DENIS Observations of Multibeam Galaxies in the Zone of Avoidance

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Abstract

Roughly 25% of the optical extragalactic sky is obscured by the dust and stars of our Milky Way. Dynamically important structures might still lie hidden in this zone. Various surveys are presently being employed to uncover the galaxy distribution in the Zone of Avoidance (ZOA) but all suffer from (different) limitations and selection effects.

We illustrate the promise of using a multi-wavelength approach for extragalactic large-scale studies behind the ZOA, *i.e.*, a combination of three surveys – optical, systematic blind H I and near-infrared (NIR), which will allow the mapping of the peculiar velocity field in the ZOA through the NIR Tully – Fisher relation. In particular, we present here the results of cross-identifying H I-detected galaxies with the DENIS NIR survey, and the use of NIR colours to determine foreground extinctions.

Keywords: galaxies: distances – galaxies: photometry – large scale structure of the universe

1 Introduction

Understanding the origin of the peculiar velocity of the Local Group and the dipole in the Cosmic Microwave Background is one of the major goals of the study of large-scale structures. Theoretical reconstruction methods, however, still suffer from large interpolation uncertainties across the Zone of Avoidance (ZOA), which extends over about 25% of the optically visible extragalactic sky. Dynamically important structures might still lie hidden in this zone, such as the recently discovered nearby Dwingeloo galaxy (Kraan-Korteweg *et al.* 1994) and the rich massive cluster Abell 3627 (Kraan-Korteweg *et al.* 1996). Important large-scale structures, *e.g.*, the Supergalactic Plane and other filaments and wall-like structures, seem to continue across this zone. Results from various theoretical approaches still vary strongly, however, in predicting clusters and voids even in the nearby universe (Sigad *et al.* 1998). This is mainly due to differences in the theoretical reconstruction methods and the adopted parameters, the different galaxy samples to which they are applied, and the selected interpolation mechanisms to bridge the scarcity of data in the ZOA. A more complete knowledge of the distribution of galaxies in redshift space as well as in distance space will improve the reconstructed galaxy density fields and reduce the diversity in the theoretical predictions.

Various approaches are presently being employed to uncover the galaxy distribution in the ZOA (*cf.* Kraan-Korteweg & Woudt, this volume): deep optical searches, NIR surveys (DENIS and 2MASS), far-infrared (FIR) surveys (*e.g.*, IRAS), and blind H I searches. All methods produce new results, but all suffer from limitations and selection effects. The combination of data from an optical galaxy search, a NIR survey and a systematic blind H I survey will allow us to examine the large-scale structures behind the southern Milky Way and the peculiar velocity field associated with them. Redshift independent distance estimates can be obtained via the NIR Tully – Fisher relation.

A deep optical survey in the southern ZOA is being conducted by one of us (Kraan-Korteweg & Woudt 1994, Kraan-Korteweg *et al.* 1995, 1996, and references therein). In this region ($265^\circ \lesssim \ell \lesssim 340^\circ$, $|b| \lesssim 10^\circ$), over 11 000 previously unknown galaxies above a diameter limit of $D = 0\farcm2$ and with $B \lesssim 19\fm0 - 19\fm5$ have been identified, next to the previously known ~ 300 Lauberts galaxies with $D = 1'$ (Lauberts 1982). Galaxies can be identified visually for $A_B \lesssim 5^{\rm m}$ (or typically down to about $|b| \simeq 5^\circ$ depending on surface brightness and Galactic longitude).

The Multibeam (MB) survey of the ZOA, a systematic blind H I survey (Staveley-Smith 1997), will penetrate even the deepest extinction layers and trace gas-rich spirals out to redshifts of 12 000 km s^{-1}. The survey is currently being conducted with the Multibeam Receiver (13 beams in the focal plane array) at the 64 m Parkes telescope and will cover the whole southern ZOA ($213^\circ \lesssim \ell \lesssim 33^\circ$; $|b| \lesssim 5^\circ$) with a 5σ detection limit of 10 mJy. Hardly any of the 1500 predicted detections are expected to have an optical counterpart, but at these latitudes many might be visible in the NIR. This new prospect becomes feasible with the currently ongoing NIR surveys such as DENIS (DEep NIR southern sky Survey; Epchtein 1997, Epchtein *et al.* 1997) and 2MASS (Skrutskie *et al.* 1997). First results from the DENIS survey, which is expected to cover the entire southern sky by the year 2001, are discussed in the following sections.

2 The DENIS survey

Observations in the NIR can provide important complementary data to other surveys. NIR surveys will

- be sensitive to early-type galaxies — tracers of massive groups and clusters — which are missed in IRAS and H I surveys,
- have less confusion with Galactic objects compared to FIR surveys,
- be less affected by absorption than optical surveys.

Furthermore, because recent star formation contributes only little to the flux at this wavelength, the NIR gives a better estimation of the stellar mass content of galaxies and is hence ideally suited for the application of the Tully – Fisher relation.

The DENIS survey has currently imaged 40% of the southern sky in the $I\,(0.8\,\mu)$, $J\,(1.25\,\mu)$ and $K_s(2.15\,\mu)$ passbands with a resolution of $1''$ in I_c and $3''$ in J and K_s. In a pilot study, we have assessed the performance of the DENIS survey at low Galactic latitudes (Schröder *et al.* 1997, hereafter Paper I, Kraan-Korteweg *et al.* 1998, hereafter Paper II). We (a) tested the po-

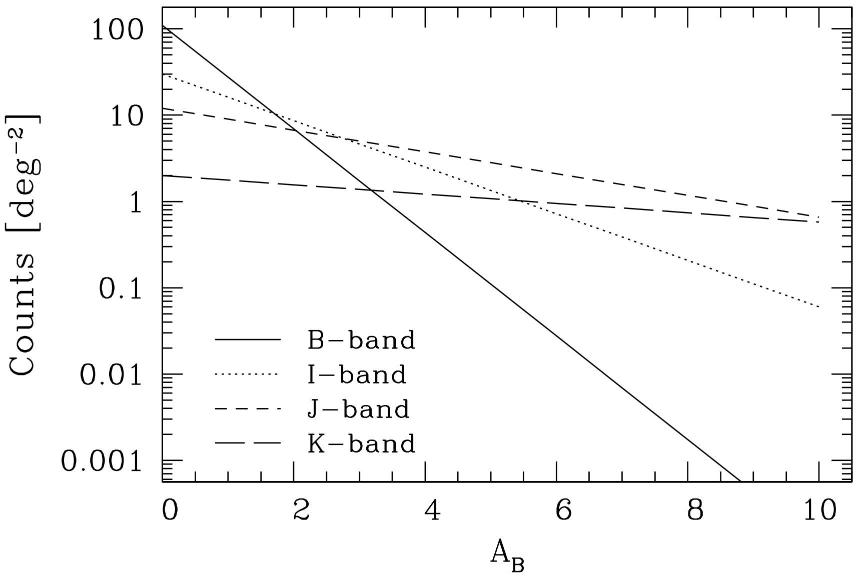

Figure 1: Predicted galaxy counts in B, I_c, J and K_s as a function of absorption in B, for highly complete and reliable DENIS galaxy samples and a $B_J \leq 19^{\rm m}$ optical sample.

tential of the DENIS survey to detect galaxies where optical and FIR surveys fail, *i.e.*, at high foreground extinctions and in crowded regions, (b) established that the NIR colours of galaxies lead to values for the foreground extinction, (c) determined preliminary I_c^o, J^o and K_s^o galaxy luminosity functions in the rich cluster A3627, and (d) cross-identified highly obscured galaxies detected in a blind H I search at $|b| < 5°$.

Number counts of galaxies are lower in the ZOA due to the high foreground extinction, but the effect depends on wavelength. Interpolating from Cardelli *et al.* (1989), the extinctions in the NIR passbands are $A_{I_c} = 0\overset{\rm m}{.}45$, $A_J = 0\overset{\rm m}{.}21$, and $A_{K_s} = 0\overset{\rm m}{.}09$ for $A_B = 1\overset{\rm m}{.}0$, hence the decrease in number counts as a function of extinction is considerably slower in the NIR than in the optical. Figure 1 shows the predicted surface number density of galaxies for DENIS (Mamon et al. 1998) and for $B < 19$, as a function of Galactic foreground extinction (*cf.* Paper II).

The NIR becomes notably more efficient at $A_B \gtrsim 2 - 3^{\rm m}$. The J-band is the most efficient passband to find galaxies at intermediate extinctions, but at $A_B \simeq 10^{\rm m}$ K_s becomes superior to J. Even at $A_B > 10^{\rm m}$ we can expect to find galaxies in J and K_s. A new air conditioning system for the K_s-band camera installed in April 1997 has decreased its instrumental background by $0\overset{\rm m}{.}7$, which makes the K_s-band now more comparable to J. These are very rough predictions and do not take into account any dependence on morphological type, surface brightness, orientation and crowding, which may lower the number of actually detectable galaxies (Mamon 1994).

3 Cross-identification of H I-detected galaxies on DENIS images

Figure 2 displays the distribution of MB galaxies in the ZOA (large circles). Dots indicate galaxies found in the optical B-band search with a diameter limit of $D = 0\overset{'}{.}2$ (Woudt *et al.* 1998). Contours

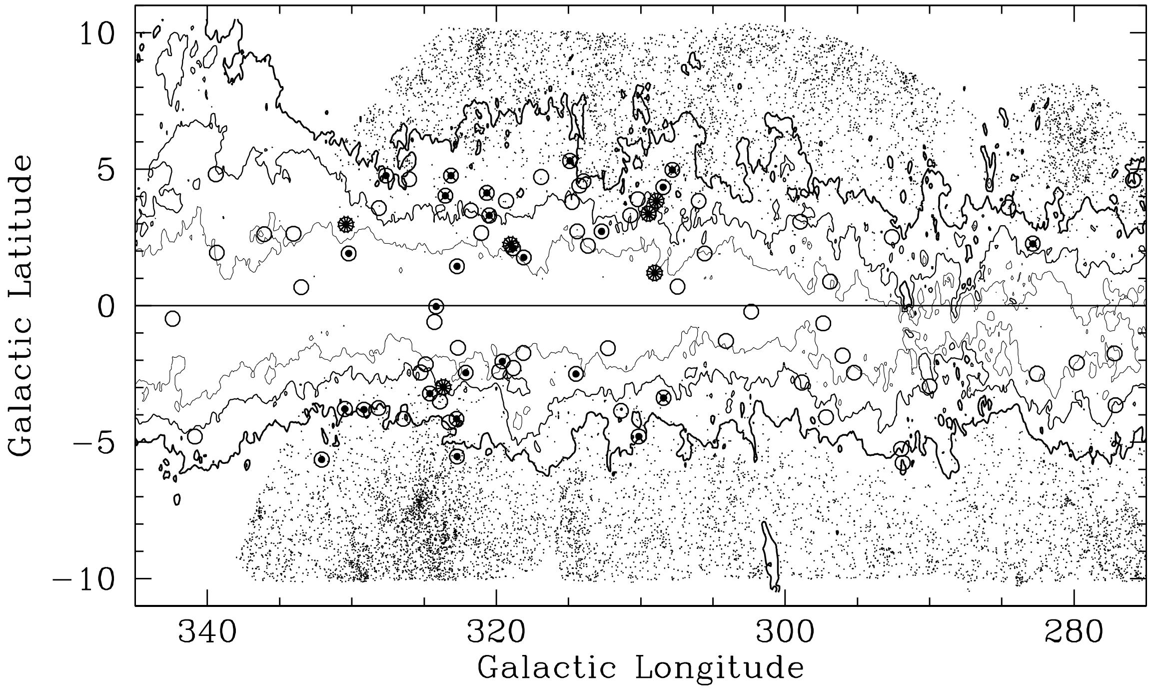

Figure 2: Galaxy distribution in part of the southern ZOA with galaxies found in an optical search (small dots) and galaxies detected with the shallow MB survey (large circles). The superimposed contours represent absorption levels of $A_B = 2\overset{\mathrm{m}}{.}75$ (*thick line*), $5\overset{\mathrm{m}}{.}0$, $10\overset{\mathrm{m}}{.}0$ (see text for details). MB galaxies for which DENIS data are available are marked with a large dot, those re-identified on DENIS images with a cross, and those without an optical counterpart with a star.

indicate extinction levels determined from the DIRBE maps (Schlegel *et al.* 1998), which are scaled to independent extinction determinations from Mg_2-indices in this region (Woudt 1998). The thick contour corresponds to $A_B = 2\overset{\mathrm{m}}{.}75$; this is the completeness limit for galaxies with an extinction-corrected diameter of $D^o = 1\overset{\prime}{.}3$ in the deep optical ZOA galaxy catalogue. The other contours indicate $A_B = 5^{\mathrm{m}}$ and 10^{m}, where the Milky Way is opaque in the optical.

For 24 of the galaxies detected in the shallow MB-ZOA survey (*cf.* Henning *et al.*, this volume), DENIS survey images ($12' \times 12'$) covering the full positional uncertainty region ($\sim 4' \times \sim 4'$) were currently available. They are displayed as large dots (including 8 detections for which only partial coverage of the H I positional uncertainty region was available on existing DENIS images). For 16 out of the 24 a clear counterpart could be identified (crosses); of these, 6 are invisible in the B-band due to large foreground extinctions (stars). For 4 out of the 24 MB-ZOA galaxies the cross-identifications are uncertain, and for the remaining 4 galaxies no counterparts could be identified. These galaxies either lie behind a very thick extinction layer (*e.g.*, one galaxy at $b \simeq 0°$ with $A_B \sim 70^{\mathrm{m}}$), or they are late-type spirals or irregular galaxies of very low surface brightness and hence below the magnitude limits of the DENIS survey. The H I survey, however, is not affected by the foreground extinction, and spiral galaxies can be found in the NIR at lower Galactic latitudes and higher foreground extinction levels than in the optical.

In Figure 3, DENIS images of five MB galaxies are presented. The I_c-band is shown in the upper panel, the J-band in the middle and the K_s-band in the bottom panel. From left to right the foreground extinction increases. The first galaxy is a nearby ($v = 1445\,\mathrm{km\ s^{-1}}$) Lauberts galaxy

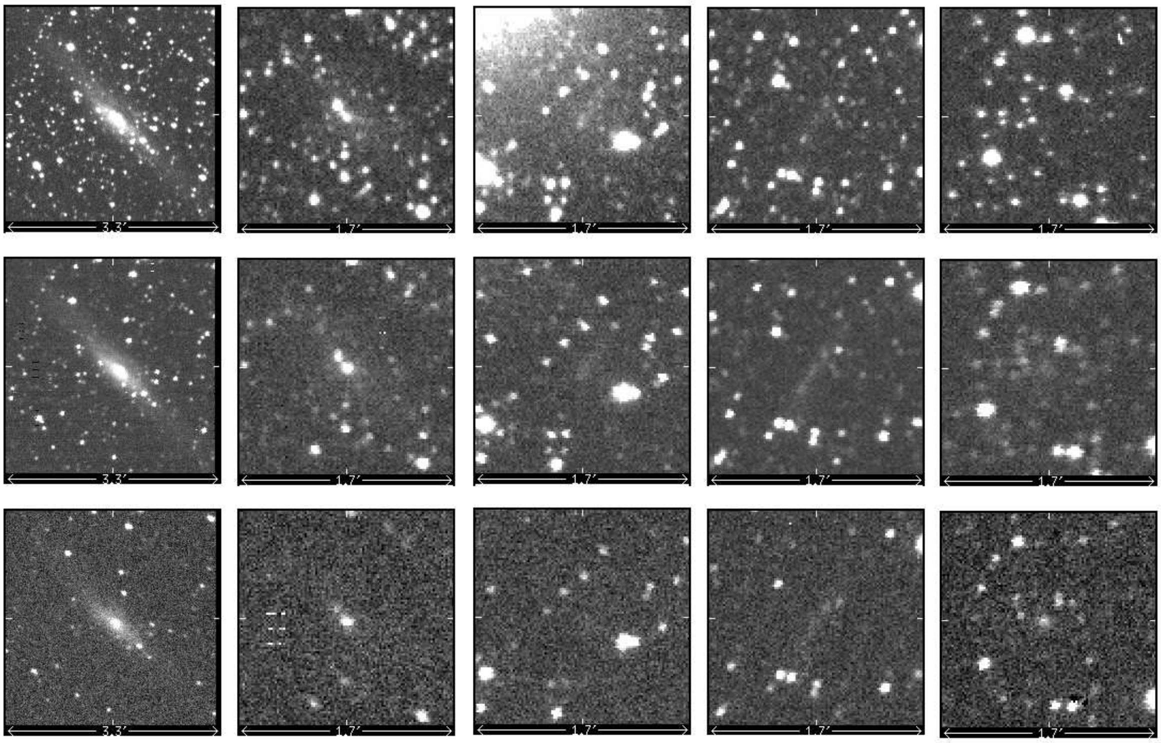

Figure 3: DENIS survey images (before bad pixel filtering) of five galaxies detected in H I with the MB survey at $|b| \leq 5°$; the I_c band image is at the top, J in the middle, and K_s at the bottom.

(ESO223-G12) at $b = +4\overset{\circ}{.}8$ and $A_B = 3\overset{\text{m}}{.}9$. It is prominent in all three NIR passbands (note the larger image scale for this galaxy, *i.e.*, $3\overset{\prime}{.}3$ instead of $1\overset{\prime}{.}7$). The second galaxy, also detected with IRAS, at $(b, A_B) = (-3\overset{\circ}{.}4, 4\overset{\text{m}}{.}4)$ is slightly more distant ($v = 2789\,\text{km s}^{-1}$). This galaxy has also been identified in B and is quite distinct in the NIR. The third and fourth galaxies at $(b, A_B) \simeq (3\overset{\circ}{.}4, 4\overset{\text{m}}{.}8)$ and $(2\overset{\circ}{.}3, 8\overset{\text{m}}{.}4)$, respectively, have no optical counterparts. Here, the extinction effects are quite obvious: while both have a similar appearance in the J-band, the third is very faint in K_s and the fourth very faint in I_c. The fifth example has been detected at the highest extinction so far: $(b, A_B, v) \simeq (+1\overset{\circ}{.}2, 11\overset{\text{m}}{.}8, 3963\,\text{km s}^{-1})$. It is fully obscured in the I_c-band and barely visible in the J-band.

Cross-identifications of galaxies detected in the MB survey are not always unambiguous. The positional accuracy for galaxies detected in the blind H I search is of the order of $\sim 4'$. Sometimes more than one possible counterpart lies within this area as illustrated in Figure 4. The position of this MB galaxy is indicated by a white rectangle on the DENIS I_c-band image; the foreground extinction is $A_B = 4.0$. Four galaxies can be seen in its vicinity: an edge-on spiral with a small companion (right and above the rectangle), an early-type spiral (left) and a late-type spiral with low surface brightness (left and above the early-type spiral). Although the last seems the most likely candidate given the H I parameters ($v = 2903\,\text{km s}^{-1}$, $w = 177\,\text{km s}^{-1}$, $I = 13.1\,\text{Jy km s}^{-1}$) and the other galaxies may be further away or have less H I mass and hence not be detectable with the shallow H I survey, the cross-identifications are not always clearcut. For such cases, follow-up observations, either with H I mapping or optical and NIR spectroscopy, are required.

Figure 4: A $12' \times 12'$ DENIS I_c-band image of an MB detection (white rectangle) and four galaxy candidates (with an uncertainty radius of $\sim 4'$) .

4 Photometry

We have used a preliminary galaxy pipeline (Mamon *et al.* 1997b, 1998), based upon the SExtractor package (Bertin & Arnouts 1996) to obtain I_c, J and K_s Kron photometry from the DENIS images at the location of MB galaxies. Although many of the galaxies have a considerable number of stars superimposed on their images, magnitudes derived from this automated algorithm agree well with independent measurements.

Figure 5 shows the dependence of the colour $J - K$ on foreground extinction A_B. Included are data from the low-latitude ($\ell = 325°$, $b = -7°$), rich cluster Abell 3627 (*cf.* Paper II), where the foreground extinction is less than 2^{m}. The group of MB galaxies with $2^{\mathrm{m}} < A_B < 5^{\mathrm{m}}$ shows a similar scatter but is offset in colour with respect to the galaxies in A3627. Also, the galaxy at $A_B = 11\overset{\mathrm{m}}{.}8$ is considerably redder than all the other galaxies.

In Paper I we discussed the NIR colour – colour diagram $I - J$ versus $J - K$ of galaxies in the A3627 cluster in detail. We found that the extinction-corrected colours of the cluster galaxies do match the colours of galaxies in unobscured high latitude regions (Mamon *et al.* 1997b, 1998), suggesting that our preliminary photometry is reasonably accurate. The shift in colour can be fully explained by the foreground extinction. Hence, the NIR colours of obscured galaxies (in particular of elliptical galaxies) provide an independent way of mapping the extinction in the ZOA (see also Mamon *et al.* 1997a) and calibrating the DIRBE maps at low Galactic latitudes (see also Mamon *et al.* 1997a).

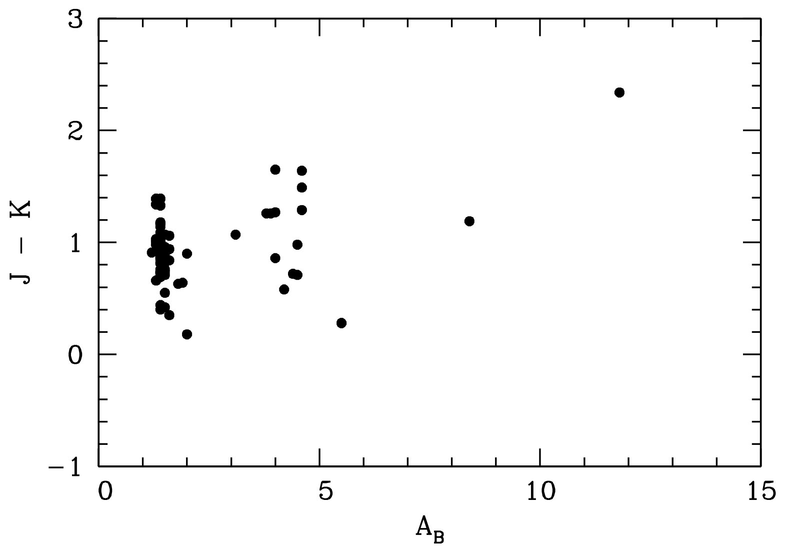

Figure 5: NIR colour as a dependence on foreground extinction.

5 Conclusions and future plans

A combination of the deep optical, systematic blind H I and NIR surveys illustrates the potential of a multi-wavelength approach for extragalactic large-scale studies behind the Milky Way. It furthermore allows the mapping of the peculiar velocity field across the ZOA through the NIR Tully – Fisher relation.

At intermediate latitudes and extinction ($5° < |b| < 10°$, $1^{\rm m} \lesssim A_B \lesssim 4 - 5^{\rm m}$), optical surveys remain superior for identifying galaxies due to their fainter magnitude limits. However, the NIR luminosities and colours will prove invaluable in analysing the optical survey data and their distribution in redshift space, and in the final merging of these data with existing sky surveys. Despite the high extinction and the star crowding at these latitudes, I_c, J and K_s photometry from the survey data can be successfully performed and lead, for instance, to preliminary I_c^o, J^o and K_s^o galaxy luminosity functions in A3627 (Paper II).

At low latitudes and high extinction ($|b| < 5°$ and $A_B \gtrsim 4 - 5^{\rm m}$), the search for 'invisible' obscured galaxies on existing DENIS images shows that NIR surveys can trace galaxies down to about $|b| \simeq 1\overset{\circ}{.}5$. The J-band was found to be optimal for identifying galaxies up to $A_B \simeq 7^{\rm m}$. NIR surveys can hence further reduce the width of the ZOA. They are furthermore the only tool that permits the mapping of early-type galaxies — tracers of density peaks — at high extinction.

The blind H I survey uncovers spiral galaxies independent of foreground extinction. For a significant fraction, a DENIS counterpart has been found. These MB-ZOA data covers the Galactic latitude range $|b| < 5°$. We will complement this area with pointed H I observations of optically identified spiral galaxies for intermediate latitudes ($5° < |b| < 10°$). About 300 spiral galaxies have already been detected (Kraan-Korteweg *et al.* 1997).

In the near future, we plan on obtaining deep K_s-band follow-up observations of the deep and complete H I-survey in the southern ZOA (*cf.* Juraszek, this volume). This will allow us (1) to study the effects of extinction on the extent and magnitudes of disks in the NIR, (2) to obtain a representative sample of galaxies across the ZOA for the application of the K_s-band Tully – Fisher relation, and (3) to study the morphology of the detected galaxies. The last will also be useful to understand the nature of the large-scale structures revealed with the blind H I survey, in particular as this galaxy sample can readily be merged with the southern sky H I survey (Kilbourne *et al.*, this volume).

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