The Population of the Galactic Plane as Seen by MSX

S.L. Lumsden, M.G. Hoare, R.D. Oudmaijer and D. Richards
Department of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK
Email – sll@ast.leeds.ac.uk, mgh@ast.leeds.ac.uk, roud@ast.leeds.ac.uk

ABSTRACT
The combination of mid-infrared data from the MSX satellite mission and ground-based near-infrared photometry is used to characterise the properties of the mid-infrared population of the Galactic plane. The colours of the youngest sources still heavily embedded within their natal molecular clouds are in general different from evolved stars shrouded within their own dust shells. Our main motivation is to use MSX for an unbiased search for a large (∼1000) sample of massive young stellar objects (MYSOs). A simple analysis shows that the MSX point source catalogue should contain most of the MYSOs within our Galaxy. We develop colour selection criteria using combined near- and mid-infrared data for MYSOs, which produces a list of 3071 objects, excluding the galactic centre region. The programme of follow-up observations already underway to separate the MYSOs from compact H II regions and other remaining objects is briefly described. We also show that these data can be used, just as IRAS data has been previously, to provide a separation between evolved stars with carbon rich and oxygen rich dust. These data may also be used to search for evidence of dust around normal main sequence stars, such as low mass pre-main sequence stars or the Vega-excess class of objects where debris disks are presumed to remain from the planet formation process. We discuss the accuracy and completeness of the MSX point source catalogue, and show that the errors present tend to be of a kind that is not significant for the main stellar populations we discuss in this paper.

Key words: infrared:stars-stars:formation-stars:pre-main-sequence-stars:late-type-Galaxy:stellar content-surveys

1 INTRODUCTION
Objects embedded in dust play an important role throughout stellar evolution. Stars are born out of dusty molecular clouds whilst in the late stages of evolution they will invariably go through phases where they generate their own dust during heavy mass-loss. These objects emit most prodigiously in the infrared region of the spectrum with dust temperatures usually in the range of 30-300 K. To study these objects there is an undeniable need for unbiased samples and these usually have to originate from the infrared where most of their bolometric luminosity emerges.

Unbiased infrared surveys started with the rocket-borne AFGL mid-infrared survey of Price (1977) and then the first far-infrared satellite survey came with the IRAS mission. Many studies have been made using IRAS colours to select and classify objects of a variety of types (see Beichman 1987). These can be split roughly into studies of evolved stars and studies of young stars. In the former category, Van der Veen & Habing (1988) and Walker & Cohen (1988) used 12, 25 and 60µm colours to classify the stars in the IRAS point source catalogue (IRAS PSC). These were mostly Asymptotic Giant Branch (AGB) stars that could be separated into those that were either oxygen-rich or carbon-rich, although first ascent Red Giant Branch (RGB) stars also have dust excesses (Plets et al. 1997; Jura 1999). Searches for evolved stars where mass-loss had stopped and the dust shells have become detached were made by Oudmaijer et al. (1992) for post-AGB stars and for planetary nebulae (e.g. Pottasch et al. 1988). Another example of the potential of IRAS for stellar astronomy was the discovery that some main sequence stars showed excess dust emission due to a remnant disk, now known as Vega-type or Vega-excess stars (Aumann 1985).

The other major area that benefited from IRAS was the study of the young stellar population in our galaxy. IRAS colour-colour diagrams were used by Hughes & MacLeod (1988) to separate H II regions from planetary nebulae and reflection nebulae for example. Prusti, Adorf & Meurs (1992) used more sophisticated techniques to extract low-mass young stellar object candidates from the IRAS PSC. Our main motivation is to build a large unbiased sample...
of massive young stellar objects (MYSOs), also known after the prototype in Orion as BN objects (see Henning et al. 1984). By this we mean a luminous ($\gtrsim 10^4$ L$_{\odot}$ or early B star), embedded source that has not yet reached the stage when the emergent Lyman continuum is sufficient to ionize the surrounding interstellar medium to form an H II region. Due to the short contraction timescale compared to the collapse timescale it is thought that these objects are already core H-burning. However, it is also likely that accretion is still ongoing. They usually possess strong ionized stellar winds (e.g. Bunn, Hoare & Drew 1995) and drive powerful bipolar molecular outflows (Lada 1985). The 30 or so currently well-known MYSOs form a heterogeneous sample (Wynn-Williams 1982; Henning et al. 1984), often found serendipitously, and may not be representative of the class as a whole. There is an obvious need for a much larger well-selected sample.

It is reasonable at this point to ask how many MYSOs are in the entire galaxy. We can make a crude estimate by normalizing a stellar mass formation rate over a Salpeter IMF to yield the currently accepted star formation rate in the galaxy of about 6M$_{\odot}$ yr$^{-1}$ (Güsten & Mezger 1982). We then simply used the Kelvin-Helmholtz timescale for contraction to the main sequence using mass-radius and mass-luminosity relations for main sequence stars. Although not strictly correct this does give appropriate timescales for the YSO phases that we are interested in, namely about 10$^4$ years for the most massive O star and 10$^5$ years for the intermediate mass Herbig Be type stars. This predicts about 1000 massive (15-100 M$_{\odot}$) YSOs in the galaxy, which is well over an order of magnitude larger than the current sample. A sample of this size is required when studying the properties of MYSOs as functions of mass, age, metallicity, etc. Hence, the task in reality is close to that of finding every MYSO in the galaxy.

Previous attempts at systematic searches for MYSOs have been made using IRAS data. Campbell, Persson & Matthews (1989) in a series of papers followed-up 400 colour-selected IRAS sources that were also bright, unconfused and not identified with a known source. The problem with any infrared colour-selection procedure is that there are other types of source that have very similar infrared colours. Basically any heat source inside an optically thick dust cloud will produce an emergent spectral energy distribution that depends mostly on the optical depth of the cloud. The population with most similar infrared colours to MYSOs are compact H II regions, for which they are the progenitors. Both are are still deeply embedded in dense molecular clouds. Young compact, planetary nebulae and very dusty evolved stars can also have similar infrared colours. Campbell et al. used single-element large aperture (8 arcsecond) near-infrared photometry to observe their IRAS candidates. They found a total of 115 candidate YSOs that were bright and red near-infrared sources, with excess emission in the K-band presumed to be from hot circumstellar dust. These candidates have luminosities in the range 10$^2$-10$^4$ L$_{\odot}$ however so only just meet our criteria for a genuinely massive YSO. Recent spectroscopy presented by Ishii et al. (2001) suggests that some are not YSOs since the III Br y equivalent width is much closer to that seen in H II regions (eg Lumsden & Puxley 1996) or PN (eg Lumsden, Puxley & Hoare 2001), than massive YSOs (eg Porter, Drew & Lumsden 1998). This highlights the importance of obtaining sufficient follow up data to confirm the nature of any candidate MYSO.

Chan, Henning & Schreyer (1996) used similar selection criteria to Campbell et al. and derived a list of 254 MYSO candidates. However, no attempt was made to eliminate compact H II regions from the sample. Indeed over 100 of the objects are listed as being strong radio sources, much brighter than the weak stellar wind emission from nearby MYSOs (S$_{\text{v}}$ < 10 mJy) (e.g. Henning, Pfau & Altenhoff 1990; Tofani et al. 1995), and are therefore very likely to be H II regions. Palla et al. (1991) put together a colour-selected bright IRAS sample of 260 objects that avoided known H II regions from single-dish radio surveys.

Of course, any infrared colour-selected sample of compact H II regions by the converse will also contain large numbers of genuine MYSOs. Wood & Churchwell (1989a) developed 12, 25 and 60\mu m colour-selection criteria based on ultra-compact H II regions detected in their VLA survey. They applied this to the whole IRAS PSC and found 1646 embedded massive stars. Codella, Felli & Natale (1994) found that much more evolved, diffuse H II regions as well as compact H II regions satisfy the Wood & Churchwell criteria and Ramesh & Shridharan (1997) found evidence for significant contamination of the Wood & Churchwell sample by cores heated by less massive stars. Kurtz, Churchwell & Wood (1994) carried out a VLA survey of 59 bright IRAS sources satisfying the Wood & Churchwell colour criteria. They found that 80% had compact radio emission and are thus compact H II regions, although some of these are weak enough to be MYSOs. Indeed several well-known MYSOs were recovered in their study. Shridharan et al. (2002) selected a sample of 69 bright, northern MYSOs that satisfied the Wood & Churchwell criteria as well as having dense gas traced via CS emission and undetected in single-dish radio continuum surveys. The latter condition was to avoid complexes and H II regions, although VLA follow-ups showed that nearly one third of their sample were still compact H II regions. Their sample was deliberately biased towards finding isolated MYSOs for detailed high resolution studies.

Walsh et al. (1998) carried out high resolution radio observations of IRAS sources originally selected in the same way as Wood & Churchwell, but mostly known to emit either radio continuum or methanol maser emission from previous single dish observations. Methanol masers have been known to trace massive star forming regions for some time (Menten 1991; Caswell et al. 1995). High fractions of IRAS selected sources and well known MYSOs are maser sources, not only methanol, but H$_2$O and OH as well. However, unfortunately any one masing species cannot be guaranteed to be present in every MYSO. Indeed a recent search for methanol emission in a sample of well-known MYSOs found that none of them were detected (Gibb, Hoare & Minier, in preparation). So although there are great advantages in using strong, unobscured radio line emission techniques for galactic searches they will not be unbiased. Similarly, radio continuum emission from MYSOs is simply too weak to allow continuum mapping to be used in providing an unobscured search method for these objects.

Clearly therefore any unbiased search must start from infrared surveys. Preferably these should be at far-infrared wavelengths where the emission from the regions peaks and the extinction across the galaxy is negligible. Purely near-
infrared surveys would be biased towards nearby and less heavily embedded (more evolved) sources due to the high extinction in the near-infrared. However, the concentrations of massive stars within \(\sim \pm 1^\circ\) of the Galactic plane (Reed 2000; Becker et al. 1994) means there is considerable source confusion in the IRAS survey due to its large beam (45 arc-seconds \(\times\) 240 arcseconds at 12\(\mu m\)). Recently the MSX satellite carried out a much higher spatial resolution survey (18 arcseconds) of the Galactic plane \((b < 5^\circ)\) at 8, 12, 14 and 21\(\mu m\), completely superseding IRAS. This provides the starting point for our unbiased search for MYSOs. The aim of this paper is to demonstrate that this mid-infrared data provides a valuable means of locating these MYSOs, and to show how the various Galactic populations that emit in the mid-infrared can be characterised from such data.

2 STELLAR POPULATIONS IN THE MID-INFRARED

2.1 The MSX Point Source Catalogue

The Mid-course Space Experiment (MSX) satellite mission included an astronomy experiment (SPIRIT III) designed to acquire mid-infrared photometry of sources in the Galactic Plane as well as other regions either not covered by IRAS, or where the IRAS data were confused due to the high source density. MSX has a raw resolution of 18.3\(^\prime\), a beam size 50 times smaller than IRAS at 12 and 25\(\mu m\).

The MSX satellite observed 6 bands between 4 and 21\(\mu m\). Full details of the mission can be found in Price et al. (2001). The most sensitive data, by a factor of \(\sim 10\), were acquired using an 8.3\(\mu m\) filter (band A: bandwidth 3.4\(\mu m\)). The point source sensitivity was similar to that of the IRAS 12\(\mu m\) band, at about 0.1 Jy. Data obtained using both the 14.7 and 21.3\(\mu m\) filters (bands D and E: widths 2.2 and 6.2\(\mu m\) respectively), although less sensitive, were also of value to us since we are primarily interested in red objects. The E band can be compared to the IRAS 25\(\mu m\) band (see Egan et al. 1999). The two filters at 4\(\mu m\) were not designed primarily for astronomical observations and little useful data is obtained from them. The final filter at 12.1\(\mu m\) (band C: width 1.7\(\mu m\)) is less sensitive than band D and consequently of lesser value, though we did use it where appropriate. Band C is effectively a narrower version of the IRAS 12\(\mu m\) filter (again see Egan et al. 1999).

The vast majority of the 300 000 point sources detected by MSX are found only as 8\(\mu m\) detections and are not found in the IRAS Point Source Catalogue. The full properties of the sources found in the MSX Point Source Catalogue (hereafter MSX PSC) are outlined in Egan et al. (1999). We used v1.2 of the catalogue. Since colour information is needed to begin to classify objects, we have mainly used a subset of the full catalogue, consisting of those sources with quality flags in the MSX PSC of 2 or greater in the A, D and E bands. Egan et al. (1999) give the definition of sources with a quality of 2 as fair or poor. Their Table 5 gives the actual definition in terms of signal-to-noise and number of repeat sightings from the separate scans of the Plane. Our ‘multi-colour’ subset comprised 14897 sources. Hereafter in this paper we will refer to these MSX bands by their central wavelengths as the 8, 12, 14 and 21\(\mu m\) bands.

We cross-correlated the multi-colour MSX sample with the IRAS Point Source Catalogue. The IRAS PSC contains 9303 (62\%) of the subset of MSX sources. Virtually all of the matches had detections in the short wavelength bands as might be expected (296 were missing at 12\(\mu m\), 218 at 25\(\mu m\) and only 20 at both 12 and 25\(\mu m\)). However, 145 were upper limits at 60\(\mu m\), 2794 were upper limits at 100\(\mu m\) and 5373 were upper limits in both these bands. The results are consistent with the increased source confusion in the larger IRAS beam, especially at long wavelength. A crude comparison of the measured fluxes in the IRAS PSC and MSX PSC for objects detected in both is also consistent with this hypothesis. Crucially only 25\% have reliable data at 60\(\mu m\) which is a key ingredient in previous source classification using IRAS data. This highlights the difficulties present in using IRAS data to detect and classify sources within the inner regions of the Galactic Plane.

We checked the claimed astrometric accuracy of the MSX PSC of \(\sim 2^\prime\) since we are interested in cross-correlating the MSX data with other catalogues. We searched for counterparts of bright stars in the Hipparcos catalogue (see Perryman et al. 1997). In order to reduce the likelihood of chance correspondences we used stars in the multi-colour MSX PSC subset with blue mid-infrared colours (ie \(F_8 > F_{14} > F_{21}\)), and matched against the full Hipparcos catalogue. We found 192 matching stars. Figure 1 shows the results of this comparison. Although the bulk of our data do follow the trend found by Egan et al. (1999) in the comparison of MSX PSC data and the MSX Astrometric Catalog (Egan & Price 1996), there is a small non-Gaussian tail of sources at large separation. We have individually checked the four sources with separations of 10\(^\prime\) or greater. Three out of the four Hipparcos stars do appear to be genuine counterparts of the MSX source after inspection of 2MASS Atlas images, whilst the fourth one is not as clear since it lies in a more crowded field, and may be a chance coincidence. The quoted measurement reliability (which is essentially a gauge of how well a point source matches the actual data) is also good for all four of these stars (quoted value at 8\(\mu m\) is 0 or 1, on a scale of 0–9, where 0 is best fit and 9 worst). The most obvious features of the 3 clearly discrepant points are that they are bright (\(F_8 > 100\)Jy) and that the MSX image data shows image artefacts. It is notable that the centre of the image is offset from the position quoted in the MSX PSC, apparently because of these artefacts. These artefacts arise from cross-talk between detectors for very bright sources in the cross-scan direction, and detector glints in the in-scan direction (see Price et al. 2001). Astrometry of sources with some saturated pixels therefore may be affected by this.

Evidence from other individual sources in the catalogues described below also suggest that very bright point sources may be offset without the measurement reliability flag being obviously poor. Furthermore, at least one of the known massive YSOs in MSX, W75N, shows a similarly large offset from its known position (almost 30\(^\prime\) in error) despite being fainter, and not showing obvious image defects. This is more worrying, since it is harder to check for such errors. Price et al. (2001: see section 4.4) note that a more sophisticated pointing algorithm was used in creating the MSX images than that used in the first version of the MSX PSC. This leaves the possibility that there are some non-saturated sources in version 1.2 of the MSX PSC with
real astrometric errors. Overall, these results suggest that there is a small but non-negligible fraction of MSX PSC sources with very poor astrometry.

The existence of a group with such poor astrometry also led us to check the accuracy of the quoted fluxes. We did find some problems in the MSX PSC. The most notable was the existence of a group of sources with detections at more than one band, but which had a non-detection at one of the key bands for our multi-colour subset. As an example, we considered those sources that were detected at 14 and 21\,\mu m, but not at 8\,\mu m (since these may have very red colours similar to young stellar objects). Unfortunately many of these appear to be erroneously catalogued in the MSX PSC as non-detections at 8\,\mu m. Some of these are undoubtedly sources in which the detectors were saturated. A good example is the case of V1489 Cyg, an oxygen-rich evolved star. The MSX PSC gives this as a non-detection at 8\,\mu m, whilst an ISO SWS spectrum shown in Molster et al. (2002) shows the 8\,\mu m flux is \sim 1000\,Jy. The original MSX image data clearly shows this very bright source, together with considerable image artefacts due to its large flux density. In this case all of the detectors at 8\,\mu m were saturated as noted by Price et al. (2001), so that no useful data was obtained however. Only four such cases of hard saturation are present in the MSX PSC. In other cases however only some of the detectors saturate and the MSX PSC flux includes a compensation for this ‘missing’ flux by fitting the remaining detectors with the known point spread function. In some of these cases, the final MSX PSC flux is too inaccurate to give a reliable measure, and hence is flagged as bad.

In addition, there are also sources detected at 14 and 21\,\mu m but not at 8\,\mu m that lie in extended confused emission regions. An example of this kind is given in Table 2, where we present MSX photometry of known MYSOs. The MSX PSC fluxes cannot be relied on in these cases. This is not especially a problem for the bright sources since we are presented with very poor astrometry. The same is not true for sources which are intrinsically fainter, or where the nondetection is due to a failure to fit a point source in a region of extended emission. Of course in the latter case the concept of a point source may be wrong in any event.

2.2 Literature Classification of MSX Sources

We have found that literature searches in order to classify the MSX sources leads to three different types of object: those with well established classification, often referred to in many different papers; those with poorly established classifications, often referred to either only in one paper or generically as an infra-red source detected by IRAS; and those with no previous classification at all.

We can illustrate this with our multi-colour subset of 14897 sources using the SIMBAD database. If we include all current references from the literature then 4896 (33\%) have no identification at all within a 10\,\arcsec radius. We have utilized the SIMBAD object types to classify the others as shown in Table 1. If an object has more than one literature classification we preferentially adopt the classifications given in the order they appear in Table 1. Over half of the remaining sources are classified simply as infrared, radio or maser, which does not actually tell us what type of object it is. Hence, 86\% of these sources have never been studied in detail before and the vast majority have never been classified by stellar type. This is further illustrated if we look at those objects that have been subjected to at least some study. For this we take all the objects with more than ten literature references which number 4363. Again three quarters of these are only known as an infrared source. Less than 6\% of MSX sources with multi-colour data are well-studied objects of known type. This indicates that the mid-infrared emitting population in our galaxy, even at these relatively bright fluxes, is still mostly unclassified.

Of course in carrying out this simple analysis, we have relied on the literature classification being correct. There will be instances in which this will not be true and the classifications are far from a homogeneous statistical sample. However the size of the sample should ensure that the trends we have found are accurate.

2.3 Mid-infrared colours of known objects

As noted above, most of the MSX sources in the multi-colour subset are previously either unknown or poorly studied. The main aim of this paper is to study how well we can use the colours of these sources to determine what type of object they might be. First, we need to study what the colours of known objects are. We have chosen representative samples of objects from compilations that are as homogeneous as possible to further analyse the characteristics of the MSX PSC sources. These lists form two major classes: evolved mass losing stars of all kinds and young stars and H II regions. The actual catalogues we used were as follows (approximately in order of increasing obscuration): the compilation of Alksnis et al. (2001) for largely unreddened carbon stars (these are mostly optically selected); for OH/IR stars we used the confirmed candidates presented in Chengalur et al. (1993); for planetary nebulae (PN) the catalogue of Acker et al. (1992); for Herbig AeBe stars the compilation of Thé et al. (1994); for compact H II regions the sources detected in the radio continuum by Wood & Churchwell (1998b), Kurtz, Churchwell & Wood (1994) and Walsh et al. (1998); and methanol maser sources without detectable radio emission also came from Walsh et al. (1998). Finally for the massive YSOs themselves we have adopted a greatly restricted list compiled by ourselves to minimize contamination from non-YSOs, and this list is given in Table 2.

In addition to these specific catalogues, we also used the classification of IRAS low resolution spectrograph detections presented by Kwok, Volk & Bidelman (1997). This provides an additional and largely independent means of identifying different classes of evolved stars. In particular, their classification of oxygen rich stellar sources according to the presence of the 9.7\,\mu m silicate feature in emission or absorption provides a clear test of the dust opacity. The Kwok et al. sample is also a useful source of more obscured carbon stars missing from the compilation of Alksnis et al.

Figure 2 shows colour-colour plots of all multi-colour MSX PSC sources for representative regions of the inner (20\,\degree < l < 30\,\degree) and outer galaxy (100\,\degree < l < 260\,\degree). We have chosen the boundaries of these regions so that there are similar numbers of sources in each sample. We have indicated the track of a blackbody of varying temperature in
this and following figures. In addition, we have also indicated the magnitude and direction of a typical extinction vector. The extinction law we have assumed varies as $\lambda^{-1.75}$ for $\lambda < 5\mu m$ and uses the data for astronomical silicate from Draine & Lee (1984) at longer wavelengths where the silicate feature dominates in the diffuse ISM and oxygen-rich circumstellar material (see Draine 1989), although it is not appropriate for carbon-rich circumstellar dust. We averaged the appropriate Draine & Lee data for the different MSX filters using the filter profiles from Egan et al. (1999). The use of the Draine & Lee (1984) extinction curve does have one consequence that is clear from Figure 2. The $F_{21}/F_{14}$ colour actually gets bluer for increasing extinction since the 14$\mu m$ filter is located in the dip between the 9.7 and 18$\mu m$ silicate features. 

There are several noteworthy features in Figure 2. The bulk of the sources lie at the ‘blue’ end of the distribution where the flux ratios are around or below unity. As we shall see these are mostly evolved stars. For this population there are clear differences in the colours seen between the inner and outer galaxy, with the inner galaxy being somewhat redder. Some of this is undoubtedly due to the effect of the additional line-of-sight extinction towards the inner galaxy region. However, the direction of the shift in colour does not agree particularly well with our reddening vectors. An increase in the extinction at 14$\mu m$ to a level similar to that at 12 and 21$\mu m$, or a decrease in the extinction at 21$\mu m$ would give a better agreement.

There is a large population of very red objects that separate out from the bulk of the stellar sources. This is clear when the $F_{21}/F_8$ ratio is considered (a constant $F_{21}/F_8$ ratio in the left hand panel is a diagonal line from top left to lower right). These are generally heavily embedded sources in which the central exciting star has little direct photospheric contribution to the MSX fluxes.

The colours of all classes of objects except those showing photospheric emission are primarily determined by the opacity and temperature of the dust surrounding them. The presence of dust features can play a large role in some wavelength bands for some classes of object. The most obvious of these are the broad silicate emission/absorption feature at 9.7$\mu m$ (with a secondary broad feature usually seen in emission near 18$\mu m$), the PAH features at 7.7, 8.6 and 11.3$\mu m$, as well as weaker complexes between 11 and 14$\mu m$ and the SiC feature at 11.3$\mu m$. For nebular sources the strong forbidden lines such as $8.99\mu m$ [ArIII], $12.8\mu m$ [NeII] and $15.56\mu m$ [NeIII] can also influence the colours. Additional weaker molecular absorption lines are also present in the evolved stars.

The role of the dust temperature-opacity and these features play is best demonstrated by examining the mid-infrared colour-colour diagrams for our well-studied samples of known types of objects. Figure 3 shows the equivalent plots to Figure 2 for our representative samples of ‘young’ sources associated with massive stars. The Herbig Ae/Be stars are the least embedded of the young sources (indeed many were discovered from optical searches). This is clearly reflected in them having less red colours, and less excess 21$\mu m$ emission than the other young sources. Our sample of well-known MYSOs is slightly bluer than the H II regions and methanol sources. This is likely to be because they are bright, nearby sources whereas the radio selected objects are typically more distant and suffer more line-of-sight extinction rather than the known MYSOs being less embedded in their circumstellar material. All the young sources are well separated from the bulk of the normal stars in both the $F_{21}/F_8$ and $F_{21}/F_{14}$ ratio, largely due to the fact that they are embedded in optically thick dust clouds.

A few of these heavily embedded sources have $F_{14}/F_{12} < 1$ despite the fact that $F_{21} > F_8$. For the HII regions this may reflect the presence of strong $12.8\mu m$ [NeII] emission. The massive YSO for which $F_{14}/F_{12} < 1$ is S106 IR. Again there is a relatively strong [NeII] line present in this object (see the ISO-SWS spectrum presented in van den Ancker, Tielens & Wesselius, 2000). Although S106 IR has many characteristics of a massive YSO (Drew, Bunn & Hoare 1993) it does power a bipolar H II region. Most massive YSOs do not show such ionised gas emission, and hence will tend to have $F_{14}/F_{12} > 1$ reflecting the fact that their continua are red and mostly featureless in the mid-infrared apart from the silicate absorption at 9.7$\mu m$ (Smith et al. 2000). The compact HII regions have similar colours, but can have stronger forbidden line emission in virtually any of the filters (e.g. Martin-Hernández et al. 2002; Giveon et al. 2002). This leads to the slightly larger scatter seen for these objects.

Figure 4 shows the same plots for the samples of evolved sources, namely carbon stars, OH/IR stars and planetary nebulae. Here there is an much greater separation of the various types. The planetary nebulae have colours similar to the HII regions as we expect since the mid-infrared emission is dominated by Lα heated dust in both cases (e.g. Hoare 1990; Hoare, Roche & Glencross 1991). There is a larger scatter in the PN colours, but their central stars have a much larger range of effective temperature than those in HII regions, leading to a wider range in line emission properties. In particular, [NeIII] and [NeV] in the 14$\mu m$ filter can be strong, naturally leading to a larger scatter in the right hand panel than seen for the HII regions (de Muizon et al. 1990).

The OH/IR stars have moderately red colours and appear to spread out in the direction of the reddening vector. A better agreement with our silicate dominated reddening vector is to be expected for these oxygen-rich stars which produce mostly silicate dust. To investigate this further we also looked at the mid-infrared spectral classifications of evolved stars by Kwok et al. (1997). These results are shown in Figure 5. We have only plotted those sources classed types E (silicate emission at 9.7$\mu m$), A (silicate absorption), C (SiC emission – ie carbon stars) and P (PAH emission without notable forbidden line emission). It can be seen that the trends shown by Figure 4 are confirmed. The silicate feature in the OH/IR stars changes from emission to absorption as they cross over the blackbody line at about $F_{21}/F_8$ between 1 and 2 in the right-hand diagram. The ones with silicate in absorption are more optically thick and this is consistent with their generally redder $F_{21}/F_8$ and $F_{14}/F_8$ ratios. The silicate feature can influence both the 8 and 12$\mu m$ fluxes in these objects. This certainly explains the behaviour of the OH/IR stars in the right hand panels. As the silicate feature goes into absorption, the $F_{14}/F_{12}$ ratio must rise. Sevenster (2002) considered the MSX colours of a larger group of OH masing objects. Her results mostly agree with those here except that a small group of her sample lie in the region where the PN are found. Hence, the colours of the OH/IR stars
can be understood as a due to increasing dust opacity as a result of higher dust production and mass-loss rates.

The carbon stars have the bluest colours of the evolved objects and lie close to the unreddened blackbody curve. They can show a strong absorption feature due to various $C_2H_2$ transitions near 13.6µm, as well as weaker absorption in the same MSX band due to HCN. The $C_2H_2$ features appear stronger in the more evolved (more obscured) carbon stars detected only in the infrared (eg Aoki, Tsuji & Ohnaka, 1999, Volk, Xiong & Kwok, 2000). The infrared carbon stars are also more likely to fit an overall blackbody shape of a few hundred K rather than the combined effect of the Rayleigh-Jeans tail of the stellar photosphere together with cool dust emission. The SiC feature also tends to become weaker as the obscuration increases (due to self absorption). The $F_{14}/F_{12}$ ratio here probably is a closer reflection of the dust temperature than that of any particular feature, since the effect of SiC emission at low opacity is probably matched by the effect of the $C_2H_2$ absorption at high opacity. Most of the sources in both Figures 4 and 5 are of classical optically selected carbon stars. Even the most dust enshrouded carbon stars still lie at the extreme red end of the distribution shown. We looked at the location of some of the more extreme dust enshrouded carbon stars studied by Volk et al. (2000) and Aoki et al. (1999) using ISO spectroscopy. Only the two objects in Aoki et al. noted as likely post-AGB objects fall outside the range shown for the carbon stars in Figures 4 and 5 (these lie near the PN population at the cool end of the blackbody line).

It is now clear that some of the differences between the colour-colour diagrams for the inner and outer galaxy in Figure 2 are due to changes in the stellar population present. There is a significant lack of carbon stars at the blue end of the right-hand diagram in the inner galaxy. Instead there is clearly a large oxygen-rich population running parallel to the extinction vector and crossing the black body line near $F_{21}/F_{8} \sim 1 - 2$. The increase in the population of carbon stars in the direction of the anti-centre has been noted before (eg. Jura, Joyce & Kleinmann 1989), and is usually attributed to metallicity effects (the lifetime of the carbon star phase increasing as metallicity decreases).

3 NEAR- AND MID-INFRARED COLOURS

3.1 Sources of near-infrared data

It is clear from the previous section that although mid-infrared data on their own allow some separation of object types there is still significant contamination of the MYSO region with PN in particular. We require data from either longer or shorter wavelengths in order to improve this situation. The main benefit of using the MSX PSC is the greatly improved spatial resolution over that provided by IRAS. This is especially important within the innermost regions of the Galactic plane. Hence, progress cannot be made with far-infrared studies until the ASTRO-F satellite makes its far-infrared survey at a resolution similar to MSX (Shibai 2000). The other available option is to use near-infrared data from the 2µm All Sky Survey Point Source Catalogue (2MASS PSC) (Skrutskie et al 1997). This was recently completed and the currently released data covers 47% of the sky. We have therefore investigated the use of combined 2MASS and MSX data in the classification of objects and the identification of young massive stars in particular. Egan, Van Dyk & Price (2001) have used combined MSX and 2MASS data in a study of the stellar populations in the LMC. However, they only used the 8µm MSX data since most of their sources were undetected in the longer wavelength MSX bands and so they could not investigate the usage of mid-infrared colour information. Egan (1999) also used the first 2MASS incremental data release (a much smaller sample than considered here) in combination with the MSX PSC to examine object classification in the Galactic plane.

An immediate problem that we encountered with using 2MASS is that objects brighter than about 5th magnitude saturate the detectors used. Since many of the well-known objects, especially the MYSOs, are as bright as this we have therefore added the compilation of photometry from the literature by Gezari et al. (1999) to the 2MASS PSC data. Where data exists in both lists we have used the 2MASS data for consistency, except where the 2MASS data are saturated. Where data exists in the literature for sources not currently in the areas covered by the second incremental data release of 2MASS we have also used those data. Lastly, where 2MASS PSC data are flagged as extended we have used the appropriate data from the 2MASS extended source catalogue instead. Only ~20 objects fall into this final category.

We used a search radius of 10 arcseconds in cross correlating the MSX source positions and the 2MASS or Gezari catalogues. This leaves the possibility that some of our sources are not visible in the near infrared and that we have picked a neighbouring, but separate, near infrared counterpart. This is especially true in massive star forming regions where dense clusters of associated stars are present (eg Carpenter 1993; Hodapp 1994) and in some cases the true MYSO may be completely obscured. We were able to determine some of the more obvious cases where this was true and remove them. This was particularly true for the catalogues presented in Section 2.3, which represent for the most part well studied objects. We believe that ≤1% of our associations are wrong based on this. Since we are mostly interested in the statistical properties of the MSX sources, we will therefore ignore this possibility in what follows.

In objects like G35.2N (Walther et al. 1990), GGD27 (Aspin et al. 1994) and IRAS 20126+4104 (Cesaroni et al. 1997) where the actual MYSO is completely obscured at near-infrared wavelengths this procedure will pick out the nearest star in the cluster or, at 2MASS resolution, a bright spot in the reflection nebulosity. In these cases, the near-infrared magnitudes will really be upper limits on the brightness of the true counterpart. Since, the associated clusters and nebulosities are also quite faint and red close to the MYSO they still have strong discriminatory power as we shall see. It is possible that there may be no 2MASS counterpart at all within 10 arcseconds. With the current limited sky coverage of 2MASS this is difficult to ascertain automatically so we only deal with detections and not upper limits here.

We assessed the quality of the available literature data by comparing it with 2MASS where there were overlaps. Figure 6 shows the comparison of 2MASS and literature data where both exist (320 objects at $J$, 338 at $H$ and 402 at $K$).
We have only used data for objects with multi-colour MSX data since these are the objects we are most concerned with in this paper. There are several points that must be made before a useful interpretation can be made of this Figure. First, much of the older data from the literature was acquired with single element detectors with a relatively large aperture. In practice we discarded all those taken with an aperture larger than 30″, and if more that one measurement was available adopted the one made with the smallest aperture. However, there will inevitably be some extended objects where the larger aperture contains more emission than the 2MASS point source. Therefore we would expect deviations from the line in the direction of fainter 2MASS fluxes. We may also expect rarer excursions from more recent imaging data where the aperture reported in the literature is smaller than the 4″ resolution of 2MASS, and there is also some evidence for this. Lastly, many of the bright sources are evolved stars and are therefore variable.

Given all of these caveats it is clear that the scatter between 2MASS data and literature data increases at fainter magnitudes. The reasons here are likely to be threefold: first, the aperture effect noted above (though most faint objects have photometry derived from arrays rather than single element detectors); second, given an array camera was used, there is a chance that we are not comparing the same targets, since the literature data may give multiple point sources within the 2MASS aperture at these faint magnitudes (or the 2MASS data may contain extended background emission); thirdly, there may be an error in the photometry in either source. The other obvious feature of Figure 6 is that there are several objects for which the literature magnitude is fainter than 5, but 2MASS reports a saturated detection. We therefore investigated the source of the 2MASS magnitude for the extreme cases in which a saturated result is reported for objects with literature magnitudes fainter than 8. All of these objects are in areas flagged as being near expected bright stars. The area around these sources is masked out in the 2MASS PSC, and a default saturated magnitude given for the anticipated bright star (note, this also means that many other sources within these masked strips are missing entirely from the 2MASS PSC). We examined the original 2MASS Atlas images and in all cases the objects were clearly closer to the literature magnitude, and the original flag marking the source as too bright for reliable 2MASS photometry is in error. A smaller number of all the 2MASS sources that are listed as being saturated are flagged to indicate that they were found to be saturated during the shortest 2MASS exposure time (the fractions are 0% at J, 11% at H and 17% at K of all listed saturated sources). In these cases the literature magnitude always agreed with that assessment and so these appear to be genuinely saturated in 2MASS.

3.2 Near- and Mid-Infrared Colour-Colour Diagrams and Source Classification

3.2.1 Sources detected in the MSX PSC at 8μm only

The combination of MSX data with near-infrared photometry provides several potential tests for the nature of the underlying source. MSX data on its own is sensitive to the presence of any warm dust. However, there is little sensitivity to the temperature of any dust emission and the level of extinction to the source. Near-infrared data on the other hand are very sensitive to the extinction. In most cases the underlying emission will be due to the stellar photosphere or nebular continuum. Only in the K-band is there likely to be a contribution from hot dust if present. Hence, the F_8/F_K ratio will increase as we go from simple reddened photospheres to objects with optically thin warm dust contributing to 8μm and possibly K and then onto deeply embedded objects.

Many of the new sources detected by MSX are seen only at 8μm. Many of these are undoubtedly showing only normal photospheric emission, without any detectable excess due to dust. As a test of this we selected all sources with reliable fluxes at 8μm in the ranges 240 < l < 250 and 10 < l < 11, but which were not detected at 14 or 21μm. There are 1780 and 2068 objects in the two respective ranges. Figure 7 shows the colours of these objects in the near-infrared and at 8μm. The left hand panels can be compared to the results presented by Egan et al. (2001) for the LMC. The majority of the sources in the outer galaxy have colours consistent with being cool giant or main sequence stars. Within the inner galaxy the results are consistent with a similar, but much more heavily reddened population.

A small but significant fraction of the objects shown in Figure 7 lie well to the right of the blackbody line. These clearly have excess mid-infrared emission compared to that expected for a standard photosphere. Most (83%) of these mid-infrared excess objects in the outer galaxy have blue near-infrared colours, and a potential counterpart in the HST Guide Star Catalogue. Objects with similar colours are also found in the multi-colour MSX PSC sample. In the inner galaxy, most of the sources with excess emission at 8μm have near infrared colours close to that expected of normal stars, though the effects of extinction are more obvious. We cannot say whether their intrinsic colours are actually blue as in the outer galaxy. Most of the sources within the inner galaxy are unknown, so we cannot be sure of their object classification either.

It seems likely that objects with a mid-infrared excess and blue near infrared colours are predominantly stars with warm (~200K), detached, optically thin dust shells or disks. Some may be isolated low mass pre-main sequence stars, which are known to show such an excess. Other possible candidates for this mid-infrared excess population include Be stars (cf Oudmaijer et al. 1992), where the excess is due to emission from the stellar wind rather than dust, and stars such as Vega with extant debris disks from the star (and planet) formation process. Few of the mid-infrared excess sources shown in Figure 7 are known IRAS sources (most lie near the limit of detection with MSX).

3.2.2 The multi-colour MSX sources

Our primary interest in MSX lies in those red objects with detections at more than 8μm however. We now investigate the additional discrimination from combining near-infrared and mid-infrared colours. In Figure 8 we plot the same inner and outer galaxy samples as were used in Figure 2 on combined near- and mid-infrared colour-colour diagrams. Figure 9 shows the same plots as Figure 8 for our selected samples of young sources, and Figure 10 shows the results for the se-
lected sample of evolved sources. Note that there are always fewer points in the right hand panel in these Figures, since they rely heavily on data from the Gezari et al. catalogue, and this often lacks J band data.

Two separate populations appear to be present in the outer galaxy population in Figure 8(b), one running along the blackbody curve and the other shifted redwards in $F_{21}/F_8$. Figure 10 reveals the identity of these populations. The sequence running along the blackbody curve is due to carbon stars, whilst the redder one is due to OH/IR stars. In each of these sequences the reddening (and hence mass-loss rate) is increasing the further up they appear. This is clear from Figure 11 where we plot the mid-infrared spectral classifications for evolved stars from Kwok et al. on these combined near- and mid-infrared colour-colour diagrams. For the OH/IR stars which have silicate features, this feature is in emission at smaller $F_K/F_J$ ratios and switches to absorption at the top of the sequence. The heavily embedded carbon stars discussed by Aoki et al. (1999) and Volk et al. (2000) also lie towards the upper tip of the carbon star sequence, making it likely that the carbon star sequence is also an extinction sequence. The evident extinction sequences show the clear value of adding near-infrared data to the MSX PSC.

The clearest result of the comparison between inner and outer galaxy shown in Figure 8 is again a lack of carbon stars within the inner galaxy. The carbon star sequence is almost completely absent in Figure 8(a). There is also evidence for the effect of greater extinction in the inner galaxy, with virtually the entire population being shifted to redder $F_K/F_J$ ratios.

The separation between the carbon and oxygen rich stars using these mid- and near-infrared indicators is similar to that proposed by Epchtein et al. (1987) for IRAS and ground-based near-infrared data (they used the IRAS $F_{25}/F_{12}$ ratio and the ground-based $K - L$ colour). In both cases we can understand this as being examples of moderate to high dust obscuration, so that the $K$ band flux reflects the observed direct light from the star and the $9μm$ flux arises from the warm dust. It is clear that the near-infrared colours alone do not follow the same trend however. Here the stars with silicate in absorption do not all have redder $F_K/F_J$ colours than those with silicate in emission. It is worth noting however that stars with the silicate feature in absorption do have higher $F_{21}/F_{12}$ ratios than those with the feature in emission, as we would expect if the $12μm$ MSX flux is partially affected by the silicate feature. It seems likely that it is the strength of the silicate feature at both 9.7 and $18μm$ that gives the actual separation between the two populations seen.

Comparison of the right-hand panels in Figures 9 and 10 shows that the majority of PN can now be separated from the H II regions (and MYSOs). PN and H II regions have similar mid-infrared and mid- to near-infrared colours since they have very similar warm dust distributions. However, PN mostly have much bluer near-infrared colours because they are not embedded in a large molecular cloud. This is certainly the case for evolved PN like NGC 7662 modelled by Hoare (1990) where their near-infrared colours are dominated by unreddened nebular continuum. There are some young, compact PN that have hot dust and/or very small grains/PAHs such as IC 418 (again see Hoare 1990), which give rise to red near-infrared colours. Other more distant PN will simply suffer line-of-sight extinction and a few of these can be seen in Figure 10 overlapping in $F_K/F_J$ with the least reddened H II regions.

4 SELECTION CRITERIA FOR MASSIVE YOUNG STELLAR OBJECTS

Our main interest in the MSX PSC is to complete a census of massive YSOs, as noted in the Introduction. It is clear from previous surveys using IRAS data that the primary selection criteria for all massive YSOs are a rising, largely featureless red continuum between 1 and 100μm. Therefore, for the MSX PSC data we require $F_8 < F_{14} < F_{21}$ as a minimum starting point. We have started from the sub-sample of multi-colour MSX PSC data in determining possible candidates. 6838 (46%) of the 14897 sources satisfy these basic colour criteria. In addition, the massive YSOs in Table 2 also have $F_{21}/F_8 > 2$. Therefore we have also imposed these criteria on the MSX PSC, leaving a sample of 4215 objects. The rejected sources are mainly nearby bright stars, evolved stars and a few planetary nebulae. If we exclude the inner-most 10° of the plane on either side of the Galactic centre, where source confusion is highest and distance determination difficult, these numbers are reduced by a further 30% to 3071. We will only deal with this smaller subset in what follows.

Inspection of Figure 4 shows that are still many evolved stars and PN that satisfy these selection criteria. The addition of the near infrared data does help to considerably reduce the number of such stars however. Again, inspection of Figure 9 shows that all the known massive YSOs satisfy $F_K/F_J > 5$ and $F_K/F_J > 2$. In particular, these criteria select against most (~2/3) of the planetary nebulae and the few OH/IR and carbon stars that pass the mid-infrared colour cuts. We found no significant separation between MYsOs and compact H II regions in a pure near-infrared J-H versus H-K colour-colour diagram. Henning et al. (1990) show a separation with compact H II regions being bluer in H-K. Unfortunately this probably reflects the photometric technique employed by Chini, Krügel & Wargau (1987) who collected the compact H II region data by raster scanning for bright sources with a large beam single-element photometer. This is more than likely to detect less obscured sources in the vicinity of the true near-infrared counterpart.

Of the 3071 candidates left after our mid-infrared colour selection, only 736 currently have suitable near-infrared data. Of these, 472 (64%) satisfy the additional colour selection using near-infrared data as described above. We expect that this fraction (~2/3) is representative of the whole sample: therefore, approximately 2000 sources will have colours in the near- and mid-infrared consistent with being young massive stars.

There will still be objects other than MYsOs in our colour-selected sample, most notably compact H II regions as expected from their very similar infrared spectral energy distributions. We carried out a further literature search on these 472 objects in a similar fashion to that presented in Section 2.2. The results of that search are also presented in Table 1. Clearly the fraction of evolved or main sequence stars left in the sample is now greatly reduced compared to
the full sample of multi-colour MSX sources. In this instance we can also be reasonably confident that most of the otherwise unknown maser sources are associated with massive star formation of some kind, and it also seems likely that the radio sources will predominantly be HII regions. Discounting those with questionable and infrared only identifications, there are 221 sources with a useful classification. It would appear that 165 (75%) of these sources are associated with star formation, confirming that our selection criteria are reasonable. At least half of these 165 appear to be H II regions rather than MYSOs. The maser sources could be associated with either MYSOs or compact H II regions.

We also repeated our cross-correlation with the IRAS point source catalogue for the 3071 candidates. Here 1605 (52%) of these actually appear in the IRAS PSC (1466 do not). Of these 43 have an upper limit at 60Jy, 560 a upper limit at 100Jy and 408 an upper limit at both 60 and 100Jy. Therefore, 2477 (81%) of our candidates suffer confusion in the IRAS beam and 1917 (62%) would not have been considered in previous searches for MYSOs using IRAS 12, 25 and 60µm colour selection criteria.

We have also examined the distribution in Galactic longitude and latitude of the MYSO candidates that pass only the mid-infrared colour selection criteria. The near-infrared data currently has a rather patchy Galactic distribution so it is better to study only the mid-infrared selected data in this regard. Figure 12 shows the results. The features present in the longitude distribution are similar to those found by Wood & Churchwell (1989a) and mostly correspond to local complexes and spiral arms. The high bulge source density within the inner ±10° of longitude is clear even for this colour restricted sample. The latitude scale height of this sample is approximately 0.8°, similar to the 0.6° found by Wood & Churchwell (1989a) for their IRAS selected sample. By comparison, the scale height of the whole multi-colour MSX sample is 1.6°. The bulk of the MYSO sample are clearly confined to within ±1° as shown by Figure 12(c), as expected if our colour selected sources are massive stars. A 0.8° scale height corresponds to 120 pc at the distance of 8.5 kpc to the galactic centre. This is somewhat larger than the scale heights of <65 pc for local OB stars derived by Reed (2000) and 30 pc for ultracompact H II regions by Becker et al. (1994), probably as a result of the residual contamination of the colour selected sample by evolved stars.

It is worth briefly considering the effect of the varying sensitivity limits on our selection criteria. First, we considered objects with 21µm detections, that are not detected at 8µm. Obviously such very red sources would be of interest. Sources that were detected at 14 and 21µm, but not at 8µm are mostly artefacts as noted in Section 2.1. There are 5431 sources in the MSX PSC with detections only at 21µm, however. Most of these are near the 21µm detection limit as well. A source at the 21µm detection limit (F_{21} ~ 2 – 4Jy) must have an intrinsic F_{21}/F_{8} ratio greater than ~ 20 – 40 to be truly undetected at 8µm. This would certainly place such a source in our region of interest for finding massive YSOs. However, given the additional constraint provided by the limit at 14µm as well of ~ 1 – 2Jy, we can see from Figure 2 that the number of sources expected to fall in the correct part of the colour-colour space is very small. We inspected several cases at random where objects were claimed as detections at 21µm but not at shorter wavelengths. In most instances, where the ‘detection’ is near the limiting sensitivity, there appears to be no object at any wavelength in the MSX images. This appears to be true regardless of the quality flag present in the MSX PSC. In a few instances the ‘object’ is simply part of a larger extended source (and probably was simply not flagged as a possible point source at the other wavelengths). There are certainly many MSX PSC sources which are actually part of more extended objects rather than point sources at all flux levels. By contrast, again by inspection of a random selection of sources, objects near the detection limit with detections in more than one band are much more likely to be real. We believe it is unlikely therefore that there is a large population of objects which are genuinely detected at 21µm, but sufficiently red to be undetected at any other wavelength.

Of course, there may be a substantial population of objects detected only at 8µm which may satisfy our colour criteria. We checked a random sample of those objects near the 8µm detection threshold without detections in other bands as well and they appear to be reliable. However, we find that the fraction of the 8µm only sources in Figure 7 that satisfy our two colour cuts involving near-infrared colours is only 0.15%. Furthermore from our multi-colour MSX sample the fraction that pass those cuts and the further mid-infrared cuts is 40%. This implies that there are less than two hundred MYSO candidates detected only at 8µm in the full 300 000 source MSX PSC.

This leads naturally to the question of whether we actually expect to detect all of the MYSOs in the galaxy in our multi-colour MSX sample. If we assume the limiting luminosity we wish to detect is 10^{3} L_{\odot}, then we can derive an approximate 21µm flux for such a source at a distance of 20 kpc. We assumed that the bolometric luminosity of these young sources is largely reprocessed by dust and emerges in the far infrared. We compared the far-infrared and MSX fluxes for the sample of known compact HII regions and MYSOs discussed in Section 2.3. For simplicity we assumed the far infrared IRAS flux was given by the relation, \( F_{\text{FIR}} = (20.6F_{12} + 7.54F_{25} + 4.58F_{60} + 1.76F_{100}) \times 10^{-12}\text{Wm}^{-2} \) (Emerson 1988). We took the relation between flux and flux density from Cohen, Hammersley & Egan (2000) for band E, which is \( F_{E} = 4.041 \times 10^{-14} F_{25} \text{Wm}^{-2} \). Typical \( F_{\text{FIR}}/F_{E} \) ratios are in the range 5 – 40. For our putative \( 10^{3} L_{\odot} \) source on the far side of the Galaxy, \( F_{\text{FIR}} \sim 10^{-12}\text{Wm}^{-2} \), and hence \( F_{E} = 2.5 \times 10^{-14} \sim 2 \times 10^{-13}\text{Wm}^{-2} \). The corresponding \( F_{21} \) range is 0.6 – 5.0Jy. Egan et al. (1999) estimate the actual completeness from the source counts as a function of Galactic longitude. They quote a 50% completeness level at 2.5 Jy in the inner two quadrants of the plane, and 3.5 Jy in the outer two quadrants. This crude analysis suggests that we should detect at least 50% of the MYSOs at 10kpc. Later versions of the MSX PSC are expected to be a factor of two deeper (Egan, private communication), so that we should actually be able to detect 100% of the MYSOs within 10kpc eventually, and all but the extremely reddened sources at 20kpc. Of course there are patches of such heavy extinction even in the mid-infrared, as illustrated by the dark clouds seen at 8µm by MSX (e.g. Carey et al. 2000).

Finally, it is worth briefly noting what other observations could be made to distinguish the MYSOs, compact H II regions and the remaining contaminating evolved sources in the colour selected sample. The Sridharan et al. (2002)
study shows that single-dish surveys cannot be relied upon to remove compact H II regions and in any case their resolution and positional accuracy is too low to separate compact H II regions from nearby MYSOs. High resolution radio continuum observations can easily distinguish the bright extended free-free emission from H II regions and PN from the weak, compact stellar wind emission from MYSOs (e.g. Hoare 2002). However, there is always the strong possibility of a MYSO (dominating the mid-infrared flux) being located very close to a compact H II region (dominating the radio flux) such as the case with the BN/KL region behind M42. Missing such MYSOs would heavily bias the final sample against possible examples of triggered/sequential star formation. Here, high resolution ground-based mid-infrared observations are essential since they will reveal any MYSOs as point sources against the extended emission from warm dust in the H II region.

Evolved stars, proto-PN, weak, very compact H II regions and compact PN will all be mid-infrared point sources and could be relatively radio quiet. These will have to be identified by high resolution ground-based near-infrared imaging. The young sources are usually associated with star clusters, nebulosity and extinction, which distinguishes them from evolved sources in the field. The MYSOs often have bipolar or mono-polar reflection nebulae and/or shocked emission, which appears different to the ionization fronts seen around compact H II regions. Near-infrared spectroscopy will be required to identify any remaining difficult cases. Kinematic distances will allow an estimate of the bolometric luminosity and distinguish low-mass and high-mass YSOs.

5 CONCLUSIONS

We have shown that the combination of the MSX and 2MASS plus literature near-infrared data is a powerful diagnostic for detecting and classifying many kinds of embedded source with the Galactic Plane (in agreement with the earlier results of Egan 1999). In particular, the combination provides a good separation between young embedded stars and evolved stars. Evolved stars can easily be separated into those which have oxygen-rich dust and those which have carbon-rich dust, in a similar fashion to that first proposed by Epchtein et al. (1987). The data are also likely to be a valuable tool in detecting normal stars with excess emission by Epchtein et al. (1987). The data are also likely to be a

6 ACKNOWLEDGMENTS

We would like to thank the referee Michael Egan for his helpful comments on the manuscript and the intricacies of the MSX dataset. SLL acknowledges the support of PPARC through the award of an Advanced Research Fellowship. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

Acker A., Ochsenbein F., Stenholm B., Tyndura R., Marcout J., Schohn C., 1992, Strasbourg-ESO Catalogue of Galactic Planetary Nebulae, ESO

Allsnis A., Balklavs A., Dzervitis U., Eglitis I., Paupers O., Pundure I., 2001, Baltic Astronomy, 10, 1

Aoki W., Tsuji T., Ohnka K., 1999, A&A, 350, 945

Aspin C., et al., 1994, A&A, 292, L9

Aumann H.H., 1985, PASP, 97, 885

Becker R.H., White R.L., Helfand D.J., Zoonematkermani S., 1994, ApJS 91 347

Beichman C.A., 1987, ARAA, 25, 521

Bunn J.C., Hoare M.G. & Drew J.E., 1995, MNRAS, 272, 346

Campbell B., Persson S.E., Matthews K., 1989, AJ, 98, 643

Carey S.J., Feldman P.A., Redman R.O., Egan M.P., MacLeod J.M., Price S.D., 2000, ApJ, 543, 157

Carpenter J.M., Snell R.L., Schloerb F.P., Skrutskie M.F., 1993, ApJ, 407, 657

Caswell J.L., Vaile R.A., Ellingsen S.P., Whiteoak J.B., Norris R.P., 1995, 272, 96

Cesaroni R., Felli M., Testi L., Walmsley C.M., Olmi L., 1997, A&A, 325, 725

Chan S., Henning Th., Schreyer K., 1996, A&AS, 115, 285

Chengalur J.N., Lewis B.M., Eder J., Terzian Y., 1993, ApJS, 89, 189

Chini R., Krügel E., Wargau W., 1987, A&A, 181, 378

Codella C., Felli M., Natale V., 1994, A&A, 284, 233

Cohen, M., Hammersley, P.L., Egan, M.P., 2000, AJ, 120, 3362

de Muizon J., Cox P., Lequeux J., 1990, A&AS, 83, 337

Draine B.T., Lee H.M., 1984, ApJ, 285, 89

Draine B.T., 1989, in Infrared Spectroscopy in Astronomy, Proceedings of the 22nd ESLAB Symposium, p 93

Drew J.E., Bunn J.C, Hoare M.G., 1993, MNRAS, 265, 12

Egan M.P., Price S.D., 1996, AJ, 112, 2862

Egan M.P., 1999, Bulletin of the American Astronomical Society, 31, 1507

Egan M.P., et al., 1999, “The Midcourse Space Experiment Point Source Catalog Version 1.2 Explanatory Guide”, (AFRL-VS-TR-1999-1522) (Springfield, VA: Natl. Tech. Inf. Serv.)

Egan M.P., Van Dyk S.D., Price S.P., 2001, AJ, 122, 1844

Emerson J.P., 1988, in Dupree A. K. & Lago M. T. V.
Table 1: The classification from the literature of all multi-colour MSX PSC sources. We have classed as a YSO any object called a YSO, T Tauri star or pre-main sequence star, as an HII region any object classed as an HII region or young stellar cluster, as a planetary nebulae any object with a firm identification, as an evolved star any star with clear mass loss such as a Mira, OH/IR star, carbon star, or pulsating variable, as a variable star any other kind of variable star not covered in the evolved star category, as an ‘other’ star any remaining stellar sources including many emission line stars. The maser sources are a heterogeneous collection, given that the transition observed is not considered, so could pertain to either end of the life of a star. Radio and infrared identifications generally imply that the source is not classified but is known. ID? refers to objects with debatable classification (often possible planetary nebulae).

| Source     | RA (1950) | Dec (1950) | $F_8$ (Jy) | $F_{14}$ (Jy) | $F_{21}$ (Jy) |
|------------|-----------|------------|------------|---------------|---------------|
| W3 IRS     | 02 21 53.3 | +61 52 21  | 183.56     | 851.11        | –             |
| GL 4029    | 02 57 34.6 | +60 17 23  | 6.36       | 17.13         | 117.72        |
| GL 437 S   | 03 03 32.0 | +58 19 12  | 17.08      | 48.64         | 338.12        |
| GL 490     | 03 23 39.2 | +58 36 35  | 57.90      | 138.66        | 271.61        |
| GL 5180    | 06 05 53.9 | +21 38 57  | 5.26       | 13.53         | 78.75         |
| S255 IRS1  | 06 09 58.6 | +18 00 13  | 101.32     | 156.96        | 263.91        |
| GL 961E    | 06 31 59.1 | +04 15 09  | 45.68      | 84.35         | 315.00        |
| GL 989     | 06 38 24.9 | +09 32 28  | 92.19      | 160.86        | 262.34        |
| NGC6334V 4 | 17 16 36.1 | -35 54 47  | –          | 25.76         | 386.49        |

Table 2: Adopted sample of confirmed massive YSOs. Fluxes are taken from the MSX PSC. Fluxes marked as – are listed as non-detections in the MSX PSC, but are clearly the result of problems of the kind indicated in Section 2.1.
Figure 1: The histogram of the separation in quoted position between MSX PSC and related Hipparcos catalogue entries. For simplicity, and to avoid false matches, we have only used MSX PSC sources with overall blue colours.
Figure 2: Mid-infrared colour-colour plots for (a) a region in the inner galaxy with $20^\circ < l < 30^\circ$ and (b) a region in the outer galaxy with $100^\circ < l < 260^\circ$. The solid line maps the location of a black body with temperature between 200K and 5000K. Also shown is the reddening vector corresponding to a visual extinction of $A_V = 40$.

Figure 3: Same as for Figure 2 but for samples of known 'young' sources associated with massive stars. These include Herbig AeBe stars (x), massive YSOs (+), methanol maser sources without radio emission (●) and compact HII regions (○).
Figure 4: Same as for Figure 2 but for samples of known evolved sources. These include carbon stars (●), OH/IR stars (+) and planetary nebulae (∗).

Figure 5: Same as for Figure 2 but for sources classified from IRAS LRS spectra by Kwok et al. (1997). We have only plotted the carbon stars (●), silicate emission objects (+), silicate absorption objects (x) and those classed as having PAH emission without any ionised gas emission (∗). For clarity we have only plotted a random selection of one fifth of the Kwok et al. catalogue. Note in the righthand diagram how the silicate feature moves from emission to absorption along the OH/IR star sequence in direction of the plotted extinction vector. Obscuration in the carbon stars by comparison tracks the black body curve consistent with a power law dependence to the extinction.
Figure 6: Comparison of 2MASS photometry with published data from the literature for objects where both datasets exist from our multi-colour MSX PSC sample. Objects that are noted as saturated in 2MASS are shown as limits at the nominal saturation point with magnitude $\sim$5. Lower limits in the 2MASS PSC are also shown.
Figure 7: Near- and mid-infrared colour-colour plots for sources with detections only at 8µm in the MSX PSC. The data are taken from (a) a region in the inner galaxy with $10^\circ < l < 11^\circ$ and (b) a region in the outer galaxy with $240^\circ < l < 250^\circ$. The solid line maps the location of a simple black body. Also shown is the displacement for a 5000K blackbody due to a visual extinction of $A_V = 10$. 
Figure 8: Near- and mid-infrared colour-colour plots for the same inner and outer galaxy samples as shown in Figure 2(a) and (b). The relative paucity of K-band detections in Figure 8(a) is actually a result of the patchiness of the sky coverage of the 2MASS Second Incremental Release.
Figure 9: As for Figure 8 but for the young sources. The symbols are the same as in Figure 3.

Figure 10: As for Figure 8 but for the evolved sources. The symbols are the same as in Figure 4.
Figure 11: As for Figure 8 but for the sources classified by Kwok et al. The symbols are the same as in Figure 5. In this case we have plotted all the points from the Kwok et al. catalogue that have near-infrared data. Objects with classification in Kwok et al. (1997) other than those shown in Figure 5 are shown here as • for reference. These include normal stars (near the base of the blackbody curve) and objects with forbidden line emission (PN and HII regions). There is a clear separation between oxygen and carbon rich sources in both panels.
Figure 12: Galactic longitude and latitude distribution for the sources satisfying the mid-infrared colours cuts appropriate to the selection of MYSOs. Also shown in (c) is the ratio of the MYSO latitude distribution with that for the full multi-colour sample, clearly demonstrating the smaller scale height for the massive star population.