Mapping the Hidden Universe: The Galaxy Distribution in the Zone of Avoidance

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Abstract

Due to the foreground extinction of the Milky Way, galaxies become increasingly faint as they approach the Galactic Equator creating a "zone of avoidance" (ZOA) in the distribution of optically visible galaxies of about 25%. A "whole-sky" map of galaxies is essential, however, for understanding the dynamics in our local Universe, in particular the peculiar velocity of the Local Group with respect to the Cosmic Microwave Background and velocity flow fields such as in the Great Attractor (GA) region. The current status of deep optical galaxy searches behind the Milky Way and their completeness as a function of foreground extinction will be reviewed. It has been shown that these surveys – which in the mean time cover the whole ZOA (Fig. 2) – result in a considerable reduction of the ZOA from extinction levels of $A_B = 1\overset{m}{.}0$ (Fig. 1) to $A_B = 3\overset{m}{.}0$ (Fig. 3). In the remaining, optically opaque ZOA, systematic H I surveys are powerful in uncovering galaxies, as is demonstrated for the GA region with data from the full sensitivity Parkes Multibeam H I survey ($300° \leq \ell \leq 332°$, $|b| \leq 5\overset{\circ}{.}5$, Fig. 4).

Keywords: zone of avoidance — surveys — ISM: dust, extinction — large-scale structure of the universe

1 Introduction

In 1988, Lynden-Bell & Lahav for the first time prepared a "whole-sky" distribution of the extragalactic light to map the density enhancements in the local Universe, to compare them to cosmic flow fields and to determine the gravity field on the Local Group. Assuming that light traces mass, this could be realized through a diameter-coded distribution of galaxies larger than $D \gtrsim 1\overset{\prime}{.}0$ taken from the following galaxy catalogs: the Uppsala General Catalog UGC (Nilson 1973) for the north ($\delta \geq -2\overset{\circ}{.}5$), the ESO Uppsala Catalog (Lauberts 1982) for the south ($\delta \leq -17\overset{\circ}{.}5$), while the missing strip ($-17\overset{\circ}{.}5 < \delta < -2\overset{\circ}{.}5$) was filled with data from the Morphological Catalog of Galaxies MCG (Vorontsov-Velyaminov & Archipova 1963-74).

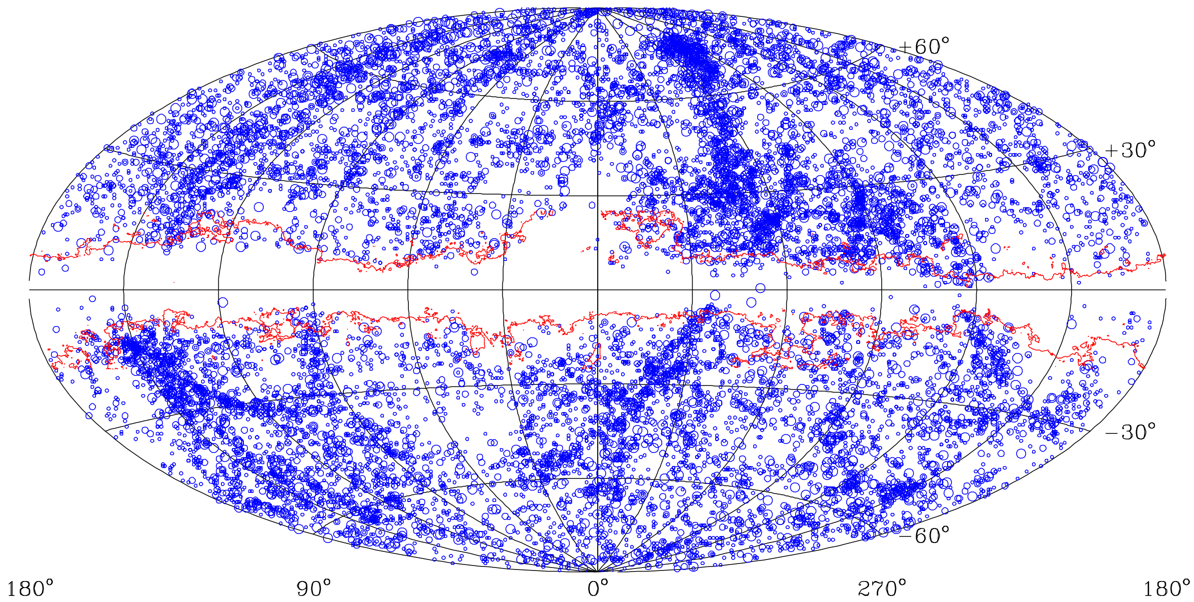

Figure 1: Aitoff equal-area projection in Galactic coordinates of galaxies with $D \geq 1\farcm3$. The galaxies are diameter-coded: small circles represent galaxies with $1\farcm3 \leq D < 2'$, larger circles $2' \leq D < 3'$, and big circles $D \geq 3'$. The contour marks absorption in the blue of $A_B = 1\fm0$ as determined from the Schlegel et al. (1998) dust extinction maps. The displayed contour surrounds the area where the galaxy distribution becomes incomplete (the ZOA) remarkably well.

Because these optical galaxy catalogs are limited to the largest galaxies they become increasingly incomplete close to the Galactic equator where the dust thickens, reducing the apparent diameters of the galaxies. Added to this are the growing number of foreground stars which fully or partially block the view of galaxy images. This is clearly demonstrated in Fig. 1, where such a light distribution is presented in an Aitoff equal-area projection centered on the Galactic plane. The same corrections as advocated in Lahav (1987) have been applied to homogenize the data of the three different galaxy catalogs, i.e. $D_{25} = 1.15 \cdot D_{UGC}, D_{25} = 0.96 \cdot D_{ESO}$ and $D_{25} = 1.29 \cdot D_{MCG}$. A cut-off at $D = 1\farcm3$ was imposed – the completeness limit of the respective catalogs according to Hudson & Lynden-Bell (1991).

Fig. 1 clearly displays the irregularity in the distribution of galaxies in the nearby Universe with its dynamically important density enhancements such as the Local Supercluster visible as a circle (the Supergalactic Plane) centered on the Virgo cluster at $\ell = 284°, b = 74°$, the Perseus-Pisces chain bending into the ZOA at $\ell = 95°$ and $\ell = 165°$, the general overdensity in the Cosmic Microwave Background dipole direction ($\ell = 280°, b = 27°$, Kogut et al. 1993) and the Great Attractor region centered on $\ell = 320°, b = 0°$ (Kolatt, Dekel & Lahav 1995) with the Hydra $(270°, 27°)$, Antlia $(273°, 19°)$, Centaurus $(302°, 22°)$ and Pavo $(332°, -24°)$ clusters.

Most conspicuous in this distribution is, however, the very broad, nearly empty band of about 20°: the Zone of Avoidance. Comparing this band with the 100μm dust extinction maps of the DIRBE experiment (Schlegel, Finkbeiner & Davis 1998) we found that the ZOA – the area where our galaxy counts are severely incomplete – is described almost perfectly by the extinction contour $A_B = 1\fm0$ (where $A_B = 4.14 \cdot E(B-V)$, Cardelli, Clayton & Mathis 1989).

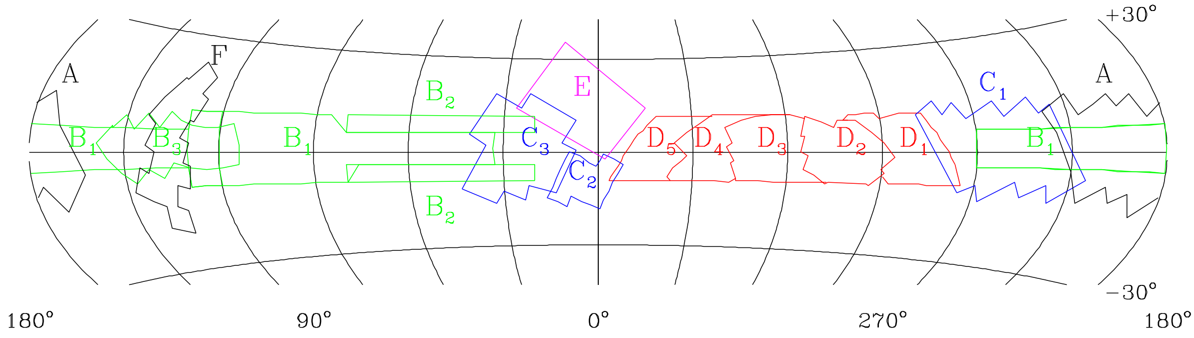

Figure 2: An overview of the different optical galaxy surveys in the ZOA centered on the Galaxy. The labels identifying the search areas are explained in the text. Note that the surveyed regions entirely cover the ZOA defined by the foreground extinction level of $A_B = 1\overset{m}{.}0$ in Fig. 1.

2 Deep Optical Galaxy Searches

Systematic deeper searches for "partially obscured" galaxies – down to fainter magnitudes and smaller dimensions ($D \gtrsim 0\overset{\prime}{.}1$) than existing catalogs – have been performed with the aim to reduce this ZOA. Using existing sky surveys (POSS I and POSS II in the north and the ESO/SERC surveys in the south), the whole ZOA has in the mean time been visually surveyed for galaxies. Here, examination by eye is still the best technique. A separation of galaxy and star images can as yet not be done by automated measuring machines (e.g. COSMOS or APM) on a viable basis below $|b| \lesssim 10° - 15°$ though surveys by eye are clearly both very trying and time consuming, and maybe not as objective.

The various surveyed regions are displayed in Fig. 2. Details and results on the uncovered galaxy distributions for the various regions are discussed in:

A: the Perseus-Pisces Supercluster by Pantoja 1997;
B_{1-3}: the northern Milky Way (B_1 by Seeberger et al. 1994, Seeberger, Saurer & Weinberger 1996, Lercher, Kerber & Weinberger 1996, Saurer, Seeberger & Weinberger 1997, and Seeberger & Saurer 1998 from POSS I; B_2 by Marchiotti, Wildauer & Weinberger 1999 from POSS II; B_3 by Weinberger, Gajdosik & Zanin 1999 from POSS II);
C_{1-3}: the Puppis region by Saito et al. 1990, 1991 [C_1], the Sagittarius/Galactic region by Roman, Nakanishi & Saito 1998 [C_2], and the Aquila and Sagittarius region by Roman et al. 1996 [C_3];
D_{1-5}: the southern Milky Way (the Hydra to Puppis region [D_1] by Salem & Kraan-Korteweg in prep., the Hydra/Antlia Supercluster region [D_2] by Kraan-Korteweg 1999, the Crux region [D_3] by Woudt 1998, Woudt & Kraan-Korteweg in prep., the GA region [D_4] by Woudt 1998, Woudt & Kraan-Korteweg in prep, and the Scorpius region [D_5] by Fairall & Kraan-Korteweg in prep.);
E: the Ophiuchus Supercluster by Wakamatsu et al. 1994, Hasegawa et al. 1999;
F: the northern GP/SGP crossing by Hau et al. 1996.

These surveys have uncovered over 50 000 previously unknown galaxies and are not biased with respect to any particular morphological type. Although the various optical surveys are based on different plate material and were performed by different groups, the search techniques overall are similar. All ZOA regions have been searched to diameter limits of at least $D \gtrsim 0\overset{\prime}{.}2$. This is considerably deeper than the previously regarded "whole-sky" catalogs with their completeness limits of $D \gtrsim 1\overset{\prime}{.}3$. How can these catalogs be merged to arrive at a well-defined whole-sky galaxy distribution with a reduced ZOA?

3 Completeness of Optical Galaxy Searches

In order to merge the various deep optical ZOA surveys with existing galaxy catalogs, Kraan-Korteweg (1999) and Woudt (1998) have analyzed the completeness of their ZOA galaxy catalogs – the Hy/Ant [D_2], Crux [D_3] and GA [D_4] region – as a function of the foreground extinction.

By studying the apparent diameter distribution as a function of the extinction E(B-V) (Schlegel et al. 1998) as well as the location of the flattening in the slope of the cumulative diameter curves log D-log N for various extinction intervals (cf. Fig. 5 and 6 in Kraan-Korteweg 1999), we conclude that our optical ZOA surveys are complete to an apparent diameter of $D = 14''$ – where the diameters correspond to an isophote of 24.5 mag/arcsec^2 (Kraan-Korteweg 1999) – for extinction levels less than $A_B = 3\overset{m}{.}0$.

How about the intrinsic diameters, i.e. the diameters galaxies would have if they were unobscured? A spiral galaxy seen through an extinction of $A_B = 1\overset{m}{.}0$ will, for example, be reduced to $\sim 80\%$ of its unobscured size. Only $\sim 22\%$ of a (spiral) galaxy's original dimension is seen when it is observed through $A_B = 3\overset{m}{.}0$. In 1990, Cameron derived analytical descriptions to correct for the obscuration effects by artificially absorbing the intensity profiles of unobscured galaxies. These corrections depend quite strongly on morphological type due to the difference in surface brightness profiles and mean surface brightness between early-type galaxies and spiral galaxies. Applying these corrections, we find that at $A_B = 3\overset{m}{.}0$, an obscured spiral or elliptical galaxy at our *apparent* completeness limit of $D = 14''$ would have an intrinsic diameter of $D^o \approx 60''$ or $D^o \approx 50''$, respectively. At extinction levels higher than $A_B = 3\overset{m}{.}0$, an elliptical galaxy with $D^o = 60''$ would appear smaller than the completeness limit $D = 14''$ and might have gone unnoticed. The here discussed optical galaxy catalog should therefore be complete to $D^o \geq 60''$ for galaxies of all morphological types down to extinction levels of $A_B \leq 3\overset{m}{.}0$ with the possible exception of extremely low-surface brightness galaxies. Only intrinsically very large and bright galaxies – particularly galaxies with high surface brightness – will be recovered in deeper extinction layers. This completeness limit could be confirmed by independently analyzing the diameter vs. extinction and the cumulative diameter diagrams for extinction-corrected diameters.

We can thus supplement the ESO, UGC and MCG catalogs – which are complete to $D = 1\overset{\prime}{.}3$ – with galaxies from optical ZOA galaxy searches that have $D^o \geq 1\overset{\prime}{.}3$ and $A_B \leq 3\overset{m}{.}0$. As our completeness limit lies well above the ESO, UGC and MCG catalogs, we can assume that the other similarly performed optical galaxy searches in the ZOA should also be complete to $D^o = 1\overset{\prime}{.}3$ for extinction levels of $A_B \leq 3\overset{m}{.}0$.

In Fig. 3 we have then taken the first step in arriving at an improved whole-sky galaxy distribution with a reduced ZOA. In this Aitoff projection we have plotted all the UGC, ESO, MCG galaxies that have *extinction-corrected* diameters $D^o \geq 1\overset{\prime}{.}3$ (remember that galaxies adjacent to the optical galaxy search regions are also affected by absorption though to a lesser extent: $A_B \leq 1\overset{m}{.}0$), and added the galaxies from the various optical surveys with $D^o = 1\overset{\prime}{.}3$ and $A_B \leq 3\overset{m}{.}0$ for which positions and diameters were available. The regions for which these data are not yet available are marked in Fig. 3. As some searches were performed on older generation POSS I plates, which are less deep compared to the second generation POSS II and ESO/SERC plates, an additional correction was applied to those diameters, i.e. the same correction as for the UGC galaxies which also are based on POSS I survey material ($D_{25} = 1.15 \cdot D_{POSSI}$).

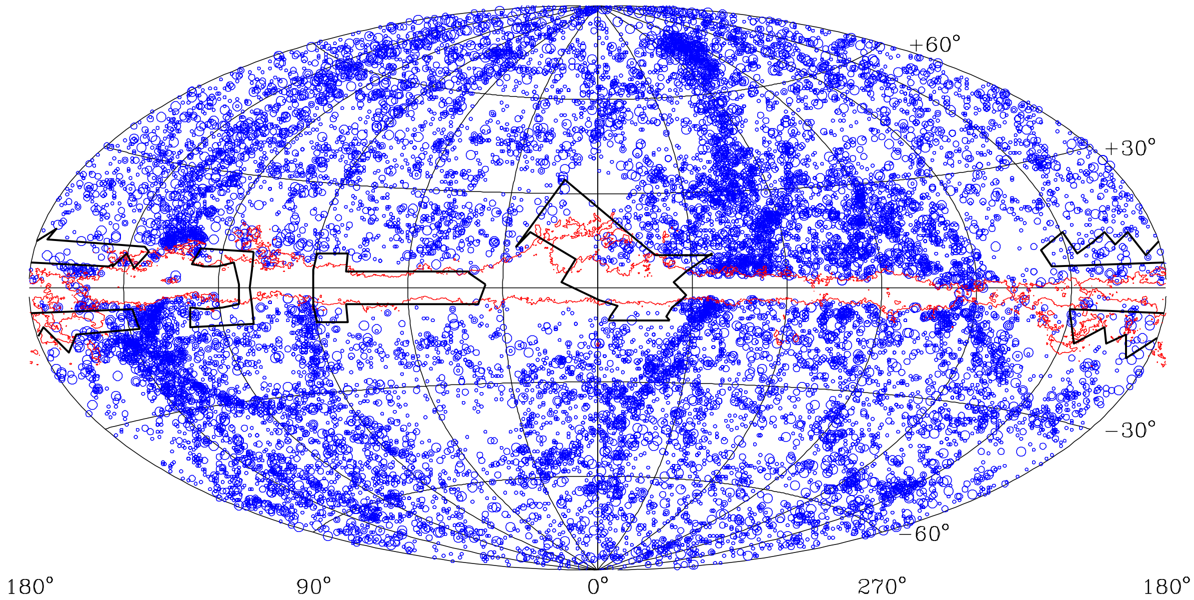

Figure 3: Aitoff equal-area distribution of ESO, UGC, MCG galaxies with extinction-corrected diameters $D^o \geq 1\farcm3$, including galaxies identified in the optical ZOA galaxy searches for extinction-levels of $A_B \leq 3\fm0$ (contour). The diameters are coded as in Fig. 1. With the exception of the areas for which either the positions of the galaxies or their diameters are not yet available (demarcated areas), the ZOA could be reduced considerably compared to Fig. 1.

A comparison of Fig. 1 with Fig. 3 demonstrates convincingly how the deep optical galaxy searches realize a considerable reduction of the ZOA; we can now trace the large-scale structures in the nearby Universe to extinction levels of $A_B = 3\fm0$. Inspection of Fig. 3 reveals that the galaxy density enhancement in the GA region is even more pronounced and a connection of the Perseus-Pisces chain across the Milky Way at $\ell = 165°$ more likely. Hence, these supplemented whole-sky maps certainly should improve our understanding of the velocity flow fields and the total gravitational attraction on the Local Group.

Redshift follow-ups of well-defined samples of ZOA galaxies will be important in analyzing the large-scale structures in redshift-space. Systematic redshift surveys have been performed for various ZOA regions and revealed a number of dynamically important structures such as

– the rich, massive ($\sim 2-5 \cdot 10^{15} M_\odot$) cluster A3627 at $(\ell, b, v) \sim (325°, -7°, 4882$ km s$^{-1})$ which seems to constitute the previously unrecognized but predicted density peak at the bottom of the potential well of the Great Attractor (Kraan-Korteweg et al. 1996)
– the 3C129 cluster at $(\ell, b, v) \sim (160°, 0°, 5500$ km s$^{-1})$ connecting Perseus-Pisces and A569 across the Galactic Plane (Chamaraux et al. 1990, Pantoja et al. 1997)
– and the Ophiuchus supercluster at $(\ell, b, v) \sim (0°, 8°, 8500$ km s$^{-1})$ behind the Galactic Center (Wakamatsu et al. 1994, Hasegawa et al. 1999).

Optical galaxy searches, however, fail in the most opaque part of the Milky Way, the region encompassed by the $A_B = 3\fm0$ contour in Fig. 3 – a sufficiently large region to hide further dynamically important galaxy densities. Here, systematic H I surveys have proven very powerful as the Galaxy is transparent to the 21-cm line radiation of neutral hydrogen and H I-rich galaxies can readily be found through detection of their redshifted 21-cm emission.

4 H I Galaxy Searches in the ZOA

In March 1997, a systematic blind H I survey began in the most opaque part of the southern Milky Way ($213° \leq \ell \leq 33°$; $|b| \leq 5\overset{\circ}{.}5$) with the Multibeam (MB) receiver (13 beams in the focal plane array) at the 64 m Parkes telescope. The ZOA is being surveyed along constant Galactic latitudes in 23 contiguous fields of length $\Delta\ell = 8°$. The ultimate goal is 25 scans per field where adjacent strips will be offset in latitude by $\Delta b = 1\overset{\prime}{.}5$ for homogeneous sampling. With an effective integration time of 25 min/beam we obtain a $3\,\sigma$ detection limit of 25 mJy. The survey covers a velocity range of $-1200 \lesssim v \lesssim 12700$km s^{-1} with a channel spacing of 13.2 km s^{-1} per channel, and will be sensitive to normal spiral galaxies well beyond the Great Attractor region.

So far, a shallow survey based on 2 out of the foreseen 25 driftscan passages has been analyzed (cf. Kraan-Korteweg, Koribalski & Juraszek 1998, Henning et al. 1999). 107 galaxies were catalogued with peak H I-flux densities of $\gtrsim 80$ mJy (rms = 15 mJy after Hanning smoothing) and their detection show no dependence on Galactic latitude, nor the amount of foreground obscuration through which they have been detected.

Four cubes centered on the Great Attractor region ($300° \geq \ell \geq 332°$, $|b| \leq 5\overset{\circ}{.}5$) of the full-sensitivity survey have been analyzed (Juraszek et al. 1999) and uncovered 236 galaxies above the 3σ detection level of 25 mJy. 70% of the detections had no previous identification.

In the left panel of Fig. 4, a sky distribution centered on the GA region displays all galaxies with redshifts v $\leq$ 10000 km s^{-1}. Next to redshifts from the literature (circles; LEDA), redshifts from the follow-up observations of Kraan-Korteweg and collaborators in the Hy/Ant-Crux-GA ZOA surveys (dashed area) are plotted. They clearly reveal the prominence of the cluster A3627 at $(\ell, b, v) = (325°, -7°, 4882$ km s^{-1}, Kraan-Korteweg et al. 1996) close to the core of the GA region at $(\ell, b, v) = (320°, 0°, 4500$ km s$^{-1})$ as predicted by Kolatt et al. (1995). Adding now the new detections from the systematic blind H I MB-ZOA survey (box), we for the first time can trace structures all the way across the Milky Way. The new picture seems to suggest that the GA overdensity is a "great-wall" like structure starting at the Pavo cluster, having its core at the A3627 cluster and then bending over towards shorter longitudes across the ZOA.

This becomes even clearer in the right panel of Fig. 4 where the galaxies are displayed in a redshift cone out to v $\leq$ 10000 km s^{-1} for the longitude range $300° \leq \ell \leq 332°$ analyzed so far of the MB full-sensitivity data. The A3627 cluster is clearly the most massive galaxy cluster uncovered by the various surveys in the GA region and therefore the most likely candidate for the previously unidentified but predicted density-peak at the bottom of the potential well of the GA overdensity.

Finding a hitherto uncharted further cluster of galaxies at the heart of the GA would have serious implications for our current understanding of this massive overdensity in the local Universe. Various indications suggest that PKS1343-601, the second brightest extragalactic radio source in the southern sky (f_{20cm} = 79 Jy, McAdam 1991), might form the center of yet another highly obscured rich cluster, particularly as it also shows significant X-ray emission (cf. Kraan-Korteweg & Woudt 1999 for further details). At $(\ell, b) \sim (310°, 2°)$, this radio galaxy lies behind an obscuration layer of about 12 magnitudes of extinction in the B-band, hence optical surveys are ineffective. Still, West & Tarenghi (1989) observed this source and identified it – with an extinction-corrected diameter of D° $\approx 4'$ and a recession velocity of v = 3872 km s^{-1} – as a giant elliptical galaxy. Giant ellipticals generally reside at the cores of clusters.

Interestingly enough, the H I MB survey does uncover a significant excess of galaxies at this position in velocity space (cf. Fig. 4). However, we do not see a "finger of God", the characteristic signature of a cluster in redshift space. Could it be that too many central cluster galaxies are

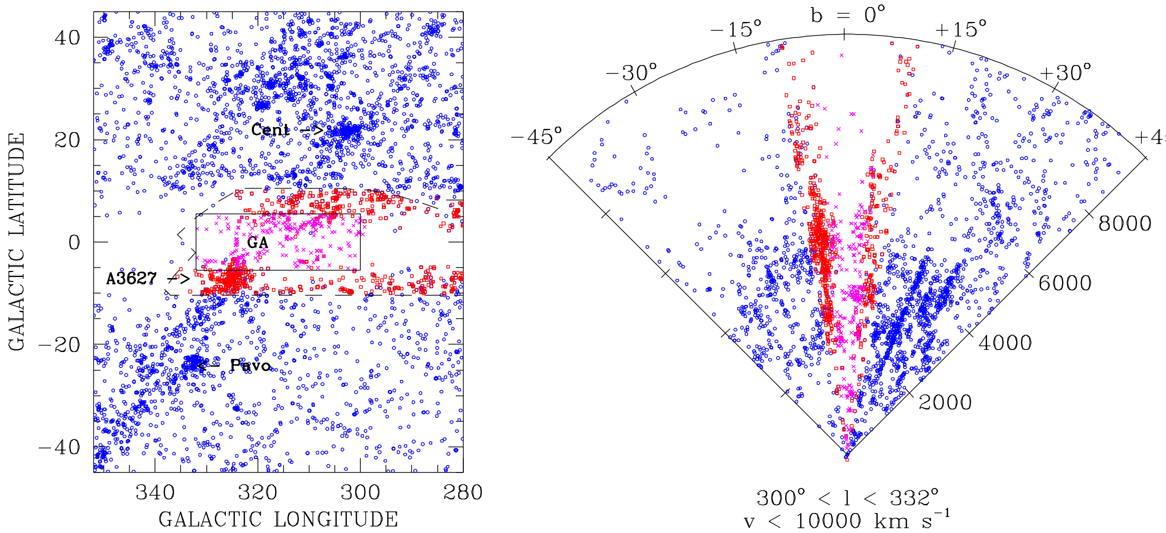

Figure 4: A sky distribution (left) and redshift cone (right) for galaxies with v<10000 km s^{-1}in the GA region. Circles mark redshifts from the literature (LEDA), squares redshifts from the optical galaxy search in the Hy/Ant-Crux-GA regions (outlined on left panel) and crosses detections in the full-sensitivity H I MB-ZOA survey (box).

missed by the H I observations because spiral galaxies generally avoid the cores of clusters? The existence of this possible cluster still remains a mystery. Meanwhile, this prospective cluster has been imaged in the near infrared (Woudt et al. in progress), where extinction effects are less severe compared to the optical, and which should uncover early-type cluster members if they are there. The forthcoming results should then unambiguously settle the question whether another cluster forms part of the GA supercluster.

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