On the Origins of the Diffuse Hα Emission: Ionized Gas or Dust-Scattered Hα Halos?

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The diffuse H\(\alpha\) emission

NGC 157 (Zurita et al. 2000)
Origins of the diffuse H\( \alpha \) emission

- The diffuse H\( \alpha \) emission is known to trace the Warm Ionized Medium (WIM) or Diffuse Ionized Gas (DIG). See Haffner et al. (2009) for a review.

- Only the O stars meet and surpass the power requirements to ionize the diffuse ISM.

- Density-bounded (leaky) H II regions
  - Turbulent or clumpy morphology of the ISM
  - Existence of enormous, H I-free bubbles/holes surrounding the O stars
However...

- How can the ionizing photons (Lyman continuum; $E > 13.6 \text{ eV}$) from O stars travel hundred of pc through the disk and into the halo?
  - Photo-absorption optical depth $\sim 1$ @ $N(\text{H I}) = 10^{17} \text{ cm}^{-2}$
  - $N(\text{H I}) > 10^{20} \text{ cm}^{-2}$ toward most of line of sights

- The WMAP data shows that the observed ratio of free-free radio continuum to $\text{H}\alpha$ is at least twice smaller than the expected value.

Dong & Draine (2011)
Alternatives?

- What about the dust-scattered light?
  - Jura (1979)
  - Mattila et al. (2007), Lehtinen et al. (2010)
  - Witt et al. (2010)
  - Seon et al. (2011a)

- Importance of the dust scattering has been rejected based on the optical line ratios ([N II] $\lambda 6583$/H$\alpha$ and [S II] $\lambda 6716$/H$\alpha$).

- Can explain the optical line ratios by dust scattering.
  - Seon et al. (2011b), Seon & Witt (2012)
Optical Line Ratios

- $[\text{N II}] \lambda 6583/\text{H} \alpha$ and $[\text{S II}] \lambda 6716/\text{H} \alpha$ in the diffuse regions are generally higher than the ratios in bright H II regions.
  - $[\text{N II}]/\text{H} \alpha \approx 0.25$ and $[\text{S II}]/\text{H} \alpha \approx 0.1$ in bright H II regions
  - $[\text{N II}]/\text{H} \alpha \approx 0.3-0.6$ and $[\text{S II}]/\text{H} \alpha \approx 0.2-0.4$ in the diffuse ISM regions.
- These differences have been regarded to indicate that the optical lines are not due to dust scattering.

Overlooked the followings:
- ① Late O- or early B-type stars
- ② Photo-ionization in the clumpy ISM
- ③ H\(\alpha\) absorption line in DGL (Diffuse Galactic Light)
[1] Spectral Type of Ionizing sources

- Hα/FUV ratio can constrain the spectral type of ionizing source.

- Late O- or/and early B-type stars may be an important source of ionization in the galaxies.

Our Galaxy (Seon et al. 2011b)
FUV data from STSAT-1 (Seon et al. 2011a), H-alpha from Finkbeiner (2003)
Photo-ionization Models of H II regions

- 1D model (Cloudy)
  - Abundances (WNM, WNM2, ISM, Orion, Bstar, Solar)
- Stellar spectra (LTE, non-LTE)
- Spectral types (O3 – B1)
- Density: 0.1 – 100 cm⁻³

### Abundances

<table>
<thead>
<tr>
<th>Element</th>
<th>WNM</th>
<th>WNM2</th>
<th>ISM</th>
<th>Orion</th>
<th>Bstar</th>
<th>Solar</th>
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<td>12.00</td>
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<td>11.00</td>
<td>11.00</td>
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<td>7.27</td>
<td>7.51</td>
<td>7.00</td>
<td>6.97</td>
<td>7.27</td>
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</table>

### Stellar types of ionizing star

<table>
<thead>
<tr>
<th>Sp. Type</th>
<th>$T_*$ (K)</th>
<th>$R_*$ (cm)</th>
<th>$Q(H^0)$ (s⁻¹)</th>
<th>$Q(He^0)$ (s⁻¹)</th>
<th>log $g_*$</th>
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<tbody>
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<td>O3V</td>
<td>48,410</td>
<td>$1.24 \times 10^{12}$</td>
<td>$9.73 \times 10^{49}$</td>
<td>$2.35 \times 10^{49}$</td>
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<td>O4V</td>
<td>45,180</td>
<td>$1.13 \times 10^{12}$</td>
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<td>O5V</td>
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Line ratios

- 1D models
- Line ratios are consistent with late O or early B
- WNM abundances
Dust-scattered halo around H II regions

- H II regions + dust-scattered halos around 04V and 09V stars
3D models (MOCASSIN)

- **U**: uniform density with $n_H = 10 \text{ cm}^{-3}$
- **C1**: clump: ff = 1/3, $n_H = 20 \text{ cm}^{-3}$, interclump: ff = 2/3, $n_H = 5 \text{ cm}^{-3}$
- **C2**: clump: ff = 1/4, $n_H = 30 \text{ cm}^{-3}$, interclump: ff = 3/4, $n_H = 10/3 \text{ cm}^{-3}$
Line ratios

- 3D models
- Line ratios are consistent with
  - late O or early B
  - WNM abundances
- Clumpier model gives higher \([\text{N II}] / \text{H} \alpha\) and \([\text{S II}] / \text{H} \alpha\) ratios.
Dust-scattered halos around O9V H II region
Comparison with Orion

Sanchez et al. (2007)
[3] Hα absorption feature in DGL

- Unresolved Stars + Diffuse Galactic Light
  - Balmer absorption lines in the underlying stellar continuum can give rise to underestimation of the diffuse Hα intensity and overestimation of the line ratios.
  - Hα absorption EW ~ 4-5Å for Sb and Sc disk galaxy
Radial profile of dust-scattered halo

- Surface brightness profiles of dust-scattered halos
  - Surface brightness profile depends only on the total luminosity of the source.

\[ I(r) = I(r_0) \left( \frac{r_0}{r} \right)^2 e^{-(r-r_0)/r_c}. \]
Increase of line ratio due to DGL

- Hα emission $EW \sim 100$-1500Å for the disk galaxies
- Increase of the line ratios

\[
\frac{I_{[\text{NI} \text{II}]}^{\text{obs}}(r)}{I_{\text{H}\alpha}^{\text{obs}}(r)} = \frac{I_{\text{H}\alpha}^{\text{em}}}{I_{\text{H}\alpha}^{\text{em}}} \left[ 1 - \frac{W_{\text{H}\alpha} \delta_{\text{late}}}{W_{\text{H}\alpha} \delta_{\text{cont}}(r)} \right]^{-1}
\]

Here, $r_0 \sim$ mean free path of dust extinction
($\sim 57$ pc for $N_H = 10$ cm$^{-3}$)
BPT diagram of star-forming galaxies

- Since about half of the H\(\alpha\) emission is known to originate from WIM and the mean ratios of [N II]/H\(\alpha\) and [S II]/H\(\alpha\) in WIM is higher than those in H II regions by a factor of \(\approx 2\), the line ratios in the integrated spectrum over an entire galaxy should be higher than the mean values of H II regions by a factor of \(\approx 1.5\).

- If the enhancement of the line ratios in WIM were not due to the underlying Balmer absorption lines, the line ratios of integrated spectra, after correction of the underlying stellar absorptions, would be significantly different from those of individual H II regions in the diagnostic line-ratio diagram (BPT diagram).
BPT diagram of star-forming galaxies

Lehnert & Heckman (1994)
Closed: star-forming galaxies
Open: AGNs

Flores-Fajardo et al. (2009)
Blue: H II regions, Red: WIM

Moustakas et al. (2006)
Dots: H II regions
Closed: star-forming galaxies
Open: AGNs

SDSS (Draine 2011, Brinchmann et al. 2004)

Lehnert & Heckman (1994)
Closed: star-forming galaxies
Open: AGNs
Hα morphology of face-on galaxies

Models of Zurita et al. (2002) and Seon (2009) are in fact radiative transfer models for a single dust-scattering simulation with an arbitrary variable dust extinction cross-section and an isotropic scattering phase function.

The obtained effective cross-section accords well with the dust-scattering cross-section of Hα photons.

\[
I(r) \propto \exp(-\tau)/r^2 \\
\sigma_{\text{eff}} = (\kappa_0 h)/N_{\text{HI}} \approx (4 - 8) \times 10^{-22} (N_{\text{HI}}/10^{21} \text{cm}^{-2})^{-1} \text{cm}^2
\]

\[
\sigma_{\text{ext}} = 3.8 \times 10^{-22} \text{ cm}^2/\text{H}
\]
Summary

- Dust scattering cannot be ruled out
- The observed optical line ratios can be well reproduced by the dust-scattered halo scenario.

① The optical lines originate from H II regions ionized by late O- or early B-type stars in the media with abundances close to WNM and scattered off by interstellar dust.

② Some part of the enhancement or fluctuation in the line ratios may be attributed to the variation of clumpiness from sightline to sightline.

③ [N II]/Hα in the diffuse ISM regions is highly likely to be consistent with that in bright H II regions, if the underlying Balmer absorption lines are properly taken into account.

- The global Hα morphology accords well with the dust-scattered halos.