THE CRAB NEBULA'S COMPOSITION AND PRECURSOR STAR MASS

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ABSTRACT

We present new photoionization calculations for investigating gaseous regions that represent potentially expected stages of nuclear processing in the Crab Nebula supernova remnant. From comparison of the theoretical models with recent, extensive emission-line measurements, most of the emitting gas appears to be nitrogen-poor and carbon-rich. These results suggest that the precursor star had an initial mass $\gtrsim 9.5 M_{\odot}$.

Key words: ISM: individual (Crab Nebula) – nuclear reactions, nucleosynthesis, abundances – supernovae: individual (SN1054) – supernova remnants

1. INTRODUCTION

The Crab Nebula (M1 = NGC 1952) is generally recognized as the remnant of the core-collapse supernova SN1054. Estimates of the precursor star's initial mass have been in the range $8-12 M_{\odot}$ (see Davidson & Fesen 1985 and references therein). The visible remnant contains at least $1-2 M_{\odot}$ of He-rich lineemitting gas (MacAlpine & Uomoto 1991),¹ the neutron star probably has about $1.4 M_{\odot}$, and the outer layers of the precursor may have left in a presupernova wind (Nomoto et al. 1982) or a shockwave (e.g., Chevalier 1977; Davidson & Fesen 1985).

Knowledge of the chemical composition of the remnant is vitally important for a better understanding of the precursor star's initial mass and associated details of the core-collapse event. According to Nomoto et al. (1982), an 8–9.5 M_{\odot} star would likely have undergone an O-Ne-Mg core collapse following electron capture, whereas a star more massive than $9.5 M_{\odot}$ would have developed an Fe-rich core. A distinguishing factor between these two possible scenarios would be the nebular carbon abundance. As pointed out by Nomoto (1985), for a precursor with initial mass less than about 9.5 M_{\odot} , high N and low C mass fractions (compared with solar) would exist from CNO-cycle processing of the He-rich gas. However, for precursor mass > 9.5 M_{\odot} , helium burning and nitrogen processing via ${}^{14}N(\alpha,\gamma){}^{18}F(\beta^{-}\nu){}^{18}O(\alpha,\gamma){}^{22}Ne$ ought to have produced high C and low N. In addition, models for a roughly $10 M_{\odot}$ precursor (Woosley et al. 1980; Woosley & Weaver 1986) have suggested the existence of off-center neon and oxygen flashes just prior to the core collapse, whereas such events may not be expected in lower-mass stars (Hillebrandt et al. 1984; Nomoto 1984).

Useful chemical composition information should be obtainable. Because of its young age and location roughly 180 pc from the Galactic plane, the Crab Nebula is relatively uncontaminated by interstellar material. In addition, measured temperatures indicate that its line-emitting gas is ionized and heated primarily by locally generated synchrotron radiation (rather than shock heating), so the ionization and thermal and chemical characteristics of the gas can be accurately analyzed using self-consistent numerical photoionization codes.

Although there has been a long history of observational and theoretical investigations aimed at understanding abundances in the Crab Nebula, to some extent the results have been inconclusive or contradictory. As summarized by Henry (1986), Henry & MacAlpine (1982) and Pequignot & Dennefeld (1983) compared measured line-intensity data available at the time with detailed photoionization calculations. In both studies, the deduced C and N mass fractions were roughly solar or below, but there were problems with interpretation of near-infrared (NIR) [C1] $\lambda\lambda 9823, 9850$ emission lines (see below). Davidson et al. (1982) and Blair et al. (1992) also obtained satellite observations of the ultraviolet C IV λ 1549 and [C III] λ 1908 lines for certain locations, and they concluded no definitive evidence for a carbon excess, although both studies left open the possibility. More recently, using extensive long-slit spectroscopy covering much of the nebula, MacAlpine et al. (1996) deduced high nitrogen mass fractions in some filaments and also high abundances for products of oxygen burning, such as sulfur (S) and argon (Ar), at other locations. All of the above results, taken together, have generally been interpreted as suggestive of a precursor in the 8–9.5 M_{\odot} range, although high sulfur and argon abundances would appear to argue for a more massive star.

In this paper, we report on the results of new photoionization computations (summarized by MacAlpine et al. 2007b), which were developed in combination with new line-intensity measurements extending to 1 μ m (MacAlpine et al. 2007a, hereinafter Paper 1). These analyses suggest that strong [N II] $\lambda\lambda$ 6548, 6583 emission lines measured at many locations by MacAlpine et al. (1996, 2007a) do *not* necessarily imply high nitrogen abundances, while strong measured [C I] λ 9850 emission *can* be interpreted as indicative of high carbon mass fractions. In addition, high mass fractions for S and Ar in some locations are confirmed. The results argue *consistently* for a precursor star initial mass $\gtrsim 9.5 M_{\odot}$.

2. PHOTOIONIZATION COMPUTATIONS AND NUCLEAR PROCESSING REGIONS

Photoionization models were produced using the numerical code Cloudy, version 06.02 (described by Ferland et al. 1998). Guided by line-intensity measurements and correlations in Paper 1, we developed plane-parallel computations for a range of physical conditions and chemical abundances in efforts to

¹ Fesen et al. (1997) used global line photometry to infer a higher nebular mass of ionized and neutral material (along with dense clumps), approaching that once postulated by MacAlpine et al. (1989). However, as discussed by MacAlpine & Uomoto (1991), large spatial variations in the He/H ratio can cause spuriously large mass estimates based on global line photometry. Emitting-gas estimates should take into account spatially resolved line photometry in order to allow for the effects of helium abundance variations on N(S)/N(H), which is used along with [S II] line intensities to estimate the amount of neutral gas present.



Figure 1. Correlation between H α -normalized [NII] λ 6583 and [SII] λ 6731 measured line intensities from Figure 4 of Paper 1. Investigated "gas domains" are indicated.

investigate gaseous regions that may represent expected stages of nuclear processing for potentially relevant stellar models (e.g., Woosley & Weaver 1995). As emphasized by Davidson (1973), cylindrical or spherical geometric configurations may provide a more realistic representation of Crab Nebula "filaments" immersed within a synchrotron radiation field. We will first examine models that are reproducible with the Cloudy code and then consider potential geometric effects toward the end of this paper.

Three potential nuclear processing "domains" were initially postulated from the observations in Paper 1. Figure 1 (reproduced from Figure 4 of Paper 1) shows the correlation between measured, H α -normalized, reddening-corrected [N II] λ 6583 and [S II] λ 6731 line intensities for 180 widely distributed nebular locations. It was suggested in Paper 1 that the strongest nitrogen emission may represent gas that has progressed no further than the CNO cycle, whereas the apparent majority of measurements (e.g., with normalized [N II] λ 6583 over the range 1–2.5) could represent material in which some helium burning has taken place and nitrogen has been converted into neon. The strongest sulfur emission was postulated to represent more advanced processing through oxygen burning. In this paper, the above will be called nuclear-processing "Domains 1, 2, and 3," respectively; and they are illustrated with bounding lines and labels in Figure 1.

2.1. Domain 2 (Helium Burning and Nitrogen Depletion)

We begin by discussing details of our analysis for Domain 2, because it involves the most prevalent nebular gas. In addition, the relevant photoionization models also help us to understand the other domains.

First, we developed a representative "median observed spectrum" for Domain 2. This involved a subset of 19 spectra for which we have both optical and NIR measurements (see Paper 1) and for which the H α -normalized [NII] λ 6583 emission lies in the range 1–2.5. For each emission-line



Figure 2. Domain 2 hydrogen and helium ionization fractions as a function of the distance into a cloud.

measurement, we identified a median value and combined those, as given in Table 1. Then we adjusted photoionization model input parameters and chemical abundances in order to obtain a satisfactory fit to the observed median data.

Following considerable experimentation, all models presented here employ the ionizing synchrotron radiation spectrum given by Davidson & Fesen (1985), with added points across the unobserved ultraviolet range as suggested in the documentation that accompanies the Cloudy code. In addition, we employed a constant hydrogen density of 3000 cm⁻³ and log ionization parameter = -3.2. The ionization parameter is defined as $U = \Phi/cN$, where Φ is the flux of photons more energetic than 1 ryd striking the face of a cloud, c is the speed of light, and N is the total density of hydrogen. The ionizing spectrum did a good job of producing typically observed HeII/HeI line ratios (e.g., MacAlpine et al. 1989), the adopted hydrogen density led to calculated electron densities in S⁺ zones comparable with those measured by Davidson (1979) and Fesen & Kirshner (1982), and the $\log U$ value was necessary to obtain a consistent overall emission-line spectrum that matches the observations, in particular the [S III] λ 9069/[S II] λ 6731 ratio.

The ionization parameter employed here is almost a factor of 10 lower than that which is necessary to account for observed ultraviolet C IV and [C III] lines (see Davidson et al. 1982; Blair et al. 1992). Henry & MacAlpine (1982) noted similar ionization parameter differences when comparing photoionization calculations that could match optical and ultraviolet observations separately. We do not consider this to be a problem. As discussed by Davidson (1978), Davidson et al. (1982), and Blair et al. (1992), much of the ultraviolet line emission probably comes from lower density, more diffuse gas, compared with the gas in bright optical-line-emitting filaments analyzed here.

For our Domain 2 model, the derived helium abundance was 89% by mass fraction, consistent with some stellar model expectations (Woosley & Weaver 1995) for a region with partial helium burning and also with numerous observations of He I λ 5876 emission (e.g., Uomoto & MacAlpine 1987; MacAlpine et al. 1989; Paper 1).

Figure 2 presents the computed Domain 2 hydrogen and helium ionization fractions as a function of depth into an emittinggas cloud, with ionizing radiation entering from the left. We note that the He²⁺ and He⁺ zones do not extend far into the cloud. Because of the high helium abundance, ionizing photons more

 Table 1

 Measured and Computed Line Intensities^a

Domain 3	
mputed	
0.25	
0.44	
0.52	
3.6	
0.35	
0.90	
0.70	

Note. ^a Normalized to H α .



Figure 3. Domain 2 temperature (K) and electron density (cm^{-3}) as a function of the distance into a cloud.



Figure 4. Domain 2 carbon and nitrogen ionization fractions as a function of the distance into a cloud.

energetic than 54.4 eV (the ionization potential of He⁺) and 24.6 eV (the ionization potential of He⁰) are absorbed before they can penetrate a substantial distance. The hydrogen-ionized depth is about 10^{16} cm, which is consistent with observations for Crab Nebula filaments (see Davidson & Fesen 1985).

Figure 3 shows the computed electron temperature and density, plotted as a function of the distance into the cloud. The electron density is roughly 8000 cm⁻³ where helium is ionized, drops to 3000 cm⁻³ through the H⁺ zone, and then falls to 400–800 cm⁻³. The temperature peaks near 1.2×10^4 K, is



Figure 5. Expanded view of carbon and nitrogen ionization fractions below the value 0.1 on the vertical axis of Figure 4.

about $6-8 \times 10^3$ K through the H⁺ zone, and then remains above about 6000 K to the depth plotted.

Figure 4 gives the modeled carbon and nitrogen ionization. Because the C⁺ ionization potential is comparable with that for He⁰, and the C⁰ ionization potential is below that for H⁰, the dominant ionization stage for carbon is C⁺, all the way from the He⁺ zone to where the calculations were stopped at a depth of approximately seven times the hydrogen ionization zone thickness. In addition, because the N⁺ and N⁰ ionization potentials are slightly above those for He⁰ and H⁰, respectively, N⁺ occupies an extensive, very proficient "[N II] emitting zone" along with the neutral helium and ionized hydrogen, in which the temperature and electron density effectively support collisional excitation.

Figure 5 presents an expanded view of the lower 10% of the vertical scale from Figure 4. This illustrates how a relatively small, but significant amount of C^0 exists in the zones where helium and hydrogen are ionized. Progressing from left to right in the figure, there is a small peak in the C^0 fraction where the electron density is highest due to ionized helium. Then there is a gradual C^0 increase as the temperature declines, and finally there is essentially no C^0 beyond the hydrogen ionization edge where the electron density becomes very low. These distribution characteristics for C^0 are consistent with what would be expected from $C^+ \rightarrow C^0$ recombination.

Figure 6 shows selected, computed line emissivities for this model, as a function of depth into the cloud. First, we note that $[N II] \lambda 6583$ is "off the chart" because of electron collisional excitation in the warm, high-electron-density [N II]emitting zone discussed above. HI $\lambda 6563$ illustrates what would be expected from recombination, and $[C I] \lambda 9850$ shows a



Figure 6. Selected Domain 2 line emissivities as a function of the distance into a cloud.

similar distribution since it results from $C^+ \rightarrow C^0$ recombination followed by electron collisional excitation. The [O I] $\lambda 6300$ line arises from collisional excitation of O^0 , and it is primarily important in the neutral hydrogen region because of charge exchange processes between hydrogen and oxygen.

Previously, high nitrogen mass fractions for many locations were deduced from observations of strong [N II] $\lambda\lambda$ 6548, 6583 emission and models using the Cloudy code in MacAlpine et al. (1996). However, those models did not adequately take into account high helium abundance and its effect on broadening the [N II] emitting zone. The helium mass fraction over most of the nebula ranges from about 75% to greater than 90% (Uomoto & MacAlpine 1987). For such helium-rich regions, strong [N II] lines would *not* necessarily imply nitrogen mass fractions greater than solar.

It has been known for decades that $[C_I] \lambda 9850$ emission is very strong in parts of the Crab Nebula (Dennefeld & Andrillat 1981; Henry et al. 1984). Pequignot & Dennefeld (1983) tried to match the observed strengths of this line by postulating a high dielectronic recombination rate, and Henry et al. (1984) postulated that collisional excitation by H⁰ could play an important role. Neither group was successful in using $[C_1] \lambda 9850$ for reliable carbon abundance estimates. Therefore, difficult measurements of the ultraviolet [CIII] and C IV emission were attempted, as noted previously. However, production of those lines may not be well understood either, in the sense that model predictions can be wrong by as much as a factor of 2 depending on how He II L α absorption is treated (Eastman et al. 1985). In the present calculations, we do understand the production of modeled [C1] λ 9850 emission as being due to thermal electron collisional excitation. This ${}^{1}D_{2} \rightarrow {}^{3}P_{2}$ transition is an analog of the [O III] λ 5007 line. Making use of modeled ionization fractions, electron densities, temperatures, and the relevant effective collision strengths given by Pequignot & Aldrovandi (1976), we manually calculated λ9850 emissivities at various locations and matched the modelcomputed emissivities exactly.

Predicted relative emission-line intensities from this model are shown in Table 1, where it may be seen that there is a reasonable match with the Domain 2 median spectrum for element mass fractions given in Table 2. The deduced Domain 2 nitrogen mass fraction is about a third of its solar value. We also note that the carbon mass fraction required to produce the observed median [C I] λ 9850 emission in Domain 2 is roughly six times solar, and the deduced oxygen mass fraction is close to

 Table 2

 Deduced Element Mass Fractions

Element	Mass Fraction		
	Domain 1	Domain 2	Domain 3
Helium	89%	89%	89%
Nitrogen	Solar	0.35 solar	0.28 solar
Carbon	0.50 solar ^a	$6 \times solar$	$11 \times solar$
Oxygen	Solar	Solar	$10 \times solar$
Sulfur	0.21 solar	0.28 solar	$4 \times solar$
Argon	0.24 solar	0.55 solar	$6 \times solar$

Note. ^a Assumed (see text).

solar. Finally, we note that the sulfur and argon mass fractions necessary to account for their observed, median emission lines are about a fourth and half of their solar values, respectively.

2.2. Domain 1 (Strongest Nitrogen Emission)

The most suitable photoionization calculations for our defined Domain 1 gas employed the same ionizing spectrum, hydrogen density, and ionization parameter as discussed above; and the model characteristics are similar to those in Figures 2–6. The median measured spectrum and computed line intensities are shown in Table 1. Measured H α -normalized [N II] λ 6583 values for Domain 1 range from 3.1 to 5.6, and the adopted median is 4.5. Unfortunately, the subset of NIR data with measured [C I] λ 9850 did not include any nebular locations for [N II] λ 6583/ H α > 2.5 (see Figure 10 of Paper 1). Therefore, no [S III] or [C I] line values are given for this domain in Table 1.

As may be seen in Table 2, the helium mass fraction required to match the observed He_I λ 5876 line is again taken to be 89% for Domain 1, which is reasonably consistent with expectations for a zone containing largely CNO-processed material. However, we note that the inferred nitrogen mass fraction is only solar, because [N II] λ 6583 arises so effectively in the [NII] emitting zone discussed above and illustrated in Figures 4 and 6. We could expect the nitrogen mass fraction to be several times solar for gas in which processing has ended with the CNO cycle, so this result suggests significant gas mixing or helium burning to match our Domain 1 median spectrum. The most extreme [NII] emission would imply a somewhat larger nitrogen mass fraction, but that would involve only a very small fraction of the overall nebular gas. The deduced Domain 1 oxygen mass fraction is solar, while the data suggest that sulfur and argon are significantly less than solar, even more so than in Domain 2. Because [C1] λ 9850 was not measured (suggesting weakness) in this domain, the carbon mass fraction input to the Domain 1 model was *assumed* to be 0.5 solar.

2.3. Domain 3 (Strongest Sulfur and Weak Nitrogen Emission)

Our defined Domain 3 for the [N II]:[S II] plane is illustrated in Figure 1. It involves extreme cases with measured [S II] $\lambda 6731/$ H α over the range 3–5.9 and with [N II] $\lambda 6583/$ H $\alpha < 1$.

The measured median spectrum and computed line intensities for Domain 3 are also shown in Table 1. The best-fit photoionization model was similar to that for Domains 1 and 2, except it was necessary in this case to lower the value of log U to -3.5to reproduce the measured [S III] λ 9069/[S II] λ 6731 ratio.

As seen in Table 2, the adopted helium mass fraction to match observed median He I λ 5876 is still 89% for Domain 3, which would seem to imply gas mixing for regions in which processing beyond helium burning has taken place. As expected, the nitrogen mass fraction is now well below solar. The deduced

carbon and oxygen mass fractions are both about ten times solar. We note that the [O I] λ 6300 line emissivity plotted in Figure 6 illustrates that it arises in a different region from [C I] λ 9850, so the inferred, correlated carbon and oxygen mass fractions are *not* the result of high-optical-depth regions in the emitting gas.

The sulfur mass fraction is roughly four times solar in this domain where it is hypothesized that oxygen burning has taken place. Further support for oxygen burning comes from the even higher inferred argon mass fraction in this domain, as well as from Figure 6 of Paper 1, which shows a very tight correlation between [Ar III] and [S II] emission, reinforcing the idea that sulfur and argon are produced together by the same process. Finally, a correlation shown in Figure 8 of Paper 1 is consistent with the related hypothesis that some iron-peak nuclei like nickel are produced by "alpha-rich freezeout" (see Woosley & Weaver 1995; Jordan et al. 2003) in Domain 3 regions that contain enhanced silicon-group elements from oxygen burning.

3. SUMMARY AND DISCUSSION

The photoionization calculations presented here, compared with emission-line measurements from Paper 1, are used to investigate three potentially expected nuclear processing "domains" for gas in the Crab Nebula.

Domain 1: Gas with the strongest [N II] lines ([N II] $\lambda 6583/$ H $\alpha > 3$) has roughly solar deduced nitrogen and oxygen mass fractions and significantly less-than-solar sulfur and argon mass fractions. This domain with 89% helium has been previously postulated as largely CNO-cycle-processed material. However, results of the current calculations suggest significant gas mixing or that some helium burning and nitrogen depletion have taken place even in these regions with exceptionally strong nitrogen emission.

Domain 2: A large fraction of the emitting nebular gas, with [N II] $\lambda 6583/H\alpha$ in the range 1–2.5, also has ~89% helium implied by its median observed spectrum. For this domain, the deduced nitrogen mass fraction is depleted to roughly a third of its solar value. In addition, the carbon mass fraction is about six times solar, while oxygen is solar, and sulfur and argon have approximately a fourth to half of their solar values. This domain probably represents gas in which significant helium burning has taken place.

Domain 3: The third domain defined and examined here has very high [S II] λ 6731 measured line intensities, along with weak [N II] lines. We find that the inferred helium mass fraction is still comparable with the other domains, and the nitrogen mass fraction is about a fourth of solar. The carbon and oxygen mass fractions are roughly ten times solar, while the sulfur and argon mass fractions are about four to six times solar. This is considered to be a domain in which oxygen burning has occurred and some mixing has also taken place.

Gas resulting from the CNO cycle and gas with products of oxygen burning were suggested previously (e.g., MacAlpine et al. 1996), where the former was assumed to be the primary component due to strong observed nitrogen emission throughout most of the nebula. However, the current computations indicate that strong [N II] $\lambda\lambda$ 6548, 6583 emission does *not* necessarily imply high nitrogen abundance, whereas strong [C I] $\lambda\lambda$ 9823, 9850 emission from much of the gas *does* imply high carbon abundance. Implications of solar or lower nitrogen mass fractions and higher-than-solar carbon mass fractions throughout most of the Crab Nebula gas are particularly significant because they suggest that the supernova precursor star had an initial mass $\gtrsim 9.5 M_{\odot}$.

3.1. Need for More [C I] Measurements

It is important that we consider whether the NIR emission-line measurements presented in Paper 1, and used here, may be biased toward high [C I] λ 9850 emission. As discussed in Paper 1, the NIR data were obtained during nonoptimal observation conditions, and [C1] measurements were made only where potentially useful [SIII] or [CI] line-emission could be identified in the two-dimensional, NIR spectral images. To investigate the possibility of consequent biasing, we compared the current measurements with [C1] $\lambda\lambda$ 9823, 9850 emission reported by Henry et al. (1984). The ranges of measured λ 9850 from that study and this one are comparable, with marginally lower and higher values in the larger data set used here. However, we still suspect that the current median spectrum for Domains 2 and 3 may be biased toward stronger [C1] in view of how the measured positions were selected. That having been said, we note that the primary reasons for the current suggestions of high carbon mass fractions are new photoionization calculations whereby we can derive potentially useful carbon abundances from the measured [C I] emission. Furthermore, even though our λ 9850 median values may bias the inferred carbon mass fractions for our domains, the individual measurements alone imply that carbon-rich gas exists at numerous locations in the nebula. In any case, a more extensive set of NIR spectra would be useful for understanding the overall nebular carbon.

3.2. Filament Geometry Considerations

Here we discuss the fact that the Cloudy photoionization code gave results for plane-parallel geometrical situations, whereas line-emitting gas in the Crab Nebula may be immersed in ionizing synchrotron radiation from all directions (see, e.g., Davidson 1973 and Figure 1 therein). We developed algorithms for converting the plane-parallel results to what would be expected for convex cylindrical and spherical clouds. For a computed plane-parallel model, the line emissivities (erg cm⁻³ s⁻¹) as a function of depth into the cloud were extracted. Then, considering the end point of the calculations (at greatest cloud depth) to be the central axis (or center) of a cylindrical (or spherical) configuration, the data were integrated outward, weighting by appropriately enhanced volume factors, in order to obtain total computed line emission (erg s^{-1}) for each geometry. Potentially noteworthy changes in Ha-normalized lines occurred for only [S II] $\lambda 6731$ and [O I] $\lambda 6300$ emission. In going from the plane-parallel to spherical geometry, the computed $\lambda 6731/H\alpha$ could be reduced by as much as 30%, and $\lambda 6300/H\alpha$ could be reduced by about 40%.

By employing convex cylindrical or spherical emitting clouds, we could increase the computed oxygen or sulfur mass fractions by perhaps as much as 30–40%. The deduced oxygen would still be roughly solar or higher in the various domains, and sulfur (as well as argon) would still be low in Domains 1 and 2. We note that Henry & MacAlpine (1982) also found lower-than-solar sulfur mass fractions for particular filaments.

Furthermore, because adopted ionization parameters for the photoionization calculations involved matching the observed [S III] λ 9069/[S II] λ 6731 ratio, an employed ionization parameter could be slightly lower for a convex spherical geometry. However, we investigated this possibility and found that it would probably not have a significant effect on the conclusions presented here. The most significant emission lines for supporting the primary conclusions of this investigation

are $[N II] \lambda 6583$ and $[C I] \lambda 9850$, both of which arise mainly within the ionized regions of the models and are not significantly affected by geometry. Therefore, we believe our primary conclusions that nitrogen abundances are *not* strongly enhanced and that carbon *is* enhanced throughout much of the Crab Nebula gas would not be changed by more elaborate geometrical considerations.

3.3. Possibility of Nonequilibrium in Low-Ionization Gas

The photoionization calculations employed here assume that the emitting gas is in ionization and thermal equilibrium. However, as first pointed out by Davidson & Tucker (1970), lowdensity emitting gas that has not had time to achieve equilibrium since the Crab Nebula formed may exist. This could impact the computation of some low-ionization lines produced in neutral gas. For the present calculations, the line with the greatest potential to be impacted is $[O_I] \lambda 6300$, which is produced in gas where recombination times can be about a sixth of the observed age of the nebula. All other relevant lines develop in gas with higher electron density. In particular, the [C I] and [N II] lines, which are of primary importance for the conclusions of this work, are produced within the hydrogen-ionized gas (see Figure 6) where recombination times are more like a thirtieth the age of the nebula and where the gas is likely to be in ionization equilibrium.

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