

DISTRIBUTION OF FORBIDDEN NEUTRAL CARBON EMISSION IN THE RING NEBULA (NGC 6720)¹

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ABSTRACT

The spatial distribution of [C I] 9823, 9850 Å emission in NGC 6720 is reported. Like [O I], the [C I] radiation appears enhanced in the region of the bright filaments. A few percent of the carbon atoms in the filaments are neutral. This neutral fraction is consistent with ionization equilibrium calculations made under the assumption of complete shielding of direct stellar radiation by hydrogen. The observed carbon lines are excited by photoelectrons produced from hydrogen by the nebular diffuse radiation field. The [C I] observations confirm that the filaments in NGC 6720 are regions of locally enhanced shielding.

Subject headings: nebulae: individual — nebulae: planetary

I. INTRODUCTION

Many planetary nebulae display emission lines from neutral atoms of low ionization potential which are considerably stronger than would be expected on the basis of standard ionization models. This fact is usually taken to indicate that some regions of the nebulae may be shielded from the ionizing UV radiation of the central star, thus permitting neutral atoms to survive against ionization (Capriotti, Cromwell, and Williams 1971; Van Blerkom and Arny 1972; Capriotti 1973). Low ionization potential neutral atoms such as O I show a patchy and knotted distribution suggesting inhomogeneous distribution of shielding material in the nebulae. The shielding might be provided either by high-density blobs of neutral hydrogen or by nebular dust particles.

However, evidence for the presence of shielded regions is not totally compelling. In particular, oxygen has a first ionization potential of 13.62 eV, only marginally different from the value for hydrogen, 13.60 eV. This, in addition to the presence of a strong charge exchange reaction with ionized hydrogen, can lead to the stability of O I at the edges of H II zones in planetary nebulae without the necessity of special shielding.

Carbon has a first ionization potential of 11.26 eV, considerably less than the values for oxygen and hydrogen. The charge exchange cross section is unknown but is expected to be relatively small. In the absence of shielding carbon atoms would be rapidly ionized by the

central star's UV radiation. Following an initial detection of [C I] in NGC 7027 by Danziger and Goad (1973), we have confirmed their result on that nebula and have searched for the 9823, 9850 Å ³P-¹D lines of [C I] in five other planetary nebulae. A map of the spatial distribution of [C I] in NGC 6720 is the main topic of this paper.

II. OBSERVATIONS

The observations were taken using the Palomar 1.5 m telescope on UT 1982 March 23 and 24, and the Hale 5.1 m telescope on UT 1982 March 31. The Space Telescope WF/PC Investigation Definition Team CCD and the "PFUEI" camera were used for all observations (Gunn and Westphal 1981). In its direct camera mode PFUEI was used to obtain high-resolution two-dimensional images through narrow bandpass interference filters. The image scale on the 800 × 800 pixel CCD chip was 0''.55 per 15 μm pixel at the Cassegrain focus of the 1.5 m telescope and 0''.42 per pixel at the prime focus of the 5.1 m telescope.

In its spectrographic mode PFUEI was used to obtain slit spectra in the range 6000-10000 Å. A grating blazed in the second order at 8100 Å was employed in conjunction with a 105'' × 2'' slit. The dispersion was approximately 8.6 Å per pixel. Spectrum lines had FWHM of 5.2 pixels corresponding to 45 Å.

The high quantum efficiency (0.7 at 7000 Å wavelength and 0.2 at 10000 Å) and the large dynamic range of the CCD were crucial to the success of the observations. It proved possible to simultaneously record spectrum lines having intensity ratios of several thousands. In addition, the long slit permitted seeing-limited spatial resolution in the direction perpendicular to the dispersion. This enabled crude maps of emission-line intensi-

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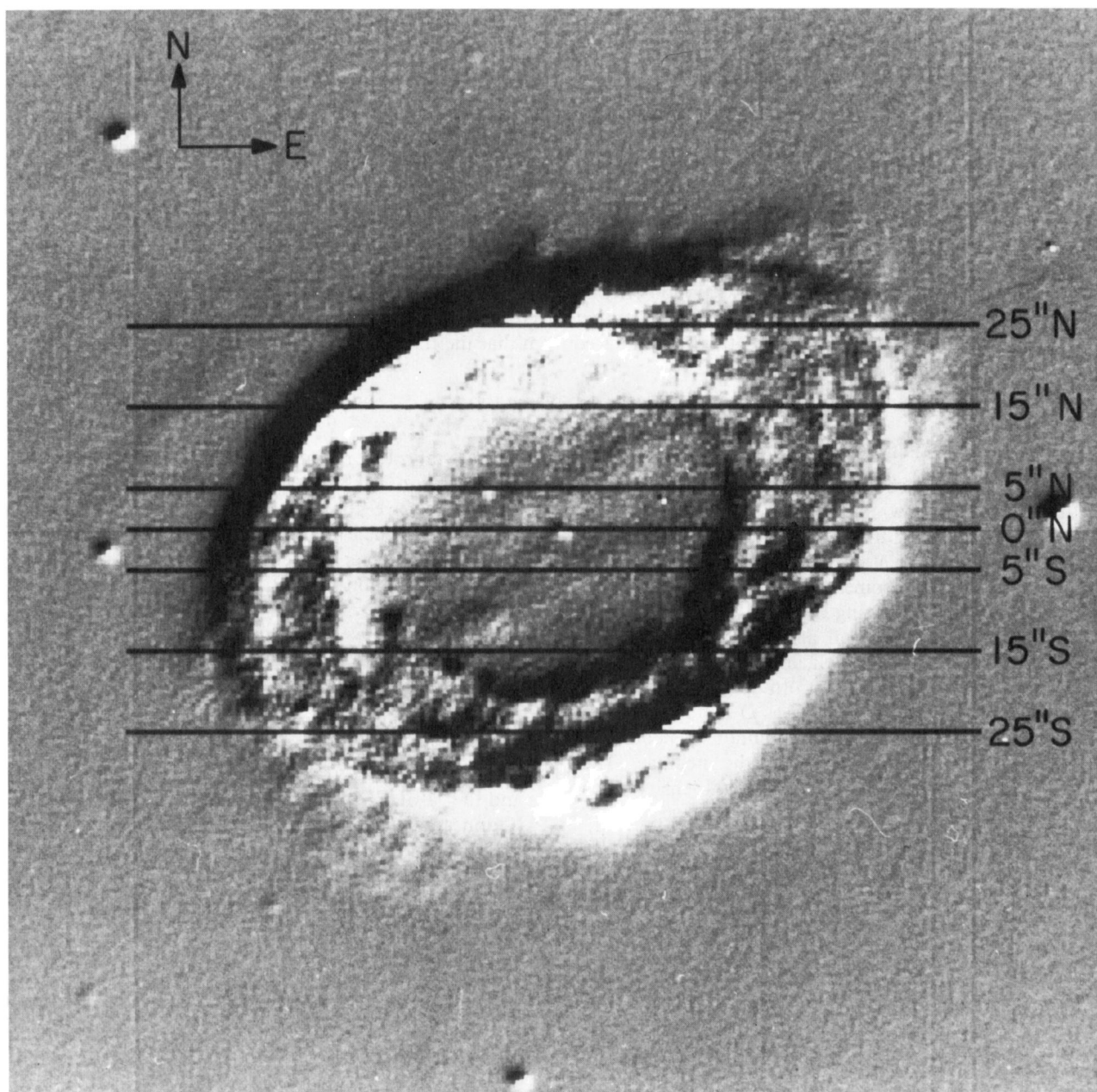


FIG. 1.—An image of the first spatial derivative of the surface brightness of NGC 6720. The derivative of the surface brightness has been computed with respect to distance along a line running from northwest to southeast in the plane of the sky. Most of the light comes from $H\alpha$ (6563 Å) but some is from $[N\ II]$ (6548, 6588 Å). The seven slit positions used to obtain Fig. 2 are shown. The image emphasizes the long sharp filaments in the main ring.

ties to be constructed by taking data at several slit positions. The long slit also allowed the simultaneous recording of pure night sky emissions from the regions where it projected outside the nebula.

To facilitate data reduction, erase (zero exposure) and flat-field frames were recorded intermittently during the observing periods. These were used to remove the effects of zero offsets from the chip and to divide out pixel-to-pixel variations in the chip sensitivity. Absolute flux calibration was obtained through observations of the flux standard stars HD 84937 and BD +26°2606 at similar airmasses.

Spectra of NGC 2392, 3587, 6210, 6543, 6720, and 7027 were taken with the slit placed across the central stars at position angles 0° and 90°. NGC 2392 and NGC 6720 were more comprehensively mapped by taking several spectra at widely spaced positions over the surfaces of these nebulae. In the case of NGC 6720 the slit was moved to positions 5", 15", and 25" north and south of the central star and exposures of 300 s duration were taken at each position using the 5.1 m telescope.

III. RESULTS

Figure 1 is an image of the first spatial derivative of the H α surface brightness of NGC 6720 with respect to distance in the plane of the sky at a position angle 135°. It was obtained at the 1.5 m telescope using a single 200 s exposure made through a filter centered at 6562 ± 20 Å (FWHM). The first derivative of the surface brightness is presented because it strongly emphasizes the structure in the main shell of the nebula; in particular, several long curved filaments are enhanced. These filaments have characteristic widths of about 1" in the H α filter. The seven slit positions used to map the carbon emission are indicated in the figure.

Spectra of NGC 2392, 3587, and 6543 fail to show the [C I] 9823, 9850 Å lines. However, NGC 6210, 6720, and 7027 display [C I] emission. Nebulae other than NGC 6720 will be discussed in a future paper. In NGC 6720 the [C I] 9823 + 9850 Å lines were clearly recorded in the CCD spectra. They appear merged into a single broad line (FWHM 68 Å) centered at 9843 ± 2 Å. This is consistent with the combined effects of the instrumental resolution function and the 1:2.97 ratio of line intensities expected from the ratio of the transition probabilities (Nussbaumer and Rusca 1979). The [C I] 9823 + 9850 Å emission distribution along seven slits projected across NGC 6720 is shown in Figure 2. The [O I] 6300 Å distribution, taken from the same spectra as the [C I] data, is shown for comparison. The emission is confined to a shell of about 20" internal radius and 25" thickness, centered on the central star. From the figure it may be seen that [C I] and [O I] emissions are strongly spatially correlated. Nowhere does the ratio of the two emissions vary by more than a factor of about 2. Both [C I] and [O I] are irregularly distributed: comparison with Figure

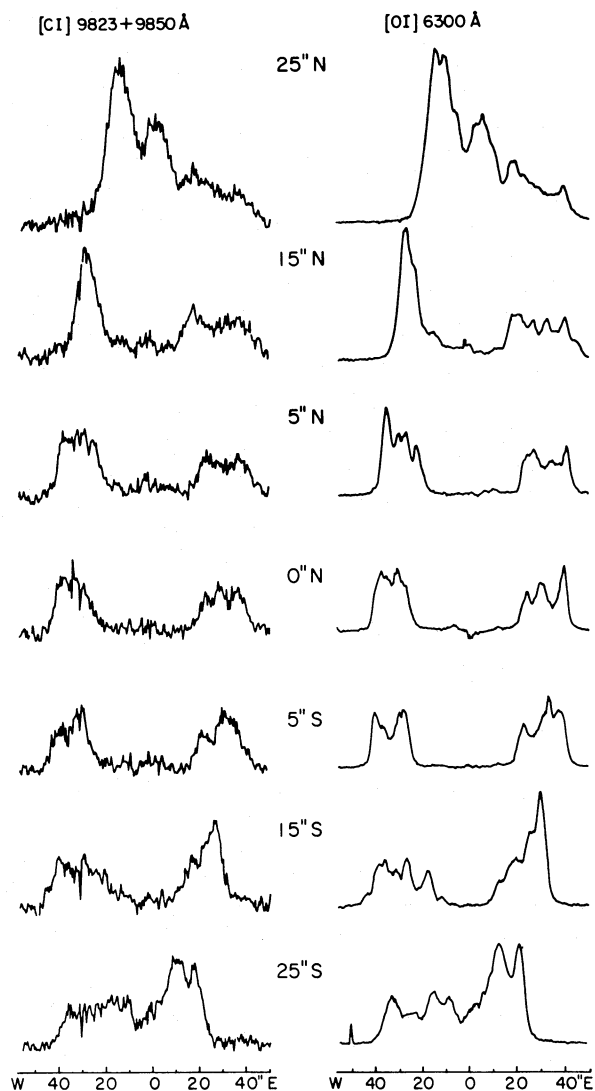


FIG. 2.—Comparison of the [C I] 9823, 9850 Å and [O I] 6300 Å emission distributions in NGC 6720. Relative flux is plotted as a function of distance east and west of the central star for each of seven slit positions. The displacements of the different slit positions in the north-south direction are indicated. Sky and nebular continuum emissions have been subtracted.

1 shows that both lines appear bright where the slits cross the sharp filaments. In the central region of the planetary nebula the [O I] appears only faintly while the [C I] is virtually absent. Likewise, outside the main shell of the nebula both emissions fall to zero. Figures 1 and 2 together suggest that the [O I] and [C I] radiations originate from the same volumes of the nebula and that these volumes lie within the bright filaments.

The surface brightness in the [C I] 9823 + 9850 Å lines was measured to be $(1.3 \pm 0.1) \times 10^{-8} \text{ W m}^{-2} \text{ sr}^{-1}$, from only the eastern half of the central slit spectrum. If the

distance to the nebula is $\Delta \sim 700$ pc the interstellar absorption at 9800 Å amounts to about 0.3 mag (Allen 1973). The interstellar extinction correction is small enough that our conclusions are not sensitive to it. The corrected surface brightness is then $S = (1.7 \pm 0.2) \times 10^{-8} \text{ W m}^{-2} \text{ sr}^{-1}$ and the total radiated power from the whole nebula is $4\pi S \Delta^2 \Omega \approx 1 \times 10^{25} \text{ W}$ ($\sim 0.03 L_\odot$). Here, $\Omega = 1.2 \times 10^{-7} \text{ sr}$ is the solid angle subtended by the bright shell of the nebula.

The [C I] 8727 Å $^1D-^1S$ line was not detected in our observations. If present it must be blended with another nebular line only 13 Å away. Numerically generated spectrum lines were artificially blended in various proportions in order to estimate an upper limit to the [C I] 8727 Å line flux. Comparison with actual spectra shows that the [C I] 8727 Å line would have been detected if its surface brightness exceeded $(1.2 \pm 0.2) \times 10^{-9} \text{ W m}^{-2} \text{ sr}^{-1}$. Hence we find a 1σ upper limit to the ratio

$$G = S(8727)/S(9823 + 9850) < 0.07 \quad (1)$$

which is useful for comparison with theoretical calculations (see next section).

IV. DISCUSSION

The principal difficulty with the interpretation of the present observations is that the electron temperature, T_e , and the electron density, N_e , are unknown in the [C I] emitting regions. This is because existing determinations of T_e and N_e are derived from line-of-sight averaged emission-line intensity ratios from ions of relatively high ionization potential. The line-of-sight averages do not necessarily reflect the conditions inside the filaments where the [C I] radiation is produced. However, in the absence of other evidence we adopt the T_e , N_e measurements reported by Kupferman (1983). These are in quantitative agreement with independent determinations by Hawley and Miller (1977) and Barker (1980) but have the advantage of showing the two-dimensional dependences of T_e and N_e over the surface of the nebula.

The observation of [C I] may be used to estimate the number density of neutral carbon atoms in NGC 6720. [C I] emission has been computed as a function of N_e and T_e by Pequignot and Aldrovandi (1976). They employed a three-level atom model and used the emission cross sections of Le Dourneuf *et al.* (1975). Under the assumption of a purely collisional excitation mechanism the equilibrium number density of C I is

$$N(\text{C I}) = L/[N_e \epsilon(T_e, N_e) V], \quad (2)$$

where N_e (m^{-3}) is the local electron density, $\epsilon(T_e, N_e)$ ($\text{J m}^3 \text{ s}^{-1}$) is the emission coefficient in the 9823 + 9850 Å lines, and L (W) is the total luminosity within the same lines produced within a volume V (m^3). N_e and T_e were taken to be 10^9 m^{-3} and 10^4 K , respectively

(Kupferman 1983). The luminosity per unit volume was estimated from $L/V = 4\pi S/l$, where S is the observed surface brightness and l is a characteristic length for the emitting region along the line of sight. The neutral carbon number density is found to be

$$N(\text{C I}) \sim \frac{10^{19}}{l}, \quad (3)$$

with l in meters. The major uncertainty in $N(\text{C I})$ results from the difficulty in assigning a value to l . An absolute upper limit to l can be set equal to $3 \times 10^{15} \text{ m}$, the path length through the entire nebula at the observed position of the [C I] emission. The variation of the emission across the nebular filaments (see Fig. 2), strongly suggests that l is similar to the characteristic width of these filaments, namely $l \sim 10^{14} \text{ m}$. The resulting C I number densities are $N(\text{C I}) \geq 3 \times 10^3 \text{ m}^{-3}$ and $N(\text{C I}) \sim 10^5 \text{ m}^{-3}$, respectively, with the latter value being the more plausible.

In passing we note that Pequignot and Aldrovandi (1976) predict a line intensity ratio $G = 0.06$ at our assumed values $N_e = 10^9 \text{ m}^{-3}$, $T_e = 10^4 \text{ K}$. This is consistent with the empirical upper limit $G < 0.07$. If N_e were 50% higher or T_e were 40% higher than the values we have used, the predicted and observed ratios would not agree. However, all lower values of N_e and T_e would be consistent with $G < 0.07$. $\epsilon(T_e, N_e)$ is a very weak function of N_e but would increase (decrease) by a factor of 4 if T_e were increased (decreased) by a factor of 2.

Assuming the cosmic abundance of carbon to be $10^{-3.4}$ that of hydrogen, we find $N(\text{C I})/N(\text{C}) > 10^{-2}$ and $N(\text{C I})/N(\text{C}) \sim 10^{-1}$ corresponding to the two length scales discussed above. The abundance of C I relative to hydrogen is $\sim 10^{-6}$. These values apply only to the filaments observed in [C I] emission.

The major questions arising from the observed high neutral carbon abundance are: (1) How can the carbon remain neutral against the effects of the ionizing stellar flux? and (2) How are the observed lines excited? We propose that the neutral carbon is located in regions of the nebula which are shielded from the direct stellar radiation and that photoionization of shielded hydrogen by photons from the diffuse radiation field provides the high electron densities needed to excite the neutral carbon atoms.

The equation of ionization equilibrium for hydrogen in the nebula is

$$4\pi N(\text{H I}) \int_{\nu_1}^{\infty} a(\nu) \frac{J_\nu}{h\nu} d\nu = N_e N(\text{H II}) \alpha(\text{H I}, T_e), \quad (4)$$

where $N(\text{H I})$, $N(\text{H II})$, and N_e are the number densities of neutral and singly ionized hydrogen and of free electrons, respectively. The term $a(\nu)$ is the photoioni-

zation cross section for neutral hydrogen, $\alpha(\text{H I}, T_e)$ is the hydrogen recombination coefficient, and ν_1 is the frequency of radiation at the Lyman limit. J_ν is the mean intensity of the radiation. To good approximation the photoionization cross section may be set equal to

$$a(\nu) = A_H \left(\frac{\nu_1}{\nu} \right)^3 \quad (5)$$

where A_H is the cross section at $\nu = \nu_1$.

In general J_ν may be expressed as the sum of contributions from the direct but attenuated stellar radiation and from the diffuse radiation field. In the shielded regions of the nebula, only the diffuse radiation is important. We use the approach of Van Blerkom and Army (1972) and approximate the mean intensity at optical depth, τ , by

$$J_\nu(\tau) = D(\tau) B_\nu(T_e), \quad (6)$$

where $B_\nu(T_e)$ is the Planck function at electron temperature T_e and

$$D(\tau) = \left(\frac{1-\epsilon}{\epsilon} \right) \times W \frac{\int_{\nu_1}^{\infty} \left(\frac{\nu_1}{\nu} \right)^3 \frac{B_\nu(T_s)}{h\nu} \exp \left[- \left(\frac{\nu_1}{\nu} \right)^3 \tau \right] d\nu}{\int_{\nu_1}^{\infty} \left(\frac{\nu_1}{\nu} \right)^3 \frac{B_\nu(T_e)}{h\nu} d\nu}. \quad (7)$$

Here $1-\epsilon$ is the probability that a given recombination will occur to the ground state; and W is a geometrical dilution factor equal to $(R_s/R)^2$, where R_s is the radius of the central star and R is the radius to the shielded region in the nebula. The optical depth, τ , is measured at $\nu = \nu_1$ along a radial direction from the central star. For simplicity the central star is approximated by a blackbody having temperature T_s .

Equations (4)–(7) have been used to compute the neutral hydrogen fraction in the shielded region. Assumed values were $N(\text{H I}) + N(\text{H II}) = 10^9 \text{ m}^{-3}$, $T_e = 10^4 \text{ K}$, $T_s = 10^5 \text{ K}$ and $W = 10^{-14}$. The values of A_H , ϵ , and $\alpha(T_e)$ were taken to be $6.3 \times 10^{-22} \text{ m}^2$, 0.62 and $4.2 \times 10^{-19} \text{ m}^3 \text{ s}^{-1}$, respectively (Osterbrock 1974). The computed neutral fraction $\chi(\text{H}) = N(\text{H I})/[N(\text{H I}) + N(\text{H II})]$ is given as a function of τ in the second column of Table 1.

In the case of carbon the ionization equilibrium equation (4) was solved under the assumption that all free electrons come from hydrogen so that $N_e = N(\text{H II}) = 10^9[1 - \chi(\text{H})]$. The C I photoionization cross section was approximated by (Osterbrock 1974)

$$a(\nu) = a_T \left[\beta \left(\frac{\nu_1}{\nu} \right)^s + (1-\beta) \left(\frac{\nu_1}{\nu} \right)^{s+1} \right], \quad (8)$$

TABLE 1
COMPUTED NEUTRAL FRACTIONS

τ	$\text{Log } \chi(\text{H})$	$\text{Log } \chi(\text{C})$
0 ...	-3.67	-3.59
20 ...	-2.21	-2.13
40 ...	-1.75	-1.67
60 ...	-1.45	-1.38
80 ...	-1.24	-1.16
100 ...	-1.07	-1.00

where $a_T = 1.22 \times 10^{-21} \text{ m}^2$, $\beta = 3.32$, $s = 2.0$, and $\nu_1 = 2.73 \times 10^{15} \text{ Hz}$. The recombination coefficient was taken to be $\alpha(\text{C I}, T_e) = 4 \times 10^{-19} \text{ m}^3 \text{ s}^{-1}$ (Osterbrock 1974). The computed neutral carbon fraction $\chi(\text{C})$ is given as a function of τ in the third column of Table 1.

It is evident from the table that a significant fraction of the carbon atoms in the shielded regions may exist in the neutral state. Moreover, neutral carbon fractions on the order of 1%–10% occur even though the shielded hydrogen is quite strongly ionized, $1 - \chi(\text{H}) > 0.9$. This result remains true for other plausible choices of T_s and W . The electrons produced by the ionization of the hydrogen atoms are able to collisionally excite the neutral carbon atoms. Hence the observation of [C I] emission is consistent with the presence of shielded regions in NGC 6720. Furthermore, the distribution of [C I] radiation shows that the shielded regions are located within the bright filaments.

The $609 \mu\text{m } ^3P_1 - ^3P_0$ line of neutral carbon has been observed in several interstellar clouds (Phillips and Huggins 1981). Assuming a line width due to turbulence of 1 km s^{-1} and an Einstein A -coefficient equal to $8 \times 10^{-8} \text{ s}^{-1}$, the $609 \mu\text{m C I}$ emission from NGC 6720 would be expected to lead to an antenna temperature $T_A < 10^{-2} \text{ K}$. This is about 100 times too weak to be detected using present submillimeter technology. Molecular hydrogen has been detected in the Ring Nebula and may be present in the shielded regions (Beckwith *et al.* 1978). It remains to be seen whether all nebulae showing [C I] emission also show molecular hydrogen emission.

Numerous approximations have been made in this simple treatment. For example, the stellar flux may be poorly represented by a Planck function, and helium has not been included in the calculations. When solving equation (4) we have neglected the (factor of 2) N_e and T_e differences in the shielded regions. However, the uncertainties in the interpretation of the data probably do not warrant a treatment substantially more detailed than the one presented here.

V. SUMMARY

Neutral carbon emission in NGC 6720 is concentrated in several bright filaments and indicates a

fractional concentration $N(\text{C I})/[N(\text{C I}) + N(\text{C II})] \sim 1\% - 10\%$. The $[\text{C I}]$ radiation probably emanates from regions of the nebula which are locally shielded from the direct stellar radiation. Carbon in the shielded regions is able to remain neutral at the $1\% - 10\%$ level against photoionization by the nebular diffuse radiation field. Much of the hydrogen in the shielded regions is ionized by the diffuse radiation. The photoelectrons produced

from the hydrogen are responsible for the collisional excitation of the neutral carbon.

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