entire sky as far North as +30°. EMU may be compared to the NRAO VLA Sky Survey (NVSS), except that it will have about 45 times the sensitivity, and five times the resolution. EMU will also have much better sensitivity to diffuse emission than previous large surveys, and is expected to produce a large catalogue of relics, tailed galaxies, and halos, and will increase the number of known clusters by a significant factor. Here we describe the EMU project and its impact on the astrophysics of clusters.

Key words. Telescopes—surveys—stars: activity—galaxies: evolution—galaxies: formation—clusters: observations.

1. Introduction

The Australian SKA Pathfinder (ASKAP: Johnston *et al*. 2007, 2008; DeBoer *et al*. 2009) is a new radio telescope under construction in Western Australia. Not only will ASKAP be a technology pathfinder for the Square Kilometre Array (SKA), but it will also be a major survey telescope in its own right, likely to generate significant new astronomical discoveries, through projects such as EMU (Evolutionary Map of the Universe). In this paper, we describe ASKAP in §2 and EMU in §3. In §4 we discuss one of the science goals of EMU, which is to detect and study clusters of galaxies. Full details of EMU, including a discussion of all the science goals, the techniques being developed to achieve them, and the plans for the EMU survey, can be found in Norris *et al*. (2011).

2. ASKAP

ASKAP comprises 36 12-metre antennas spread over a region 6-km in diameter, each equipped with a novel phased-array feed (PAF) of 96 dual-polarization pixels, operating in the 700–1800 MHz band, giving ASKAP a field of view (FOV) of ∼30 deg^2. The ASKAP array configuration (Gupta *et al*. 2008) includes a central core of 30 antennas distributed over a region ∼700 m in diameter, corresponding to a point spread function of ~30 arcsec using natural weighting, and a further six antennas arranged with a maximum baseline of 6 km, corresponding to a point spread function of ~10 arcsec using uniform weighting. The array gives excellent UV coverage between declination −90° and +30°.

The outputs of the 96 dual-polarization receivers are combined in a beam-former to form up to 36 beams within a 30-deg^2 envelope. The EMU observing strategy will be to observe one field for 12 hours, reaching an rms sensitivity of ~10 μJy/bm over a ~30 deg^2 FOV, with a uniformity (after dithering) of ~2% , so that the images from the 36 beams can be imaged and deconvolved as a single image covering the FOV. Because of the short spacings of ASKAP, the ~10 μJy/bm rms continuum sensitivity in 12 hours is approximately constant for beam sizes from 10 to 30 arcsec, then increases to ~20 μJy/bm for a 90 arcsec beam and ~40 μJy/bm for a 3 arcmin beam.

The high ASKAP data rate (~2.5 GB/s) requires processing (including calibration, imaging, and source-finding: Cornwell *et al*. 2011) in an automated pipeline processor. Initial observations will produce a global sky model (an accurate description of all sources stronger than ~1 mJy) which will then be subtracted from the visibility data before processing. This sky model also enables self-calibration of all fields without any need for separate calibration observations. EMU will observe a 300 MHz band, split into 1 MHz channels, with full Stokes parameters measured in each channel. As well as producing images and source catalogues, the processing pipeline will measure spectral index, spectral curvature, and all polarization products across the band. All ASKAP data will be placed in the public domain after quality control, and should be available to the astronomical community by the end of 2013.

3. EMU

Two projects to survey the entire visible sky, EMU and WALLABY, will dominate the initial usage of ASKAP, and are primarily driving its design, with a further eight projects (listed on http://askap.org) also being supported. EMU (Evolutionary Map of the Universe: Norris *et al*. 2011) is a 20-cm continuum survey whilst WALLABY (Koribalski *et al*. 2011) is a survey for neutral hydrogen. EMU and WALLABY are expected to observe commensally, i.e., they will observe the sky in both continuum and HI modes at the same time, splitting the two data streams into separate processing pipelines.

Figure 1 shows how EMU compares with other major 20-cm continuum radio surveys. All current surveys are bounded by a diagonal line that roughly marks the limit of available telescope time of current-generation radio telescopes. The region to the left of this line is currently unexplored.

The primary goal of EMU is to make a deep (10 μJy/bm rms) radio continuum survey of the entire Southern Sky, extending as far North as +30°. EMU will cover roughly the same fraction (75%) of the sky as NVSS (Condon *et al*. 1998), but will be 45 times more sensitive, and will have an angular resolution (10 arcsec) 4.5 times better, as well as having higher sensitivity to extended structures. EMU is expected to generate a catalogue of about 68million galaxies, some 40 times greater than NVSS. Of these, about 51million are expected to be star-forming galaxies at red-shifts up to $z \sim 2$, and the remainder AGNs up to $z \sim 5$ (Norris *et al*. 2011).

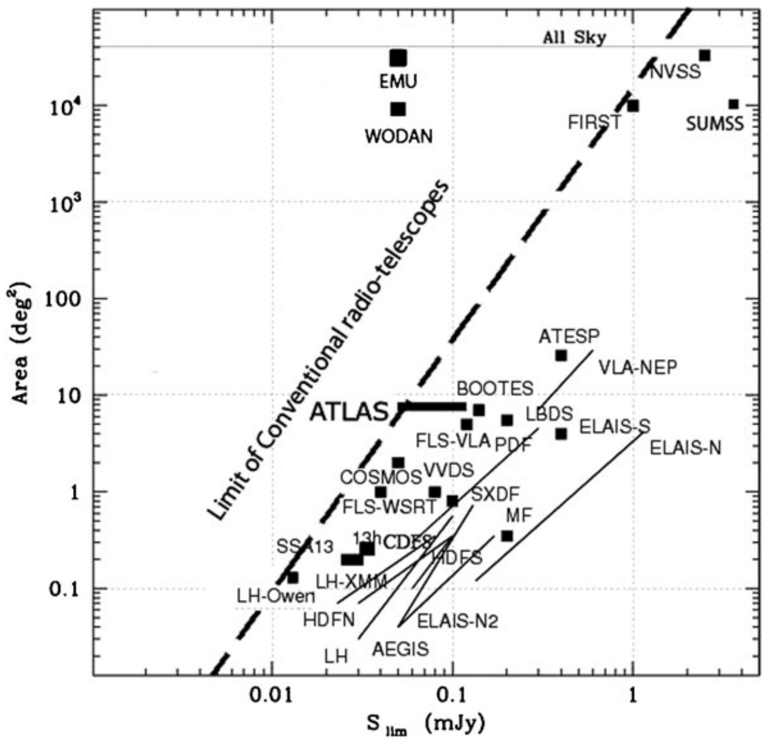

Figure 1. Comparison of EMU with existing deep 20 cm radio surveys. Horizontal axis is 5-σ sensitivity, and vertical axis shows the sky coverage. The largest existing radio survey is the wide but shallow NRAO VLA Sky Survey (Condon *et al*. 1998) in the top right. The most sensitive radio survey is the deep but narrow Lockman Hole observation (Owen & Morrison 2008) in the lower left. The squares at top centre represent the EMU survey, discussed here, and the complementary Northern WODAN survey.

In the Northern hemisphere, EMU will be complemented by the WODAN survey (Röttgering *et al*. 2010) which has been proposed for the upgraded Westerbork telescope. WODAN will cover the northern 25% of the sky (i.e. North of declination +30°) that is inaccessible to ASKAP, with a small overlap for consistency and calibration checks. Together, EMU and WODAN will provide a full-sky 1.4 GHz survey at ∼10–15 arcsec resolution to an rms noise level of 10 μJy/bm.

Whilst previous large surveys such as NVSS were dominated by radio-loud active galactic nuclei (AGN), surveys at this sensitivity level are dominated by star-forming galaxies (Seymour *et al*. 2008). Thus, whereas most traditional radio-astronomical surveys had their greatest impact on the niche area of radio-loud AGN, EMU will be dominated by the same star-forming galaxies as are studied by optical and IR surveys, making it an important component of multi-wavelength studies of galactic evolution. Consequently, we also plan to cross-identify the EMU radio sources with sources in major optical/IR surveys as part of the EMU project.

We are fortunate in having access to earlier surveys such as ATLAS (Norris *et al*. 2006; Middelberg *et al*. 2008) and HDFS (Norris *et al*. 2005; Huynh *et al*. 2005) with a sensitivity and resolution (and dynamic range challenges!) similar to those of EMU, but over a much smaller survey area. We are therefore using these as a test-bed for the EMU Design Study, and the prototype EMU source extraction and identification pipeline will be used for the final ATLAS data release in late 2011 (Banfield *et al*. 2011).

The key science goals for EMU are:

- To trace the evolution of star-forming galaxies from $z = 2$ to the present day, using a wavelength unbiased by dust or molecular emission.
- To trace the evolution of massive black holes throughout the history of the Universe, and understand their relationship to star formation.
- To use the distribution of radio sources to explore the large-scale structure and cosmological parameters of the Universe, and to test fundamental physics.
- To explore an uncharted region of observational parameter space, with a high likelihood of finding new classes of object.
- To use radio sources to trace clusters and large-scale structure, and explore the astrophysics of dark matter haloes.
- To create the most sensitive wide-field atlas of galactic continuum emission yet made in the Southern Hemisphere, addressing areas such as star formation, supernovae, and galactic structure.

The remainder of this paper focuses on just one of these science goals: the study of clusters of galaxies.

4. Clusters of galaxies

The study of clusters of galaxies has changed significantly in recent years with the realization that, rather than being isolated entities, they represent the intersections of filaments and sheets in the large-scale structure of the Universe, as represented by the Millennium simulation (Springel *et al*. 2005). Cluster studies therefore aim not only to understand the physics of clusters themselves, but also to trace the evolution of structure in the Universe.

Clusters are typically found either through X-ray searches (Rosati *et al*. 1998; Romer *et al*. 2001; Pierre *et al*. 2004) or by using optical colour as a surrogate for red-shift, enabling searching for clusters in colour-position space (Gladders & Yee 2005; Wilson *et al.* 2008; Kodama *et al.* 2007). As a result, tens of thousands of clusters are currently known, but only a few at $z > 1$ (Wilson *et al.* 2008, Kodama *et al.* 2007), with the highest red-shift at $z = 2.07$ (Gobat *et al*. 2011).

At radio wavelengths, clusters of galaxies are characterized by three different powering mechanisms (Kempner *et al*. 2004) in addition to the radio emission from their constituent galaxies:

- halos at the centres of clusters,
- relics (representing shocks from cluster–cluster collisions) at the periphery, and
- tailed radio galaxies, which are an important tracer and barometer of the intra-cluster medium.

Not only are these three types of radio source important as tracers of clusters, but all three are diagnostics of the physics of clusters, particularly when combined with X-ray data. However, the number of currently detected cluster radio sources is limited by the present telescope sensitivities (see Fig. 2). EMU will push beyond the present

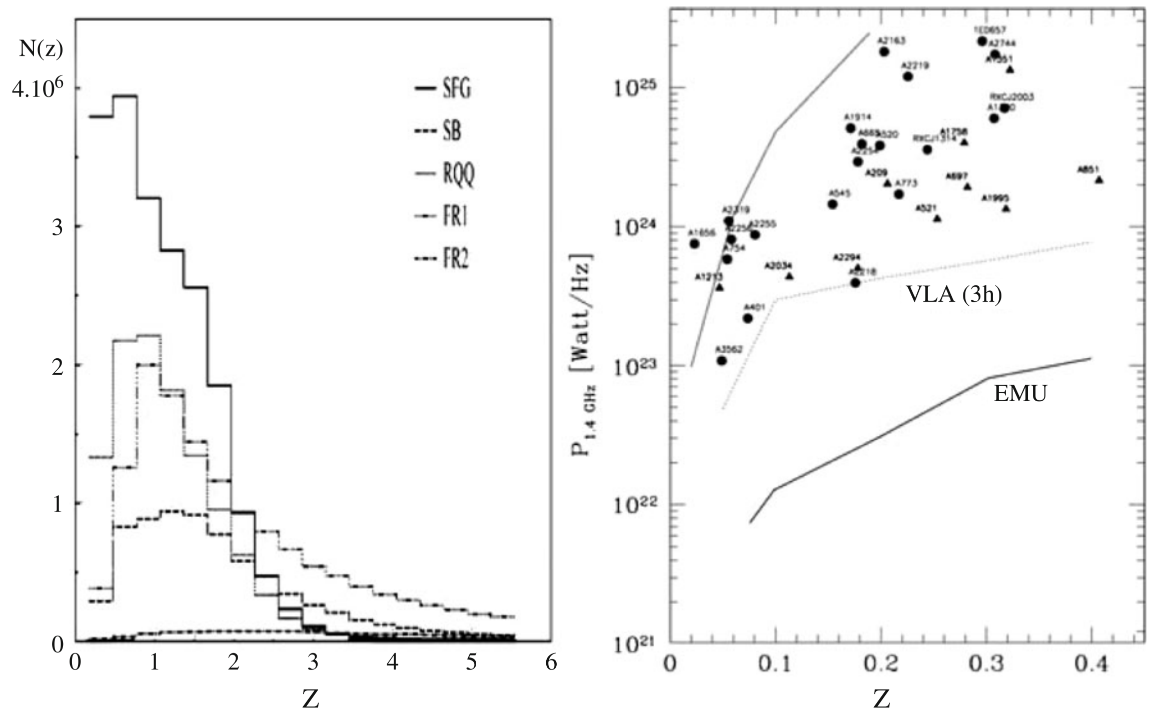

Figure 2. *Left*: Estimate of the red-shift distribution of EMU sources (Norris *et al*. 2011). The four lines indicate star-forming galaxies (SFG), starburst galaxies (SB), radio-quiet quasars (RQQ), and radio-loud galaxies of Fanaroff–Riley types I and II. The mean red-shift for EMU-detected AGNs is $z = 1.88$ for AGNs, and $z = 1.1$ for star-forming galaxies. *Right*: 1.4 GHz radio power of detected cluster halos as a function of red-shift showing the detection limits of previous cluster observations, adapted from Giovannini *et al*. (2009), and the calculated 5-σ detection limit of EMU, assuming a halo with a diameter of 1 Mpc, using the calculated ASKAP sensitivity on different scale sizes given by Norris *et al*. (2011). The upper line shows the limit corresponding to a scale size of 15 arcmin, which is approximately the largest size object that can be imaged with the VLA unless single-dish data is added to the interferometry data. At high red-shifts, sensitivity may be limited by confusion, although we expect to overcome this by subtracting off compact sources.

limits to detect diffuse sources with a range of powers over a larger red-shift range, greatly improving our understanding of these sources.

4.1 *Halos*

Diffuse synchrotron radio halos are found in clusters and groups of galaxies, indicating strong magnetic fields and relativistic particles, presumably accelerated by the released potential energy of cluster formation. Only a few tens of radio halos are known, and are typically discovered by making deep radio surveys of X-ray-detected haloes (Venturi *et al.* 2008). The ATLBS survey (Subrahmanyan *et al*. 2010), which has surveyed 8.4 deg^2 to an rms sensitivity of 80 μJy/bm on a scale size of 50 arcsec at 1.4 GHz, has detected tens of diffuse sources, of which about 20 have been tentatively identified as cluster and group haloes (Saripalli *et al*. 2011). If these numbers are confirmed, then EMU, with significantly greater sensitivity to extended structures than the LBS survey, should detect ~60000 cluster and group halos, which dramatically increases the number of known clusters. Brunetti *et al.* (2009), Cassano *et al.* (2010), and Schuecker *et al.* (2001) have suggested that radio halos in the centres of clusters are distributed bimodally as a function of X-ray luminosity, with halos generally found only in those clusters which have recently undergone a merger, resulting in a disturbed appearance at X-ray wavelengths. As well as discovering new clusters, EMU will provide a uniform radio sample of emission across all clusters which will allow us to test whether very faint radio halos occur in all galaxy clusters.

4.2 *Relics*

On the periphery of clusters, elongated radio 'relics' are found, typically oriented perpendicular to the radius vector from the cluster centre. These are interpreted as shock structures (Brown *et al*. 2011; Markevitch 2010; van Weeren *et al*. 2010) and provide important diagnostics for the dynamics of accretion and mergers of clusters (Barrena *et al*. 2009). Only 44 radio relics are currently known (Giovannini *et al*. 2011), and a few have been discovered in current radio surveys because of the relatively poor sensitivity of most surveys to low-surface-brightness structures. One has been discovered in the seven square degrees of ATLAS (Middelberg *et al*. 2008; Mao *et al.* 2010), at $z \sim 0.2$. EMU will have greater sensitivity to such low-surface-brightness structures than ATLAS, and so in the 30000 deg^2 of EMU we expect to detect >4000, although this number is clearly very uncertain.

4.3 *Tailed radio galaxies*

Tailed radio galaxies are found in large clusters, and are believed to represent radio-loud AGN in which the jets are distorted by the intra-cluster medium (Mao *et al.* 2010). Mao *et al.* (2011b) have found 6 tailed galaxies in ATLAS, from which they estimate between 26×10^3 and 2×10^5 tailed galaxies will be detected by EMU, depending on their luminosity function and density evolution. Deghan *et al.* (2011), using high-resolution images of one of the ATLAS fields, find 12 tailed galaxies in 4 deg^2, implying $\sim 10^5$ tailed galaxies in EMU. Importantly, such galaxies can be detected out to high red-shifts (Wing & Blanton 2011; Mao *et al*. 2010), providing a powerful diagnostic for finding clusters.

5. Red-shifts and polarization

To interpret data from EMU, red-shifts are invaluable. However, no existing or planned red-shift survey can cover more than a tiny fraction of EMU's 68million sources. For nearby galaxies, HI red-shifts will be available from WALLABY, which will provide $\sim 5 \times 10^5$ red-shifts, and smaller numbers will be provided by other red-shift surveys such as SDSS (York *et al*. 2000) and GAMA (Driver *et al*. 2009). The remaining $\sim$99% of EMU galaxies will not have spectroscopic red-shifts.

Photometric red-shifts, in which SEDs of template galaxies are fitted to the measured multi-band photometry of target galaxies, are often used as a surrogate for spectroscopic red-shifts. While the relatively sparse photometry available for most EMU sources can not generate accurate photometric red-shifts, it will enable *estimates* to be made for about 30% of EMU galaxies. Even a non-detection can carry useful information, and radio data themselves can add significantly to the choice of SED template, and hence to a probabilistic estimate of red-shift. For example, high red-shift radio galaxies can be identified from their strong radio emission coupled with a K-band non-detection (Willott *et al*. 2003). The radio data alone can also weigh the probability of a particular red-shift range. For example, a steep radio spectral index increases the probability of a high red-shift (De Breuck *et al*. 2002), while the angular size of a particular galaxy class can be loosely correlated with red-shift (Wardle & Miley, 1974).

Fortunately, for many purposes, such as cosmological tests (Raccanelli *et al*. 2011), approximate red-shifts are sufficient. In such 'statistical red-shifts', only a fraction of objects will have an approximately correct red-shift, the remaining incorrect red-shifts merely generating noise can be cancelled in a statistical study of a sufficient number of objects. It is important, for this purpose, that reliability and completeness are carefully calibrated in a small well-studied area with deep spectroscopic red-shifts.

Polarization data can also be used to make statistical statements about red-shifts. POSSUM (Gaensler *et al*. 2010) is an ASKAP project that will run commensally with EMU, generating a catalogue of polarized fluxes and Faraday rotation measures (or upper limits) for all sources detected by EMU. POSSUM data will help us to distinguish (e.g.) the largely polarized tailed galaxies and relics from the largely unpolarized halo emission. Compact sources that are strongly polarized are nearly always AGN (Hales *et al*. 2011), and so have a mean $z \sim 1.8$, while unpolarized sources are mainly star-forming galaxies with a mean $z \sim 0.8$. Consequently, cosmological tests may be made by treating unpolarized sources as a low-redshift screen in front of background high-redshift polarized sources.

6. Discussion and conclusion

EMU will provide an unbiased radio survey for cluster haloes, relics and tailed galaxies. It will be important to compare the properties of these radio-selected clusters to those of the X-ray selected population from surveys such as the eROSITA all-sky X-ray survey (Predehl *et al*. 2010), and the Sunyaev–Zeldovich surveys made with the South Pole Telescope (Williamson *et al*. 2011), Atacama Cosmology Telescope (Marriage *et al*. 2010) and Planck (Planck Collaboration 2011) surveys, which are biased towards the detection of high-mass clusters at high red-shifts.

Quite apart from the value of an unbiased radio survey of known clusters, EMU will detect at least 3×10^4, and possibly hundreds of thousands of new clusters, roughly doubling the number of known clusters. This is particularly important at red-shifts $z > 0.5$ where current constraints on large-scale structure are weaker, and traditional detection techniques like X-ray surveys and use of the Red Cluster Sequence (Gladders & Yee 2005) become less effective, while a few clusters have already been detected using radio techniques up to high red-shifts (Blanton *et al.* 2003; Wing *et al.* 2011).

In principle, radio techniques can be used to detect clusters even beyond $z = 1$. While the highest-redshift tailed galaxy currently known ($z = 0.96$; Blanton *et al.* 2003) is detectable by EMU up to $z \sim 3$, high-resolution follow-up will be needed to confirm an initial EMU candidate list. But extrapolation beyond $z = 1$ is uncertain: we do not know the luminosity function of these galaxies, nor their evolution. Furthermore, inverse Compton cooling of electrons by the cosmic microwave background is expected to quench their synchrotron radio emission at $z \gg 1$, although the same mechanism would also be expected to distort the far-IR-radio correlation at high red-shift, which is not observed (Mao *et al.* 2011a).

In summary, EMU will deliver a next-generation radio survey covering three quarters of the sky to sensitivity levels that are currently reached only by intensive small-area surveys. It will remain the largest radio survey until the SKA, with significant impact on many areas of astronomy. EMU will be especially productive for cluster research, and may discover more clusters than any other technique. The deep unbiased survey will also be invaluable for comparison with cluster properties at X-ray and other wavelengths.

To ensure that the science goals are achieved, it is necessary to work carefully through each of them in detail before the survey starts in 2013, ensuring that the survey strategy is optimized to generate science. To achieve this, we welcome interactions and collaborations with observers and theoreticians, and with other surveys, to increase our common scientific productivity. Further information on EMU can be found on http://askap.org/emu

Acknowledgements

The EMU team consists of over 180 members from 14 countries, all of whom are listed on http://askap.pbworks.com/TeamMembers. This paper draws on the expertise and ideas of all of them. I particularly thank the coauthors of Norris *et al.* (2011) for their permission to incorporate the ideas expressed in that paper.

References

Banfield, J. M. *et al*. 2011, in preparation.
Barrena, R., Girardi, M., Boschin, W., Dasí, M. 2009, *Astr. Ap.*, **503**, 357.
Blanton, E. L. *et al*. 2003, *Astron. J.*, **125**, 1635.
Brown, S., Duesterhoeft, J., Rudnick, L. 2011, *Astrophys. J. (Lett.)*, **727**, L25.
Brunetti, G., Cassano, R., Dolag, K., Setti, G. 2009, *Astr. Ap.*, **507**, 661.
Cassano, R. *et al*. 2010, *Astrophys. J. (Lett.)*, **721**, L82.
Condon, J. J. *et al*. 1998, *Astron. J.*, **115**, 1693.
Cornwell, T. J. *et al*. 2011, ASKAP Memo ASKAP-SW-0020.

DeBoer, D. R. *et al*. 2009, *IEEE Proc.*, **97**, 1507.
Deghan, S. *et al*. 2011, *J. Astrophys. Astr.*, **32(4)**, 491.
De Breuck, C. *et al*. 2002, *Astron. J.*, **123**, 637.
Driver, S. P. *et al*. 2009, *Astr. & Geophys.*, **50**, 12.
Gaensler, B. M. *et al*. 2010, *Bull. Amer. Astron. Soc.*, **42**, 515.
Giovannini, G. *et al*. 2009, *Astr. Ap.*, **507**, 1257.
Giovannini *et al*. 2011, submitted.
Gladders, M. D., Yee, H. K. C. 2005, *Astrophys. J. Suppl.*, **157**, 1.
Gobat, R. *et al*. 2011, *Astr. Ap.*, **526**, A133.
Gupta, N. *et al*. 2008, "The Initial Array Configuration for ASKAP", ASKAP Internal Report.
Hales, C. A. *et al*. 2011, in prep.
Huynh, M. *et al*. 2005, *Astron. J.*, **130**, 1373.
Johnston, S. *et al*. 2007, *Publ. Astron. Soc. Australia*, **24**, 174.
Johnston, S. *et al*. 2008, *Experimental Astron.*, **22**, 151.
Kempner, J. C. *et al*. 2004, The Riddle of Cooling Flows in Galaxies and Clusters of galaxies, 335, http://www.astro.virginia.edu/coolflow.
Kodama, T. *et al*. 2007, *Mon. Not. R. Astron. Soc.*, **377**, 1717.
Koribalski, B. S. *et al*. 2011, *Publ. Astron. Soc. Australia*, in preparation.
Mao, M. *et al*. 2010, *Mon. Not. R. Astron. Soc.*, **406**, 2578.
Mao, M. *et al*. 2011a, *Astrophys. J.*, in press.
Mao, M. *et al*. 2011b, *J. Astrophys. Astr.*, **32(4)**, 585.
Marriage, T. A. *et al*. 2010, arXiv:1010.1065.
Markevitch, M. 2010, arXiv:1010.3660.
Middelberg, E. *et al*. 2008, *Astron. J.*, **135**, 1276.
Norris, R. P. *et al*. 2005, *Astron. J.*, **130**, 1358.
Norris, R. P. *et al*. 2006, *Astron. J.*, **132**, 2409.
Norris, R. P. *et al*. 2011, *Publ. Astron. Soc. Australia*, in press (arXiv:1106.3219).
Owen, F. N, Morrison, G. E. 2008, *Astron. J.*, **136**, 1889.
Pierre, M. *et al*. 2004, *J. Cosm. & Astroparticle Phys.*, **9**, 11.
Planck Collaboration *et al*. 2011, arXiv:1101.2024.
Predehl, P. *et al*. 2010, *Proc. SPIE*, **7732**, 77320U.
Raccanelli, A. *et al* 2011, in preparation
Romer, A. K. *et al*. 2001, *Astrophys. J.*, **547**, 594.
Rosati, P. *et al*. 1998, *Astrophys. J. (Lett.)*, **492**, L21.
Röttgering, H. *et al*. 2010, http://www.astron.nl/radio-observatory/apertif-eoi-abstracts-and-contact-information.
Saripalli, L. *et al*. 2011, in preparation.
Schuecker, P. *et al*. 2001, *Astr. Ap.*, **378**, 408.
Seymour, N. *et al*. 2008, *Mon. Not. R. Astron. Soc.*, **386**, 1695.
Springel, V. *et al*. 2005, *Nature*, **435**, 629.
Subrahmanyan, R. *et al*. 2010, *Mon. Not. R. Astron. Soc.*, **402**, 2792.
van Weeren, R. J. *et al*. 2010, *Science*, **310**, 347.
Venturi, T. *et al*. 2008, *Astr. Ap.*, **484**, 327.
Wardle, J. F. C., Miley, G. K. 1974, *Astr. Ap.*, **30**, 305.
Williamson, R. *et al*. 2011, arXiv:1101.1290.
Willott, C. J. *et al*. 2003, *Mon. Not. R. Astron. Soc.*, **339**, 173.
Wilson, G. *et al*. 2008, *Infrared Diagnostics of Galaxy Evolution*, **381**, 210.
Wing, J. D., Blanton, E. L. 2011, *Astron. J.*, **141**, 88.
York, D. G. *et al*. 2000, *Astron. J.*, **120**, 1579.