COMPARISON OF THE DIFFUSE Hα AND FUV CONTINUUM BACKGROUNDS: ON THE ORIGINS OF THE DIFFUSE Hα BACKGROUND

KWANG-IL SEON1, ADOLF WITT2, IL-JOONG KIM1, JONG-HO SHINN1, JERRY EDELSTEIN1, KYOUNG-WOOK MIN4, AND WONYONG HAN1

1 Korea Astronomy and Space Science Institute, Daejeon 305-348, Korea; kiseon@kasi.re.kr
2 Ritter Astrophysical Research Center, University of Toledo, Toledo, OH 43606, USA
3 Space Sciences Laboratory, University of California, Berkeley, CA 94702, USA
4 Korea Advanced Institute of Science and Technology, Daejeon 305-701, Korea

Received 2011 August 31; accepted 2011 November 8; published 2011 December 2

ABSTRACT

We compare the diffuse Hα map of our Galaxy with the FUV (1370–1710 Å) continuum map. The Hα intensity correlates well with the FUV intensity. The Hα/FUV intensity ratio increases in general with the Hα intensity and the FUV hardness ratio (1370–1520 Å to 1560–1710 Å), implying that late OB stars may be the main source of the Hα recombination line at high latitudes. The variation of the Hα intensity as a function of the Galactic latitude is also very similar to that of the FUV intensity. The results likely suggest that not only the original radiation sources of the Hα and FUV backgrounds but also the radiative transfer mechanisms responsible for the diffuse backgrounds are largely composed of two components, Hα photons produced by in situ recombination at the ionized regions around late OB stars and dust-scattered light of the Hα photons originating from late OB stars.

Key words: diffuse radiation – ISM: structure – ultraviolet: ISM

Online-only material: color figures

1. INTRODUCTION

The diffuse Hα background is generally believed to originate from the extended, nearly fully ionized regions (called warm ionized medium, or WIM) along the lines of sight (Reynolds et al. 1998; see Hafler et al. 2009 for a recent review). The volume filling fraction of the WIM increases from ~0.1 at the midplane to >0.3–0.4 at |z| = 1 kpc (Kulkarni & Heiles 1987; Reynolds 1991; Peterson & Webber 2002). The large energy requirement of the WIM strongly suggests that O stars in the Galactic plane are the primary ionization source (Reynolds 1984, 1990a). There have been numerous investigations about how the Lyman continuum (Lyc) photons can escape the immediate vicinity of the O stars (or the bright H II regions) in the Galactic plane and ionize the diffuse interstellar medium (ISM; Miller & Cox 1993; Dove & Shull 1994; Seon 2009a; Wood et al. 2010). However, the question of how the Lyc photons can propagate almost up to the scale height (~1 kpc) of the WIM has not been fully resolved because the photoionization models require the presence of very low density paths through the ISM.

In this paper, we explore two alternatives to explain the diffuse Hα emission of our Galaxy. The first scenario, which was investigated for external galaxies, is that late, field OB stars outside the bright H II regions ionize some of the WIM, reducing the required Lyc leakage from the bright H II regions in the galactic plane (Hoopes & Walterbos 2000; Hoopes et al. 2001). The mean spectral type of stars in the field is later than that in H II regions (Massey et al. 1995; Hoopes & Walterbos 2000). As the Hα intensity is directly proportional to Lyc intensity in the ionization bounded regions and the later-type stars would produce a lower ratio of ionizing Lyc to non-ionizing far-ultraviolet (FUV) luminosities, the Hα/FUV intensity ratio can constrain the spectral type of the ionizing stars. Hoopes & Walterbos (2000) and Hoopes et al. (2001) measured Hα/FUV intensity ratios for 10 nearby spiral galaxies, and concluded that late OB stars in the field are indeed an important source of ionization in those galaxies.

Second, we note that the majority of the Hα excess intensity in a number of high-latitude clouds in our Galaxy can be understood as light scattered off the interstellar dust (Mattila et al. 2007; Lehtinen et al. 2010; Witt et al. 2010). The possible presence of scattered Hα radiation at high-latitude clouds was first considered by Jura (1979). Photoionization by an external field of Lyc is expected to result in ionization of a thin outer shell of an isolated interstellar cloud, while the observations of the Hα light from the high-latitude clouds clearly showed the dense inner core of the cloud as the brightest feature. Witt et al. (2010) argued that both a substantial fraction of the diffuse high-latitude Hα background intensity and much of the variance in the high-latitude Hα background are due to scattering by interstellar dust of Hα photons originating elsewhere in the Galaxy. If this is the case, the diffuse Hα emission should be closely related to the FUV continuum background, which is mostly dust-scattered light of the FUV stellar radiation (Bowyer 1991; Seon et al. 2011).

Therefore, comparison of the diffuse Hα emission with the FUV continuum background could not only provide a clue to the spectral type of ionizing sources of the WIM in our Galaxy but also confirm the significance of dust scattering in the diffuse Hα. In fact, Seon et al. (2011) found a strong correlation between the diffuse FUV (1370–1710 Å) and Hα backgrounds, suggesting a similarity between the origins of both backgrounds. In this paper, we present a more detailed comparison of the Galactic Hα map with the FUV continuum map and propose a scenario for the origin of the diffuse Hα emission. We describe the data used in the present study in Section 2. In Section 3, the spectral type of the stars responsible for the diffuse Hα emission is investigated. Section 4 contains a discussion on the dust scattering of Hα photons. We discuss the main result in Section 5. A brief summary is presented in Section 6.
2. DATA

The FUV data were obtained by the Spectroscopy of Plasma Evolution from Astrophysical Radiation (SPEAR) instruments, also known as Far-Ultraviolet Imaging Spectrograph (FIMS; Edelstein et al. 2006a, 2006b; Seon et al. 2011). The SPEAR/FIMS instrument is a dual-channel FUV imaging spectrograph ("Short" wavelength channel [S-band] 900–1150 Å, “Long” wavelength channel [L-band] 1350–1750 Å; \( \lambda / \Delta \lambda \sim 550 \)) with a large field of view (S-band, 4° × 4°; L-band, 7° × 4° × 4°) and 10" imaging resolution onboard the first Korean astronomical satellite STSAT-1, designed to observe diffuse FUV emission. The SPEAR/FIMS survey observations were performed by scanning the sky at constant ecliptic longitude from the north ecliptic pole to the south ecliptic pole, during the eclipses. The pole-to-pole scanning drifted 360° along the ecliptic equator for one year because of the properties of a Sun-synchronous orbit. The mission observed \( \sim 80\% \) of the sky.

The diffuse FUV map in L band was obtained by eliminating stars from the total FUV sky map and by binning photon events using the Hierarchical Equal Area isoLatitude Pixelization (HEALPix) tessellation scheme (Górski et al. 2005) with \( \sim 1° \) pixel (resolution parameter \( N_{\text{side}} = 64 \)). We excluded the wavelength regions of the strongest emission lines (Si iv \( \lambda \lambda 1398, \) Si ii * \( \lambda 1532, \) C iv \( \lambda \lambda 1548, 1551, \) and Al ii \( \lambda 1671 \)) and averaged the data in the wavelength regions of 1370–1520 Å, 1560–1660 Å, and 1680–1710 Å. A detailed description of the FUV continuum map is presented in Seon et al. (2011).

The all-sky survey maps in Hα and 100 \( \mu \)m were obtained from Finkbeiner (2003) and Schlegel et al. (1998), respectively. The all-sky map of H i column density is from the Leiden/Argentina/Bonn (LAB) Survey (Kalberla et al. 2005). The data interpolated onto an HEALPix projection were obtained from the Legacy Archive for Microwave Background Data Analysis (LAMBDA).

3. SPECTRAL TYPE OF IONIZING SOURCES

Figure 1 shows the Hα/FUV intensity ratio maps obtained by dividing the Hα intensity with the FUV continuum intensity and smoothed with a spherical Gaussian function with a full width at half-maximum (FWHM) \( \sim 3° \) (Seon 2006). The smoothing was performed using the spherical harmonic transform in the HEALPix scheme so as to smear the same surface areas in all directions. We excluded the regions with low signal-to-noise ratio (S/N < 3) and two regions between the edges of observing strips centered at \((l, b) \sim (45°, -35°)\) and \(\sim (225°, 45°)\), which appeared to produce an artifact with very high Hα/FUV intensity ratios after the smoothing. The FUV and Hα intensities are expressed in units of rayleighs (1 rayleigh \([\text{R}] = 10^9/4\pi \) photons \(\text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\)) and continuum units (1 CU = photons \(\text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{Å}^{-1}\)). In the figure, the region with higher Hα/FUV ratio is represented in blue. The top and bottom panels show the intensity ratio maps before and after dust-extinction correction, respectively. Using the standard approach of Bennett et al. (2003) for the emitting medium co-existing with dust and the extinction map of Schlegel et al. (1998), the correction for dust extinction was performed for both radiations. In the top panel of the figure, it is clear that bright H ii regions have higher Hα/FUV ratios than the diffuse Hα regions. Correction for dust extinction lowers the ratio because the correction for FUV is larger than for Hα. As dust extinction is stronger at low latitudes, the correction for H ii regions is bigger than for the WIM. Therefore, the distinction between the bright H ii and the WIM regions becomes less clear after the dust-extinction correction, as shown in the bottom panel.

For the quantitative comparison, the WIM regions (we will use the term WIM to denote the diffuse Hα regions that are not related to the bright H ii regions, regardless of physical origin) were isolated in the Hα image using a masking procedure similar to that described in Hoopes et al. (2001). The Hα image was smoothed with a median filter using a pixel size of \( \sim 15° \) which corresponds approximately to the size of the largest H ii regions. The smoothed image was subtracted from the original, leaving an image of the small-scale structures only. In other words, the smoothly varying component was subtracted. On this image a mask was created by assigning the value “1” to the pixels with intensity lower than a prescribed threshold and “0” to the others. We tried several threshold values between 0.1 and 50 R as the separation between the WIM and H ii regions was rather fuzzy. The unsmoothed Hα image was then multiplied by the mask, leaving an image of only the WIM. A WIM FUV image was also created using the same mask. The Hα and FUV images for H ii regions were created by multiplying the inverted WIM mask.

Figure 2(a) shows the histograms of the Hα/FUV intensity ratios for the WIM and H ii regions in our Galaxy, with the thresholds of 1, 5, 10, and 20 R. The threshold “1 R” masks most of the H ii regions and “20 R” the brightest ones. The mean ratios for the H ii regions are generally higher than the mean ratios in the WIM. The difference in the logarithm of the average ratio between the H ii regions and the WIM increases smoothly from 0.40 \( \pm 0.40 \) to 0.62 \( \pm 0.39 \) dex as the threshold increases from 1 to 20 R. These values are smaller than those found in 10 external galaxies in Hoopes et al. (2001), although the largest value of \( \sim 0.62 \) is consistent with the results for NGC 2903, NGC 5457, and NGC 1512 within the error ranges. Figure 2(b) shows the histograms of the Hα/FUV intensity ratios after dust-extinction correction. Correction for dust extinction lowers the difference in the average ratio, as in the bottom panel of Figure 1.

The smaller difference of the mean ratios in our Galaxy compared with other galaxies may be attributable to geometrical effects, as the WIM and H ii regions overlap in our Galaxy while in the face-on external galaxies examined in Hoopes & Walterbos (2000) and Hoopes et al. (2001) the two regions are better separated from each other. The field stars in the Galactic plane overlapping with H ii regions would lower the Hα/FUV intensity ratio observed toward the bright H ii regions. Some of the Hα and FUV photons originating from H ii regions are scattered into high latitudes (Wood & Reynolds 1999; Witt et al. 2010; Seon et al. 2011). The dust scattering of Hα and FUV photons from the H ii regions to high latitudes would then increase the ratio for the WIM, further lowering the difference of the ratios. Furthermore, all the H ii regions are at the same distance in a face-on external galaxy, while in the Milky Way the apparent size of H ii regions is potentially dominated by their distances making the separation more difficult. Therefore, the difference between the H ii regions and the WIM in our Galaxy may not be significantly different from other galaxies when the Galaxy is viewed face-on.

Along the top axis of Figure 2 are shown the stellar spectral types that would yield the corresponding Hα/FUV ratios. We derived a temperature and effective gravity for given spectral types using the calibration of Vacca et al. (1996). We then calculated the Ly α and FUV photon luminosities \( L_{\text{Ly\alpha}} \) and \( L_{\text{FUV}} \) for spectral types of B2–O3 stars in the wavebands \( \lambda < 912 \AA \).
Figure 1. Mollweide projections of the diffuse Hα to FUV intensity ratio maps. The top panel shows the ratio map before dust-extinction correction. The bottom panel shows the ratio map after dust-extinction correction. The dust-extinction correction was performed assuming uniformly mixed gas and dust. Here, 1 R (rayleigh) = $10^6 / 4\pi$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ and 1 CU (continuum unit) = photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Å$^{-1}$. Galactic coordinates centered at (l, b) = (0°, 0°) with longitude increasing toward the left are shown with latitude and longitude lines on a 30° grid.

(A color version of this figure is available in the online journal.)

and 1370–1710 Å, respectively, by interpolating on a grid of Kurucz models (Castelli & Kurucz 2003). The Hα luminosities $L_{\text{H}\alpha}$ equal 0.46$L_{\text{LyC}}$, assuming case B recombination. Since Vacca et al. (1996) cover spectral types only earlier than or equal to B0.5, we extrapolated the calibration down to B2. The temperatures estimated in this way were $\sim$5%–19% higher than the values obtained from the older calibration of Straižys & Kuriliene (1981). The extrapolation to B2 would be accurate within $\sim$19%. Figure 2 suggests that the difference between the Hα/FUV ratios in the WIM and those in the H ii regions is due to the difference in main ionizing sources.

An interesting result in Figure 2 is that the median value of the observed ratios in the WIM corresponds to a value predictable from $\sim$ O9–B0 stars with effective temperatures of $\sim$35,000 K. Sembach et al. (2000) modeled the WIM as a combination of overlapping H ii regions and found that typical values of the line ratios [S ii] $\lambda 6716$/Hα $\sim$ 0.2–0.4, [N ii] $\lambda 6583$/Hα $\sim$ 0.3–0.6, [O i] $\lambda 6300$/Hα $\sim$ 0.01–0.03, [O iii] $\lambda 5007$/Hα $\lesssim$ 0.1, and He i $\lambda 5876$/Hα $< 0.02$ observed in the Galactic WIM can be well reproduced by an ionizing spectrum of a star with $T_{\text{eff}} \sim 35,000$ K; Domgörgen & Mathis (1994) also found that the WIM observations best agree with $T_{\text{eff}} \sim 38,000$ K. The results are consistent with the Hα/FUV ratios, thereby strongly supporting that the Hα emission originates from late OB-type stars. The optical line ratios will be discussed more in Section 5. We also note that the Hα/FUV ratio has a well-defined limiting value corresponding to B2 stars, meaning that the latest stellar type that is capable of ionizing the WIM may be about B2.

The mean Hα/FUV intensity ratio after and before the dust-extinction correction as a function of Hα intensity is shown together with the standard deviation of ratios from the mean.
value for a given Hα intensity interval in Figure 3(a). The uncertainty of the ratio toward an individual sightline is much smaller than the deviation of the ratios. Red and black symbols represent the intensity ratio before and after the dust-extinction correction, respectively. There is a general trend for the average ratio to increase with the Hα intensity, although it scatters a lot. Both the general trend and large scatter are qualitatively similar to those found in the external galaxies in Hoopes et al. (2001). The scatter in the ratio tends to increase with the Hα intensity. At low latitudes and high Hα intensities, the Hα radiation may be dominated by recombination lines originating from H II regions around early O-type stars, while the FUV background is from dust scattering (Seon et al. 2011). Therefore, a much wider range of variability in the Hα intensity and the Hα/FUV ratio is found. On the other hand, at high latitudes and low values of Hα intensity, much of the structure in the faint Hα background may have the same origin as that of the FUV background and the variation of Hα/FUV decreases. In other words, the Hα contribution from dust scattering becomes increasingly important at higher latitudes. A similar feature was found in Figure 21 of Seon et al. (2011), where a linear correlation of the Hα intensity with the FUV intensity was found only at low intensities. In addition, at the lowest Hα intensities, only early B-type stars would contribute to both backgrounds and the ratio would then converge to a single value. The converged value corresponds to a spectral type of B0–B1.

Interestingly, the line ratios [S ii]/Hα and [N ii]/Hα, and the Hα/FUV ratio show a similar trend with decreasing Hα intensity, except the line ratios increase while the Hα/FUV ratio decreases. Mean values of the optical line ratios increase with decreasing Hα intensity. The ratios also show large scatter as the Hα/FUV ratio does. The mean Hα/FUV ratio decreases rapidly below an Hα intensity of ~0.7–1 R with decreasing Hα intensity in Figure 3(a). The mean line ratios increase most dramatically below the same Hα intensity (~0.7–1 R) (Figures 6, 12, and 15 in Madsen et al. 2006). The similar trend in both the optical line ratios and the Hα/FUV ratio may be understood as an increasing contribution of late OB stars to the WIM as the Hα intensity decreases.

We also plotted the hardness ratio in FUV wavelengths versus the Hα/FUV ratio as the FUV hardness ratio might also provide an additional clue to the spectral type of the ionizing source of the WIM. The hardness ratio is defined as the ratio of average intensities at $\lambda\lambda$1370–1520 to $\lambda\lambda$1560–1710, excluding the bright C IV, S II, and Al II emission lines, as in Seon et al. (2011). We found an overall correlation between the FUV hardness ratio with the Hα/FUV intensity ratio, as shown in Figure 3(b), where the standard deviation of the FUV hardness ratios from its mean value for a given Hα/FUV bin is also indicated. The mean FUV hardness ratio shows a rather rapid decrease below Hα/FUV ~ 1 (R/10^3 CU), corresponding to the approximate mean value of the Hα/FUV ratio of the WIM. Seon et al. (2011) found that a map of the hardness ratio of 1370–1520 Å to 1560–1710 Å
band intensity shows that the sky is divided into roughly two parts, which are determined by the longitudinal distribution of OB-type stars in the Galactic plane. Therefore, the correlation between the FUV hardness ratio and a large portion, if not all, of the Hα/FUV ratio supports that the diffuse Hα background is produced by relatively late-type stars rather than H ii regions in the Galactic plane.

Statistically significant correlation coefficients of 0.9 and 0.8 for Figures 3(a) and (b), respectively, were obtained. We also note that most of the Hα/FUV intensity ratios are so concentrated to ~1 (R/10^5 CU), as can be noted in Figure 2, that the two-dimensional histograms and/or contours as in Figure 4 show strong peaks at the Hα/FUV intensity ratio of ~1 (R/10^5 CU). Therefore, the average intensity ratio versus the abscissa in Figure 3 was the best way to represent clearly the correlations. We note that the Hα/FUV ratio map (Figure 1) does not match perfectly with the FUV hardness ratio map (Figure 14 of Seon et al. 2011). However, the maps generally correlate well with each other, except in a few regions such as near (l, b) ~ (30°, 30°).

Hoopes & Walterbos (2000) and Hoopes et al. (2001) compared the observed Hα/FUV ratios with the theoretical calculations assuming that the FUV photons are emitted from unresolved point sources in the observed regions. However, FUV photons are well scattered by interstellar dust grains to large distances and the diffuse FUV emission is widespread over regions where no point sources are present (Bowyer 1991; Witt et al. 1997; Schiminovich et al. 2001; Seon et al. 2011). The FUV intensity used in the analysis of face-on galaxies would be produced by in situ point sources as well as dust-scattered light in the regions, whereas the FUV data in the present study are dominated by dust-scattered light originating from late O- and early B-type stars (Henry 2002; Seon et al. 2011). We also note that the spectral type of the dominant radiation source of the FUV continuum background is consistent with that inferred from the Hα/FUV intensity ratio.

It would be interesting to estimate how a large portion of the ionizing power required for the Hα background can be provided by late OB stars. If the Hα emission originates from ionized gas in a plane–parallel geometry, the hydrogen recombination rate \( r_G \) per unit area of the Galactic disk in the vicinity of the Sun is given by

\[
  r_G \approx 4 \times 10^9 I_{H\alpha}(b) \times \sin |b| \text{ s}^{-1} \text{ cm}^{-2},
\]

where \( I_{H\alpha}(b) \) is the Hα intensity at the Galactic latitude \( b \) (Reynolds 1984). Using an approximate Hα intensity distribution \( I_{H\alpha}(b) \approx 1.0 \csc |b| \text{ R} \), which was obtained from rather limited observations, Reynolds obtained \( r_G \approx 4 \times 10^6 \text{ s}^{-1} \text{ cm}^{-2} \). However, using the result of Hill et al. (2008) obtained from the full WIM observations, the distribution of Hα at high latitudes is fitted on average by \( I_{H\alpha}(b) \approx 0.625 \csc |b| \text{ R} \) (see also Dong & Draine 2011). This leads to a lower recombination rate of \( r_G \approx 2.5 \times 10^6 \text{ s}^{-1} \text{ cm}^{-2} \). The Lyc luminosities per unit area of the Galactic disk estimated for the solar neighborhood are (10–29) \times 10^8 and (0.5–1) \times 10^6 photons s^{-1} cm^{-2} for O and B stars, respectively (Reynolds 1984). The fraction of Lyc luminosity of O9 and O9.5 stars in the total Lyc luminosity due to O stars is ~7%–10% (Terzian 1974; Torres-Peimbert et al. 1974). The Lyc luminosity from stars later than or equal to O9 would
then be \((1.2 - 3.9) \times 10^6\) photons \(s^{-1} cm^{-2}\). Therefore, late OB stars are able to account for at least one-half of the required ionizing power. In fact, Elmegreen (1975) considered the intensity of the \(H\alpha\) background at \(|b| < 30^\circ\) and concluded that isolated \(H\alpha\) regions surrounding early B stars could account for up to one-half of the observed \(H\alpha\) background in some regions of the Galactic plane. He predicted that near the Galactic poles, B star \(H\alpha\) regions would account for a mean \(H\alpha\) intensity of \(\sim 0.1\ R\). This result is consistent with our estimation.

4. DUST SCATTERING

The late OB-type stars may not have enough power to produce the whole \(H\alpha\) background if the \(H\alpha\) photons originate purely from ionized gas around late OB stars, as noted by Reynolds (1984) and in Section 3. However, if dust scattering plays an important role, the dust-scattered \(H\alpha\) photons originating from the sources other than O stars in bright \(H\alpha\) regions would contribute a larger portion to the \(H\alpha\) background at high latitudes and the severe requirement of \(LYC\) leakage from \(H\alpha\) regions in the midplane may be potentially alleviated. In this section, we examine how the contribution of dust scattering could be significant in the \(H\alpha\) background.

Galactic observables may generally correlate with each other because of the general property of a plane–parallel ISM. The correlation between a pair of Galactic quantities would be enhanced when their sources and radiative transfer mechanisms are analogous. If a large portion of the diffuse \(H\alpha\) intensity is due to dust scattering, the \(H\alpha\) intensity would show a better correlation with FUV intensity than with other quantities, such as neutral hydrogen column density \(N(HI)\). On the other hand, if the radiative transfer mechanism for the diffuse \(H\alpha\) emission is not related with the dust scattering, the correlation between the \(H\alpha\) and FUV intensities would not be improved.

Figure 4 shows the correlation plots of \(H\alpha\) intensity with \(100\ \mu m\) dust emission and \(HI\) column density \(N(HI)\) in the same forms of two-dimensional histograms and contours as in Figure 21 of Seon et al. (2011), in which the FUV intensity is compared with \(100\ \mu m\) intensity, \(N(HI)\), and \(H\alpha\) intensity. Correlation coefficients estimated in logarithmic scale are also shown in the figure. We find that the correlation of \(H\alpha\) intensity with FUV (shown in Figure 21(c) of Seon et al. 2011) is a bit better, at least qualitatively, than with the other ISM tracers shown in Figure 4. The correlation relations with \(100\ \mu m\) intensity and \(N(HI)\) are a bit curved and flaring, whereas the correlation with the FUV background is quite straight. However, the correlation coefficient between the \(H\alpha\) and FUV backgrounds is not significantly higher than the other correlation coefficients.

The fact that the correlation coefficients show no significant differences may be caused by large scatter in the correlation relations and the general similarity in the latitude dependence of the data sets (the \(HI\) column density, \(100\ \mu m\), \(H\alpha\), and FUV intensities). Although the \(H\alpha\) emissivity and \(HI\) column density have different dependences on the gas density, their latitude dependences have the same trend with inverse \(\sin b\) if they arise in plane–parallel geometries. The inverse \(\sin b\) dependence of the data sets dominates the correlations in Figure 4. To reduce the latitude dependence and scatter, we therefore plotted the average intensities multiplied by \(\sin b\) versus \(\sin b\) within each of the \(\Delta \sin b = 0.01\) latitude intervals for \(N(HI)\), \(100\ \mu m\), \(H\alpha\), and FUV intensities in Figure 5. In the figure, the curves were paired and arbitrarily moved to compare the shapes. The top two curves compare the \(N(HI)\) and \(100\ \mu m\) emission. The middle and bottom pairs show the variations of \(H\alpha\) and FUV intensities after and before dust-extinction correction, respectively. The \(N(HI)\) and \(100\ \mu m\) emissions are well described by the plane–parallel or inverse \(\sin b\) law, whereas the \(H\alpha\) and FUV intensities deviate from the law. The deviation of \(H\alpha\) and FUV intensities from the inverse \(\sin b\) law is mainly attributable to the effect of dust absorption and scattering. A radiative transfer model of diffuse Galactic light in a plane–parallel dust layer shows the similar dependence of \(I \sin b\) on \(\sin b\) as in the bottom curves of Figure 5 (van de Hulst & de Jong 1969; see also Wood & Reynolds 1999; Seon 2009b). We also note that the inverse \(\sin b\) equation of the \(H\alpha\) intensity described in Section 3 is still a good approximation because of the major dependence of the \(H\alpha\) intensity on inverse \(\sin b\), especially at high latitudes, even \(I \sin b\) is not a constant in Figure 5.

We note from the bottom two curves before dust-extinction correction that the dependences of the \(H\alpha\) and FUV backgrounds on the Galactic latitude are very similar at high latitudes (\(\sin b > 0.3\)) (see also Figure 13 of Haffner et al. 1999 and Figure 9 of Seon et al. 2011), whereas at low latitudes (\(\sin b < 0.3\)) they show a difference. Stronger dust extinction in FUV would suppress the FUV intensity near the Galactic plane, as shown at low latitudes. We therefore corrected the dust extinction as denoted by the middle two curves (red and black solid lines for \(H\alpha\) and FUV, respectively). The dust-extinction correction for both backgrounds was performed using the standard approach of Bennett et al. (2003). The variations of both backgrounds are remarkably similar to each other. The FUV radiation can be emitted even from late B-type stars, whereas the \(H\alpha\) emission requires excitation from earlier stars. Therefore, the scale height of the FUV sources is a bit higher than that of the \(H\alpha\) sources. On the other hand, ionized \(HI\) regions must be more extended than point sources for the FUV photons, and the dust-scattered \(H\alpha\) originating from \(HI\) regions should be more extended than that from point sources. Accordingly, the...
dependences of both backgrounds on the Galactic latitude are very similar even at low latitudes, after extinction corrections are applied.

In Figure 6, we also examine correlations of the diffuse Hα intensity with N(H i), 100 μm emission, and the diffuse FUV background after the removal of the inverse sin |b| dependence. In the correlation plot, we used only the latitude range of sin |b| > 0.3 to avoid the strong dust-extinction effect. Red and black symbols represent the data points after and before the dust-extinction correction, respectively. The figure also shows correlation coefficients. It is obvious that the correlation with the FUV background is now significantly stronger than the correlations with others. Seeon et al. (2011), we compared the FUV continuum background with other ISM tracers and found that the FUV intensity correlates better with the Hα intensity than with others. The two-photon emission in the WIM is unlikely to be the cause of the strong correlation between the Hα and FUV backgrounds (Seon et al. 2011). We are therefore convinced of the result that a significant portion of the diffuse Hα emission at high latitudes is dust-scattered light originating from elsewhere in the Galaxy.

We now estimate the fraction of dust-scattered Hα emission. Seeon et al. (2011) derived two equations (Equations (7) and (8)) relating the FUV intensity to 100 μm and Hα emissions at high latitudes. Since the constant terms in the relations are often regarded as extragalactic background, they should be identical. The difference between the constant terms is indeed negligible.

In the correlation plot, we used only the latitude range of sin |b| > 0.3 to avoid the strong dust-extinction effect. Red and black symbols represent the data points after and before the dust-extinction correction, respectively. The figure also shows correlation coefficients. It is obvious that the correlation with the FUV background is now significantly stronger than the correlations with others. In Seeon et al. (2011), we compared the FUV continuum background with other ISM tracers and found that the FUV intensity correlates better with the Hα intensity than with others. The two-photon emission in the WIM is unlikely to be the cause of the strong correlation between the Hα and FUV backgrounds (Seon et al. 2011). We are therefore convinced of the result that a significant portion of the diffuse Hα emission at high latitudes is dust-scattered light originating from elsewhere in the Galaxy.

The Astrophysical Journal, 743:188 (10pp), 2011 December 20
Seon et al.

Figure 6. Correlation of the diffuse Hα intensity with neutral hydrogen column density (left), 100 μm emission (middle), and the diffuse FUV intensity (right). Red and black dots represent the data points before and after the dust-extinction correction, respectively. Numbers outside and inside the parentheses are correlation coefficients estimated after and before the dust-extinction correction, respectively.

(A color version of this figure is available in the online journal.)

shown in Figure 5 of Witt et al. (2010) is more or less anti-correlated with the Hα/FUV ratio map of Figure 1, verifying our expectation.

5. DISCUSSION

By comparing previous results, we propose that most of the diffuse Hα background at high latitudes may originate from relatively late O and early B stars outside the bright H II regions and from dust-scattered Hα photons from elsewhere in the Milky Way. The observed Hα/FUV intensity ratio in general increases with the Hα intensity, indicating that late OB stars could be important contributors to the diffuse Hα. As suggested by the strong correlation between the diffuse Hα and FUV backgrounds, dust scattering may widely spread out the Hα recombination photons into regions where there is no ionizing source.

5.1. Ionizing and Heating Sources

The present scenario is able to explain the line ratios observed in the WIM much more easily than or equally as well as the photoionization models. The higher [SII] λ6716/Hα and [NII] λ6583/Hα line ratios observed in the diffuse Hα regions compared to those in H II regions have been believed to be the strongest evidence against the theory of a dust-scattering origin of the diffuse Hα emission (Reynolds 1990b). However, we have to note that the argument has been based solely on comparison with the line ratios from the bright H II regions. If the line ratios from the ionized regions due to the late-type OB stars are compared with the line ratios in the WIM, the present scenario seems to explain the trend equally as well as the previous photoionization models do.

As already noted in Section 3, mean values of [SII]/Hα and [NII]/Hα intensity ratios in the diffuse Hα regions are well reproduced with late OB stars (Sembach et al. 2000). Figure 3 in Reynolds (1988) shows that the [SII]/Hα ratios observed in H II regions around late-type stars are higher than those found around earlier-type stars. Recently, O’Dell et al. (2011) pointed out that the similarity of the line ratios between Barnard’s Loop, the Orion–Eridanus Bubble, and the typical WIM samples is striking and probably indicates a common set of their physical conditions. The ionizing stars of the Barnard’s Loop are O9.5 and O9 types. O’Dell et al. found that photoionization models
with ionization parameter \( U = -3.07 \sim -3.67 \) and stellar temperature \( T_{\text{star}} = 31,000 \text{ K} \)–\( 40,000 \text{ K} \) fully enclose the space of \([\text{S}\text{II}]/\text{H}\alpha\) versus \([\text{N}\text{II}]/\text{H}\alpha\) occupied by Barnard’s Loop, the Orion–Eridanus Bubble, and the WIM samples. It is also noticeable that most of the WIM samples in their Figure 7 occupy the region defined by a stellar temperature lower than \( 40,000 \text{ K} \), probably \( \sim 35,000 \text{ K} \). Another interesting fact to note is that the elemental abundances required to explain the line ratios in the WIM are close to the B star abundances both in Sembach et al. (2000) and in O’Dell et al. (2011). These results strongly support the late OB star origin of the diffuse H\( \alpha \) emission.

Weak \([\text{O}\text{III}]/\text{H}\alpha\) and \([\text{He}\text{II}]/\text{H}\alpha\) emission line ratios also indicate that the spectrum of the diffuse interstellar radiation field is significantly softer than that from the average Galactic O star population (Reynolds & Tufte 1995; Madsen et al. 2006).

The increase of the line ratios \([\text{S}\text{II}]/\text{H}\alpha\) and \([\text{N}\text{II}]/\text{H}\alpha\) can be understood as a significant ionization contribution by late OB stars to the WIM. However, their highest values observed in the WIM may need other non-ionizing heating sources, such as shocks, photoelectric heating, and/or turbulent mixing layers (Reynolds & Cox 1992; Slavin et al. 1993; Collins & Rand 2001). Other heating sources may include cooling, falling galactic fountain gas initially raised from the midplane by supernovae and microflares from magnetic reconnection (Raymond 1992; Shapiro & Benjamin 1993). It should be noted that the pure photoionization models by O-type stars in the midplane also need additional heating sources to explain the highest ratios (Reynolds et al. 1999). The emission lines due to the heating sources that provide the highest line ratios would also be scattered into more extended regions than those originally produced by the heating/ionizing sources. Therefore, the dust scattering will hamper the clear identification of the original ionization sources.

As noted by Hoopes & Walterbos (2003), the \([\text{S}\text{II}]/[\text{N}\text{II}]\) ratio is almost independent of ionizing stellar temperature but depends on the ionization parameter. The photoionization models explain the enhanced \([\text{S}\text{II}]/\text{H}\alpha\) line ratios by a diluted radiation field and thus the lowered ionization parameter. Hence, the models cannot reproduce the observed constancy of the \([\text{S}\text{II}]/[\text{N}\text{II}]\) ratios. Instead, the dust-scattering scenario can naturally explain the constancy of the line ratios.

### 5.2. Physical Properties

Dust scattering has a significant impact on line ratios which are used to determine physical properties of H\( \pi \) regions (O’Dell & Goss 2009; O’Dell & Harris 2010). Scattered light is enhanced at shorter wavelengths, which can lead to observed Balmer line ratios that are theoretically impossible. This effect can also lead to overestimates of the electron temperatures derived from the auroral and nebular line ratios of forbidden lines, such as \([\text{N}\text{II}]/\lambda5755/[\text{N}\text{II}]/\lambda6583\) which has been used to derive the temperature of the WIM. Serious discrepancies between the H\( \alpha \) intensity and radio and/or IR intensities could be found when a large portion of the H\( \alpha \) intensity is due to dust scattering. This effect was found in the Extended Orion Nebula (EON). O’Dell & Goss (2009) combined 327.5 MHz radio observations and optical spectroscopy to study conditions in the EON. They found an increase in the ratio of emission measures derived from the H\( \beta \) line and the 327.5 MHz radio continuum with increasing distance from the dominant photoionizing star \( \theta^1 \) Ori C, indicating the increasing contribution of a dust-scattering component to the H\( \beta \) intensity with the distance.

Recent observations using the Wilkinson Microwave Anisotropy Probe have found that the ratio of the free–free radio continuum to H\( \alpha \) is surprisingly low in the WIM (Davies et al. 2006; Dobler & Finkbeiner 2008; Dobler et al. 2009; Gold et al. 2011). Dong & Draine (2011) proposed a three-component model consisting of a mix of (1) hot gas currently being photoionized, (2) gas that is recombining and cooling after removal of a photoionizing source, and (3) cold H\( \text{i} \) gas. In the standard model for explaining the observed intensity ratios of the free–free radio continuum to H\( \alpha \) and \([\text{N}\text{II}]/\lambda6583\) to H\( \alpha \), they assumed that the scattered fraction of the H\( \alpha \) originating from the hot gas is 20%. The fractions of the hot, cooling, and H\( \text{i} \) gases were found to be 22%, 56%, and 2%, respectively. The model predicted that the photoionization should switch off and the gas begins to cool and recombine in a much shorter time (\( \sim 1 \times 10^6 \) yr) than O star lifetimes (\( \sim 3 \times 10^6 \) yr). Such a short photoionization timescale is rather surprising in that O stars have been generally favored as the source of ionization for the WIM. They therefore suggested that the ionizing radiation for the WIM may be provided in large part by runaway O and B stars, with space velocities \( \gtrsim 100 \text{ km s}^{-1} \). In the analysis, they assumed the \([\text{N}\text{II}]/\text{H}\alpha\) line ratio of \( \sim 0.4 \) for the WIM, which is well reproduced by late OB-type stars (Sembach et al. 2000). The ratio of free–free to H\( \alpha \) is estimated to be \( \psi = 0.16 \text{ kJy sr}^{-1} \text{ R}^{-1} \) for the WIM with a temperature of 8000 K (Equation (11) in Dong & Draine 2011), which is about 1.9 times larger than the observed ratio of 0.085 kJy sr\(^{-1}\) R\(^{-1}\). If we assume that \( \sim 37\% \) of the observed H\( \alpha \) intensity is from dust scattering and the temperature of the WIM is 8000 K, the fractions of the hot and cooling gases are found to be \( \sim 44\% \) and \( \sim 18\% \), respectively.

The WIM is thought to have a temperature 2000 K higher than the bright classical H\( \pi \) regions (Reynolds et al. 2001; Madsen et al. 2006). However, O’Dell et al. (2011) found no evidence that the WIM components have a systematically higher temperature than the well-known higher-density H\( \pi \) regions. As already noted, the temperature derived from \([\text{N}\text{II}]/\lambda5755/[\text{N}\text{II}]/\lambda6583\) may be uncertain. The temperature of Barnard’s Loop is found to be \( \sim 5960–6100 \text{ K} \) (Heiles et al. 2000; O’Dell et al. 2011). From the similarity of the physical conditions between Barnard’s Loop and the typical WIM sample, we may assume an extreme case that the temperature of the WIM is \( \sim 6100 \text{ K} \), and there is no contribution from either cooling or cold H\( \text{i} \) gas. The assumptions may be rather extreme, but still plausible at some sightlines since the physical conditions and contribution of dust scattering in individual sightlines would generally differ from the average and vary from sightline to sightline (Madsen et al. 2006; Witt et al. 2010). The free–free to H\( \alpha \) ratio of \( (1–0.37)\psi (6100 \text{ K}) \sim 0.085 \) is then obtained, which agrees with the observed ratio. Therefore, relatively late O- and/or early B-type stars, as proposed in the present study, appear to explain the observed values of not only optical line ratios but also free–free to H\( \alpha \) intensity ratios even without considering a significant contribution of either cooling or cold H\( \text{i} \) gas. However, we emphasize that the aim of this study is to explain averaged observational results and our results do not indicate that all the diffuse H\( \alpha \) emission is produced by late OB stars outside bright H\( \pi \) regions and dust scattering. The large scatter found in Figure 3 also indicates that not only the physical conditions and contributions of various components (dust-scattered component, hot and cooling gases) but also the
Low extinction at the 2.17 $\mu$m Br$\gamma$ emission line should allow us to probe the WIM throughout the Galactic plane. A pilot survey of the Br$\gamma$ emission carried out using the Goddard–Wisconsin near-IR cryogenic spectrometer revealed that the volume filling fraction of the Br$\gamma$-emitting medium is typically around 1%, indicating the Br$\gamma$ emission is likely related to more compact sources (Kutyrev et al. 2001, 2004). If the Lyc photons are indeed leaked out of the bright H$\text{II}$ regions in the Galactic plane and photoionize the surrounding medium to produce the diffuse H$\alpha$ emission, as usually supposed, the filling fraction of the Br$\gamma$-emitting gas in the Galactic plane should be equal to or higher than the filling fraction of $\sim$10% obtained from the H$\alpha$ observations (Kulkarni & Heiles 1987; Reynolds 1991; Peterson & Webber 2002). This discrepancy strongly suggests that the Lyc leaked out of bright H$\text{II}$ regions is unlikely the major source of the diffuse H$\alpha$ background and a significant portion of the H$\alpha$ background originates from dust scattering. More detailed observations using hydrogen recombination lines in the near-IR wavelengths, such as Pa$\alpha$ (1.87 $\mu$m), Br$\alpha$ (4.05 $\mu$m), and Br$\gamma$, would be needed to understand the origin of the diffuse H$\alpha$ emission. The Multi-purpose Infra-Red Imaging System (MIRIS) is being developed to survey the Galactic plane at the Pa$\alpha$ emission line, which may help to understand the origin of the diffuse H$\alpha$ emission (Han et al. 2010).

The volume filling fraction and scale height of the WIM were estimated from the assumption that the pulsar dispersion measure and the H$\alpha$ photons probe the same ionized medium. However, as a large portion of the diffuse H$\alpha$ background at high latitudes may be the result of dust scattering, the filling fraction and scale height must be reexamined. We also found that some of the small-scale features in the FUV sky coincided with the H$\alpha$ sky, but not always. A detailed examination of small-scale correlation between the H$\alpha$ and FUV background, which should provide a better understanding of the origin of the diffuse H$\alpha$ emission, will be presented in the future.

### 5.3. Radiative Transfer Mechanisms

Assuming the conventional photoionization models of the H$\alpha$ background, the ISM may have low-density paths and voids that allow for ionizing photons from midplane OB stars to reach and ionize gas many kiloparsecs above the Galactic plane (Wood et al. 2010). Pathways that provide lower than average densities to high latitudes could enhance both scattered FUV and gas ionized by the Lyc from the same OB stars in the Galactic plane. Stars that can reproduce most of the FUV continuum background in the radiative transfer models (e.g., Witt et al. 1997; Schiminovich et al. 2001) are located within only a few hundred pc from the Sun. FUV photons are predominantly scattered in the forward direction (Witt et al. 1997; Schiminovich et al. 2001; Lee et al. 2008), implying that dust scattering occurs mostly in between the observer and the source. Preliminary results from our Monte Carlo three-dimensional radiative transfer models for the FUV continuum background indicate that most of the FUV continuum background originates from stars and dust located within a volume with a size of $\pm$1 kpc centered at the Sun (K. I. Seon et al. 2012, in preparation). The H$\alpha$ photons of the WIM are thought to originate within 2–3 kpc distance (e.g., Reynolds 1984), implying that Lyc photons would also originate from a volume within a few kpc. In this regard, we note that the dust-scattering cross-section at 1550 Å is $\sim 1.3 \times 10^4$ times lower than the photoionization cross-section at 912 Å (Weingartner & Draine 2001; Verner & Yakovlev 1995), assuming a Galactic dust-to-gas ratio. This suggests that FUV photons should originate from a much (probably $\sim 10^4$ times) larger volume than H$\alpha$ photons, which is in contrast to the radiative transfer models of the FUV continuum background. Meanwhile, the dust-scattering cross-section for H$\alpha$ photons is lower than that for FUV (1550 Å) by a factor of $\sim 2$ (Weingartner & Draine 2001), indicating that dust scattering of the FUV photons will occur at closer distances than H$\alpha$ photons. Therefore, the dust scattering of H$\alpha$ photons provides a much easier way to explain the diffuse H$\alpha$ background than the conventional photoionization models.

Wood & Reynolds (1999) found that the H$\alpha$ intensity from midplane H$\text{II}$ regions that is scattered by dust at high latitudes is in the range 5%–20% of the total intensity. However, we should note that in situ H$\alpha$ recombination photons at high latitudes would be also scattered and this component was not included in the estimation. In Figure 3 of Wood & Reynolds (1999), the scattered H$\alpha$ intensity that is originating from the WIM through in situ recombination is compatible with the scattered light from bright H$\text{II}$ regions (point sources) at some high latitudes, indicating a higher fraction of dust scattering than 5%–20%. Moreover, as noted in Witt et al. (2010), the highly structured distribution in the ratio of H$\alpha$ scattering to H$\alpha$ in situ emission was not accounted for in the model of Wood & Reynolds (1999). The dust-scattered light of in situ H$\alpha$ emission (originating mostly from late OB-type stars) at high latitudes and the complex structures of the ISM and ionizing sources may result in a higher fraction of dust scattering than predicted by the simplistic calculation.

If late OB stars produce about half of the diffuse H$\alpha$ intensity, the dust-scattered fraction of the H$\alpha$ intensity is more or less at the same level as that due to in situ recombination. The direct FUV starlight and the diffuse FUV background were found to contribute approximately the same amounts to the total FUV intensity on average (Seon et al. 2011). The similarity of the dust-scattered fractions between the FUV continuum and H$\alpha$ backgrounds supports again the idea wherein their sources and radiative transfer mechanisms are similar.

### 6. SUMMARY

In summary, we found that the H$\alpha$/FUV intensity ratio increases with the H$\alpha$ intensity and FUV hardness ratio, implying that late OB-type stars mostly produce the diffuse H$\alpha$ at high latitudes. We also found that the H$\alpha$ correlates with the FUV background very well. The correlations strongly suggest that a large portion of the diffuse H$\alpha$ photons originate from late OB-type stars and dust scattering. We therefore propose a scenario wherein both late OB-type stars and dust scattering play significant roles in the diffuse H$\alpha$ emission. The H$\alpha$ background at high Galactic latitudes may mostly originate from late OB stars existing outside the bright H$\text{II}$ regions and dust scattering of the H$\alpha$ photons. The proposed scenario appears to reproduce most of the observed line ratios, such as the average values of $[\text{S}\text{II}]/\text{H}\alpha$, $[\text{N}\text{II}]/\text{H}\alpha$, $[\text{O}\text{III}]/\text{H}\alpha$ and He$\text{I}/\text{H}\alpha$, and the free–free to H$\alpha$ ratios. Their extreme values may need additional heating sources, as is also needed in the pure photoionization models. Our scenario is also in better accord with the relative constancy of the $[\text{S}\text{II}]/[\text{N}\text{II}]$ intensity ratio, which cannot be explained with the standard photoionization models.
SPEAR/FIMS is supported by NASA grant NAG5-5355 and flies on the STSAT-1 Mission, supported of the Korea Ministry of Science and Technology. We acknowledge the use of the Legacy Archive for Microwave Background Data Analysis (LAMBDA). Support for LAMBDA is provided by the NASA Office of Space Science. K.-I. S. was supported by a National Research Foundation of Korea grant funded by the Korean government.

REFERENCES

Bennett, C. L., Hill, R. S., Hinshaw, G., et al. 2003, ApJS, 148, 97
Bowyer, S. 1991, ARA&A, 29, 59
Castelli, F., & Kurucz, R. L. 2003, in IAU Symp. 210, Modelling of Stellar Atmospheres, ed. N. Fiskunov, W. W. Weiss, & D. F. Gray (San Francisco, CA: ASP), poster A20 (arXiv:astro-ph/0405087)
Collins, J. A., & Rand, R. J. 2001, ApJ, 551, 57
Davies, R. D., Dickinson, C., Banday, A. J., et al. 2006, MNRAS, 370, 1125
Dobler, G., Draine, B., & Finkbeiner, D. P. 2009, ApJ, 699, 1374
Domgörken, H., & Mathis, J. S. 1994, ApJ, 428, 647
Dobler, G., & Finkbeiner, D. P. 2008, ApJ, 680, 1235
Dong, R., & Draine, B. T. 2011, ApJ, 727, 35
Dove, J. B., & Shull, J. M. 1994, ApJ, 430, 222
Edelstein, J., Min, K.-W., Han, W., et al. 2006b, ApJ, 644, L159
Edelstein, J., Korpela, E. J., Adolfo, J., et al. 2006a, ApJ, 644, L159
Elmegreen, B. G. 1975, ApJ, 198, L31
Finkbeiner, D. P. 2003, ApJS, 146, 407
Gold, B., Odegard, N., Weiland, J. L., et al. 2011, ApJS, 192, 15
Górski, K. M., Hivon, E., Banday, A. J., et al. 2005, ApJ, 622, 759
Haffner, L. M., Reynolds, R. J., & Tufte, S. L. 1999, ApJ, 523, 223
Haffner, L. M. 2009, Rev. Mod. Phys., 81, 969
Han, W., Lee, D.-H., Park, Y., et al. 2010, Proc. SPIE, 7731, 77311W
Heiles, C., Haffner, L. M., Reynolds, R. J., & Tufte, S. L. 2000, ApJ, 536, 335
Henry, R. C. 2002, ApJ, 570, 697
Hill, A. S., Benjamin, R. A., Kowal, G., et al. 2008, ApJ, 686, 363
Hoopes, C. G., & Walterbos, R. A. M. 2000, ApJ, 541, 597
Hoopes, C. G., & Walterbos, R. A. M. 2003, ApJ, 586, 902
Hoopes, C. G., Walterbos, R. A. M., & Bothun, G. D. 2001, ApJ, 559, 878
Jura, M. 1979, ApJ, 227, 798
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, A&A, 440, 775
Kulkarni, S. R., & Heiles, C. 1987, in The Atomic Component, Interstellar Processes, ed. D. J. Hollenbach & H. A. Thronson, Jr. (Astrophysics and Space Science Library, Vol. 134; Dordrecht: Dredrecht: Reidel), 87
Kutyrev, A. S., Bennett, C. L., Mosley, S. H., Reynolds, R. J., & Roesler, F. 2001, in ASP Conf. Proc. 231, Tetons 4: Galactic Structure, Stars, & the Interstellar Medium, ed. C. E. Woodward, M. D. Bicay, & J. M. Shull (San Francisco, CA: ASP), 360
Kutyrev, A. S., Bennett, C. L., Mosley, S. H., Reynolds, R. J., & Roesler, F. 2004, in How Does the Galaxy Work? A Galactic Tertulia with Don Cox and Ron Reynolds, ed. E. J. Alfaro et al. (Astrophysics and Space Science Library, Vol. 315; Dordrecht: Kluwer), 79
Lee, D.-H., Seon, K.-I., Min, K.-W., et al. 2008, ApJ, 686, 1155
Lehtinen, K. M., Juvela, M., & Mattila, K. 2010, A&A, 517, A79
Madsen, G. J., Reynolds, R. J., & Haffner, L. M. 2006, ApJ, 652, 401
Massey, P., Lang, C. C., DeGioia-Eastwood, K., & Garmany, C. D. 1995, ApJ, 438, 188
Mattila, K., Juvela, M., & Lehtinen, K. 2007, ApJ, 654, L131
Miller, W. W., III, & Cox, D. P. 1993, ApJ, 417, 579
O’Dell, C. R., Ferland, G. J., Porter, R. L., & van Hoof, P. A. M. 2011, ApJ, 733, 9
O’Dell, C. R., & Goss, W. M. 2009, ApJ, 693, 1235
Peterson, J. P., & Webber, W. R. 2002, ApJ, 575, 217
Raymond, J. C. 1992, ApJ, 384, 502
Reynolds, R. J. 1984, ApJ, 282, 191
Reynolds, R. J. 1988, ApJ, 333, 341
Reynolds, R. J. 1990a, ApJ, 349, L17
Reynolds, R. J. 1990b, in IAU Symp. 139, The Galactic and Extragalactic Background Radiation, ed. S. Bowyer & C. Leinert (Dordrecht: Kluwer), 157
Reynolds, R. J. 1991, ApJ, 372, L17
Reynolds, R. J., & Cox, D. P. 1992, ApJ, 400, L33
Reynolds, R. J., Haffner, L. M., & Tufte, S. L. 1999, ApJ, 525, L21
Reynolds, R. J., Hausen, N. R., Tufte, S. L., & Haffner, L. M. 1998, ApJ, 494, L99
Reynolds, R. J., Sterling, N. C., Haffner, L. M., & Tufte, S. L. 2001, ApJ, 548, L221
Reynolds, R. J., & Tufte, S. L. 1995, ApJ, 439, L17
Schiminovich, D., Friedman, P. G., Martin, C., & Morrissey, P. F. 2001, ApJ, 563, L161
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Sembach, K. R., Howk, J. C., Ryans, R. S. I., & Keenan, F. P. 2000, ApJ, 528, 310
Seon, K.-I. 2006, J. Korean Phys. Soc., 48, L31
Seon, K.-I. 2009a, ApJ, 703, 1159
Seon, K.-I. 2009b, Publ. Korean Astron. Soc., 24, 1
Seon, K.-I., Edelstein, J., Korpela, E. J., et al. 2011, ApJS, 196, 15
Shapiro, P. R., & Benjamin, R. A. 1993, in Star Formation, Galaxies, and the Interstellar Medium, ed. J. Franco, F. Ferrini, & G. Tenorio-Tagle (Cambridge: Cambridge Univ. Press), 275
Slavin, J. D., Shull, J. M., & Begelman, M. C. 1993, ApJ, 407, 83
Straižys, V., & Kurilienė, G. 1981, Aps&SS, 80, 353
Terzian, Y. 1974, ApJ, 193, 93
Torres-Peimbert, S., Lazcano-Araujo, A., & Peimbert, M. 1974, ApJ, 191, 401
Vacca, W. D., & Shull, J. M. 1996, ApJ, 460, 914
van der Hulst, H. C., & de Jong, T. 1969, Physica, 41, 151
Verner, D. A., & Yakovlev, D. G. 1995, A&AS, 109, 125
Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296
Witt, A. N., Friedmann, B. C., & Sasseen, T. P. 1997, ApJ, 481, 809
Witt, A. N., Gold, B., Barnes, F. S., III, DeRoo, C. T., & Vrij, U. P. 2010, ApJ, 724, 1151
Wood, K., Hill, A. S., Joung, M. R., et al. 2010, ApJ, 721, 1397
Wood, K., & Reynolds, R. J. 1999, ApJ, 525, 799