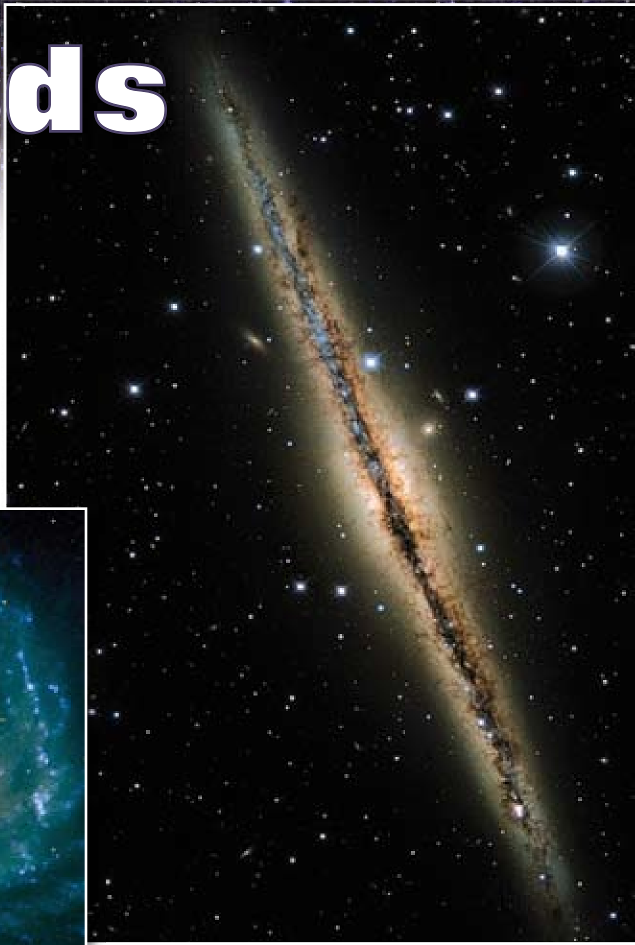
Hidden worlds behind the Milky Way

Renée C. Kraan-Korteweg and **Patrick A. Woudt** describe amazing discoveries in the previously concealed skies of the Zone of Avoidance.



The band of the Milky Way, a superb feature of the night sky, displays the light emitted by hundreds of millions of stars – and by starlight scattered by dust grains – in the disk of our own Galaxy, the Milky Way. We are located about 24 000 light years from its centre in the midst of the fairly thin Galactic disk[1].

Our location in our Galaxy hampers the study of the galaxies and their distribution in the part of the sky dominated by the Milky Way. Our view of the Universe is hardly affected when we observe the sky in a direction perpendicular to the plane of the Milky Way. However, observations within the plane of the Galaxy encounter such dense dust that the light of galaxies lying behind the Milky Way are completely absorbed, making them invisible to viewers on Earth. Because it seemed as if galaxies were 'avoiding' this region of the sky, it was named the 'Zone of Avoidance' (ZOA)[2].

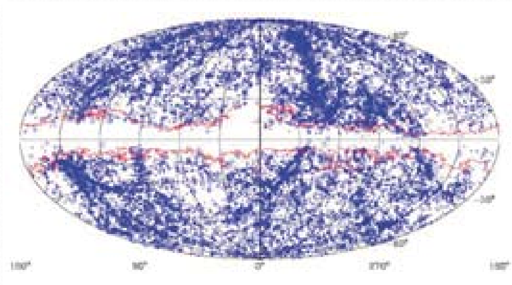
Few galaxies have been recognized in the band around the sky where light is absorbed, but the size and shape of this region varies according to the wavelength in which it is viewed. In the optical, as much as a quarter of the Universe is blocked from our view! Astronomers who study the large-scale distribution of galaxies normally avoid the ZOA and concentrate on other parts of the sky, but explorers of this avoided region persist in their efforts, irreverently referring to our gorgeous Milky Way as 'foreground pollution'.

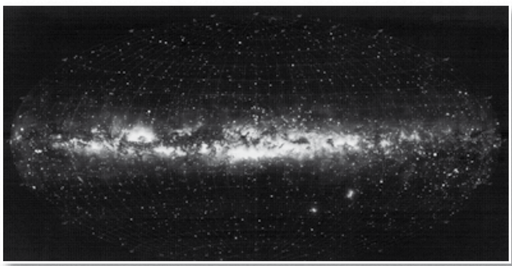
Why bother with the ZOA?

Does 75–80% of the sky – that is, of our Universe – not offer sufficient territory for exploring the most important questions in astronomy and astrophysics? The answer is no. The ZOA raises important cosmological questions, and has sparked intensive research efforts in the last couple of decades.

One question is: "Could another nearby Andromeda-like galaxy be hidden by the Milky Way's light pollution?" If so, it could change the way we explain the formation of the Local Group (LG) – the group of galaxies about 3 million light years in diameter that contains our own Galaxy[3]. ▷▷

1. The galactic disk is the major structural component of certain types of galaxy, and it contains stars and (for spirals and irregulars) gas and dust, which orbit the galaxy's centre. The thickness of the disk is small in relation to its diameter. The disk of our own Galaxy extends some 80 000 light years from the galactic centre. Its total thickness is about 1 500 light years as measured by the distribution of older stars, and just 600 light years for young stars, gas, and dust.
Source: Ian Ridpath (ed.), *A Dictionary of Astronomy* (Oxford University Press, 2003).
2. The detailed structure of the Zone of Avoidance is irregular, and varies in width between 38° (towards the galactic centre) and 12°, with some fairly transparent regions known as 'galactic windows'.
3. The Local Group has 36 confirmed members, of which the brightest are the three spirals: the Andromeda Galaxy, our Galaxy, and M33. The nearest other prominent galaxies (Sculptor and M81 groups) are considerably further away, at about 10 million light years.

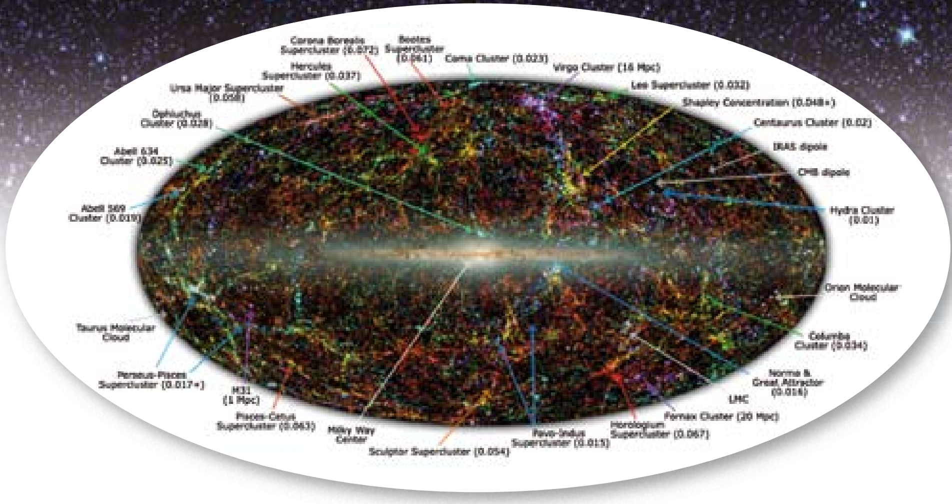




Top left and right: Two spiral galaxies that greatly resemble our own Galaxy, the Milky Way. The first, NGC 1232 (left), is seen face-on, revealing the spiral arms with their star-forming regions as well as its central bulge. (If this were a picture of the Milky Way, our Sun would lie about two-thirds out from the centre close to a spiral arm.) The other galaxy, NGC 891, is seen edge-on. While the central bulge is visible above and below the disk of the galaxy, the spiral arms cannot be made out. Moreover, the starlight close to the plane of the disk is almost completely obscured by the light-absorbing dust particles there. Images: ESO (European Southern Observatories) and CFHT (Canada France Hawaii Telescope), respectively.

Above left: These two pictures, one above the other, show optically catalogued galaxies with apparent diameters larger than one arc minute in a projection centred on the disk of the Milky Way with the Galactic Bulge at its centre (that is, an Aitoff or equal area projection in galactic coordinates). In the upper picture, the broad band empty of galaxies makes up more than 20% of the sky. Its form is like a near-perfect negative of the optical light distribution as depicted in the famous composite (shown below it) made by Swedish astronomer Knut Lundmark in 1940, and is well traced by the dust. The red contour marks light obscuration of 1 magnitude in the optical, and corresponds to a reduction in the intensity of the received light by a factor of 2.5.

Above lower right: Optical 3-colour image (obtained with the Isaac Newton Telescope in La Palma) of the Dwingeloo 1 galaxy, originally discovered by Renée Kraan-Korteweg in 1994 at radio wavelengths (see next page). The numerous stars of our Milky Way can be seen in the foreground.



Above: Large-scale structure in the local Universe. The image shows 2MASS galaxies colour-coded by redshift (Jarrett, 2004). Familiar galaxies are labelled (numbers in brackets represent redshift). Image: Courtesy of T.H. Jarrett (IPAC/Caltech)

Top: Panel above (left, middle, right): Images based on the Hydra Galaxy cluster, which lies 28° above the Galactic plane (and therefore far from dust interference).

The left-hand picture shows the near-infrared J, H, K[5] colour-composite image of an 8 x 8 arcmin field centred on the Hydra Galaxy cluster. This image was obtained with the 1.4-m Japanese telescope at the SAAO (South African Astronomical Observatory) in Sutherland.

The middle picture simulates the effects of the light absorption on the appearance of the same cluster if it were located deep into the Milky Way. Here, the galaxies appear fainter and smaller in size, and also redder, because of the selective extinction effects, which are stronger in the blue filter band and weaker in the red filter band.

The right-hand panel shows how the previous field would appear deep in the ZOA. Light absorption is not the only effect that plagues identification of galaxies behind the Milky Way: there is also an increase in star density. Even when we know the location of the galaxies (as in the left-hand image), it is difficult to identify even the largest and brightest ones in the right-hand image. Images: T. Nagayama (Ph.D. thesis, University of Nagoya, 2004)

Above: The 1.4-m Japanese telescope at the SAAO in Sutherland.

▷ The possibility is not as farfetched as it may seem, and was substantiated by the discovery of a neighbouring galaxy, Dwingeloo 1, in a systematic search for gas-rich galaxies behind the Milky Way with the 25-m Dwingeloo radio telescope in the Netherlands. Subsequent optical observations (from the Isaac Newton Telescope on La Palma, Canary Islands) revealed this previously unknown galaxy. Were it not located behind the disk of our Milky Way, this magnificent barred spiral galaxy would show up as the eighth brightest in the sky.

Other questions relate to the sizes of the largest groupings of galaxy structures (known as 'superclusters'). Do their filamentary structures (see the picture *above left* on p. 3) connect across the ZOA? How large are these superclusters and how did they form? And perhaps most important: What is the nature of what is called the Great Attractor?

In 1987, seven astronomers (dubbed the Seven Samurai) noticed a systematic pattern of movement over and above the smooth uniform expansion of the Universe. All galaxies in the local Universe – including our own Galaxy – seem to be streaming with a velocity of about 500–600 km/s towards the constellation of Norma. Such a huge peculiar motion had not been seen before and raised some consternation. The only reasonable explanation was the gravitational attraction of a huge mass concentration existing in that direction of the sky. No prominent, large-scale galaxy agglomeration was visible, however, so this mysterious mass-overdensity was nicknamed the 'Great Attractor'. The problem was that the apex of this flow motion pointed deep into the Milky Way, to an area of the extragalactic sky that is severely obscured from our view.

Lifting the veil of the Milky Way

How do astronomers find galaxies that are so heavily obscured? They apply instruments that survey the sky and reveal objects at different wavelengths[4].

Deep optical surveys

The light of the galaxies (and their size on photographic plates) gradually diminishes the closer they lie to the Galactic equator, where dust obscuration steadily increases. By identifying what appear to be fainter and smaller galaxies, we increasingly pick up galaxies that are intrinsically bright but more and more obscured. Scrutiny of deep photographic plates has, over the last decade, revealed more than 50 000 previously unknown and partly obscured galaxies – close to 20 000 of these by University of Cape Town researchers.

Near-infrared surveys

Observing in the infrared makes obscured galaxies easier to find. It has become possible with the advance of large near-infrared CCD (charge-coupled device) detectors in the past five years or so. The 2MASS (2 Micron All Sky Survey), a systematic near-infrared survey of the whole sky in the J, H, and K bands[5], became available in 2003. It was expected to revolutionize ZOA research, and to lay bare the extragalactic sky in the ZOA, given that light absorption is a factor of 10 lower in the K-band than in the optical waveband.

The distribution of the approximately 1.6 million galaxies discovered in this survey gives a superb glimpse of the web-like large-scale structure of galaxies in the nearby Universe (the colours reflect different distance intervals), with filaments and great walls outlining large areas devoid of (luminous) matter.

But expectations that these filaments would also be fully traceable across the ZOA have not

Lucky views of the sky

The 20% of the sky obscured by our Milky Way seems to hide exciting objects and mass-overdensities. Is our position particularly unlucky for observers? In fact, it could be much worse.

If we were, for instance, located in our neighbouring Andromeda Galaxy, the obscured part of the sky would not look much different, but our clear view to the nearest galaxy cluster in Virgo would be 'affected by extinction' (that is, not visible at all). So our view of the extragalactic sky is in fact quite good.

But we're unlucky in another way. The Sun has an epicycle motion above and below the Galactic equator. At present, we are elevated only 40 light years (l.y.) above this equator. If our motion were slower – or if we waited another 70 million years – we would be located nearly 300 l.y. above the Galactic equator, which is beyond the thickest layer of obscuration. So, in 70 million years' time, we will have a better view of the extragalactic sky than we do today.

4. A wave is defined as a periodic disturbance in a medium (such as water) or in space. The wavelength is the distance in metres between successive peaks or troughs in a wave. The wavelengths of electromagnetic radiation range from the shorter wavelengths (including gamma- and X-rays) to the longer wavelengths (including infrared and radio).
5. We use specialist glass light filters that allow light to pass only in 'bands' of the near-infrared centred on 1.25, 1.65, and 2.15 µm, three terrestrial windows of low atmospheric extinction. They are an extension of the optical colours, which go from ultraviolet (U) to blue (B) to visual (V) to red (R) and then infrared (I). In the past, our detectors could not go beyond the I-band, but when they did (in the 1960s), the letters after "I" (that is, J, H, and K) were used for the longer wavelength bands.

been entirely fulfilled. While we are now able to see almost all the galaxies in the Galactic Anti-Centre region, the hidden ZOA persists within about 90° of the Galactic Centre. The culprit now is star-crowding, which becomes so severe that the galaxies are completely blocked from our view by foreground stars.

Mid-infrared surveys

Moving to even longer wavelengths provides other avenues for ZOA penetration. Observing in the mid-infrared (MIR) became possible with the launch, on 25 August 2003, of the Spitzer Space Telescope with its 0.85-m mirror (Earth's atmosphere is not transparent to MIR radiation, so observing with the aid of MIR can be done only from space). This MIR imaging and spectroscopy telescope can penetrate thick gas and dust layers, and is sensitive to both elliptical and spiral galaxies. That this indeed may lead to the discovery of new galaxies has already been confirmed (see picture at *top right*, and next section).

Radio surveys

At the longest (radio) wavelengths of the electromagnetic spectrum, gas-rich spiral galaxies – though not the gas-poor elliptical galaxies – can be detected by means of radiation corresponding to the detectable 21-cm line emitted by neutral hydrogen gas[6]. This observing technique is extremely powerful (as illustrated by the discovery of Dwingeloo 1) because the emitted radiation suffers no absorption by dust particles.

A systematic survey was initiated with the large 64-m Parkes radio telescope in Australia. This instrument has 13 receivers (in an array) in its focus instead of just one, thereby increasing what is visible in the sky at any one time – as well as increasing the survey speed – by a factor of 13.

6. Different gases give off light at different wavelengths, which give them characteristic 'signatures'. Astronomers observing the line emitted by neutral hydrogen gas are looking at radiation corresponding to a wavelength of 21 cm – that is, corresponding to a spectral line resulting from an atomic transition in neutral (or, un-ionized) hydrogen when the spin of the electron flips between two states, giving out light. Mapping at 21 cm is so good because light at that wavelength passes through almost anything.

With this development, extensive systematic sky surveys became a realistic option.

Our recently completed large survey of the southern ZOA with this multibeam receiver resulted in the detection of close to one thousand galaxies through the deepest dust layers of the Galaxy. It proved important in tracking the Great Attractor across the highest dust and star density region of the Milky Way, because, finally, it allowed astronomers to map the galaxy distribution in the optical ZOA.

Some highlights of discoveries in the ZOA

The heart of the Great Attractor

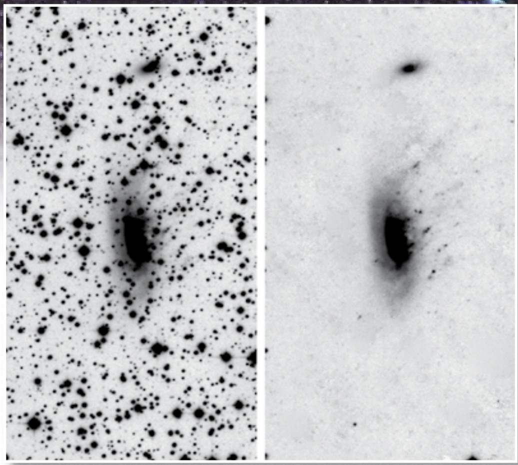
During our deep optical decade-long search in the ZOA, which encompassed the overall Great Attractor (GA) region, we recognized – very close to the GA's predicted centre – the presence of a massive cluster that we called the Norma cluster because of its location in the Norma constellation. With a mass of a quadrillion (10^{15}) solar masses, it is the nearest to the Milky Way of the massive galaxy clusters in the Universe, and was only recognized as such in 1996, when measurements ▷▷

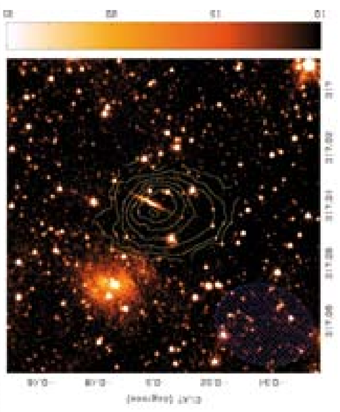
Top right and top left: The picture at top left is a close-up of part of the picture at top right. Inspection of the Spitzer Legacy Survey "GLIMPSE" (Galactic Legacy Infrared Mid Plane Survey Extraordinaire), which covered the deepest obscuration layers of the Milky Way, has found previously hidden galaxies: the close-up of the lower right-hand part of the GLIMPSE mosaic reveals two spiral galaxies (lying behind an absorption layer of 22 magnitudes in the optical).
Images: Courtesy of Marilyn Meade (UWisconsin) and the GLIMPSE team

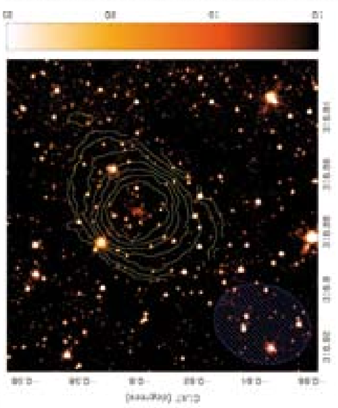
Above (middle): Artist's impression of the Spitzer Space Telescope, operated by NASA, projected against the Milky Way. Image: Courtesy Spitzer Science Center

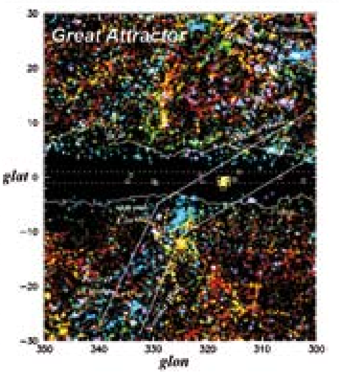
Above: The Parkes 64-m telescope (in Australia) was important in uncovering galaxies in the ZOA, in mapping the Great Attractor region, and in the discovery of one of the most massive spiral galaxies.

Left: This image, taken with the 2.2-m MPG/ESO telescope at the La Silla Observatory in Chile, shows the central 0.2 x 0.2 degrees of the Norma cluster of galaxies, near the centre of the Great Attractor. Several bright galaxies and many smaller dwarf ones are visible in this colourful vista.









Top: A detailed view of the galaxy WKK 6176 (before and after star-subtraction). The faint streams (right) show gas stripped from the host galaxy as WKK 6176 moves at high speed through the cluster.
Image: P.A. Woudt (presented at a conference in Sydney, Australia, in July 2007)

Above: Deeper neutral hydrogen radio surveys of the ZOA are among the projects envisioned for MeerKAT, a world-class radio telescope (consisting of an array of 90 telescopes, each 15 m in diameter), currently under construction in the northern Karoo. MeerKAT will be commissioned around 2012 and is a technology demonstrator for the Square Kilometre Array, which South Africa is bidding to host in competition with Australia. (See "Planning the Karoo Array Telescope" in QUEST*, vol. 2, no. 2, pp. 28–29.)*
Image: SKA South Africa Project Office

Panel on left: The contours superimposed on these GLIMPSE images – Glimpse G1 (top left) and Glimpse G2 (middle left) – outline the extent of the gas in the disks of these spiral galaxies.
Image: Courtesy Baerbel Koribalski, Australia Telescope National Facility

Lower left: Proposed deep surveys of the Great Attractor Wall footprint are outlined in this zoomed-in region area (from the Large-scale Structure map reproduced on p. 4).

of the motions of galaxies in the cluster led to the first determination of its mass. Thus far, it is also the most massive cluster in the GA and, in all likelihood, marks its core[7].

A galaxy in the act of transformation

The high-density Norma cluster, because of its relative proximity to us (and being the nearest galaxy-rich cluster in the Universe), is an excellent laboratory for studying galaxy–galaxy or galaxy–cluster interactions. It's believed that the evolution of galaxies is significantly altered by such interactions within clusters, since these interactions change the properties of the galaxies (such as colour, gas content, and morphology).

The nearest example of a galaxy undergoing strong transformation is the galaxy WKK 6176, in the Norma cluster. Various other galaxies – even small groups of them – seem to be 'falling' into this dense cluster and will be absorbed by it. They also exhibit peculiar morphologies, though none as dramatic as those of WKK 6176.

The most heavily obscured Great Attractor galaxies ever uncovered

Two galaxies discovered in the Spitzer GLIMPSE survey – we refer to them as Glimpse G1 and Glimpse G2 – are located at just the position where we think the Great Attractor extends across the ZOA.

All the combined ZOA explorations indicate the GA to be a great wall-like structure with the Norma cluster at its centre. The two galaxies might well form part of the hitherto hidden section of this wall. Baerbel Koribalski, from the Australia Telescope National Facility in Sydney, observed these two galaxies using the Australia Telescope Compact Array, a radio interferometer of 6 radio dishes with 22-m diameters. She confirmed that they are indeed normal star-forming galaxies lying at the distance of the Norma cluster.

This was a fantastic finding – the process uncovered galaxies that are obscured in the optical by about 22 magnitudes (that is, the light we're able to collect is 300 million times dimmer than the actual inherent brightness of these spiral structures)! The follow-up observations at radio frequencies allowed us to pinpoint the location of the galaxies in 3D space by also measuring the redshift of the 21-cm line emitted by the hydrogen gas in both galaxies. This has made it possible to map the elusive GA structure – even the parts that we previously thought would forever remain unexplored.

7. Rosalind Skelton, a master's student in the Department of Astronomy at the University of Cape Town, has been using our near-infrared images of the Norma cluster to measure the distribution of galaxy luminosities (that is, how many there are of particular brightnesses) for a benchmark comparison with more distant galaxy clusters. This will tell us how they evolve with time.

Women in astronomy – explorers of the ZOA

The proportion of women working in astronomy is respectable (~20%) compared to their involvement in other areas in natural sciences such as mathematics and physics, though percentages vary dramatically from country to country (from zero to over 50%), and seem uncorrelated – if not anti-correlated – with the financial wealth of countries.

The prevalence of women in the exploration of the ZOA seems astounding, even to me, who has worked in this field for nearly two decades. At times the teams (though small) consisted solely of women, with other collaborative efforts made up of up to 80% of women. The team spirit in such projects has always been great and uplifting, whatever the proportion of women or men – so the message is, let's all of us, whoever we are, just go for it! – *Renée Kraan-Korteweg*

It has motivated us to start up a further new survey that might lead to a complete map of the Great Attractor Wall and the mass that invokes such a strong velocity flow field around it.

With our Japanese colleagues Ken Wakamatsu (Gifu University) and Taka Nagayama (Kyoto University), we have begun a deep near-infrared survey using the Infrared Survey Facility at the South African Astronomical Observatory (SAAO)[8]. The central, most obscured part of the GA will be investigated during the next cycle of Spitzer Space Telescope observations over the next year, and our hope is to be able to cover the whole footprint (see picture *lower left* on opposite page). We then plan to survey this same region in the radio with MeerKAT once it is commissioned.

Discovery of one of the most massive spiral galaxies known to date

The systematic neutral hydrogen gas radio survey for gas-rich galaxies in the southern ZOA with the Parkes multibeam receiver led unexpectedly to the discovery (by author R.K.K.) of the most massive spiral galaxy known to date, HIZOA J0836-43.

The growth of a spiral galaxy to such a great size is hard to explain with current galaxy formation and evolution models. We therefore decided to explore the surroundings of this galaxy to discover the reason. Did this galaxy grow so fat by gobbling up many satellite dwarf galaxies, or does it lie in a high-density region that promoted growth through a particularly high rate of merging?

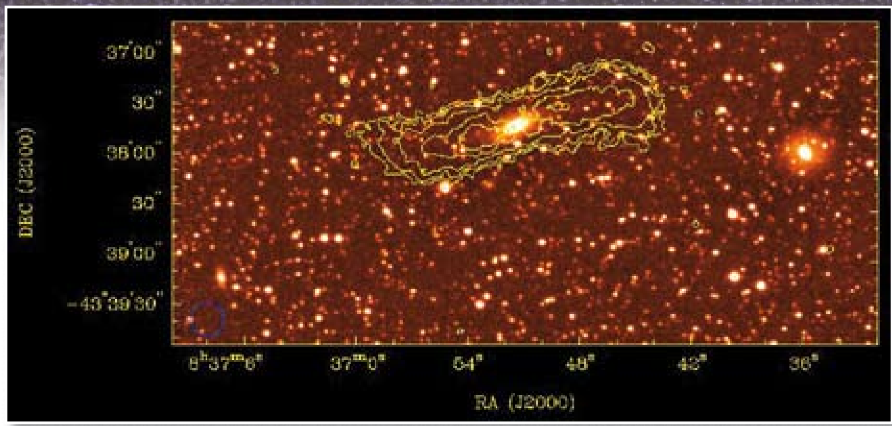
Before attempting to investigate the matter further, we verified the facts with deeper and spatially resolved radio observations with the Australia Telescope Compact Array. Deep near-infrared images were also obtained with the Anglo-Australian Telescope. These data were analysed by Jennifer Donley (then a Fulbright fellow at the Australia Telescope National Facility), who confirmed the excessive mass of this galaxy, which otherwise seems like any other normal spiral star-forming galaxy (see, for instance, those in pictures *top left and right* on p. 3).

Since it lies in the ZOA and is invisible in the optical (where its light emission is reduced by 10 magnitudes), exploring it is difficult. The only way forward is to try to probe the surroundings of this mysterious galaxy in the near- and mid-infrared. We have surveyed an area of 1.6° × 1.6° around the massive galaxy in the near-infrared with the 1.4-m telescope at the SAAO. Moreover, we obtained observing time with the (highly competitive) Spitzer Space Telescope to image the immediate environment of this galaxy, including spectroscopy. The latter might clarify whether this galaxy hosts an active galactic nucleus (an indication of recent cannibalistic or merging activities)[9].

More to follow

The exploration of the ZOA began as an attempt to answer a few specific questions concerning the dynamics in the nearby Universe as best we could, given the inherent difficulties in mapping that part of the sky and the observing tools at hand. To our delight, the various systematic surveys at different wavebands succeeded in clarifying (and narrowing down) the extent of the ZOA, and gave much-improved answers to unsolved questions.

Also, as is so often the case in research, we were led to unexpected exciting discoveries – discoveries that provided new insights into other astronomical areas and suggested new windows for exploring the ZOA further. This is by no means the end of the ZOA saga – who knows what other secrets the Milky Way is hiding from us? □



Above: A deep near-infrared K-band figure of the massive galaxy (revealing two nearby companions as well) obtained with the Anglo-Australian Telescope. The superimposed contours show the extent of the disk of neutral gas revealed by the Australia Telescope Compact Array.
Image: Courtesy of Donley *et al.*, 2006

Above: The central of the 150 survey fields of 8 x 8 arcminutes obtained with the Infrared Survey Facility at Sutherland to study the environment of the massive spiral galaxy.

Having worked in countries around the world, Professor Kraan-Korteweg is now head of the Astronomy Department, University of Cape Town. She is a world leader in surveying and uncovering large-scale structures behind the Milky Way using various observational techniques (optical, near-infrared, and radio). Dr Woudt, her colleague in the same department, is an expert on the Great Attractor and has started using the Southern African Large Telescope in Sutherland to study galaxy transformation processes in distant superclusters.

For details of discoveries described in this article, read the scientific papers. For Dwingeloo 1, read Renée Kraan-Korteweg *et al.*, "Discovery of a nearby spiral galaxy behind the Milky Way", *Nature*, vol. 372 (1994), p.77.

Recommended review articles include Renée Kraan-Korteweg, "Cosmological structures behind the Milky Way" in *Reviews in Modern Astronomy 18*, edited by S. Röser (New York, Wiley, 2005); and "Galaxies behind the Milky Way and the Great Attractor", Lectures in Physics, *GTO lectures on Astrophysics*, edited by D. Page and J. Hirsch (Heidelberg, Springer, 2000).

For more, visit **http://mensa.ast.uct.ac.za/~kraan**; the Parkes MultiBeam Research website at **www.atnf.csiro.au/research/multibeam/**; and the Spitzer Survey of the Great Attractor at **http://spider.ipac.caltech.edu/staff/jarrett/irac/ZoA/**. For more on MeerKAT and the Square Kilometre Array, visit **www.ska.ac.za**.

To revise the basics, visit **http://coolcosmos.ipac.caltech.edu/cosmic_classroom/ir_tutorial/** and **http://en.wikipedia.org/wiki/Infrared_astronomy**.

8. The advantage over the existing 2MASS survey is the increased depth of coverage through longer integration times (600 compared to 7.8 seconds) and improved angular resolution (by a factor of 4).
9. These data were in fact obtained over the period April–June 2007. Their reduction and analysis form the core of Michelle Cluver's doctoral project in the University of Cape Town's Astronomy Department (for preliminary results visit **http://mensa.ast.uct.ac.za/~michelle**).