THE GALACTIC SPATIAL DISTRIBUTION OF OB ASSOCIATIONS AND THEIR SURROUNDING SUPERNova-GENERATED SUPERBUBBLES

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ABSTRACT

The Galactic spatial distribution of OB associations and their surrounding superbubbles (SBs) reflect the distribution of a wide range of important processes in our Galaxy. In particular, it can provide a three-dimensional measure not only of the major source distribution of Galactic cosmic rays, but also the Galactic star formation distribution, the Lyman continuum ionizing radiation distribution, the core-collapse supernova distribution, the neutron star and stellar black hole production distributions, and the principal source distribution of freshly synthesized elements. Thus, we construct a three-dimensional spatial model of the massive-star distribution based primarily on the emission of the H II envelopes that surround the giant SBs and are maintained by the ionizing radiation of the embedded O stars. The Galactic longitudinal distribution of the 205 µm N II radiation, emitted by these H II envelopes, is used to infer the spatial distribution of SBs. We find that the Galactic SB distribution is dominated by the contribution of massive-star clusters residing in the spiral arms.

Key words: cosmic rays – H II regions – ISM: bubbles – open clusters and associations: general – stars: formation – supernovae: general – supernovae: individual (SN 2008hw)

Online-only material: color figure

1. INTRODUCTION

Supernovae (SNe) created by the core collapse of massive stars have long been recognized (e.g., Baade & Zwicky 1934; Zwicky 1939; Hayakawa 1956; Ginzburg & Syrovatskii 1964; Zatsepin & Sokolskaya 2007) as the major source of Galactic cosmic-ray acceleration. But these same SNe are also the sources of Galactic neutron stars and stellar black holes (e.g., Heger et al. 2003) and the principal source of freshly synthesized elements (e.g., Timmes et al. 1995), while their progenitor stars are the major source of the Lyman continuum (Lyc) ionizing radiation (e.g., Baldwin et al. 1981; McKee & Williams 1997; González Delgado & Leitherer 1999), and their Galactic spatial distribution reflects that of the OB associations (OBAs) and their surrounding superbubbles (SBs; e.g., Higdon & Lingenfelter 2005).

However, observations have demonstrated that collapse SNe are quite complex. Currently, the principal categories of core-collapse supernovae (CCSNe), classified by their optical spectra, are II-P (plateau), II-L (linear), IIn (narrow emission lines), IIPb (transitional), Ib, and Ic (e.g., Filippenko 1997). The most common CCSNe are SN II-P and SN Ic, which constitute 48% ± 6% and 15% ± 4%, respectively, of CCSNe in spiral galaxies (Smith et al. 2011).

The minimum stellar mass necessary to produce a CCSN has been found to be 8 ± 1 M⊙ from the discoveries of red supergiant progenitors in Hubble Space Telescope (HST) pre-explosion images of SN II-P (e.g., Smartt 2009). At solar metallicity an 8 M⊙ star corresponds to the spectral classification of B3 V (Drilling & Landolt 2000). We estimate the main-sequence age of such an 8 M⊙ star as ≈35 Myr via interpolation from a tabulation of mass-dependent main-sequence ages (Massey & Meyer 2001).

The stellar progenitors have not been identified in SN Ic pre-explosion images (e.g., Smartt 2009), but they are thought to be very massive stars which have been stripped of both their hydrogen and helium envelopes prior to collapse (e.g., Filippenko 1997). SN Ic models require the core collapse of either rotating single stars initially ~40–120 M⊙ (Georgy et al. 2009), which have lost their stellar envelopes via stellar winds (e.g., Gaskell et al. 1986), or initially less massive (~25 M⊙) primaries (Dessart et al. 2012) in close binary systems which have lost their stellar envelopes to smaller companion stars through Roche lobe overflow or common envelope evolution (e.g., Paczyński 1967; Podsiadlowski et al. 1992). At solar metallicity zero-aged 25 and 120 M⊙ stars correspond to spectral classifications of O8 V and O3 V; these are short-lived with main-sequence ages of 6.4 and 2.6 Myr, respectively (Massey 2003).

The progenitors of CCSNe are not distributed uniformly in spiral galaxies. It has been known for close to a century that massive stars cluster (Kapteyn 1914). This is not surprising since the majority of stars are born in stellar clusters embedded in molecular clouds (McKee & Williams 1997; Lada & Lada 2003; Portegies Zwart et al. 2010). Moreover, the vast majority (70%–80%) of all O stars reside still in the stellar clusters in which they were born (Gies 1987; Mason et al. 1998; Neugent & Massey 2011). The giant molecular clouds creating the massive CCSN progenitor stars usually produce around five separate episodes of star formation over ~20 Myr (Blauw 1964, 1991; McKee & Williams 1997). Together these sub-clusters constitute what is called an OBA (Blauw 1964).

Analyses of Hipparcos proper-motion measurements of OB stars residing in nearby (~kpc) OBAs have found that the upper limit on internal OBA velocity dispersions is ~3 km s⁻¹ or 3 pc Myr⁻¹ (de Zeeuw et al. 1999). This modest velocity dispersion is the fundamental reason why CCSNe occur primarily in SBs since even an 8 M⊙ SN II-P stellar progenitor does not travel too far (~10² pc in its 35 Myr lifetime) from its birth site before it dies as a CCSN. Therefore, the core-collapse deaths of (120–8 M⊙) progenitor stars occur within ~10–10² pc of their birth sites. Each stellar death releases ~10⁵¹ erg of energy in the core-collapse supernova distribution, the neutron star and stellar black hole production distributions, and the principal source distribution of freshly synthesized elements.
the surrounding interstellar medium (e.g., Chevalier 1977) with a mean pre-SN wind contribution of less than 10% (Leitherer et al. 1999).

Consequently, as was noted several decades ago, such correlated SNe are expected to create giant (>10^2 pc) expanding cavities of hot, tenuous plasmas while sweeping up the ambient interstellar media into thin, denser, cooler shells (e.g., McCray & Snow 1979; McCray & Kafatos 1987; Mac Low & McCray 1988). These large interstellar structures are termed either “supershells” or “SBs.” Most of the mass of the swept-up shells is expected to be cool (∼10^2 K) H I or H_2, yet for the first ∼10 Myr the ionizing radiation from the embedded O stars of the parent OBA photoionizes the inner rim of the swept-up shells (e.g., McCray 1988). In the present study we use 205 μm N_II line emissions from these photoionized supershell rims to derive the Galactic distribution of SBs.

In this investigation we create a three-dimensional Galactic distribution of OBAs and their surrounding SBs.

1.1. Outline

Although the actual determination of the Galactic spatial distribution of SBs is straightforward, all the details involved make the derivation lengthy and complicated.

In Section 2 we investigate the relationship between CCSN occurrences and sites of massive-star formation in other spiral galaxies. Of particular interest is the study by Anderson et al. (2012) of the correlation of SN II occurrences and extragalactic star formation sites as traced by near-ultraviolet (NUV) continuum emissions. Such emissions are sensitive indicators of the presence of moderate-mass (8–20 M⊙) SN II stellar progenitors.

In Section 3 we present a concise summary of SB properties gleaned from multi-wavelength observations of both Galactic and extragalactic SBs.

In Section 4 we discuss the spectral signatures specific to SBs. We find that on the Galactic scale the best SB signature turns out to be N_II far-infrared lines which have been resolved by the Far Infrared Absolute Spectrophotometer (FIRAS) aboard the Cosmic Background Explorer (COBE; Fixsen et al. 1999). We expect that the majority of such far-infrared lines are radiated by ∼10^2 pc sized (1–10 cm^-3) photoionized envelopes surrounding the hot, tenuous SBs. These H II envelopes absorb the majority of ionizing radiation emitted by the embedded OBAs (e.g., McKee & Williams 1997).

In Section 5 we first consider a simple three-dimensional N_II emissivity model and simulate the FIRAS 205 μm intensities, as a function of Galactic longitude, assuming that the spatial distribution of Galactic SBs follows that of an axisymmetric disk population. This modeled FIRAS 205 μm intensity, displayed in Figure 1, poorly reproduces the measured FIRAS 205 μm intensity. More complicated source models are clearly required.

Therefore, in Section 6 we present three-dimensional N_II emissivity distributions based on models consisting of four spiral arms (e.g., Vallée 2008). We find that such spiral-arm distributions can reproduce the measured (Fixsen et al. 1999) FIRAS 205 μm intensity once the contribution of two nearby (∼kpc) H II regions is included.

In Section 7 we consider the fact that the SB spatial distribution does not scale linearly with the N_II 205 μm emissivity distribution due to the presence of a large-scale radial gradient in the ratio of interstellar nitrogen to hydrogen abundances. Here we present the spatial distribution of solely the massive-star population. This distribution represents the best measure of the Galactic spatial distribution of SBs and their embedded OBAs.

In Section 8 we interpret the very bright 205 μm FIRAS features at Galactic longitudes, around 80° and 265°, not as spiral-arm tangents, but as nearby H_II sources. We model the strong 205 μm FIRAS feature at Galactic longitude, ≈80°, as an H_II envelope of an SB, excited by a rich embedded OBA, Cyg OB2, the closest massive association. We model the other 205 μm FIRAS feature at Galactic longitudes, ≈265°, as a component of the Vela Nebula, a nearby (≤0.35 kpc) H_II region, primarily excited by a single close O star, η Puppis.

Finally, in Section 9 we summarize the results of this investigation.

2. THE RELATIONSHIP BETWEEN CCSN OCCURRENCES AND STAR FORMATION SITES

The majority (~70%) of CCSNe are expected to be mid- and early B stars, since massive stars follow a Salpeter initial mass function (e.g., Bastian et al. 2010) and the minimum CCSN progenitor mass is 8 M⊙ (e.g., Smartt 2009). Yet Galactic OBMA membership is invariably determined by bright O stars (Gies 1987; Mason et al. 1998; Maíz-Apellániz et al. 2004). As noted by Maíz-Apellániz et al. (p. 140), “the quality of the data regarding membership to a cluster or an OBA is extremely varied and for stars located at farther distances information is usually poorer.” Cluster membership of the early and mid-B stars, which constitute the majority of the CCSN stellar progenitors, is seldom investigated. In this section we discuss the evidence for stellar clustering of lower-mass, B star (<20 M⊙) CCSN progenitors.

James & Anderson (2006) investigated the correlation of extragalactic CCSNe to star formation sites using Hα CCD images of the parent galaxies. In order to moderate contributions of faint star formation sites, they employed all the pixels of an Hα image in their analysis. They sorted all the pixels of a digitized image in order of increasing pixel counts starting with the most negative sky pixels (created by background subtractions) and ending with the pixel corresponding to the brightest star formation region. The initial negative pixel values are set to zero. Then a cumulative distribution is created from...
the ranked sequence and is normalized to the total Hα flux of the image. Thus, an NCR (their acronym for the normalized cumulative rank pixel function) value of 0 corresponds to background sky values, and NCR of 1 corresponds to the brightest pixel in an image.

If the CCSN progenitor was a member of the massive-star population which creates the tracer (here Hα) emission, it is equally likely to come from any part of the NCR distribution (James & Anderson 2006). Thus, over a long period of time the large numbers of pixels constituting the 0.0–0.1 NCR segment contribute as much to total tracer emission as the few bright pixels comprising the 0.9–1.0 segment. In such a case the NCR distribution will be uniform and have a mean value of 0.5 (James & Anderson 2006).

Using the above NCR pixel statistic, Anderson et al. (2012) investigated the relationship between CCSNe and star formation sites, traced by Hα emission, for a large sample of 260 (164 SN Type II and 96 Type Ib/c) CCSNe. Their effective pixel size corresponds typically to a dimension of 130 pc. In view of their sample size they applied the NCR statistic to the six sub-type classifications (II-P, II-L, IIn, IIb, Ib, and Ic) applicable to CCSNe. Their results are listed in Table 1, where n refers to the number of SNe in the sample. Using the Kolmogorov–Smirnov (K-S) test, they found that three NCR distributions, SN IIb, SN II–L, and SN Ic, agree well with a massive-star population as traced by Hα emission. Yet, the K-S test demonstrates that two Type II sub-types, SN II-P (the most common CCSNe) and SN IIn, as well as SN Ib, are not consistent with a massive-star population as traced by Hα line emission. However, as we shall see, Hα emission is not the sole tracer of massive stars.

Anderson et al. investigated further the correlation of CCSNe and star formation sites, but now used near-ultraviolet (NUV 1750–2750 Å) images taken by the Galaxy Evolution Explorer (Martin et al. 2005). NUV continuum emission is particularly well suited for the identification of 10 Myr old stellar clusters, which radiate negligible LyC emission. Such NUV emission provides a direct measure of star formation on timescales ∼10^5 Myr (Martin et al. 2005). Note that a ∼10^5 Myr lifetime corresponds to a 5 M_⊙ B5 V star (Massey & Meyer 2001). Using NUV emissions, they found for the SN II-P (50 SNe) (NUV) = 0.50 ± 0.045 and SN IIn (18 SNe) (NUV) = 0.38 ± 0.065. The K-S test showed that these two NCR distributions are consistent with that expected for flat distributions, and, consequently, these two SN II sub-types track stellar clusters containing older (10–100 Myr) but still massive (5–20 M_⊙) stars.

Thus, analyses of sites of extragalactic CCSNe demonstrate that the great majority of these CCSNe occur in or close to (≤150 pc) stellar clusters of massive stars all with the potential to generate SNe.

### Table 1

| SN Class | n   | ⟨NCR⟩_{Hα} |
|----------|-----|-------------|
| Ib       | 39  | 0.32 ± 0.040 |
| Ic       | 52  | 0.46 ± 0.040 |
| II-L     | 13  | 0.37 ± 0.100 |
| IIb      | 13  | 0.40 ± 0.100 |
| II-P     | 58  | 0.26 ± 0.039 |
| IIn      | 19  | 0.21 ± 0.065 |

3. **SUPERBUBBLE PROPERTIES**

Here we review published analyses of multi-wavelength observations of SN-dominated SBs to constrain their fundamental properties. These analyses suggest that for a typical SB the mean cavity density, n_e, is small, <10^{-2} cm^{-3}, the mean cavity temperature, T_e, is high, >10^6 K, the cavity is enveloped by shells of denser interstellar gases, and, finally, the mean radius is ∼130 pc.

In the Orion–Eridanus SB, Burrows et al. (1993) found that n_e ≈ 4 × 10^{-3} cm^{-3} and T_e ≈ 2 × 10^6 and that the SB cavity is roughly ellipsoidal with a semimajor axis of 160 pc and a semiminor axis of 70 pc. Further, using Hα and [NII] λ6584 emission lines, Reynolds & Ogden (1979) found that this SB is enveloped by an expanding (∼15 km s^{-1}) shell of warm (∼8000 K), predominantly ionized (>80%–90%) gas with a mean shell density of ∼1 cm^{-3}. This HII shell is in turn surrounded by an expanding HII shell of mean density ∼1 cm^{-3} and a mass ∼3 × 10^5 M_⊙ (Brown et al. 1995).

The source of massive stars whose CCSNe and winds created the Orion–Eridanus SB is expected to be the Orion OB1 association (e.g., Reynolds & Ogden 1979; Burrows et al. 1993; Brown et al. 1995; Heiles et al. 1999; Heiles 2001).

Heiles (1998) also identified a new, nearby (∼800 pc) SB, comparable in angular size (∼35°) to the Orion–Eridanus SB, from coupled emissions in HII, IR, radio continuum, and soft X-rays. He found that this SB had n_e of ∼6 × 10^{-3} cm^{-3} and T_e of ∼1.3 × 10^6 K and is much larger than the Orion–Eridanus SB with a semimajor axis of ∼500 pc and a semiminor axis of ∼200 pc. He established that this tenuous plasma cavity was enveloped by an expanding (∼8 km s^{-1}) HI shell of ∼2.7 × 10^6 M_⊙, 10 times that of the Orion–Eridanus shell. Noting its kinematic expansion age of 20 Myr, Heiles suggested that the stellar cluster, Collider 121, whose most massive star is a B2, located within the SB, at a distance of ∼550 pc, was the source of the CCSNe which created this SB.

Bisnovatyi-Kogan & Silich (1995) have suggested that the best evidence3 for the correlated SN origin for SBs was the analyses of X-ray emissions from the cavities of two large supershells, LMC-2 and LMC-4, located in the Large Magellanic Cloud (LMC). Wang & Helfand (1991b) found that the LMC-2 (∼500 pc) cavity is filled with a hot (∼5 × 10^6 K), tenuous (∼9 × 10^{-3} cm^{-3}) plasma with a total thermal energy of ∼10^{32} erg, equivalent to the combined ejecta kinetic energy of ∼10^5 CCSNe. Bomans et al. (1994) determined that the thermal plasma inside the LMC-4 bubble, the largest (∼600 pc × 1200 pc) Magellanic supershell, is hot (∼2.4 × 10^6 K) and tenuous (∼8 × 10^{-3} cm^{-3}).

Supershells are most easily resolved in neutral interstellar gases from velocity resolution (e.g., Heiles 1998). Consequently, a large number of HII supershells have been identified in the Milky Way (Heiles 1979, 1985; McClure-Griffiths et al. 2002), M31 (Brinks & Bajaja 1986), M33 (Deu & Hertog 1990), Helming II (Puche et al. 1992), the Small Magellanic Cloud (Staveley-Smith et al. 1997), and the LMC(Kim et al. 1999). Of special interest is the study of Kim et al., who observed the LMC in both 21 cm and Hα emission at similar

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3 Larger (>10^5 pc) SBs are not the only class of SBs where supernova-generated X-ray emissions have been resolved. Bright X-ray emissions have been detected from a number (>10) of small (<50 pc), young (<5 Myr) SBs in the LMC; such X-ray emissions have been interpreted (Chu & Mac Low 1990; Wang & Helfand 1991a) as the result of a recent (<10^8 yr) impact of a single supernova remnant on the HII rim of a stellar-wind-blown SB.
resolutions and created a 21 cm mosaicked map with a 1′ resolution (~15 pc linear scale, using a distance to the LMC of 50 kpc) and an Hα image with pixels corresponding to 21″ (~5 pc linear scale). They resolved 126 H i shells with radii, $R_i$, between 40 and 630 pc and identified 23 H i shells with $R_i > 5$ Myr of 180 pc, the scale height of the H i gas; they termed these latter shells as “supergiant.” They interpreted the supergiant shells as chimneys (e.g., Norman & Ikeuchi 1989), where hot gas created in the shell interiors flows from tenuous shell cavities to the halo surrounding LMC. Moreover, they detected corresponding Hα emissions from 20 of these 23 supergiant shells. In addition, they identified 103 smaller H i shells. They found it difficult to relate their measured Hα fluxes with these smaller H i shells, yet they noted that “in many cases” these smaller H i shells were associated with individual H ii regions tabulated in the Davies et al. (1976) catalog.

We use the catalog of Kim et al. of LMC H i shells to estimate the radius of a typical SB in the Milky Way. However, first we must consider the contributions of isolated SN remnants to H i shell catalogs, as noted by Oey & Clarke (1997). The inclusion of H i shells, created by single, isolated SN remnants, biases the size distribution at $R_i < 10^5$ pc. Isolated SNe expanding in the diffuse interstellar medium outside4 SBs create shells of cold neutral gas late in their evolution (e.g., Chevalier 1974; McCray & Snow 1979). Modeling the evolution of SN remnants in homogeneous interstellar media, Slavin & Cox (1993) found that isolated remnants reached a maximum size of 66 pc for a representative magnetic field of $5 \times 10^{-6}$ G and a gas density of $0.3$ cm$^{-3}$ in the Milky Way. Using the Kim et al. shell catalog and discarding the eight H i shells with radii $R_i \leq 66$ pc gives a median $R_i$ of 130 pc.

4. MODELING OF THE GALACTIC SUPERBUBBLE SPATIAL DISTRIBUTION

We are interested in radiation signatures specific to Galactic SBs. To us the best indicator of SBs is soft X-ray emission from large (>10$^5$ pc) cavities filled with hot (~10$^6$ K) plasmas. Yet photoelectric absorption by intervening interstellar gas hinders the detection of such soft X-rays from SBs located in the Galactic disk beyond the solar vicinity. Here we propose to employ radiation emitted by inner rims of supershells, ionized by massive O stars residing inside the SBs, to trace globally their Galactic spatial distribution.

The modifier globally is used here in the following sense. The dynamics of SBs, resulting from around five separate episodes of massive star formation, are dominated energetically by the contribution of Type II SNe, produced by the CCSN of ~8–20 $M_\odot$ stellar progenitors, which are relatively long-lived, 35–100 Myr, yet the O stars that photoionize the supershell rims are short-lived, ~9–2.5 Myr. Consequently, we expect SBs to be visible via H ii emissions ~50% of the time since ionizing photons persist for ~30 Myr, 20 Myr of star formation episodes (e.g., Blaauw 1964, 1991; Heiles 1990; McKee & Williams 1997) plus ~9 Myr, the stellar lifetime of the lowest mass (20 $M_\odot$) O star (Massey 2003), while the longer-lived B stars continue to inject mechanical energy in the form of CCSNe for ~55 Myr, 20 Myr of star formation episodes plus ~35 Myr, the stellar lifetime of an 8 $M_\odot$, the lowest mass CCSN stellar progenitor. The expectation that signatures of photoionized gases are visible over ~50% of SB lifetimes agrees with analyses of Anderson et al. (2012), who found that occurrences of Type II-P SNe correlate well with NUV emissions from stellar clusters, populated by ~5 $M_\odot$ stars, but not with Hα line emissions, created by ~20 $M_\odot$ O stars.

The Galactic H ii interstellar phase can be classified as three components: first, radio H ii regions, dense ($n_e \geq 10^{3}$ cm$^{-3}$), small (<pc) gas clumps surrounding young O stars residing still in their parent molecular clouds; second, an extended component, less dense ($n_e \sim 5$ cm$^{-3}$), and more distant (~50–10$^5$ pc) from the exciting O stars; and, third, a widely distributed component5 of $n_e \sim 0.1$ cm$^{-3}$ and more distant still (>200 pc) from exciting O stars (e.g., Smith et al. 1978; Mezger 1978; Güsten & Mezger 1982).

The second phase, the extended H ii regions, absorbs the majority of the Lyc photons emitted by Galactic O stars (e.g., Smith et al. 1978; Mezger 1978; Güsten & Mezger 1982; McKee & Williams 1977). In their seminal study of Galactic OBAs McKee & Williams (1997) found that, first, only ~1/10 of the ionizing photons emitted by massive O stars are required to maintain the diffuse warm ionized medium, second, ~1/3 of the ionizing photons are absorbed in radio H ii regions, and third, the majority, ~2/3, of the Lyc photons emitted by O stars are absorbed in the extended H ii gas with its electron density of ~5 cm$^{-3}$.

The nature of the radio H ii regions seems to be well understood. Analyses of 2.6 mm CO line surveys have shown that nearly all radio H ii regions are associated with giant molecular clouds (e.g., Wilson et al. 1974; Habing & Israel 1979; Gillespie et al. 1977; Myers et al. 1986). Further, the radio H ii regions are usually composed of a number of compact6 H ii regions (Güsten & Mezger 1978).

The nature of the extended H ii component has been a subject of debate, and a variety of sites have been proposed: the diffuse interstellar medium (e.g., Gordon & Gottesman 1971; Cesarsky & Cesarsky 1971), large (>500 pc) H ii complexes (e.g., Matthews et al. 1973), small H ii regions (e.g., Jackson & Kerr 1975), outer envelopes6 of H ii regions (e.g., Hart & Pedlar 1976; Mezger 1978; Lockman 1979, 1980; Anantharamaiah 1985; McKee & Williams 1997), and photoionized supershells (e.g., Heiles et al. 1996).

Analyses of low-frequency (<GHz) radio recombination-line (RRL) surveys, which are sensitive to electron densities in the range 0.5 cm$^{-3} \leq n_e \leq 50$ cm$^{-3}$, suggest that the properties of the extended H ii gas are 0.5 cm$^{-3} \leq n_e \leq 15$ cm$^{-3}$ with a mean density ~5 cm$^{-3}$ and total path lengths of 20–200 pc (e.g., Shaver 1976; Anantharamaiah 1985, 1986; Roshi & Anantharamaiah 2000). Analyses of high-frequency radio recombination surveys support these values. For example, resolving 1.4 GHz recombination lines from 418 lines of sight, Heiles et al.

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5 Mezger (1978) defines a “radio H ii region” as a thermal source with a 5 GHz antenna temperature $T_A \geq 1–2$ K when observed at a beam resolution, $\theta_B$, of ~5″.

6 This phase has been termed the warm ionized medium or the diffuse ionized gas and was identified in the local interstellar medium via faint, ubiquitous Hα line emissions and it extends about a kpc above and below the Galactic plane (e.g., Reynolds et al. 1973; Reynolds 1984, 1987; Haffner et al. 2009). The escape of Lyc photons from O star H ii regions seems to be its likely origin (e.g., Miller & Cox 1993; Dom¨orgen & Mathis 1994; Dove & Shull 1994).

7 The modifier “compact” describes H ii regions which are dense ($n_e > 5000$ cm$^{-3}$), small (diameters < 0.5 pc), and are associated with early-type stars of spectral types B0 through O4 (Habing & Israel 1979).

8 Based on Hα observations of bright extragalactic H ii regions, the core-envelope description of H ii regions was first suggested by Sandage & Tamman (1974).
found $n_e$ of 5 cm$^{-3}$, total path lengths of 150 pc, and individual clump sizes of 20–50 pc. Further, longitude–velocity diagrams constructed from low-frequency recombination-line emissions agree well with that of high-frequency recombination-line emissions, produced by the compact, radio H$\text{II}$ regions and that of 2.6 mm 12CO lines, generated by star formation sites embedded in giant molecular clouds (Anantharamaiah 1986; Roshi & Anantharamaiah 2000, 2001).

Taken together, the evidence above suggests that the extended H$\text{II}$ component is produced by a combination of H$\text{II}$ envelopes and photoionized supershells (e.g., Heiles et al. 1996; McKee & Williams 1997). The fundamental properties of H$\text{II}$ envelopes have been best described by McKee & Williams. In their Section 8 they employed a value of 50 pc as the typical size$^9$ of an H$\text{II}$ envelope. In Section 5.2 and in Appendix B they characterized the electron density of the H$\text{II}$ envelopes by $n_e^2 \phi \approx 5$ cm$^{-6}$, where $\phi$ represents the volume filling factor of the photoionized gas in the H$\text{II}$ region and setting $\phi \approx (1/2)$, and found $n_e \approx 3$ cm$^{-3}$, since they expect half of an H$\text{II}$ volume to be filled with hot plasmas of the enclosed SB. They noted that (p. 153) “an ionized worm around an association is essentially equivalent to the H$\text{II}$ envelope of an association.”$^{10}$ Further, they observed that the number of giant worms, discovered by Heiles et al., agrees with their expected number of large OBAs. For the reasons presented here, we suggest that for all but the smallest OBAs H$\text{II}$ envelopes can be viewed most simply as photoionized supershells.

In their investigation of OBAs McKee & Williams (1997) employed far-infrared N$\text{II}$ line emissions together with radio continuum radiation to determine the Galactic Lyc emission of OBAs. We will use far-infrared N$\text{II}$ line emissions to determine the spatial distribution of H$\text{II}$ envelopes of SBs. Recently, Steiman-Cameron et al. (2010) have employed such N$\text{II}$ line emissions to determine the Galactic spatial distribution of photoionized gas. Our study differs from this investigation in several important respects, which will be discussed later.

The rationale for using far-infrared N$\text{II}$ line emissions to trace H$\text{II}$ emission is the following. Since the ionization potentials of H$\text{I}$ and N$\text{I}$ are 13.6 eV and 14.5 eV, H$\text{II}$ and N$\text{II}$ regions are essentially coincident. Thus, we use the N$\text{II}$ far-infrared lines at 122 $\mu$m and 205 $\mu$m as observed by FIRAS aboard COBE (Fixsen et al. 1999) to infer the spatial distribution of these moderate-density H$\text{II}$ envelopes. Note that the ratio of the 122 $\mu$m line flux to the 205 $\mu$m line flux is density dependent and rises with increasing electron density, $n_e$. In the limit of very low densities, where all the nitrogen ions are in the ground state, the ratio of the 122 $\mu$m line flux to 205 $\mu$m line flux is 0.7; the ratio rises from 1 to 1.6 for $n_e$ between 10 and 35 cm$^{-3}$ for uniform-density H$\text{II}$ regions (Wright et al. 1991). Yet at $n_e$ of 10$^2$ cm$^{-3}$ the ratio increases to 3 and at even higher densities it saturates at 10 (Rubin 1985). However, Fixsen et al. found that FIRAS instrumental noise precluded a detailed derivation of 122 $\mu$m line flux but the overall Galactic disk mean ratio of 122 $\mu$m line flux to 205 $\mu$m line flux is 1.1 ± 0.1. Thus, the FIRAS N$\text{II}$ line flux ratio infers that typical electron densities are similar to the values expected (e.g., McKee & Williams 1997; Roshi & Anantharamaiah 2001) for H$\text{II}$ envelopes.

Where are such SBs expected to be located in the Galaxy? In their investigation McKee & Williams (1997) made the simplifying assumption that the surface density of OBAs could be approximated by an axisymmetric Galactic disk population, $S(\rho) \propto e^{-\rho/\rho_c}$, where $S$ represents the population’s surface density and $\rho$ a source planar distance from the Galactic center (GC). They determined that $H_\rho = 3.34+0.71-1.24$ kpc when they used an investigation of luminous radio H$\text{II}$ regions (Smith et al. 1978), which found that all bright disk H$\text{II}$ regions are restricted to $\rho_{\text{min}} \leq \rho \leq \rho_{\text{max}}$, where $\rho_{\text{min}} = 0.39 R_s$, $\rho_{\text{max}} = 1.3 R_s$, and $R_s$ is the distance of the Sun from the GC. We now model the longitudinal FIRAS 205 $\mu$m intensity distribution corresponding to an axisymmetric truncated exponential disk.

5. CALCULATION OF THE SPATIAL DISTRIBUTION OF THE N$\text{II}$ EMISSIVITY FOR A TRUNCATED AXISYMMETRIC DISK SOURCE MODEL

Such a source distribution is best represented in a galactocentric Cartesian coordinate system, where the y-axis is aligned along the Sun-GC line, and the x-axis, which passes through the GC, is parallel to the galactic longitude $l = 90^\circ$. There a galactocentric cylindrical $(\rho, \theta, z)$ coordinate system is parameterized as $\rho = \sqrt{(x^2 + y^2)}$, $\theta = \tan^{-1}(y/x)$, and $z$ is measured normal to the plane. We employ the above $S(\rho)$ to represent the disk N$\text{II} 205$ $\mu$m emissivity and then determine the corresponding longitudinal distribution of the N$\text{II} 205$ $\mu$m intensity. The N$\text{II}$ intensity must be calculated in Earth-centered coordinates $(r, l, b)$, where $r$ is distance, $l$ is Galactic longitude, and $b$ is Galactic latitude, which are related to the previously defined galactocentric cylindrical coordinates $(\rho, \theta, z)$,

$$
\rho = \sqrt{r^2 \cos^2 b + R_s^2 - 2 R_s \cos b \cos l}, \\
\theta = \tan^{-1} \left( \frac{R_s - r \cos b \cos l}{r \cos b \sin l} \right), \quad z = r \sin b. \quad (1)
$$

The N$\text{II} 205$ $\mu$m line emissivity, $e^D(\rho)$, in units of erg s$^{-1}$ cm$^{-3}$, is calculated from $S(\rho)$, discussed above for $R_s = 7.6$ kpc, in the following way:

$$
e^D(\rho) = L_{\text{N}205}\mu m S(\rho) P_z(z)/A_D, \quad (2)
$$

where the galactocentric planar distance, $\rho(r, l, b)$, is a function of Earth-centered $(r, l, b)$, $L_{\text{N}205}\mu m$ is the total Galactic 205 $\mu$m luminosity in erg s$^{-1}$, $P_z(z)$ represents the height dependence of the H$\text{II}$ SB envelopes, and $A_D$ represents the source-weighted Galactic disk area. Once $P_z(z)$ is defined, the disk emissivity can be used to calculate a line energy flux, $F$,

$$
F = \int_{\rho_{\text{min}}}^{\rho_{\text{max}}} \int_{b_{\text{min}}}^{b_{\text{max}}} \int_{l_{\text{min}}}^{l_{\text{max}}} e^D(\rho(r, l, b)) \frac{4\pi r^2}{4\pi r^2} dr dl \cos b db, \quad (3)
$$

in units of erg cm$^{-2}$ s$^{-1}$.

Using COBE, Bennett et al. (1994) performed a far-infrared spectral line survey from over 99% of the sky with a 7$^\circ$ beam, resolving the Galactic longitudinal distributions of 122 and 205 $\mu$m N$\text{II}$ lines; see their Figures 2(d) and (c). Subsequently, Fixsen et al. (1999) analyzed further the FIRAS data and produced a factor of two improvement in the signal-to-noise ratio of the line emissions as well as a more complete sky map of the N$\text{II} 205$ $\mu$m line emissions. Consequently, we employ the later analyses of Fixsen et al. in comparisons with our intensity models. In their Figure 5(e), Fixsen et al. plot the mean

$^9$ Interpreting the clumps as ionized supershells, Heiles et al. suggested that the value of 25 pc represents the thickness of the wall of a typical ionized supershell.

$^{10}$ The term “worm” describes interstellar structures which are thought to be walls of SBs which have broken through the H$\text{I}$ interstellar gas disk (Koo et al. 1992).
intensity in units of W m$^{-2}$ sr$^{-1}$ of the N II fine-structure ground-state transition at 205 $\mu$m averaged over Galactic longitudes (centered on the Galactic plane) of $\Delta l = 5^\circ$ and $\Delta b = 1^\circ$. As noted by Fixsen et al. the 7$^\circ$ FIRAS beam does not resolve the latitudinal distributions of the far-infrared lines; consequently, we compare the FIRAS N II 205 $\mu$m line measurements with our models of the mean line intensity, averaged over $\Delta b = 1^\circ$ and $\Delta l = 5^\circ$ in the following way:

$$
\frac{d^2 I}{db} = \frac{1}{\Delta b} \int_{-5}^{5} \int_{-\sigma_z}^{\sigma_z} \frac{\rho(l, \theta)}{4\pi} \rho_0 \frac{\sigma_z^2}{\sqrt{2\pi}} \exp\left[-\frac{\sigma_z^2}{2\pi\sigma_z^2}\right] \cos b \, db \, dr, \hspace{1cm} (4)
$$

in units of erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

Before we calculate our modeled disk intensity, we must address how we represent $P_z(z)$. Here we assume a Gaussian distribution as a function of $z$,

$$
P_z(z) = \frac{e^{-0.5z^2/\sigma_z^2}}{\sqrt{2\pi}\sigma_z}. \hspace{1cm} (5)
$$

As noted above, FIRAS observations did not resolve the latitudinal extents of the far-infrared line fluxes, yet the low-frequency RRL observations (Roshi & Anantharamaiah 2001) found that in the inner Galaxy the low-frequency RRL intensities as a function of Galactic latitude, $b$, possess FWHM of $\sim 1^\circ$. In order to reproduce such FWHM transverse the Galactic plane, our modeling of the diffuse Galactic N II 205 $\mu$m line emissions required $\sigma_z = 150$ pc, significantly greater than 45 pc, the scale height of OB stars (e.g., Reeder 2000), or 35 pc, the scale height of molecular clouds (e.g., Stark & Lee 2005). But our $\sigma_z$ of 150 pc is consistent with the scale height expected (McKee & Williams 1997) for H II envelopes.

Our Figure 1 shows a modeled FIRAS 205 $\mu$m mean intensity distribution corresponding to an axisymmetric truncated exponential disk with a radial scale, $H_\rho$, of 2.5 kpc. Note that the radial gradient of the N II emissivity distribution is steepened (e.g., McKee & Williams 1997) by the presence of a radial gradient in the interstellar nitrogen-to-hydrogen abundance ratio. Thus, a massive-star distribution with a radial scale, $H_\rho$, of 3.4 kpc creates a steeper N II emissivity distribution with an $H_\rho$ of 2.5 kpc due to the existence of a large-scale Galactic gradient in N/H, $e^{-\rho/H_\rho}$, with an $H_\rho$ of 10 kpc (Daffon & Cunha 2004). We normalized this modeled FIRAS 205 $\mu$m intensity to the measured line intensity at $l = 30^\circ$, which required a total Galactic N II 205 $\mu$m luminosity of $1.85 \times 10^{40}$ erg s$^{-1}$. Inspection of this figure shows that such a modeled intensity, created by an axisymmetric disk distribution, decreasing monotonically in $\rho$, falls off too slowly with Galactic longitude $>30^\circ$ and fails to reproduce the observed FIRAS longitudinal intensities. More complicated emissivity models are necessary.

6. CALCULATION OF THE SPATIAL DISTRIBUTION OF THE N II EMISSIVITY FOR SPIRAL-ARM SOURCE MODELS

Based on optical observations, Morgan et al. (1952) were the first to discern that H II regions traced out spiral arms in the Milky Way. In a later groundbreaking study, using both Hα and high-frequency RRL observations of H II regions, Georgelin & Georgelin (1976) found that the Galactic H II distribution delineated a spiral structure comparable to the large-scale spiral configurations observed in other galaxies and the majority (80%) of the luminous Galactic H II regions fell along two symmetrical pairs of arms with pitch angles of 12$^\circ$. Subsequent studies of spiral galaxies have demonstrated that the principal spiral-arm tracers are massive star formation sites defined by massive stars, photoionized gas, and giant molecular clouds (e.g., Baade 1963; Boulanger et al. 1981; Rorum & Kaufman 1983; Russeil 2003; Hou et al. 2009; Efremov 2011).

Since that first pioneering investigation by Morgan et al. (1952), Galactic spiral arms have been traced primarily by H II regions (e.g., Georgelin & Georgelin 1976; Downes et al. 1980; Caswell & Haynes 1987; Watson et al. 2003; Russeil 2003; Russeil et al. 2007; Paladini et al. 2004; Hou et al. 2009), as well as by giant molecular clouds (e.g., Cohen et al. 1986; Dame et al. 1986; Grabelsky et al. 1988; Digel et al. 1990; May et al. 1997; Heyer et al. 2001; Dobbs et al. 2006; Stark & Lee 2006; Nakanishi & Sofue 2006; Hou et al. 2009). However, other tracers such as H I (e.g., Engmaier & Gerhard 1999; Russeil & Sofue 2003; Levine et al. 2006) as well as infrared emissions (e.g., Hayakawa et al. 1981; Bloemen et al. 1990; Drimmel & Spergel 2001; Benjamin et al. 2005) also have been used to determine some spiral-arm properties, particularly the locations of spiral-arm tangents.

In a detailed study evaluating and critically weighing the past evidence of Galactic spiral structure, Vallée (2008) has compiled key spiral-arm parameters and their uncertainties and, consequently, determined up-to-date locations of four logarithmic spiral arms. We employed Vallée’s spiral-arm parameters in our models of N II line FIRAS intensities. We have expanded Vallée’s model by the inclusion of the falloffs of the spatial density of H II envelopes parallel to the spiral arms and normal to them. In the present section thus we now model the spatial distribution of the H II envelope spiral-arm population.

Vallée’s spiral-arm model can be described in the galactocentric cylindrical coordinate system, presented earlier, by

$$
\rho(\theta) = \rho_{\min} e^{k(\theta - \theta_0)}, \hspace{1cm} (6)
$$

$$
\rho_{\min} \leq \rho \leq \rho_{\max},
$$

where $k = \tan p$ and $p$ is the pitch angle. From Vallée’s Figure 1 we determined the following arm parameters for the starting points of the arms: $\rho_{\min}$ of 2.9 kpc, $\theta_0$ of 70$^\circ$ (Norma–Cygnus arm), 160$^\circ$ (Perseus arm), 250$^\circ$ (Sagittarius–Carina arm), and 340$^\circ$ (Scutum–Crux arm). For the spiral-arm pitch angles, $p$, we employed a value of 13$^\circ$, the unweighted mean value from Vallée’s Table 1 for three spiral arms (Norma–Cygnus, Sagittarius–Carina, and Perseus). In order to reproduce the observed FIRAS 205 $\mu$m line flux at $l = 310^\circ$, we used a somewhat greater pitch angle, $p$, of 15$^\circ$ for the Scutum–Crux arm in order to place its tangent at this longitude. We employ Vallée’s $\rho_{\max}$ of 35 kpc. Our rendition of Vallée’s arm model is shown in our Figure 2. We use $R_s = 7.6$ kpc, the distance of the Sun from the GC.

In our investigation we employ Equation (6) to represent the medians of the spiral arms and introduce three parameters to construct a three-dimensional spatial distribution for a spiral-arm population. First, we modeled the decrease of the arm population. First, we modeled the decrease of the arm population.

$$
P_\rho(\rho) = e^{-\rho/H_\rho}, \hspace{1cm} (7)
$$

Using a pitch angle, $p$, of 13$^\circ$ for the Scutum–Crux spiral arm produced arm tangents at $l = 26^\circ$ and $l = 315^\circ$; changing $p$ to 15$^\circ$ placed arm tangents at $l = 27^\circ$ and $l = 310^\circ$.
We employ these relative arm source densities to create arm source distributions once the fractional contribution of each spiral arm to the total \( N \) Galactic luminosity (in erg s\(^{-1}\))\( f'\), is chosen; here \( X \) represents NC (Norma–Cygnus), SA (Sagittarius–Carina), SC (Scutum–Crux), and P (Perseus). In order to use the modeled arm distributions, interpolants, \( S_X(\rho, \theta) \), were created (for each arm \( X \)) to permit the calculation of planar source densities as functions of arbitrary galactocentric coordinates (\( \rho, \theta \)),

\[
S_X(\rho, \theta) = f_X P_\rho(\rho_0(\rho, \theta)) \times P_\Delta(\Delta_j(\rho, \theta))/A_X,
\]

\[
A_X = \int_0^{\infty} \int_0^{35 \text{ kpc}} P_\rho(\rho_0(\rho, \theta)) P_\Delta(\Delta_j(\rho, \theta)) \rho d\rho d\theta.
\]

Note that each \( S_X(\rho, \theta) \) distribution, when integrated over the disk area, normalizes to \( f_X \), and, thus, the sum of these four integrated distributions equals unity.

We now employ these \( S_X(\rho, \theta) \) interpolants to represent the spiral-arm contribution to the \( N \) 205 \( \mu \)m emissivity and then determine the corresponding longitudinal distribution of the \( N \) 205 \( \mu \)m intensity. The \( N \) 205 \( \mu \)m line emissivity in each arm, \( \epsilon_X \) in units of erg s\(^{-1}\) cm\(^{-3}\)), is calculated from \( S_X(\rho, \theta) \) in the following way:

\[
\epsilon_X(\rho, \theta, z) = L_{N\text{205} \mu m} S_X(\rho(\rho, l, b), \theta(\rho, l, b)) P_z(z),
\]

where the galactocentric planar distance, \( \rho(\rho, l, b) \), and the polar angle, \( \theta(\rho, l, b) \), are functions of Earth-centered (\( r, \theta, z \)) and \( L_{N\text{205} \mu m} \) is the total Galactic 205 \( \mu \)m luminosity in erg s\(^{-1}\).

Using Equation (5) to model \( P_z(z) \), these arm emissivities can be used to calculate mean line intensity, averaged over \( \Delta b = 1^\circ \), in the following way:

\[
\frac{d^2 F_X}{dldb} = \frac{1}{\Delta b} \int_{-3.5^\circ}^{3.5^\circ} \int_0^{r_{\text{max}}} \frac{\epsilon_X(\rho, \theta, z)}{4\pi r^2} r^2 dr \cos b db,
\]

in units of erg cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\).

In Figure 3, intensities, \( d^2 F / dldb \), summed over all four arms, calculated from Equation (10), are shown for a total Galactic \( N \) 205 \( \mu \)m luminosity of \( 1.4 \times 10^{10} \) erg s\(^{-1}\) and nominal spiral-arm parameters of \( \sigma_A = 0.5 \) kpc and \( H_\rho = 2.4 \) kpc for four sets of relative arm luminosities, \( f_{SA}, f_{SC}, f_{NC}, \) and \( f_P \). The calculations illustrated in Figure 3 demonstrate that the equal spiral-arm luminosities cannot reproduce the observed FIRAS 205 \( \mu \)m longitudinal intensity falloff at \( l \geq 35^\circ \) and \( l \geq 335^\circ \) in the \( N \) 205 \( \mu \)m intensities and, consequently, the contributions of the Norma–Cygnus and Sagittarius–Carina arms must be decreased by a factor of \( \sim 2 \) relative to the contributions of the Scutum–Crux and Perseus arms. In their spiral-arm model of far-infrared \( N \) line emissions Steiman-Cameron et al. (2010) noted similar behavior.

Such differences in the arm contributions have also been identified in analyses of other spiral-arm tracers. Drimmel & Spergel (2001) modeled near-infrared and far-infrared continuum emissions measured by COBE/DIRBE and found that two spiral arms (Scutum–Crux and Perseus) dominate the infrared spiral-arm signatures and that the contribution of the Sagittarius–Carina arm must be reduced relative to the contribution of the Scutum–Crux arm. Such a two-armed continuum infrared spiral signature is supported by a recent derivation (Benjamin et al. 2005; Benjamin 2008) of the stellar source distribution from the Spitzer/GLIMPSE mid-infrared survey of...
Figure 3. Representative 205 μm NⅠ intensities calculated from Equation (10) for a total Galactic spiral-arm luminosity of $L_{N\sp{\text{II}}205\mu m}$ of $1.4 \times 10^{40}$ erg s$^{-1}$ and nominal arm parameters of $H_{\sigma} = 2.4$ kpc and $\sigma_A = 0.5$ kpc are displayed. Four different sets of relative arm luminosities, $f_{SA}$, $f_{SC}$, $f_{NC}$, and $f_p$, have been considered, and we find that the second set of relative luminosities appears to give the best fit of the four, so as we discuss in the text, we use them hereafter.

As in Figure 1, the mean longitudinal FIRAS 205 μm intensities (Figure 5(e) of Fixsen et al. 1999) averaged over Galactic longitudes of $\Delta = 5^\circ$ are shown as a histogram. Also included, in addition to the modeled intensities, are the contributions of nearby local HⅠ regions, Cygnus X, at $l \approx 80^\circ$, and Vela Complex, at $l \approx 262^\circ$.

Figure 4. Longitudinal spiral-arm distribution as a function of variations in $H_{\sigma}$. Modeled representative 205 μm NⅠ intensities calculated for a total spiral-arm luminosity of $L_{N\sp{\text{II}}205\mu m}$ of $1.4 \times 10^{40}$ erg s$^{-1}$ and a fixed arm-width parameter, $\sigma_A$, of 0.5 kpc are plotted for a range of radial parameters, $H_{\sigma}$, between 1.8 and 3.0 kpc, showing that the value of about 2.4 appears to give the best fit, and we use that hereafter. As in Figure 1, the mean longitudinal FIRAS 205 μm intensities (Figure 5(e) of Fixsen et al. 1999) averaged over Galactic longitudes of $\Delta = 5^\circ$ are shown as a histogram. Also included, in addition to the modeled spiral arms, are the contributions of nearby local HⅠ regions, Cygnus X, at $l \approx 80^\circ$, and Vela Complex, at $l \approx 262^\circ$.

Galactic NⅠ 205 μm luminosity of $1.4 \times 10^{40}$ erg s$^{-1}$ for a fixed $\sigma_A = 0.5$ kpc and a range of radial arm parameters $H_{\sigma}$ from 1.8 to 3.0 kpc showing that the value of 2.4 kpc gives the best fit. In Figure 5, intensities, $d^2 F/dldb$, summed over all four arms, calculated from Equation (10), are illustrated for a fixed total Galactic NⅠ 205 μm luminosity of $1.4 \times 10^{40}$ erg s$^{-1}$ for a fixed radial arm parameter, $H_{\sigma}$, of 2.4 kpc for a range of arm-width parameters, $\sigma_A$, from 0.25 to 0.75 kpc, showing that the value of 0.5 kpc gives the best fit. Also, we include in these last two figures our estimates of the contributions of the two nearby HⅠ regions: a ~6°-sized Cygnus X diffuse HⅠ region with its center at $l = 80^\circ$ and $b = 0^\circ$, and a 10°-sized Vela complex HⅠ region, with its center at $l = 262^\circ$ and $b = -2^\circ$. The properties of these two nearby HⅠ regions are addressed in Section 8.

From these two figures, we find that $H_{\sigma} = 2.4 \pm 0.3$ kpc and $\sigma_A = 0.5 \pm 0.1$ kpc reproduce well the diffuse FIRAS $L_{N\sp{\text{II}}205\mu m}$ longitudinal intensity, when the two strong local HⅠ sources are included. These parameters thus define our three-dimensional spiral-arm luminosity model for NⅠ 205 μm emission, as shown in Figure 6 together with the individual contributions from each of the spiral arms, for a total spiral arm NⅠ 205 μm luminosity of $\approx(1.4 \pm 0.15) \times 10^{40}$ erg s$^{-1}$.

Using these values and our nominal Galactic luminosity NⅠ 205 μm of $1.4 \times 10^{40}$ erg s$^{-1}$, our model results suggest that total Galactic 205 μm line luminosity inside the solar circle ($\rho \leq R_S$) is $1.2 \times 10^{40}$ erg s$^{-1}$. From their analyses of FIRAS line measurements, Bennett et al. (1994) estimate, with a ~50% uncertainty, a somewhat greater total 205 μm Galactic line luminosity inside the solar circle of $2.6 \times 10^{40}$ erg s$^{-1}$.

As can be seen in Figures 4 and 5, all our models systematically overproduce the observed NⅠ 205 μm intensity along the tangent to the Sagittarius spiral arm at $55^\circ \leq l \leq 30^\circ$, where it is known (e.g., Georgelin & Georgelin 1976; Forbes 1983) that a 5 kpc portion of the Sagittarius is “devoid” of luminous HⅠ regions.

From these figures we also see that the introduction of a galactic interarm population is not required. A lack of evidence...
Figure 6. Individual spiral-arm contributions to 205 µm N II Intensities. The solid curve shows the modeled 205 µm N II intensity distribution for a total spiral-arm luminosity, $L_{NII,205}$, of $1.4 \times 10^{56}$ erg s$^{-1}$ and a fixed arm-width parameter, $\sigma_A$, of 0.5 kpc for a radial parameter, $H_{\rho}$, of 2.4 kpc. As in Figure 1, the mean longitudinal FIRAS 205 µm intensities (Figure 5(e) of Fixsen et al. 1999) averaged over Galactic longitudes of $\Delta \rho = \pm$ are shown as a histogram. Also included in addition to the modeled spiral arms, are the contributions of nearby local OBAs, Cygnus X, at $l \approx 80^\circ$ and Vela Complex, at $l \approx 262^\circ$.

for an interarm SB population is perhaps surprising. Recent analyses of high-resolution Hα observations of two nearby spiral galaxies shed some light on this thorny issue. Employing HST images, Lee et al. (2011) cataloged 19,598 H II regions at a resolution of 0′′.1 (5 pc) in M51, a system of two interacting galaxies, NGC 5194, a two-armed, grand-design spiral, and a small barred lenticular galaxy NGC 5195. In NGC 5194 they determined the numbers of H II regions in the arms, nucleus, and the interarm region: 12,245, 4422, and 2636, respectively. They determined that, although ∼40% of the H II regions occurred in the interarm region, the much less luminous interarm H II regions contributed only 15% of the total Galactic Hα luminosity. Based on such Hα observations, we suggest that a modest (∼10%) interarm SB contribution is difficult to discern due to uncertainties in the spiral-arm models as well as in the contribution of nearby H II regions.

Recently Steiman-Cameron et al. (2010) published a spiral-arm source model to characterize COBE/FIRAS far-infrared emissions for the C II 158 µm line as well as for the N II 205 µm line. Our approach differs from their study in several important respects. We focus our investigation solely on 205 µm radiation from H II interstellar phases, assuming an H II envelope/SB origin, and, consequently, we used as ancillary data low-frequency RRL observations from Roshi & Anantharamaiah (2001). This led to our choice of $\sigma_A$ of 150 pc for the Gaussian dispersion for H II envelopes transverse the Galactic plane. Steiman-Cameron et al. did not employ the H II envelope/SB origin for N II gas. Instead, they used a $\sigma_A$ of 70 pc that is appropriate to the C II 158 µm latitude distribution which has been resolved in a balloon experiment (Nakagawa et al. 1998). A significant component of the C II 158 µm line emission may be emitted (e.g., Bennett et al. 1994; Roshi & Anantharamaiah 2001) by dense photodissociation regions of molecular clouds, which possess a relatively small scale height transverse the Galactic plane (e.g., Stark & Lee 2005). Thus, we chose a greater value for $\sigma_A$. Further, they convolved their modeled intensities over the FIRAS beam, while we employed the published (Fixsen et al. 1999) area-averaged intensities. We also represented the geometry of the spiral-arm terminators differently.

Nonetheless, the COBE/FIRAS 205 µm data are robust. Although there exist significant differences in approach, the fundamental results of both investigations are the same: first, four-armed spiral models with differing relative arm luminosities fit the FIRAS 205 µm longitudinal distributions, and second, an interarm source contribution is not required.

7. CALCULATION OF THE SPATIAL DISTRIBUTION OF LYMAN CONTINUUM EMISSION

Based on this model for the N II 205 µm emission, we now calculate the spiral-arm density distribution of the Lyc emission from the O stars which produced it. As discussed above, the Galactic Lyc radiation does not scale simply with N II 205 µm emissivity distribution due to the presence (e.g., Shaver et al. 1983) of a gradient, as a function of galactocentric radius, in the interstellar abundance of nitrogen. Subsequently, Daflon & Cunha (2004) analyzed the emissions of OB stars located at 4.7 kpc $\leq \rho \leq$ 13.2 kpc and derived a nitrogen abundance gradient of $-0.042$ dex per kpc or an equivalent $H_{\rho,N}^{H/II}$ of 10 kpc. Thus, from the spiral-arm N II emissivity distributions $H_{\rho} = 2.4 \pm 0.3$ kpc that reproduced the FIRAS 205 µm line intensities, we expect that $1/H_{\rho,N}^{H/II} \approx 1/H_{\rho,N}^{H/II} + 1/H_{\rho,N}^{LYC}$, and, consequently, the actual falloff in the Galactic Lyc emissivity, $H_{\rho,N}^{LYC} \approx 3.2 \pm 0.5$ kpc. This is in excellent agreement with the axisymmetric source model of McKee & Williams (1997), where $H_{\rho} = 3.3$ kpc. From a radial scale of $H_{\rho,N}^{LYC}$ of 10 kpc for the interstellar N-to-H ratio and nominal spiral-arm parameters ($H_{\rho} = 2.4$ kpc and $\sigma_A = 0.5$ kpc), we find that the Galactic source weighted N/H = 1.78(N/H)$_0$.

The resulting spiral-arm Lyc luminosity density model for $H_{\rho} = 3.2$ kpc and $\sigma_A = 0.5$ kpc, normalized to a total Galactic Lyc luminosity of unity, is shown in Figure 7. This figure represents the best measure of the Galactic spatial distribution of SBs and their embedded OBAs. Also included in this figure are the two nearby OBAs discussed in the next section.

8. NEARBY SOURCES OF DIFFUSE 205 µm N II EMISSIONS

Investigations (e.g., Weaver 1970; Vázquez et al. 2008) of young stars in the solar vicinity ($\leq$ kpc) reported that the Sun is “located in an arm-like structure” terminated by the Cygnus region at one end at $l \sim 80^\circ$ and Vela at the other end at $l \sim 264^\circ$; such a feature was termed (e.g., Weaver 1970) a “spur” or “offshoot” of the Sagittarius arm. Vallée refers to the structure as the “Orion armlet” or “Orion bridge,” describing it as a “local aggregate of stellar clusters.” This local structure is not viewed as a separate component of the global spiral-arm structure (e.g., Georgelin & Georgelin 1976; Taylor & Cordes 1993; Vallée 2008). Yet inspection of the observed FIRAS 205 µm longitudinal intensity (Fixsen et al. 1999), illustrated in our Figures 1, 3, 4, 5, and 6, shows significant emission at $l \sim 80^\circ$ and $l \sim 265^\circ$ from this “Orion Spur,” or “local aggregate of stellar clusters.”

Therefore, in addition to the contribution of the large-scale, Galactic spiral-arm distribution in this investigation, we consider the emission from two nearby (∼kpc) H II regions, the Cygnus X region at $l \approx 80^\circ$ and the Vela Complex at $l \approx 265^\circ$. A
comparison of measured (Fixsen et al. 1999) FIRAS intensities at N\(^{\text{ii}}\) 205 \(\mu\)m (Figure 5(e)) and at 122 \(\mu\)m (Figure 5(f)) shows that the ratios of these two line intensities in the vicinities of \(l \approx 80^\circ\) and \(l \approx 265^\circ\) agree with the overall Galactic ratio. Consequently, we assume that the photoionized gas which radiates these lines has approximately the same electron density, \(\sim 5 \text{ cm}^{-3}\), as the H\(^{\text{ii}}\) envelopes in the inner Galaxy which radiate the bulk of the spiral-arm 205 \(\mu\)m N\(^{\text{ii}}\) line emission.

8.1. Cygnus Region

We interpret the bright 205 \(\mu\)m FIRAS feature at \(l \approx 80^\circ\) as an H\(^{\text{ii}}\) envelope excited by a rich, nearby OB, Cyg OB2. The Cygnus-OB2 stellar cluster is visually obscured, but nearby at a distance of 1.45 kpc (Hanson 2003) with its center at \(l = 80.1^\circ\) and \(b = +0.9^\circ\) (Humphreys 1978). In a groundbreaking study employing infrared observations in the \(J\), \(H\), and \(K\) bands, Knödlseder (2000) estimated that this rich stellar cluster contained as many as 100 O stars and, clearly, is the closest massive Galactic star formation site. Recently, employing Chandra X-ray point-source data as well as complementary optical and near-IR photometry, Wright et al. (2010) found that Cygnus OB2 encompasses an estimated 75 O stars as well as \(\sim 1200\) OB stars. There is a large spread of stellar ages, 2–10 Myr, in this rich stellar cluster (e.g., Hanson 2003; Drew et al. 2008; Wright et al. 2010; Comeron & PasquaI 2012). Most recently, from this massive star formation site Fermi has detected and resolved a large 4\(^{\circ}\) (\(\sim 10^2\) pc) SB, illuminated in 0.1–10\(^2\) GeV \(\gamma\)-rays emitted by freshly accelerated cosmic rays in the Cygnus SB (Ackermann et al. 2011). This exciting new observation provides direct evidence that cosmic rays are accelerated in SBs.

Lozinskaya et al. (2002) investigated the kinematics of photoionized gas in the Cygnus region via H\(^{\alpha}\) measurements. In this study they posed a fundamental question (p. 227)—“where are the observational manifestations of the action of intense ionizing radiation from Cyg OB2 on the ambient gas?” They proposed that Cygnus X is the “observational manifestation” of Cyg OB2. Cygnus X is an extended H\(^{\text{ii}}\) region delineated by an irregular ring of optical H\(^{\alpha}\) filaments \(\approx 8^\circ\) in radius (Ikhnav 1961). Other investigators have also suggested that Cygnus X and Cygnus OB2 are related (e.g., Ikhnav 1961; Veron 1965).

We propose that Cygnus X, ionized by O stars in the embedded Cyg OB2, radiates the bulk of the 205 \(\mu\)m line emission resolved by FIRAS from \(l \approx 80^\circ\). We estimate the corresponding ionizing luminosity, \(Q_0\), for this association to be \(\sim 1.1 \times 10^{51} \text{ s}^{-1}\), from 75 young O stars, employing a time-averaged, ionized stellar luminosity relation\(^{12}\) and an initial stellar mass function with a slope of \(\sim 1.35\) (e.g., Bastian et al. 2010). The Cyg OB2 association is very luminous, exceeding by a factor of \(\sim 40\) the ionizing luminosity, \(Q_0\), of the familiar Orion OBA of only \(2.7 \times 10^{49} \text{ s}^{-1}\) (e.g., Williams & McKee 1997).

Lozinskaya et al. (2002) pointed out that the absence of intense H\(^{\alpha}\) emissions, expected for such a large number of O stars, could be explained by strong visual absorption, but corresponding thermal radio emissions must be observed regardless of visual obscuration. However, they remarked that in the Cygnus X region radio point sources are detected against a strong diffuse radio source \(\sim 6^\circ\) in size centered on the Cyg OB2 association (e.g., Wendker 1970; Huchmeier & Wendker 1977). In a 2.7 GHz radio survey Wendker (1970) measured a flux density, \(S_v\), of 5390 Jy for the total emission including resolved sources and solely 2260 Jy for the diffuse component of the Cygnus X.

The ionizing luminosity, \(Q_0\), required to produce such diffuse thermal radio emission can be estimated (e.g., Afflerbach et al. 1997) as

\[
Q_0 \approx \frac{7.6 \times 10^{48}}{\nu_{\text{GHz}}} \left(\frac{S_v}{\text{Jy}}\right) \left(\frac{v}{\text{GHz}}\right)^{0.1} \left(\frac{r}{\text{kpc}}\right)^2
\]

in units of \(\text{s}^{-1}\), where \(v\) is the radio frequency in GHz and \(T_e\) represents the electron temperature. Thus, to maintain the diffuse Cygnus X 2.7 GHz radio source at a distance, \(r\), of 1.45 kpc, and a \(T_e \approx 8000\) K requires \(Q_0\) of \(0.45 \times 10^{51}\) s\(^{-1}\). To maintain the entire Cygnus radio emission, discrete sources as well as the diffuse background, requires \(\sim 10^{51}\) s\(^{-1}\). Thus, the embedded Cyg OB2 massive stars are potentially capable of maintaining the entire Cygnus thermal radio emission.

We propose that the \(\sim 6^\circ\) (\(\sim 75\) pc) radio Cygnus X is the source of the N\(^{\text{ii}}\) 205 \(\mu\)m line emissions, resolved by FIRAS. Thus, we represent the modeled Cygnus X source, illustrated in Figures 4–6, as a uniform sphere with a 75 pc radius, whose center is located at \(l = 80^\circ\) and \(b = 0^\circ\). We assume that the source is resolved normal to the Galactic plane. To approximate the effect of the 7\(^{\circ}\) beam of the FIRAS instrument, we weighted the source intensity over a Gaussian profile with an FWHM of 7\(^{\circ}\). To reproduce the observed 205 \(\mu\)m intensities in Figures 4–6, we found that the required N\(^{\text{ii}}\) line flux of our modeled source is \(2.1 \times 10^{-7}\) erg \(\text{s}^{-1}\) cm\(^{-2}\), which corresponds to an N\(^{\text{ii}}\) 205 \(\mu\)m luminosity of \(2.4 \times 10^{37}\) erg \(\text{s}^{-1}\) at a distance of 1.45 kpc.

This powerful single source contributes \(1.7 \times 10^{-3}\) of the total Galactic 205 \(\mu\)m luminosity. How does this line luminosity compare to the expected Cygnus contribution to the total number of ionizing photons absorbed by photoionized gas in the Galaxy?\(^{12}\)

\[Q_0(M) = 5.5 \times 10^{42} M^4 \text{ s}^{-1}\] for stars born in the mass range \(20 M_\odot \leq M \leq 40 M_\odot\), and \(Q_0(M) = 8.2 \times 10^{45} M^2 \text{ s}^{-1}\) for \(40 M_\odot \leq M \leq 120 M_\odot\) (McKee & Williams 1997).
Based on analyses of free–free radio emissions and N II far-infrared line emissions, McKee & Williams estimate a total Galactic ionization rate, $Q_{\text{G}}^G$, of $1.9 \times 10^{53} \text{ s}^{-1}$. However, this value should be decreased by a factor $(R/8.5)^2 \sim 0.8$ due to the decrease in the assumed distance of the Sun from the GC of 8.5–7.6 kpc. Consequently, we estimate a total Galactic $Q_{\text{G}}^G$ of $1.5 \times 10^{53} \text{ s}^{-1}$.

If we assume that interstellar gas in the H II shell around Cyg OB2 has solar composition, then its expected fraction of the Galactic Lyc luminosity, implied by N II line emissions, is $\sim 1.78 \times 1.7 \times 10^{-3} = 3 \times 10^{-2}$. Thus, we estimate that the value of $Q_0$ required to maintain the Cygnus X N II line emissions is $4.5 \times 10^{50} \text{ s}^{-1}$, equal to the ionizing luminosity required to maintain the diffuse Cygnus X free–free radio emission. Such an estimated $Q_0$ is only 45% of the $Q_0$ we calculated from the number of O stars present. Consequently, we view the nearby Cyg X as the source of N II 205 μm from the Cygnus region.

8.2. Gum Nebula–Vela Region

We interpret the bright 205 μm FIRAS feature at $l \approx 265^\circ$ as an H II region excited primarily by a single close O star, $\eta$ Puppis. The Gum Nebula–Vela Complex contains only three O stars, compared to ~75 O stars residing in the rich Cyg OB2, but the Complex is closer by a factor of ~5. Also its observed N II 205 μm line intensity is smaller by a factor of ~3 than that of the Cygnus X N II source. The large, nearby Gum Nebula forms an Hα ring on the sky with $\sim 18^\circ$ radius with its center at $l \approx 258^\circ$ and $b \approx -2^\circ$ (Gum 1956; Chanot & Sivan 1983). These Hα emissions most likely are powered by stellar UV fluxes from $\eta$ Puppis (O4I) and $\gamma^2$ Velorum (WC8+O9I binary) (e.g., Gum 1956; Beuermann 1973; Reynolds 1976; Wallerstein et al. 1980; Chanot & Sivan 1983).

However, the origin of the Gum Nebula itself is controversial. The Gum Nebula has been modeled as: (1) a fossil Strömgren sphere, created by the stellar progenitor of the Vela SN remnant (e.g., Brandt et al. 1971; Alexander et al. 1971); (2) an old ($>\text{Myr}$) SN remnant, ionized by UV fluxes from $\eta$ Puppis and $\gamma^2$ Velorum (Reynolds 1976); and (3) an ordinary H II region (e.g., Gum 1956; Beuermann 1973). Subsequently, Wallerstein et al. (1980) investigated the properties of interstellar gas in the Gum Nebula, using both optical and UV line observations. They found that their data were generally consistent with a model of the Gum Nebula as an ordinary H II region, ionized by OB stars, $\eta$ Puppis, $\gamma^2$ Velorum, and by the stellar progenitor of the Vela SN remnant with the gas stirred by multiple stellar winds.

Ionized interstellar components with gas densities of order $\geq 1 \text{ cm}^{-3}$, relevant to N II 205 μm emissivities, can be found in a number of sites in the Gum Nebula. For example, Reynolds (1976) estimated that the Hα emission shell is 15–30 pc thick and the electron densities $\sim 5$–2.5 cm$^{-3}$. Recently, Sushch et al. (2010) investigated the complex interactions of the Vela SN remnant and the 5°-sized stellar-wind bubble of $\gamma^2$ Velorum. They found that the interstellar density around $\gamma^2$ Velorum is $\sim 12 \text{ cm}^{-3}$.

The O star catalog of Maiz-Apellániz et al. (2004) lists the $\gamma^2$ Velorum binary at $l = 262^\circ$, $b = -7^\circ$–7, with spectral types O9I and WC8, and $\eta$ Puppis, a runaway O star, at $l = 256^\circ$, $b = -4^\circ$–7, with spectral class O4I. The total stellar $Q_0$ is found to be $\sim 1.32 \times 10^{50} \text{ s}^{-1}$; $\eta$ Puppis, a very luminous O4I star, has an expected $Q_0$ of $1.05 \times 10^{50} \text{ s}^{-1}$ (Vacca et al. 1996), the O9I star of the $\gamma^2$ Velorum binary has a $Q_0$ of $2.14 \times 10^{50} \text{ s}^{-1}$ (Vacca et al. 1996), and the WR star of the $\gamma^2$ Velorum binary has a $Q_0$ of $6 \times 10^{48} \text{ s}^{-1}$ (De Marco et al. 2000). Using radial velocity measurements, North et al. (2007) determined that the $\gamma^2$ Velorum binary is close, at a distance, $r$, of 336 ± 8 pc. Hipparchos parallel measurements provide a distance to $\eta$ Puppis of 329 $^{+120}_{-77}$ pc (van der Hucht et al. 1997). The runaway star $\eta$ Puppis contributes ~80% of the total stellar $Q_0$, and these two stellar systems are close, separated only by ~40 pc.

Based on these parameters, we assumed a single source of N II line emission, a uniform sphere with a 30 pc radius, whose center is located at $l = 262^\circ$ at a distance of 330 pc. To approximate the effect of the 7° beam of the FIRAS instrument, we weighted this source intensity over a Gaussian profile with an FWHM of 7°. We found that our model required an N II line flux of $7.7 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$, which corresponds to a 205 μm luminosity of $10^{36}$ erg s$^{-1}$ at the assumed distance of 0.33 kpc.

The Vela source contributes $10^{36}/1.4 \times 10^{40} \approx 7 \times 10^{-5}$ of the total galactic 205 μm line luminosity. If we assume that interstellar gas in the vicinity of Vela has solar composition, then its expected fraction of the Galactic Lyc luminosity implied by N II line emissions is $\sim 1.78 \times 7 \times 10^{-5} = 1.25 \times 10^{-4}$. Scaling the Galactic $Q_{\text{G}}^G$ by $1.25 \times 10^{-4}$, we estimate the value of $Q_0$ required to maintain the Vela N II line emissions to be $\sim 1.1 \times 10^{49} \text{ s}^{-1}$. Since the Vela O stars actually radiate $\sim 1.3 \times 10^{50} \text{ s}^{-1}$, only ~10% of the stellar ionizing luminosity is required to power the N II 205 μm emission observed by FIRAS.

9. SUMMARY

CCSNe of OB stars, formed in large OBAs, blow giant SBs, in which their collective shocks accelerate most of the Galactic cosmic rays. With the sites of cosmic-ray acceleration now generally recognized, we can now proceed to more sophisticated model tests of how the cosmic rays propagate within the Galaxy. In order to define the initial conditions for such models of cosmic-ray propagation on a Galactic scale, we have constructed a three-dimensional spatial model of the Galactic distribution of SBs, using the measured FIRAS Galactic longitudinal distribution of the 205 μm N II luminosity, emitted by H II envelopes surrounding hot tenuous SB cores. These H II envelopes in turn are excited by the Lyc radiation of the massive O stars embedded in the SB cores.

Recently Vallée (2008) critically evaluated past evidence of Galactic spiral structure and determined up-to-date Galactic-plane locations of four spiral arms. We expanded his model by the inclusion of the falloffs of the spatial density of H II envelopes both parallel and normal to the positions of spiral arms. Once suitable choices were made of the parameters governing these density falloffs, we found that the observed FIRAS 205 μm N II longitudinal distribution is reproduced well by spiral-arm source models when emissions from two nearby H II regions were included. One nearby source is the Cyg OB2 association, one of the richest Galactic OBAs, located at a distance of 1.45 kpc. The other source, at a distance of 0.3 kpc, is ionized by the nearest runaway O star, $\eta$ Puppis, and the O star binary $\gamma^2$ Velorum. Finally, as illustrated by our Figures 4–6, the Galactic SB distribution, as traced by H II envelope emission, is dominated by the contribution of massive-star clusters residing in the spiral arms and two nearby H II regions.

We have presented in Figure 7 a representative planar spiral-arm distribution of the Lyc luminosity which we expect to reflect the Galactic spatial distribution of OBAs and their surrounding SBs. But we would also expect rescaling of this distribution to reflect that of other important processes, including the Galactic star formation distribution, the CCSN distribution, the neutron star and stellar black hole production distribution, the principal
Reed, B. C. 2000, AJ, 120, 314
Reynolds, R. J. 1976, ApJ, 203, 151
Reynolds, R. J. 1984, ApJ, 282, 191
Reynolds, R. J. 1987, ApJ, 323, 118
Reynolds, R. J., & Ogden, P. M. 1979, ApJ, 229, 942
Reynolds, R. J., Scherb, F., & Roesler, F. L. 1973, ApJ, 185, 869
Roshi, D. A., & Anantharamaiah, K. R. 2000, ApJ, 535, 231
Roshi, D. A., & Anantharamaiah, K. R. 2001, ApJ, 557, 226
Rubin, R. H. 1985, ApJS, 57, 349
Rumstay, K. S., & Kaufman, M. 1983, ApJ, 274, 611
Russel, D. 2003, A&A, 397, 133
Russell, D., Adami, C., & Georgelin, Y. M. 2007, A&A, 470, 161
Sandage, A., & Tammann, G. A. 1974, ApJ, 190, 525
Shaver, P. A. 1976, A&A, 49, 1
Shaver, P. A., McGee, R. X., Newton, L. M., Danks, A. C., et al. 1983, MNRAS, 204, 53
Slavin, J. D., & Cox, D. P. 1993, ApJ, 417, 187
Smartt, S. J. 2009, ARA&A, 47, 63
Smith, L. F., Biermann, P., & Mezger, P. G. 1978, A&A, 66, 65
Smith, N., Li, W., Filippenko, A. V., et al. 2011, MNRAS, 412, 1522
Stark, A. A., & Lee, Y. 2005, ApJL, 619, L159
Stark, A. A., & Lee, Y. 2006, ApJ., 641, L113
Staveley-Smith, L., Sault, R. J., Hatzidimatriou, D., et al. 1997, MNRAS, 289, 225

Steiman-Cameron, T. Y., Wolfire, M., & Hollenbach, D. J. 2010, ApJ, 722, 1460
Sushch, I., Hnatyk, B., & Neronov, A. 2010, A&A, 525, A154
Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674
Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, ApJS, 98, 617
Vacca, W. D., Garmany, C. D., & Shull, J. M. 1996, ApJ, 460, 914
Vallée, J. P. 2008, AJ, 135, 1301
Van der Hucht, K. A., Schrijver, H., Stenholm, B., et al. 1997, NewA, 2, 245
Vázquez, R. A., May, J., Bronfman, L., et al. 2008, ApJ, 672, 930
Veron, P. 1965, AnAp, 28, 391
Wallenstein, G., Silk, J., & Jenkins, E. B. 1980, ApJ, 240, 834
Wang, Q., & Helfand, D. J. 1991a, ApJ, 373, 497
Wang, Q., & Helfand, D. J. 1991b, ApJ, 379, 327
Watson, C., Araya, E., sewilo, M., et al. 2003, ApJ, 587, 714
Weaver, H. 1970, in IAU Symp. 38, Spiral Structure of Our Galaxy, ed. W. Becker & G. I. Kontopoulos (Dordrecht: Reidel), 126
Wendker, H. J. 1970, A&A, 4, 378
Williams, J. P., & McKee, C. F. 1997, ApJ, 476, 166
Wilson, W. J., Schwartz, P. R., Epstein, E. P., et al. 1974, ApJ, 191, 357
Wright, E. L., Mather, J. C., Bennett, C. L., et al. 1991, ApJ, 381, 200
Wright, N. J., Drake, J. J., Drew, J. E., & Vink, J. S. 2010, ApJ, 713, 871
Zatsepin, V. I., & Sokolowskaya, N. V. 2007, AstL, 33, 25
Zwicky, F. 1939, PhRv, 55, 986