Galactic Centre Studies

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This note is intended as a summary of some of my contributions and not as a general review of the field. Many collaborators were involved.

JHK Maps of the Galactic Centre Region

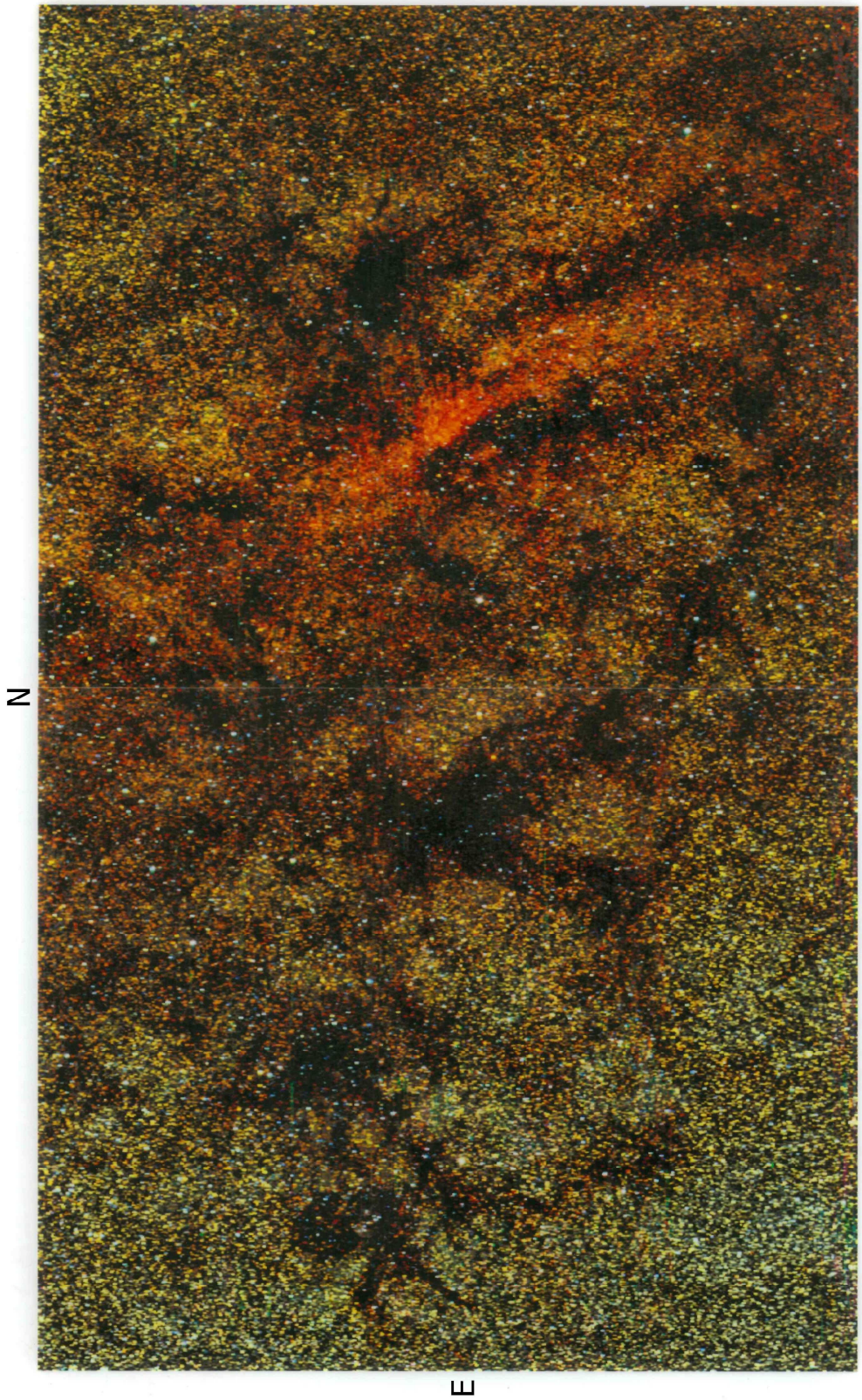
This project was conceived around 1982. At that time, the only degree-scale map of the Galactic Centre in the infrared was that of Becklin, Neugebauer and Early (*PASP* **90**, 35, 1974) that did not in general resolve individual stars although Storey & Allen (*MN* **214** 1153, 1983) and others had made maps of < 1 arcmin^2 around the Nucleus, showing the unexpected presence of young objects. Area detectors for the infrared had not yet become available and images had to be built up from laborious single-element scans. Advantages we had at SAAO were the fact that the Galactic Centre passes directly overhead and that we could get fairly large amounts of telescope time, so I conceived a plan for making a moderately high-resolution map of the Galactic Centre using drift scanning.

This project was divided up as follows: I designed and constructed a special 3-channel photometer that could observe J, H and K one after the other as the scan proceeded. Patricia Whitelock wrote the acquisition software and Robin Catchpole did the data reduction (the last of which turned out to be the heaviest task). All three of us participated in the observing. A total of 477 drift scans in RA of 10 mins each, spread over three observing seasons, were necessary. The apertures used were 6 x 12 arcsec^2 ($\alpha \times \delta$); scans overlapped by 4 arcsec in Dec and the total area covered was 2.2° x 1.1° ($\alpha \times \delta$).

The resulting maps of the Inner Bulge (See Fig 1) were the best available for a number of years. Apart from stars, they show shadows cast across the background by the large numbers of dark clouds, many of them clearly in the foreground. With the detection limit at K of 12 mag, it is clear from the absence of stars in some regions that the extinction must be $A_K > 5$ mags or $A_V > 60$ mags in some places. The extinction is so ubiquitous at J that much of it must arise from the band of molecular clouds at 4-8kpc distance.

I correlated many maps from other wavelength regions with the infrared ones. The clearest association was found between the ^{13}CO maps (Bally et al) at low radial velocities and many of the dark cloud cores. ^{12}CO is probably optically thick towards this region. The high-velocity ^{13}CO, in spite of often having quite high equivalent widths, does not in general coincide with cloud features (Glass, Catchpole and Whitelock, *MN* **227,** 373, 1987).

Fig 1: (Next page) False colour Galactic Centre image (J – blue, H - green, K - red) of the area $17^h\ 40^m < \alpha < 17^h\ 28^m$, $-28°\ 27' < \delta < -29°\ 31'$. The Centre region is not obvious at J. At Ha there is fairly general widespread extinction but be K a number of well-separated dark clouds and filaments are visible (map prepared by RM Catchpole).



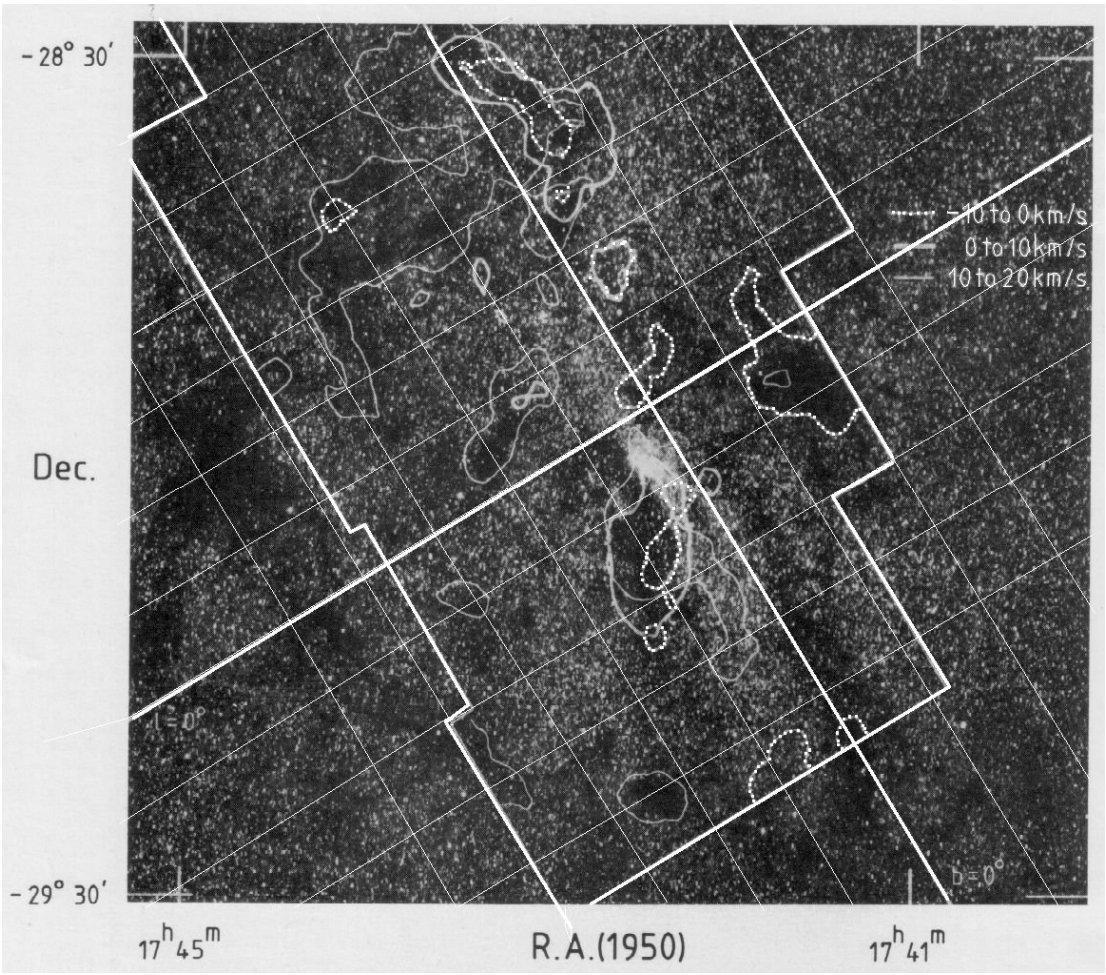


Fig 2: K image of a 1.1 × 1.1 degree² part of the survey field with low-velocity ^{13}CO 15K km s^{-1} contours and an approximate galactic coordinate grid (0.1° spacing) superimposed. The contours coincide with several of the dark clouds, implying that they lie in circular orbits well outside the Centre. Nagayama et al (PASJ **61**, 283, 2009) *identify the chain of clouds from l, b = -0.4, -0.2 to +0.4, -0.5, mostly off the left of the outlined ^{13}CO area, with a radial velocity feature at 15-20 km s^{-1} seen in ^{12}CO. This is in agreement with the fragments above seen in ^{13}CO between 10 and 20 km s^{-1}. They place these clouds at 3.2 to 4.2 kpc. The very dark foreground feature at l, b = 0.06, +0.17 is coincident with IRAS17417-2851 and is seen in emission at 1.1mm (Bally et al ApJ* **721**, 137, 2010*). The IRAS source has K=11.2 and has colours typical of HII regions (Glass, 1988).*

What became known as the Quintuplet Cluster is also conspicuous at l=0.15, b= -0.05. This was noted as coincident with compact continuum sources identified by Downes et al (*A&A Suppl*, **35**, 1, 1978), IRAS 17430-2848 and a bright knot at in the 20cm radio map (Yusef-Zadeh et al *Nature* **310**, 557, 1984).

Quantitative data were extracted from the scans by Catchpole, Whitelock and Glass (*MN* **247,** 479, 1990). The image was divided into areas of 400 × 400 arcsec² and for each of these colour-magnitude diagrams in J-K and H-K vs K were constructed. The modal displacement of what were assumed to be giant stars from an unreddened giant locus was then calculated for each area. A

reddening map of the whole image could then be created. The entire map was then de-reddened and counts of stars in corrected K magnitude ranges were made within elliptical and circular zones centered on the Galactic Centre. Crowding corrections based on a Monte-Carlo type technique were applied (to the original rather than the de-reddened images). Further, corrections for the proportion of each annulus affected by dark cloud regions were inserted.

The results are presented in a series of Log (Number of sources per square degree) vs log (radius) diagrams, for various magnitude intervals and various limits to the measurable A_V.

One conclusion was that the proportion of luminous (and so probably younger) sources increases towards the Centre.

IRAS Sources near the Galactic Centre

The IRAS Catalog of Beichman et al (*IRAS Point Source Catalog*, JPL, Pasadena, USA 1985) shows a high density of point sources (observed at 12, 25, 60 and 100μm) towards the Galactic Centre and is confusion-limited, so that its sensitivity is degraded in this region. The sources that were reported mostly had fluxes greater than 4 Jy - much brighter than expected for M giants at this distance. It was interesting to find out what these luminous sources actually are. Their IRAS colours suggested that most are HII regions and that they are relatively numerous towards the Galactic Centre. Many could be identified with known Compact Continuum Radio Sources from (Downes et al *A&A Sup* **35**, 1, 1978).

I made charts for IRAS source error boxes within about 15 arcmin of Sgr A and searched for them at L by scanning areas somewhat larger than the error boxes. Photometry at JHKLM (1.25 to 4.8μm) was undertaken for the sources found (Glass *MN* **234,** 115, 1988).

Of the 24 error boxes examined, 6 were completely empty. Three of these were not detected by IRAS at 12 μm, two were at the limit of detection and the remaining one was quite faint. Clearly these were very cool sources.

Plotting the detected sources on a H-K vs K-L diagram they could be divided into those likely to be reddened ordinary stars and those showing infrared excesses. Six stars having similar positions in the diagram suggested that the overall reddening for the field is about $A_V = 30$ mags, in agreement with previous estimates.

The remaining detections can be considered to be the counterparts of the IRAS sources. Almost all are **very red** and their flux distributions when extrapolated are compatible with the IRAS 12 μm values.

The most interesting of these was IRAS 17430-2848, which seemed to be coincident with a triplet of very red sources and two compact HII regions. It also appears as a bright knot in the 20cm map of Yusuf-Zadeh et al *Nature* **310** 557,

1964, and as a cluster on the infrared maps mentioned in the previous section. It is discussed individually in the next section. Its position in galactic coordinates is l=0.15, b= -0.05. This complex, now known as the **Quintuplet**, was found independently somewhat earlier by Okuda et al (See IAU Symposium 115, Star Forming Regions, p. 556, Reidel, Dordrecht, 1987). It is also known as AFGL2004.

Images and Photometry of the cluster near G0.15-0.05 (The "Quintuplet")

During 1989-1990 I engaged in a cooperative programme with Andrea Moneti and Alan Moorwood (ESO) to make images with the ESO Infrared Camera IRAC of the "very red" IRAS sources mentioned in the previous section.

The most unexpected result concerned the "Quintuplet", so named by Okuda et al (IAU Symposium 136, The Center of the Galaxy, p. 281, Reidel, Dordrecht), who saw it as a group of five sources.

The ESO IRAC camera had a format of 32 x 32 pixels and used a Philips detector. A mosaic was constructed from 10 exposures in the K band at a scale of 0.3 arcsec per pixel and is shown in Fig…

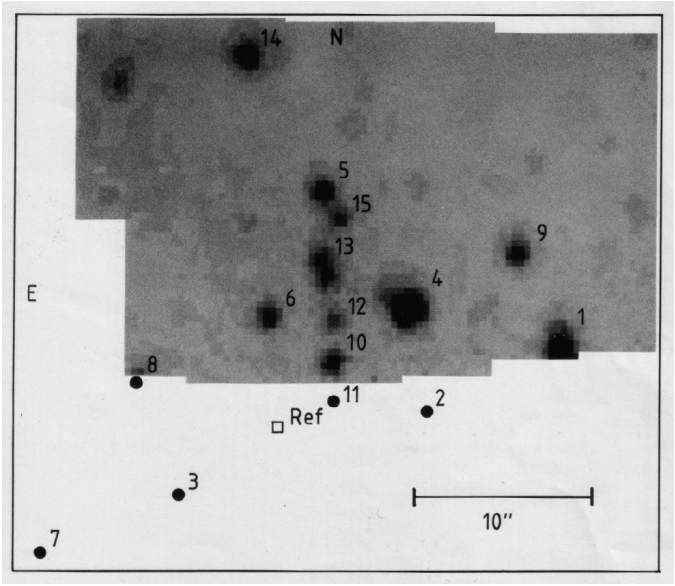


Fig 3: Composite K image of the Quintuplet. Sources 2, 3, 7 8 and 11 were not included in the image. "Ref" is the position of a visible star used for astrometry.

The Quintuplet turned out to be a much more complex cluster than previously thought, some 15 sources being identified. (Glass, Moneti & Moorwood, *MN* **242,** 55p, 1990; better reproduction of image **244** 767)

Aperture photometry was carried out at SAAO with some difficulty using mainly a 6 second aperture. This was used to calibrate the H and K-band camera images and obtain H-K colours. From colour-magnitude diagrams the foreground reddening was estimated to be $A_V \sim 22$.

The temperatures of two of the very red sources were found to be 736K and 946K and their absolute bolometric mags (if they are at 8kpc) to be -6.6 and -6.8.

Okuda et al (*ApJ* **351**, 89, 1990) found several CO absorption components with radial velocities suggesting that they are near the Galactic Centre. They further have deep 9.7μm absorption features likely to be of interstellar origin.

The extremely red colours of several stars, the predominance of luminous members, the tightness of the cluster and the association with compact continuum sources led us to conclude that the Quintuplet cluster is one of protostellar sources or "young stellar objects".

Improved images and infrared spectroscopy were presented by Moneti, Glass and Moorwood **(***Mem S A It* **62,** 755 1991). Sources 1,2 and 3 were featureless, but 7 showed CO absorption and 10 had HeI emission with a P Cyg profile. Another source about 30 sec S of no 10 also showed HeI emission and we referred to this object as the "Serendipitous Star".

It was concluded that the luminous sources are probably dust-enshrouded massive stars younger than a few million years.

Further investigation of the Very Red IRAS Sources near the Centre

In Glass (1988) above, eight of the IRAS sources sources were identified as "very red" (VR) and 7 of the fields of these these were examined in more detail with the IRAC camera at ESO (Moneti Glass & Moorwood *MN* **258,** 705, 1992) with various different pixel scales. The first results for VR source 5, the Quintuplet, are described in the previous section.

Each field showed a number of sources and usually one of these could be identified as the IRAS counterpart. The original 1988 photometry sometimes did not agree with that derived from the images, mainly because of crowding problems.

In addition, Gunn i-band images were obtained to aid in the astrometry. One or more visible stars could be identified in the J images. Infrared spectroscopy was performed for four of the objects; only IRAS 17434-2858 showed Br γ emission.

The source IRAS 17433-2838 is in a region of diffuse emission about 15 arcsec long, overlapping with a compact continuum radio source.

Two of the other sources can be identified with compact continuum radio sources, including IRAS 17434-2858 that showed Brγ emission as mentioned.

An analysis of the IRAS catalogue for fields spaced 0.25° apart near the Galactic Centre shows that the proportion of objects with nebulous type colours compared to those with stellar colours is very low away from latitude b = 0 and that along the plane it decreases rapidly with |l|.

Spectral energy distributions were obtained for several sources. In general, we concluded that these sources are very young and that some may be objects still deeply embedded in the molecular clouds from which they are forming.

Spectroscopy and Further Imaging

Moneti, Glass & Moorwood *(MN* **268,** 194, 1994) contains better images, photometry and spectroscopy of the 8 sources, including IRAS 17438-2832 which was not examined before. The latter is an extended nebulous object showing Brγ emission and is coincident with a compact continuum source. We classified it as an HII region.

The Very Red sources are IRAS:

17417-2851 Brγ, variable
17423-2855 Brγ, HeI, compact continuum radio source, HII region
17428-2854
17430-2851 Near compact continuum radio source; HII region, coccoon star,
17430-2848 (The Quintuplet) Contains coccoon stars etc.
17433-2838 Brγ, compact continuum source, star embedded in nebulosity
17434-2858 Brγ
17438-2832 Brγ, HeI, compact continuum source, HII region

The Coccoon stars have featureless spectra and luminosities corresponding to late O zero-age Main Sequence stars.

The "Serendipitous Star" shows strong Brγ.

Luminous Variables in the Quintuplet Cluster

As a by-product of the survey for large-amplitude variables near the Galactic Centre (Glass et al *MN* **321**, 77, 2001) we examined the stars of the Quintuplet Cluster for variability (Glass et al *MN* **304**, L10, 1999). In fact, a number of fairly certain variables had been found in the main reduction (2001). The more detailed 1999 paper included also two of the coccoon stars, a possible Mira and two luminous blue variables (LPVs) [The "serendipitous star" referred to earlier had been suggested to be a LPV by Figer et al (*ApJ* **506**, 384, 1998) and re-named the "Pistol Star". Another LBV, called D6 had also been identified]. The variability date helped secure the classifications.

Mauerhan et al (*ApJL***, 713**, L33, 2010) identified another potential LBV with a spectrum similar to the two already known in the Quintuplet and 7pc in projection from it. They confirmed its variability using data from the Glass et al (2001) survey. It is surrounded by a circular nebula visible in Paα that it probably ejected 5000 to 10000 years ago.

Large Amplitude Variables Near the Galactic Centre

This was a multi-year programme to survey the central 25 x 25 arcmin^2 of the Galaxy for red variables. (*MN* **321**, 77, 2001 errata **336**, 1390). See the accompanying piece on "Red Giant variables". Many Mira-like variables and OH/IR sources were identified. They were afterwards searched for SiO masers to determine their radial velocities. The identification of the long-period variables

turned out to be useful later on when interpreting ISOGAL images from the heavily obscured fields in the Centre.

ISOGAL

I was an Associate Member of the ISOGAL consortium that made use of the ISO infrared satellite to explore a large number of fields along the Galactic Plane at around 7 and 15 μm. I suggested that ISOGAL should include the Baade's Window fields of low extinction close to the Galactic Centre as these would give us an idea of what kinds of objects were being detected in the other fields, many of which were so obscured by interstellar dust that visible counterparts to the ISOGAL sources would not be seen.

In the Baade's Window fields we confirmed that the brightest objects were long-period variables stars on the AGB but also that other late-type M giants, the Semiregular Variables, were showing mass loss and hence were bright at ISO wavelengths.

The results of the M giant and other AGB work are described in the accompanying note on "Red Giant Variables".

Omont et al A&A **403,** 975, 2003 contains a summary of the programme and results. The spatial resolution and sensitivity of the ISOGAL survey of small fields along the Galactic Plane using ISO were such that it was about 2 orders of magnitude deeper than IRAS. It made use of extensive cross-correlations with the DENIS IJK Southern Hemisphere survey to yield photometry of sources in five infrared bands.

A Particular ISOGAL field

In ISOGAL fields close to the Plane, especially near the Galactic Centre, there is a diffuse background and many other point-like or almost point-like sources besides AGB stars. It was of interest to find the contribution from young massive objects and ultimately to estimate the rate of star formation in the Central Molecular Zone of the Galaxy..

Schuller et al (*A&A 453*, 535, 2006) examined one of the closest ISOGAL fields to the Galactic Centre (Fig 4). About 90% of the sources had near-IR counterparts brighter than K=11.3.

Some 110 LPVs were found in the overlap area between the Glass et al (2001) Large Amplitude Variable search and the ISOGAL field. 97 of these are associated with ISOGAL sources and 89 are detected at both 7 and 15μm, with [7] – [15] colours around 1 mag. Known OH/IR sources, of which there are 37 in the ISOGAL field, are among the brightest stars and have colours $0.8 < [7] - [15] < 2.3$.

In addition to the known LPVs and the OH/IR stars, there were ISOGAL counterparts seen in the cm radio continuum. These radio continuum sources

are compact or have small extension. Some of them are catalogued but others show up in radio maps as small but uncatalogued faint sources. Some 11 IRAS sources also fall in this field, generally with IRAS colours appropriate to HII regions {Note that IRAS 174210-2902 has colours appropriate to a moderately reddened foreground star [Glass, 1988] though it has IRAS colours appropriate to an HII region).

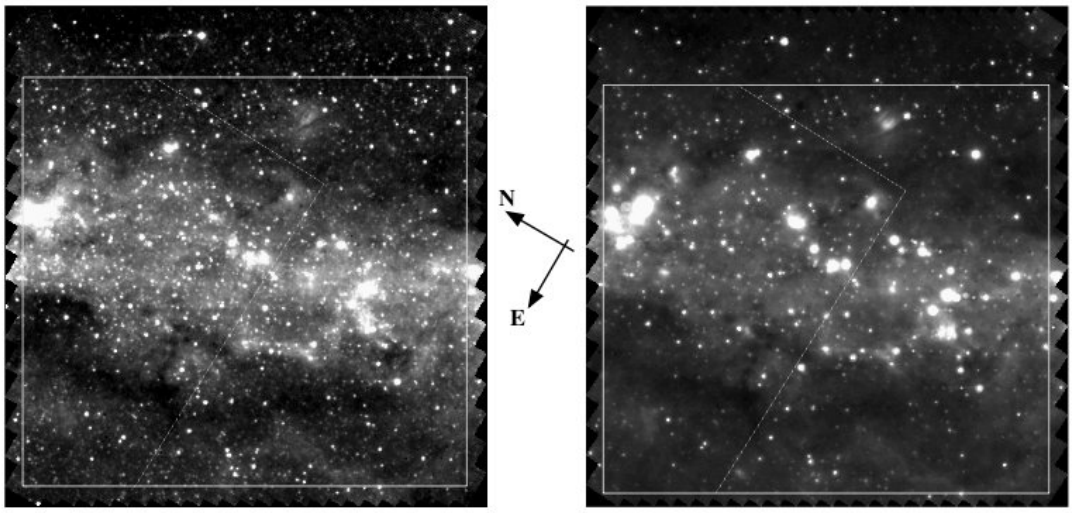


Fig 4: ISOGAL 7μm image (left) and 15μm image (right) of the area -0.424 < l < -0.115, -0.194 < b , 0.089, whose K-band image can be picked out from Fig2. Nearly half this field overlaps the area searched for Large Amplitude Variables by Glass et al 2001.

The lower-resolution MSX Galactic Plane survey in six bands from 4 to 21μm found 333 sources in this field, though cross-identification with ISOGAL objects is sometimes insecure. Nevertheless they can be used to confirm sources likely to be young.

Spectroscopy in the H and K bands of 65 sources in this field was done by Schultheis et al (*A&A* **403** 531 2003). Most of the stars with [7] – [15] < 2 were found to be AGB stars. However, there are a few OH/IR stars with colours in excess of this, which means that young objects cannot be identified only by their [7] – [15] colours.

However, in the course of reduction of the ISOGAL data, a parameter σ_{15}, relating to the extension of a source, was derived from the residual between the source profile and the analytical PSF used for the reduction. Certain combinations of [7] – [15] colour and σ_{15} were found to yield strong criteria for separating out young objects. Some 46 candidate massive young objects were identified in this way.

If situated at the Centre, the implied bolometric magnitudes of typical non-stellar sources are consistent with about that of a single B0 star. Strong continuum emission, sometimes peaked, is observed at the positions of these objects.

A follow-up paper (Immer et al, *A&A* **537**, A121, 2012; not involving me) used Spitzer mid-IR spectra to further refine the criteria for separating evolved from

young objects. It was possible to estimate that the star formation rate in the Central Molecular Zone is about 0.08 $M_{\odot}$ per year.