STAR FORMATION IN MASSIVE CLUSTERS VIA THE WILKINSON MICROWAVE ANISOTROPY PROBE AND THE SPITZER GLIMPSE SURVEY

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ABSTRACT

We use the Wilkinson Microwave Anisotropy Probe (WMAP) maximum entropy method foreground emission map combined with previously determined distances to giant H ii regions to measure the free–free flux at Earth and the free–free luminosity of the Galaxy. We find a total flux f_r = 54,211 Jy and a flux from 88 sources of f_r = 36,043 Jy. The bulk of the sources are at least marginally resolved, with mean radii ~60 pc, electron density n_e ~ 9 cm^{-3}, and filling factor f_{H II} ≈ 0.005 (over the Galactic gas disk). The total dust-corrected ionizing photon luminosity is \[ Q = 3.2 \times 10^{53} \pm 5.1 \times 10^{52} \text{ photons s}^{-1} \], in good agreement with previous estimates. We use GLIMPSE and Midcourse Space Experiment (MSX) 8 μm images to show that the bulk of the free–free luminosity is associated with bubbles having radii r ~ 5–100 pc, with a mean of ~20 pc. These bubbles are leaky, so that ionizing photons emitted outside the bubble escape and excite free–free emission beyond the bubble walls, producing WMAP sources that are larger than the 8 μm bubbles. We suggest that the WMAP sources are the counterparts of the extended low density H ii regions described by Mezger. The 18 most luminous WMAP sources emit half the total Galactic ionizing flux. These 18 sources have \[ 4 \times 10^{51} \text{ s}^{-1} \lesssim Q \lesssim 1.6 \times 10^{52} \text{ s}^{-1} \], corresponding to \[ 6 \times 10^4 \, M_\odot \lesssim M_\star \lesssim 2 \times 10^5 \, M_\odot \], half to two thirds of this will be in the central massive star cluster. We convert the measurement of Q to a Galactic star formation rate (SFR) \( M_\star = 1.3 \pm 0.2 \, M_\odot \, \text{yr}^{-1} \), where the errors reflect only the error in free–free luminosity. We point out, however, that our inferred \( M_\star \) is highly dependent on the exponent \( \Gamma \approx 1.35 \) of the high-mass end of the stellar initial mass function. For 1.21 < \( \Gamma < 1.5 \), we find 0.9 \( M_\odot \, \text{yr}^{-1} \lesssim M_\star \lesssim 2.2 \, M_\odot \, \text{yr}^{-1} \). We also determine a SFR of 0.14 \( M_\odot \, \text{yr}^{-1} \) for the Large Magellanic Cloud and 0.015 \( M_\odot \, \text{yr}^{-1} \) for the Small Magellanic Cloud.

Key words: Galaxy: fundamental parameters – H ii regions – ISM: bubbles – stars: formation

Online-only material: color figure, machine-readable table

1. INTRODUCTION

The star formation rate (SFR) of the Milky Way Galaxy is a fundamental parameter in models of the interstellar medium (ISM) and of Galaxy evolution. The rates at which energy and momentum are supplied by massive stars, which are proportional to the SFR, are the dominant elements driving the evolution of the ISM. The hot gas (~10^4 K) component of the ISM is contributed almost exclusively, in the form of shocked stellar winds and supernovae, by massive stars, whose numbers are also proportional to the SFR. Finally, the amount of gas in the ISM is reduced by star formation, as the latter locks up material in stars and eventually in stellar remnants. Since the SFR is of order a solar mass per year, and the gas mass is roughly 10^9 \( M_\odot \), either the gas will be depleted in 10^9 yr, or it will be replaced by stellar evolution (asymptotic giant branch (AGB) stars), from satellite galaxies, or from the halo surrounding the Milky Way.

Estimates of the SFR generally rely on measuring quantities sensitive to the numbers of massive stars, including recombination line emission (H_n, [N ii]), far-infrared emission from dust (heated primarily by massive stars), and radio free–free emission. Mezger (1978) and Gusten & Mezger (1982) showed that the latter is dominated not by classical radio giant H ii regions, but rather by what Mezger called “extended low density (ELD)” H ii emission. In fact, only ~10%–20% of the free–free emission comes from classical H ii regions—the bulk comes from the ELD. Free–free emission from H ii regions or the ELD is powered by the absorption of ionizing radiation (photons with energies beyond the Lyman edge, i.e., greater than 13.6 eV). Thus the free–free emission is often characterized by the rate Q, the number of ionizing photons per second needed to power the emission (the conversion from free–free luminosity L to Q is given by Equation (7)). Previous measurements of Q are given in Table 1, along with the value determined in this work. The average of the previous values is \( Q = 3.2 \times 10^{53} \text{ s}^{-1} \).

The ionizing flux can be estimated from recombination lines as well. Bennett et al. (1994) use observations of the [N ii] 205 μm line and find \( Q = 3.5 \times 10^{53} \text{ s}^{-1} \); McKee & Williams (1997) use the same observations to estimate \( Q = 2.6 \times 10^{53} \text{ s}^{-1} \).

The nature of the ELD is uncertain; it may be associated with H ii regions, in which case it is also referred to as extended H ii envelopes (Lockman 1976; Anantharamaiah 1985a, 1985b). The latter author lists the properties of the ELD, based on the emission seen in the H272α line; for Galactic longitudes l < 40° the line is seen in every direction (in the Galactic plane) irrespective of whether there was an H ii region, a supernova remnant, or no point source. The electron densities are in the range 0.5 cm^{-3} < n < 6 cm^{-3}; emission measures were in the range 500–3000 pc cm^{-6}, with corresponding path lengths 50–200 pc; the filling factor is ~0.005, and the velocities of the H ii regions, when present, agree well with that of the H272α line velocity.

We note that Taylor & Cordes (1993) model the free electron distribution of the inner Galaxy with two components, one with a mean electron density \( \langle n_e \rangle = 0.1 \, \text{cm}^{-3} \) and a scale height
of 150 pc, and the second, associated with spiral arms, having \( n_e \approx 0.08 \text{ cm}^{-3} \) and a scale height of 300 pc; both components are reminiscent of the ELD.

We present evidence that the bulk of the ELD is associated with photons emitted from massive clusters not previously identified. We are motivated by the distribution of free–free emission in the Wilkinson Microwave Anisotropy Probe (WMAP) free–free map, shown in Figure 1, and by comparison of higher resolution radio images, e.g., Whiteoak et al. (1994); Cohen & Green (2001) with GLIMPSE (Benjamin et al. 2003; Churchwell et al. 2006, 2007) and the Midcourse Space Experiment (MSX; Price et al. 2001) data. Figure 2 shows the WMAP sources in more detail, while Figure 3 shows the locations of the sources in the plane of the Galaxy.

In this paper, we determine the SFR in our Galaxy using the free–free flux measured by the WMAP. We describe our data processing and source identification and extraction methods in Section 2. By comparing to catalogs of H\(_{\alpha}\) regions with known distance, we estimate the distance to the WMAP sources in Section 3. The H\(_{\alpha}\) catalogs are known to be biased against H\(_{\alpha}\) regions at large distances; we follow Mezger (1978) and Smith et al. (1978) and crudely account for this by calculating the luminosity of the nearest half of the Galaxy, and then doubling the result to find the total \( L_{\alpha} \). In Section 4, we examine GLIMPSE images to solidify our identifications; in this process, we identify 5–75 pc bubbles associated with the bulk (>75%) of the emission. We show that the bubbles and the free–free emission are both powered by massive central star clusters. We derive the ionizing flux \( Q \) and the SFR of the Galaxy in Section 5. Half the star formation occurs in the 18 most massive clusters and their retinue; the central clusters have \( M_* = 4 \times 10^8 M_\odot \). We discuss our results in Section 6. In the Appendix, we describe the machinery needed to convert from ionizing flux \( Q \) to SFR \( M_* \).

2. MICROWAVE DATA AND WMAP

The only wavelength range in which free–free dominates the emission from the Galactic plane is in the microwave, between 10 and 100 GHz, placing this in the center of the frequency range of cosmic microwave background (CMB) experiments (Dickinson et al. 2003). Synchrotron radiation and vibrational dust emission are also important contributors in this frequency range. The free–free emission is characterized by a spectral index \( \beta \), where the antenna temperature \( T_A \propto \nu^{-\beta} \), and \( \beta \approx 2.1 \). In contrast, the spectral index for synchrotron radiation is \( \beta \approx 2.7–3.2 \) and for dust emission \( \beta \approx 1.5–2 \). In order to isolate

the free–free component, some form of the multi-wavelength fitting technique must be used.

In order to optimize the WMAP measurements of cosmological parameters, the galactic foreground emission had to be accurately characterized. This was done using a maximum entropy model (MEM), resulting in maps of the free–free, synchrotron, and dust emission (Bennett et al. 2003a).

These models agree with the observed galactic emission to within 1% overall, with the individual synchrotron and dust emission models matching observations to a few percent. In the case of the free–free map, the correlation to the H\(_{\alpha}\) map is found to be within 12%. This indicates that the MEM process is consistent with H\(_{\alpha}\) where the optical depth is less than 0.5 (Bennett et al. 2003a).

The WMAP free–free model is the only single dish all-sky survey of free–free Galactic emission to date, so it is an attractive database to use to measure the Galactic ionizing photon luminosity and subsequently the Galactic SFR.

2.1. Data Processing

We transformed the WMAP free–free maps from an all-sky HEALPix map to multiple tangential projections centered about the galactic plane. The antenna temperature was converted into flux density using the conversion

\[
F_\nu = \frac{2k_B\nu^2}{c^2}\Delta T_A, \tag{1}
\]

where \( \nu \) is the frequency of the WMAP band, \( k_B \) is Boltzmann’s constant, \( c \) is the speed of light, and \( \Delta T_A \) is the antenna temperature (Bennett et al. 2003b). To determine all-sky flux statistics, an all-sky Cartesian projection of the free–free maps was produced.

The WMAP beam diameter varies from 0.82 to 0.21 from the \( K \) band to the \( W \) band. As part of the map making process, all bands were smoothed to a resolution of 1\(^\circ\) (Bennett et al. 2003a). The characteristic size of most H\(_{\alpha}\) regions is of order the smoothed resolution of the foreground maps. Thus we suffer from source confusion from regions with small angular separations. We discuss our method of separating the confused sources in Section 2.2, but argue that in many cases, spatially separate H\(_{\alpha}\) regions are physically associated.

2.2. Source Identification and Extraction

Sources within the free–free maps were identified using the Source Extractor package from Bertin & Arnouts (1996). The fluxes were measured in the WMAP \( W \) band, at 93.5 GHz. After an automated search over the entire map, a few sources were visually identified and extracted. The measured fluxes are isophotal with an assumed background flux level of zero.
Using this method, the smallest extractable flux is approximately 10 Jy, with a number of higher flux objects being unextractable due to confusion within the Galactic plane. The smallest H\textsc{ii} region extracted had a semimajor axis of 0\textdegree.4, half the \~1\textdegree beam diameter of the WMAP free–free map. In total, 88 sources have been identified and extracted.

We have also used the two-dimensional version of the ClumpFind routine by Williams et al. (1994), finding that the sensitivity of the isophote parameter provides unreliably variable sizes and structures for each of the H\textsc{ii} regions. Henceforth, we use the sources found by the Source Extractor.

3. DISTANCE DETERMINATION

As a first pass at distance determination, we use the source list of Russeil (2003), who lists both giant Molecular Clouds and H\textsc{ii} regions; only the latter are relevant here. In cases where the sources have both a kinematic distance and photometric distance, we use the photometric distance.

Table 3 in Russeil (2003) lists 481 H\textsc{ii} regions; we find 88 sources, with a much higher total flux. It follows that we have likely confused individual sources in comparison to the Russeil (2003) list. Thus, we have initially assumed that each of the 88 sources that we have extracted consists of one or more Russeil sources projected onto the same location in the sky. We use the following procedure to separate these confused sources.

First, in 13 cases we have a source where Russeil has none. In these cases we inspect either MSX or GLIMPSE images to identify likely sources, and use SIMBAD to find any H\textsc{ii} regions at promising locations. For example, we find a source at $l = 6\textdegree.38$, $b = +23\textdegree$, with a flux of 246.5 Jy, having no counterpart in Russeil (2003). We identify this source with
the ζ Ophiuchi diffuse cloud, at a distance of 140 pc (Draine 1986), and find $Q_\text{ff} = 7.4 \times 10^{47} \text{ s}^{-1}$ from the free–free emission; we use a subscript to denote the origin of the estimated luminosity (the conversion from $L_\nu = 4\pi D^2 f_\nu$ to $Q$ is given in Equation (7)). This ionizing photon luminosity is reasonably consistent with the estimated stellar rate $Q_s = 1.2 \times 10^{48} \text{ s}^{-1}$ (Martins et al. 2005), and suggests that $\sim 35\%$ of the ionizing photons are absorbed by dust grains.

The most outstanding example of a WMAP source with no associated H II region in Russell (2003) is that at $l = 81^\circ 1, b = 0^\circ 5$. This source was, however, mapped by Westerhout (1958), who identified it as part of the Cygnus X region. Examination of the MSX image shows that there are two large bubbles in the region, one centered roughly on Cygnus OB2, and one on Cygnus OB9.

We identify the WMAP source at $l = 81^\circ 1, b = 0^\circ 5$ with the southwestern wall of a large bubble in the Cygnus region (see Figure 4). The bubble contains Cyg OB2 (see also Schneider et al. 2006). A second bubble lies further to the southwest, and appears to contain Cyg OB9. The boundary between the two bubbles is a shared wall, which contains Russell (2003) source 118 at $l = 78^\circ 5 b = 0^\circ 0$. Her sources 120 and 121 are in the interior of the northern bubble, near the center of Cyg OB2. The southeastern rim of the southern bubble contains Russell’s source 115.

We assign a distance $D = 1.7 \text{ kpc}$ (Hanson 2003) to both bubbles (and to the WMAP sources at $l = 76^\circ 0, l = 78^\circ 6$, and $l = 81^\circ 1$). We assign the flux from the WMAP source at $l = 76^\circ 0$ to the southern bubble, and that of the source at $l = 81^\circ 1$ to the northern bubble. The free–free flux from the wall separating the two bubbles could be powered by photons emitted by clusters inside either bubble. Lacking any further information, we assume that half the ionizing flux comes from clusters located in each of the two bubbles. Split this way, $Q_\text{ff} = 1.75 \times 10^{47} \text{ s}^{-1}$ for the northern bubble, and $Q_\text{ff} = 1.04 \times 10^{47} \text{ s}^{-1}$ for the southern bubble. We find a total free–free flux in the region of $4033 \text{ Jy}$; Westerhout (1958) finds a total flux of $2520 \text{ Jy}$ in “point sources” in the region.

We argue that the free–free flux from the vicinity of the northern bubble can easily be powered by Cyg OB2. Counting only the O stars with spectroscopically determined types listed in Table 5 of Hanson (2003) yields 49 O stars with $Q \approx 5 \times 10^{50} \text{ s}^{-1}$. More recently, Negueruela et al. (2008) find 50 O stars, and suggest that there may be as many as 60–70 in the cluster, allowing for some incompleteness due to the strong reddening. This is equal to the number of O stars in the Carina region as tabulated by Smith (2006), who also gives $Q_s = 10^{47} \text{ s}^{-1}$, which we also adopt for Cyg OB2; the total ionizing flux for the region will be somewhat larger, as there are a number of O and Wolf–Rayet stars with projected locations inside the bubble but outside Cyg OB2.

We suggest that there must be a similar number of O stars in the interior of the southern bubble as well. These stars are difficult to detect since the extinction toward them is large (see the discussion at the end of Section 4).

Returning to the distance determinations, if there is a unique Russell (2003) source at the location of a WMAP source, we use his distance as a first guess; there are 43 such objects, about half the sample. As in the previous case, we then inspect either MSX or GLIMPSE images at the location of the Russell source. In
some cases, we find sources we believe to be better candidates than the source in the Russell catalog.

Finally, in 30 cases, we find multiple Russell (2003) objects in the same direction as our WMAP source. We then assign a portion of our measured flux to each of the Russell objects. We divide up the WMAP flux using the excitation parameter of each Russell object. The excitation parameter, $U \propto f_j D^2$, compares the ionizing luminosities of the Russell objects. Using the distances provided by the catalog, we calculate the free–free luminosity of each Russell object. The result is a separation of the confused WMAP source into individual H II regions with flux, distance, and luminosity corresponding to the Russell (2003) objects.

Using this method, we are able to assign distances to all but 2 of the 88 regions. (One of the original 13 missing regions corresponds to the Large Magellanic Cloud (LMC); we identified 10 using SIMBAD, and their distances are given in Table 2). We assigned the average distance of the known sources to the remaining two unidentified sources.

We list 183 H II regions in Table 2. For all confused sources, the galactic coordinates, semimajor and semiminor axis sizes are for the WMAP source, not the individual H II regions. Maps of these regions are presented in Figures 1–3. The distribution of free–free luminosities, $dN/dL$, of these regions is presented in Figure 5, and will be discussed in Section 4.

### 3.1. WMAP Sources, the ELD, and Dispersion Measures

The WMAP free–free sources range in radius (or semimajor axis) from 0:4 to 10°. The latter is the fitted radius for the nearby H II region S264 (around λ Orionis) at $l = 195°05$, $b = -11°995$, and $D = 400$ pc (Fich & Blitz 1984). A visual

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**Figure 5.** (a) Distribution of free–free luminosity of the WMAP H II regions within the Galaxy, with the corresponding ionizing luminosity indicated on the top axis. The number of sources at low flux is reduced by confusion. The dashed line indicates the half luminosity line, where the sum of the luminosity of the sources to the right of this line is equal to half the total measured luminosity in the Galaxy. The slope on the luminous end is $(dN/dL) \sim L^{-\alpha}$, where $\alpha = 1.9 \pm 0.1$. (b) The distribution for our clumped sources. The slope on the luminous end is $\alpha = 1.7 \pm 0.2$.

**Table 2**

Identified H II Regions

| $l$ | $b$ | Semimajor Axis (deg) | Semiminor Axis (deg) | Free–Free Flux (Jy) | Distance (kpc) | Distance Reference | Free–Free Luminosity (erg s$^{-1}$ Hz$^{-1}$) | Associated Region |
|-----|-----|----------------------|----------------------|---------------------|----------------|--------------------|-------------------------------------------|-----------------|
| 6.4 | 23.1| 2.5                  | 2.1                  | 247                 | 0.1            | -1                 | 1.90E+25                                  | ζ Oph           |
| 6.7 | -0.5| 1.8                  | 1.2                  | 11                  | 12.3           | 6                  | 2.00E+24                                  |                 |
| 6.7 | -0.5| 1.8                  | 1.2                  | 9                   | 13.6           | 7                  | 2.10E+24                                  |                 |
| 6.7 | -0.5| 1.8                  | 1.2                  | 6                   | 16.2           | 8                  | 2.00E+24                                  |                 |
| 6.7 | -0.5| 1.8                  | 1.2                  | 618                 | 1.6            | 9                  | 1.90E+24                                  | M8              |
| 6.7 | -0.5| 1.8                  | 1.2                  | 8                   | 12.8           | 10                 | 1.50E+24                                  |                 |
| 6.7 | -0.5| 1.8                  | 1.2                  | 281                 | 2.5            | 11                 | 2.10E+24                                  | W28             |
| 6.7 | -0.5| 1.8                  | 1.2                  | 165                 | 2.7            | 12                 | 1.40E+24                                  | M20             |
| 6.7 | -0.5| 1.8                  | 1.2                  | 16                  | 13.5           | 14                 | 3.60E+24                                  |                 |
| 6.7 | -0.5| 1.8                  | 1.2                  | 76                  | 4.8            | 15                 | 2.10E+24                                  | W30             |
| 10.4| -0.3| 0.6                  | 0.4                  | 104                 | 4.3            | 17                 | 2.30E+24                                  |                 |
| 10.4| -0.3| 0.6                  | 0.4                  | 66                  | 14.9           | 18                 | 1.80E+25                                  | W31             |
| 10.4| -0.3| 0.6                  | 0.4                  | 85                  | 5.5            | 19                 | 3.10E+24                                  |                 |
| 10.4| -0.3| 0.6                  | 0.4                  | 20                  | 14.0           | 20                 | 4.80E+24                                  |                 |
| 14.7| -0.5| 1.4                  | 0.5                  | 43                  | 4.4            | 30                 | 1.00E+24                                  |                 |

**Notes.**

a References to distances are given in Table 3 of Russell (2003).
b Sources with negative numbers in Column 5 have distances given by references as follows: (1) Draine 1986. Refer to the text for more details.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
inspection yields a radius $\sim 5^\circ$ or 35 pc, closer to the radius $r = 45.5$ pc given by Fich & Blitz. As noted above, the effective beam diameter for the free–free map is $\sim 1^\circ$. Six sources have mean angular radii (the geometric mean of the semimajor and semiminor axes) smaller than the effective beam radius; these are likely to be unresolved. The physical radii range from $\sim 6$ pc for ζ Ophiuchi to $\sim 150$ pc, with a mean radius ($r$) $\sim 55$ pc. We find a filling factor for the WMAP sources (not the diffuse emission) of $\phi_{\text{HII}} \approx 5 \times 10^{-3}$, where $\phi_{\text{HII}}$ is the ratio of the (summed) free–free source volume divided by the volume of the galactic disk assuming disk radius $R = 8$ kpc and scale height $H = 200$ pc appropriate for the disk between 3–8 kpc, e.g., Binney & Merrifield (1998). Note that the filling factor of the WMAP sources is equal to that of the ELD.

The ionizing luminosities fall in the range $10^{48}$ s$^{-1} < Q < 1.8 \times 10^{52}$ s$^{-1}$, with $\langle Q \rangle = 2 \times 10^{51}$. The median $Q = 2.8 \times 10^{50}$ s$^{-1}$ (all these values are uncorrected for dust absorption).

We can determine the mean electron density for each source from the expression

$$n_e = \sqrt{\frac{3Q}{4\pi r^2 \alpha(H^+)\phi}}, \quad (2)$$

where $\alpha(H^+) = 3.57 \times 10^{-13}$ cm$^3$ s$^{-1}$ is the hydrogen recombination coefficient (Osterbrock 1989) and $\phi$ is the filling factor of ionized gas in a given WMAP source region. The electron density ranges from $n_e \approx 1\phi^{-1/2}$ cm$^{-3}$ to $n_e \approx 35\phi^{-1/2}$ cm$^{-3}$, with a mean $n_e \approx 9\phi^{-1/2}$ cm$^{-3}$. The density averaged over the disk (i.e., multiplying by the volume filling factor $\phi_{\text{HII}}$) is $(n_e) \approx 0.05$ cm$^{-3}$. The typical dispersion measured through a WMAP source is $\Delta n_e \approx 500$ cm$^{-3}$. For a free–free source in ground-based surveys do not increase much with decreasing flux, such sources do not contribute much to the total free–free luminosity of the Galaxy.

On the other hand, there does appear to be a diffuse component to the WMAP free–free sky map (diffuse even compared to the ELD). The total flux over the entire sky is $f = 54211.6$ Jy, while that in WMAP sources is $36043.0$ Jy. We give a rough accounting of this emission by assuming that it arises from gas that has the mean density of the sources, i.e., we multiply the free–free luminosity emitted by the WMAP sources by the ratio $f = 54211.6/36043 \approx 1.5$ to find our final estimate for the Galactic free–free luminosity,

$$L_v = 1.8 \times 10^{27} \pm 2.9 \times 10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1}. \quad (4)$$

The error estimate comes from a simple error propagation in the determination of Galactic longitude $l$ (with $\Delta l = 0.5$), the circular velocity of the Galaxy $v_c = 220 \pm 10$ km s$^{-1}$, and the radial velocities of the associated H ii regions $\Delta v = 5$ km s$^{-1}$. The radial velocity error is by far the largest component.

4. BUBBLES, H ii REGIONS, AND MASSIVE STAR CLUSTERS

We show in this section that many of the H ii regions listed in Russell (2003) and earlier compilations are physically connected. In particular, when several sources appear within $\lesssim 1^\circ$ on the sky, and have radial velocities within $\Delta v_c \approx 10$ km s$^{-1}$, examination of Spitzer band 4 GLIMPSE (8 µm) images reveal large (10–100 pc) bubbles, with the H ii regions arrayed around the rim of the bubble. We interpret these bubbles as radiation and H ii gas pressure driven structures powered by a central massive cluster. Here we give one example; more will be presented in a forthcoming paper.

The GLIMPSE images reveal hundreds of small (1–10 pc) bubbles, many listed by Churchwell et al. (2006, 2007). The bubbles we identify are typically larger than 10 pc, ranging up to 100 pc. None of our bubbles are listed in these two references. However, we do find a number of the GLIMPSE team’s bubbles contained inside some of our bubbles.

We stress the difference between the WMAP sources we find and the bubbles contained in them. The sources are identified by their free–free emission, and necessarily have sizes comparable to or larger than the WMAP beam (approximately 1$^\circ$); many of the WMAP sources are resolved, but many are not. In contrast, the ~5–30’ bubbles we find in the GLIMPSE images, identified by their morphology as revealed by 8 µm polycyclic aromatic hydrocarbon (PAH) emission, are well resolved, and substantially smaller than the surrounding free–free emission regions. We interpret this by asserting that many of the ionizing photons emitted by the clusters associated with the bubbles escape from the bubble to be absorbed by gas in the interior of the WMAP source. These are the photons that produce the ELD (see Section 3.1).

4.1. WMAP Sources are Powered by Massive Star Clusters

There are several arguments that the WMAP sources, and their enclosed, apparently empty large bubbles actually contain the largest star clusters in the Milky Way.

The first is the very large ionizing fluxes found using WMAP, $Q \approx 3 \times 10^{51}$ s$^{-1}$, for the top 20 or so sources. These
sources have WMAP-detected radii of order 100 pc, so either there are \(3-10\) Carina size clusters all within 100 pc, and \(dN/dM\) is very different than we believe, or there is a single dominant cluster.

The second argument is provided by the shape of the GLIMPSE and MSX 8 \(\mu\)m bubbles inside the WMAP sources. The bubbles are elliptical, with axis ratios one to two or so. This argues for a single massive cluster, which dominates the luminosity of the region.

The third argument is that many of the bubbles show prominent pillars pointing back to a single location in the bubble, again consistent with a single dominant source.

Finally, we present a quantitative argument for the WMAP source G298.3-0.34, showing that there should be a massive cluster \(M \approx 4 \times 10^3 M_\odot\) providing the bulk of the ionizing radiation. Along the way we show that the classical giant H\(\text{ii}\) regions associated with this region are powered by compact star clusters with masses \(Q \approx 7 \times 10^{50} \text{ s}^{-1}\), and \(M_\text{q} \approx 10,000 M_\odot\). The total \(Q \approx 7.7 \times 10^{51} \text{ s}^{-1}\) for the region; we find this most likely arises from a cluster at the location pointed to by the giant pillars in Figure 6, near \(l = 298:66, b = -0:51\).

Cohen & Green (2001) have shown that the 8 \(\mu\)m emission traces free–free emission reasonably well. This allows us to use the 8 \(\mu\)m images to examine the WMAP sources with much higher resolution.

Figure 6 shows the GLIMPSE image in the direction of the WMAP free–free source G298.4-0.4. SIMBAD lists 7 H\(\text{ii}\) regions within 0.5 of the center of the bubble (at \(l = 298:5, b = -0:556\); we interpret 2MASX J12100188-62500 to be the same source as [GSL2002] 29, and [WMG70] 298.9-0.4 to be the same source as [CH87] 298.868-0.432. The five unique sources are marked by circles in Figure 6 (see Table 3). The H\(\text{ii}\) recombination line radial velocities range from +16 km s\(^{-1}\) to +30.3 km s\(^{-1}\), with a mean around +23 km s\(^{-1}\). Given the arrangement of sources around the wall, and the range of radial velocities, we interpret the source as an expanding bubble, with mean \(v_{\text{bubble}} \approx 55(D/10 \text{ kpc}) \text{ pc} \) and expansion velocity \(\sim 7 \text{ km s}^{-1}\). We interpret the H\(\text{ii}\) regions around the rim as triggered star formation. The two largest H\(\text{ii}\) regions on the rim, G298.227-0.340 and G298.862-0.438, have fluxes \(f_r \approx 47 \text{ Jy} \) and 42 Jy, respectively, corresponding to \(Q \approx 7.5 \times 10^{50}(D/10 \text{ kpc}) \text{ s}^{-1}\) and \(6.6 \times 10^{50}(D/10 \text{ kpc}) \text{ s}^{-1}\). The total flux from the H\(\text{ii}\) regions on the rim is 111 Jy, compared to the WMAP flux of 313 Jy. We suggest that there is a massive cluster \((Q \approx 3-5 \times 10^{51} \text{ erg s}^{-1}, \text{ or } M_\text{q} \approx 5 \times 10^3 M_\odot)\) in the interior of the bubble; the pillars point to the location of the cluster.

We note that even so-called giant H\(\text{ii}\) regions are spatially compact, of order a few to 10 pc in radius (e.g., Conti & Crowther 2004); the two classical giant H\(\text{ii}\) regions, [CH87] 298.868-0.432 (G298.9-0.4 here) and [GSL2002] 29, and [WMG70] 298.8-0.3 to be the same source as [CH87] 298.868-0.432. The large white dotted ellipse shows the WMAP source found by Source Extractor. We find a bubble in the GLIMPSE image, which we approximate with the smaller solid white ellipses, having semimajor axis \(a \approx 1370^\circ\) and semiminor axis \(b \approx 892^\circ\). We have set the intensity and contrast to show the faint bubble outline, resulting in saturated H\(\text{ii}\) regions. Large pillars are evident at \(l = 298:67, b = 0:75\), and \(l = 298:5, b = -0:35\). Also shown (by white circles) are the H\(\text{ii}\) regions listed in Table 3; the velocities range from +16 km s\(^{-1}\) to +30.3 km s\(^{-1}\). We interpret this as a bubble expansion velocity of \(\sim 7 \text{ km s}^{-1}\). The distance to the H\(\text{ii}\) regions is \(D \approx 11.7 \text{ kpc}\).

\begin{table}[h]
\centering
\begin{tabular}{lllllll}
\hline
Name & Galactic \(l\) & Galactic \(b\) & R.A.(2000) & Decl.(2000) & Flux & \(v_r\) & Distance & Reference \\
& (deg) & (deg) & (hh:mm:ss) & (deg:mm:ss) & (Jy) & (km s\(^{-1}\)) & (kpc) & \\
\hline
[KC97c] G298.2-0.0 & 298.1869 & -0.7821 & 12:09:03.7 & -63:15:46 & 2.4 & +16 & 10.9 & 1 \\
GSL2002 29 & 298.228 & -0.3308 & 12:10:04.0 & -62:49:27 & 47.4 & +50.3 & 12.3 & 1 \\
KC97c G298.6-0.1 & 298.5589 & -0.1141 & 12:13:12.6 & -62:39:39 & 2.8 & +23 & 11.7 & 1 \\
WMG70 298.8-0.3 & 298.8377 & -0.3467 & 12:15:19.9 & -62:55:52 & 16.0 & +25 & 12.0 & 2 \\
CH87 298.868-0.432 & 298.8683 & -0.4325 & 12:15:29.6 & -63:01:13 & 42.4 & +25 & 12.0 & 1 \\
\hline
\end{tabular}
\caption{H\(\text{ii}\) Regions within 0.5 of \(l = 298:5, b = -0:556\)}
\end{table}

\textbf{Figure 6.} GLIMPSE 8 \(\mu\)m image in the direction of the WMAP free–free source G298.4-0.4. The large white dotted ellipse shows the WMAP source found by Source Extractor. We find a bubble in the GLIMPSE image, which we approximate with the smaller solid white ellipses, having semimajor axis \(a \approx 1370^\circ\) and semiminor axis \(b \approx 892^\circ\). We have set the intensity and contrast to show the faint bubble outline, resulting in saturated H\(\text{ii}\) regions. Large pillars are evident at \(l = 298:67, b = 0:75\), and \(l = 298:5, b = -0:35\). Also shown (by white circles) are the H\(\text{ii}\) regions listed in Table 3; the velocities range from +16 km s\(^{-1}\) to +30.3 km s\(^{-1}\). We interpret this as a bubble expansion velocity of \(\sim 7 \text{ km s}^{-1}\). The distance to the H\(\text{ii}\) regions is \(D \approx 11.7 \text{ kpc}\).

\textbf{Note.} Fluxes for [GSL2002] 29 and [CH87] 298.868-0.432 are taken from Conti & Crowther (2004); all others are from Caswell & Haynes (1987).

\textbf{References.} (1) Caswell & Haynes 1987; (2) Wilson et al. 1970.
The apparent location of the cluster (the slopes are and from the two giant H\nregions G298.9-0.4 and G298.2-0.3; thin solid lines; the upper curve near is G298.2-0.3). The straight dotted and dashed lines are least-squares fits for to for G298.9-0.4 and G298.2-0.3; the slopes are and i.e., . Extrapolating to , the upper limit for the luminosity of G298.2-0.3 is 4/14 of that of the region as a whole, while that of G298.9-0.4 is 1/5 of the total; the ratios found from the free–free emission are somewhat smaller. The fact that the entire region has a luminosity larger than that of the brightest classical H\nregions, combined with the presence of a diffuse \mum emission region much larger than either H\nregion could illuminate, strongly suggests the presence of a much more luminous star cluster in the interior of the bubble. The interior of the bubble shows little emission, as the gas and dust have been pushed to the bubble wall.

The figure also shows the azimuthally averaged radial surface brightness profile from the putative location of the massive cluster at . In converting from degrees to parsecs, labeled along the top of the figure, we have assumed a distance and an inclination of 23 km s\(^{-1}\) in this direction.

The figure shows that neither of the classical H\nregions can illuminate the gas and dust in the bubble interior. The surface brightness of the entire region also falls off as 1/r from the point , as expected if there is a massive cluster near or at this location.

It follows that the total \mum luminosity is at least \(\sim 3.5\) times that of G298.9-0.4 (the ratio of the surface brightness at large radii in the least-squares fits) and five times that of G298.2-0.3; if the emission associated with the H\nregions does not extend to the edge of the observed \mum emission, their contribution to the total flux will be smaller.

The azimuthal averaging leads to an artificially thick bubble wall; surface brightness measurement along radial lines shows that the radial thickness of the bubble wall is \(\Delta r \sim 4\) (\(D/10\) kpc) pc, about 10% of the bubble radius.

We noted above that the WMAP free–free source G298 has a radius of \(r \approx 160\) (\(D/10\) kpc) pc, similar to the radius (\(200\)\((D/10\) kpc) pc of the \mum source we found, once again illustrating the correlation between \mum emission and free–free emission.

The total free–free flux in the region is 312 Jy, compared to 47.4 Jy for G298.2-0.3 (\(\sim 1/6\) of the total) and 42.4 Jy (1/7) for G298.9-0.4; note that these ratios are roughly consistent with the \mum flux ratios. We estimate a total flux of \(\sim 110\) Jy for all the classical H\nregions in the area, leaving 202 Jy, which we attribute to the massive central cluster. We inferred above that the cluster has an ionizing luminosity \(Q = 5 \times 10^{47} (D/10\) kpc) s\(^{-1}\), and a stellar mass \(M \approx 5 \times 10^{5} (D/10\) kpc) \(M_{\odot}\), similar to that of Westerlund 1.

Thus we have a slightly different interpretation of the ELD than Lockman (1976) and Anantharamaiah (1985a, 1985b), at least for our most luminous WMAP sources (recall that these 20 or so sources supply the bulk of the ionizing luminosity of the Galaxy). The cited authors associate the ELD with photons leaking out of classical H\nregions. We argue that the classical H\nregions are not the source of the bulk of the ionizing photons. Rather, in the WMAP sources, the majority of the ionizing flux is produced by a central massive star cluster \((M \sim 5 \times 10^{5} \; M_{\odot} \text{ or larger})\). These central clusters excite free–free and 8 \mum emission out to 50–200 pc. They have also blown \(\sim 10–100\) pc bubbles in the surrounding ISM, as seen in Spitzer or MSX images. The rims of the bubbles contain triggered star formation regions, which are younger than the central clusters. Because the triggered clusters are younger, and substantially less luminous (typically by a factor of 5), they have not blown away their natal gas. As a result, they appear as very high surface brightness free–free sources in classical radio emission catalogs (and as bright 8 \mum sources); thus Lockman (1976) and Anantharamaiah (1985a, 1985b) attribute the ELD to photons from the smaller, younger, and more embedded clusters, while we attribute them to the larger, less embedded central clusters.

While these young, compact sources are bright and hence easily identified, they are not the source of the ionizing photons in the ELD. Instead, the massive central clusters are the source of the ionizing photons powering the ELD; ionizing photons leak out of the bubbles in all directions, since the bubble walls are far from uniform.

Using the definition of an H\nregion (treating all the H\nregions associated with a GLIMPSE bubble as one region) alters the luminosity function somewhat. The new luminosity function is shown in the right panel of Figure 5. At the high-luminosity end, we find \(dN/dL \sim L^{-1.7\pm0.2}\), i.e., most of the luminosity (and stellar mass) is in massive sources \((\alpha = 2\) corresponds to equal numbers per logarithmic luminosity bin). Half the luminosity due to sources is in the nine most luminous objects, with \(Q > 3.2 \times 10^{50}\) s\(^{-1}\) (not corrected for dust absorption). These sources have luminosities similar to that of the Galactic center, \(L_{\odot} > 3 \times 10^{25}\) erg Hz\(^{-1}\), or \(Q > 7 \times 10^{51}\) s\(^{-1}\). This corresponds to cluster masses \(M_{cl} > 10^{5} \; M_{\odot}\), ranging up to 2.6 \(\times 10^{5}\) \(M_{\odot}\).

Kennicutt et al. (1989) survey nearby galaxies and construct Her luminosity functions; they find a range of values for \(\alpha\) between 1.5 and 2.5, with values below 2 being slightly more prevalent. McKee & Williams (1997) fit the data presented in Kennicutt et al. (1989) using truncated power-law fits, and find a lower range, \(1.4 < \alpha < 2.3\), with a mean \(\alpha = 1.75 \pm 0.23\).

We conclude this section with a short discussion of a simple question: why has the central cluster that we suggest powers G298 not been noticed before?

We start by noting that similarly massive (but slightly older) clusters like Westerlund 1 (Figer et al. 1999), red supergiant cluster 1 (RSGC1, Figer et al. 2006), RSGC2 (Davies et al. 2007), and RSGC3 (Clark et al. 2009) escaped detection, or

![Figure 7. Surface brightness (MJy sr\(^{-1}\)) as a function of radius, starting from the apparent location of the cluster (l = 298.66, b = -0.507; thick solid line) and from the two giant H\nregions G298.9-0.4 and G298.2-0.3 (thin solid lines; the upper curve near r = 0.1 is G298.2-0.3). The straight dotted and dashed lines are least-squares fits for 0.01 < r < 0.2 for G298.9-0.4 and G298.2-0.3; the slopes are -0.9 and -0.98, i.e., J(r) \sim 1/r. Extrapolating to r = 2, the upper limit for the luminosity of G298.2-0.3 is 1/4 of that of the region as a whole, while that of G298.9-0.4 is 1/5 of the total; the ratios found from the free–free emission are somewhat smaller. The fact that the entire region has a luminosity larger than that of the brightest classical H\nregions, combined with the presence of a diffuse \mum emission region much larger than either H\nregion could illuminate, strongly suggests the presence of a much more luminous star cluster in the interior of the bubble. The interior of the bubble shows little emission, as the gas and dust have been pushed to the bubble wall.](image-url)
were not understood to be massive, until a few years ago. All these clusters are closer to Earth than G298. The RSGCs, as well as G298, have $A_K \sim 1–2$, implying $A_e \sim 10–20$; such clusters are difficult to identify using optical data. The RSGCs are easy to find in GLIMPSE images (we found Westerlund 1 and RSGC1 before realizing they were in the literature). In contrast, the central clusters we identify are younger than $\sim 3.6$ Myr, so their most massive stars have not evolved into red supergiants. As a result they are not very prominent in the GLIMPSE images, in contrast to the RSGCs.

Like the RSGCs, the clusters we identify have cleared bubbles around themselves, limiting the IR surface brightness, and even the free–free surface brightness, of the clusters and their surroundings. However, we use these same large bubbles to infer the presence of a massive cluster. A more direct and convincing demonstration of the existence of the large central clusters we identify would be highly desirable.

5. IONIZING LUMINOSITIES OF H\textsc{ii} REGIONS AND THE GALACTIC STAR FORMATION RATE

The emissivity of the free–free flux from an ionizing region is given by

$$\epsilon_{ff} = \frac{2^5 \pi e^6}{3n_e^2c^3} \left(\frac{2\pi}{3kT}\right)^{1/2} T^{-1/2} Z^2 n_e n_i e^{-h\nu/kT} g_A, \quad (5)$$

where $Z$ is the charge per ion, $T$ is the electron temperature, $n_e$ and $n_i$ are electron and ion densities, respectively, and $g_A$ is the Gaunt factor. For a fully ionized H\textsc{ii} region, we adopt $n_e = n_i$ and $Z = 1$. Further, we adopt an electron temperature, $T_e = 7000$ K for H\textsc{ii} regions, and a Gaunt factor $g_A = 3.3$ (Sutherland 1998). At radio frequencies we approximate this as $\epsilon_{ff} = \epsilon_0 \nu^2$, where $\epsilon_0 = 2.7 \times 10^{-39}$ g cm$^5$ s$^{-3}$ Hz$^{-1}$.

To keep an isotropic H\textsc{ii} region ionized, the total number of ionizing photons required is

$$Q_{\text{tot}} = \int n_e^2 \alpha(H^+) dV, \quad (6)$$

where $V$ is the volume of the ionized region.

The total ionizing luminosity (in photons s$^{-1}$) of a given H\textsc{ii} region is then

$$Q_{\text{tot}} = \frac{\alpha(H^+)}{\epsilon_0} L_\nu \approx 1.33 \times 10^{26} L_\nu \text{ s}^{-1}. \quad (7)$$

Using this expression, we find that the ionizing luminosity of the Galaxy, before correction for absorption by dust, is $Q_{\text{tot}} = 2.34 \times 10^{53}$ photons s$^{-1}$.

The final step is to correct for the effect of absorption by ionizing photons by dust grains. Following McKee & Williams (1997), we multiply by 1.37, and find

$$Q_{\text{tot}} = 3.2 \times 10^{53} \pm 5.1 \times 10^{52} \text{ photons s}^{-1}. \quad (8)$$

The error estimate does not take into account any systematic distance bias.

5.1. Star Formation Rate

To estimate the SFR from $Q$, we follow Mezger (1978) and McKee & Williams (1997), and use the expression

$$M_e = Q \frac{\langle m_e \rangle}{\langle q \rangle} \frac{1}{\langle t_\phi \rangle}, \quad (9)$$

where $\langle q \rangle$ is the ionizing flux per star averaged over the initial mass function (IMF), and $\langle m_e \rangle$ is the mean mass per star, in solar units. The quantity $\langle t_\phi \rangle$ is the ionization-weighted stellar lifetime, i.e., the time at which the ionizing flux of a star falls to half its maximum value, averaged over the IMF; all the averaged terms are discussed in the Appendix.

All of these averaged quantities depend on the IMF of the stars, in particular on the high-mass slope $\Gamma$ of the IMF, as discussed in the Appendix; as an example, and to fix notation, the Salpeter (1955) IMF is given by $\xi(m) \equiv mdN/dm = N m^{-\Gamma}$, with $\Gamma = 1.35$.

Using the stellar evolution models of Bressan et al. (1993) we find $\langle q \rangle = 3.9 \times 10^8$ yr (for $\Gamma = 1.35$). This is slightly longer than the ionizing flux-weighted main-sequence lifetime $\langle t_{\text{ms}} \rangle = 3.7$ Myr used by McKee & Williams (1997), which is in turn somewhat larger than the 3 Myr used by Mezger (1978). This value is only weakly dependent on $\Gamma$.

The WMAP satellite is sensitive to free–free emission, which as we have just indicated is produced by main-sequence O stars with lifetimes of $\sim 3.9$ Myr; i.e., stars with masses in excess of $\sim 40 M_\odot$. Most of the stars driving the free–free emission we see have not been identified. We have examined Two Micron All Sky Survey (2MASS) images, and found that in most cases the stars in the bubble interiors have $J - K$ colors indicating that they are heavily reddened ($A_K \sim 2$), which is presumably why they have not been identified as O stars, as noted at the end of Section 4.

5.1.1. The Mean Ionizing Flux per Solar Mass

The mean ionizing flux per solar mass, $\langle q \rangle / \langle m_e \rangle$, is much more problematic; it depends sensitively on $\Gamma$. Figure 8(a) shows $\langle q \rangle / \langle m \rangle$ using $Q(m)$ as determined by Martins et al. (2005; the solid line) and as given by Vacca et al. (1996; their evolutionary masses); in making this figure we used the Muench et al. (2002) IMF. The difference between the two estimates for $Q(m)$ results in a difference in $\langle q \rangle / \langle m \rangle$ of $\sim 10\%$. The filled square represents our favored value,

$$\frac{\langle q \rangle}{\langle m_e \rangle} = 6.3 \times 10^{46} \text{ s}^{-1} M_\odot^{-1}, \quad (10)$$

at $\Gamma = 1.35$.

For the Muench et al. (2002) IMF $\langle m_e \rangle = 0.71$ when $\Gamma = 1.35$; $\langle q \rangle = 4.5 \times 10^{46}$ s$^{-1}$. This is a factor of 5 larger than the value quoted by McKee & Williams (1997), $\langle q \rangle = 8.9 \times 10^{45}$ s$^{-1}$; this difference is not primarily a result of our using different expressions for $Q(m)$, since the dashed line uses Vacca et al. (1996), as McKee & Williams (1997) used.

We show that this factor of 5 arises mostly from the use of a different IMF, with two contributing factors, the use of a different value of $\Gamma$, and a different IMF shape, so that McKee & Williams (1997) find fewer massive stars at a fixed value of $m$, even when $\Gamma$ is chosen to be the same for the two IMFs; in this comparison, we choose $\Gamma = 1.5$ to match their work.

Figure 8(b) shows the mean ionizing flux per solar mass for the Scalo-type IMF used by McKee & Williams (1997; dot-dashed line), the Muench et al. (2002) IMF (solid line), and the Chabrier (2005) IMF (long-dash line), all as a function of $\Gamma$. In making this plot, we have used the relation between $Q$ and evolutionary mass given by Vacca et al. (1996), so that the dot-dashed curve goes through the McKee & Williams (1997) result. We note that Scalo (1998) no longer recommends use of the Scalo (1986) IMF.
From this plot we can see that the variation in $\Gamma$ is responsible for about a factor of 2 out of the total factor 5 difference; the rest comes from the different shapes of the IMF; with the more recent IMFs (Muench et al. 2002; or Chabrier 2005) having many fewer low-mass stars, or alternately, more high-mass stars, even for fixed $\Gamma$.

The figure shows that small changes in $\Gamma$ lead to large changes in the inferred SFR. Recent observations of young massive clusters have suggested that $\Gamma$ varies from the Salpeter value (Stolte et al. 2002; Harayama et al. 2008); if confirmed, these variations, combined with the results presented here, would lead to large variations in the estimated SFR of the Galaxy.

Using the ionizing flux given by Martins et al. (2005), we can integrate over a Muench et al. (2002) like IMF (Equation (A3)), with $\Gamma$ as a free parameter. In the Appendix, we find

$$\frac{\langle q \rangle}{m_\star} \approx 6.3 \times 10^{46} \left( m_\star Q^{1.35-\Gamma} \right) s^{-1} M_\odot^{-1},$$

where $m_\star Q \approx 35 M_\odot$ is the location of the break in a power-law fit to $Q(m)$ (Figure 9).

Finally, we find a SFR for the Milky Way of

$$M_\star = 4.1 \times 10^{-54} Q = 1.3 \pm 0.2 M_\odot \text{ yr}^{-1}.$$  \hspace{1cm} (12)

Using the McKee & Williams (1997) value of $\Gamma = 1.5$ results in $M_\star = 2.2 M_\odot \text{ yr}^{-1}$, lower than their $4.0 M_\odot \text{ yr}^{-1}$ due to the different forms of the IMF (aside from the high-mass slope $\Gamma$) and our use of the Martins et al. (2005) temperature scale; as seen in Figure 8, using their IMF and Vacca et al. (1996), we recover $M_\star \approx 4 M_\odot \text{ yr}^{-1}$. Using the Muench et al. (2002) slope, the result is $0.9 M_\odot \text{ yr}^{-1}$.

5.2. The Magellanic Clouds

We were able to measure the free–free flux of the LMC and Small Magellanic Cloud (SMC), and thus provide an SFR for each of these galaxies. We find $f_\alpha = 92.2 \text{ Jy}$ for the LMC and $f_\alpha = 6.4 \text{ Jy}$ for the SMC. We adopt a distance to the LMC of $D = 48.1 \text{ kpc}$ (Macri et al. 2006), and $D = 60.6 \text{ kpc}$ for the SMC (Hilditch et al. 2005). This leads to free–free luminosities of $L_\alpha = 2.54 \times 10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1}$ and $L_\alpha = 2.81 \times 10^{25} \text{ erg s}^{-1} \text{ Hz}^{-1}$, respectively. Using Equations (7) and (12) we determine an SFR of $0.14 M_\odot \text{ yr}^{-1}$ for the LMC and $0.015 M_\odot \text{ yr}^{-1}$ for the SMC. Our estimate for the LMC is slightly lower than but consistent with the estimate of 0.25 $M_\odot \text{ yr}^{-1}$ found using Hα and MIPS data by Whitney et al. (2008). Our estimate for the SMC is significantly lower than the Hα estimate of 0.08 $M_\odot \text{ yr}^{-1}$ determined by Kennicutt & Hodge (1986) and the IR estimate of 0.05 $M_\odot \text{ yr}^{-1}$ determined by Wilke et al. (2004).

6. SUMMARY AND DISCUSSION

We have combined the WMAP free–free map with previous determinations of distances to HII regions to measure the ionizing flux of the Galaxy. We find $Q = 3.2 \times 10^{53} \pm 5.1 \times 10^{52} \text{ s}^{-1}$, in agreement with previous determinations. We found 88 sources responsible for a flux of 3604 Jy, out of a total flux of 54211.6 Jy.

The mean WMAP source radius is $\sim 60 \text{ pc}$. Inspection of Spitzer GLIMPSE images and MSX images shows that diffuse 8 $\mu$m emission, which closely tracks the free–free emission, gives sizes consistent with the WMAP sizes, e.g., Figure 7, suggesting that many of the WMAP sources are in fact resolved.

The mean source electron density is $\sim 9 \text{ cm}^{-3}$; hence the mean dispersion measure across a source is $DM \approx 540 \text{ cm}^{-3} \text{ pc}$; from Figure 1, most of the sources are within $\sim 60^\circ$ of the galactic center. Thus we identify these sources with the inner Galaxy and spiral arm components of the free electron model of Taylor & Cordes (1993). The density-weighted scale height of the sources is 114 pc. The total volume filling factor of...
the sources is $\sim 0.005$. Thus the Galactic mean electron density is $(n_e) \approx 0.045$ cm$^{-3}$.

We used GLIMPSE and MSX images to study the WMAP sources with higher resolution. We found that the bulk of the Galactic star formation (of order half) occurs in $\sim 20$ sources, each with $Q \approx 5 \times 10^{31}$ s$^{-1}$. These sources should be examined in other wave bands, including X-rays. The 8 $\mu$m images revealed large bubbles, with $r \sim 20$ pc, ranging up to 100 pc, in most of these sources; these bubbles are much larger (up to a factor of 10) than those described by Churchwell et al. (2006, 2007).

We showed that classical giant H II regions associated with the WMAP sources were located in the bubble walls, and interpreted them as triggered star formation. We argued that the bubbles are powered by massive star clusters responsible for the bulk of the ionizing flux in each WMAP source. We estimate that these clusters have masses $M_* \approx 4 \times 10^4 M_\odot$ or larger.

We note that there are now a number of slightly older (but still young, 10–20 Myr old) Milky Way clusters known to harbor stars with mass in excess of $10^4 M_\odot$, with $0.1 \leq m \leq 120$. The first is the Salpeter (1955) IMF:

$$\xi(m) \equiv mdN/dm = N(\Gamma)m^{-\Gamma}. \quad (A1)$$

Salpeter found $\Gamma = 1.35$.

The second IMF is the McKee & Williams (1997) version of Salco (1986), which at the high-mass end looks like the Salpeter IMF:

$$mdN/dm = Nm^{-\Gamma}, \quad (A2)$$

with $N = 0.063 C_F$; they take $C_F = 1.4$. McKee & Williams (1997) use $\Gamma = 1.5$.

Third, we use a modified Muench et al. (2002) IMF:

$$\xi_{M,m_1}(m) \equiv m dN/dm = \int_{m_1}^m N_0 \{ m^{\Gamma-1} \} \left\{ \begin{array}{ll} m_U > m > m_1 & m_U \in \left[m_1, m_2\right] \\ m_1 > m > m_{0,73} & m_2 > m > m_{0,73} \end{array} \right. \quad (A3)$$

Muench et al. (2002) found $\Gamma = 1.21$ for the Orion region. As indicated above, $m_U = 120$ and $m_{0,73} = 0.1$. We use $m_1 = 0.6$ as the characteristic break mass.

Finally, we use the Chabrier (2005) IMF:

$$\xi(m) = N_0 \left\{ \begin{array}{ll} \exp \left( \frac{\log(m) - \log(0.08)}{2 \times (0.35)^{-1}} \right) & 0.0446 m_1^{-\Gamma} \\ 1 & m \leq m_U \end{array} \right. \quad (A4)$$

We use the normalization

$$\int_{m_L}^{m_U} \xi(m) \frac{dm}{m} = 1. \quad (A5)$$

In that case, the ionizing flux per solar mass is

$$\frac{<q>}{<m>} \equiv \int_{m_L}^{m_U} Q(m)\xi(m)\frac{dm}{m} \int_{m_L}^{m_U} \xi(m)dm, \quad (A6)$$

where

$$<m> \equiv \int_{m_L}^{m_U} \xi(m)dm \quad (A7)$$

is the mean mass per star.

We use both the Vacca et al. (1996) and Martins et al. (2005) compilations of ionizing fluxes as a function of stellar mass; the ionizing flux $Q(m)$ is given per star by both. Since many clusters harbor stars with mass in excess of 100 $M_\odot$, but neither paper models stars with $M > 88 M_\odot$, we have added the result

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of Martins et al. (2008), who find \( Q \approx 10^{50} \) for each of four WN7-8h stars with \( \log L/L_\odot > 6.3 \) (all of which they model by stars with \( M \gtrsim 120 M_\odot \); see their Table 2 and Figure 2). These stars are slightly evolved, but still very young. Figure 9 shows \( Q(m_*) \) for both Vacca et al. (1996) and Martins et al. (2005).

The function \( Q(m) \sim m^3 \) for \( 15 < m \lesssim m_Q \) (where \( m_Q \approx 40 \)), but \( Q(m) \sim m^{1.5} \) for \( m > m_Q \). The integral \( \langle Q \rangle \propto \int m Q(m) \phi(m) dm \sim m^{1.65} \) for \( m < m_Q \), and \( \sim m^{1.15} \) for larger \( m \), indicating that the bulk of the ionizing flux occurs for stars with mass around \( m_Q \), for all of our IMFs. Doing the integrals on the right-hand side of Equation (A6) from \( m_L \) to \( m_Q \) gives

\[
\langle q_s \rangle \sim m^{-3} Q^{(1+\alpha)},
\]

which fits the numerical result rather well; it is shown as the dotted line in Figure 8.

The ionizing flux-weighted lifetime of a cluster is given by

\[
(t_Q) \equiv \int_{m_L}^{m_U} Q(m) \gamma(m) dm \int_{m_L}^{m_U} Q(m) \xi(m) dm,
\]

where \( t(m) \) is the main-sequence lifetime of a star of mass \( m \).

REFERENCES

Anantharamaiah, K. R. 1985a, J. Astrophys. Astron., 6, 177
Anantharamaiah, K. R. 1985b, J. Astrophys. Astron., 6, 203

Benjamin, R. A., et al. 2003, PASP, 115, 953
Bennett, C. L., et al. 1994, ApJ, 434, 587
Bennett, C. L., et al. 2003a, ApJS, 148, 97
Bennett, C. L., et al. 2003b, ApJ, 583, 1
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Binney, J., & Merrifield, M. (ed.) 1998, in Princeton Series in Astrophysics QB857.B522, Galactic Astronomy (Princeton, NJ: Princeton Univ. Press)
Brandner, W., Clark, J. S., Stolte, A., Waters, R., Negueruela, I., & Goodwin, S. P. 2008, A&A, 478, 137
Bressan, A., Fagotto, F., Bertelli, G., & Chiosi, C. 1993, A&AS, 100, 647
Caswell, J. L., & Haynes, R. F. 1987, A&A, 171, 261
Chabrier, G. 2005, in The Initial Mass Function 50 Years Later, ed. E. Corbelli & F. Palla (Berlin: Springer), 41
Churchwell, E., et al. 2006, ApJ, 649, 759
Churchwell, E., et al. 2007, ApJ, 670, 428
Clark, J. S., et al. 2009, A&A, 498, 109
Cohen, M., & Green, A. J. 2001, MNRAS, 325, 531
Conti, P. S., & Crowther, P. A. 2004, MNRAS, 355, 899
Davies, B., et al. 2007, ApJ, 671, 781
Dickinson, C., Davies, R. D., & Davis, R. J. 2003, MNRAS, 341, 369
Draine, B. T. 1986, ApJ, 310, 408
Fich, M., & Blitz, L. 1984, ApJ, 279, 125
Figer, D. F., Kim, S. S., Morris, M., Serabyn, E., Rich, R. M., & McLean, I. S. 1999, ApJ, 525, 750
Figer, D. F., et al. 2006, ApJ, 643, 1166
Gusten, R., & Mezger, P. G. 1982, Vistas Astron., 26, 159
Hanson, M. M. 2003, ApJ, 597, 957
Harayama, Y., Eisenhauer, F., & Martins, F. 2008, ApJ, 675, 1319
Hilditch, R. W., Howarth, I. D., & Harries, T. J. 2005, MNRAS, 357, 304
Kennicutt, R. C., Jr., Edgar, B. K., & Hodge, P. W. 1989, ApJ, 337, 761
Kennicutt, R. C., Jr., & Hodge, P. W. 1986, ApJ, 306, 130
Lockman, F. J. 1976, ApJ, 209, 429
Macri, L. M., Stanek, K. Z., Bersier, D., Greenhill, L. J., & Reid, M. J. 2006, ApJ, 652, 1133
Martins, F., Hillier, D. J., Paumard, T., Eisenhauer, F., Ott, T., & Genzel, R. 2008, A&A, 478, 219
Martins, F., Schaerer, D., & Hillier, D. J. 2005, A&A, 436, 1049
McKee, C. F., & Williams, J. P. 1997, ApJ, 476, 144
Mezger, P. G. 1978, A&A, 70, 565
Muench, A. A., Lada, E. A., Lada, C. J., & Alves, J. 2002, ApJ, 573, 366
Negueruela, I., Marco, A., Herrero, A., & Clark, J. S. 2008, A&A, 487, 575
Osterbrock, D. E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley, CA: Univ. Science Books)
Price, S. D., Egan, M. P., Carey, S. J., Mizuno, D. R., & Kuchar, T. A. 2001, AJ, 121, 2819
Russell, D. 2003, A&A, 397, 133
Salpeter, E. E. 1955, ApJ, 121, 161
Scalo, J. 1986, Fundam. Cosm. Phys., 11, 1
Scalo, J. 1998, in ASP Conf. Ser. 142 (38th Herstmonceux Conf.), The Stellar Initial Mass Function, ed. G. Gilmore & D. Howell (San Francisco, CA: ASP), 201
Schneider, N., Bontemps, S., Simon, R., Jakob, H., Motte, F., Miller, M., Kramer, C., & Stutzki, J. 2006, A&A, 458, 855
Smith, L. F., Biermann, P., & Mezger, P. G. 1978, A&A, 66, 65
Smith, N. 2006, MNRAS, 367, 763
Stolte, A., Grebel, E. K., Brandner, W., & Figer, D. F. 2002, A&A, 394, 459
Sutherland, R. S. 1998, MNRAS, 300, 321
Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674
Vacca, W. D., Garmany, C. D., & Shull, J. M. 1996, ApJ, 460, 914
Westerhout, G. 1958, Bull. Astron. Inst. Neth, 14, 215
Whiteoak, J. B. Z., Cram, L. E., & Large, M. I. 1994, MNRAS, 269, 294
Whitney, B. A., et al. 2008, AJ, 136, 18
Wilke, K., Klaas, U., Lemke, D., Mattila, K., Stickel, M., & Haas, M. 2004, A&A, 414, 69
Williams, J. P., de Geus, E. J., & Blitz, L. 1994, ApJ, 428, 693
Wilson, T. L., Mezger, P. G., Gardner, F. F., & Milne, D. K. 1970, A&A, 6, 364

Figure 9. Ionizing flux \( Q \) as a function of stellar mass \( M \). The open squares (joined by a dashed line) show the results using the evolutionary masses of Vacca et al. (1996), while the solid squares (joined by a solid line) show the results using those of Martins et al. (2005); both have been supplemented by the addition of a slightly evolved model for a 120 \( M_\odot \) star taken from Martins et al. (2008). The slope below \( M_Q \approx 40 M_\odot \) for both models is \( d \ln Q/d \ln M \approx 4 \), while that for \( M_Q \approx 1 \).