MSX Mid Infrared Imaging of Massive Star Birth Environments. I: Ultracompact H\textsc{ii} Regions

Paul A. Crowther*, and Peter S. Conti*  
Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, UK;  
JILA and APS Department, University of Colorado, Boulder CO 80303 USA

ABSTRACT
We present mid-IR 21\mu m images of a sample of radio selected Ultracompact H\textsc{ii} (UCH\textsc{ii}) regions, obtained with the Midcourse Space Experiment (MSX). All, with one possible exception, are detected at mid-IR wavelengths, sampling the warm dust emission of the cocoons of the OB star central exciting sources. Many of the UCH\textsc{ii} regions have nearby (up to \approx few pc distant) companion dust emission sources, which represent other potential star birth sites. In some objects the companion dominates the IRAS point source catalogue entry for the UCH\textsc{ii} region. We compare the mid- and far-IR dust emission, measuring the embedded hot star luminosity, with published UCH\textsc{ii} radio emission, measuring the Lyman continuum luminosity. We find a spectral type dependence, as predicted by the standard model of an ultracompact ionized hydrogen region, surrounded by a natal dust shell, with some scatter, which can be understood by consideration of: 1) dust absorption of some fraction of the emitted Lyman continuum photons; 2) fainter companion stars within the UCH\textsc{ii} region; 3) the structure of the UCH\textsc{ii} regions differing from star to star. Overall, the higher spatial resolution offered by MSX alleviates difficulties often encountered by comparison of IRAS far-IR fluxes with radio derived ionizing fluxes for UCH\textsc{ii} regions.

Key words: H\textsc{ii} regions; stars: formation; infrared: ISM; stars: early-type

1 INTRODUCTION
Massive O and B-type stars are born individually in molecular clouds or collectively within giant molecular clouds (GMCs), which contain substantial amounts of dust. From the collapse and fractionation of the GMC to the final product of a visible star (or a cluster) a number of physical processes are occurring. These include, but are not limited to, the following stages for the star: rapid accretion, the (possible) formation of a disk, slow accretion, the initiation of the zero age main sequence (ZAMS), and normal main sequence evolution. At the same time, but not with identical timescales, its surrounding environment is evolving: the molecular hydrogen is dissociated then ionized into a gradually expanding H\textsc{ii} region; the ice mantles of the dust are evaporated, and the natal cocoon expands, lowering its overall density and opacity. For a recent summary of this general topic, the reader is referred to The Earliest Stages of Massive Star Birth (Crowther 2002).

The wavelength at which the material becomes optically thin to the stellar radiation shifts to shorter and shorter values from the IR. The dust in the cocoon and in the surroundings absorbs and reprocesses the stellar radiation and re-emits it in the far and mid IR (FIR–MIR) regions (from 1 mm down to 10\mu m). As this evolution proceeds, we would expect to observe the following phenomena for each individual stellar object:

- A ‘Hot Core’ phase (e.g., Kurtz et al. 2000) in which a source of IR dust emission surrounding a buried star is found. The star is sufficiently luminous to heat the dust but it is not (yet?) hot enough to produce sufficient Lyman Continuum photons. Alternatively, the infalling material is “quenching” the formation of an H\textsc{ii} region (e.g. Osorio et al. 1999).

- The star forms an ultracompact H\textsc{ii} (UCH\textsc{ii}) region (e.g., Churchwell 1999ab) which can be identified from its free-free radio emission. The ionized hydrogen is surrounded by a natal dust cocoon which radiates in the FIR–MIR.

- The UCH\textsc{ii} region expands, becoming a compact H\textsc{ii} (CH\textsc{ii}) region, as the dust evaporates and the overlying cocoon expands and thins out (as in, e.g., W49A – Conti & Blum 2002). The FIR–MIR emission gradually diminishes.

- The dust becomes optically thin at visible wavelengths. Eventually the star no longer has any surrounding
natal material (e.g., a disk). We will identify this time as the end of the birth process for an individual massive star.

Two key parameters of the birth processes for massive stars are those of the H\textsc{ii} region and those of the dust emission. The former can be estimated from the Lyman continuum luminosity, or extreme ultraviolet (EUV) radiation, which is highly dependent on the stellar temperature (e.g., Smith, Norris & Crowther 2002); the latter from the overall stellar luminosity (primarily the UV radiation) along with the dust properties (thickness, extent, and distance from the star). As the birth process goes forward, we would expect both of these parameters to change in response to the stellar evolution and the varying dust in the surrounding cocoon. The dust emission will undergo the largest change as it responds to the evolution of the environment. The Lyman continuum and the UV luminosity should not change dramatically as once the star “turns on” (at the ZAMS) as one would expect that substantial accretion will come to a halt (thus $T_{\text{eff}}$ and $L_{\text{bol}} \approx \text{constant}$). For cases in which the central O star is obscured by hundreds of magnitudes of visual extinction, the situation is much simpler at mid-IR wavelengths, where the extinction is several hundred times lower.

Until recently, there had not been any MIR Galactic plane surveys of medium spatial resolution\textsuperscript{1}. The Midcourse Space Experiment (MSX) remedied this situation, with a complete Galactic plane survey within $|b| \leq 5^\circ$ (Price et al. 2001) at 18\arcsec spatial resolution. Ultimately, the Space Infrared Telescope Facility (SIRTF) will achieve a much higher spatial resolution. For the moment, however, MSX permits the comparison between radio and MIR fluxes of almost all known massive star birth sites, so as to better understand the relationship between the H\textsc{ii} regions and the dust cocoons. In this paper we shall begin with a study of a sample of the UCH\textsc{ii} regions in our Galaxy, which are generally believed to be excited by one or a few dominant stars, and ought to represent the simplest cases to investigate. A subsequent paper will consider our results for H\textsc{ii} and giant H\textsc{ii} (GH\textsc{ii}) regions.

We begin in Section 2 by outlining the extraction procedure for obtaining MIR data from the MSX satellite. In Section 3 we list the sample of UCH\textsc{ii} objects from the catalogs of Wood & Churchwell (1989) and Kurtz, Churchwell \& Wood (1994) that we have studied. We discuss in Section 4 the MIR images at 21 \textmu m of the UCH\textsc{ii} regions, and comment on similarities and differences between the objects. Many objects are multiple, with close (within a few pc) companions. In some of these, the IRAS fluxes of the UCH\textsc{ii} regions will have been affected by the nearby objects, in a few cases drastically so. In Section 5 we first consider the relationships among the MSX medium resolution and IRAS low resolution data for our sources. After accounting for the multiplicity of some sources in the IRAS data, and noting a “colour” term in the MSX data, we recover the spectral type dependence of the EUV to UV fluxes of the sources, as predicted by relatively simple models of UCH\textsc{ii} regions. Conclusions are given in Section 6.

\textsuperscript{1} IRAS had 30\arcsec, 30\arcsec, 1\arcmin, 2\arcmin resolutions for the 12\textmu m, 25\textmu m, 60\textmu m, 100\textmu m filters, respectively

![Figure 1. Comparison between the broad band, mid-IR filter profiles of MSX, of which Band C (12\textmu m) and Band E (21\textmu m) are used here, and the IRAS 12 and 25\textmu m filters, together with the ISO/SWS spectrum of the UCH\textsc{ii} region G29.956–0.016 (Morisset et al. 2002) for comparison. Strong fine-structure nebular lines include [Ne ii] 12.8\textmu m, [Ne iii] 15.5\textmu m and [S iii] 18.7\textmu m.](image-url)
Table 1: Mid-IR (MSX/IRAS) and radio (VLA/Arecibo) fluxes (in Jy) for Galactic UCH\textsc{ii} regions from Wood & Churchwell (1989, WC) and Kurtz et al. (1994, KCW). UCH\textsc{ii} regions with multiple radio peaks are summed together (e.g. G10.47+03 A,B,C).

| UCH\textsc{ii} G | IRAS | 12\textmu m MSX | 21\textmu m MSX | 25\textmu m IRAS | 100\mu m VLA | 2 cm VLA | d Ref | log N LyC | 21\mu m a | 25\mu m a | 21\mu m a | 100\mu m | Radio morph | MSX morph |
|----------------|------|----------------|----------------|----------------|--------------|---------|-------|----------|----------|----------|----------|----------|----------------|----------------|
| [WC89] 5.476–0.243 | 17559-2420 | 23 | 89 | 194 | 2170 | 0.12 | 14.3 | 1 | 48.35 | 0.59 | 0.34 | — | — | Core-Halo | Extended |
| [WC89] 5.885–0.392* | 17574-2403 | 128 | 776 | 2190 | 26780 | 6.54 | 2.90 | 2.0 | 48.54 | 0.78 | 0.45 | 2.08 | 3.61 | Shell | Multiple |
| [WC89] 5.972–1.174 | 18006-2422 | 120 | 762 | 1842 | 9036 | 0.28 | 2.7 | 2.7 | 47.71 | 0.80 | 0.65 | — | — | Core-Halo | Extended |
| [WC89] 8.669–0.356* | 18034-2137 | <0.8: | 10 | 154 | 5221 | 0.57 | 0.63 | 4.6 | 48.09 | >1.1: | 1.19 | 1.23 | — | — | Core-Halo | Double |
| [WC89] 10.304–0.147* | 18060-2005 | 53 | 189 | 1042 | 12010 | 0.51 | 6.0 | 2 | 48.21 | 0.55 | 0.74 | — | — | — | — | Cometary | Multiple |
| [WC89] 10.460+0.032* | 18056-1952 | 5.3 | 18 | 106 | 10160 | 0.12 | 5.8 | 2 | 48.22 | 0.53 | 0.77 | — | — | Spherical | Double |
| [WC89] 10.472+0.027* | 18056-1952 | 3.1 | 19 | 106 | 10160 | 0.05 | 5.8 | 2 | 47.20 | 0.79 | 0.75 | — | — | Spherical | Double |
| [WC89] 10.623–0.384* | 18075-1956 | 3.8 | 41 | 148 | 21370 | 2.13 | 1.21 | 1 | 49.82 | 1.03 | 1.28 | — | — | Core-Halo | Multiple |
| [KCW94] 10.841–2.592 | 18162-2048 | 22 | 149 | 347 | 3709 | 0.009 | 1.9 | 3 | 5.00 | 0.83 | 0.45 | 2.08 | 3.61 | Multiple | |
| [WC89] 11.938–0.616 | 18110-1854 | 12 | 99 | 222 | 4930 | 1.07 | 0.88 | 5.2 | 47.71 | 0.80 | 0.65 | — | — | Cometary | Double |
| [WC89] 12.209–0.103* | 18097-1825A | 2.7 | 7 | 10 | 4221 | 0.23 | 13.5 | 2 | 48.62 | 0.41 | 0.16 | 1.46 | — | — | Cometary | Multiple |
| [WC89] 12.429–0.049 | 18099-1811 | 1.8: | 3 | 8 | 510 | 0.04 | 16.7 | 1 | 47.99 | 0.2: | 0.5: | — | — | Cometary | Single |
| [KCW94] 18.146–0.284 | 18222-1317 | 43 | 138 | 394 | 8494 | 0.011 | 4.2 | 3 | 46.82 | 0.51 | 0.45 | 4.10 | 5.89 | Shell | Double |
| [KCW94] 18.608–0.234 | 18248-1158 | 47 | 195 | 407 | 7093 | 0.31 | 0.80 | 3.5 | 47.62 | 0.62 | 0.32 | 2.80 | 4.36 | Cometary | Extended |
| [WC89] 20.080–0.135* | 18253-1130 | 4.6 | 21 | 76 | 2761 | 0.51 | 3.4 | 2 | 47.78 | 0.66 | 0.56 | 1.61 | 3.73 | Cometary | Multiple |
| [WC89] 23.455–0.201* | 18319-0834 | <1.2: | 2: | 122 | 9595 | 0.01 | 9.0 | 1 | 46.84 | 0.2: | 1.8: | — | — | Spherical | Multiple |
| [WC89] 23.711+0.171* | 18311-0809 | 20 | 78 | 184 | 2904 | 0.15 | 8.9 | 2 | 48.02 | 0.59 | 0.37 | — | — | Core-Halo | Double |
| [WC89] 25.716+0.049* | 18353-0628 | 5.0 | 31 | 105 | 2435 | 0.02 | 9.3 | 2 | 47.08 | 0.79 | 0.53 | — | — | Spherical | Multiple |
| [KCW94] 28.200–0.049 | 18403-0417 | 63 | 473 | 178 | 3937 | 0.77 | 9.1 | 3 | 48.47 | 0.53 | 0.40 | 1.96 | 3.71 | Single | |
| [WC89] 33.915+0.110 | 18502+0051 | 208 | 1022 | 1697 | 11670 | 2.66 | 1.37 | 7.4 | 49.17 | 0.69 | 0.22 | 2.58 | 3.64 | Cometary | Multiple |
| [WC89] 34.255–0.145 | 18507+0110 | 106 | 434 | 1106 | 32460 | 4.18 | 1.58 | 4.0 | 48.83 | 0.61 | 0.41 | 2.02 | 3.89 | Cometary | Multiple |
| [WC89] 35.199–1.743 | 18592+0108 | 88 | 471 | 1073 | 13960 | 2.37 | 1.93 | 3.1 | 48.40 | 0.73 | 0.34 | 2.30 | — | Cometary | Extended |
| [WC89] 37.545–0.112* | 18577+0358 | 13 | 48 | 106 | 1867 | 0.23 | 9.9 | 2 | 48.30 | 0.57 | 0.34 | — | — | Core-Halo | Extended |
| [KCW94] 38.784–0.399 | 18590+0408 | 42 | 129 | 304 | 4524 | 3.07 | 9.2 | 3 | 49.18 | 0.49 | 0.37 | 1.62 | 3.18 | Single | |
| [WC89] 43.889–0.783 | 19120+0917 | 15 | 74 | 145 | 1511 | 0.51 | 0.36 | 4.2 | 47.96 | 0.69 | 0.29 | 2.16 | 3.47 | Cometary | Extended |

(1) Wood & Churchwell (1989); (2) Churchwell et al. (1990); (3) Kurtz et al. (1994); (4) Acord et al. (1998)

(a) entries are presented in logarithms for ready comparison with figures.
Table 1: (continued)

| UCH II G | IRAS      | 12µm | 21µm | 25µm | 100µm | 2 cm | 6 cm | d Ref | log N | 21µm/12µm | 25µm/21µm | 21µm/21µm | 100µm/21µm | Radio | MSX |
|----------|-----------|------|------|------|-------|------|------|------|------|------------|------------|------------|------------|--------|-----|
|          |           | MSX | MSX | IRAS | IRAS | VLA | VLA | kpc  | Ly C | 12µm       | 21µm       | 21µm      | 21µm      | morph | morph |
| [WC89]   | 45.071+0.132 | 19110+1045 | 47   | 234  | 494  | 7497 | 0.59 | 0.14 | 6.0  | 2           | 48.33      | 0.70       | 0.32       | 2.60   | 4.10  |
| [WC89]   | 45.122+0.132 | 19111+1048 | 260  | 1007 | 1395 | 7497 | 3.68 | 1.17 | 6.9  | 2           | 49.25      | 0.59       | 0.14       | 2.44   | 3.31  |
| [WC89]   | 45.456+0.060 | 19120+1103 | 71   | 367  | 640  | 7890 | 0.42 | 0.6  | 6.6  | 2           | 48.21      | 0.71       | 0.24       | --     | --    |
| [WC89]   | 45.466+0.046* | 19120+1103 | 0.6  | 17   | 640  | 7890 | 0.08 | 0.6  | 1.46 | 1.6:       | --         | --         | --         | --     | --    |
| [WC89]   | 48.606+0.024* | 19181+1349 | 9.3  | 33   | 175  | 5227 | 0.06 | 9.7  | 3    | 47.59      | 0.55       | 0.72       | 2.74       | --     | --    |
| [WC89]   | 49.490–0.370* | 19213+1424 | 402  | 1658 | 4344 | 26760| 5.35 | 0.50 | 6.6  | 2           | 49.37      | 0.62       | 0.42       | 2.49   | --    |
| [WC89]   | 54.094–0.060 | 19294+1836 | 6.7  | 22   | 50   | 2136 | 0.002| 7.9  | 1    | 46.00      | 0.52       | 0.36       | --         | --     | --    |
| [KCW94]  | 60.884–0.128 | 19442+2427 | 30   | 208  | 425  | 5174 | 0.029| 2.3  | 3    | 46.50      | 0.84       | 0.31       | 3.86       | 5.26   | --    |
| [WC89]   | 61.473+0.093* | 19446+2505 | 64   | 458  | 1185 | 13210| 0.25 | 6.5  | 2    | 47.22      | 0.85       | 0.41       | --         | --     | --    |
| [WC89]   | 61.694+0.024* | 19598+3324 | 290  | 927  | 1780 | 12980| 5.15 | 8.6  | 3    | 49.29      | 0.51       | 0.28       | 2.26       | 3.38   | --    |
| [KCW94]  | 70.293+1.600* | 19598+3324 | 15   | 58   | 1780 | 12980| 0.23 | 8.0  | 3    | 48.15      | 0.60       | 1.49       | 2.41       | --     | --    |
| [WC89]   | 75.783+0.343* | 20198+3716 | 8.2  | 45   | 480  | 6985 | 0.04 | 4.1  | 2    | 46.78      | 0.74       | 1.03       | --         | --     | --    |
| [WC89]   | 75.835+0.400 | 20197+3722 | 109  | 656  | 1225 | 6985 | 0.27 | 5.5  | 1    | 47.86      | 0.78       | 0.27       | --         | --     | --    |
| [KCW94]  | 76.383–0.621 | 20255+3712 | 164  | 1050 | 2510 | 13130| 0.017| 1.0  | 3    | 45.06      | 0.81       | 0.38       | 4.80       | 5.90   | --    |
| [KCW94]  | 78.438+2.659 | 20178+4046 | 26   | 339  | 551  | 2877 | 0.036| 3.3  | 3    | 46.83      | 1.12       | 0.21       | 3.98       | 4.91   | --    |
| [WC89]   | 81.679+0.537* | ...       | 27   | 307  | 0.88 | 2.0  | 3    | 47.52 | 1.06 | --         | 2.54       | --         | Core-Halo | Double  |
| [KCW94]  | 81.683+0.541 | ...       | 33   | 397  | 0.61 | 2.0  | 3    | 47.35 | 1.08 | --         | 2.81       | --         | Core-Halo | Double  |
| [KCW94]  | 109.871+2.113 | 20543+6145 | 5.3  | 249  | 820  | 20470| 0.027| 0.7  | 3    | 44.62      | 1.67       | 0.52       | 3.97       | 5.88   | --    |
| [KCW94]  | 111.282–0.663 | 23138+5945 | 16   | 92   | 233  | 2164 | 0.080| 2.5  | 3    | 46.68      | 0.75       | 0.40       | 3.06       | 4.34   | Core-Halo |
| [KCW94]  | 111.612+0.374 | 23133+6050 | 38   | 371  | 581  | 2694 | 0.68 | 5.2  | 3    | 48.21      | 0.98       | 0.19       | 2.74       | 3.59   | Shell |
| [KCW94]  | 133.947+1.064* | 02232+6137 | 32   | 250  | 536  | 10600| 2.53 | 3.0  | 3    | 47.92      | 0.89       | 0.33       | 2.00       | 3.62   | Spherical |
| [KCW94]  | 139.909+0.197* | 03035+5819 | 25   | 237  | 396  | 1297 | 0.018| 4.2  | 3    | 46.43      | 0.98       | 0.22       | 4.11       | 4.85   | Spherical |
| [KCW94]  | 192.584–0.041* | 06099+1800 | <1.5: | 16   | 371  | 5285 | 0.026| 2.5  | 3    | 46.03      | >1.05      | 1.37       | 2.79       | --     | Multiple |

(1) Wood & Churchwell (1989); (2) Churchwell et al. (1990); (3) Kurtz et al. (1994); (4) Acord et al. (1998)
(a) entries are presented in logarithms for ready comparison with figures.
known IRAS 12µm and 25µm bands as illustrated in Fig. 11 where ISO/SWS spectroscopy of the prototypical UCH\(\text{ii}\) region G29.956–0.016 is also presented (Morisset et al. 2002). The calibration and photometric accuracy of MSX are discussed in detail by Egan et al. (1999). The zero magnitude flux is based on the Kurucz model for Vega (Cohen et al. 1992), and correspond to \(9.259 \times 10^{-13}\) W m\(^{-2}\) (Band C) and \(3.555 \times 10^{-13}\) W m\(^{-2}\) (Band E).

Individual UCH\(\text{ii}\) images were obtained from the MSX Image Server at IPAC [http://irsa.ipac.caltech.edu/applications/MSX/](http://irsa.ipac.caltech.edu/applications/MSX/). For our purposes, we sought integrated MIR fluxes in Janskys for comparison with radio fluxes. Consequently, the MSX point source catalogue was not appropriate, given the need to use apertures precisely centred on the radio coordinates. Spatial integration was measured in Gaia (Draper, Gray & Berry 2001) using a circular aperture of radius 3 pixel (\(18''\)). Aperture centres were selected to precisely mimic those of the corresponding radio observations. Thin annuli, with 3 pixel radii (\(18''\)), were used to correct for the background flux levels, taking care to avoid sources in the annuli. Spatial integration over the images provides fluxes in units of W m\(^{-2}\), after correction for the \(6''\) \(\times\) \(6''\) pixel-area, i.e. \(8.4615 \times 10^{-16}\) sr. Division by the filter bandwidth then provides fluxes in W m\(^{-2}\) Hz\(^{-1}\) (= \(10^{26}\) Jy). Finally, a multiplication by 1.113 is required to convert the square area pixels into the correct Gaussian area (Cohen, priv. comm.). The total scale factor for Band C corresponds to a multiplicative factor of 26.45 in order to convert the IPAC integrated fluxes to mJy, whilst the corresponding factor is 23.72 for Band E.

### 3 SELECTION OF SAMPLE

We included all the UCH\(\text{ii}\) regions from Wood & Churchwell (1989) and Kurtz et al. (1994) for which 2 or 6 cm radio fluxes (and so ionizing fluxes) exist, and contain MSX datasets for which data could be extracted. We have omitted G15.042–0.676 since its MIR flux is totally dominated by the surrounding GH\(\text{ii}\) region M17. Distances have been kinematically determined from Galactic rotation model by Churchwell, Walmsley & Cesaroni (1990) or Kurtz et al. (1994), except where noted. Table 1 lists the parameters of the UCH\(\text{ii}\) regions we have studied in the MIR. The various columns will be discussed in due course.

### 4 MID-IR MORPHOLOGIES

#### 4.1 Discussion of individual objects

Figures A.1– 8 in the Appendix contain 21\(\mu\)m images of our sources at spatial scales of \(10'\) \(\times\) \(10'\), having first been transformed from (l, b) to (RA, Dec.) for epoch J2000.0. We have indicated the physical scales, using the distances derived from Churchwell et al. (1990) or Kurtz et al. (1994).

We have also made corresponding images of the 12\(\mu\)m data from MSX (not presented here). For the most part, these appear similar with the exception that 1) several UCH\(\text{ii}\) sources are not visible at this wavelength and 2) some other point sources are seen at the shorter wavelength but not the longer one. The former are inordinately red sources with a cool dust origin, whilst the latter are probably stars, which would typically be brighter at 12\(\mu\)m. NIR images of the central \(0.5'\) \(\times\) \(0.5'\) for many UCH\(\text{ii}\) regions are presented by Hanson, Luhman & Rieke (2002).

To facilitate the presentations below, we have indicated with an asterisk (*) those sources for which the lower resolution IRAS photometry and its Point Source Catalog (PSC) will be affected by a brighter nearby companion as suggested by our images.

#### 4.1.1 [WC89] G5.476–0.243

The 21\(\mu\)m image of G5.476 is presented in Fig. A1(a), revealing a single core, but within a spatially extended source. The nearest mid-IR source is much fainter, and is probably unrelated as it lies 150'' (at least \(\sim\)10 pc) away to the north east.

#### 4.1.2 [WC89] G5.885–0.392*

G5.885, alias W28 A2(1), is amongst the brightest UCH\(\text{ii}\) in our sample at mid-IR wavelengths. The mid-IR morphology is shown in Fig. A1(b), and reveals an elongation to the SE, probably due to another source. From MSX, a separate spatially extended region is only 2.5'' away (\(\sim\)1.5 pc) which also contains a bright point source at G5.898–0.441 (same IRAS source as G5.885). Kim & Koo (2001) have recently presented 21cm VLA observations with a spatial resolution comparable to MSX, revealing a morphology very similar to Fig. A1, with G5.885 corresponding to their more compact western source. Since the larger eastern source is a radio emitter it is not a hot core. These are embedded within a large region (\(14' \times 9'\)) of weak emission.

Note that we have adopted 2 kpc for the distance to G5.89 as determined by Acord, Churchwell & Wood (1998). This object was used as the basis of the standard model of an UCH\(\text{ii}\) region by Wolfire & Churchwell (1994). Feldt et al. (1999) discuss arcsecond resolution NIR and MIR images of G5.885.

#### 4.1.3 [WC89] G5.972–0.174

G5.972, within the Lagoon Nebula (M8), appears as an extended mid-IR source in the MSX image Fig. A1(c), although it is uniquely surrounded by a very large, extended halo, several parsec in extent. The flux enclosed within a radius of 36 arcsec is a factor of 2 times larger than the nominal (18 arcsec radius) value. Stecklum et al. (1998) discuss high spatial resolution optical, IR and radio observations of G5.972. 21cm data, showing the larger scale structure, are presented by Kim & Koo (2001), revealing a very large (\(14' \times 10'\)) extended envelope surrounding the UCH\(\text{ii}\) region, including an arclike structure originating from the SE, that has no obvious mid-IR counterpart.

#### 4.1.4 [WC89] G8.669–0.356*

From our sample, G8.669 has amongst the reddest 12–21\(\mu\)m index, such that it is barely detectable at 12\(\mu\)m, with a corresponding low dust temperature. The mid-IR flux measured
by IRAS at the location of G8.669–0.356 is actually dominated by a probable hot core some 40″ or 0.9 pc away - Fig. A1(d). Consequently, previously derived luminosities obtained from the IRAS PSC for this UCHII represent a strong overestimate, i.e. 19 Jy was measured by IRAS at 12µm versus <0.8 Jy obtained here for the UCHII region.

4.1.5 [WC89] G10.304–0.147*

The mid-IR image of G10.304, within the W31 HII complex, is shown in Fig. A1(e), and reveals it to be spatially extended, with a faint dust tail extending north-west, with a probably related strong extended source, centred 70″ away (~2 pc) to the NE at G10.321–0.157. IRAS 18060–2005 contains both IR sources, such that the IR luminosity of G10.304 has previously been strongly overestimated. Kim & Koo (2001) present 21cm VLA observations of G10.304, also revealing strong, concentrated emission in the bright mid-IR source to the NE. A faint radio envelope surrounds both components, extending 13′ × 5′ to the NW and SE.

4.1.6 [WC89] G10.472+0.032* and 10.460+0.027*

From Fig. A1(f) MSX separates the two UCHII regions G10.46 and G10.47 45″ or 1.2 pc apart, hitherto unresolved by IRAS (18056-1952). A third mid-IR source lies to the south, alias IRAS 18056-1954. Hatchell et al. (2000) present JCMT SCUBA images of this region, revealing a strong peak in the 850µm flux at the source A of Wood & Churchwell (1989), with G10.460+0.027A also weakly detected. Garay et al. (1993) show 20cm radio observations.

4.1.7 [WC89] G10.623–0.384*

MSX images of the environment of G10.623 reveal a complex of mid-IR sources, as shown in Fig. A2(a), of which the UCHII itself has a nearby, fainter, point source 25″ to the north east, plus a brighter mid-IR source G10.598–0.383 to the south west 90″ (8 pc) away. The IRAS source 18075–1956 is dominated by the latter, at least in the 12–25µm bands.

4.1.8 [KCW94] G10.841–2.592

Fig. A2(b) shows that a bright IR source is coincident with the radio position of G10.841, with two close, fainter companions ~30″ away to the east and north-west. G10.841 itself, coincident with the GGD 27 complex, has been the subject of high resolution mid-IR imaging by Stecklum et al. (1997). Peeters et al. (2002) have recently presented ISO spectroscopy of G10.841.

4.1.9 [WC89] G11.938–0.616

Fig. A2(c) indicates that G11.938 is elongated, with a much fainter IR source 70″ away (1.4 pc) to the SW.

4.1.10 [WC89] G12.209–0.135*

The UCHII G12.209 is a very weak mid-IR source according to Fig. A2(d), with two potentially related and much brighter IR sources that dominate the 21µm flux. The closest of these is 60″ or 4 pc away to the SW at G12.193–0.104. Kim & Koo (2001) present low resolution 21cm VLA observations of G12.209, revealing a spatial morphology very similar to the mid-IR, with the two sources to the SW and SE brighter than the UCHII itself, such that these are not hot cores. Faint extended radio emission also extends NE of the G12.209, as in the mid-IR. Hatchell et al. (2000) present 850µm and 450µm SCUBA images of this region, showing a peak associated with the UCHII region.

4.1.11 [WC89] G12.429–0.049

G12.429 appears single but is extremely weak at 12µm and 21µm as measured by MSX. It has the bluest color index of our sample, implying the highest dust temperature. This object is well isolated with no other mid-IR source within 10 pc as illustrated in Fig. A2(e). Kim & Koo (2001) have presented 21cm radio data of G12.429.

4.1.12 [KCW94] G18.146–0.284

Fig.A2(f) reveals that G18.146 lies at the peak of a very extended (~2 pc) region of dust emission with multiple sources arranged along a NS axis.

4.1.13 [WC89] G19.608–0.234

G19.608 is spatially extended with a faint halo, according to Fig. A3(a), albeit no other nearby mid-IR companions.

4.1.14 [WC89] G20.080–0.135*

MSX images reveal G20.080 to be double, with a potentially related companion only 36″ or 0.6 parsec to the south – see Fig. A3(b). The companion is brighter than G20.080 at 12µm, though comparable at 21µm, such that it may be stellar in origin. IRAS 18253-1130 contains both sources. Faint, nearby companions lie to the north and west.

4.1.15 [WC89] G23.455–0.201*

This UCHII is unique amongst our sample in that it is essentially invisible to MSX at both 12 and 21µm – Fig. A3(c). The strong IRAS source 18319–0834 commonly used to constrain the spectral energy distribution of G23.455 is in fact located 80″ to the south, within a complex, extended region centred at 23.437–0.209. Consequently, we measure an upper limit of ~2 Jy for G23.46 itself at 21µm, in contrast with 122 Jy obtained from the IRAS PSC at 25µm. We could find no evidence for an error in the published radio position, or with our MSX coordinates. Indeed, Kim & Koo (2001) present 21cm radio observations that confirm the mid-IR view, namely that G23.455 lies at the northern edge of a strong radio source, spatially coincident with G23.437–0.209 which must be more evolved than a hot core. Further to the south radio emission extends along an east-west direction, coincident with a series of fainter mid-IR sources.
Fig. A3(d) reveals that G23.711 is double, with a companion 36" to the south east. The companion has a comparable 12μm flux to the UCH II, but is 30% fainter at 21μm which suggests that it may be stellar in origin. IRAS 18311–0809 contains both sources. Kim & Koo (2001) included G23.711 in their 21cm survey of UCH II regions, also showing a spatial extension from G23.711 to the SE.

The UCH II region G25.716 appears to be single, albeit with a nearby brighter mid-IR region 100" or 4 pc to the south – see Fig. A3(e). IRAS 18353–0628 is centred on the brighter IR source, such that an IR luminosity inferred from IRAS for the UCH II would represent a strong overestimate. This UCH II region was also studied at 21cm by Kim & Koo (2001). Although the radio spatial morphology closely matches the mid-IR view, Kim & Koo argued that the source to the south is not physically connected to G25.716 owing to a very different radial velocity.

G28.200 appears to be single from MSX 21μm images presented in Fig. A3(f).

MSX imaging reveals the core of G28.288 be elongated, as illustrated in Fig. A4(a). There is also a companion a factor of four times fainter at 21μm 100" to the east. IRAS 18416–0420 contains both sources.

G29.956 is the prototypical cometary UCH II region, and is amongst the brightest of our sample at mid-IR wavelengths despite its large distance (7.4 kpc, Churchwell et al. 1990). Fig. A4(b) reveals the core of G29.956 to be extended. Very high spatial resolution (0.5") mid-IR imaging has recently been presented by De Buizer et al. (2002). The closest mid-IR source is G29.935–0.055, an extended region located 2.5' away to the south east, which is also prominent in 21cm radio observations of Kim & Koo (2001). These, together with a further source to the SW, lie within a complex extended region.

This UCH II region is excited by an O5–6V star according to near-IR spectra discussed by Watson & Hanson (1997) and Hanson et al. (2002). Peeters et al. (2002) present the ISO spectrum of G29.956, which is analysed by Morisset et al. (2002) with reference to the ionizing source (see, however, Lumsden et al. 2003).

G30.535 appears to have a single core in the mid-IR as shown in Fig. A4(c), albeit with a faint halo.

G31.414 appears to have a single core, again with an extended halo – see Fig. A4(d). Garay et al. (1993) present 2-20cm radio images of G31.414. The SCUBA sub-mm emission reveals a central peak coincident with the UCH II region, with some extension to the south (Hatchell et al. 2000).

G32.798 is single according to our MSX images presented in Fig. A4(e). Peeters et al. (2002) presented the ISO spectrum of G32.80. Garay et al. (1993) present 2-20cm VLA radio observations, whilst Kurtz et al. (1999) have identified extended emission from 3.6cm imaging.

G33.915 again appears to have a single core, but with a faint halo – Fig. A4(f). The ISO spectrum of G33.92+0.11 is presented by Peeters et al. (2002). Fey et al. (1992) and Garay et al. (1993) discuss the radio morphology of G33.915 from 2 to 20cm.

G34.255 appears fuzzy with a strong dust tail extending east-west below the central source – Fig A5(a). G32.80 contains a central dense, core but with an envelope with a condensation extending 90" or ≈ 2 pc to the south – see Fig. A5(b). Takahashi et al. (2000) infer stellar properties of G35.199 from mid-IR imaging in the [Ne II] 12.8μm filter.

G35.199 contains a central dense, core but with an envelope with a condensation extending 90" or ≈ 2 pc to the south – see Fig. A5(a). Takahashi et al. (2000) infer stellar properties of G35.199 from mid-IR imaging in the [Ne II] 12.8μm filter.

G37.545 appears spatially extended with another possible embedded source – Fig. A5(c). Kim & Koo (2001) present 21cm radio observations of G37.545.

G37.87 appears to be single, with faint extended dust emission extending ~60", as illustrated in Fig. A5(d).

This UCH II appears as a point source at 21μm according to Fig. A5(e), with extended emission extending SE containing a condensation. The sub-mm SCUBA image of Hatchell et al. (2000) reveals a single peak towards to the radio position.
4.1.30 [WC89] G45.071+0.132 and G45.122+0.132

G45.071 and G45.122 are 3′ apart on the sky, such that their physical separation is ~6 pc if they lie at a common distance of 6.5 kpc. Churchill et al. (1990) suggest a distance of 6 kpc to G45.07 and 6.9 kpc to G45.12. These UCH\(\text{II}\) regions have previously been resolved by IRAS at 12 and 25\(\mu\)m, such that G45.071 is IRAS 19110+1045, whilst G45.122 is IRAS 19111+1048. The latter has a companion 50″ away to the north west, at G45.134+0.144 – see Fig. A5(f). This weakly contaminates the 25\(\mu\)m IRAS measurement of G45.122. Lumsden et al. (2003) infer a cluster of OB stars, rather than a single O star, power both UCH\(\text{II}\) regions, while Takahashi et al. (2000) infer stellar properties of G45.122 from mid-IR imaging in [Ne\(\text{II}\)] 12.8\(\mu\)m. Hunter et al. (1997) discuss sub-mm observations of the molecular cores containing these two UCH\(\text{II}\) regions, suggesting that G45.122+0.132 is at a more advanced state of star formation.

4.1.31 [WC89] G45.456+0.060 and G45.466+0.046*

G45.456 is very bright at mid-IR wavelengths, with an elongated core. Of the three nearby, much fainter 21\(\mu\)m sources seen in Fig. A6(a), only the object 60″ to the north west is also seen at 12\(\mu\)m. Indeed, the faint source 70″ to the east of G45.456 is the UCH\(\text{II}\) G45.466+0.046 which has an exceptionally red mid-IR color of F(21\(\mu\)/12\(\mu\))>30. If these lie at the same distance their separation is 2 pc. A further bright source lies 4.5″ away to the NW at G45.479+0.133. Another H\(\text{II}\) region, which is very bright at 21\(\mu\)m, lies to the NW at G45.479+0.133, and is also thought to be part of the same star forming complex.

Feldt et al. (1998) discuss high spatial resolution near- and mid-IR observations of G45.456, whilst Garay et al. (1993) present 6 and 20cm radio maps. Lumsden et al. (2003) have recently argued in favour of a cluster of OB stars ionizing the UCH\(\text{II}\) region, instead of a single star.

4.1.32 [KCW94] G48.606+0.024*

This UCH\(\text{II}\) region is revealed as a point source within a large extended mid-IR emitting region, with a nearby bright source centred on G48.595+0.044 – see Fig. A6(b). The IRAS source 19181+1349 is dominated by the latter object. Another faint source lies nearby to the north. 3.6cm imaging by Kurtz et al. (1999) revealed extended emission in the H\(\text{II}\) region surrounding G48.606.

4.1.33 [WC89] G49.490–0.370* (W51d)

This is an extremely complicated portion of the well known GH\(\text{II}\) region W51 at mid-IR wavelengths, as indicated by Fig. A6(c). G49.490 is an exceptionally bright source at 21\(\mu\)m. Another mid-IR bright source lies very close, 40″ (≈ 2 pc) away, to the south east at G49.488–0.381, that possesses a bright dust tail. IRAS 19213+1424 includes both these bright sources, such that the IR luminosity of the UCH\(\text{II}\) region will be strongly overestimated via use of the IRAS flux. Consequently for this particular example, arguments made by Lumsden et al. (2003) in favour of a cluster of OB stars powering this UCH\(\text{II}\) region will be affected. Several other fainter mid-IR sources lie to the south, south west, west and north east. High resolution mid-IR imaging and spectroscopy of W51d, alias W51 IRS2, have been presented by Okamoto et al. (2001) and by Kraemer et al. (2001).

4.1.34 [WC89] G54.094–0.060

This is an isolated double source, with a dust tail extending to the south east – see Fig. A6(d).

4.1.35 [KCW94] G60.884–0.128

This source, alias Sh 2-87, sits within an small extended region with a nearby (1 pc if physically related) point source to the west at G60.872–0.107 – see Fig. A6(e). Peeters et al. (2002) present the ISO spectrum of G60.884. Kurtz et al. (1999) identified extended radio emission at 3.6cm in G60.884.

4.1.36 [WC89] G61.473+0.093

G61.473 (Sh 2-88) appears to have an spatially extended core, plus an extensive dust halo with a diameter of 80″ (~2 pc) – see Fig. A6(f). 6cm and 20cm radio observations have been presented by Garay et al. (1993).

4.1.37 [WC89] G70.293+1.600* and G70.330+1.586*

Fig. A7(a) reveals that G70.293, alias K3-50A, lies at the centre of a small cluster of at least three sources, of which it is the brightest mid-IR source. G70.330 is much fainter and lies 2.5″ away to the NE. All sources contribute to the IRAS source 19598+3324.

Okamoto et al. (2003) have recently presented mid-IR spectroscopy and imaging of G70.293 suggesting that it is ionized by a cluster of two or three late O stars, instead of a single dominant source. Lumsden et al. (2003) arrives at similar conclusions from near-IR observations.

4.1.38 [WC89] G75.783+0.343*

The relatively high spatial resolution obtained by MSX permits the UCH\(\text{II}\) G75.783 to be identified as a rather weak mid-IR source, in contrast to the commonly assumed coincidence between G75.78 and IRAS 20198+3716 – see Fig. A7(b). The IRAS flux, at least for the 12–25\(\mu\)m bands, is totally dominated by a source 60″, or 1.2 pc to the south west. The IRAS source has a 12\(\mu\)m flux of 423 Jy of which only 8 Jy is from G78.78 3 according to our Band C MSX images.

4.1.39 [WC89] G75.835+0.400

G75.835 (Sh 2-105), located 5 arcmin north of G75.783 is a bright mid-IR source, dominating IRAS 19111+1048. It has a close, much fainter companion 45″ to the north – see Fig. A7(c). If these lie at the same distance, as would appear probable, this corresponds to a separation of 1.2 pc. Garay et al. (1993) present 2-20cm radio maps of G75.835.
This UCH\textsc{ii}, alias Sh 2-106, appears to be single, though is spatially extended some 90\arcsec in the north-south direction. A faint IR point source is seen 80\arcsec ($\approx 0.4$ pc) to the south in Fig. A7(d). Kurtz et al. (1999) identified extended radio emission in G76.383.

Fig. A7(e) indicates that G78.438 appears single, with a very faint dust tail to the south, and no nearby mid-IR source. Once again, Kurtz et al. (1999) observed extended radio emission at 3.6cm for G78.438.

Mid-IR imaging of DR21 reveals a 21\mu m bright extended source, containing G81.679+0.537 and G81.683+0.541, though centred on neither. In addition, a diffuse region extends east–west – see Fig. A7(f). Several faint point sources are also seen, the brightest of which is 3\arcmin to the NW. Kraemer et al. (2001) present high resolution mid-IR imaging of DR21, revealing separate N and SW components at 13\mu m, together with comparisons to radio continuum measurements. No IRAS source is catalogued at the position of DR21. Peeters et al. (2002) present a mid-IR spectrum obtained with ISO.

G109.871 is a bright, though extended, 21\mu m source, as shown in Fig. A8(a), with a faint companion 2\arcmin ($\approx 1$ pc) north west. G109.871 is extremely faint at 12\mu m such that it has a 21/12\mu m ratio of $\sim 47$, the highest of our present sample of UCH\textsc{ii} regions, indicating the lowest dust temperature. Unusually, no extended radio emission was observed by Kurtz et al. (1999).

Fig. A8(b) reveals G111.282 (Sh 2-157B) to lie at the centre of an extended 2\arcmin complex, with faint emission to the NE. In addition, a companion lies several arcmin to the south at G111.279–0.707 that is extremely red, since it is barely detectable at 12\mu m. No stellar photospheric features were detected by Hanson et al. (2002) from NIR spectroscopy of G111.282. Kurtz et al. (1999) identified extended radio emission surrounding this UCH\textsc{ii} region.

G111.61, alias Sh 2-157, is identified as a bright, spatially extended source with no nearby mid-IR companions in Fig.A8(c). Hanson et al. (2002) present NIR spectroscopy of the central source, revealing strong nebular HeI 2.11\mu m emission, indicating a very hot (early O) ionizing source. Peeters et al. (2002) discuss the ISO spectrum of G111.612. No extended radio emission was observed in this UCH\textsc{ii} region by Kurtz et al. (1999).

This UCH\textsc{ii} region, alias W3(OH), appears single at mid-IR wavelengths – see Fig. A8(d) – with a halo and a nearby faint companion $\sim 30\arcsec$ to the east. High resolution mid-IR imaging was presented recently by Stecklum et al. (2002).

G139.909 appears to be a point source at 21\mu m, Fig. A8(e), but has a close faint 12\mu m companion, which is probably a star. Hanson et al. (2002) present NIR spectroscopy of (probably) the central star of G139.909, revealing a late O or early B spectral type.

This UCH\textsc{ii} region is extremely faint at 21\mu m relative to a nearby extended source, 1\arcmin to the south which dominates the IRAF 12 and 25\mu m fluxes – see Fig. A8(f). Indeed, G192.584 is not detected with MSX at 12\mu m, such that it has a 21/12\mu m flux ratio in excess of $>11$. Other faint, equally red, sources lie to the south and to the west which are probably other members of the same complex.

4.2 Overall morphology

We have listed in Table 1 the UCH\textsc{ii} radio morphology\footnote{Radio morphologies are listed as either cometary, core-halo, spherical or shell by Wood & Churchwell (1989)} as found by the radio measurements at spatial scales of a few arcsec. We also indicate in this table our evaluation of the dust morphology as indicated by the MSX 21\mu m images, which is on spatial scales of a few arcmin or more. We call sources single if the core image appears roughly circular with little or no elongation. Those labelled extended are elongated or have faint dust surrounding the core which may contain other objects. Sources with multiple cores, or with “companions” nearby are called double, or multiple. There does not seem to be any correlation between the radio and the dust morphologies, which may not be too surprising given the very different scales of these phenomena.

Many of the sources appear to be resolved by MSX, i.e. their diameters are $\geq 18\arcsec$, the spatial resolution of the instrument. This resolution corresponds to different physical scales, depending on the source distances, as may be seen by examination of Figures A1–8. Looking at the two nearest sources, their core diameters correspond to a few tenths of a pc. Many others have larger core diameters of up to $\approx 1$ pc. The surrounding halos extend to even greater distances in some cases.

We were surprised to find most of our MSX images to have MIR sources in addition to the UCH\textsc{ii} region located nearby. Those we consider double or multiple have companions within about 5 pc (projected) if they are at the same distance (radial velocities are generally not available). In some cases, already noted in the discussion of individual objects, the IRAS photometry will be dominated by the companion. At 21\mu m normal stars will be fainter than at 12\mu m, so we expect the companions to be dust emission sources.
Some might be ‘hot cores’ (e.g., Churchwell 2002), although Kim & Koo (2001) revealed that many such companions are radio sources, indicating that they are at a more advanced state of evolution. There are 53 sources in our Table 1, of which 12 are single with no extended dust or obvious companions. It appears that in most cases, this sample of field UCH<sub>ii</sub> objects are not isolated star formation sites but are connected with nearby (few pc distant) activity.

5 COMPARISON BETWEEN MIR–FIR AND RADIO FLUXES

5.1 The standard model

A well known model of the dust emission from an UCH<sub>ii</sub> region (e.g., Churchwell 1999) is spherically symmetric (1D) with two major constituents: the inner ionized hydrogen volume and an outer thick shell of molecular gas and dust. The outer boundary of the ionized hydrogen region is typically up to 0.1 pc in radius, the surrounding cocoon dust some ten times larger. The cocoon is optically thick to the visible–UV radiation of the exciting star and is thus heated by it (Kahn 1974; Osorio et al. 1999).

The dust emission will dominate the observed spectral energy distribution (SED). This typically has a broad peak, close to 100 µm, fortuitously coincident with the long wavelength IRAS filter. Thermal radiation from the dust cocoon extends from about 1 mm down to a few microns. This dust is not at a single temperature but has a broader wavelength distribution than a black body. Most of the dust is at a temperature of about 30K, although some of that nearest the star could be at 100K or more (see discussion in Wolfire & Churchwell 1994). Their modelling of the IRAS SEDs indicated that the dust density distribution in the shell was more or less constant (no fall off with radius). A more recent study by Hatchell et al. (2000) using the DUSTY radiative transfer code required a r<sup>−3/2</sup> density profile distribution to reproduce the sub-mm radial emission profiles. 2D geometries in the near future will provide a better model for comparison purposes. We use the phrase ‘standard model’ to refer to the situation where the radio emission comes from an inner spherical region and the IR emission from the outer cocoon.

Radiation from wavelengths longer than about 1 mm will arise from the inner region of ionized hydrogen surrounding the central OB star. Lyman continuum photons are emitted from the stellar surface and ionize the hydrogen. According to the standard model, the H<sub>ii</sub> region is ionization bounded, that is, all the LyC photons are used up within this volume which produces the radio emission. Note that some photons emitted by the star might be absorbed by dust within the H<sub>ii</sub> region<sup>3</sup>. These photons would not produce radio emission and would not be counted when one is trying to infer properties of the star from the H<sub>ii</sub> region. Whether this is an important problem for UCH<sub>ii</sub> regions will be discussed below.

We are interested here in the relationship between the

---

<sup>3</sup> Lyman α photons are efficiently absorbed by dust in compact H<sub>ii</sub> regions and probably represents the dominant dust heating mechanism.

---

Figure 2. Comparison between 30″ aperture 25µm IRAS fluxes for Galactic UCH<sub>ii</sub> regions and the 18″ aperture 21µm MSX fluxes, based on data from Wood & Churchwell (1989) and Kurtz et al. (1994). Open circles: sources with brighter close companions; filled circles: sources without such companions. Agreement between the 21µm and 25µm measurements for sources without companions is good.

IR emission from the dust, which is determined by the stellar luminosity which for hot stars is the UV radiation, and the radio emission of the H<sub>ii</sub> region, which is dependent upon the EUV luminosity of the star. This ratio ought to be spectral type dependent, ranging from 10<sup>2</sup> for early O type stars to 10<sup>6</sup> for early B types (Churchwell 1999). We will now see if the standard model of UCH<sub>ii</sub> regions can fit stars with this wide a range of parameters.

5.2 Comparison of MSX 21µm flux with 25µm IRAS flux

We have identified a number of UCH<sub>ii</sub> regions which at the spatial resolution of MSX are found to have nearby companions. These may be affecting the IRAS Point Source Catalog (PSC) entries, particularly the long wavelength 100µm filter with its 2′ spatial resolution. In some cases the companion may dominate the flux, even at the shorter wavelengths. As we wish to infer the parameters of the dust cocoons from the MIR–FIR photometry, let us first examine quantitatively how much of a problem contamination plays.

In Figure 2 we plot the 25µm/21µm (log) flux ratio vs. the 21µm (log) flux (both are distance independent), where we have distinguished between sources without bright companions and those with them. Many of the latter have wildly different fluxes in the MSX and IRAS filters. Leaving these outliers aside, there is no trend of flux ratio with the strength of the MIR flux, and the mean ratio (not log units) is 2.20±0.46. The differences in the IRAS and MSX filter bandwidth alone accounts for a factor of 1.6 (recall Fig. 1). The rest is due to the IRAS filter being somewhat redwards of the MSX filter, thus nominally brighter in these red sources. In the following figures we shall concentrate on those objects without bright companions (filled circles) although we will show all sources throughout.
One outlier in Fig. 2 without a close companion, G5.972–1.174, is highly extended, such that our quoted MSX 21 µm flux of extended sources is underestimated. The color of the dust cocoon will have to be accounted for in detailed modeling of individual sources.

5.3 Color-magnitude diagrams

Stellar astrophysicist’s typically prepare colour magnitude diagrams (CMD), which plot the luminosities of stars vs. their colors, or temperature. As we are not observing the exciting stars of the UCH ii regions directly, we have to use other measurable parameters. The MIR–FIR fluxes, corrected to a uniform 10 kpc distance, may serve as a surrogate for the luminosity since nearly all of the stellar radiation has been converted to heating the dust cocoon. We can measure the color of the cocoon, an indicator of the dust temperature distribution, by obtaining the MSX 21 µm/12 µm flux ratio.

Fig. 3 presents an MIR CMD, namely the MSX 21/12µm index versus the 21µm flux, adjusted to a uniform distance of 10 kpc. We see a fairly wide scatter along the abscissa suggesting a large range of colours for the dust cocoons. This indicates that they do not all have the same slopes of theSED on the short wavelength side. The vertical extent, of course, represents different luminosities of the dust, thus of the central exciting stars. We see that there is little if any dependence of the luminosity (ordinate) on the color. Thus the dust luminosity and its SED are not correlated. The color of the dust cocoon will have to be accounted for in detailed modeling of individual sources.

We have considered whether effects other than temperature might affect the 21/12µm index, namely nebular contributions and extinction. Many sources are strong emitters in mid-IR fine structure lines of neon and sulphur, of which [Ne ii] 12.8µm and [S iii] 18.7µm lie in the 12 and 21µm filters. From inspection of a range of UCH ii regions observed with ISO/SWS (e.g. G29.956–0.016 in Fig. 3), we conclude that this contribution at most 10% of the continuum dust emission. Variable extinction may be more problematic, since many sources are very heavily reddened. The 12µm Band C filter of MSX does include the red wing of the familiar silicate absorption feature centred at 9.7µm (e.g. Fig 2 of Morris et al. 2000), this is compensated to some extent by the much greater linewidth of the 21µm Band E filter. Nevertheless, one should bear in mind that 21µm and especially 12µm flux measurements are affected to some degree by extinction, in contrast with far-IR and radio fluxes.

5.4 MIR vs. radio relationships

Radio fluxes from Wood & Churchwell (1989) and Kurtz et al. (1994) were generally obtained at high spatial resolution with interferometric techniques, and so are restricted to the central regions of each UCH ii region at 0.5–5″ resolution. In contrast, the somewhat lower spatial resolution of the MSX fluxes presented here sample a larger region. There is increasing evidence in the literature that some LyC photons are finding their way out beyond the UCH ii region where they ionize the hydrogen found there.

These halos have been investigated by Kurtz et al. (1999) and Kim & Koo (2001) who re-examined the radio properties of UCH ii regions at larger scales (see also Araya et al. 2002). As we have discussed above, there is an excellent consistency between the Kim & Koo 21cm dataset and our mid-IR MSX images, particularly for complex regions such as G5.885–0.392, G10.304–0.147, G12.209–0.103 and G23.455–0.201. In most cases, the larger aperture leads to a higher radio flux, i.e. the commonly adopted radio fluxes (dense, ionized components) provide only a fraction of the total when the less dense, extended surrounding regions are considered. These extended regions range in size from 15″ to more typically 60″. Larger aperture fluxes generally exceed the Wood & Churchwell (1989) and Kurtz et al. (1994) VLA results at 6cm by a factor of 3, although the factor may be as large as 29 (for G60.88–0.13; Araya et al. 2002).

Unfortunately, the sample observed with these techniques is small to date, so we have to follow the original VLA fluxes from Table 1 for our analysis of the UCH ii region sample. Nevertheless, we will keep this multiplicative factor in mind in what follows, hoping that it is reasonably the same from source to source. The existence of ionized hydrogen halos of UCH ii regions implies that the standard model is density, not ionization, bounded.

We ratio the 21µm and VLA B-array 2cm fluxes as a function of the observed N(LyC) photons in Fig. 4 for all UCH ii regions for which 2cm fluxes are available. The abscissa, which is distant dependent, is used as a surrogate for the temperature (spectral type) of the exciting star. We see a trend in the MIR/radio flux ratio with the temperature of the exciting star, which is predicted by the standard model. A linear regression analysis leads to
\[
\log(21\mu m/2\text{cm}) = C_1(50 - \log N(\text{LyC})) + C_2,
\]
where \(C_1 = 0.600 \pm 0.068\) and \(C_2 = 1.401 \pm 0.178\). This is an empirical relationship which will be useful below for it’s scatter. A slight note of caution is necessary, however, since the \(21\mu m/2\text{cm}\) ratio would be suppressed in the case of extremely high extinction, because the denominator has no dependence, whilst the numerator has a weak dependence – recall that a visual extinction of 100 magnitudes corresponds to a \(21\mu m\) extinction of 0.5 mag (0.2 dex in Fig. 4).

Kurtz et al. (1994) made an analogous plot of IR to radio flux ratio but used the \(100\mu m\) luminosity rather than the \(N(\text{LyC})\) photons. They attributed their scatter to two sources: 1) some LyC photons are being absorbed by the dust and 2) some UCH II regions have multiple sources within them. Either or both of these effects could contribute to our scatter in the following ways: 1) If LyC photons are being absorbed by the dust, a point in Fig. 3 would have moved leftwards and upwards in the diagram; 2) If other stars are present and contributing to the IR flux, a point would have moved vertically upwards. Before attributing our scatter to these same influences we realized that here might be an additional parameter influencing the scatter in our plot.

The \(21\mu m\) wavelength has a strong color term (recall Fig. 3) due to it being on the short wavelength slope of the SED, which is itself not uniform from object to object. We will next show an analogous plot using the IRAS \(100\mu m\) flux, which is at the peak of the dust cocoon SED, taking account of the problem of the multiplicity of the sources.

5.5 FIR vs. radio relationships

In Fig. 4 we plot the IRAS \(100\mu m\) flux/VLA B-array 2 cm flux vs. the \(N(\text{LyC})\) photons. We see a very clear linear relationship, extending over 5 orders of magnitude in the number of \(N(\text{LyC})\) photons and 3 orders in the IR/radio ratio. A fit to the UCH II regions without bright companions is shown as a dotted line (see text).

\[
\log(21\mu m/2\text{cm}) = C_1(50 - \log N(\text{LyC})) + C_2,
\]

where \(C_1 = 0.600 \pm 0.068\) and \(C_2 = 1.401 \pm 0.178\). This is an empirical relationship which will be useful below for it’s scatter. A slight note of caution is necessary, however, since the \(21\mu m/2\text{cm}\) ratio would be suppressed in the case of extremely high extinction, because the denominator has no dependence, whilst the numerator has a weak dependence – recall that a visual extinction of 100 magnitudes corresponds to a \(21\mu m\) extinction of 0.5 mag (0.2 dex in Fig. 4).

Kurtz et al. (1994) made an analogous plot of IR to radio flux ratio but used the \(100\mu m\) luminosity rather than the \(N(\text{LyC})\) photons. They attributed their scatter to two sources: 1) some LyC photons are being absorbed by the dust and 2) some UCH II regions have multiple sources within them. Either or both of these effects could contribute to our scatter in the following ways: 1) If LyC photons are being absorbed by the dust, a point in Fig. 3 would have moved leftwards and upwards in the diagram; 2) If other stars are present and contributing to the IR flux, a point would have moved vertically upwards. Before attributing our scatter to these same influences we realized that here might be an additional parameter influencing the scatter in our plot.

The \(21\mu m\) wavelength has a strong color term (recall Fig. 3) due to it being on the short wavelength slope of the SED, which is itself not uniform from object to object. We will next show an analogous plot using the IRAS \(100\mu m\) flux, which is at the peak of the dust cocoon SED, taking account of the problem of the multiplicity of the sources.

5.5 FIR vs. radio relationships

In Fig. 4 we plot the IRAS \(100\mu m\) flux/VLA B-array 2 cm flux vs. the \(N(\text{LyC})\) photons. We see a very clear linear relationship, extending over 5 orders of magnitude in the number of \(N(\text{LyC})\) photons and 3 orders in the IR/radio ratio. A fit to the UCH II regions without bright companions is shown as a dotted line (see text).

\[
\log(100\mu m/2\text{cm}) = C_3(50 - \log N(\text{LyC})) + C_4,
\]

where \(C_3 = 0.571 \pm 0.048\) and \(C_4 = 2.929 \pm 0.124\), having omitted the one outlier, G18.15-0.28, which lies well above the mean relation. (This source sits in a very extended region of dust emission with multiple fainter sources which may be affecting its fluxes - see Fig. A2). Notice that the scatter here is significantly less than that shown in Fig. 4 when we used the \(21\mu m\) wavelength. The scatter in this diagram presumably represents the effects of dust absorption of LyC photons and that of other stellar contributers to the dust emission. These effects are relatively small.

Since many Wood & Churchwell (1989) UCH II sources were without cm flux measurements, in Fig. 5 we compare the IRAS \(100\mu m\) to VLA 6cm index with Lyman continuum ionizing flux. This relationship is similar to that shown in the previous figure, except that there are no fainter stars in the Wood & Churchwell sample. Arrows indicate revised locations for those UCH II observed (or inferred) with larger radio beams (Araya et al. 2002). Notice that these more or less move along the empirical relationship towards higher radio fluxes and \(N(\text{LyC})\), in keeping with predictions.

Finally, let us construct a CMD for the exciting central stars of UCH II regions, using as the ordinate the FIR luminosity, and as abscissa, the \(N(\text{LyC})\) photons as a surrogate for the spectral type. This result is shown in Figure 7, and we reversed the abscissa so it looks like those of stellar astrophysicists. Considering only the stars unaffected by companions, we see that there is a range in luminosity of 5 magnitudes between early O stars \(N(\text{LyC})\) photons with \(\approx 10^{49.5}\) s\(^{-1}\) and early B stars, with \(N(\text{LyC})\) photons \(\approx 10^{45}\) s\(^{-1}\). This is broadly in agreement with models of hot, luminous stars as indicated in the key in the Figure. This follows the recent OB grid of Smith et al. (2002), adapted to take effect of the revised temperature calibration of Martins, Schaerer.
& Hillier (2002). We have not converted the FIR luminosity to a magnitude system on the figure, since the 100μm flux does not take into account dust emission from longer wavelengths. This correction is a factor of a few. Similarly, the N(LyC) photons measured for the inner UCH ii region have not accounted for the halo of ionized material. We already saw that this correction was also a factor of a few.

We see in Figure 4 that the objects without much influence of a companion have a reasonably tight relationship between their luminosities and temperatures. We can interpret this diagram as the ZAMS for hot, luminous stars. There is not much scatter although G18.15-0.28 (recall Figure 2 of Morris et al. 2000). Consequently, only 25% of all radio selected UCH ii regions would have led to strong overestimates of bolometric luminosities in ~50% of cases. This result, although widely anticipated, reduces inferred stellar luminosities, without affecting LyC fluxes. This may affect recent claims that clusters of stars, rather than a single dominant source, ionize individual UCH ii regions (e.g. G49.490-0.370, Lumsden et al. 2003).

6 CONCLUSIONS

Young, massive stars are obscured at UV, optical and near-IR wavelengths due to extremely high extinction from their circumstellar, birth envelopes. For every magnitude of extinction suffered in the mid-IR at 25μm, that in the K-band is 20 times greater, whilst the visual extinction is 200 times greater (e.g. Fig 2 of Morris et al. 2000). Consequently, only 10% of OB stars ionizing an UCH ii region can be detected in the near-IR (Hanson et al. 2002). Since the star may not be directly observed in most cases, we have to rely on indirect probes at mid-IR, far-IR and radio wavelengths. In the current study we have presented MSX mid-IR observations of dust surrounding UCH ii regions. These are sites of massive star birth, with central ionizing stars spanning spectral types of early B in G109.871+2.113 to early O in G10.623-0.384, at a higher spatial resolution than that which IRAS offered. Only 25% of all radio selected UCH ii regions surveyed here were not found to be extended, or have close companions, themselves often radio emitters. In most cases, field UCH ii regions lie within larger complexes of star formation. Consequently, previous use of IRAS fluxes for the spectral energy distributions of UCH ii regions would have led to strong overestimates of bolometric luminosities in ~50% of cases. This result, although widely anticipated, reduces inferred stellar luminosities, without affecting LyC fluxes. This may affect recent claims that clusters of stars, rather than a single dominant source, ionize individual UCH ii regions (e.g. G49.490-0.370, Lumsden et al. 2003).

Comparison between MSX 21μm and 12μm fluxes permit colour information on the dust cocoon to be made in each case. We find a large range of colours, indicating a variety of dust temperature distributions. Consequently, because of this colour term, we may not blindly use 21μm fluxes as representative of the dominant far-IR luminosity, and so resort to the IRAS 100μm fluxes for those UCH ii regions that appear to well isolated. From a comparison between MSX 21μm and 25μm fluxes, we identify those IRAS sources for which the UCH ii regions are the sole principal source of mid-IR radiation, and so the likely principal source of far-IR flux. A comparison is made between the 100μm flux and Lyman continuum radiation, inferred from radio observations, revealing a linear relationship, as predicted by the standard model for UCH ii regions. Any remaining scatter may be attributed to dust absorption by the emitted LyC radiation and fainter companions within the UCH ii region. Finally, we compare the UCH ii region Lyman continuum flux with observed 100μm fluxes, adjusted to a uniform distance, again revealing a tight spectral type dependence, also in general accord with the standard model.

Overall our results are encouraging, but we should not neglect remaining problems. As discussed above, MSX reveals large scale information on the stellar nurseries of massive stars, with a spatial resolution somewhat higher than...
IRAS. In contrast, ground-based near-IR and mid-IR observations at a much better spatial resolution reveal structure on a quite different, complementary scale. Most radio observations compare more closely with the latter, except for recent data of Kurtz et al. (1999) and Kim & Koo (2001). In the future, 2MASS and SIRTF will permit comparisons of large numbers of UCHii regions to be made on a similar scale. Individual massive Young Stellar Objects (YSOs) have recently been studied using MSX by Lumsden et al. (2002).

In contrast, our next study will investigate the mid-IR properties of a complete radio sample of Giant HII (GHII) regions in the Milky Way.

ACKNOWLEDGEMENTS

PAC and PSC appreciate continuing support by the Royal Society and the NSF, respectively. We wish to thank Martin Cohen for help with MSX flux calibration, Robert Stencel, Nathan Smith and Matt Redman for useful comments. This research made use of data products from the Midcourse Space Experiment. Processing of the data was funded by the Ballistic Missile Defense Organization with additional support from NASA Office of Space Science. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration, and the SIMBAD database, operated at CDS, Strasbourg, France. GAIA is a Starlink derivative of the ESO Skycat catalogue and image display tool.

REFERENCES

Acord, J.M., Churchwell E., Wood D.O.S., 1998, ApJ 495, L107
Araya E., Hofner P., Churchwell E., Kurtz S., 2002, ApJS 138, 63
Churchwell E., 1999a, ARA&A 40, 27
Churchwell E., 1999b, in The Origins of Stars and Planetary Systems, ed. C.J. Lada & N.D. Kylafis (Dordrecht: Kluwer), p515
Churchwell E., 2002, in Hot Star Workshop III: The Earliest Stages of Massive Star Birth (ed. P.A. Crowther), ASP Conf. Ser 267, 3
Churchwell E., Walmsley, C.M., & Cesaroni, R. 1990, A&A Supp. 83, 119
Cohen, M., Walker R.G., Barlow, M.J., Deacon J.R., 1992, AJ, 104, 1650
Conti, P.S. & Blum, R.D. 2002, in Hot Star Workshop III: The Earliest Stages of Massive Star Birth (ed. P.A. Crowther), ASP Conf. Ser 267, 297
Crowther P.A. (ed.), 2002, Hot Star Workshop III: The Earliest Stages of Massive Star Birth, ASP Conf. Ser 267
De Buizer J.M., Watson A.M., Radomski J.T., Pina R.K., Telesco C.M., 2002, ApJ 564, L101
Draper, P.W., Gray N., & Berry, D.S., 2001, Starlink User Note 2149, Rutherford Appleton Laboratory, UK
Egan M.P., et al. 1999, MSX Point Source Catalog Explanatory Guide, AFRL-VS-TR-1999-1522, (Springfield: NTIS)
Feldt M., Stecklum, B., Henning Th., et al., 1998, A&A 339, 759
Feldt M., Stecklum, B., Henning Th., Launhardt R., Hayward T.L., 1999, A&A 346, 243
Fey A.L., Clauussen M.J., Gaume R.A., Nedouhau G.E., Johnston K.J., 1992, AJ 103, 234
Garay G., Rodriguez L.F., Moran J.F., Churchwell E., 1993, ApJ 418, 368
Hatchell J., Fuller G.A., Millar T.J., Thompson M.A., Macdonald, G.H., 2000, A&A 357, 637
Hanson M.M., Luhman, K.L., Rieke G.H., 2002, ApJS 138, 35
Hunter T.R., Phillips T.G., Menten, K.M., 1997, ApJ 478, 283
Kahn F.D., 1974, A&A 37, 149
Kim K-T, Koo B-C, 2001, ApJ 549, 979
Kraemer K.E., Jackson J.M., Deutsch L.K. et al. 2001, ApJ 561, 282
Kurtz, S.E., Churchwell, E., & Wood, D.O.S. 1994, ApJS, 91, 659
Kurtz S.E., Watson A.M., Hofner P., Otte, B., 1999, ApJ 514, 232
Kurtz, S.E., Cesaroni, R., Churchwell, E., Hofner, P., & Walmsley, C.M. 2000 in Protostars and Planets IV, ed. V. Mannings, A.P.Boss, & S.S. Russell (Tucson: Univ. of Arizona Press), p299
Lumsden S.L., Hoare M.G., Oudmaijer R.D., Richards D., 2002, MNRAS 336, 621
Lumsden, S.L., Puxley P.J., Hoare M.G., Moore T.J.T., Ridge, N.A., 2003, MNRAS in press (astro-ph/0212135)
Martins F., Schaefer D., Hillier D.J., 2002, A&A 382, 999
Morris P.M., van der Hucht K.A., Crowther P.A. et al. 2000, A&A 353, 624
Okamoto Y.K., Kataza H., Yamashita T. Miyata T, Onaka T., 2001, ApJ 553, 254
Okamoto Y.K., Kataza H., Yamashita T. et al., 2003, ApJ, 584, 368
Osorio M., Lizano S., D’Alessio P., 1999, ApJ 525, 808
Peeters E., Martin-Hernandez N.L., Damour F., Cox P., Roelfsema P.R. et al. 2002, A&A 381, 571
Price S.D., Egan M.P., Carey S.J., Mizuno D.R., Kuchar T.A., 2001, AJ, 121, 2819
Smith L.J., Norris R.F.P., Crowther P.A., 2002, MNRAS 337, 1309
Stecklum B., Feldt, M. Richichi A. et al. 1997, ApJ 479, 339
Stecklum B., Henning T., Feldt, M. et al. 1998, AJ 115, 767
Stecklum B., Brandl B., Henning T. et al. 2002, A&A 392, 1025
Watson A.M., Hanson M.M., 1997, ApJ 490, L165
Wolfire, M.G., Churchwell, E. 1994, ApJ, 497, 339
Wood D.O.S., Churchwell E., 1989, ApJS, 69, 831

This paper has been typeset from a TeX/ LATEX file prepared by the author.
Figure A1. MSX Band E images of UCH\textsc{ii} regions. Each field covers a field-of-view of 10×10 arcmin, and is presented in a logarithmic intensity scale (units are W m$^{-2}$ sr$^{-1}$).
Figure A2: MSX Band E images of UCH\textsc{ii} regions. Each field covers a field-of-view of $10 \times 10$ arcmin, and is presented in a logarithmic intensity scale (units are $W \text{ m}^{-2} \text{ sr}^{-1}$).
Figure A3: MSX Band E images of UCHii regions. Each field covers a field-of-view of 10×10 arcmin, and is presented in a logarithmic intensity scale (units are W m⁻² sr⁻¹).
Figure A4: MSX Band E images of UCH\,\textsc{ii} regions. Each field covers a field-of-view of $10 \times 10$ arcmin, and is presented in a logarithmic intensity scale (units are W m$^{-2}$ sr$^{-1}$).
Figure A5: MSX Band E images of UCH\(\text{II}\) regions. Each field covers a field-of-view of 10×10 arcmin, and is presented in a logarithmic intensity scale (units are W m\(^{-2}\) sr\(^{-1}\)).
Figure A6: MSX Band E images of UCH\textsc{ii} regions. Each field covers a field-of-view of 10×10 arcmin, and is presented in a logarithmic intensity scale (units are W m\(^{-2}\) sr\(^{-1}\)).
Figure A7: MSX Band E images of UCH\textsc{ii} regions. Each field covers a field-of-view of 10×10 arcmin, and is presented in a logarithmic intensity scale (units are W m\(^{-2}\) sr\(^{-1}\)).
Figure A8: MSX Band E images of UCH\textsc{ii} regions. Each field covers a field-of-view of 10×10 arcmin, and is presented in a logarithmic intensity scale (units are W m$^{-2}$ sr$^{-1}$).
