A 21-cm Multi-Beam Receiver[1]

Australia
R.D. Ekers, K.C. Freeman, R.F. Haynes,
D.S. Mathewson, L. Staveley-Smith, A.E. Wright

United Kingdom
R.D. Davies, M.J. Disney

United States
F.H. Briggs, F.J. Kerr, J.R. Mould, O.-G. Richter

Others
P.A. Henning, R.C. Kraan-Korteweg & W.H. McCutcheon

Summary
We propose a λ21-cm multi-beam receiver system for the Parkes Telescope to undertake deep, large area surveys for neutral hydrogen in external galaxies. The proposed system has nine feeds, each detecting orthogonal linear polarisations, arranged in a 3×3 grid. We will use it to: (1) survey for galaxies behind the southern Galactic Plane, a vital region for the study of large-scale structure and deviations from the Hubble flow; (2) extend the mass function of galaxies to well beyond the optically accessible range, providing insight into fundamental processes of star and galaxy formation. The existing Parkes AT correlator, augmented with the Mopra and LBA correlators for the duration of the experiment, provide the necessary spectrometer capability.

1. Introduction
Virtually all galaxy surveys in the 21cm line of neutral hydrogen (HI) have been conducted in a pointed manner (with the notable exception of the work by Henning and Kerr 1989, and Henning 1990). That way a previously determined position from optical sky surveys is used to point the telescope in order to measure the HI content of that object. Obviously, this approach has a number of drawbacks. Firstly, it clearly breaks down where galaxies can no longer be unambiguously detected optically, namely behind the dusty obscuring disk of our own Milky Way. Secondly, it biases our view of the distribution and content of galaxies. All-sky surveys in other wavebands like the far-infrared (IRAS) and X-ray (HEAO) domains have shown that the bolometric luminosity of galaxies (and quasars) is often dominated by wavebands other the the optical, and that optical studies give a rather biased indication of the large-scale mass distribution in the Universe. Also, since the fraction of gaseous mass increases steadily toward intrinsically fainter (and more numerous) galaxies, it is possible that a large fraction of the total baryonic matter in the universe may be locked up in a vast 'sea' of faint but gas-rich objects.

This document summarizes the technical details of the proposed 9-beam focal plane array in §2 & 3. The proposed scientific uses of an instrument which simultaneously has a large collecting area and a large field of view are given in §4.

2. The Receiver
The proposed multi-beam receiver (Fig.1) is a 3 × 3 square grid of horns which feed a

[1] Version LSS 19/3/93

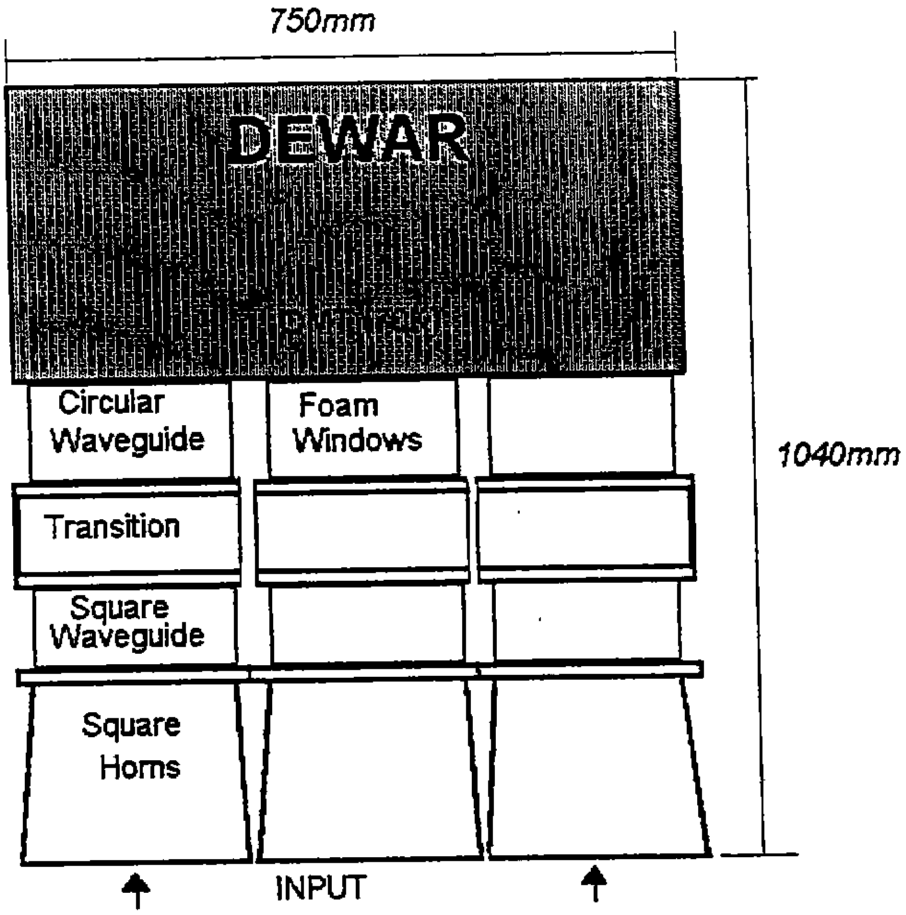

Figure 1: Schematic sideways view of the multi-beam receiver.

set of 18 low noise-temperature amplifiers situated in a common dewar. The envisaged frequency range is 1270 - 1470 MHz, with a mid-range amplifier temperature < 3K. The total system temperature at the zenith will be < 30K.

The overall width of the array is 3.6λ or $\sim$ 750mm with a beam separation of 1.2λ, or $\sim$ 26 arcmin on the sky. The beam separation is somewhat greater than the individual beamwidths (FWHP 15 arcmin) in order to minimimize the crosstalk between elements. Thus, a fully sampled survey of a region of sky will require an interleave factor of 2 in each spatial dimension, resulting in an effective area coverage of 0.422 deg^2 per pointing. The loss of aperture efficiency at the corners is neglibible (< 1%).

3. The Correlator

The proposed standard observing configuration is for an instantaneous bandwidth of 64 MHz on each of the 18 intermediate frequency (IF) channels (9 beams $\times$ 2 polarizations). With a total of 18 AT correlator modules, this will allow 512 autocorrelation channels in the spectral domain for each IF. This allows a velocity coverage of 0 - 14000 km s^{-1}, with a channel spacing of 27 km s^{-1}. This will require a correlator of capacity nine times greater than the existing Parkes correlator (2 blocks). However, the temporary use of the Mopra correlator (4 blocks), the LBA correlator (8 blocks) coupled with the fabrication of an additional 4 blocks from the existing spare stock of chips will be sufficient.

4. Scientific Goals

4.1 Galaxies in the Zone of Avoidance

Dust distributed in the plane of our own Milky Way substantially obscures our view of the extragalactic Universe within a region of up to 25° on either side of the galactic equator. In several regions one can easily identify the brightest and nearest galaxies closer to the galactic plane, but within about 10° of galactic latitude optical surveys become rapidly incomplete, morphological galaxy classifications become impossible, determination of several optical properties, like diameters and magnitudes, become meaningless, while optical redshift measurements become extremely difficult. Yet, several cosmologically relevant observations highlight the need to find more galaxies behind the Milky Way. For example, the Local Group velocity vector determined from the cosmic microwave-background (CMB) anisotropy points close to the southern Galactic plane. Modelling of the currently available data on distances of external galaxies out to radial velocities of order 5000 km s^{-1} has led Lynden-Bell et al. (1988) to propose a "Great Attractor" located just 9° from the Galactic Plane. Their result is not universally accepted, but other groups (e.g. Mould et al. 1991) also find the need for a very large mass distribution in a direction not far from that of the CMB anisotropy.

Existing optical surveys in the zone of avoidance to very faint magnitude limits have revealed hints of major galaxy structures across the galactic plane. For instance, the search for galaxies in the galactic plane ($b \leq 2°$) in the northern hemisphere (Weinberger, 1980) found a relative overdensity around $l = 160°$ indicating a continuation of the Perseus-Pisces supercluster through the Milky Way which then joins the Gemini-Lynx supercluster (Focardi et al. 1984). Recent HI observations of these highly obscured galaxies (Chamaraux et al. 1990) strongly support this suspicion. Alternative approaches have been taken to search for galaxies behind the Milky Way. The IRAS point source catalogue has been searched for objects with galaxy-like spectra. However, even with a radio telescope as sensitive as the Arecibo 1000 ft the success rate for detections has been less than 25% (Haynes 1988, priv.comm.). Moreover, the most numerous class of low metallicity, and therefore infrared-quiet, HI rich dwarf irregular galaxies cannot be found in this manner.

The 21cm line of HI does not suffer from extinction by the dust or gas in our own Milky Way or the matter in our terrestrial atmosphere. Since it stems from one of the abundant constituents of the most numerous class of late-type galaxies it is the obvious choice to search for galaxies behind the zone of avoidance.

Because of the very large areas to be covered, reasonably complete HI Observations of the whole zone of avoidance are not possible. A multi-feed approach is therefore called for. Our proposed system will allow to observe nine positions in the sky simultaneously with virtually identical sensitivity, reducing the amount of time required by nearly an order of magnitude. The Parkes telescope is clearly the only choice in the southern hemisphere for the location of such a system.

By necessity, this survey will generate an HI-selected sample of galaxies. At present we do not know how such a sample will differ from our current optically selected galaxy samples. There will be relatively little that can be done to study these differences from our sample. since the optical domain will not provide sufficient information within the zone of avoidance. This leads us naturally to propose a continuation of the survey into higher-latitude areas where all modern tools of extragalactic astronomy can be employed to study selection effects. This is discussed in §5.

4.2 Peculiar Velocities in the Nearby universe out to 13000 km s^{-1}

In addition to mapping the HI distribution and the galaxy redshift distribution in the region of the microwave dipole apex, the survey will yield information on the large scale distribution of matter in this direction. Lynden-Bell et al. (1987) were the first to point out that a large volume is moving with us in this direction. Aaronson et al. (1989) confirmed that most of the clusters of galaxies with redshifts up to 4500 km s^{-1} are similarly, or in some cases, more strongly accelerated. This flow is evident both north and south of the Galactic plane (Mould et al. 1991).

To measure peculiar velocities of galaxies requires measurement of relative distances independent of galaxy redshifts. This is a difficult problem under the best conditions, and will be particularly so in the obscured regions which are the major emphasis of the proposed survey. For this purpose we plan to make use of the 21cm Tully-Fisher relation (e.g. Staveley-Smith and Davies 1989) and the infrared Tully-Fisher relation (Aaronson, Huchra, and Mould 1979). The 21cm Tully-Fisher relation is the relation between HI flux and line width, and, while it exhibits more scatter than the original optical relation, is completely unaffected by dust obscuration. We shall be able to use it to see if galaxies behind the Galactic plane are flowing towards 'the Great Attractor' (Dressler 1988) in the same way as galaxies on either side of the Galactic plane.

We also intend to pursue identification and imaging of obscured galaxies in the 1 - 2 micron spectral region in order to obtain morphological information on these galaxies. Separate application will be made to large optical telescopes (e.g. the Anglo-Australian Telescope) for this purpose and to follow up on our 21cm survey.

4.3 Ultra-deep HI Surveys in Selected High-latitude Areas

The low end of the HI mass function of galaxies is not well known at this point in time, yet is of considerable importance in theories of galaxy formation and evolution. Paradoxically, more may be known about the dwarf galaxy population at high redshifts through the damped Lyman-α lines seen against background quasars than in the local Universe. Almost all of the HI information we have right now about galaxies has been gathered at sensitivities of several times 10^{19} atom cm^{-2}. There are no existing observations which convincingly rule out the existence of a large quantity of low surface-density HI objects. In fact it is feasible, if not likely, that most of the neutral baryonic material since the epoch of galaxy formation has been locked up in low mass galaxies. Deep pencil-beam imaging surveys have turned up unexpectedly large numbers of faint blue galaxies not visible at the present time. It has been suggested (Cowie et al. 1991) that these are the progenitors of a present-day invisible population of dwarf galaxies. Some deep HI observations have been made of small selected fields by Weinberg et al. (1991) who conclude that voids do not contain a larger fraction of dwarf galaxies than superclusters. This result would be interesting if confirmed on a larger scale, since it has often been suggested that dwarf, or invisible. galaxies may fill the voids in the Universe with the visible structure just arising from the very highest density spikes ('biased' galaxy formation). It has also been suggested (Efstathiou 1992) that dwarf galaxy formation near existing galaxies by be inhibited as a result of photoionization.

Clearly there is a case for a sensitive, large area survey for a hidden dwarf galaxy population. Since ultra-deep observations of reasonably large carefully selected areas will be required, the telescope time saving of a factor of nine will be the crucial factor for such a survey. A sensitivity level not far from 10^{18} atom cm^{-2} must be reached for a meaningful result. Therefore, a significant amount of observing time is required for this particular study.

4.4 An All-sky HI selected Sample of Galaxies

Galaxy catalogues are usually limited by optical (blue or photographic) magnitude or diameter. At this point in time there is only one other remotely similar sample, namely the IRAS galaxy catalogue which has proven invaluable for many cosmological studies. An HI selected sample may be expected to be of similar importance if it is continued in the northern hemisphere with comparable sensitivity, though has the advantage that the radial velocity information is obtained during the survey and redshift-independent distance information can be extracted via the HI linewidth.

The pilot survey by Kerr and Henning (1987) detected a galaxy in a little more than 1% of all pointings in the radial velocity range from about 0 - 6500 km s^{-1} . The slightly larger beam of the Parkes telescope and the planned coverage to perhaps twice the quoted radial velocity will ensure that we'll find a galaxy in roughly every 40 beams. The 9-feed system would therefore detect a galaxy in every fifth pointing, or so. In principle, a comparison sample in the region unobscured by the Milky Way would need to be only as large as the region surveyed in the zone of avoidance. However, once that were done, half the sky would have been observed already and the benefits of creating a true all-sky sample seem obvious. At that moment we will only need additional telescope time, a commodity presumably not really requiring additional cost (except, perhaps, for operating a northern hemisphere telescope for some more time).

4.5 Giant Gas-Rich Galaxies

There is mounting evidence that significant number of objects exist which contain large amounts of neutral hydrogen but are very faint and inconspicuous in the optical (c.f. Schneider 1985, Bothun et al. 1987, Giovanelli and Haynes, 1989). The archetypal failed galaxy is Malin-1 which has an angular diameter of almost 3′ and a radial velocity of about 25,000 km s^{-1} . Within the distance limit of our proposed survey similar objects will fill the telescope beam of the Parkes radio telescope (15 arcmin). Given the large amount of neutral hydrogen present we will detect virtually all such galaxies. While it is difficult to assess their numbers with any accuracy, Briggs (1990) estimates that even as many as several thousand such objects could be closer than the prototype. The determination of their actual abundance will be of great relevance to the study of galaxy formation.

4.6. Other Projects of Astronomical Significance

Other projects of importance, some of which would require further hardware (narrow-band filters for Galactic and Magellanic work) but that nevertheless demonstrate the broad range of scientific usefulness of the 9-beam receiver, are listed:

Fully sampled HI survey of the Magellanic System

In addition to the search for external galaxies, the proposed multi-beam system will be an excellent tool to extend our knowledge of the neutral hydrogen gas associated with the Magellanic System.

The Magellanic Clouds are the closest external galaxies, and are visible only from the Southern Hemisphere. From the first detection of the 21cm HI line in the Clouds (Kerr, Hindman and Robinson 1954), the size of the 'System' has progressively increased. The original observations showed that the two gaseous objects were larger than the well-known stellar bodies. Soon afterwards, a bridge of gas was detected, joining the Large and Small Clouds. Each new survey gave more detail and a somewhat greater size for the whole object.

The biggest expansion occurred with the discovery of the 'Magellanic Stream' (Mathewson, Cleary and Murray 1974), which had the appearance of a long streamer of gas which may have been pulled out by an interaction between the Clouds and our Galaxy. Continuing studies have revealed larger and larger areas of sky containing Magellanic System gas. The density is always low, but the large extent of the gas results in the mass of hydrogen in the Stream being about equal to the hydrogen mass in either of the Clouds.

The greater sensitivity of the new receiving equipment would presumably lead to a further substantial increase in the known extent of the Magellanic System. To achieve this, the whole-sky survey, already carried out at higher velocities, would need to be repeated in a lower velocity range, say -500 to +500 km s^{-1} . This survey would have another dividend, because it would be the first complete coverage of the sky for high-velocity clouds, which are HI clouds at unknown distances, found in many parts of the sky. One population of the high-velocity clouds may be identical with entities in the Magellanic System, but there are probably other populations as well. These objects should all be found in the intended velocity range of -500 to +500 km s^{-1} .

A high resolution, fully-sampled HI survey of the southern Galactic Plane

The most effective way of determining the structure of our own Galaxy is by surveying the HI in the Galactic disk. The 21-cm emission from HI is not hindered by the dust and high star density in the disk, allowing study of regions that cannot be probed optically. By measuring the intensity and shape of the 21-cm line along lines of sight in the Galaxy and making assumptions about the large-scale velocity field, the Galaxy's structure can be studied. These observations are particularly crucial in the portion of the disk outside of the Sun's orbit, the outer Galaxy, where HI is the only abundant tracer of Galactic structure. Investigation of HI in the outer Galaxy is vital for understanding the effects of the 'dark matter', whose gravitational potential dominates the motion of the gas. Early work concentrated on the large-scale morphology and kinematics of the Galaxy, and recently, effort has been aimed at studying the details of the gas distribution. Furthermore, the Galactic Bar will leave detectable imprints on the velocities toward the inner galaxy. Since the bar is not axi-symmetric both northern and southern studies are needed. Also, because some of the motions of the HI close to the bar will be highly turbulent on small scales (10 - 100 pc) we will need both a high-resolution fully sampled survey and high velocity resolution. For such studies the most damaging limitation has been poor angular resolution.

Previous surveys of Galactic HI have been conducted at coarse resolutions, typically a half-degree, or worse. The southern Milky Way has been fully surveyed, but only at a resolution of 48 arcminutes (Kerr et al. 1986). Very small northern portions of the Milky Way have been mapped at higher resolutions (a few arcminutes), and this work has revealed greater and greater complexity as resolution improves. Work at high latitudes indicates that the HI is not distributed smoothly, but is made up of filaments, loops, and shells (e.g. Heiles 1979). This is thought to be true of HI at low latitudes as well, but the poor angular resolution of present work which causes blending of structures sampled by the same telescope beam, has left this question open. A survey with the 15 arcminute resolution of the Parkes 64-m telescope would help immensely. It would provide information at scale lengths of 50 pc at distances of 10 kpc, a considerable improvement over past work.

Conducting a high resolution Galactic HI survey would also allow better comparison of the atomic with molecular and infrared components of the interstellar medium. The relationship between these components is difficult to determine, because their structures have been sampled on different scales. A Parkes HI survey would be more directly comparable to surveys of molecular gas, such as the Galactic CO survey of Dame et al. (1987) and would be much better suited for comparison with the IRAS data than the existing low resolution studies.

In order to attain all the information possible about the structure of Galactic HI, the survey must be fully sampled. This means that the observations have to be closely spaced on the sky. As with the work in the zone of avoidance, observing Galactic HI one 15 arcminute beam at a time would take too long to be practical. A fully sampled survey done with the proposed multi-beam system and sensitive receivers would still be a large job, but would provide for a major advance in the study of Galactic structure and the interstellar medium. Without such a system, significant progress will require a daunting investment of telescope time. The observations for this project will be possible concurrently with the Magellanic System survey, since the velocity coverage will encompass both entities.

Search for extremely faint dwarf galaxies in nearby galaxy groups

The faintest HI containing galaxy in our Local Group of Galaxies is the Pisces irregular galaxy (A0101+21). The HI mass is just 2×10^5 $M_\odot$ and the absolute blue magnitude is only about -9 mag. Such an object would be hard to recognize optically even in groups as nearby as the M81 Group or the Centaurus group. Yet, their HI flux would be just above the detection limit of the all-sky survey. Dynamical studies of groups are usually hampered by the fact that so few galaxies have measured redshifts which confirm them as members. The very faintest galaxies form ideal test particles to probe to gravitational potential and mass distribution in groups. The more can be identified, the better the results will be. Pilot surveys in the Centaurus group by Freeman and co-workers have shown that quite a few objects can be detected (priv.comm.) Use of a single-beam detection system requires a large amount of telescope time. Therefore, such surveys might be limited to just a handful of the closest groups. The multi-feed system cuts the time so dramatically that we will be able to survey many groups out to distances about half that of the Virgo cluster.

References

Aaronson. M., Bothun, G., Cornell, M.. Dawe, J., Dickens, R., Hall. P., Han. M., Huchra,

J., Lucey, J., Mould, J., Murray, J., Schommer, R. and Wright. A. 1989, Ap.J. 338, 654.
Aaronson, M., Huchra, J., and Mould, J. 1979, Ap.J. 229, 1.
Bothun, G.D., Impey, C.D., Malin, D.F., and Mould, J.R. 1987, A.J. 94, 23.
Briggs, F.H., 1990, A.J. 100, 999.
Chamaraux, P., Cayatte, V., Balkowski, C., and Fontanelli, P. 1990, A.&A. 229, 340.
Cowie, L.L., Songalia, A., and Hu, E.M., 1991, Nature, 354, 460.
Focardi, P., Marano, B., and Vettolani, G. 1984, A.&A. 136, 178.
Dame, T.M., Ungerechts, H., Cohen, R.S., de Geus, E.J., Grenier, I.A., May, J., Murphy, D.C., Nyman, L.-A., and Thaddeus, P. 1987, Ap.J. 322, 706.
Dressler, A. 1988, Scientific American 257, 46.
Efstathiou, G., 1992, MNRAS, 256, 43P.
Heiles, C. 1979, Ap.J. 229, 533.
Henning, P.A. 1990, Ph.D. thesis, Univ. of Maryland.
Henning, P.A. and Kerr, F.J. 1989, Ap.J. 347, L1.
Impey, C. and Bothun, G. 1989, Ap.J. 341, 89.
Kerr, F.J., Bowers, P.F., Jackson, P.D., and Kerr, M. 1986, A.&A.Suppl. 66, 373.
Kerr, F.J. and Henning, P.A. 1987, Ap.J. 320, L99.
Kerr, F.J., Hindman, J.V. and Robinson, B.J. 1954, Austr.Journ.Phys. 7, 297.
Kraan-Korteweg, R.C., 1988, in 'Large Scale Structure: Observations and Instrumentation', eds. C. Balkowski and S. Gordon (Meudon, Observatoire de Paris press, p. 155.
Kraan-Korteweg, R.C., 1989, in "Large Scale Structures and Peculiar Motions in the Universe", eds. D.W. Latham and L.N. da Costa (ASP Conference Ser.), p.
Lauberts, A., 1982, "The ESO/Uppsala Survey of the ESO (B) Atlas", ESO, Garching.
Lynden-Bell, D., 1989, in "Large Scale Structures and Peculiar Motions in the Universe, eds. D.W. Latham and L.M. da Costa (ASP Conference Ser., p.
Lynden-Bell, D., Faber, S., Burstein, D., Davies, R., Dressler, A., Terlevich, R. and Wegner, G. 1988, Ap.J. 326, 19.
Mathewson, D.S., Cleary, M.N. and Murray, J.D. 1974, Ap.J. 190, 291.
Mould, J., Staveley-Smith, L., Schommer, R., Bothun, G., Hall, P., Han, M., Huchra, J., Roth, J., Walsh, W., and Wright, A. 1991, Ap.J. 383, 467.
Staveley-Smith, L. and Davies, R.D. 1989, MNRAS, 241, 787.
Weinberg, D.H., Szomoru, A., Guhathakurta, P., van Gorkom, J.H. 1991, Ap.J. 372, L13.
Weinberger, R., 1980, A.&A.Suppl. 40, 123.