Multi-wavelength Observations of Galaxies in the Southern Zone of Avoidance

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Abstract. We discuss the possibilities of extragalactic large-scale studies behind the Zone of Avoidance (ZOA) using complementary multi-wavelength data from optical, systematic blind H I, and near-infrared (NIR) surveys. Applying these data to the NIR Tully–Fisher relation permits the mapping of the peculiar velocity field across the ZOA. Here, we present results of a comparison of galaxies identified in the rich low-latitude cluster Abell 3627 in the B-band with NIR (DENIS) data, and cross-identifications of galaxies detected with the blind Parkes H I Multi-beam survey with NIR data – many of which are optically invisible.

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. Reconstructions of large-scale structures, for instance, 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 galaxy Dwingeloo 1 (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. 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 help to explain the origin of the peculiar velocity of the Local Group and the dipole in the Cosmic Microwave Background.

Various approaches are presently being employed to uncover the galaxy distribution in the ZOA (cf. Kraan-Korteweg & Lahav 2000): deep optical searches, NIR surveys (DENIS and 2MASS), far-infrared surveys (e.g., IRAS), and blind
H\textsc{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\textsc{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. Bouche & Schneider (these proceedings) have shown that the $K_s$-band is ideal for this approach.

Here we use (i) data from the diameter-limited, deep $B$-band galaxy survey by Kraan-Korteweg and collaborators for cross-identifications at intermediate extinctions, (ii) spiral galaxies detected with the systematic blind H\textsc{i} survey of the southern ZOA ($|b| \lesssim 5^\circ$) with the Parkes Multibeam (MB) receiver, plus pointed H\textsc{i} observations of partially obscured galaxies at intermediate latitudes $5^\circ < |b| < 10^\circ$ (Kraan-Korteweg et al. 2000), and (iii) the DENIS survey:

(i) The deep optical survey in the southern ZOA is being conducted by one of us (cf. Kraan-Korteweg & Woudt 1994, Kraan-Korteweg 2000, Woudt et al., these proceedings). 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 $D=0\farcs2$ have been identified, next to the previously known $\sim 300$ Lauberts galaxies with $D \geq 1\arcmin$ (Lauberts 1982). As shown by Kraan-Korteweg (2000), this diameter limited survey is complete to $A_B \simeq 3\,\text{mag}$, although galaxies can be identified to $A_B \sim 5\,\text{mag}$ (or $|b| \simeq 5^\circ$ on average).

(ii) The Multibeam (MB) ZOA survey is a systematic H\textsc{i} survey of the southern ZOA within $|b| \lesssim 5^\circ$ (see Henning et al., Staveley-Smith et al., these proceedings). It will trace gas-rich spirals out to redshifts of $12,000\,\text{km}\,\text{s}^{-1}$ with no hindrance from the Galactic dust. The survey is being conducted with the Multibeam receiver (13 beams) at the 64 m Parkes telescope and should detect of the order of 1500 galaxies above the $5\sigma$ detection limit of 10 mJy. Only few of these predicted galaxies will have an optical counterpart, but many might be visible in the NIR. Their identifications become feasible with the NIR surveys such as DENIS (Epchtein 1997, Epchtein et al. 1997) and 2MASS (Skrutskie et al. 1997).

(iii) The DENIS survey has currently imaged about 80\% of the southern sky in the $I$ ($0.8\,\mu\mu$), $J$ ($1.25\,\mu\mu$) and $K_s$ ($2.15\,\mu\mu$) passbands with a resolution of 1$''$ in $I$ 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; Schröder et al. 1999, hereafter Paper III). After giving some details about the DENIS survey, we present improved results on the photometry of galaxies in the cluster Abell 3627 (Sect. 3), and on cross-identifications with galaxies detected in the H\textsc{i} MB survey (Sect. 4).

2. The DENIS Survey

Observations in the NIR have several advantages over other ZOA surveys, and they provide important complementary data. Compared to the optical, the NIR is less affected by the foreground extinction (the extinction in $K_s$ is about 10\% of the extinction in $B$). The NIR is sensitive to early-type galaxies, tracers of massive groups and clusters which are neither uncovered in far infrared surveys.
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Figure 1. Predicted galaxy counts in $B$, $I$, $J$ and $K_s$ as a function of absorption in $B$, for highly complete and reliable DENIS galaxy samples and a $B_J \leq 19^m$ optical sample.

nor in the 21 cm radiation. The NIR shows little confusion with Galactic objects such as young stellar objects and cool cirrus sources. Moreover, the NIR allows a good estimation of the stellar mass content of galaxies because recent star formation contributes only little to the flux at this wavelength. It is hence ideally suited for the application of the Tully–Fisher relation.

Number counts of galaxies decrease in the ZOA due to the increasing foreground extinction. This effect depends, however, on wavelength. Interpolating from Cardelli et al. (1989), the extinctions in the NIR passbands are $A_I = 0^m45$, $A_J = 0^m21$, and $A_{K_s} = 0^m09$ for $A_B = 1^m0$. Thus 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 as a function of Galactic foreground extinction for the DENIS completeness limits of $I_{\text{lim}} = 16^m5$, $J_{\text{lim}} = 14^m8$, $K_{\text{lim}} = 12^m0$ (Mamon 1998) and for $B_{\text{lim}} = 19^m0$ (Gardner et al. 1996). The figure suggests that the NIR becomes notably more efficient at $A_B \gtrsim 2^m$, that the $J$-band is the most efficient passband to find galaxies at intermediate extinctions, and that $K_s$ becomes superior to $J$ at $A_B \simeq 12^m$. While the diameter-limited samples of the optical searches become incomplete at $A_B \simeq 3^m$, the $J$- and $K_s$-bands will easily detect galaxies up to $A_B = 10^m$, or even higher extinctions. 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).
Figure 2. The colour–colour diagram for the Norma cluster. The dashed box marks the colour range of unobscured galaxies. Observed colours are displayed in the left panel with the arrow indicating the expected mean offset due to extinction. The right panel shows extinction-corrected colours.

3. NIR Photometry in the Norma Cluster

We investigated currently available DENIS data at the core of the Great Attractor, i.e., in the low-latitude ($\ell = 325^\circ$, $b = -7^\circ$), rich cluster Abell 3627 (cf. Woudt et al., these proceedings), where the Galactic extinction is well determined (Woudt et al. 1998). Five high-quality DENIS strips cross the cluster Abell 3627. The inspected 110 images cover about one-fifth of the cluster area within its Abell-radius of $R_A = 1^\circ.75$ (each DENIS image is 12$'$x12$'$, offset by 10$'$ in declination and right ascension). The extinction over the cluster area varies as $0.6 \lesssim A_B \lesssim 2.2$.

We cross-identified the galaxies found in the optical survey with the DENIS $I$, $J$, and $K_s$ images. On the 110 images, 234 galaxies had been identified in the optical. We have recovered 198 (85%) galaxies in the $I$ band, 183 (78%) in the $J$ band, and 123 (53%) in the $K_s$ band (not including galaxies visible on more than one image). At these extinction levels, the optical survey does remain the most efficient in identifying obscured galaxies. In the NIR, the $I$- and $J$-band are equally efficient, though the severe star crowding makes identification of faint galaxies difficult in $I$.

We have obtained preliminary $I$, $J$ and $K_s$ Kron photometry using the automated galaxy extraction pipeline (Mamon et al. 1997b) on the galaxies visually identified by us. Although many of the galaxies have a considerable number of stars superimposed on their images, comparison of the magnitudes derived from this fairly automated algorithm agree well with the few known, independent measurements.

The NIR magnitudes have been used to study the colour–colour diagram $I - J$ versus $J - K$ (Fig. 2). In the left hand panel, observed colours (from a 7" aperture) are displayed; in the right hand panel the colours are corrected for foreground extinction using Mg2-indices values and interpolations according to the Galactic HI distribution. As a comparison, the range in colours of galaxies at high latitudes (Mamon et al. 1998) is indicated by the box. The displacement
Figure 3. Distribution of 100 galaxies detected with the shallow MB survey in the southern ZOA. The superimposed contours represent absorption levels of $A_B = 3^{\text{m}0}$ (outer contour) and $10^{\text{m}0}$ (see text for details). MB galaxies detected with DENIS data are marked with a cross (visible in $I$) or a triangle (not visible in $I$); those with an optical counterpart are displayed with a large circle; those not detected in either $B$ or the NIR are marked with a filled circle.

of the points agrees well with the path of extinction (arrow) based on the mean extinction in these five strips of $A_B = 1^{\text{m}3}$ (Woudt et al. 1998), suggesting that our preliminary photometry is reasonably accurate. Moreover, the shift in colour can be fully explained by the foreground extinction or, more interestingly, the NIR colours of obscured galaxies provide, in principle, an independent way of mapping the extinction in the ZOA (see also Mamon et al. 1997a).

4. Cross-identification on DENIS Images of H$\text{I}$-detected Galaxies

Figure 3 displays the distribution of galaxies detected in the shallow MB-ZOA survey (Henning et al. 2000). Contours indicate extinction levels determined from the DIRBE maps (Schlegel et al. 1998). The outer contour corresponds to $A_B = 3^{\text{m}0}$, the completeness limit for galaxies with an extinction-corrected diameter of $D^* = 1.3$ in deep optical ZOA galaxy catalogues (see Kraan-Korteweg, these proceedings). The inner contour indicates $A_B = 10^{\text{m}}$ (the Milky Way becomes opaque in the optical at $A_B \lesssim 5^{\text{m}}$).

For 100 of the 110 galaxies detected in the shallow H$\text{I}$ survey, DENIS images ($12' \times 12'$) covering the full positional uncertainty region ($\sim 4' \times 4'$) were currently available. 77 galaxies can be detected in the NIR: 69, 67 and 58 in $I$ (crosses), $J$, and $K_s$ respectively, while only 48 have been detected in the $B$-band (large circles in Fig. 3). Triangles indicate the 8 galaxies visible in $J$ and/or $K_s$ but not in the $I$-band. They are clearly at higher extinction levels than the
Figure 4. Galaxy detections as a function of foreground extinction (shaded area). The unshaded region refers to all galaxies detected in the shallow survey.

galaxies seen in \( I \) or \( B \). This is clear also in the histogram in Fig. 4 which shows the wavelength-dependence of detection rate (shaded versus unshaded regions) as a function of foreground extinction. While the detection rate in the \( B \)-band decreases rapidly with increasing extinction, the decrease in \( I \) and particularly in \( K_s \) is much slower. The \( J \)-band (together with the \( J \)-band) seems to be the best passband to find galaxies at extinction levels between 2\( m \) and \( \sim 10^m \) (cf. previous section), and the \( K_s \)-band becomes superior at \( A_B > 10^m \). Keeping in mind (a) the low number statistics, (b) the fact that MB galaxies are gas-rich spiral and irregular galaxies, and (c) that the optical searches are diameter limited rather than magnitude limited, Fig. 4 and Fig. 1 compare very well.

For 23 galaxies no counterpart could be found. These galaxies either lie behind a very thick extinction layer (e.g., one galaxy at \( b \simeq 0^\circ \) has \( A_B \sim 70^m \) according to the DIRBE maps), or they are late-type galaxies of very low surface brightness, hence below the magnitude limits of the DENIS survey. The \( \text{H I} \) survey (unshaded region in Fig. 4), is, however, not affected by the foreground extinction, therefore superior to other passbands in uncovering spiral galaxies at
Figure 5. NIR colour versus foreground extinction. Stars refer to galaxies in the Norma cluster, while open circles are galaxies found with the shallow HI survey.

low Galactic latitudes and high foreground extinction levels. The low number rate at high extinctions is partly due to confusion with Galactic continuum sources at lowest latitudes, as well as the Local Void (e.g., Henning et al., these proceedings).

Figure 5 shows the dependence of the observed $J-K$ colour of these galaxies (from a 7$''$ aperture) on foreground extinction $A_B$, including data from the low-latitude cluster Abell 3627 (stars; see previous section). The broader scatter for the shallow survey galaxies (and some of their companions) can be explained by the larger error in the photometry due to the increase in star crowding. However, the systematic offset towards the red with increasing extinction (the reddening path is indicated by the arrow) is clearly evident.

5. Conclusion

We have demonstrated the potential of a multi-wavelength approach to penetrate the extinction layers of the Milky Way for studying extragalactic large-scale structures. The detection rate of the three surveys (a deep optical, a systematic blind HI and a NIR survey) depends on galaxy type and foreground extinction. The three surveys together find galaxies at all extinction levels and Galactic latitudes. Furthermore, with the available photometry, the NIR Tully–Fisher relation can be applied to most of these galaxies. The latter allows the mapping of the peculiar velocity field across the whole ZOA.

Optical surveys are superior for identifying galaxies at intermediate latitudes and extinctions ($|b|>5^\circ$, $A_B<3^\text{m}$). The additional NIR luminosities and colours will prove invaluable in analysing the optical survey data as well as the
distribution of the galaxies in redshift space, and in the final merging of these data with existing sky surveys.

With the DENIS NIR survey we can trace galaxies down to $A_B < 15^m$, i.e. very low latitudes. Though the $I$-band is strongly affected by star crowding (which mainly depends on the limiting magnitude of the survey), it is best suited for identifying galaxies up to $A_B < 4^m$ because of the higher spatial resolution ($1''$). At higher foreground extinctions, the $J$-band and the $K_s$-band (for $A_B > 10^m$) become important. NIR surveys thus further reduce the width of the ZOA. In particular, they provide the only tool with which to identify early-type galaxies at high extinction. Despite the star crowding at these latitudes, $I$, $J$ and $K_s$ photometry from the survey data can be successfully performed and the colours can be used to calibrate the DIRBE extinction maps locally.

In addition, we can complement the NIR data-set using the $H$-band and the $K_s$-band (with a fainter magnitude limit) of 2MASS (see also Huchra et al., these proceedings) to obtain a wider range in colours.

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

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