A TWO-DIMENSIONAL MAP OF THE COLOR EXCESS IN NGC 3603

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ABSTRACT

Using archival Hubble Space Telescope/Wide Field Camera 3 images centered on the young HD 97950 star cluster in the giant H II region NGC 3603, we computed the pixel-to-pixel distribution of the color excess, \( E(B-V)_g \), of the gas associated with this cluster from its \( \text{H} \alpha/\text{Pa}B \) flux ratio. At the assumed distance of 6.9 kpc, the resulting median color excess within 1 pc from the cluster center is \( E(B-V)_g = 1.51 \pm 0.04 \) mag. Outside the cluster (at \( r > 1 \) pc), the color excess is seen to increase with cluster-centric distance toward both north and south, reaching a value of about 2.2 mag at \( r = 2 \) pc from the cluster center. The radial dependence of \( E(B-V)_g \) westward of the cluster appears rather flat at about 1.55 mag over the distance range 1.2 pc < \( r < 3 \) pc. In the eastern direction, \( E(B-V)_g \) steadily increases from 1.5 mag at \( r = 1 \) pc to 1.7 mag at \( r = 2 \) pc and stays nearly constant at 1.7 mag for 2 pc < \( r < 3 \) pc. The different radial profiles and the pixel-to-pixel variations of \( E(B-V)_g \) clearly indicate the presence of significant differential reddening across the 4.9 pc \( \times \) 4.3 pc area centered on the HD 97950 star cluster. We interpret the variations of \( E(B-V)_g \) as the result of stellar radiation and stellar winds interacting with an inhomogeneous dusty local interstellar medium whose density varies spatially. From the \( E(B-V)_g \) values measured along the rims of the prominent pillars MM1 and MM2 in the southwest and southeast of the HD 97950 cluster, we estimate an \( \text{H}_2 \) column density of \( \log_{10}(N_{\text{H}_2}) = 21.7 \) and extrapolate it to \( \log_{10}(N_{\text{H}_2}) = 23 \) in the pillars’ interior. We find the pillars to be closer to us than the central ionizing cluster and suggest that star formation may be occurring in the pillar heads.

Key words: dust, extinction – H II regions – open clusters and associations: individual (NGC 3603) – stars: massive – stars: winds, outflows

Online-only material: color figure

1. INTRODUCTION

The young massive HD 97950 star cluster in the giant H II region NGC 3603 is located in the Sagittarius–Carina arm of the Milky Way. This cluster is one of the most massive young star clusters in the Galaxy (~10^4 \( M_\odot \); Harayama et al. 2008). The cluster hosts 10 times more OB stars than the Orion Nebula Cluster, including the two most massive binaries currently known in the Galaxy (Schnurr et al. 2008). The HD 97950 cluster displays pronounced mass segregation (e.g., Sung & Bessell 2004; Harayama et al. 2008). Earlier studies trying to age-date the HD 97950 cluster found the massive stars on the upper main sequence (MS) to be very young (e.g., 1–2 Myr according to the spectroscopic study by Melena et al. 2008), while the pre-main-sequence stars (PMS) were found to show a larger age spread of 2–3 Myr (e.g., Eisenhauer et al. 1998; Grebel 2004, 2005; Harayama et al. 2008; Pang et al. 2010). The PMS stars in the outer cluster regions and in the surroundings of the cluster may, in part, be older, but different authors arrive at different age ranges (e.g., 4–5 Myr; Sung & Bessell 2004; Rochau et al. 2010) or up to 10 Myr (Beccari et al. 2010). Also the evolved supergiants around the HD 97950 cluster support the idea of a large age spread or alternatively sequential or multiple episodes of star formation (e.g., Moffat 1983; Tapia et al. 2001; Crowther et al. 2008; Melena et al. 2008). On the other hand, the size of the wind-blown bubble around the cluster suggests an age much lower than 2.5 Myr when taking the kinetic energy input of the massive stars into account (see the discussion in Drissen et al. 1995). At present, the age(s) and the star formation history of the HD 97950 star cluster and its surroundings in NGC 3603 are uncertain. One of the uncertainties in stellar age dating is introduced by the high and variable reddening in NGC 3603.

The HD 97950 star cluster lies in a wind-blown cavity north of a large molecular cloud in the giant H II region NGC 3603 (e.g., Clayton 1986; Melnick et al. 1989). The gaseous surroundings of the cluster show a complex and variable velocity and density structure (e.g., Clayton 1990; Drissen et al. 1995). Since the nebular density varies spatially, one would expect that also the dust extinction changes with position across the cluster area as denser clouds can shield dust from stellar radiation better than less dense clouds. The resulting variable reddening is known as differential reddening and was shown to be present in NGC 3603 (e.g., Sagar et al. 2001). When this effect is not taken properly into account, it may make stars appear redder and hence older in the color–magnitude diagram depending on their spatial position with respect to the line of sight. This may introduce a considerable uncertainty in the estimation of the stellar ages.

Differential reddening could be one of the causes why the age spread among PMS stars in the HD 97950 star cluster appears to be as large as up to 10 Myr. In fact, as shown by Beccari et al. (2010, their Figure 7), PMS stars are spatially more widely distributed than the MS stars and reside in areas with different reddening. Sung & Bessell (2004) find that the color excess of the stars within the HD 97950 cluster core (at radii \( r < 0.7 \) pc; Harayama et al. 2008) is \( E(B-V)_g \approx 1.25 \) mag and rapidly increases to 2.1 mag in the outer regions (\( r \sim 12 \) pc).

We take advantage of the publicly available images of the HD 97950 cluster taken with the Wide Field Camera 3 (WFC3) aboard the Hubble Space Telescope (HST) through narrowband filters and derived the color excess (e.g., Claret & Osorio 2000). Using archival Hubble Space Telescope/Wide Field Camera 3 images centered on the young HD 97950 star cluster in the giant H II region NGC 3603, we computed the pixel-to-pixel distribution of the color excess, \( E(B-V)_g \), of the gas associated with this cluster from its \( \text{H} \alpha/\text{Pa}B \) flux ratio. At the assumed distance of 6.9 kpc, the resulting median color excess within 1 pc from the cluster center is \( E(B-V)_g = 1.51 \pm 0.04 \) mag. Outside the cluster (at \( r > 1 \) pc), the color excess is seen to increase with cluster-centric distance toward both north and south, reaching a value of about 2.2 mag at \( r = 2 \) pc from the cluster center. The radial dependence of \( E(B-V)_g \) westward of the cluster appears rather flat at about 1.55 mag over the distance range 1.2 pc < \( r < 3 \) pc. In the eastern direction, \( E(B-V)_g \) steadily increases from 1.5 mag at \( r = 1 \) pc to 1.7 mag at \( r = 2 \) pc and stays nearly constant at 1.7 mag for 2 pc < \( r < 3 \) pc. The different radial profiles and the pixel-to-pixel variations of \( E(B-V)_g \) clearly indicate the presence of significant differential reddening across the 4.9 pc \( \times \) 4.3 pc area centered on the HD 97950 star cluster. We interpret the variations of \( E(B-V)_g \) as the result of stellar radiation and stellar winds interacting with an inhomogeneous dusty local interstellar medium whose density varies spatially. From the \( E(B-V)_g \) values measured along the rims of the prominent pillars MM1 and MM2 in the southwest and southeast of the HD 97950 cluster, we estimate an \( \text{H}_2 \) column density of \( \log_{10}(N_{\text{H}_2}) = 21.7 \) and extrapolate it to \( \log_{10}(N_{\text{H}_2}) = 23 \) in the pillars’ interior. We find the pillars to be closer to us than the central ionizing cluster and suggest that star formation may be occurring in the pillar heads.

Key words: dust, extinction – H II regions – open clusters and associations: individual (NGC 3603) – stars: massive – stars: winds, outflows

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filters centered on the Hα and Paβ lines and through broadband filters sampling the continuum emission, in order to extend the work of Sung & Bessell (2004). We compute a pixel-to-pixel map of the color excess, $E(B-V)$, across a $2.43 \times 2.14$ (4.9 × 4.3 pc) field centered on the HD 97950 cluster. Since only some of the gas contributing to the reddening is located in front of the majority of the stars, the reddening of the gas that we derive is an upper limit to the true reddening experienced by the stars. Thus the two-dimensional distribution of the color excess associated with the gas is the first step toward correcting individual MS and PMS stars for reddening in the WFC3 field of view. Multi-band stellar photometry will be needed in order to establish the conversion between the reddening of the gas and that of the stars. This will ultimately allow us to constrain more tightly the age spread of PMS stars and the recent star formation history of the HD 97950 star cluster and of its immediate surroundings (X. Pang et al. 2011, in preparation). Our present paper focuses on the reddening map. The data and their reduction are described in Section 2, while the two-dimensional map of the color excess is presented and discussed in Section 3. Conclusions and a summary are presented in Section 4.

### Table 1

| Filter   | Exposure Time |
|----------|---------------|
| F555W   | 1000 s        |
| F656N   | 1550 s        |
| F814W   | 990 s         |
| F127M   | 2397.697 s    |
| F128N   | 1197.694 s    |
| F139M   | 2397.697 s    |

2. OBSERVATIONS AND DATA REDUCTION

Multi-wavelength imaging of the HD 97950 star cluster was carried out in 2010 with HST/WFC3 (proposal ID: 11360, PI: Robert O’Connell). For our analysis we use the optical images taken in the F555W (∼V), F656N (Hα), and F814W (∼I) filters with the WFC3 ultraviolet-visible detector (0.04 arcsec pixel$^{-1}$) and near-infrared images in the F127M (continuum in $J$), F128N (Paβ), and F139M (continuum in $J$) filters obtained with the WFC3 IR detector (0.13 arcsec pixel$^{-1}$). The total exposure time in the different filters is summarized in Table 1.

All images were reduced with the WFC3 pipeline and the IRAF MULTIDRIZZLE task. We note that no narrowband filter sampling the continuum emission close to the Hα or Paβ line was used during the observations. Thus we use the broadband $V$ and $I$ filters to estimate continuum in Hα and the medium-band $J$-continuum filters for Paβ.

2.1. Hα and Paβ Emission

Radiation emitted at shorter wavelengths is absorbed by dust more effectively than by photons of longer wavelengths. Given that the Hα line (rest-frame wavelength 6563 Å) is emitted at a shorter wavelength than Paβ (rest-frame wavelength 12802 Å), the interstellar dust along the line of sight decreases the Hα flux detected by the observer more than the Paβ flux emitted by the same source. Therefore, the observed Hα/Paβ flux ratio is smaller than the theoretical one computed for the same conditions of electron density ($N_e$) and temperature ($T_e$) of the source in the absence of dust.

Equation (1) (taken from Calzetti et al. 1996) illustrates the relation between the color excess, $E(B-V)_g$, of the interstellar gas, and the observed and theoretical Hα/Paβ flux ratios of this same gas ($R_{obs}$ and $R_{int}$, respectively) under the assumption of a specific extinction law (represented by $\kappa(\lambda) = A(\lambda)/E(B-V)$):

$$E(B-V)_g = \frac{\log(R_{obs}/R_{int})}{0.4[A(\lambda_{Hα}) - \kappa(\lambda_{Paβ})]} \text{ mag.} \quad (1)$$

In order to apply Equation (1), we need to derive the Hα and Paβ emission fluxes per pixel from the available WFC3 images, and for this purpose we make use of IRAF standard routines. We first determine an average point-spread function (PSF) in each filter for 15–20 stars in common to all images. Since the PSF is largest in the F139M image, we degrade all the other images by convolving them with a Gaussian function whose dispersion, $\sigma^2$, is the difference between the PSF $\sigma^2$ of the F139M image and that of the image in the filter in question. We also re-scale the optical images to the same pixel scale of the near-infrared ones and align all images to the one taken through the F139M filter. We calibrate all images in flux by multiplying them by their respective filter PHOTFLAM value as given in the WFC3 manual (Dressel et al. 2010). We derive the continuum emission at the Hα (Paβ) wavelength by interpolating the flux in the F555W and F814W (F127M and F139M) images pixel by pixel with a simple first-order polynomial. Such an interpolation allows us to take into account the slope of the continuum emission of the stars and to better remove the stars from the final, pure line-emission images.

The continuum emission derived by interpolating the flux between F555W and F814W (F127M and F139M) is subtracted from the F656N (F128N) image, and the output is multiplied by the width of the narrowband filter. In this way we are able to construct the images of the pure Hα and Paβ emission as well as their observed $R_{obs}$ flux ratio. We derive $R_{int} = 17.546$ from Osterbrock (1989) under the assumption that $T_e = 10,000$ K and $N_e = 100$ cm$^{-3}$. We adopt a normal extinction law with a ratio of total to selective extinction of $R_V = 3.1$, and derive $\kappa(\lambda_{Hα}) = 2.355$ and $\kappa(\lambda_{Paβ}) = 0.7644$ from Fitzpatrick’s (1999) extinction law. Finally, we apply Equation (1) to the image of the observed $R_{obs}$ flux ratio to construct the pixel-to-pixel map of $E(B-V)_g$ shown in Figure 1. In panel (a) of Figure 2, we show the histogram of the $E(B-V)_g$ per pixel, normalized by the total number of pixels in the $R_{obs}$ image. The total line-of-sight color excess is always larger than the foreground reddening of $E(B-V) = 1.1$ mag (Pandey et al. 2000). More than 90% of the pixels have $E(B-V)_g$ between 1.6 and 2.2 mag.

2.2. Uncertainty of $E(B-V)_g$

In order to estimate the accuracy of our derived $E(B-V)_g$ values, we assume that the electron counts in the images follow a Poisson distribution. Therefore, we start with a Poisson error on the electron counts per pixel in the input images, and propagate these errors through the entire computation of the continua, their subtraction from the F656N and F128N images, and the computation of the $E(B-V)_g$ image according to Equation (1).

We present the histogram of the uncertainties $\sigma_{E(B-V)_g}$ per pixel in panel (b) of Figure 2, normalized by the total number of pixels in the $R_{obs}$ image. The histogram peaks at $\sigma_{E(B-V)_g} = 0.1$ mag, and the percentage of pixels with
Assuming that the flux density of the continuum is the same in both the F127M and F128N filters, we can use the flux ratio $F127M/F128N$ (where both filters were multiplied by their respective PHOTFLAM and bandwidth) to derive the contribution of the Paβ line to the flux in F127M. We find this contribution to be about 13%. No hydrogen lines are found in the wavelength range of the F139M filter, only a few faint He emission lines, which should not significantly contribute to the flux in this filter. The F555W filter includes four strong emission lines: the Hβ and the [OIII]λ = 4959–5007 Å line, where the filter response is $\sim$27% and the Hα line at a response of $\sim$3%. The F814W filter contains the [SII] and [ArIII] emission lines at wavelengths where its response is lower than 10%. Unfortunately, we cannot estimate the contribution of these lines to the flux detected in each filter, because the only available spectrum taken of NGC 3603 in the range of 3000–10400 Å by García-Rojas et al. (2006) was acquired at a position outside the WFC3 field of view. If we assume that the line contamination is about 10% in F555W and F814W as it is for F127M, the color excess would then increase by 0.05 mag on average.

2. The adopted extinction law also contributes to the systematic uncertainties. If we replace Fitzpatrick’s (1999) extinction law with that of Cardelli et al. (1989), we obtain an $E(B-V)_g$ systematically smaller by 0.1 mag ($R_V = 3.1$). When we vary $R_V$ by $\pm 0.5$ in Cardelli et al.’s (1989) extinction law, $E(B-V)_g$ decreases by $\sim 0.3$ mag ($R_V = 3.6$) or increases by $\sim 0.2$ mag ($R_V = 2.6$).

3. The assumed electron temperature and density of the gas may be affected by systematic errors. García-Rojas et al. (2006) and Lebouteiller et al. (2008) obtained $T_e = 10,000$ K and $N_e = 1000$ cm$^{-3}$ for the NGC 3603 giant HII region. Since this electron density is not available in Osterbrock (1989), we calculated $R_{\text{int}}$ for $T_e = 10,000$ K and $N_e = 10,000$ cm$^{-3}$ and derived a new pixel-to-pixel map of $E(B-V)_g$. A factor of 100 difference in $N_e$ results in an average difference of 0.0025 mag in $E(B-V)_g$, which is well within the errors in $E(B-V)_g$ due to photon noise.

3. A TWO-DIMENSIONAL MAP OF THE COLOR EXCESS

3.1. Global Properties of $E(B-V)_g$

The pixel-to-pixel map of $E(B-V)_g$ obtained for $T_e = 10,000$ K and $N_e = 100$ cm$^{-3}$ is presented in Figure 1. The resulting $E(B-V)_g$ is integrated along the different lines of sight toward NGC 3603 and includes the Galactic foreground reddening, which amounts to $E(B-V) = 1.1$ mag according to Pandey et al. (2000). The HD 97950 cluster core ($r < 0.52$ pc) where dozens of OB stars reside is masked out in order to avoid saturated bright stars in the F555W and F814W filters. Since the PSFs of the different filters may be slightly different even after the convolution procedure to obtain the same PSF described in Section 2.1, the subtraction of the continua from the Hα and Paβ images can produce negative values around the stars in the pure emission images, and thus negative $E(B-V)_g$ in the color excess map. This is particularly true for saturated stars and their spikes. Therefore, we smooth the color excess map by replacing the negative $E(B-V)_g$ at the position of a star with the median value of $E(B-V)_g$ in an annulus around it.

In Figure 1, $E(B-V)_g$ is seen to decrease by 0.2 mag when going from the eastern or the western edge of the field of view.
to the cluster center. Overall, the gas color excess in the east is 0.1 mag larger than in the west. However, in the north–south direction $E(B-V)_g$ is systematically larger by 0.4–0.5 mag than in the east–west direction. In general, the southern region has the largest color excess as may be expected since here we are moving toward the densest regions of the giant molecular cloud in the cluster vicinity (e.g., Nüntherger et al. 2002). Our findings support earlier suggestions that the line-of-sight dust cloud in the cluster vicinity (e.g., Nüntherger et al. 2002). Our measurements of the color excess in the bright rims of the northeastern and southwestern lobes of the hourglass nebula (Brandner et al. 1997a, 1997b). We have measured the color excess in the bright rims of the northeastern and southwestern lobes of the hourglass nebula (Table 2; see also)

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Panel (a): histogram of the pixel $E(B-V)_g$. Panel (b): histogram of the uncertainty $σ_{E(B-V)_g}$ of the pixel $E(B-V)_g$ due to photon noise. Panel (c): dependence of $σ_{E(B-V)_g}$ on $E(B-V)_g$.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Radial dependence of $E(B-V)_g$ from the cluster core toward east, west, north, and south. The solid line is the median $E(B-V)_g$ value, while the upper and lower long-dashed lines are the 84 and 16 percentile values, respectively, of the $E(B-V)_g$ distribution as a function of distance from the cluster.

### Table 2

| Object Name | Right Ascension ($^h$ $^m$ $^s$) | Declination ($^\circ$ $^\prime$ $^\prime\prime$) | $E(B-V)_g$ (mag) |
|-------------|----------------------------------|----------------------------------------|-----------------|
| Proplyd 1   | 11 15 13.13                      | -61 15 50.0                           | 1.6             |
| Proplyd 3   | 11 15 04.41                      | -61 14 45.7                           | 1.9             |
| Sher 25: northeast lobe | 11 15 09.71                      | -61 15 13.2                           | 2.0             |
| Sher 25: southwest lobe | 11 15 05.89                      | -61 15 25.0                           | 1.6             |

#### Notes.

The designations Proplyd 1 and 3 are adopted from Brandner et al. (2000), while the coordinates of Sher 25 are from Brandner et al. (1997b). All coordinates are J2000 coordinates.

$r = 1$ pc to 1.7 mag at $r = 2$ pc and then remains nearly constant at 1.7 mag for 2 pc $< r < 3$ pc. The most dramatic changes in $E(B-V)_g$ are seen along the northern and southern directions, where $E(B-V)_g$ gets larger by 0.3–0.5 mag as the distance from the cluster center increases. Specifically, the color excess increases from about 1.7 mag at $r = 1$ pc to 2.2 mag at a distance of 2 pc. The pronounced increase toward the south does not come as a surprise since the overall density of the giant molecular clouds in NGC 3603 increases in this direction (see, e.g., Figure 1 in Brandner et al. 1997b).

In the two-dimensional map of the color excess (Figure 1), some specific sources are associated with a locally higher $E(B-V)_g$. This is the case for two of the “proplyd-like” (protoplanetary-disks-like) objects first detected by Brandner et al. (2000). Proplyd 1 is located east of the HD 97950 star cluster, while Proplyd 3 is in the northwest. Both are tadpole-shaped and rim-brightened sources with extended tails pointing away from the cluster core.

Mid-infrared observations (Nüntherger & Stanke 2003) do not reveal any point-like source that might be associated with the proplyds. These authors suggest that these objects are small dense clumps of gas and dust, which are being photoevaporated by the intense ionizing radiation of the massive stars in the HD 97950 cluster instead of being disks around young stars as proposed by Brandner et al. (2000). In particular, Proplyd 3 shows extended faint emission at 11.9 $\mu$m, which may be caused by carbon-rich dust grains (see Goebel et al. 1995). Assuming that the dust properties are the same for these three proplyds, the higher color excess of Proplyd 3 (0.3 mag redder than Proplyd 1, see Table 2) would be consistent with a higher dust content (if both proplyds are at the same distance), and hence with the fact that Proplyd 3 is the only proplyd detected at 11.9 $\mu$m (Nüntherger & Stanke 2003).

To the north of the HD 97950 cluster, we find Sher 25, a blue supergiant with a circumstellar ring and an hourglass nebula (Brandner et al. 1997a, 1997b). We have measured the color excess in the bright rims of the northeastern and southwestern lobes of the hourglass nebula (Table 2; see also...
(1986) found HD 97950 cluster. For this second shell-like feature, Clayton (1986) estimated the diameter in the image.

Figure 4. Color composite image of NGC 3603, obtained with the map of the color excess (red), the Paβ emission image (green), and the Hα emission image (blue). The positions of the shell and of the pillars MM1 and MM2 are indicated in the image.

and the outer layer of gas ionized by the OB stars of the HD 97950 cluster. See the text for a more detailed description.

Figure 5. Cartoon to illustrate why the observed $E(B - V)_g$ in the rims of the pillar is larger than in the center. The pillar is represented by a cylinder (neutral in its interior and with a density gradient from head to tail) surrounded by an outer layer of gas ionized by the OB stars of the HD 97950 cluster. See the text for a more detailed description.

possibly because the strong radiation field of the massive stars in the cluster core (about 60 OB stars; see Melena et al. 2008) destroys dust grains, dissociates complex molecules, and pushes the gas out. In doing so, these stars would thus reduce the color excess within the area and produce a cavity with lower $E(B - V)_g$ in the reddening map. The western edge of this cavity appears to be delineated by the shell structure seen in the reddening map.

3.3. The Molecular Pillars

In the southern region of NGC 3603, we can see two prominent pillars to the southwest and southeast of the cluster (Figures 1 and 4). Following Nünberger et al. (2002), we refer to them as MM1 and MM2, respectively. Figure 4 is a composite color image showing the Hα emission (in blue), the Paβ (in green), and the color excess (in red). The heads of both MM1 and MM2 stand out because of their strong Hα and Paβ emission. They are gradually being photoevaporated by the cluster’s massive OB stars as is also indicated by the shocked and ionized material in their heads (Nünberger et al. 2002; Nünberger & Stanke 2003).

According to Bertoldi (1989) and Bertoldi & McKee (1990), in clouds experiencing photoevaporation a velocity gradient will eventually emerge, leading to a configuration where the head of a pillar moves more slowly than its tail. Applying this to the Eagle nebula (M16), Pound (1998) points out that the measured radial velocity gradients depend on our viewing angle and provide clues about the three-dimensional structure of the nebular features with respect to the ionizing stars. The tail of a pillar located in front of the ionizing stars will then have lower radial velocities than the pillar’s head, since the tail is being blown toward the observer (while the opposite radial velocity gradient would be observed across a pillar located behind the ionizing OB stars). Both Nünberger et al. (2002) and Röllig et al. (2011) found that the radial velocity in the head of MM1 is larger than that of the tail. Thus in NGC 3603 we have a configuration where the pillar is located in front of the stars of the HD 97950 cluster as seen from our position, with some tilt with respect to the light of sight.

The RMS of MM1 and MM2 have a high $E(B - V)_g$ of ~1.8 mag, implying a large amount of dust. Along the pillar’s main body, though, the color excess is lower than at the rim (~1.5 mag) owing to “limb brightening” effects. We explain this phenomenon in a cartoon in Figure 5. The pillar is represented by a cylinder whose density decreases from the head to the tail.
The empirical relation (Equation (2)) of Seward (1999):  

\[ \log_{10}(N_{H}) = 22.8 \]

within the cloud. The heads of these pillars may experience ionizing radiation emitted by a massive star can enhance the ionized layer (Figure 5), the color excess measured in the pillar of the long path traveled by the light emitted in A and B of the filament. Because the interior is largely shielded and mostly neutral. Because the column density at the rims, the central H_2 column density of the pillar, \( \log_{10}(N_{H}) \), may be as high as about 22.7–23 according to Mackey & Lim (2010), which agrees with the column density of MM1 and MM2 (\( \log_{10}(N_{H}) = 22.6–23 \)) as derived by Nürnberg et al. (2002).

This value is consistent with the H_2 column density of bright-rimmed clouds (BRCs) undergoing star formation. Urquhart et al. (2009) studied a number of BRCs, which are isolated molecular clouds located on the edges of evolved H ii regions. Some BRCs show evidence of significant interaction between their molecular gas with the ionizing radiation coming from the near by H ii regions. These BRCs are thus comparable in their properties to the ionized heads of molecular clouds. They have been found to host star formation activity, most likely triggered by the ionizing front coming from the nearby H ii regions. The column density of molecular hydrogen in BRCs with triggered star formation is 20.9 ≤ \( \log_{10}(N_{H}) \) ≤ 22.8 (Urquhart et al. 2009).

The similarity in \( \log_{10}(N_{H}) \) between star-forming BRCs and the pillars in NGC 3603 suggests that the heads of MM1 and MM2 may be sites of star formation. Indeed Caswell et al. (1989) and De Pree et al. (1999) found methanol and water maser sources in the heads of both MM1 and MM2; these sources are the typical signatures of newborn stars obscured by dusty molecular envelopes. The star formation in the pillars is likely triggered by photoionization-induced shocks due to the expansion of the H ii region in which the HD 97950 cluster resides. The strong Heii and Pas emission in heads of MM1 and MM2 is another indication that the OB stars in the HD 97950 cluster are ionizing the pillars. The ionization shock fronts were detected at mid-infrared wavelengths by Nürnberg & Stanke (2003).

4. SUMMARY

In the present paper, we extend previous studies of the differential reddening around the young star cluster HD 97950 in the NGC 3603 giant H ii region (e.g., Sung & Bessell 2004). We derive a two-dimensional map of the color excess of the gas around the cluster from HST/WFC3 images, which allows us to measure the Heii/ Pas flux ratio and its decrement due to dust extinction (see Calzetti et al. 1996). Our reddening map covers an area of 4.9 pc × 4.3 pc with a scale of 0.004 pc pixel \(^{-1}\) (assuming that NGC 3603 is at a distance of 6.9 kpc). The median value of the color excess within the central cavity (\( r < 1 \) pc, where the HD 97950 cluster resides) is \( E(B-V)_{g} = 1.51 \pm 0.04 \) mag. Going from the cavity to either the northern or the southern edge of the field of view, \( E(B-V)_{g} \) is seen to increase from 1.5 mag to 2.2 mag at a distance of 2 pc from the cluster. From the cluster toward either the eastern or western edge of the field of view (at a distance of 2 pc), \( E(B-V)_{g} \) rises from 1.5 mag to 1.6 mag. The average uncertainty of the derived color excess is about 0.1 mag.

We find a shell structure 1.2 pc west of the cluster with a mean \( E(B-V)_{g} \) of 1.59 mag, about 0.08 dex higher than in the central cavity. We interpret this shell structure as the surface at which the expanding gas shell detected by Clayton (1986) in the north–south direction interacts with a denser molecular cloud.

The ionizing radiation emitted by the OB stars in the HD 97950 cluster is likely to be responsible for the formation of the two molecular pillars MM1 and MM2 seen 1.2–2.5 pc southwest and southeast of the cluster, respectively. We use our
reddening map to estimate the column density of H$_2$ in MM1 and MM2. We derive log$_{10}(N_{H_2}) = 21.7$ in the pillars’ rims and up to log$_{10}(N_{H_2}) = 23$ in the pillars’ center, in agreement with the earlier estimates by Nürnberg & Stanke (2003). Based on the velocity gradient detected in earlier studies, we argue that the pillars are closer to us than the ionizing HD 97950 cluster.

The strong H$_\alpha$ and Pa$\beta$ emission in the heads of the pillars MM1 and MM2 traces the ionization of the pillar heads by the OB stars in the HD 97950 cluster. The pillar heads appear to be undergoing star formation as indicated by the presence of methanol and water maser sources (Caswell et al. 1989; De Pree et al. 1999). Such a star formation activity is likely triggered by photoionization-induced shocks due to the expansion of the H II region surrounding the HD 97950 cluster.

The two-dimensional map of $E(B-V)_g$ derived in this work paves the way to deredden individual stars in the same field of view by providing an upper limit to the true stellar reddening. Individual reddening corrections in regions suffering substantial differential reddening are essential for analyses of stellar photometry, e.g., for constraining the age spread in the HD 97950 cluster and its surroundings.

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