ANALYSIS OF SPATIAL STRUCTURE OF THE SPICA H II REGION

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ABSTRACT

Far ultraviolet (FUV) spectral images of the Spica H II region are first presented here for the Si II λ1533.4 and Al II λ1670.8 lines and then compared with the optical Hα image. The Hα and Si II images show enhanced emissions in the southern part of the H II region where H I density increases outward. This high density region, which we identify as part of the “interaction ring” of the Loop I superbubble and the Local Bubble, seems to bound the southern H II region. On the other hand, the observed profile of Al II shows a broad central peak, without much difference between the northern and southern parts, which we suspect results from multiple resonant scattering. The extended tails seen in the radial profiles of the FUV intensities suggest that the nebula may be embedded in a warm ionized gas. Simulation with a spectral synthesis code yields values of the Lyman continuum luminosity and the effective temperature of the central star similar to previous estimates with $10^{46.2}$ photons s$^{-1}$ and 26,000 K, respectively, but the density of the northern H II region, 0.22 cm$^{-3}$, is much smaller than previous estimates for the Hα brightest region.

Key words: H II regions -- ISM: individual objects (Spica) -- ultraviolet: ISM

1. INTRODUCTION

H II regions are generally located in the vicinity of OB stars because these hot stars can produce strong ultraviolet radiation, thereby photoionizing hydrogen atoms in the region. The energy balance between photoelectrons and forbidden line cooling sets the gas temperature to $\sim 10^{3.8}$ K in the H II region (Osterbrock 1989, p. 422). The structure of the H II region has been studied in terms of the Balmer recombination lines of hydrogen atoms, the observations of other optical forbidden lines (e.g., [S II] λ6716, [O II] λ3727; Peimbert et al. 1993; Peimbert 2003; Wang et al. 2004), and infrared fine-structure lines (e.g., [O III] 88 μm, [S II] 33 μm; Martín-Hernández et al. 2002). The theoretical advances have also been made by means of various photoionization models (e.g., Stasińska 1982; Ercole et al. 2003; Morisset et al. 2005). Our understanding of the H II region has been advanced considerably in recent times with the aid of the Wisconsin Hα Mapper (WHAM) data (Haffner et al. 2003). With a velocity resolution capability of 8–12 km s$^{-1}$, WHAM measured the Hα emission from warm ionized objects within $\sim 100$ km s$^{-1}$ of the Local Standard of Rest and provided the first large-scale Hα survey, covering three-quarters of the northern sky. The survey results show that enhancements can generally be seen near the planetary nebulae and H II regions surrounding massive O and early B-type stars; the results also confirm the presence of unidentified high galactic components (Reynolds et al. 2005).

The α Vir (Spica), one of the brightest stars at high galactic latitude, was found to be a double-lined spectroscopic binary with spectral types B1 V and B4 V (Herbison-Evans et al. 1971). The existence of an H II region around α Vir was suggested because the region appeared to be a hole in radio observations (Fejes 1974) and ultraviolet absorption lines were seen for the star of the nearby sightline (York & Kinahan 1979). Equipped with a Fabry–Perot spectrometer, Reynolds (1985) made Hα scans and revealed that the region was indeed ionized with a gas density of $\sim 0.6$ cm$^{-3}$. The hydrogen ionization rate of the whole H II region was estimated to be $\sim 10^{46.3}$ photons s$^{-1}$. The ratio of [S II] λ6716 to the Hα line, which signifies the contribution of collisional excitation with enhanced temperature, was also made for the Spica H II region (Spica Nebula). While the Spica Nebula is generally accepted to be a normal H II region, the ratio was found to be rather high (0.16 at the center and 0.21 at the edge) compared to those of other H II regions such as the Orion Nebula (Peimbert 2003; Peimbert & Torres-Peimbert 1977) and the Sharpless 261 (0.059, Hawley 1978), though its origin was not clearly identified (Reynolds 1988). Recently, the Spica Nebula was observed in the WHAM survey (Reynolds 2004), but no detailed study of this set of data has yet been published.

Si IV and C IV ion lines were detected in the far ultraviolet (FUV) absorption line study toward Spica, and their origin was ascribed to the Local Bubble (LB) surrounding the Sun (Savage & Wakker 2009). Being a photoionized H II region, the Spica Nebula may not be associated with these high-stage FUV lines, but it can still be a source of FUV emission from low-stage ions, especially in view of the high [S II] λ6716 to Hα line ratio. In this paper, we analyze the FUV Si II and Al II emission lines as well as the WHAM survey data to study the H II region around Spica. It should be noted that the ionization potentials of Si 2+ and Al 2+ are similar to that of hydrogen: 16.4 eV for Si 2+ and 18.8 eV for Al 2+. As the spatial structure of the Spica H II region was not explored previously and there have been no reports of the emission line study in the FUV wavelengths, we believe that the present study should provide useful information about the global morphology of the nebula. For the FUV study, we use the same data set as the one used for our previous analysis of Loop I superbubble (L1, Park et al. 2007); that data set was obtained from the Far-ultraviolet Imaging Spectrograph (FIMS) on the Korean microsatellite STSAT-1 (Edelstein et al. 2006). The FIMS is an instrument optimized for the measurement of diffuse FUV emissions with a large field of view (7$^\circ$ x 4.3$^\circ$) for the wavelength band of 1330–1720 Å. We also compare the observational results with the results of the Ferland et al. (1998) Cloudy photoionization model so that we can constrain the physical parameters associated with the H II region and α Vir itself.
2. OBSERVATIONS

In Figure 1, we plot spectra for the three distinct regions of the Spica Nebula: the core region within a 0:5 circle including the central point source, $\alpha$ Vir, in the top panel; the nebula region defined by a 0:5–8:0 circle (Reynolds 1985) in the middle panel; and the background of a 12° × 12° square outside the nebula bottom panel. The spectra were binned with 1 Å and smoothed with a boxcar whose width is 3 Å. For comparison, we also include in the top panel the spectrum for $\alpha$ Vir as observed by the International Ultraviolet Explorer (IUE).

As can be seen in the top panel, the prominent absorption lines of Si IV $\lambda\lambda$1393.8, 1402.8 in the IUE spectrum, which undoubtedly originated from the stellar atmosphere, appear as strong emission lines in the diffuse FIMS spectrum; these lines indicate the extended hot gas around the central star. Similar features can also be identified for Si II*, C IV doublet, and Al II. Moreover, the Si IV doublet and Al II lines become less prominent compared to the nebula region. Hence, only the Si II*, C IV doublet, and Al II may actually be the dominant emission lines in the nebula region as the C IV doublet seen in the middle panel could be contributed by the projected background.

We have constructed FUV spectral images of the Spica Nebula (radius of ~8°; Reynolds 1985), extended to 12° × 12° to include the nearby background medium. The Si II*, and Al II images were made by utilizing the HEALPix scheme (Górski et al. 2005) with a pixel resolution of ~0:92. The Si II*, and Al II lines were fitted with single Gaussian profiles in the spectral range 1520–1546 Å and 1658–1684 Å, respectively, for each pixel. The images were smoothed with a Gaussian function whose full width at half-maximum (FWHM) was 3°. The resulting signal-to-noise ratios for the bright features of the nebula are above 3.0 for both Si II* and Al II.

Figure 2 shows the final Si II* and Al II images taken from FIMS. It also displays the Hα image taken from Finkbeiner (2003) and the H I map taken from Kalberla et al. (2005). We designated $\alpha$ Vir in these images with an asterisk at (R.A., decl.) = (201°3, −11°2). The black circles with a radius of 8° correspond to 12 pc for a distance of 80 pc to $\alpha$ Vir; they indicate the region conventionally defined as the Spica Nebula (Reynolds 1985). First, we note that the Si II* image in Figure 2(a) shows an asymmetric feature with strong enhancement in the southern region below $\alpha$ Vir. The southern enhancement is also seen in the Hα map of Figure 2(c) and seems to be related to the high neutral hydrogen density shown in Figure 2(d). This asymmetric feature is less clear in the Al II map of Figure 2(b); it does not show much difference between the northern and southern parts though the image seems to extend from the round-shaped central peak to the northwest direction, where the emission of Hα is somewhat enhanced. In Figure 2(c), we overplotted the H I contours from 2.0 × 10^{20} cm^{-2} to 8.0 × 10^{20} cm^{-2} with 2.0 × 10^{20} cm^{-2} intervals: <2.0 × 10^{20} cm^{-2} generally corresponds to the northern region above $\alpha$ Vir, 2.0 × 10^{20} ~ 6.0 × 10^{20} cm^{-2} represents a band that passes through the southern H I region, and >6.0 × 10^{20} cm^{-2} represents the area below the Spica Nebula. In Figure 2(d), an H I cavity is seen in the vicinity of $\alpha$ Vir which is probably generated by the strong Lyman continuum from the star that causes almost all of the neutral hydrogen atoms to be ionized.

We constructed radial profiles of the Hα, Si II*, and Al II intensities for the Spica Nebula. Because the Hα and Si II* images show strong asymmetry, we made the northern and southern intensity profiles separately by averaging the intensity for the corresponding concentric semicircles of 1° bins up to 8°. We subtracted the background radiation in these profiles: 1.4 Rayleigh (R) for Hα, the average value of the galactic latitudes between 40° and 60° (Reynolds 1984), 0.03 R for Si II*, and 0.04 R for Al II where 1 R = 8.0 × 10^{19} photons cm^{-2} s^{-1} sr^{-1}. We also made extinction corrections by using the extinction curve given by Cardelli et al. (1989) though the corrections are not significant. With an assumed $E(B−V)$ value of 0.01 for the H I region, the extinction corrected intensities of Hα, Si II*, and Al II are, respectively, about 1.02, 1.08, and 1.07 times the observed intensities (Galazutdinov et al. 2008).

The top panel in Figure 3 shows the resulting profiles. The solid line represent the northern profiles and the dashed lines represent the southern profiles. The rather large error bars come from the significant spatial variation that still exists within each semicircle bin. As expected, in the Hα and Si II* intensities we see a marked difference between the northern and southern regions with a much slower decrease for the southern profiles; in contrast, the Al II intensity does not show a marked difference.
between the northern and southern profiles. The southern Hα profile even shows a flat region from 3 pc to 8 pc, which is undoubtedly due to the fact that the density increases with distance. The bottom panel in Figure 3 shows the model profiles obtained from a photoionization simulation and will be discussed in later section.

In Figure 4, we show a scatter plot of $N$(H) against the Hα intensity. A correlation is seen for $N$(H) below $6.0 \times 10^{20}$ cm$^{-2}$ and the 0.62 correlation coefficient confirms that the Hα enhancement in the southern Spica region can be attributed to that region’s high neutral hydrogen density. Hence, the Spica Nebula is ionization bounded in the southern region with an ionization front at $N$(H) = $6.0 \times 10^{20}$ cm$^{-2}$. The Hα intensity drops significantly to 1.6 R (log Hα = 0.2) for $N$(H) > $6.0 \times 10^{20}$ cm$^{-2}$ (log $N$(H) = 20.78), and the intensity drop implies that any H ionization photons that pass through this dense ambient medium are dissipated in the medium. It should be noted that the 1.6 R value that we obtained here is very similar to the average value (1.4 R) for the galactic latitudes between 40° and 60°, which were estimated by Reynolds (1984).

Figure 2. Spectral images of the Spica H ii region: (a) FIMS Si ii*, (b) FIMS Al ii, (c) WHAM Hα (Finkbeiner 2003), and (d) $N_H$ map (Kalberla et al. 2005). The large black circles of radius of 8° in panels (a)–(d) indicate the region conventionally defined as the Spica Nebula. The $N_H$ contours are overlaid in panel (c). Note: LU = photons s$^{-1}$ cm$^{-2}$ sr$^{-1}$.

Figure 3. Radial profiles of the Hα, Al ii, and Si ii* for the Spica Nebula. Top panel shows the observed profiles with 1σ error bars for the northern (solid lines) and southern (dashed lines) regions. The results of the spectral synthesis models for the corresponding northern and southern regions are shown in the bottom panel.
to increase outward. As our goal was to study the general trends
southern profiles. Figure 4. \(N(H\alpha)\) is plotted against \(H\alpha\) in the logarithmic scale for the Spica Nebula region 8'. Correlation is seen for \(N(H\alpha)\) below \(6.0 \times 10^{20}\ \text{cm}^{-2}\) (marked as a black horizontal line). These data points represent the correlation coefficient of 0.62.

3. DISCUSSION

The observed intensity profiles of the northern and southern H\(\alpha\) regions shown in the top panel of Figure 3 are compared with model calculations for the corresponding regions. When we ran the photoionization simulation code Cloudy, we varied the Lyman continuum luminosity, \(Q(H)\), the effective temperature of the central star, and the density of the ambient medium. The simulation was performed for a spherically symmetric nebula by using the stellar atmospheric model of Castelli & Kurucz (2004) and by assuming the B star abundance reported by Kilian-Montenbruck et al. (1994) and Sembach et al. (2000). We obtained the volume emissivity as a function of the radius and calculated the intensity toward a line of sight defined by the offset angle from the central star. Finally, we smoothed the profiles with a Gaussian function whose FWHM was 3\(^\circ\) for a direct comparison with the observations.

First, the calculation was performed for a constant density medium, corresponding to the northern region where density is more or less uniform. The results are shown as solid lines in the bottom panel of Figure 3. The model that best fits the northern \(H\alpha\) profile was obtained with \(Q(H) = 10^{46.2}\) photons \(s^{-1}\), effective temperature of 26,000 K, and density of 0.22 \(\text{cm}^{-3}\). The values of \(Q(H)\) and effective temperature are quite similar to previous estimates of \(10^{46.3}\) photons \(s^{-1}\) in Reynolds (1985) and 25,791 K in Kunzli et al. (1997), respectively. However, the density is much smaller than the result of 0.6 \(\text{cm}^{-3}\) estimated by Reynolds (1985), probably because the observation was made for the brightest portion of the nebula which is located in the central region. On the other hand, the model profiles of Si\(\alpha\)\(^+\) and Al\(\alpha\)\(\beta\) are quite different from the corresponding observed profiles, especially in the outer region beyond 3 pc, where the observed profiles show a much slower decrease with distance and have extended tails. In addition, the Al\(\alpha\)\(\beta\) model profile shows a much higher central peak intensity with a sharper decrease than the observed profile even inside 3 pc. These aspects will be discussed later, together with the results of the southern profiles.

Next, we modeled the southern region in which \(N(H\alpha)\) is seen to increase outward. As our goal was to study the general trends affected by the density gradient, not to reproduce the observed profiles exactly, we used the power-law model built in the code Cloudy, even though it may not represent the density profile accurately:

\[
n(r) = n_0 \left(\frac{r}{r_0}\right)^{-\alpha},
\]

where \(n_0\) is the density at \(r_0\), which was taken to be 0.3 pc. The best fit was obtained by matching the \(H\alpha\) profiles with fixed \(Q(H)\) and effective temperature from the simulation for the northern region. The resulting value is \(\alpha = -0.15\) (corresponding to a density of 0.38 \(\text{cm}^{-3}\) at \(r = 12\) pc), and the model profiles are shown as dashed lines in the bottom panel of Figure 3. The \(H\alpha\) fit looks more or less reasonable although the model shows a little higher central peak with a sharper decrease, which probably originates from the limits imposed by the power-law profile of the model. However, the most significant discrepancies seem to be in the Si\(\alpha\)\(^+\) and Al\(\alpha\)\(\beta\) profiles. For example, the model Si\(\alpha\)\(^+\) profile does not show such an enhancement as the one seen in the observed profile region between 2 pc and 8 pc, and does not respond to the outward density increase. The density gradient effect is not manifested in the Al\(\alpha\)\(\beta\) model result, either, with a profile very similar to that of the northern region. In fact, for Al\(\alpha\)\(\beta\), both the northern and southern observations look similar, with smaller central peaks and broader profiles than the models.

Hence, several discrepancies exist between the observation results and those of a simple photoionization model such as Cloudy. For example, the observed Si\(\alpha\)\(^+\) and Al\(\alpha\)\(\beta\) profiles show extended tails not reproduced by Cloudy. The observed Si\(\alpha\)\(^+\) profile shows the effect of the increasing density gradient in the southern region of the nebula while the model does not reproduce the feature. The observed Al\(\alpha\)\(\beta\) profile, compared to the model profile, is significantly broader with a much smaller central peak (about 25% of the model). In addition, the observed Al\(\alpha\)\(\beta\) profile does not respond to the density gradient. We would like to discuss these peculiar features here. First, we believe that the extended tails seen in the observed profiles are caused by the background of enhanced temperature. Figure 1 clearly shows the existence of the C\(\text{IV}\) doublet in the nebula regions as well as in the background, which can hardly be produced by photoionization in H\(\alpha\) regions. It should also be noted that Si\(\alpha\)\(^+\) and C\(\text{IV}\) ions were detected recently toward Spica (Savage & Wakker 2009). We will argue later that the Spica Nebula is located close to the interface between the L1 and LB, which contain hot gases. In addition to this background hot gas, the Spica Nebula may actually be embedded in a medium of enhanced temperature. The temperature profile obtained from our photoionization model for the southern region of the nebula shows a temperature drop from \(~5000\) K to \(~3000\) K with a change in distance from 1 pc to 4 pc, while it remains more or less at \(~5000\) K in the northern region. In this regard, it should be noted that the ratio of [Si\(\alpha\)] \(\lambda\lambda6716,6731\) to the \(H\alpha\) line was observed to be rather high in the Spica Nebula region with its value of 0.21 at (R.A., decl.) = (205\degree3, -11\degree1) (Reynolds 1988), as mentioned previously. Assuming the general line ratio of 1.3 for [Si\(\alpha\)] \(\lambda\lambda6716,6731\) (Chantot & Sivan 1983), the [Si\(\alpha\)] \(\lambda\lambda6716 + 6731/H\alpha\) is estimated to be 0.36. This value is rather high for a photoionized H\(\alpha\) region and actually resides between those of a general H\(\alpha\) region and a mixing layer of shocked gases (Lasker 1977). We suspect that the model Si\(\alpha\)\(^+\) profile would have been more responsive to the density increase if the ambient medium was assumed to be of enhanced
temperature, the situation which the present Cloudy model does not simulate.

The enhanced temperature may also cause broadening of the observed Al\textsc{ii} profile. However, the profile, both in the observation and in the model, does not show north–south asymmetry. Moreover, the observed central peak is much smaller than that expected from the model. We believe that this discrepancy originates from the multiple resonant scattering of Al\textsc{ii} in the nebula, which is not properly considered in the photoionization model Cloudy. The resonance lines, such as Al\textsc{ii}, undergo many resonant scattering events, resulting in a much longer random walk before they can escape the nebula. The numerous scatterings can yield a consequently higher probability of being absorbed by dust. While detailed calculation requires extensive scattering simulations which are not pursued here, a simple estimation would demonstrate the effect of increasing density in the southern region may also have become obscured out radially through random walks. The effect of increasing temperature, based on the fact that the observed emission profiles have long extended tails and they respond to the density increase in the southern region of the nebula, which is not explained by photoionization only.

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4. CONCLUSION

The H\alpha distribution as well as those of Si\textsc{ii} and Al\textsc{ii} obtained in the FUV wavelengths was analyzed for a 12'×12' sky around the Spica Nebula. The spatial variation, shown in both H\alpha and Si\textsc{ii} images, confirmed that the Spica Nebula is bounded by a high density H\textsc{i} shell in the southern region which we relate to the IntR of the L1 and the LB. We have also argued that the nebula is possibly embedded in a gas of enhanced temperature, based on the fact that the observed emission profiles have long extended tails and they respond to the density increase in the southern region of the nebula, which is not explained by photoionization only.

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