The RMS Survey: A Galaxy-wide Sample of Massive Young Stellar Objects

J. S. Urquhart¹, M. G. Hoare¹, S. L. Lumsden¹, R. D. Oudmaijer¹, T. J. T. Moore²

¹School of Physics and Astrophysics, University of Leeds, Leeds, LS2 9JT, UK, Astrophysics Research Institute
²Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead, CH41 1LD, UK

Abstract.
Here we describe the Red MSX Source (RMS) survey which is the largest, systematic, galaxy-wide search for massive young stellar objects (MYSOs) yet undertaken. Mid-IR bright point sources from the MSX satellite survey have been followed-up with ground-based radio, millimetre, and infrared observations to identify the contaminating sources and characterise the MYSOs and UCHII regions. With the initial classification now complete the distribution of sources in the galaxy will be discussed, as well as some programmes being developed to exploit our sample.

1. Introduction

Massive stars ($M > 8 M_\odot$, $L > 10^4 L_\odot$) play a fundamental role in many areas of astrophysics. They are the principal source of UV radiation and heavy elements in galaxies, and are responsible for injecting huge amounts of kinetic energy into the ISM through powerful molecular outflows, strong stellar winds and supernova explosions. The momentum imparted through these processes provides an important source of mixing and turbulence within the ISM. They are also thought to play a key role in regulating star formation, either by disrupting molecular clouds before stars have been able to form, or constructively through the expansion of their HII regions (e.g., collect and collapse) or the propagation of strong shocks into their surroundings (e.g., radiatively driven implosion). Massive stars have an enormous influence not only on the physical structure and chemistry of their local environment, but also on the structure and evolution of their host galaxies.

Despite the importance of massive stars the processes involved in their formation and the early stages of their evolution are still poorly understood. Massive stars reach the main sequence while still deeply embedded within their natal molecular clouds, and therefore their entire pre-main sequence formation and evolution is hidden behind high levels of extinction. They are extremely rare and as a consequence are generally located farther away than regions of low-mass star formation. The large distances are compounded by the fact that massive stars are through to form exclusively in clusters and limited spatial resolution makes it difficult to identify and attribute derived quantities to individual
sources. Furthermore, the evolution of massive stars is extremely rapid, which means that key stages in their early evolution are short lived. Due to these observational difficulties, until relatively recently, the only catalogue of massive young stellar objects (MYSOs) had been limited to 30 or so serendipitously detected sources (Henning et al. 1984) most of which are nearby.

2. Colour-selection of MYSO candidates

As massive stars reach the main sequence while still deeply embedded, the obvious place to begin to search for MYSOs is at infrared wavelengths where the majority of the bolometric luminosity ($>10^4 L_\odot$; Wynn-Williams 1982) is emitted after reprocessing by dust. Nuclear fusion has almost certainly begun due to the very short Kelvin-Helmholtz contraction time scale compared to their free-fall time scale (Behrend & Maeder 2001). Accretion is likely to be taking place as the majority of MYSOs are associated with massive outflows (Wu et al. 2004), generally thought to be powered by accretion. Although fusion is taking place, the ongoing accretion is thought to impede the formation of an HII region either by: 1) significantly increasing the star’s radius, leading to a lower effective stellar temperature and characteristic accretion disk temperature (Hoare & Franco 2007), or 2) the HII region being quenched by high infall rates (Walmsley 1995). MYSOs are also known to possess ionised stellar winds that are weak thermal radio sources ($\sim$1 mJy at 1 kpc; Hoare 2002). MYSOs can be roughly parametrised as mid-infrared bright, and thus slightly later than the hot core phase, and radio quiet, and thus earlier than the UCHII region phase, with luminosities consistent with young O and early B-type stars.

To date there have been several attempts to search for MYSOs using colour-selection criteria and the IRAS point source catalogue (e.g., Molinari et al. 1996; Walsh et al. 1997; Sridharan et al. 2002). However, due to confusion in the large IRAS beam ($\sim$3-5' at 100 $\mu$m) these samples tended to avoid dense clustered environments and the Galactic mid-plane where the majority of MYSOs are expected to be located since the scale height of massive stars is $\sim$30' (Reed 2000). Although these IRAS selected samples have identified many genuine MYSOs, they tend to be biased towards bright, isolated sources that are probably not representative of the general population of MYSOs. There is a need for an unbiased sample of MYSOs that is large enough to have a sufficient number of sources in each luminosity bin to allow the processes involved in massive star formation to be investigated in a statistically robust way.

The Midcourse Space eXperiment (MSX; Price et al. 2001) surveyed the whole Galactic plane ($|b|<5^\circ$) in four mid-infrared bands centred at 8, 12, 14 and 21 $\mu$m at a resolution of 18' in all bands. Although the sensitivity of MSX is similar to that of IRAS, its beam size is $\sim$50 times smaller than that of the IRAS 12 and 25 $\mu$m bands and thus avoids most of the confusion problem found with IRAS. The MSX survey therefore offers us the opportunity, for the first time, to identify a truly representative sample of MYSOs located throughout the Galaxy. More recently the Spitzer satellite has surveyed a large region of the inner Galaxy (GLIMPSE; Benjamin et al. 2005) with unprecedented spatial resolution and sensitivity, offering a great improvement on MSX data. However,
most MYSOs are found to be highly saturated and would be missed in any GLIMPSE colour-selected sample.

In order to select potential MYSOs we compared the colours of known MYSOs with sources identified in the MSX and 2MASS point source catalogues (Egan et al. 2003 and Cutri et al. 2003 respectively) and developed colour selection criteria (Lumsden et al. 2002). A lower limit of 2.7 Jy was placed on the 21 µm flux. The detection of a source in 2MASS was not necessary as MYSOs can be totally obscured in the near-infrared; these data were just used to exclude sources that are too blue. The MSX images of all colour selected sources were visually inspected to eliminate sources that are not point-like (see below). Sources toward the Galactic centre (|l| < 10°) were excluded due to confusion and difficulties in calculating kinematic distances. In total we identified approximately 2000 MYSO candidates.

3. Multi-wavelength follow-up observations

The shape of the spectral energy distribution from an optically thick cloud is insensitive to the type of heating source. This is a problem with a colour-selected sample such as ours, as it results in contamination of our sample by several other types of embedded, or dust enshrouded objects that have similar near- and mid-infrared colours to MYSOs (e.g., ultra compact (UC) HII regions, evolved stars and planetary nebulae (PNe)). The core of the RMS survey is a multi-wavelength programme of follow-up observations designed to distinguish between genuine MYSOs and these other types of embedded or dusty objects (Hoare et al. 2005) and to compile a database of complementary multi-wavelength data with which to study their properties.

The main source of contamination of our sample is likely to be by UCHII regions. These can easily be identified through the free-free emission emitted by their ionised nebular gas. Radio continuum observations are thus an essential part of our follow-up programme. We have completed a programme of 5 GHz observations using the ATCA (Urquhart et al. 2007) and the VLA (Urquhart et al. in prep.) of all MYSOs candidates. These observations have a spatial resolution of 1″ and a sensitivity of 1 mJy (3σ), sufficient to detect a B0.5 or earlier type star on the far side of the Galaxy (Giveon et al. 2005). About 25% of RMS sources have detectable radio emission, the majority of which are classified as UCHII regions, due to their morphologies and tight correlation around the Galactic mid-plane.

Mid-infrared imaging has been used to identify genuine point sources from more extended emission. Given the typical size of MYSOs at 10 µm is 0.005 pc (Churchwell et al. 1990) and a spatial resolution of 1″ we would not expect to be able to resolve a MYSO at distances > 1 kpc. However, UCHII regions with a typical size of ~0.1 pc would be resolved at a distance of 15 kpc (~1.4″) as would most PNe. Therefore, mid-infrared imaging can prove extremely useful in identifying, and removing extended mid-infrared objects. Moreover, mid-infrared imaging is complementary to the radio continuum observations and can be used to obtain accurate astrometry and avoid excluding MYSOs that are located in close proximity to UCHII regions. For the majority of our sources the GLIMPSE data have been used for this purpose, however, the ~700 sources
located outside the GLIMPSE region have been observed using UKIRT, Gemini and the ESO 3.6 m telescope at La Silla (Mottram et al. 2007).

To obtain kinematic distances we have made molecular line observations towards every source using $^{13}$CO ($J=2-1$) and ($J=1-0$) transitions and Mopra, Onsala and Purple Mountain Observatory telescopes, and the JCMT (Urquhart et al. 2007; Urquhart et al. submitted to A&A). We have complemented these observations with archival data extracted from the Galactic Ring Survey (GRS; see Jackson et al. 2006 for details). In cases where multiple CO components are detected towards an RMS source we have used a combination of nearby methanol and water masers, or CS ($J=2–1$) observations to identify the component associated with the MYSO candidate. We have calculated kinematic distances using the source $v_{\text{LSR}}$ and the rotation curve of Brand & Blitz (1993); these are crucial for calculating luminosities and thus distinguishing between nearby low- and intermediate-mass YSOs from genuine MYSOs. The majority (~80%) of our sample is located within the solar circle and therefore the rotation curve produces two possible kinematic distances, referred to as the ‘near’ and ‘far’ distances; this is known as the kinematic distance ambiguity. We have used the HI self-absorption technique (Jackson et al. 2002) and HI data from the International Galactic Plane Survey (IGPS; for details see http://www.ras.ucalgary.ca/IGPS/) to resolve these distance ambiguities (e.g., Busfield et al. 2006).

While the observations just discussed are useful in eliminating the vast majority of UCHII regions, PNe and low- and intermediate-mass YSOs, they are not so effective at eliminating evolved stars. We have eliminated most of these using near infrared images in combination with other available data since they tend to appear as isolated point sources at all wavelengths, and are not generally associated with strong CO emission ($^{12}$CO ($J=1-0$ and $J=2-1$) typically less than 1 K; Loup et al. 1993). In contrast, near-IR images of MYSOs often show associated shocked emission from outflows, reflection nebulosity, extinction lanes, as well as clusters of lower mass YSOs.

The combination of near- and mid-infrared imaging, radio continuum and molecular line observations allows us to eliminate most of the contaminating sources. However, there are a few weak UCHII regions, or chance alignments of evolved stars with molecular material, that are not identified. To weed out any remaining contaminating sources, and to confirm the identifications of our final sample of MYSOs, we are obtaining near-infrared spectroscopy from which a definitive classification can be made (e.g., Clarke et al. 2006). We have obtained spectra towards approximately 350 RMS sources so far.

4. Results

As the observational data have become available they have been used to classify the sources in our sample. So far we have classified all but a few of the ~2000 sources and have identified ~450 YSOs and a further ~500 UCHII regions (see Fig. 11 for a detailed breakdown). Along with the YSOs and UCHII regions so far identified, a further ~200 sources have been identified as either YSOs and/or UCHII regions. We are waiting on additional data before making a final
Figure 1. Classification and distribution of RMS sources identified so far using data obtained from our multi-wavelength observations.

Classification. Potentially, taking into account these sources the final number of YSOs and UCHII regions identified so far will be significantly larger.

In the left panel of Fig. 2 we present a histogram of the luminosities for sources identified as either YSOs or UCHII regions and for which good IRAS data was available. These luminosities have been calculated following Emerson (1988). Right panel: Distribution of source luminosities as a function of heliocentric distance.
intermediate-mass YSOs. However, the vast majority have luminosities consistent with late O and early B-type stars.

Figure 3. Galactic distribution of RMS sources identified as either UCHII regions or YSOs. The location of the spiral arms taken from model by Taylor & Cordes (1993) and updated by Cordes (2004) are over-plotted in grey. The positions of the Galactic centre and Sun are shown by black filled and unfilled circles respectively. The Roman numerals in the corners refer to the Galactic quadrants and the two thick black lines which originate from the location of the Sun enclose the region excluded from our survey. The two dashed circles indicate the solar circle and tangent points.

We have determined kinematic distances for all YSOs and UCHII regions, for which an unambiguous $v_{\text{LSR}}$ could be attributed, using the rotation curve of Brand & Blitz (1993). Using these distances and source positions in Fig. 3 we plot the distribution of YSOs and UCHII regions on a face-on view of the Galactic plane. On this plot we have indicated the positions of the Galactic
centre, the Sun, the solar circle and the spiral arms (see figure caption for details). Massive stars are thought to be primarily associated with the spiral arms, and thus could potentially be used as a probe of Galactic structure. Comparing the distribution of our sources and the position of the spiral arms (from the model by [Taylor & Cordes 1993] and updated by [Cordes 2004]) we find them to be reasonably well correlated with each other, especially taking into account the errors in the kinematic distances (typically ±1 kpc). The correlation is particularly apparent towards the inner Galactic arms (i.e., 1st and 4th quadrants), but quite poor for sources in the outer Galaxy.

5. Summary

The RMS survey aims to produce a large, unbiased sample of massive young stellar objects (MYSOs) located throughout the Galaxy. We have colour-selected approximately 2000 MYSO candidates from the MSX and 2MASS point source catalogues that have colours similar to known MYSOs. We have almost completed a multi-wavelength programme of follow-up observations to distinguish between genuine MYSOs and types of embedded or dust enshrouded objects that have similar mid-infrared colours that contaminate our sample. So far using these observations we have unambiguously classified ~90% of our sample, approximately half of which are identified as either YSOs and UCHII regions. The luminosities of a sub-sample of these sources, for which good IRAS data are available, confirms that we are detecting a significant number of genuine MYSOs. When complete, we estimate our database will contain a well selected sample of ~500 bona fide MYSOs and a further 500–600 UCHII regions, along with complementary multi-wavelength observations.

Now the classification is almost complete we have begun a number of observational programmes to exploit our sample and to address many open questions concerned with massive star formation. These include: high resolution observations of potentially triggered regions to investigate different triggering mechanisms; chemical surveys using millimetre lines and IR absorption features to investigate the chemistry and possible chemical evolution of MYSOs; investigation of molecular outflows associated with MYSOs; and high resolution spectroscopy of accretion disks. All of these programmes are being conducted on sub-samples selected as a function of luminosity, distance and location. The whole sample and all of the observational results of our multi-wavelength campaign are available at www.ast.leeds.ac.uk/RMS.

Acknowledgments. We would like to thank the directors and staff of the various telescopes mentioned in this article for their help and support during our observations. JSU is supported by a postdoctoral grant from the Science and Technology Facilities Council (STFC).

References

Behrend, R., & Maeder, A. 2001, A&A, 373, 190
Benjamin, R. A., et al. 2005, ApJ, 630, L149
Brand, J., & Blitz, L. 1993, A&A, 275, 67
Busfield, A. L., Purcell, C. R., Hoare, M. G., Lumsden, S. L., Moore, T. J. T., & Oudmaijer, R. D. 2006, MNRAS, 366, 1096
Churchwell, E., Wolfire, M. G., & Wood, D. O. S. 1990, ApJ, 354, 247
Clarke, A. J., Lumsden, S. L., Oudmaijer, R. D., Busfield, A. L., Hoare, M. G., Moore, T. J. T., Sheret, T. L., & Urquhart, J. S. 2006, A&A, 457, 183
Cordes, J. M. 2004, Milky Way Surveys: The Structure and Evolution of our Galaxy, 317, 211
Cutri, R. M., et al. 2003, The IRSAC 2MASS All-Sky Point Source Catalog, NASA/IPAC Infrared Science Archive. [http://irsa.ipac.caltech.edu/applications/Gator/]
Egan, M. P., et al. 2003, VizieR Online Data Catalog, 514, 0
Emerson, J. P. 1988, NATO ASIC Proc. 241: Formation and Evolution of Low Mass Stars, 193
Giveon, U., Becker, R. H., Helfand, D. J., & White, R. L. 2005, AJ, 129, 348
Henning, T., Friedemann, C., Guertler, J., & Dorschner, J. 1984, Astronomische Nachrichten, 305, 67
Hoare, M. G. 2002, Hot Star Workshop III: The Earliest Phases of Massive Star Birth, ASP Conf. 267. Ed. P. A. Crowther, p137
Hoare, M. G., et al. 2005, Massive Star Birth: A Crossroads of Astrophysics, 227, 370
Hoare, M. G., Franco, J. 2007, Diffuse Matter from Star Forming Regions to Active Galaxies, Eds T.W. Hartquist, et al. ApSS Proc. Springer Dordrecht, 2007, p.61
Jackson, J. M., Bania, T. M., Simon, R., Kolpak, M., Clemens, D. P., & Heyer, M. 2002, ApJ, 566, L81
Jackson, J. M., et al. 2006, ApJS, 163, 145
Loup, C., Forveille, T., Omont, A., & Paul, J. F. 1993, A&AS, 99, 291
Lumsden, S. L., Hoare, M. G., Oudmaijer, R. D., & Richards, D. 2002, MNRAS, 336, 621
Molinari, S., Brand, J., Cesaroni, R., & Palla, F. 1996, A&A, 308, 573
Mottram, J. C., Hoare, M. G., Lumsden, S. L., Oudmaijer, R. D., Urquhart, J. S., Sheret, T. L., Clarke, A. J., & Allsopp, J. 2007, ArXiv e-prints, 709, arXiv:0709.2040, A&A In Press.
Price, S. D., Egan, M. P., Carey, S. J., Mizuno, D. R., & Kuchar, T. A. 2001, AJ, 121, 2819
Reed, B. C. 2000, AJ, 120, 314
Sridharan, T. K., Beuther, H., Schilke, P., Menten, K. M., & Wyrowski, F. 2002, ApJ, 566, 931
Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674
Urquhart, J. S., Busfield, A. L., Hoare, M. G., Lumsden, S. L., Clarke, A. J., Moore, T. J. T., Mottram, J. C., & Oudmaijer, R. D. 2007, A&A, 461, 11
Urquhart, J. S., et al. 2007, A&A, 474, 891
Walmsley, M. 1995, Revista Mexicana de Astronomia y Astrofisica Conference Series, 1, 137
Walsh, A. J., Hyland, A. R., Robinson, G., & Burton, M. G. 1997, MNRAS, 291, 261
Wu, Y., Wei, Y., Zhao, M., Shu, Y., Yu, W., Qin, S., & Huang, M. 2004, A&A, 426, 503
Wynn-Williams, C. G. 1982, ARA&A, 20, 587