MODELING THE PHOTOIONIZED INTERFACE IN BLISTER H II REGIONS

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ABSTRACT

We present a grid of photoionization models for the emission from photoevaporative interfaces between the ionized gas and molecular cloud in blister H II regions. For the density profiles of the emitting gas in the models, we use a general power-law form calculated for photoionized, photoevaporative flows by Bertoldi. We find that the spatial emission-line profiles are dependent on the incident flux, the shape of the ionizing continuum, and the elemental abundances. In particular, we find that the peak emissivity of the [S II] and [N II] lines are more sensitive to the elemental abundances than are the total line intensities. The diagnostics obtained from the grid of models can be used in conjunction with high spatial resolution data to infer the properties of ionized interfaces in blister H II regions. As an example, we consider a location at the tip of an “elephant trunk” structure in M16 (the Eagle Nebula) and show how narrowband Hubble Space Telescope Wide Field Planetary Camera 2 (HST/WFPC2) images constrain the H II region properties. We present a photoionization model that explains the ionization structure and emission from the interface seen in these high spatial resolution data.

Subject headings: H II regions — ISM: general — ISM: individual (M16)

1. INTRODUCTION

A blister H II region is formed when a massive star is born near the edge of a molecular cloud. The radiation from the newborn star rapidly ionizes the surrounding material, and the ionization front breaks through the surface of the cloud, creating a cavity. The photoionized gas in the cavity is exposed to view and can be observed as a blister on the surface of the molecular cloud. The concept of a blister was introduced by Zuckerman (1973) to describe the Orion Nebula, one of the nearest and definitely the best studied H II region. The term “blister model” was introduced by Israel (1978), who studied a sample of about 30 galactic H II regions and, based on their positional relationship to CO-emitting molecular clouds, concluded that almost every optically observable H II region is a blister H II region.

Blister H II regions serve as useful probes of current interstellar abundances in the Galaxy, since the stars responsible for maintaining the ionization are less than about 10 million years old. Classical techniques of nebular analysis (described in several textbooks, such as Aller 1984 and Osterbrock 1989), based mainly on optical spectra, have been used to determine abundances in several H II regions and map abundances in the Galaxy (e.g., Hawley 1978; Shaver et al. 1983). These methods have two well-known uncertainties. First, lines from all the ionization stages of an element present in an H II region are usually not observed. This requires prescriptions in order to correct for unseen stages of one element based on ionic ratios of a different element. Second, temperatures derived from lines of one species (such as [O III]) are assumed when obtaining the abundance of another species (such as [S II]) that is formed in a different zone. These uncertainties are discussed by French & Grandi (1981).

An alternative method of determining abundances uses photoionization models to interpret H II region spectra. This approach has been applied in some detail to the Orion Nebula (Baldwin et al. 1991; Rubin et al. 1991) and has the advantage that the electron temperature and ionization structure are calculated self-consistently. Furthermore, it becomes unnecessary to implement ad hoc ionization correction schemes. However, a major limitation of this method (as emphasized by Rubin et al. 1998) is that the input density and geometry need to be specified in order to calculate models, and these in general are not well known.

In a blister H II region, the density profile of the interface between the molecular cloud and the ionized gas is determined by the ionizing radiation driving a photoevaporative flow off the surface of the molecular cloud. The sharply stratified ionization structure of this interface was observed in the Orion Nebula by Hester et al. (1991) in Hubble Space Telescope (HST) Wide Field Camera narrowband images. The ionization stratification was discussed, in the broader context of interpreting H II region spectra, by Hester (1991), who also suggested that most of the [S II] emission arises in a very narrow transition zone between the H II region interior and the photodissociation region of the molecular cloud. The transition zone occurs beyond the hydrogen ionization edge, where photons with energies higher than 10.4 eV (the ionization potential of S II) keep the sulphur singly ionized. More recently, Hester et al. (1996) presented HST Wide Field Planetary Camera 2 (WFPC2) images of the “elephant trunk” structures in the blister H II region M16. In these images, the photoionized interface is seen in tangency and the ionization stratification is clearly resolved. The [S II]-emitting zone is very narrow—it has a width of about $8 \times 10^{-5}$ cm ($<0.3$ at the assumed distance of 2000 pc). In that work, we used an empirical density profile derived from the Hz emission profile and presented a photoionization model that successfully reproduced the main features of the emission from the interface.

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In this paper, we use photoionization models in conjunction with high spatial resolution data to develop a framework for interpreting H II region spectra. Arbitrary assumptions about the density structure are not made, since the models are constrained by the structure observed in the high-resolution images. Once such a framework is established, it will be a powerful method for obtaining the physical properties of the emitting gas in H II regions.

We first present a grid of models for the interface in blister H II regions using the density profiles calculated by Bertoldi (1989) for photoionized, photoevaporative flows. These calculations are a significant improvement over earlier work because they allow for an ionization front of finite width, rather than treating it as a discontinuity, and they treat nonequilibrium ionization and energy deposition. We vary the incident stellar continuum, the ionizing flux, and the elemental abundances and examine the dependence of nebular properties on these input parameters. We focus on the diagnostics provided by spatially resolved line strengths (such as can be obtained by HST for several nearby H II regions). We then consider the M16 data in detail and present a photoionization model for the emission. We compare the model results with published spectra and show how knowledge of the structure of the emitting region is crucial for interpreting ground-based observations. We conclude with a summary and a consideration of the implications of our work and future directions.

2. PHOTOIONIZATION MODELS

2.1. Input Parameters

The basic input parameters for the photoionization models are the shape and intensity of the incident ionizing continuum and the elemental abundances. The interface between the molecular cloud and the H II region interior is the result of a photoevaporative flow driven by the incident stellar continuum (which is also responsible for ionizing the gas). The solutions for such a flow determine the density profile of the interface, which also needs to be specified.

Hydrodynamic models for photoionized, photoevaporative flows off spherical cloud surfaces have been calculated by Bertoldi (1989) and Bertoldi & Draine (1996). The form of the density profile they find may be written as follows:

$$n(x) = n_0 \left(1 + \frac{R - x}{r_c}\right)^{-2.5}.$$  

Here, $x$ is the distance from the ionizing source, $R$ is the distance from the source to the ionization edge, and $n_0$ is the number density at $x = R$. (Note that the density is a function of the distance from the interface, $R - x$ and that the actual distance from the source is not explicitly required in the models). The radius of curvature of the evaporating surface is given by $r_c$ and is effectively the scale length for the flow. The values of $R$ and $n_0$ depend on the ionizing continuum. For each of our models (see below), we start by performing a calculation with $R = 5 \times 10^{17}$ cm and $n_0 = 1500$ cm$^{-3}$ and then iterate using the predicted values at the ionization edge until we obtain the correct values. (We found that three iterations were sufficient in every case). We keep the value of $r_c$ fixed at $2 \times 10^{17}$ cm for all the models, anticipating our analysis of the M16 data in § 3.

The validity of using equation (1) for the density profile is subject to the following caveat. The models calculated by Bertoldi (1989) did not include the effects of dust on the flow. It was shown by Baldwin et al. (1991) that grains absorb, and are ionized by, the incident continuum and cause a radial acceleration of the gas away from the star. This phenomenon will affect the outer regions of the flow and alter the density profile. In order to assess the effect on the density profile at and near the interface (which we are concerned with here), the hydrodynamic and photoionization problem would have to be solved self-consistently, taking into account the presence of dust—a task beyond the scope of this paper.

We calculate a grid of 60 models, using all combinations drawn from four stellar atmospheres, three values for the ionizing flux, and five sets of elemental abundances. The stellar atmospheres used are PHOENIX models of B0 ($T_{\text{eff}} = 33,340$ K), O8 ($T_{\text{eff}} = 38,450$ K), O6 ($T_{\text{eff}} = 43,560$ K), and O4 ($T_{\text{eff}} = 48,670$ K) stars, all with gravities log $g = 3.9$ (Hauschildt, Baron, & Allard 1997; J. Aufdenberg 1998, private communication). PHOENIX models represent an advance over earlier model stellar atmospheres, since they use spherical geometry, calculate the strongest lines of important elements in non-LTE, and include line blanketing. In Figure 1 these model spectra are plotted, normalized to their respective peak values. Also shown on the plot are the ionization potentials of S$^0$ (10.36 eV) and O$^+$ (35.1 eV). The values used for the incident ionizing flux are $\log [\Phi(H)] = 10.5, 11.0$, and 11.5, where $\Phi(H)$ is the number of ionizing photons (energy $\geq 13.6$ eV) per second per square centimeter incident on the gas. In all the models, we keep the helium abundance at solar. The heavier element abundances are varied simultaneously and values of 0.2, 0.4, 0.6, 0.8, and 1.0 times solar (where solar values are taken from Grevesse & Anders 1989) are used in the grid of models. We use the publicly available code, CLOUDY (Ferland et al. 1998) to calculate the photoionization models.

One concern about the modeling procedure is that we are using an equilibrium code (CLOUDY) to model the emission from a photoevaporative flow where nonequilibrium
effects may be important. At the interface, the cooling times are short (a few tens of years) compared with the dynamic timescales (a few thousand years), so thermal equilibrium is a valid assumption. However, sufficiently close to the ionization front, photoionization equilibrium will not hold. The effect of nonequilibrium on the predicted emission lines was studied by Harrington (1977). He found that the ionization fraction differed only moderately between equilibrium and nonequilibrium models, and that that happened within about $10^{15}$ cm of the front. He also found that the line strengths most affected were [N i] $\lambda 5199$ and [O i] $\lambda 6300$, which varied about 40% and 15%, respectively. Both these lines are formed beyond, and are narrower than, the [S ii] zone. While it would be useful to examine the effect of photoionization nonequilibrium in detail for a wider range of conditions than was done by Harrington (1977), we expect our models to be suitable representation of reality.

2.2. Results

The photoionization models predict the highly stratified ionization structure of the interface. The H$\alpha$ more or less follows the density profile as expected. The [S ii] comes from a narrow zone near the interface that peaks sharply just beyond the Hz peak, in a region where the ionization fraction of hydrogen is rapidly falling and sulphur (whose ionization potential is lower than hydrogen) is kept singly ionized. The [O iii] emission profile is always less peaked and often quite extended compared with the Hz and [S ii]. While all models show these general characteristics of the low-ionization and high-ionization gas, there are significant differences in the details of the spatial profiles and line strengths among the various models. We now turn to a discussion of these differences and their dependence on input parameters.

In Figure 2 we show the density and the Hz, [S ii] $\lambda 6716, 6731$, and [O iii] $\lambda 5007$ emissivities as a function of distance from the interface for two models. Both models use an O6 star continuum and abundances of 0.6 solar for elements heavier than helium. The models differ in the incident ionizing fluxes: $\Phi_H = 10^{10.5}$ photons s$^{-1}$ cm$^{-2}$ (top panel) and $\Phi_H = 10^{11.5}$ photons s$^{-1}$ cm$^{-2}$ (bottom panel). The most dramatic difference between the two models is the density at the ionization front, which is about 3 times higher for the higher incident flux. Consequently, the peak Hz emission is higher by about a factor of 10 (since emissivity is proportional to the square of the density). This is a result of the ionization front being pushed into a cloud where the density increases toward the interior—a larger flux of ionizing photons will push the front farther up the density ramp. The [S ii] and [O iii] emissivities are also correspondingly higher.

In both plots of Figure 2, the origin of the x-axis is chosen to be at the peak of the [S ii] emission. We can see from these plots that the width of the [S ii] zone varies considerably with changes in the incident ionizing flux. If we define the width as being the distance at which the [S ii] emissivity falls to half its peak value, then the widths for the two cases shown are $11.2 \times 10^{15}$ cm for the lower ionizing flux (top panel) and $4.4 \times 10^{15}$ cm for the higher ionizing flux (bottom panel). At a distance of 1 kpc, these widths correspond to 0‘75 and 0‘29, respectively.

In Figure 3, models with different shapes for the incident continuum are shown. The top and bottom panels show models using O8 and O4 stellar atmospheres. Both models use an incident ionizing flux of $10^{11.0}$ photons s$^{-1}$ cm$^{-2}$ and metal abundances of 0.6 times solar. The [O iii] emission is higher by a factor of about 6 for the O4 model, while Hz and [S ii] are about the same. This is because the fraction of photons produced that are capable of ionizing oxygen to O$^+$ is much lower for O8 stars than for O4 stars (Fig. 1). Here again, the [S ii] profiles are significantly different. The O8 star produces an [S ii] zone that is $\sim 12.3 \times 10^{15}$ cm wide (top panel), and the hotter O4 star produces a narrower [S ii] zone ($\sim 6.4 \times 10^{15}$ cm).

The variation of emission profiles with abundance is shown in Figure 4. Both models use an O6 stellar atmosphere and an ionizing flux of $10^{11.0}$ photons s$^{-1}$ cm$^{-2}$. The models shown in the top and bottom panels have the abundances of all elements heavier than helium set to 0.2 times solar and 0.8 times solar, respectively. The Hz intensity is about the same in both cases, and the total [S ii] intensity is 1.6 times higher in the model with the higher abundance. The ratio of the peak [S ii] emissivity to the peak Hz emissivity shows a stronger contrast between the models. In the case of the low-abundance model, this ratio is 0.27, while for the high-abundance model it is 0.55, which is a factor of 2 higher.
2.2.1. Stellar Atmosphere Models

The spectral energy distribution of the incident ionizing continuum is a key ingredient in H II region models. Since the ionizing photons cannot be observed for any but a handful of stars, we depend on continua predicted by theoretically computed stellar atmospheres. In this paper we are using atmospheres calculated by the PHOENIX code, which treats the atmosphere as spherically symmetric, includes line blanketing, and treats the strongest lines of several important elements in non-LTE. These models are an improvement over the widely used ATLAS models (Kurucz 1991), which are plane-parallel and neglect non-LTE effects entirely.

Another set of theoretical non-LTE stellar atmospheres, the CoStar Models (Schaerer & de Koter 1997), have also been used recently in H II region models (Stasińska & Schaerer 1997). COSTAR and PHOENIX models differ in significant ways. COSTAR models include the effects of stellar winds on the emitted continuum, while the PHOENIX models are spherically extended but hydrostatic atmospheres. However, COSTAR models do not include line blanketing in the calculation of the temperature structure, whereas PHOENIX models include line blanketing in a self-consistent way in determining the temperature structure of the atmosphere. Furthermore, COSTAR models treat only H and He in non-LTE, while PHOENIX treats over 50,000 of the strongest lines of several elements in non-LTE. In this section, we examine the effect of using different model atmospheres on the predicted H II region photoionization model.

Figure 5 shows the spectral energy distributions of the PHOENIX O4V model ($T_\text{eff} = 48,670$ K) and the COSTAR E2 model ($T_\text{eff} = 48,500$ K). Also shown are the S$^0$ and O$^{++}$ ionization edges. The COSTAR spectrum is flatter and has a greater flux at higher energies than the PHOENIX spectrum. This effect is due to the wind and is seen in Stasińska & Schaerer (1997), where COSTAR and ATLAS spectra are compared. In order to understand the effects of using different stellar atmospheres on H II region spectra, we calculated a photoionization model using the COSTAR spectrum along with an incident ionizing flux of $10^{11.0}$ photons s$^{-1}$ cm$^{-2}$, and metal abundances of 0.6 times solar. In Figure 6 we compare this COSTAR model with a model using the PHOENIX O4V ionizing continuum with the same incident flux and abundances. The difference between these models is significant—the COSTAR continuum produces twice as much [O III] as the PHOENIX continuum. The COSTAR model also produces more [S II] and has a
somedwhat broader [S II] zone. The peak H\alpha is lower in the COSTAR model, so the peak [S II] to peak H\alpha ratio is higher by a factor of 2 compared with the PHOENIX model.

We wish to caution the reader that currently it is very uncertain as to which of these models (PHOENIX or COSTAR) is closer to reality. However, our comparison has shown that, in their current forms, the ionizing continua from PHOENIX and COSTAR predict very different H II region line strengths. A thorough understanding of H II region spectra can be of value in validating atmosphere models, as pointed out by Rubin, Kunze, & Yamamoto (1995). It is beyond the scope of this work to pursue this issue further, and for the rest of the paper we will discuss models using only PHOENIX stellar continua.

### 2.3. Diagnostics

The grid of models we have calculated predicts several quantities that could serve as useful starting points in analyzing spectra of blister H II regions, particularly for the cases in which the emitting interface is spatially resolved. We now present and discuss some of these diagnostics.

In most of the following plots, we will be visualizing the data in a somewhat specialized way, which is worth describing here. The quantity of interest is plotted on the y-axis. The x-axis is simply the model number (from 1 to 60, with the tick marks suppressed). The four large divisions in the plot correspond to stellar atmospheres used in the model (models 1 through 15 use a B0 atmosphere, and so on). Within each set of 15 models, groups of five (differentiated by the symbols used) correspond to different values for the ionizing flux. Finally, within each group of five, the heavy element abundances go from 0.2 solar to 1.0 solar in steps of 0.2 with increasing model number.

In the top panel of Figure 7, we show the maximum density reached in each model. This is the hydrogen density at the ionization edge defined (for convenience) to be the point where $n_e/n_H$ has fallen below 0.001. (We note, however, that the observed lines are not emitted so far into the photodissociation region—for instance, the [S II] peak occurs where $n_e \sim 0.7n_H$.) The density at the ionization edge depends strongly on the ionizing flux (for the reason mentioned in the previous section). There is, however, no dependence on the stellar temperature; (note that the four large divisions in the plot correspond to different ionizing stars). For higher incident flux, there is a noticeable dependence on the abundance. A higher abundance of metals implies that more atoms compete for the ionizing photons and the maximum density reached is lower. The peak H\alpha emission depends on the density at the ionization edge. The bottom panel of Figure 7 is a scatter plot of the peak H\alpha against the maximum density reached in the models. As expected, there is a strong correlation between the H\alpha peak emissivity and the maximum density. This in turn implies that the peak H\alpha emissivity is a good discriminant for the incident ionizing flux.

Next, we discuss the peak emissivities and total line intensities of three important diagnostic lines in H II regions: [O III] $\lambda$5007, [S II] $\lambda\lambda$6716, 6731, and [N II] $\lambda\lambda$6584. In what follows, all peak emissivities and total intensities are taken relative to H\alpha, and this is to be understood even if not explicitly mentioned. Note that the peak emissivity for different lines occurs at different locations.
Figure 7.—Top: Plot shows the densities at the ionization edge for the grid of models. Different symbols stand for models with different ionizing flux. The plot is divided into four broad regions along the x-axis, each with models using a particular stellar ionizing continuum. Within each group of five consecutive models, the abundance of metals heavier than helium varies from 0.2 to 1.0 in steps of 0.2 going from left to right. The strong dependence of maximum density reached on incident ionizing flux is clearly seen. (The organization of this plot is used for the plots shown in Figs. 8, 9, and 10). Bottom: Scatter plot of peak Hα emissivity vs. maximum density reached shows the strong correlation between these two quantities. The maximum density in turn is most sensitive to the ionizing flux.

Figure 8 shows plots of the peak [O III] emissivity (top panel) and the total [O III] intensity (bottom panel) for the grid of models. Both these quantities are most sensitive to the stellar type. [O III] λ5007 is a high-ionization line, and in spectra of H II regions it is an indicator of the hardness of the ionizing spectrum. For a given ionizing flux, either the peak [O III] emissivity or the total [O III] intensity could be used to distinguish the shape of the incident ionizing continuum. For models using a given star type and ionizing flux, the [O III] peak emissivity and intensities reach a maximum for abundances about 0.4 solar. The decrease in emission for lower abundances is simply because there is less oxygen. For higher abundances, the increased oxygen abundance leads to the [O III] 52 and 88 μm infrared lines dominating the cooling and lowering the electron temperature of the gas (see, e.g., Henry 1993). At lower temperatures the intensity of [O III], a collisionally excited line, decreases.

In contrast to [O III], the [S II] λλ6716, 6731 lines trace low-ionization gas. These [S II] lines are the only strong optical lines for any ionization stage of sulphur and therefore have been of great importance in estimating S abundances in nebulae. However, the dominant state of sulphur in most H II regions is S^{+ +}, and obtaining only the S^{+} abundance leads to large uncertainties in the total sulphur abundance estimates (e.g., Dennefeld & Stasińska 1983). In Figure 9 we show plots of the peak [S II] emissivity (top panel) and the total [S II] intensity (bottom panel) for the grid of models. (Note that the y-axis scales are different on the two plots). For models with the same ionizing continuum and flux, the peak [S II] emissivity is more sensitive than the total [S II] intensity to changes in abundance, at least for lower abundances. The sensitivity gets better when the ionizing continuum is from hotter stars (O4 and O6 in our grid). Conversely, the peak [S II] is less sensitive than the total [S II] intensity to the incident ionizing flux. (Both quantities decrease with increased ionizing flux). Therefore, with spatially resolved data for an H II region interface, the peak [S II] emissivity can be used to estimate the sulphur abundance.

The ionization potential of N^{0} is 14.5 eV, somewhat higher than that of hydrogen. In addition to direct ionization from the ground state, N^{0} in the excited 2D state can be ionized by photons below the Lyman limit, and in some
cases the latter may dominate the ionization balance and affect the [N II] emission lines. However, in all our models, the [N II] λ6584 emission arises between the [S II] zone and the [O III] zone and can be considered a tracer of intermediate ionization gas. The strength of this line is generally used to estimate the abundance of N^+ and, with the use of an ionization correction factor, the total nitrogen abundance as well (e.g., Mathis 1982). Figure 10 shows the peak [N II] emissivity (top panel) and the total [N II] intensity (bottom panel) for the grid of models. As was the case for [S II], these plots show that the peak [N II] is a more sensitive indicator of abundance than the total intensity. For models using O8, O6, and O4 stellar continua, the [N II] intensity decreases with increasing flux. Also, the [N II] intensity decreases for hotter ionizing stars. The reason is that in both these cases more nitrogen gets ionized to N^++ because of the larger number of energetic photons. However, the peak emissivity depends on the N^+ density in the zone in which the emission actually reaches its maximum. This ion density is proportional to the total density, which increases with increasing ionizing flux. The peak [N II] emissivity is therefore higher for greater ionizing flux and for hotter stars.

We have presented a grid of models and discussed the results and diagnostics obtained from them. We now consider the specific case of the blister H II region M16 as an example of how these model results can be applied.

### 3. THE BLISTER H II REGION M16

*HST/WFPC2 images of three elephant trunk structures in M16 have been presented and discussed in detail by Hester et al. (1996).* Figure 11 shows the planetary camera image of the head of the second column. The images have a resolution of 0.046, corresponding to a linear distance of 1.35 \times 10^{15} \text{ cm} at an assumed distance of 2000 pc (e.g., Hillenbrand et al. 1993). The Hα and [S II] images show the ionized interface between the opaque molecular cloud and the H II region. Striations in the Hα image are due to emission from the photoevaporated gas streaming away from the molecular cloud surface. The [O III] emission is much more extended than the Hα and [S II] emission. The ratio map of [S II] to Hα peaks around the edge of the column. While it may not be obvious from the image, the ratio along most of the interface is more or less uniform.

For our analysis and modeling, we will concentrate on the emission along a spatial cut across the interface at the...
tip of the column. The location is shown in the [S II] image in Figure 11. Line flux profiles were taken along the cut and averaged over a width of 5 pixels. Background intensities were subtracted off, and in addition the [O III] profile was smoothed to remove noise. We note that the background intensity is mainly due to the back wall of the cavity, with some contribution from the outer parts of the photoevaporative flow. Here we are concentrating on emission from a narrow region around the interface itself. Plots of the H\(_\alpha\), [S II], and [O III] intensity profiles are shown in Figure 12 (top panel). The intensities shown in these plots are reddening-corrected, taking \( E_{B-V} = 0.7 \) (Chini & Krügel 1983) and the ratio of total to selective extinction, \( R = 3.1 \), the standard value. For the photoionization model, we assume that the density profile for the emitting gas is given by equation (1), and from Figure 11, we find the radius of curvature, \( r_c \), to be \( 2 \times 10^{17} \) cm.

The peak H\(_\alpha\) surface brightness is about \( 5.5 \times 10^{-13} \) ergs s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\). From the observed geometry (see Fig. 11) we estimate that the path length through the emitting region lies between about \( 6.0 \times 10^{16} \) and \( 7.5 \times 10^{16} \) cm. These values give a peak H\(_\alpha\) emissivity lying between about \( 4 \times 10^{-18} \) and \( 5 \times 10^{-18} \) ergs s\(^{-1}\) cm\(^{-3}\). The conversion of observed to intrinsic flux depends on the extinction. For M16, Chini & Krügel (1983) have reported that \( R \) may be as high as 4.7 (rather than the standard value of 3.1 that we have so far assumed). In that case, the H\(_\alpha\) emissivity is much higher. Therefore, from Figure 7 we estimate that the observed H\(_\alpha\) emission requires the density at the interface \( n_H \geq 4000 \) cm\(^{-3}\) and correspondingly an incident ionizing flux \( \Phi_H > 10^{11.0} \) photons s\(^{-1}\) cm\(^{-2}\).

The observed [O III] emission is weak relative to the H\(_\alpha\) emission (Fig. 12, top panel). By integrating the observed profiles out to a distance of about \( 2 \times 10^{17} \) cm, we estimate...
that the total \([O\ III]\) intensity is 0.7 times the H\(\alpha\) intensity. The ionizing flux from stars hotter than O6 or cooler than O8 cannot produce this ratio (Fig. 8, **bottom panel**). The ratio of the peak \([S\ II]\) emissivity to the peak H\(\alpha\) emissivity is between 0.2 and 0.3 (Fig. 12, **top panel**). From our diagnostic plot (Fig. 9, **top panel**), this implies a sulphur abundance lower than about 0.4 solar. Our grid of models uses abundance sets where all the elements heavier than helium vary in lock-step. This is a simplification. For modeling the interface in M16, we fixed all abundances (except for sulphur) based on the values reported by Hawley (1978), Shaver et al. (1983), and Dennefeld & Stasińska (1983). These values are helium solar; nitrogen 0.5 times solar; oxygen and the other metals 0.8 times solar. The sulphur abundance was allowed to vary.

The H\(\alpha\), \([S\ II]\), and \([O\ III]\) profiles, along with the density profile for our final M16 model, are presented in the bottom panel of Figure 12. The ionizing continuum used in the model is from an O7 Ia supergiant, with \(T_{\text{eff}} = 38720\) K, and the ionizing flux at the interface is \(3 \times 10^{11}\) photons s\(^{-1}\) cm\(^{-2}\). The sulphur abundance is 0.4 times solar. The photoionization model reproduces the observed emission from the interface, including the stratified ionization structure of the flow. In matching the model to the observation, we have assumed a plane-parallel geometry—clearly reality is more complex (indeed we have assumed a scale length for the flow based on the radius of curvature of the column). However, since we are concentrating on the emission from close to the interface, for our purposes the plane-parallel approximation is sufficient.

In Table 1 we present the observed (reddening-corrected) spectrum of M16 measured by Hawley (1978) along with the spectrum predicted by our final model. All intensities are given relative to H\(\alpha = 100\). The two observed spectra were taken along slits 2′4 by 4′0 separated by 35′′ along an east-west line in a region at the top of the first column of the HST image presented by Hester et al. (1996). The spectra at the observed positions vary significantly. \([S\ II]\) \(\lambda 6716, 6731\), for example, is higher by a factor of 4 at position 2. \([O\ III]\) \(\lambda 5007\), on the contrary, is lower by a factor of \(\frac{1}{2}\). Our model spectrum matches the position 1 spectrum rather well. The major exception is the \([O\ III]\) \(\lambda 3727\) line, where the mismatch may be due to a repositioning error since the \([O\ III]\) line was taken through a separate grating (see Hawley 1978). Another difference is in the ratio between the two \([S\ II]\) lines. Since the exact location of the observed spectrum is not known and since the observation and model pertain to two different regions (the first and second columns, respectively), the reason for the difference is not clear. The total strength of the two lines (relative to H\(\alpha\)) however, is reproduced by the model. It is well known that spectra vary within an H\(\Pi\) region. The significance here is that our model matches one of the spectra so well. This allows us to infer that the major reason for the differences in the two observed spectra are due to different orientations of the slit with respect to the highly stratified emitting interface.

### 4. CONCLUDING REMARKS

In this work, we have presented photoionization models for the emission from the photoevaporative interface between the ionized gas and the molecular cloud in blister H\(\Pi\) regions. The density profile of the interface is a power law that can be parameterized by the distance from the...
ionizing source to the ionization front and the density at the ionization front (Bertoldi & Draine 1996). The values of these parameters depend upon the shape and strength of the ionizing continuum.

From the grid of models, which have systematically varying input parameters, we find that the Hz peak emissivity is strongly dependent on the incident ionizing flux, increasing for higher values of flux. We also find that the [O III] emission is most sensitive to the type of star responsible for ionizing the interface. Stars cooler than O8 produce photoionized interfaces with virtually no [O III] emission. The low ionization [S II] emission is confined to a very sharp zone. We find that the peak [S II] emissivity is more sensitive than the total [S II] intensity to the sulphur abundance. The same holds true for the intermediate ionization [N II] line. It is worth noting that in the [S II] zone, the [S II] λλ6716, 6731 to Hz ratio can get relatively high (e.g., it is >0.5 for the model shown in the bottom panel of Fig. 3). Such high ratios are often considered to be a signature of shock-excited gas, but our models show that they can also occur in photoionized interfaces.

We then considered narrowband HST data of the blister H II region M16. The emission and ionization structure seen at high resolution was used to constrain the properties of the ionizing continuum and the sulphur abundance. We presented a specific model that reproduced the observations in detail. We found that the integrated spectrum predicted by the model matched one of two ground-based spectra taken by Hawley (1978) at a nearby location. These data also validate our photoionization models. Our being able to match the observed emission and ionization structure with these models is strong evidence that blister H II regions can be described by a photoionized, photoevaporative flow.

The method we have presented here is important for the study of H II regions, both in our Galaxy and in other galaxies. In the case of sufficiently nearby objects (such as M16), we can obtain spatially resolved spectra. Then, our current study indicates that we could use photoionization modeling to obtain elemental abundances without having to make assumptions about the structure of the emitting region. Carrying out such an exercise for a large sample of H II regions will be a crucial test for the applicability of the model for a range of conditions. We can apply our understanding of the emission from nearby H II regions to more distant H II regions (governed by the same physical mechanisms). Specifically, we can calculate photoionization models of photoevaporative flows in order to interpret spectra of these objects. One important class of distant emission nebulae that we may be able to study within this framework is the giant extragalactic H II regions (GEHRs).

It is promising that narrowband HST images of 30 Doradus, the nearest GEHR, show the optical emission concentrated in sharp photoevaporative interfaces, much as in M16 (Scowen et al. 1998). A direct application of our method to study the conditions in 30 Doradus would be an important step toward extrapolating to GEHRs in other galaxies.

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