**TITLE**
ASP Conference Series, Vol. **VOLUME***, **YEAR OF PUBLICATION**
**NAMES OF EDITORS**

# The Universe behind the Southern Milky Way

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**Abstract.** A first analysis of a deep blind HI survey covering the southern Zone of Avoidance plus an extension towards the north ($196° \leq \ell \leq 52°$) obtained with the Multibeam receiver at the 64 m Parkes telescope reveals slightly over a thousand galaxies within the latitude completeness limit of $|b| \leq 5°$. The characteristics and the uncovered large-scale structures of this survey are described, in particular the prominence of the Norma Supercluster, the possible cluster around PKS 1343−601 (both in the Great Attractor region), as well as the Local Void and the clustering in the Puppis region.

In this blind HI survey, HIZOA J0836−43, one of the most massive spiral galaxies known to date was discovered ($M_{\rm HI} = 7.3 \cdot 10^{10}{\rm M}_\odot$, $M_{\rm T} = 1.1 \cdot 10^{12}{\rm M}_\odot$; ${\rm H}_0 = 75\,{\rm km/s/Mpc}$). Although of similar mass as Malin 1-like objects, this galaxy does not share their typical low-surface brightness properties but seems an exceptionally massive but normal, high-surface brightness, star-forming galaxy.

## 1. Introduction

Based on the intensive multi-wavelength surveys of the Zone of Avoidance (ZOA) in the last decade – aimed at addressing cosmological questions about the dynamics of the Local Group, respectively the possible existence of nearby hidden massive galaxies, dipole determinations based on luminous galaxies, the continuity and size of nearby superclusters, the mapping of cosmic flow fields – enormous progress has been achieved in uncovering the galaxy distribution in this obscured region of the sky (see Kraan-Korteweg & Lahav 2000 for a review).

In particular, the near infrared, whole-sky homogeneous surveys such as 2MASS (see Huchra et al., these proceedings) have resulted in a magnificent reduction of the ZOA. However, even this survey does become increasingly incomplete at low Galactic latitudes in the larger Galactic Bulge (GB) area ($\ell \approx 0° \pm 90°$), including the Great Attractor (GA) region. Even if obscured galaxies can be identified, redshifts are difficult if not impossible to obtain at the higher extinction levels.

Because of the transparency of the Galaxy to the 21 cm radiation of neutral hydrogen, systematic HI-surveys are particularly powerful in mapping large-scale structure (LSS) in this part of the sky. The redshifted 21 cm emission of HI-rich galaxies are readily detectable at lowest latitudes and highest extinction levels and the signal will furthermore provide immediate redshift and rotational velocity information.

## 2. The Parkes Multibeam HI ZOA Survey

For these reasons, a systematic deep blind HI survey of the southern Milky Way was begun in 1997 with the Multibeam receiver at the 64 m Parkes telescope. The data presented here consist of the preliminary analysis of 27 consecutive slightly overlapping data cubes, offset by $\Delta\ell = 8°$, centered on the southern Galactic Plane (GP): $196° \le \ell \le 52°$, $|b| \le 5°$. The 23 central cubes cover the *southern* Milky Way (Henning et al., in prep.), while the other four are extensions to the north (Donley et al., in prep.). The coverage in redshift space is $-1200 \lesssim v_{\rm hel} \lesssim 12700$ km/s. With an integration time of 25 min/beam – respectively 25 scans – an rms = 6mJy is achieved, making this survey sensitive to the lowest mass dwarf galaxies in the local neighborhood and to normal spirals well beyond the GA region.

Results based on a shallow subsample of this survey (2 out of 25 scans) were presented in Henning et al. 2000 (henceforth HIZSS) and resulted in the detection of 110 mainly nearby galaxies, 67 of which were previously unknown.

## 3. The Detected Galaxies

A careful analysis of the 27 data cubes by at least two, sometimes three, individual researchers with the subsequent neutral evaluation of inconsistent cases in the detection lists by a third party yields 1075 galaxies. The final list may vary slightly. Thirty-nine of these galaxies have latitudes above $|b| = 5°$. As the sensitivity decreases for $|b| > 5°$, and therewith the completeness, these 39 galaxies are not included in the presented graphs and discussions.

Figure 1 displays the distribution along the Milky Way of the in HI detected galaxies. An inspection of this distribution shows that the HI survey nearly fully penetrates the ZOA with hardly any dependence on Galactic latitude. This is confirmed by the left panel in Fig. 2, which shows the detection rate as a function of Galactic latitude. The small dip in the detection rate between $-2° \lesssim b \lesssim +1°$ stems mainly from the GB regions and to a lesser extent from the GA region ($\ell \approx 300° - 340°$). The former is due to the high number of continuum sources at low latitudes in the GB region, while the latter probably is due to the high galaxian density where a moderate number of continuum sources may already result in a detection-loss for the on average higher velocity, hence fainter, GA galaxies. This explanation is supported by the fact that this dip is not noticeable in the shallower HIZSS data (lower histogram).

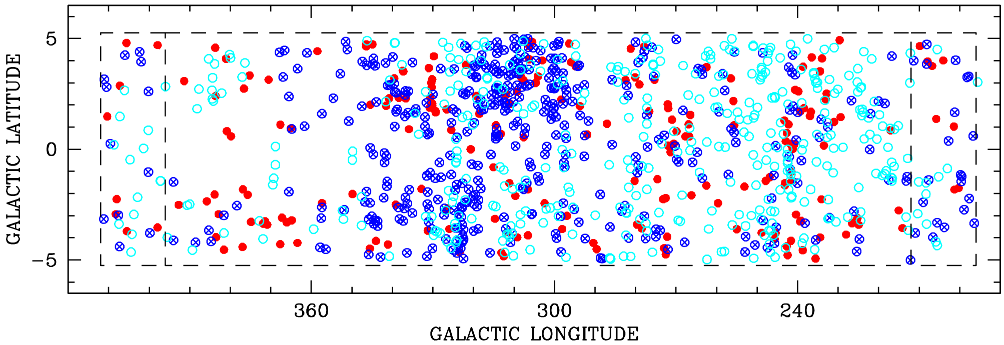


Figure 1. Distribution in Galactic coordinates of the 1036 galaxies detected in the deep HI ZOA survey. Open circles: $v_{\rm hel} < 3500$; circled crosses: $3500 < v_{\rm hel} < 6500$; filled circles: $v_{\rm hel} > 9500\,$km/s.

A much stronger variation is apparent in the number density as a function of Galactic longitude (see also middle panel of Fig. 2). This can be explained entirely with large-scale structure (see also next section) such as the nearby – and therefore in HIZSS prominent – Puppis filament ($\ell \approx 240°$), the Hydra-Antlia filament ($\ell \approx 280°$), the very dense GA region ($\ell \approx 300-340°$), followed by an underdense region ($52° \gtrsim \ell \gtrsim 350°$) which is strongly influenced by the Local and Sagittarius Void (see also HIZSS histogram).

These LSS have left their imprint also on the velocity diagram (right panel of Fig. 2), which shows two conspicuous broad peaks. The low-velocity one is due to a blend of various structures in the GP or crossing the GP (see next section) while the second around 5000 km/s clearly is due to the GA overdensity, respectively the Norma Supercluster (see also Fig. 3). The velocity histogram moreover shows that galaxies are found all the way out to the velocity limit of the survey of $\sim 12000\,$km/s, hence probe the galaxy distribution considerably deeper than HIZSS, the HI Bright Galaxy Catalog BGC (Koribalski et al. 2003) or the HI Parkes All Sky Survey HIPASS (see Zwaan et al., these proceedings).

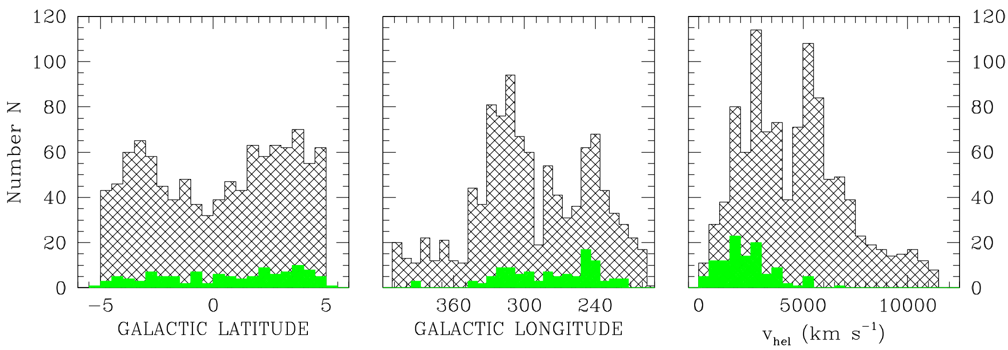


Figure 2. Distributions as a function of the Galactic latitude, longitude and the heliocentric velocity of the 1036 in HI detected galaxies. The lower histograms represent the results from the HIZSS.

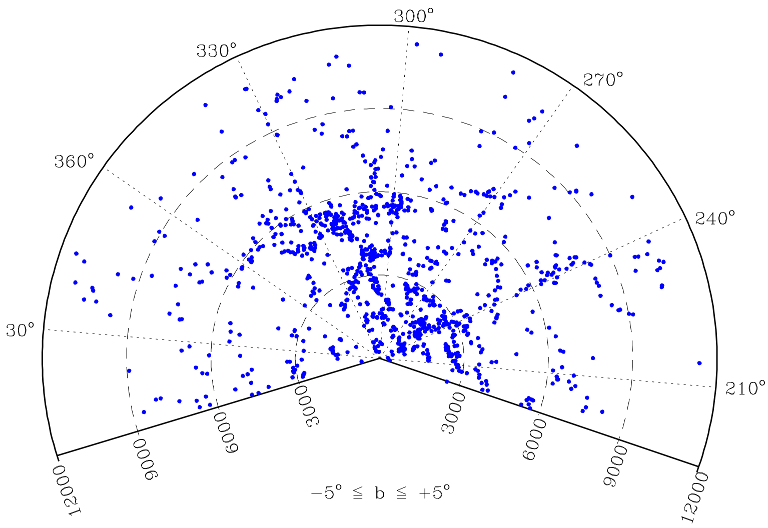


Figure 3. Galactic latitude slice with $|b| \leq 5°$ out to 12000 km/s of the 1035 in HI detected galaxies. Circles mark intervals of 3000 km/s.

## 4. Uncovered Large-Scale Structures

Figure 3 shows a Galactic latitude slice with $|b| \leq 5°$ out to 12000 km/s of the 1035 galaxies detected in the deep Parkes HIZOA survey within $196° \leq \ell \leq 52°$. The first very obvious conclusion when inspecting this figure is that, yes, the HI survey really permits to trace LSS in the most opaque part of the ZOA in a homogenous way, unbiased by the clumpiness of the foreground dust contamination and shows good coverage out to about 7000 km/s.

While discussing some of the most interesting features revealed with Fig. 3, it is suggested to simultaneously consult Fig. 4, which shows the HIZOA data with data extracted from LEDA surrounding the ZOA in sky projections for three velocity shells of thickness 3000 km/s to show the newly discovered features in context to known structures.

The most prominent LSS in Fig. 3 certainly is the *Norma Supercluster* which seems in this plot to stretch from 360° to 290°, lying always just below the 6000 km/s circle, with a weakly visible extension towards Vela ($\sim 270°$) at 6-7000 km/s. The latter is stronger at latitudes above the HIZOA (see panel 2 and 3 in Fig. 4). This wall-like feature seems to consist of various concentrations, where the one around 340° is seen for the first time in the HIZOA. Because of the high extinction there, it cannot be assessed whether this overdensity extends further than $|b| = 5°$. The clump at 325° is due to the low-latitude side of the Norma cluster A3627 at ($\ell, b, v = 325°, -7°, 4880$ km/s; Kraan-Korteweg et al. 1996). The next two due to groups/clusters at 310° and 300° respectively, both at $|b| \sim 4°$, are very distinct in the middle panel of Fig. 4. Between these two clusters at slightly higher latitude we see a small finger of God, which belongs to the by Woudt (1998) identified Centaurus-Crux cluster.

This is not the only overdensity in the GA region. A significant agglomeration of galaxies is evident closer by at $(\ell, v) = (311°, 3900$ km/s) with two fila-

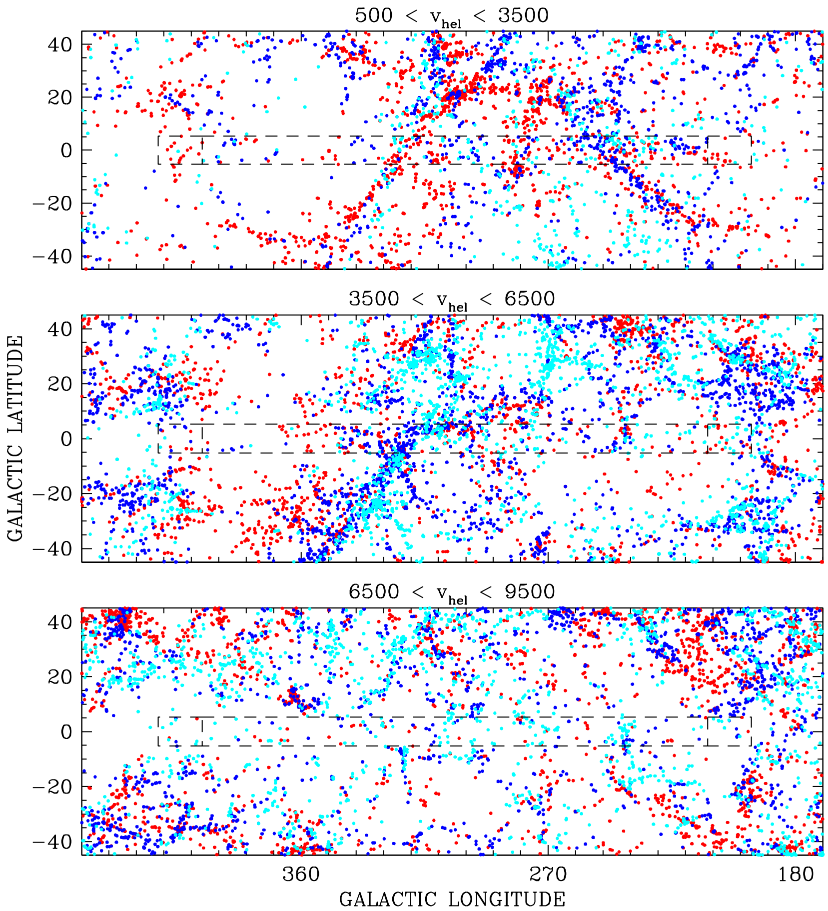


Figure 4. Sky projections of three redshift slices of depth $\Delta v$ = 3000 km/s showing the HIZOA data in combination with data from LEDA. The HIZOA survey area is outlined.

ments merging into it. Although no finger of God is visible (never very noteable in HI redshift slices), this concentration forms part of the by Kraan-Korteweg & Woudt (1999) suspected heavily obscured cluster ($b = 2^\circ, A_\mathrm{B} = 12^\mathrm{m}$) around the strong radio source PKS 1343−601. A deep $I$-band survey (Kraan-Korteweg et al., in prep.) as well $J, H, K$ imaging of its core (Nagayama et al., in prep.) are consistent with this being an intermediate size cluster similar to Hydra.

Although the overdensity in the GA region looks remarkable here, a preliminary analysis of the 4 cubes covering $300^\circ \leq \ell \leq 332^\circ$ by Staveley-Smith et al. 2000 shows an excess mass above the background of 'only' $\sim 2 \cdot 10^{15} \Omega_0 \mathrm{M}_\odot$.

To the left of the GA overdensity we find an underdense region conformed of the *Local Void* and the *Sagittarius Void* at about $\ell = 360^\circ$ and central velocities of $\sim$ 1500 and 4500 km/s (quite conspicous also in the first two panels of Fig. 4). Except for the tiny group of galaxies at about (350°, 3000 km/s), the distribution here and in Fig. 4 rather suggest one big void than two seperate ones.

The righthand side of Fig. 4 is quite crowded, in particular the Puppis region ($\ell \sim 240°$) with its two nearby groups (800 and 1500 km/s) followed by the Hydra Wall at about 3000 km/s that extends from the Monocerus group (210°) to the concentration at 280°. The latter is not the signature of a group but due to a filament emerging out of the Antlia cluster (273°, 19°; see Fig. 4). Regarding the here recognized possible filamentary connection between the Monocerus group and Antlia (top panel Fig. 4), the dinosaur that left its footprint on our Universe must actually have been four-toed and not three-toed as envisioned by Lynden-Bell.

## 5. A Supermassive Spiral Galaxy

While searching the data cube Z264, centered on $\ell = 264°$, an exceptionally strong signal ($S_{\rm peak} = 47\,$mJy) for its very high velocity ($v_{\rm hel} = 10700\,$km/s) was identified. With the very broad width of the signal ($\Delta v \approx 600\,$km/s), the data was indicative of a galaxy of HI mass $M_{\rm HI} = 6{\cdot}10^{10}{\rm M}_\odot$ (assuming $D = v_{\rm CMB}/{\rm H}_0$; ${\rm H}_0 = 75\,$km/s/Mpc). This would place it amongst the most massive spiral galaxies known to date, in the range of, e.g., Malin 1 ($5 - 10 \cdot 10^{10}{\rm M}_\odot$; Bothun et al. 1987; Pickering & Impey 1997). Surprising, considering the fact that no equivalently massive galaxy was uncovered in the recent systematic HI sky-survey BGC (N = 1000 galaxies) and only one with $M_{\rm HI} > 5{\cdot}10^{10}{\rm M}_\odot$ in HIPASS (N = 4300, Kilborn, priv. comm.), even though the probability of detecting galaxies in this mass range is smaller for the ZOA survey compared to both the BGC and HIPASS. Indeed the steep exponential fall-off at the high mass end of the HI mass function (HIMF) below $M_*$ (Zwaan et al. 2003, based on BGC; $M_* = 6 \cdot 10^{10}{\rm M}_\odot$, $\alpha = -1.30$, $\theta_* = 0.0086$, see his Fig. 4) is so strong, that the above galaxy candidate would lie well beyond the by them obtained HIMF – though it must be maintained that the volume densities of such high mass galaxies still remain ill-constrained.

An optical counterpart could not be identified which actually was hardly likely with a foreground extinction of $A_{\rm B} = 9\overset{\rm m}{.}8$ (Schlegel et al. 1998) at the position in the sky of $(\ell, b) = (262\overset{\circ}{.}45, -1\overset{\circ}{.}62)$. Both the DENIS and 2MASS infrared surveys reveal, however, two possible weak counterparts.

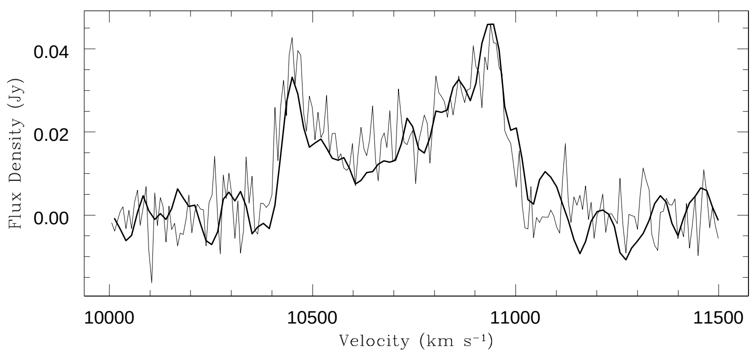


Figure 5. HI profile of HIZOA J0836−43. Thick contour from Parkes HI ZOA survey; thin contour from ATCA follow-up observations.

The confirmation of this galaxy as an individual galaxy and therewith its mass will help narrow down the number density of these rare objects, an important value for galaxy formation and evolution models.

The galaxy candidate was then observed in February 2003 with the Australia Telescope Compact Array ATCA (12 hrs in 750D configuration; 6.6 km/s velocity resolution after Hanning smoothing; Donley et al., in prep.). As can be verified from Fig. 5, which shows the profiles from both observations, the ATCA spectral line profile is entirely consistent with the Parkes MB detection. The galaxy HIZOA J0836−43 is in fact a single system (see Fig. 6) at a velocity of $v_{\rm hel} = 10689$ km/s. With a linewidth of $\Delta v_{20} = 610$ km/s and a flux of $I = 14.5$ Jy km/s, the ATCA observations do confirm the high mass of this object, providing a final value of $7.3 \cdot 10^{10} \mathrm{M}_\odot$.

In April 2003, the Anglo Australian Telescope (AAT) was used to obtain $K_s$- and $H$-band images. Figure 6 shows the 6 x 6 arcmin $K_s$-band image with the velocity integrated HI-emission overlaid. There are two galaxies in the field of view, both of which have counterparts in the 2MASS Extended Source Catalog. The galaxy 2MASX J08365157−4337407, at an offset of only 9″ and a similar inclination angle as the HI gas, clearly is the optical counterpart. The second visible galaxy seems at similar distance but was not detected. This is not really surprising as this galaxy, to have been detected with our ATCA observation, should have an HI-mass of over $M_{\rm HI} > 5 \cdot 10^9 \mathrm{M}_\odot$ which is high for a normal fairly face-on galaxy. The HI and $K_s$-band morphology do not show any obvious sign of interaction between the galaxies.

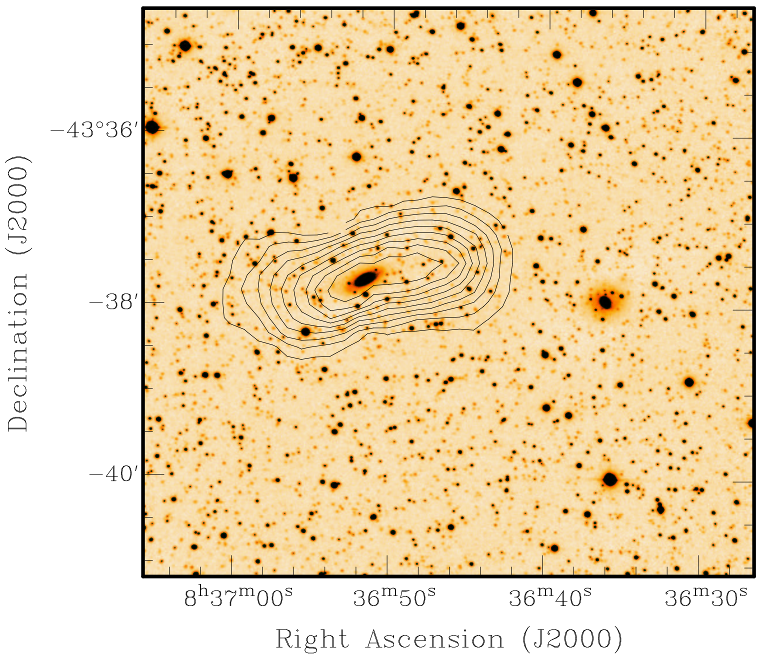


Figure 6. $K_s$-band image of HIZOA 0836−43 from the AAT with the HI contours obtained with ATCA superimposed. The HI contour level range from 10% to 90% of the peak value. Synthesized beam: 58″×41″.

With an inclination of $i = 66°$ (from $K_s$-band photometry) and a linear radius of 50 kpc, the dynamical mass turns out to be $M_{\rm T} = 1.1 \cdot 10^{12} {\rm M}_{\odot}$, also amongst the highest ever measured for spiral galaxies.

*Discussion:* Is this galaxy a new example of the giant LSB class galaxies like Malin 1? The observations clearly do not support this. The rotation curve is steep in the center, remaining constant at large radii, consistent with normal spiral galaxies having a dark matter halo that extends well beyond the optical disk. The galaxy has a HSB bulge of about 4 kpc – and a disk that can be traced out to 20 kpc, even with the extinction in $K_s$ of $A_{\rm K} = 0\overset{\rm m}{.}83$. Moreover, the HI density peak is a factor of $2-3$ higher compared to values measured for LSB giant spiral galaxies by Pickering et al. (1997) and the star formation rates determined from our radio continuum data, as well as from IRAS far infrared fluxes (Cao et al. 2003) indicate a healthy star formation rate of about $20 - 30 {\rm M}_{\odot}/{\rm yr}$.

HIZOA J0836−43 therewith has the properites of a normal HSB spiral galaxy albeit of extreme mass. This is confirmed by the fact that it fits perfectly on the $K$-band Tully–Fisher relation as determined by Macri et al. (2003). As such, this galaxy is an interesting object to study in further detail – its intrinsic properties as well as its environment – in order to better understand how such a supermassive galaxy could have formed by today within the current hierarchical galaxy formation models.

**Acknowledgments.** The contributions of the ZOA team (A.J. Green, R.D. Ekers, R.F. Haynes, R.M. Price, E.M. Sadler, I. Stewart and A. Schröder) and other participants in this survey are gratefully acknowledged. This research used the Lyon-Meudon Extragalactic Database (LEDA), supplied by the LEDA team at the Centre de Recherche Astronomique de Lyon, Obs. de Lyon. RCKK thanks CONACyT for their support (research grants 27602E and 40094F).

## References

Bothun, G.D., Impey, C.D., Malin, D.F., & Mould, J.R. 1987, AJ, 94 23

Cao, Y., Tereby, S., Prince, T.A., & Beichman, C.A. 2003, ApJ, submitted

Henning, P.A., Staveley-Smith, L., Ekers, R.D. et al. 2000 AJ, 119, 2686

Koribalski, B.S., Staveley-Smith, L., Kilborn, V.A., et al., AJ, submitted

Kraan-Korteweg, R.C., & Lahav, O. 2000, A&ARv, 10, 211

Kraan-Korteweg, R.C., & Woudt, P.A. 1999, PASA, 16, 53

Kraan-Korteweg, R.C., Woudt, P.A., Cayatte, V., et al. 1996, Nature, 379, 519

Macri, L., Mould, J., Huchra, J., et al. 2003 in IAU Symp. 216, Maps of the Cosomos, IAU GA Abstract Book, p. 16

Pickering, T.E., Impey, C.D., van Gorkom, J.H., & Bothun, G.D. 1997, AJ, 114, 1858

Schlegel, D.J., Finkbeiner, D.P., & Davis, M. 1998, ApJ, 500, 525

Staveley-Smith, L., Juraszek, S., Henning, P.A., Koribalski, B.S, & Kraan-Korteweg, R.C. 2000, ASP Conf. Ser. 218, 207

Woudt, P.A., 1998, PhD thesis, Univ. of Cape Town

Zwaan, M.A., Staveley-Smith, L., Koribalski, B.S., et al. 2003, AJ, 125, 2842