Discovery of Highly Obscured Galaxies in the Zone of Avoidance

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ABSTRACT

We report the discovery of twenty-five previously unknown galaxies in the Zone of Avoidance. Our systematic search for extended extra-galactic sources in the GLIMPSE and MIPSGAL mid-infrared surveys of the Galactic plane has revealed two overdensities of these sources, located around $l \sim 47$ and 55° and $|b| \lesssim 1^\circ$ in the Sagitta-Aquila region. These overdensities are consistent with the local large-scale structure found at similar Galactic longitude and extending from $|b| \sim 4$ to 40°. We show that the infrared spectral energy distribution of these sources is indeed consistent with those of normal galaxies. Photometric estimates of their redshift indicate that the majority of these galaxies are found in the redshift range $z \simeq 0.01 - 0.05$, with one source located at $z \simeq 0.07$. Comparison with known sources in the local Universe reveals that these galaxies are located at similar overdensities in redshift space. These new galaxies are the first evidence of a bridge linking the large-scale structure between both sides of the Galactic plane at very low Galactic latitude and clearly demonstrate the feasibility of detecting galaxies in the Zone of Avoidance using mid-to-far infrared surveys.

Subject headings: galaxies: distances and redshifts — large-scale structure of universe — infrared: galaxies

1. Introduction

The last frontier in mapping the large-scale structure of the local Universe is the Zone of Avoidance (ZoA). Starting in the late 1980s, redshift surveys have provided an increasingly

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detailed picture of the large-scale structure in the northern and southern Galactic hemispheres, above and below the ZoA (e.g., CfA Redshift Survey, Geller & Huchra 1989; 2dF Redshift Survey, Colless et al. 1999; Las Campanas Redshift Survey, Shectman et al. 1996). However, the precise way the coherent structures of the two halves connect remains largely unknown and is not trivially predictable from the existing data. Moreover, it is quite likely that undiscovered structures incorporating significant mass concentrations lie behind the ZoA, as appears to be the case in the region of the "Great Attractor" (Galactic longitude $l \sim 320°$ and latitude $b \sim 0°$), and finding these is essential for determining the dynamics of our local Universe.

Many dedicated surveys of the ZoA have searched for hidden mass concentrations of galaxies (see reviews by Kraan-Korteweg & Lahav 2000; Kraan-Korteweg 2005). These have been primarily undertaken in the optical (e.g., Roman, Iwata, & Saitō 2000), near-infrared (DENIS, Schröder et al. 1999; 2MASS, Jarrett et al. 2000), far-infrared (IRAS, Lecher et al. 1996) and HI/radio (Parkes, see e.g. Henning et al. 2000), resulting in a considerable reduction of the ZoA. For example, the southern hemisphere HI survey with Parkes was able to map over a thousand new galaxies within $|b| < 5°$, extending the prominence of the Norma supercluster. The most heavily investigated region, using the widest wavelength regimes, has been the Great Attractor region, where a large mass overdensity of 5×10^{16} solar masses has been predicted from the systematic infall of 400 ellipticals (Dressler et al. 1987). However, the most obscured regions ($|b| \leq 1°$) of the Milky Way, with visual extinction larger than 13 mag, remain largely unexplored.

2. Data

In this paper, we present the results of a galaxy search in the ZoA based on data obtained from the two *Spitzer Space Telescope* Legacy Surveys of the Galactic Plane; the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) (Benjamin et al. 2003) and the MIPS Galactic Plane Survey (MIPSGAL) (Carey et al. 2005, 2008). GLIMPSE surveyed 2/3 of the inner Galactic disk with a pixel resolution of 1.2″, using the Infrared Array Camera (IRAC) at 3.6, 4.5, 5.8, and 8.0 μm. The survey covered Galactic latitudes $|b| < 1°$ and longitudes $|l| = 10 - 65°$, both sides of the Galactic center. The following year, the GLIMPSE survey was complemented by MIPSGAL, essentially covering the same region of the Plane at 24 and 70 μm.

3. Detection of Galaxies and Cross-Identification

Our systematic search, covering $\sim 25°$ in Galactic longitude, successfully revealed two overdensities of a total of twenty-five new galaxies, located around $l \sim 47$ and $55°$ in the Sagitta-Aquila region. Their IRAC 3.5, 4.5, and 8 μm color composite images are shown in Figure 1. Of these, twenty-two were found to have a 24 μm counterpart in the MIPSGAL images, as three fell outside the MIPS survey, and nine had measurable fluxes at 70 μm.

We cross-identified our candidate galaxies with their Two Micron All Sky Survey (2MASS) J, H, and Ks counterparts. As can be seen in Figure 1, our galaxies are typically very faint in all IRAC bands (median value of IRAC 8 μm = 8.9 mag), and just barely visible in the 2MASS near-infrared images (median value of Ks 2.17 μm = 11.9 mag).

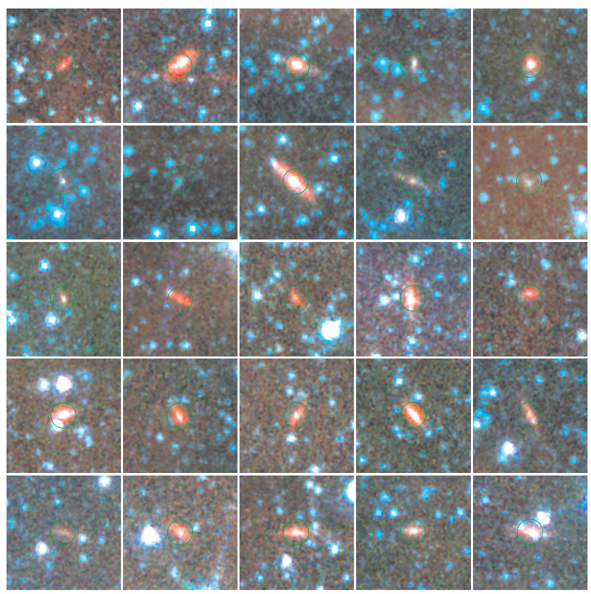

Fig. 1.— IRAC 3.5 (*blue*), 4.5 (*green*), and 8 μm (*red*) color composite postage stamps of our sample of twenty-five newly discovered galaxies. Most of these galaxies are at the edge of the GLIMPSE survey detection limit. The FOV of each image is $53'' \times 53''$ ($0.6''$ per pixel) with N up and E to the left. The *green* circles overlayed on the images are $12''$ diameter in size. The scale parameters of the postage stamps were optimized for each individual source and therefore differ for each image.

4. Photometric Measurements

The spectral energy distribution (SED) of each candidate galaxy was derived using photometric measurements obtained in all nine bands (from 1.25 to 70 μm). The aperture position and size for each object were fixed in order to measure the colors or broadband SED at the same physical region of each galaxy. The photometry was done using an aperture radius of 6″ and the background contributing to the total flux within the same aperture was removed. This aperture size was chosen to avoid as much as possible contamination due to foreground stars, mostly seen in the near-infrared images, while matching the average size, i.e. two times the full width at half maximum (FWHM), of the point spread function (PSF) at 24 μm (FWHM of 6″) given that all candidate galaxies are essentially point sources at 24 μm. Nevertheless, the flux measurements of some galaxies, e.g. SPITZER193633+225125, had to be corrected due to contamination from foreground stars. This was done by interpolating over the neighboring galaxy pixel values. Aperture corrections were applied. Dust extinction towards each galaxy was inferred from the IRAS/DIRBE far-infrared maps (Schlegel et al. 1998) and transformed to the 2MASS passbands using the extinction curve of Dutra et al. (2002). Extinction corrections at the IRAC and MIPS wavelengths were derived using the extinction curve of Mathis (1990).

5. Spectral Energy Distribution

The SEDs of the twenty-five candidate galaxies, covering the wavelength range of 1.25 to 24 μm, were obtained. From top to bottom, the SEDs are ordered in decreasing Ks-band magnitude and a constant is added to their measured fluxes to allow for direct comparison. For nine of the extra-galactic sources, a flux was also measured in the 70 μm images.

We selected the infrared SED distribution models of normal star-forming galaxies of Dale et al. (2001) and Dale & Helou (2002) to create generic galaxy SED templates and compare them with the observations. These model SEDs were generated using a value for the parameter α of 1.5, 2.0 and 4.0 and normalized to the Ks flux of each galaxy. They were chosen to approximately mimic the range of behaviour of the measured SEDs. The first striking result of this model-to-data comparison is that the SEDs of all our candidate extra-galactic sources are unambiguously consistent with the SEDs of normal galaxies. Moreover, we found that the majority of them, i.e. twenty-three out of twenty-five, showed an extended disk at 8 μm (see Figure 1). This fraction drops to 50% in the near-infrared as the extinction becomes larger at shorter wavelengths. The two sources that appeared compact at 8 μm also revealed their disk-like morphology in their 2MASS images.

6. Identify Membership to Local Large-Scale Structure

6.1. Location in the 2-D Sky

In order to ascertain the location of the newly discovered galaxies within the two-dimensional local large-scale structure, we first queried the NASA Extragalactic Database (NED) to cross-check these new sources within the existing database and to also identify any previously detected galaxies listed for our survey region ($l = 40 - 65°$, $|b| \lesssim 1°$and $z < 0.1$). The outcome of this search was negative, and no matches were found. As this first query returned only sources with redshift, we queried NED again at each of the candidate galaxy location without any redshift constraint and found this time seven matches, five classified as detections from the NRAO/VLA Sky Survey (NVSS), two from the Westerbork Synthesis Radio Telescope Galactic Plane Survey (WSRTGP) and one from the First White+Giommi+Angelini ROSAT X-Ray sources list (1WGA). We carefully examined all NVSS postage stamps and confirmed the five NVSS and two WSRTGP detections returned by NED as well as an additional four detections, bringing the total to eleven sources with believeable detections at 1.4 GHz. The 1WGA source returned from NED did not have a detection at 1.4 GHz.

We then looked at the location of the discovered galaxies within the two-dimensional distribution of the known galaxies in the local Universe, i.e. we extended our search to a larger area in the sky (l = 35 - 95°, $|b| \leq 32°$) and within a redshift space of $z = 0.0 - 0.04$ ($\sim$ 7000 galaxies). We find that these overdensities of galaxies are located in the sky near a local large-scale structure, seen also in the 2MASS extended source catalog (Jarrett 2004) for redshifts $z = 0.01 - 0.03$, and extending from $|b| = 4 - 40°$. Detection of HI galaxies, with no match to ours, is also reported at $l = 36 - 52°$ by Donley et al. (2005). However, although close to the Galactic plane, these are all found at higher Galactic latitude than the GLIMPSE and MIPSGAL surveys ($|b| > 1°$). Our findings therefore provide the first strong evidence of a bridging at very low Galactic latitude between the two large-scale structures on both sides of the Galactic plane.

6.2. Distance/Redshift Determination

Although the overdensities of galaxies which we have discovered appear to be near a filament, this does not necessarily prove their membership. However, a photometric redshift estimate can certainly narrow down the probability that these discovered galaxies are part of this local super-structure.

We were able to estimate the distance and therefore redshift to our candidate galaxies using two independent methods. The first method simply made use of the Ks-band magnitudes of the sources and assumed the spectral energy distribution of an L^* galaxy, with $M_K^* = -24$ mag obtained from the K-band field luminosity function (Kochanek et al. 2001). The inferred distances are 54 to 356 Mpc. This puts our galaxies in the $4050 - 26700$ km/s velocity range, or at a redshift of $0.013 - 0.084$ (in our calculations, we assume a cosmology with $H_0 = 75$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$).

The second and more robust method made use of the full SED, weighted most heavily on the IRAC channel 1 and 2 flux density measurements, which suffered the least from uncertainties associated with extinction (more important at shorter wavelengths) and PAHs emission features (more important in IRAC channel 3 and 4), to estimate the distance to the galaxies. The new fits, weighted to the IRAC channel 1 and 2, for some of the galaxies does not pass directly through the Ks-band data point. The galaxies found in this region of the sky have estimated redshifts ranging between 0.016 and 0.068 (distance of 66 to 288 Mpc). Note that the candidate galaxy that had the highest IRAS/DIRBE visual extinction value of 31.0 mag has now an estimated extinction value of 22.2 mag based on the SED fit, a difference of 8.8 mag.

We find that the majority of the twenty-five discovered galaxies occupy the redshift range $z \simeq 0.01 - 0.05$, with one source located at $z \simeq 0.07$. We compare these sources with the redshift distribution of all known galaxies in the redshift range $z = 0.0 - 0.1$ and with $l = 30 - 110°$ and $|b| \leq 40°$, i.e. of the order of 20000 galaxies. The overdensity in redshift space of our sample agrees remarkably well with the one of the previously known local large-scale structure in this region. This seems to agree again with the interpretation that these newly revealed galaxies belong to an extension to lower Galactic latitude of the already known local super-structure and belong to a bridge extending the filamentary structure seen on each side of the Galactic plane. However, remember that our redshift determination depends on the assumption that these are all L^* galaxies. If they are not, then clearly their redshift distribution will change. For example, it is possible that the galaxy with the largest redshift is not an L^* galaxy but somewhat fainter and that we are overestimating its distance.

7. Summary

We reported in this paper the discovery of twenty-five galaxies in the ZoA located around $l \sim 47$ and $55°$ and $|b| \lesssim 1°$ in the Sagitta-Aquila region. These overdensities are consistent with the local large-scale structure found at similar Galactic longitude and extending from $|b| \sim 4$ to $40°$. We presented their SEDs and provided evidence of their extra-galactic nature.

Their redshifts were estimated using the infrared photometric measurements obtained from 2MASS and *Spitzer*. We found that the majority of the newly discovered galaxies occupy the redshift range $z \simeq 0.01 - 0.05$, with one source located at $z \simeq 0.07$. Comparison with known sources in the local Universe revealed that these galaxies are located at similar overdensities in redshift space. This seems to imply that these newly discovered galaxies belong to an extension to lower Galactic latitude of the already known local super-structure, providing a first view of the bridging between both sides of the Galactic plane.

However, we must emphasize that these photometric redshifts, which suffer from the uncertainties associated with the extinction correction and are based on the assumption that these are all L^* galaxies, can only be determined with certainty using spectroscopic data. Therefore, we are carrying out follow-up near-infrared spectroscopic observations of the newly discovered galaxies with ground-based telescopes. The spectroscopic redshifts will allow us to derive a better estimate of the amount of extinction in the direction of our sources, which is highly uncertain. In addition, with their distance fixed, we will be able to calculate their intrinsic luminosities and estimate their stellar masses.

In conclusion, we would like to emphasize that the work presented here clearly demonstrates the power of mid-to-far infrared surveys in finding galaxies in highly obscured regions such as the plane of our Galaxy, surveying even the lowest Galactic latitudes of $|b| \lesssim 1°$. Moreover, the relative success of our survey implies that the ZoA should no longer be avoided and further studies should be undertaken to expand our knowledge of the local large-scale structure in this heavily obscured part of the Universe.

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