Exploitation of LOFAR surveys to study galaxy clusters

M. Brüggen (Bremen), G. Brunetti (Bologna), T.A. Enßlin (Garching), C. Ferrari (Nice), H.J.A. Röttgering (Leiden), G. Miley (Leiden), P. Best (Edinburgh), A. Edge (Durham), M. Arnaud (Saclay), L. Ferrero (Bologna), R.F. Pizzo (Groningen), E. Orrú (Nijmegen), R.J. van Weeren (Leiden, ASTRON), M. Wise (Amsterdam), A. Bonafede (Bremen), M.A. Brentjens (ASTRON), G. Macario (Nice), R. Cassano (Bologna), J. Croston (Southampton), K. Ferriere (Toulouse), M. Hoeft (Tautenburg), K. Chyży (Krakow), L. Birzan (Leiden), D. Rafferty (Leiden), C. Horellou (Onsala), E. A. Valentyn (Kapteyn) (Cluster Science Team)

1 Introduction

Clusters of galaxies are one of the main science drivers for LOFAR. Besides the hot thermal gas observed in X-rays, the intra-cluster-medium (ICM) contains relativistic electrons (E≈Gev) and magnetic fields (∼1−10 µGauss) that have been detected via synchrotron emission in the radio band. Synchrotron emission provides unique diagnostics of the large-scale magnetic fields and relativistic particles in the ICM. These non-thermal components play key roles in controlling transport processes in clusters and are sources of additional energy and pressure support in the intra-cluster-medium (e.g. Ruszkowski et al. 2007; Brunetti & Lazarian 2007; Schekochihin et al. 2009). Moreover, radio galaxies in clusters are probes of the surrounding medium (e.g. Miley 1980). The cluster weather affects the morphology and evolution of these sources, while their feedback on the ICM has important implications for cluster evolution. Bubbles launched from radio galaxies are also sources of relativistic particles and magnetic fields (e.g. Brüggen & Kaiser 2002); other sources of radio emission are starburst galaxies whose evolution is also affected by the environment (e.g. Butcher & Oemler 1978). Diffuse synchrotron emission from the ICM as well as radio bubbles and cluster radio galaxies have steep spectra, making them ideal targets for LOFAR. Moreover, LOFAR will map the cosmic web through the detection of synchrotron emission from accelerated particles, and will probe the evolution of cluster radio galaxies and their feedback on the ICM with unprecedented detail.

2 Main science questions

2.1 Diffuse emission in galaxy clusters

Diffuse radio sources in galaxy clusters are usually divided into three main classes (giant and mini halos, relics) depending on their morphology, position in the cluster, and on the physical properties of their host system (e.g. Ferrari 2008). Radio halos and relics are currently found only in a fraction of massive galaxy clusters, all of which show signatures of recent mergers (Buote 2001; Cassano et al. 2010). Radio halos are either produced by secondary electrons injected during collisions between thermal and CR protons that are confined in turbulent magnetic fields (e.g. Dennison 1980; Blasi & Colafrancesco 1999; Enßlin et al. 2011), or by relativistic electrons (including secondaries) re-accelerated in-situ by MHD turbulence generated in the ICM during cluster mergers (e.g. Brunetti et al. 2001; Petrosian 2001; Cassano & Brunetti 2005; Brunetti & Lazarian 2011). Radio relics are most likely associated with shock waves which formed during mergers (e.g. Enßlin et al. 2006).
1998\textsuperscript{17}; Röttger et al. 1999\textsuperscript{18}; Enßlin & Gopal-Krishna 2001\textsuperscript{19}; Enßlin & Brüggen 2002\textsuperscript{20}), although the details of the CR acceleration processes are still unclear.

Relics and halos trace cosmic rays and magnetic fields in galaxy clusters, and are links between the cosmological process of cluster formation and the complex microphysics that governs the ICM. For this reason they are also potential cosmological tools to constrain the cluster merging rate in the universe. So far the lack of sensitivity of current radio telescopes and the failure to detect non-thermal components in other wavebands, implies that in terms of observations we are still only scratching the surface and theoretical models remain poorly constrained. Owing to their low surface-brightness and steep spectra, currently only few diffuse radio sources are known. The number of known radio halos/relics is ≤ 50 and most of them have been detected in low-z (≤ 0.4), X-ray luminous clusters ($L_X \geq 10^{44}$ ergs$^{-1}$). In order to test current models of radio halo/relic formation, one needs, both, statistical studies of the fraction of observed clusters with radio halos/relics as a function of cluster mass and z (e.g. Cassano et al. 2008\textsuperscript{21}), and detailed studies of how the relations between the radio emission and the physical properties of clusters evolve with redshift (e.g. Hoeft et al 2008\textsuperscript{22}).

It has been shown that high-sensitivity surveys at low radio frequencies have the potential to unravel radio halos in the universe providing an unbiased statistical census of the halo population (Enßlin & Röttgering 2002\textsuperscript{23}). Turbulence in the ICM may play a key role in accelerating relativistic particles in radio halos (e.g. Brunetti et al. 2008\textsuperscript{24}), in which case halos with very steep spectrum should be more common in the universe (e.g. Cassano et al. 2006\textsuperscript{25}) and would show up preferentially at lower radio frequencies.

We identify the following sub-projects:

i) **Surveys of diffuse radio emission:** The LOFAR Tier 1 survey at 150 MHz is expected to discover about 400 giant radio halos at redshift ≤ 0.6-0.7, most of them with very steep spectra with $\alpha \leq -1.5$, as shown by Cassano et al 2010\textsuperscript{26} (Figure 2). About a few hundred radio halo sources are needed to properly analyze the statistical properties of these sources as function of $z$, mass, $L_X$, etc., The detailed models from Cassano et al. show a noise level of 0.1 mJy at 150 MHz is required to detect such a number of sources in the Tier-1 survey. Moreover, up to 50-100 radio halos can be discovered by these surveys in the redshift range 0.5-1. This will allow a gigantic step in our understanding of the statistical properties of giant halos and on their origin and evolution with cosmic time. The same is true for radio relics: about 40 relics are known today. LOFAR surveys Tier I is expected to discover about 1000 relic candidates (Nuza et al 2012). Cross-correlation with, e.g. X-ray cluster surveys and follow-up observations will lead to a huge sample relics, comprising several hundreds of relics.

ii) **Studying the merger – radio halo/relic connection:** X-ray cluster catalogues in the northern hemisphere, such as eBCS and NORAS (Böhringer et al 2000\textsuperscript{27}; Ebeling et al 2000\textsuperscript{28}) contain several hundred galaxy clusters in the redshift range 0–0.6 with X-ray and optical information. Recent radio follow-ups of X-ray selected cluster samples, such as the GMRT RH Survey (Venturi et al. 2008), start to address the evolution of radio halos and the merger–halo connection in X-ray luminous galaxy clusters at $z < 0.4$. LOFAR Tier 1 surveys will extend these studies: they will improve the statistics by almost an order of magnitude and will address unexplored territories, such as the formation of radio halos and relics in less massive systems (Cassano 2010\textsuperscript{29}; Nuza et al 2012\textsuperscript{30}). When combined with statistical information at higher frequencies (e.g. from GMRT Surveys and ongoing radio follow ups of MACS clusters) Tier 1 will provide a unique multi-frequency view of the origin of non-thermal diffuse sources in galaxy clusters.

iii) **Spectrum of radio halos:** The shape of the spectrum of radio halos and relics is a fundamental observable to understand the mechanisms responsible for particle acceleration in the ICM (e.g.

\begin{thebibliography}{99}
\bibitem{}\textsuperscript{17}\textit{A&A} 332 395
\bibitem{}\textsuperscript{18}\textit{ApJ} 518 603
\bibitem{}\textsuperscript{19}\textit{A&A} 366 26
\bibitem{}\textsuperscript{20}\textit{MNRAS} 331 1011
\bibitem{}\textsuperscript{21}\textit{A&A} 480 687
\bibitem{}\textsuperscript{22}\textit{MNRAS} 391 1511
\bibitem{}\textsuperscript{23}\textit{A&A} 396 83
\bibitem{}\textsuperscript{24}\textit{Nature} 455 944
\bibitem{}\textsuperscript{25}\textit{MNRAS} 369 1577
\bibitem{}\textsuperscript{26}\textit{A&A} 509, 68
\bibitem{}\textsuperscript{27}\textit{ApJS} 129, 435
\bibitem{}\textsuperscript{28}\textit{MNRAS} 318 333
\bibitem{}\textsuperscript{29}\textit{A&A} 517, 10
\bibitem{}\textsuperscript{30}\textit{MNRAS} 420, 2006
\end{thebibliography}
Present observations typically cover a small frequency range (typically 330–1400 MHz) for an inadequate number of sources. Tier 1 surveys will allow us to detect all radio halos in the northern hemisphere that are known so far with unprecedented signal to noise and to measure accurately their flux in the frequency range 15–200 MHz.

iv) Spectral and polarisation studies of radio relics: It is not yet clear whether the origin of relics is due to shock acceleration of thermal particles (Enßlin et al. 1998; Roettiger et al. 1999) or to re-energization of relativistic plasma due to the shock passage (Enßlin & Gopal-Krishna 2001). These models have different expectations in terms of synchrotron spectral shape and polarisation that can be tested only through sensitive observations down to lower frequencies. Observations at low frequencies allow for imaging of the steep-spectrum emission downstream of the shock and that probes the plasma and the magnetic field in this region (Clarke & Enßlin 2006; Markevitch et al 2005; Giacintucci et al. 2008; van Weeren et al 2010).

v) Spatial properties of synchrotron emission in galaxy clusters: The brightness distribution of Mpc-scale sources in galaxy clusters reflects the underlying distribution of magnetic field and CR electrons. In particular brightness fluctuations (filaments and patches) in the emission of radio halos and relics provide crucial information on the magnetic field power spectrum (see Murgia et al 2004) and CR acceleration and transport/diffusion processes. In order to start addressing these issues radio observations must be able to resolve scales smaller than the typical coherent scales of magnetic fields and of turbulent eddies in galaxy clusters (≤ 30 – 50 kpc), still preserving high brightness sensitivity. Deep LOFAR Tier 2 observations will provide sensitive, high-resolution mapping of a number of selected diffuse cluster radio sources.

2.2 Magnetic fields in galaxy clusters

Studying cluster magnetic fields is fundamental to understand the physical conditions and energetics of the ICM. Because of LOFAR’s high sensitivity and large beamsize, LOFAR offers the possibility to detect fields in regions of low surface brightness in clusters and filaments.

The magnetic field in clusters of galaxies can be determined via the Rotation Measure (RM) with background and embedded radio sources, as well as with RM-synthesis. The magnetic fields in typical galaxy clusters are of the order of 1 µG on coherence scales of the order of 10 kpc. In cool cores of clusters fields have been observed to have magnetic strengths up to ~12 µG (e.g. Carilli & Taylor 2002).

Studies of the Rotation Measure of radio galaxies located within or behind clusters of galaxies provide unique tools to constrain the field properties (e.g. Clarke et al 2001; Enßlin & Vogt 2003).

RM Synthesis takes advantage of the broad λ^2 coverage that is possible with LOFAR and is developed in collaboration with the Magnetism Key Science Project (Bell & Enßlin 2012). The precision with which one can determine the RM for a source is given by the signal-to-noise ratio of the detected polarised flux. The minimum wavelengths determines the maximum detectable Faraday depth of the emitting and rotating region, the channel width determines the maximum RM of Faraday screens, and the total span in wavelength determines the resolution in Faraday space. RM Synthesis can only be done for high elevation sources as the noise in Q and U increases as sin^{-1}(elevation). This means that polarisation measurements will only be feasible for objects with δ > 23 degrees. Planned observation will attempt to use the full 48 MHz (200 MHz clock) bandwidth with a subband selection between 120 and 180 MHz. With a frequency resolution of Δν ~ 30 kHz one will be able to detect absolute values of rotation measures up to 1000 rad m^{-2}. The resulting RM resolution will be of the order of 0.1 rad m^{-2} and maybe higher if Galactic foregrounds allow. Where feasible, we will investigate...
the relationship between magnetic fields and cluster properties, such as mass, central entropy and presence of diffuse radio emission.

The particular advantage of LOFAR regarding such observations is its big field of view, combined with good sensitivity. This enables us to study nearby clusters with one or two pointings, while detecting already tens of polarised radio sources.

2.3 Radio galaxies in clusters

Extragalactic radio sources have long been used as probes of the surrounding intergalactic gas. Radio sources are affected by the pressure from the ambient gas. In addition, shocks in the ambient gas (e.g. at the boundaries of galaxies or clusters) can re-accelerate older electrons and modify the radio spectra. Tailed radio sources (wide-angle tail (WAT) sources and narrow-angle tail (NAT) sources) are “fossil records” of the galaxies’ motions and their interaction with the ambient gas, and can thus be used as “tracers” of gas motions inside clusters. The motion of galaxies through the gas during the lifetime of these sources can radically distort the shapes of the radio sources, resulting in long tails of radio emission (Miley et al. 1972\textsuperscript{45}). Such long tails can also be used to probe large-scale turbulence in the ICM via the expected distortions due to the turbulent motions. Electrons in the tails trace the evolution of radio galaxies over longer time-intervals with increasing distance from the head of the galaxies. Due to synchrotron aging, low-frequency observations with adequate angular resolution are necessary to image old electrons and thus to constrain their evolution and that of the radio galaxies over fairly long time-scales.

The effect of environment on source evolution will also be addressed through the radio luminosity functions (or bivariate radio-optical luminosity function) of cluster radio sources to an unprecedented depth, at the LOFAR frequencies, and by comparing them with those of field radio sources. Another excellent tool which can trace environmental effects is the polarized emission. It is sensitive to compression (shocks) and shear motions and contains information about the gas flows in the sky plane.

2.4 Late evolution of radio lobes

Hot gas in dynamically relaxed clusters must achieve a rapid cooling in the central regions (e.g. Fabian et al. 1984\textsuperscript{46}). This is not observed at the expected rate implying that there must be a feedback mechanism that prevents catastrophic cooling in cluster cores. The most popular mechanism is heating by AGN-driven outbursts that drive large bubbles into the ICM (e.g. McNamara et al. 2000\textsuperscript{47}; Blanton et al. 2001\textsuperscript{48}). While AGN in cool-core clusters are observed to drive bubbles, the synchrotron radiation emitted by the relativistic electrons in these bubbles fades and becomes difficult to detect after about $10^8$ years. Moreover, the corresponding X-ray surface brightness depressions are only visible near the centre of the cluster where the contrast is large. Thus, it is unclear how far AGN-driven cavities rise in the cluster, how they couple to the surrounding medium, and how they evolve (Brüggen & Scannapieco 2009\textsuperscript{49}).

Owing to its sensitivity and frequency range, LOFAR will be able to trace AGN-inflated bubbles to much larger distances and will provide a deep census of radio-loud AGN populations to high redshift. With LOFAR one can study the evolution of bubbles and of their spectrum as they rise through the cluster, trace multiple outbursts in cluster-centres, and study relation between outburst histories and global cluster properties. Also LOFAR will offer a chance to study the effect of hydrodynamical instabilities on bubble morphology and the properties of the hot plasma inside the bubbles, such as the equation of state, particle and magnetic field content and filling factor. Related to these issues is the question how to best measure the energetics of AGN-inflated bubbles. It is now standard procedure to use the size of a bubble and the ambient pressure at its location to get an estimate of the $pdV$ work needed to inflate the bubble, which is then used to infer the energy associated with the outburst.

\textsuperscript{45}Nature 237, 269
\textsuperscript{46}Nature 310, 733
\textsuperscript{47}ApJ 534, L135
\textsuperscript{48}ApJ 558, L15, and ref therein
\textsuperscript{49}MNRAS 398, 548
(Birzan et al 2004\textsuperscript{50}). Interestingly, if one plots the inferred energy as a function of radius for the known X-ray cavities, one finds that the energy increases as a function of bubble distance from the cluster centre (Rafferty et al 2006\textsuperscript{51}). This effect is not only apparent in a large sample of different clusters, but even within the few individual clusters with known multiple bubbles, such as Hydra A and Perseus. Understanding this effect is crucial for the question whether AGN can be a general solution to the cooling flow problem.

### 2.5 Starbursts

All observational evidence indicates a gradual truncation of star formation in clusters, with the disappearance of star forming galaxies in the center of rich systems since $z \sim 1$. At present, we still miss a detailed comprehension of the physics driving the observed evolution (Poggianti et al 2006\textsuperscript{52}). The local radio-FIR correlation for star forming galaxies is very tight, and seems to hold at up to high redshift (Kovacs et al 2006\textsuperscript{53}); also in this case the involved physical processes are however poorly understood.

The low-frequency radio window opened by LOFAR will offer a unique tool to address this open question: the non-thermal emission of galaxies will not be contaminated by the free-free emission at LOFAR frequencies thus allowing for studying with unprecedented detail the still poorly understood phases between star formation and synchrotron emission in galaxies. A quantitative interpretation of the observed synchrotron spectrum will be possible, giving important insights into the physics of star formation in cluster galaxies (e.g. Condon 1992\textsuperscript{54}).

Tier-1 & 2 LOFAR observations will reach star-forming objects with SFR $\sim 100$ and $\sim 10$ $M_\odot$ yr$^{-1}$ out to $z \sim 1.5$. At low-$z$ we can expect to obtain the entire low-frequency spectrum of all the cluster starbursts and investigate differences in the SF properties of cluster and field galaxies. At intermediate-$z$, it will be possible to study SFR variations as a function of the density of the environment.

The detection of strong starburst galaxies at high-$z$ can be used to detect proto-clusters at $z \geq 1.5$. Combining LOFAR survey data with Herschel data, one can conduct unbiased searches of proto-clusters in the redshift range 1.5-2.5. The comparison of LOFAR and Herschel data will also allow to analyze the evolution with redshift of the correlation between radio continuum emission and FIR dust emission from starburst galaxies, that is one of the tightest correlations known in the low-$z$ universe. Research will be carried out in collaboration with the \textit{SF working group}.

### 3 Observational goals and survey design

The main observational goals of the present proposal are:

- Discover diffuse emission in a unprecedentedly large number of clusters (up to large distances, $z \approx 1$) and relate observations to models of cluster evolution
- Make detailed maps and spectral studies of diffuse emission at low frequencies to address the magnetic-field structure and the coupling between CR and magnetic fields
- Study the interaction of radio sources with the cluster gas (e.g. radio-blown cavities) in order to constrain physical processes and the evolutionary history of clusters
- Map the 3-dimensional distribution of magnetic fields in nearby clusters via Faraday synthesis and polarization studies of background radio sources
- Detect the cosmic web in the radio via shocked synchrotron filaments in very deep surveys
- Study starburst galaxies in clusters

\textsuperscript{50} ApJ 607 800 \hspace{1cm} \textsuperscript{51} ApJ 652 216 \hspace{1cm} \textsuperscript{52} ApJ 642 188 \hspace{1cm} \textsuperscript{53} ApJ 650 592 \hspace{1cm} \textsuperscript{54} ARA&A 30 575
LOFAR Surveys have been designed to address these goals (see umbrella proposal). This has led to a three-tiered survey plan. For clusters, the first two tiers are most relevant, which we briefly describe in the following:

- **Tier 1:** This set of observations is designed to survey the northern hemisphere at 15-40, 40-65, and 120-170 MHz. The survey is designed to unveil diffuse synchrotron emission in galaxy clusters and cluster outskirts and to obtain spectral constraints on the detected emission. As a starting point, we will follow up at 150 MHz 60 priority clusters targets that show diffuse radio emission in the form of radio halos, relics and AGN-driven bubbles or that have dynamical properties suitable to host radio halos and relics (table 1). More specifically, these sources were selected according to the following criteria: i) host a known halo, mini-halo, relic, bubble or show high potential (HP) for the presence of cluster-scale diffuse radio emission as e.g. massive and dynamically active galaxy clusters (from Planck, eBCS or MACS catalogs), ii) availability of other wavelength data, iii) sufficient brightness in radio (or expected for the HP targets) and extension of the radio emission > 1 arcmin, and iv) declination $\delta > 0$. This step is intended to maximize the impact of the first data from Tier 1. In a second step, cluster radio sources will be extracted from Tier 1 observations using the available X-ray and SZ cluster catalogs. This has the goal of discovering new radio sources in galaxy clusters and to study the statistical properties of different populations of radio sources in clusters. Based on present models and on present survey sensitivities, detection of radio halos and relics is expected in more than 500 clusters (up to $z = 1$) at 150 MHz. The area and depth for the tier 1 high-band survey is determined by our wish to get up to 100 halos at $z > 0.6$.

- **Tier 2:** In this tier, we plan to carry out deep observations of 6 nearby galaxy clusters at 30-60 MHz and of 15 selected clusters at 120-190 MHz (table 2). The main goal of Tier 2 is to obtain extremely-deep high-resolution observations of synchrotron sources in galaxy clusters and to derive polarisation properties of these sources.

### 4 Commissioning

During commissioning, the cluster WG has worked on a number of objects, most importantly A2255, A2256, Virgo (Fig. 3), Coma and MACS J0717+3745. The paper on the LBA observations of A2256 has just been submitted (also see Fig. 4) and the other projects are also expected to lead to publications. During commissioning, essential advances were made in calibration and imaging. Notably, progress in the demixing of bright sources in the field and in developing the new imager were driven by commissioning in this WG.

### 5 Organization

As described in the umbrella proposal of the LOFAR Survey Key Science Project (SKSP), the overall Surveys team has been split into a number of science working groups. Our cluster working group is led by M. Brüggen and G. Brunetti and comprises expertise from various communities across Europe (both observational and theoretical). It will also benefit from close collaborations with the Magnetism KSP (that include a number of members of our group) and with other working groups of the SKSP, mainly: (i) the physics of nearby AGN led by R. Morganti, (ii) the distant radio galaxies team led by G. Miley, and (iii) the cosmic star formation history team led by M. Lehnert and P. Barthel.
Figure 1: **a)** Radio Halo in Abell 2163: radio contours at 1.4 GHz overlaid on the ROSAT X-ray emission (Feretti et al. 2001). **b)** Radio Relics in the cluster Abell 3376: radio contours at 1.4 GHz overlaid on the ROSAT X-ray emission (Bagchi et al. 2006).

Figure 2: **Upper panels** (from Cassano et al. 2010) : **Left**: number of expected giant radio halos at 120 MHz as a function of z and assuming the sensitivity of the Tier 1 survey. **Right**: number of giant radio halos detected at 120 MHz as a function of spectral index. **Lower panel**: expected number counts of radio halos (at 1.4 GHz) at different redshifts (from Röttgering & Enßlin 2002).
Figure 3: LOFAR-HBA image of Virgo A at 140 MHz. The map noise is 0.006 Jy/beam and the beam size is 19” × 14” (grey ellipse in the bottom-left corner). The contour line is at 60 Jy/beam and emphasizes the direction of the core jets. De Gasparin et al. (in preparation).
Figure 4: Overview of the A2256 field at 61-67 MHz as observed with LOFAR. Bottom right: Zoomed version of the 61-67 MHz image with a synthesized beam of 22" x 26". From van Weeren et al. 2012 (submitted).
<table>
<thead>
<tr>
<th>name</th>
<th>RA (J2000)</th>
<th>DEC (J2000)</th>
<th>z</th>
<th>RADIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>A399</td>
<td>02 57 56.4</td>
<td>+13 00 59</td>
<td>0.07</td>
<td>RH</td>
</tr>
<tr>
<td>A401</td>
<td>02 58 56.9</td>
<td>+13 34 56</td>
<td>0.07</td>
<td>RH</td>
</tr>
<tr>
<td>A503</td>
<td>04 54 19.0</td>
<td>+02 56 49</td>
<td>0.203</td>
<td>GRH</td>
</tr>
<tr>
<td>A523</td>
<td>04 59 01.6</td>
<td>+08 46 29</td>
<td>0.10</td>
<td>GRH</td>
</tr>
<tr>
<td>A665</td>
<td>08 30 45.2</td>
<td>+65 52 55</td>
<td>0.182</td>
<td>GRH</td>
</tr>
<tr>
<td>A697</td>
<td>08 42 53.3</td>
<td>+36 20 12</td>
<td>0.280</td>
<td>GRH</td>
</tr>
<tr>
<td>A746</td>
<td>09 09 37.3</td>
<td>+51 32 48</td>
<td>0.232</td>
<td>GRH</td>
</tr>
<tr>
<td>A773</td>
<td>09 17 59.4</td>
<td>+51 42 23</td>
<td>0.210</td>
<td>GRH</td>
</tr>
<tr>
<td>A851</td>
<td>09 42 58.0</td>
<td>+46 59 12</td>
<td>0.41</td>
<td>RH?</td>
</tr>
<tr>
<td>A1213</td>
<td>11 16 29.1</td>
<td>+29 15 37</td>
<td>0.047</td>
<td>RH/R?</td>
</tr>
<tr>
<td>A1351</td>
<td>11 40 32.7</td>
<td>+58 32 21</td>
<td>0.322</td>
<td>GRH</td>
</tr>
<tr>
<td>COMA</td>
<td>12 59 48.7</td>
<td>+27 58 50</td>
<td>0.023</td>
<td>GRH+R</td>
</tr>
<tr>
<td>A1772</td>
<td>13 32 32.1</td>
<td>+50 30 37</td>
<td>0.280</td>
<td>GRH</td>
</tr>
<tr>
<td>A1914</td>
<td>14 26 03.0</td>
<td>+39 37 42</td>
<td>0.17</td>
<td>GRH</td>
</tr>
<tr>
<td>A2034</td>
<td>15 10 13.1</td>
<td>+33 31 41</td>
<td>0.11</td>
<td>RH/R?</td>
</tr>
<tr>
<td>A2142</td>
<td>15 58 16.1</td>
<td>+27 13 39</td>
<td>0.091</td>
<td>RH</td>
</tr>
<tr>
<td>A2218</td>
<td>16 35 54.0</td>
<td>+66 16 00</td>
<td>0.176</td>
<td>GRH</td>
</tr>
<tr>
<td>A2219</td>
<td>16 40 21.1</td>
<td>+46 41 16</td>
<td>0.228</td>
<td>GRH</td>
</tr>
<tr>
<td>A2254</td>
<td>17 17 40.2</td>
<td>+19 42 51</td>
<td>0.178</td>
<td>GRH</td>
</tr>
<tr>
<td>A2255</td>
<td>17 12 31.0</td>
<td>+64 05 33</td>
<td>0.08</td>
<td>GRH+R</td>
</tr>
<tr>
<td>A2256</td>
<td>17 03 45.3</td>
<td>+78 43 03</td>
<td>0.058</td>
<td>GRH+R</td>
</tr>
<tr>
<td>A2319</td>
<td>19 20 45.3</td>
<td>+43 57 43</td>
<td>0.056</td>
<td>GRH+R</td>
</tr>
<tr>
<td>A115</td>
<td>00 55 59.5</td>
<td>+26 19 14</td>
<td>0.197</td>
<td>R</td>
</tr>
<tr>
<td>A1240</td>
<td>01 23 32.1</td>
<td>+43 36 32</td>
<td>0.159</td>
<td>R</td>
</tr>
<tr>
<td>A2061</td>
<td>01 21 15.3</td>
<td>+30 39 17</td>
<td>0.078</td>
<td>H+R</td>
</tr>
<tr>
<td>RXCJ1053.7+5452</td>
<td>10 53 47.5</td>
<td>+54 50 59</td>
<td>0.07</td>
<td>R</td>
</tr>
<tr>
<td>CIZAJ2242.8+5301</td>
<td>22 42 53.0</td>
<td>+53 01 05</td>
<td>0.192</td>
<td>R+GRH</td>
</tr>
<tr>
<td>A1502</td>
<td>02 42 16.0</td>
<td>+42 13 00</td>
<td>0.225</td>
<td>R+GRH</td>
</tr>
<tr>
<td>A115</td>
<td>05 55 59.5</td>
<td>+26 19 14</td>
<td>0.197</td>
<td>R</td>
</tr>
<tr>
<td>A1240</td>
<td>01 23 32.1</td>
<td>+43 36 32</td>
<td>0.159</td>
<td>R</td>
</tr>
<tr>
<td>A2061</td>
<td>01 21 15.3</td>
<td>+30 39 17</td>
<td>0.078</td>
<td>H+R</td>
</tr>
<tr>
<td>RXCJ1053.7+5452</td>
<td>10 53 47.5</td>
<td>+54 50 59</td>
<td>0.07</td>
<td>R</td>
</tr>
<tr>
<td>CIZAJ2242.8+5301</td>
<td>22 42 53.0</td>
<td>+53 01 05</td>
<td>0.192</td>
<td>R+GRH</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>name</th>
<th>RA (J2000)</th>
<th>DEC (J2000)</th>
<th>z</th>
<th>RADIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>A520</td>
<td>04 54 19.0</td>
<td>+02 56 49</td>
<td>0.2</td>
<td>GRH</td>
</tr>
<tr>
<td>A665</td>
<td>08 30 45.2</td>
<td>+65 52 55</td>
<td>0.182</td>
<td>GRH</td>
</tr>
<tr>
<td>A773</td>
<td>09 17 59.4</td>
<td>+51 42 23</td>
<td>0.217</td>
<td>GRH</td>
</tr>
<tr>
<td>COMA</td>
<td>12 59 48.7</td>
<td>+27 58 50</td>
<td>0.023</td>
<td>GRH+R</td>
</tr>
<tr>
<td>A1914</td>
<td>14 26 03.0</td>
<td>+39 37 42</td>
<td>0.17</td>
<td>GRH</td>
</tr>
<tr>
<td>A2163</td>
<td>15 15 34.1</td>
<td>+06 07 26</td>
<td>0.2</td>
<td>GRH</td>
</tr>
<tr>
<td>A2219</td>
<td>16 40 21.1</td>
<td>+46 41 16</td>
<td>0.228</td>
<td>GRH</td>
</tr>
<tr>
<td>A2254</td>
<td>17 17 40.2</td>
<td>+19 42 51</td>
<td>0.178</td>
<td>GRH</td>
</tr>
<tr>
<td>A2255</td>
<td>17 12 31.0</td>
<td>+64 05 33</td>
<td>0.08</td>
<td>GRH+R</td>
</tr>
<tr>
<td>A2256</td>
<td>17 03 45.3</td>
<td>+78 43 03</td>
<td>0.058</td>
<td>GRH+R</td>
</tr>
<tr>
<td>A2256</td>
<td>17 03 45.3</td>
<td>+78 43 03</td>
<td>0.058</td>
<td>GRH+R</td>
</tr>
<tr>
<td>A2256</td>
<td>17 03 45.3</td>
<td>+78 43 03</td>
<td>0.058</td>
<td>GRH+R</td>
</tr>
<tr>
<td>A2256</td>
<td>17 03 45.3</td>
<td>+78 43 03</td>
<td>0.058</td>
<td>GRH+R</td>
</tr>
</tbody>
</table>

Table 1: tier 1

<table>
<thead>
<tr>
<th>name</th>
<th>RA (J2000)</th>
<th>DEC (J2000)</th>
<th>z</th>
<th>RADIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>A520</td>
<td>04 54 19.0</td>
<td>+02 56 49</td>
<td>0.2</td>
<td>GRH</td>
</tr>
<tr>
<td>A665</td>
<td>08 30 45.2</td>
<td>+65 52 55</td>
<td>0.182</td>
<td>GRH</td>
</tr>
<tr>
<td>A773</td>
<td>09 17 59.4</td>
<td>+51 42 23</td>
<td>0.217</td>
<td>GRH</td>
</tr>
<tr>
<td>COMA</td>
<td>12 59 48.7</td>
<td>+27 58 50</td>
<td>0.023</td>
<td>GRH+R</td>
</tr>
<tr>
<td>A1914</td>
<td>14 26 03.0</td>
<td>+39 37 42</td>
<td>0.17</td>
<td>GRH</td>
</tr>
<tr>
<td>A2163</td>
<td>15 15 34.1</td>
<td>+06 07 26</td>
<td>0.2</td>
<td>GRH</td>
</tr>
<tr>
<td>A2219</td>
<td>16 40 21.1</td>
<td>+46 41 16</td>
<td>0.228</td>
<td>GRH</td>
</tr>
<tr>
<td>A2254</td>
<td>17 17 40.2</td>
<td>+19 42 51</td>
<td>0.178</td>
<td>GRH</td>
</tr>
<tr>
<td>A2255</td>
<td>17 12 31.0</td>
<td>+64 05 33</td>
<td>0.08</td>
<td>GRH+R</td>
</tr>
<tr>
<td>A2256</td>
<td>17 03 45.3</td>
<td>+78 43 03</td>
<td>0.058</td>
<td>GRH+R</td>
</tr>
</tbody>
</table>

Table 2: tier 2