Carina’s Defiant Finger: HST Observations of a Photoevaporating Globule in NGC 3372

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ABSTRACT

We present Hubble Space Telescope Wide Field Planetary Camera 2 images of a prominent externally-ionized molecular globule in the Carina Nebula (NGC 3372), supplemented with ground-based infrared images and visual-wavelength spectra. This molecular globule has a shape resembling a human hand, with an extended finger that points toward its likely source of ionizing radiation. Following an analysis of the spatially-resolved ionization structure and spectrum of the photoevaporative flow from the Finger, we conclude that the dominant ionizing source is either the WNL star WR25 (HD 93162), the adjacent O4 If-type star Tr16-244, or perhaps both. We estimate a mass-loss rate of \( \sim 2 \times 10^{-5} \, M_\odot \, \text{yr}^{-1} \) from the main evaporating surface of the globule, suggesting a remaining lifetime of \( 10^5 \) to \( 10^6 \) years. We find a total mass for the entire globule of more than \( 6 \, M_\odot \), in agreement with previous estimates. The hydrogen column density through the globule derived from extinction measurements is a few times \( 10^{22} \, \text{cm}^{-2} \), so the photodissociation region behind the ionization front should be limited to a thin layer compared to the size of the globule, in agreement with the morphology seen in H\(_2\) images. Although a few reddened stars are seen within the boundary of the globule in near-infrared continuum images, these may be background stars. We do not detect a reddened star at the apex of the finger, for example, down to a limiting magnitude of \( m_K \sim 17 \). However, considering the physical properties of the globule and the advancing ionization front, it appears that future star formation is likely in the Finger globule, induced by radiation-driven implosion.

Key words: H\(_\text{II}\) regions — ISM: globules — ISM: individual (NGC 3372) — stars: formation

1 INTRODUCTION

Compact bright-rimmed molecular globules are common in evolved massive star forming regions, and are among the last vestiges of the molecular cloud that gave birth to the OB stars powering the H\(_\text{II}\) region (e.g., Bok & Reilly 1947). These globules are externally illuminated and are photoevaporated and photoionized by UV radiation. They typically range in size from 0.1 to 1 pc, and appear striking in [S\(_\text{II}\)] \( \lambda \lambda 6717,6731 \) and H\(_\alpha\) emission arising in the limb-brightened surfaces of their thin ionization fronts. Famous examples of this class of objects are Thackeray’s globules in IC 2944 (Thackeray 1950; Reipurth et al. 2003), as well as similar features in the Rosette Nebula (Herbig 1974), the Gum Nebula (Hawarden & Brand 1976; Reipurth 1983), and the Carina Nebula (Walborn 1975; Cox & Bronfman 1995).

Material evaporated from these clumps partly fills the interior of an H\(_\text{II}\) region and may help stall the advance of the main ionization front by absorbing incident Lyman continuum radiation and converting it to a recombination front, but perhaps the most pertinent role played by these globules is that they are potential sites of continued star formation. Some globules show clear evidence for embedded star formation, while others do not (Reipurth 1983; Reipurth et al. 2003). If they are sites of star formation, one
possibility is that they are simply dense cores that spontaneously collapsed to form stars and were then uncovered by the advancing ionization front. Another more intriguing idea is that pressure from the ionization-shock front at the surface propagates through a globule and helps to overcome the magnetic, turbulent, and thermal pressure that supports it against collapse, thereby inducing a star to form in the globule. This process of radiation-driven implosion is often referred to as triggered star formation. However, direct and unambiguous observational evidence for actively triggered star formation remains elusive; the pillars in M16 may be an example of this phenomenon (White et al. 1999; Hester et al. 1996; Williams et al. 2001; McCaughrean & Andersen 2002).

Numerous investigators have examined theoretical aspects of these evaporating globules, including details of the photoevaporative flows, their effect on the surrounding H II region, the globule’s shaping, destruction, and acceleration (through the “rocket effect”), and the possibility of triggered collapse and star formation due to the pressure of the impinging ionization front (Oort & Spitzer 1955; Kahn 1969; Dyson 1973; Dyson et al. 1995; Elmegreen 1976; Bertoldi 1989; Bertoldi & McKee 1990; Bertoldi & Draine 1996; Lizano et al. 1996; Gorti & Hollenbach 2002; Williams 1999; Williams et al. 2001). The evolution of these globules depends strongly on the incident UV radiation field, the initial size and density of the globule, and other properties, so observations of them in a wide variety of different environments are useful.

A rich population of these globules resides in the Carina Nebula (NGC 3372; d=2.3 kpc), with the most notable grouping clustered around the famous Keyhole Nebula. Their emission from ionized, photodissociated, and molecular gas has been documented by several studies (Walborn 1975; Deharveng & Maucherat 1975; Cox & Bronfman 1995; Brooks et al. 2000; Smith 2002; Rathborne et al. 2002).

There are a dozen of these clumps around the Keyhole, with typical masses of order $10 M_\odot$ (Cox & Bronfman 1995). A few of these are seen only in silhouette, but most have bright H$_2$ and polycyclic aromatic hydrocarbon (PAH) emission from their illuminated surfaces (Brooks et al. 2000; Rathborne et al. 2002). In addition, several dozen smaller features with diameters of only $\sim$5000 AU were recently discovered by Smith et al. (2003a), and additional proplyd can-
Table 1. Observations of the Finger

| Telescope | Instrument | Filter or Emiss. Lines | Exp. Time (sec) | Comment |
|-----------|------------|------------------------|----------------|---------|
| HST       | WFPC2      | F502N, [O iii] λ5007   | 320            | image   |
| HST       | WFPC2      | F656N, Hα, [N ii]     | 400            | image   |
| HST       | WFPC2      | F673N, [S ii] λ6717,6731 | 800          | image   |
| CTIO 4m   | OSIRIS     | J                      | 120            | image   |
| CTIO 4m   | OSIRIS     | H                      | 120            | image   |
| CTIO 4m   | OSIRIS     | K                      | 120            | image   |
| CTIO 4m   | OSIRIS     | He i λ10830            | 720            | image   |
| CTIO 4m   | OSIRIS     | Pa β                   | 720            | image   |
| CTIO 4m   | OSIRIS     | H₂ 1-0 S(1) 2.122 μm   | 1080           | image   |
| CTIO 1.5m | RC Spec    | blue; 3600-7100 Å     | 1200           | long-slit, P.A.=69° |
| CTIO 1.5m | RC Spec    | red; 6250-9700 Å      | 1200           | long-slit, P.A.=69° |

In this paper we undertake a detailed analysis of one particularly striking bright-rimmed globule in the Carina Nebula (see Figure 1) that we call the “Finger” because of its gesticulatory morphology (it has previously been identified as clump 4; Cox & Bronfman 1995). The defiant finger seems to point toward its dominant UV source, and as such, allows for an interesting application of models of photoevaporating globules mentioned above. In §2 we discuss our observations, and in §3 and §4 we briefly discuss the results of our imaging and spectroscopy. In §5 we undertake a detailed analysis of the photoevaporative flow, and in §6 we discuss implications for potential star formation in the globule.

2 OBSERVATIONS AND DATA REDUCTION

2.1 HST/WFPC2 Images

Images of the Keyhole Nebula were obtained on 1999 April 18 with the Wide Field Planetary Camera 2 (WFPC2) instrument onboard the Hubble Space Telescope (HST). Four different pointings were observed and combined to form a large mosaic image, which has been released by the Hubble Heritage Team. Here we focus on only a small portion of the total area observed, containing the globule that we call the Finger. Images were obtained through narrow-band filters F602N ([O iii] λ5007), F656N (Hα), and F673N ([S ii] λ6717,6731), as well as the broadband filters F469W, F555W, and F814W. Only the emission-line images will be discussed here, however. Pairs of images in each narrow-band filter were combined and processed in the usual way to remove cosmic rays and hot pixels, and to correct for geometric distortion, as described in the HST Data Handbook (however, the images were not CTE corrected). Finally, the individual frames were combined to form a single mosaic image with a pixel scale of 0.0995. Subsections of the images showing the region around the Finger are displayed in Figure 2, oriented with north up and east to the left.

2.2 Near-Infrared Images

Near-infrared (IR) images of the Finger and its immediate environment were obtained on 2003 February 25 with the Ohio State IR Imaging Spectrometer (OSIRIS) mounted on the CTIO 4m telescope. OSIRIS has a 1024×1024 NICMOS3 array, with a pixel scale of 0.0995. Subsections of the array are illuminated in this configuration, yielding a field of view of ~1.5. We obtained images in the broadband J, H, and K filters, as well as narrowband filters isolating He i λ10830, Paβ λ12818, and H₂ 1-0 S(1) A21218. In each filter, several individual exposures were taken with small offsets between them to correct for bad pixels on the array. The seeing during the observations was ~0.8. There is no position on the sky near the Finger that is suitable for measuring the background sky because of bright emission from the H ii region and nearby star clusters, so for sky subtraction we nodded the telescope to a position roughly 2° south. Flux calibration was accomplished by measuring isolated stars from the 2MASS catalog that were included in our field of view, and is valid to within about ±10%. The IR images were aligned with the WFPC2 images and are shown in Figure 3.

2.3 Optical Spectroscopy

Low-resolution (R ~ 700–1600) spectra from 3600 to 9700 Å were obtained on 2002 March 1 and 2 using the RC Spectrograph on the CTIO 1.5-m telescope. Long-slit spectra of the Finger were obtained with the 1′5-wide slit aperture oriented at P.A.≈69° crossing through the middle of the globule as shown in Figure 1. The pixel scale in the spatial direction was 1′3. Spectra were obtained on two separate nights in

1 See [http://oposite.astro.edu/pubinfo/pr/2000/06/](http://oposite.astro.edu/pubinfo/pr/2000/06/)
Figure 2. HST/WFPC2 images of the Finger. (a) F502N filter transmitting [O iii] $\lambda 5007$; grayscale range from $2.4 \times 10^{-14}$ (white) to $1.9 \times 10^{-13}$ (black) ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. (b) F656N filter transmitting H$\alpha$; grayscale range from $5.4 \times 10^{-14}$ (white) to $3 \times 10^{-13}$ (black) ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. (c) F673N filter transmitting [S ii] $\lambda\lambda 6717,6731$; grayscale range from $4.2 \times 10^{-15}$ (white) to $3.3 \times 10^{-14}$ (black) ergs s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. These observed flux levels were not corrected for reddening and extinction. The axes display offset in arcsec from an arbitrary central position in the globule.

From the resulting long-slit spectra, we extracted several one-dimensional (1-D) segments of the slit that sampled emission from the thin ionization front (IF), the ionized boundary layer (IBL), the total emission from the IF and IBL (TOT), and a nearby sample of the emission from the background Carina Nebula H II region. The sizes of these subapertures are identified in Figures 1 and 5. The blue and red wavelength ranges of these extracted 1-D spectra were merged to form a single 3600-9700 Å spectrum for each position, with a common dispersion of 2 Å pixel$^{-1}$; the average of the two was taken in the region of the spectrum near H$\alpha$ where the blue and red spectra overlapped (in the overlap region, bright line fluxes agreed to within about $\pm 5\%$, comparable to the assumed uncertainty). Finally, the background H II region spectrum was subtracted from the IF, IBL, and TOT spectra. The final flux-calibrated spectra are shown in Figure 5. Observed intensities are listed in Table 2, relative to H$\beta=100$. Uncertainties in these line intensities vary depending on the strength of the line and the measurement method. The integrated fluxes of isolated emission lines were measured; for these, brighter lines with $I > 10$ typically have measurement errors of a few percent, and weaker lines may have uncertainties of $\pm 10$ to $15\%$. The uncertainties increase somewhat at the blue edge of the spectrum. Blended pairs or groups of lines were measured by fitting Gaussian profiles. For brighter blended lines like H$\alpha$+[N ii] and [S ii], the measurement uncertainty is typically 5 to 10%. Obviously, errors will be on the high end for faint lines adjacent to bright lines, and errors will be on the low end for the brightest lines in a pair or group, or lines in a pair with comparable intensity.

3 IMAGING RESULTS

Figures 2, 3, and 4 show imaging data concentrated on a small region (less than 1 square arcminute) featuring the evaporating molecular globule that is the focus of this paper. Images showing the Keyhole Nebula and its environment on a much larger spatial scale but with lower spatial
Figure 3. Near-IR images of the Finger. (a) He I λ10830; grayscale range from 1.3×10^{-14} (white) to 4.8×10^{-14} (black) ergs s^{-1} cm^{-2} arcsec^{-2}. (b) Hydrogen Paβ; grayscale range from 1.5×10^{-14} (white) to 5.1×10^{-14} (black) ergs s^{-1} cm^{-2} arcsec^{-2}. (c) H2 v = 1 − 0 S(1) λ1218; grayscale range from 9.3×10^{-16} (white) to 5.3×10^{-15} (black) ergs s^{-1} cm^{-2} arcsec^{-2}. These observed flux levels were not corrected for reddening and extinction.

resolution, and using filters transmitting these same optical and IR emission lines, have been presented by Smith (2002), Brooks et al. (2000), Lopez & Meaburn (1984), Walborn (1975), and Deharveng & Maucherat (1975). Near-IR continuum images of the Finger will be discussed later in §6.

### 3.1 Emission Line Morphology of the Finger

The overall morphology of the Finger in Figures 2 and 3 is quite striking, and consistent with the interpretation that the emission arises from the ionized evaporating flow and dense ionization fronts of an externally-illuminated molecular globule. The [O III], Hα, and [S II] images are reminiscent of many HST/WFPC2 images of dust pillars and globules in other H II regions (e.g., Hester et al. 1996; Reipurth et al. 2003). Differences in the observed structure in various emission lines give interesting clues to the nature of the evaporating globule: In [O III] emission, the Finger is seen almost exclusively as a silhouette against the bright background, except for a faint halo from the evaporated flow around the globule. In Hα, the emission from the evaporating halo material and extinction features are almost identical to [O III], as the extended halo mostly disappears in the Hα/[O III] image in Figure 4a. Hα is significantly stronger than [O III] only near the sharp limb-brightened edges of the cloud, where strong [S II] emission is also seen at the ionization front (i.e. the Hα/[O III] flux ratio image in Figure 4a looks nearly identical to the [S II] image). The globule itself appears to be optically thick, especially at visual wavelengths where it totally obscures the background H II region; the emission from [O III] and Hα seen projected within the boundaries of the globule is due primarily to the ionized evaporating flow on the near side. The globule does not become transparent at near-IR wavelengths like the pillars in M16 (e.g., Thompson et al. 2002; McCaughrean & Andersen 2002). It is seen clearly as a silhouette in Paβ, He I λ10830, Hα, and [O III], but is not a silhouette in [S II] or H2 because the emission from the globule’s front surface is brighter than the background. This is especially clear from the [S II]/Hα ratio image in Figure 4b. The spatially-resolved structure of the stratified ionization fronts and photoevaporating halo will be discussed in more detail in §5.

There appear to be two dominant locations of active photoevaporation where the surface of the globule is directly irradiated by individual stars; these are at the southern end of the globule (the “knuckles”, if the Finger globule is imagined to resemble a human hand), and at the western side of the northern part (the “wrist”). The activity in these two re-
regions is highlighted best by emission from He\textsc{i}$\lambda$10830 (Figure 3a) and H$_2$ (Figure 3c). The He\textsc{i} line has a metastable lower level and is enhanced by collisions in dense ionized gas, such as that found in a dense ionized photoevaporative flow. H$_2$ emission will be brightest in the photodissociation region (PDR) immediately behind the strongest ionization fronts, where a strong flux of FUV (Balmer continuum) photons penetrates, or where the gas is heated by a shock or Ly\textalpha from the ionization front itself. Both He\textsc{i} and H$_2$ are most prominent in the two regions mentioned above: the “knuckles” and the “wrist”. Relatively weak limb-brightened [S\textsc{ii}] emission is seen around the periphery of the globule, probably caused by the ambient UV field and Ly\textalpha radiation.

The most obvious photoevaporating flow on the southern edge of the globule exhibits a thin straight finger protruding normal to a bright edge-on ionization front. This thin finger appears to identify its source of irradiation: It points toward P.A.$\approx$208°, close to the massive star WR25 (HD 93162) at P.A.$\approx$219° relative to the Finger, although other early-type stars are seen along the same apparent trajectory. The ionizing source is addressed quantitatively in §5.2. Extending toward the south from this main ionization front is a large-scale ionized flow, prominent in [O\textsc{iii}], H\textalpha, and Pa\beta, where it fills the lower left corner in Figures 2a, 2b, and 3b. About 6″ from the end of the finger, one can see an arc-shaped structure in these same emission lines; the density here might be enhanced in a shock as the ram pressure of the photoevaporating flow off the globule balances the pressure of the ambient ionized gas in the H\textsc{ii} region. From conservation of momentum, this should occur at a distance from the globule’s center given roughly by $r_{if}(n_{if}/n_{H\textsc{ii}})^{0.5}$, where $n_{if}$ and $n_{H\textsc{ii}}$ are the electron densities at the ionization front and in the H\textsc{ii} region, respectively, and $r_{if}$ is the radius of curvature of the ionization front. Electron densities are estimated below (Table 3), and the resulting distance is in reasonable agreement with the location of the shock.

Both of the main evaporating surfaces of the globule are found at relatively flat interfaces (a large effective radius of curvature). This may be an important factor in their enhanced emission, as the radial density profile will fall off more rapidly in a spherically divergent flow than from a planar ionization front. The northern evaporative flow (the “wrist”) is particularly interesting, as it may be caused by a very nearby star – the bright B star located only 10″ to the
Figure 5. Spectra of gas associated with the Finger. The plotted quantity is the average specific intensity in the aperture size given in each panel, and shown in Figure 1. (a) The spectrum of the ionization front (IF) on the side of the globule facing the main UV source. (b) Same as Panel a but with a different intensity scale. (c) Spectrum of the ionized boundary layer (IBL, or “photoevaporative flow”) associated with the main ionization front. (d) Spectrum of the total emission including both the ionization front and the ionized boundary layer (note that the “total” emission shown here is not a simple average of the IF and IBL; the aperture used was slightly larger than both the IF and IBL combined; see Figure 1). (e) Average spectrum of the background H \text{ii} region near the Finger.

west (Tr16-207; see Figure 1).\textsuperscript{2} The motivation for this conjecture is that both the He \text{i} and H\text{2} emission are localized, while most of the rest of the western side of the globule also appears relatively flat and normal to the same direction. If the ionizing source were a luminous star at a large distance, we might expect to see a similar level of enhanced emission all along the western side of the globule. A third region of active photoevaporation may have a different UV source from the other two just mentioned; the southeast edge of the globule shows enhanced emission in [S \text{ii}] and H\text{2}, most notably on the east side of the thin finger, while such emission is not as strong on the west side of the same finger. The very luminous and massive evolved star \eta Carinae is located toward the southeast; \eta Car may have been a prodigious FUV source in the recent past (more than 160 years ago) before it was surrounded by its young circumstellar dust shell (Smith et al. 1998). The O4 V((f+)) star HDE 303308 is seen toward the east/southeast as well, and may add to the FUV flux striking the side of the Finger.

3.2 Proplyd Candidates?
The new \textit{HST}/WFPC2 images also reveal a small group of distinct cometary clouds located immediately west of the Finger, the largest member of which has approximate dimensions of (f′5×2″) (about 1100×4500 AU). This object closely resembles the numerous “proplyd candidates” seen throughout the Carina Nebula (Smith et al. 2003a). This object, which we denote 104430.2-593953 (following the nam-

\textsuperscript{2} Additionally, we note that the northern part of the globule appears to be curved with a radius of curvature of \sim 10″, and with Tr16-207 located at the center of curvature.
ambiguous (are they analogues of Orion’s proplyds, starless cometary clouds, or something in between?), but this image of the other cometary objects in Carina, but is still larger 

$\lambda(\text{Å})$ and I.D. & IF (Obs) & IF (Dered.) & IBL (Obs) & IBL (Dered.) & TOT (Obs) & TOT (Dered.) & H II (Obs) & H II (Dered.) \\
3727 [O ii] & 312 & 436 & 105 & 146 & 178 & 248 & 93.0 & 130 \\
3869 [Ne iii] & 9.9 & 13.3 & 16.2 & 21.9 & 14.0 & 18.8 & 15.0 & 20.1 \\
3889 Hı+He ı & 19.1 & 25.5 & 22.2 & 29.7 & 21.7 & 29.0 & 20.2 & 27.1 \\
3970 He+ [Ne iii] & 18.1 & 23.7 & 19.2 & 25.2 & 20.0 & 26.2 & 20.6 & 27.1 \\
4026 He ı & 2.9 & 3.7 & 2.4 & 3.1 & 2.4 & 3.1 & 2.6 & 3.3 \\
4073 [S ii] & 3.9 & 5.0 & ... & ... & 1.6 & 2.0 & 0.7 & 1.0 \\
4102 Hıı & 24.8 & 31.3 & 23.4 & 29.6 & 23.8 & 30.0 & 23.4 & 29.5 \\
4340 Hγ & 44.6 & 52.6 & 46.3 & 54.7 & 47.5 & 56.1 & 44.9 & 53.0 \\
4363 [O iii] & 0.8 & 0.9 & 1.3 & 1.6 & 0.8 & 0.9 & 0.5 & 0.6 \\
4387 He ı & ... & ... & 0.9 & 1.1 & 0.8 & 0.9 & 0.5 & 0.6 \\
4471 He ı & 4.1 & 4.7 & 4.3 & 4.9 & 4.5 & 5.1 & 4.9 & 5.6 \\
4861 Hβ & 100 & 100 & 100 & 100 & 100 & 100 & 100 & 100 \\
4922 He ı & 1.6 & 1.6 & 1.5 & 1.5 & 1.3 & 1.3 & 1.6 & 1.5 \\
5059 [O ii] & 51.7 & 50.1 & 83.8 & 81.2 & 77.1 & 74.7 & 99 & 96.1 \\
5007 [O iii] & 161 & 153 & 254 & 242 & 236 & 225 & 300 & 286 \\
5755 [N ii] & 3.22 & 2.5 & 0.8 & 0.6 & 1.5 & 1.2 & 0.7 & 0.56 \\
5876 He ı & 15.0 & 11.2 & 16.3 & 12.2 & 15.8 & 11.8 & 16.8 & 12.5 \\
6300 [O i] & 5.1 & 3.4 & 1.3 & 0.9 & 2.2 & 1.5 & 0.9 & 0.6 \\
6312 [S iii] & 2.5 & 1.7 & 1.4 & 0.9 & 1.6 & 1.1 & 1.4 & 1.0 \\
6364 [O i] & 1.8 & 1.2 & 0.6 & 0.4 & 0.8 & 0.5 & 0.3 & 0.2 \\
6548 [N ii] & 95.1 & 61.2 & 29.1 & 18.7 & 41.8 & 26.9 & 19.2 & 12.4 \\
6563 Hα & 339 & 217 & 439 & 281 & 383 & 246 & 442 & 284 \\
6583 [N ii] & 280 & 179 & 68.3 & 43.7 & 114 & 73.0 & 37.5 & 24.0 \\
6768 [N ii] & 3.4 & 2.1 & 6.2 & 3.9 & 5.4 & 3.4 & 6.3 & 3.9 \\
6678 [S ii] & 33.7 & 20.9 & 10.4 & 6.5 & 15.3 & 9.5 & 7.0 & 4.4 \\
6717 [S ii] & 47.7 & 29.6 & 11.4 & 7.1 & 19.2 & 11.9 & 5.9 & 3.6 \\
7065 He ı & 4.6 & 2.7 & 4.7 & 2.7 & 4.1 & 2.4 & 5.0 & 2.9 \\
7136 [Ar iii] & 25.2 & 14.4 & 23.3 & 13.3 & 21.4 & 12.2 & 23.4 & 13.4 \\
7237 [Ar iv] & ... & ... & 1.2 & 0.7 & ... & ... & 0.9 & 0.5 \\
7281 He ı & ... & ... & 1.1 & 0.6 & ... & ... & 1.3 & 0.7 \\
7320 [O ii] & 22.5 & 12.4 & 4.0 & 2.2 & 7.6 & 4.2 & 1.5 & 0.5 \\
7330 [O ii] & 20.4 & 11.2 & 3.1 & 1.7 & 6.7 & 3.6 & 1.3 & 0.7 \\
7751 [Ar iii] & 6.6 & 3.3 & 5.9 & 3.0 & 5.8 & 2.9 & 6.2 & 3.1 \\
7774 O i & ... & ... & 0.6 & 0.3 & ... & ... & 0.6 & 0.3 \\
8446 O i & 3.9 & 1.7 & ... & ... & ... & ... & 1.1 & 0.5 \\
8750 Pa12 & 2.4 & 1.0 & 2.6 & 1.1 & 2.3 & 1.0 & 3.4 & 1.4 \\
8863 Pa11 & 3.4 & 1.4 & 3.0 & 2.3 & 3.5 & 2.0 & 4.0 & 1.6 \\
9015 Pa10 & 7.2 & 2.8 & 7.2 & 2.8 & 6.0 & 2.3 & 6.5 & 2.6 \\
9069 [S iii] & 68.1 & 26.6 & 66.3 & 25.9 & 59.4 & 23.2 & 86.9 & 34.0 \\
9229 Pa9 & 6.9 & 2.6 & 7.2 & 2.7 & 5.8 & 2.2 & 7.6 & 2.9 \\
9532 [S iii]+Pa8 & 219b & 79.7b & 215 & 78.5 & 145 & 52.8 & 300 & 110 \\
9711 [Fe ii] & 16.1 & 5.7 & 13.2 & 4.7 & 12.4 & 4.4 & 9.3 & 3.3 \\

a Observed line intensities were dereddened using the extinction law of Cardelli et al. (1989), with $E(B - V) = 0.37$ and $R_V = 4.8$. 

b The intensity of [S ii] $\lambda9532$ was assumed to be $3\times$[S ii] $\lambda9069$ in the IF spectrum, since that line at that position partly fell on a bad pixel on the detector.

4 SPECTROSCOPIC RESULTS

Figure 5 shows ground-based spectra extracted from the long-slit data for sub-apertures identified in Figure 1. The IF spectrum does not truly isolate emission from the thin ionization front on the surface of the globule because these ground-based data lack the requisite spatial resolution. However, emission in this sub-aperture is dominated by the limb-brightened emission from the IF; this is especially true for low-ionization lines like [S ii], whereas much of the emission in high-ionization lines like He ı and [O iii] may originate in immediately adjacent regions. The IBL spectrum samples the more extended photoevaporated flow, or the ionized boundary layer that absorbs the hard UV photons in-
cident upon the globule. The TOT spectrum includes both the IF and the IBL, and is mainly useful for comparison with some diagnostic line ratios mentioned later. Finally, the background spectrum of the Carina Nebula is shown for comparison; of course, this is a mixture of the high-ionization gas inside the H II region with the ionization front and photodissociation regions on the far side of the nebula.

The most notable aspect of the IF spectrum is its low ionization, with strong [O II] λλ3726,3729, [N II] λλ6548,6583, and [S II] λλ6717,6731 compared to Hα. These lines are typically enhanced at the ionization front or just beyond it if they are not collisionally de-excited; O has roughly the same ionization potential as H, the ionization potential of S is below 13.6 eV, and although the ionization potential of N is 14.5 eV, it can be ionized from the excited 5D state by photons with energies as low as 12.1 eV. The IBL spectrum is intermediate in ionization and excitation between the IF and the background H II region, as expected. The IF and IBL spectra qualitatively resemble the low- and high-excitation spectra, respectively, of the similar photoevaporating globule in the nearby open cluster NGC 3572 (Smith et al. 2003b).

Table 2 lists observed and dereddened line intensities relative to Hβ=100 for the various selected regions. The reddening used to correct the observed line intensities was determined by comparing observed strengths of hydrogen lines in the background H II region to the Case B values calculated by Hummer & Storey (1987). As shown in Figure 6, the observed Balmer and Paschen decrements suggest a value for $E(B - V)$ of roughly 0.37±0.03, using the reddening law of Cardelli, Clayton, & Mathis (1989) with $R_V = A_V / E(B - V) \approx 4.8$, which is appropriate for local extinction from dust clouds around the Keyhole Nebula (Smith 1987; Smith 2002). The value of $E(B - V) = 0.37$ we derive from nebular emission is close to the average value of 0.47, and within the range of values of 0.25 to 0.64, as listed for several bright O-type stars in Tr16 by Walborn (1995).

Table 3 lists representative physical quantities like electron density and temperature derived from a standard deductive nebular analysis of the usual line ratios. These are useful to guide the interpretation of the physics of the ionization front and photoevaporative flow discussed below.

5 ANALYSIS OF THE PHOTOEVAPORATIVE FLOW
Combining spectra with WFPC2 images that spatially resolve the stratified IF on the globule’s surface provides a powerful diagnostic tool, and allows us to undertake a detailed analysis of the photoevaporative flow and the incident UV field. From our narrowband images we made tracings of the observed intensity normal to the IF at five different positions around the Finger, indicated as a through e in Figure 7. The corresponding intensity tracings at these five positions are shown in Figure 8a to e. Surface brightness in Figure 8 has been corrected for reddening and extinction, with $E(B - V) = 0.37$ and $R = 4.8$.

5.1 The Stratified Ionization Fronts of the Finger
All the tracings in Figure 8 show the same general stratification with respect to the IF (at position a), although there are some detailed differences. Starting from the left, H2 emission peaks 0'5 to 1'5 (1200 to 3500 AU at d=2.3 kpc) behind the IF, while [S II], Hα, and Paβ then rise sharply. [S II] peaks at the IF and decreases exponentially thereafter, while hydrogen lines continue to rise, with their peak $\leq 0'25$ outside the IF in most cases (except position b). [O III] and He i rise sharply at the IF (due to extinction by dust), reach a broad peak (if any) outside the IF, and then decrease gradually at larger distances. The narrowest [S II] zones with a FWHM of $< 0'5$ are spatially resolved by HST, but the widths of some of the narrow Paβ and He i zones are unresolved in the ground-based images.

Far from the IF (~7') the intensities of Hα and [O III] are roughly equal in each set of tracings. Then, moving toward the IF, the intensities of Hα and [O III] diverge as hard photons capable of ionizing O+ to O2+ (with hv >35 eV) are eaten up by the photoevaporating flow and O2+ recombines (note the very strong [O II] λλ3727,3729 at the IF in Figure 5 and Table 2). At the same time, the strength of [Si II] tends to increase in proportion to the difference between Hα and [O III]. This is consistent with the qualitative similarity between the [Si II] image (Figure 2c) and the [O III] : Hα ratio (Figure 4a). Although every position shares the same basic
behavior described above, there are differences among the five positions. In particular, the IF’s of a and d are much narrower than the other positions. The stratification at position b is particularly broad. These differences are probably due to different radii of curvature (although position B may be affected by evaporation off the near side of the thin finger as well). For example, at b the IF appears nearly straight, in stark contrast to the small radius of curvature at the end of the finger at position a. In general, a smaller radius of curvature means that the photoevaporative flow diverges and the density drops faster than in a planar IF, so the stratified ionization structure is compressed. Both positions b and e seem to be nearly planar surfaces with a high-density flow extending far from the IF.

5.2 Does WR 25 Ionize the Finger?

As noted earlier, the finger at the southern end of the globule seems to point toward the luminous WNL star WR25 (HD 93162), but since some other luminous early-type stars are seen along this same general trajectory, this relationship should be tested quantitatively. By examining the properties of the IF and photoevaporative flow from the globule, we can estimate the necessary ionizing photon flux and the shape of the incident continuum. These can then be compared to likely values for candidate sources.

The electron density at the IF is the critical quantity for estimating the flux of ionizing photons striking the globule if we assume that the recombination rate roughly balances ionizations. From the ratio [S ii] λ6717/λ6731 we find \( n_e \sim 2200 \, \text{cm}^{-3} \) in the thin [S ii] emitting region on the surface of the globule (see Table 3). However, this is only the value near position b, which may be somewhat unusual because of its nearly planar geometry, as noted earlier, and ground-based spatial resolution in these spectra does not effectively sample the highest density at the thin IF. At b and other positions a, c, d, and e, the electron density at the IF can be estimated independently using the extinction-corrected Hα surface brightness \( S_{\text{H} \alpha} \) in Figure 8. If we assume \( n_e \sim n_p \), and adopt a reasonable estimate of the depth of the emitting layer\(^3\) along the line of sight \( L \), then we have

\[
S_{\text{H} \alpha} = \frac{4\pi(S_{\text{H} \alpha} \times 206265^2)}{\alpha_{\text{eff}} H_{\alpha} L} \tag{1}
\]

where \( \alpha_{\text{eff}} = 8.6 \times 10^{-14} \, \text{cm}^3 \, \text{s}^{-1} \) for \( T \approx 10^4 \, \text{K} \) (Osterbrock 1989), and 206265\(^2\) just converts from arcsec\(^{-2}\) to \( \text{cm}^{-2} \) so that we can simply use values gleaned from Figure 8. Adopted values of \( S_{\text{H} \alpha}, L \) and \( n_e \) are listed in Table 4. Since \( n_e \) derived from images is somewhat higher than that derived from the [S ii] lines for position b, as we would expect if [S ii] lines trace a region where hydrogen already has a large neutral fraction, we take the values for \( n_e \) in Table 4 as more reliable estimates of the IF density. We can then use these values of \( n_e \) to estimate the number of ionizing photons \( \Phi \) incident on an IF of radius \( r \) per second and per unit area if we assume that ionizations are approximately balanced by recombinations at the IF, so that we have

\[
\Phi \approx \Delta r \alpha_B n_e^2 \tag{2}
\]

where \( \alpha_B = 2.59 \times 10^{-13} \, \text{cm}^3 \, \text{s}^{-1} \) is the total case B hydrogen recombination coefficient for \( T \approx 10^4 \, \text{K} \) (Osterbrock 1989). To calculate \( \Phi \) for the five positions listed in Table 4, we assumed the characteristic thickness of the recombination front is \( \Delta r \approx L \div 3 \), which seemed a fair approximation based on the width of the limb-brightened surfaces seen in images. Judging by the morphology observed in Figure 2, \( \Delta r \approx 4 \times 10^{-14} \, \text{cm} \) at positions a and d, which have the least ambiguous geometry.

---

### Table 4. Ionization Front Properties

| Pos. | \( S_{\text{H} \alpha} \) (arcsec) | \( L \) (10\(^{16}\) cm) | \( n_e \) (cm\(^{-3}\)) | log\(_10(\Phi)\) (s\(^{-1}\) cm\(^{-2}\)) | Spectral Type\(^b\) |
|------|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| a... | 6.5                             | 3.5             | 6200            | 11.06           | O7.5            |
| b... | 5.5                             | 10.4            | 3300            | 10.99           | O6.5            |
| c... | 7.0                             | 6.9             | 4600            | 11.09           | O7              |
| d... | 6.0                             | 3.5             | 6000            | 11.03           | O7.5            |
| e... | 3.0                             | 10.4            | 2400            | 10.73           | \( \lesssim \) B0 |

\( ^a \) \( 10^{-13} \, \text{erg s}^{-1} \, \text{cm}^{-2} \, \text{arcsec}^{-2} \). This Hα intensity may be contaminated somewhat by [N ii] λ6583 included in the F656N filter; this effect is strongest at the IF. Using the [N ii]/Hα ratio for the IF spectrum from Table 2, combined with the transmission curve of the F656N filter of HST/WFPC2, we estimate that [N ii] contributes less than about 5% of the measured Hα flux at the IF.

\( ^b \) See Sankrit & Hester (2000).
Figure 8. Intensity tracings of the ionization fronts and photoevaporative flows from the surface of the globule. Panels a through e correspond to the positions shown in Figure 7. The left side shows intensity tracings made from HST/WFPC2 images in the [O III] $\lambda 5007$ (F502N; crosses), H$\alpha$ (F656N; thin line), and [S II] $\lambda\lambda 6717+6731$ (F673N; thick line) filters. The right shows tracings made from ground-based near-IR images in the light of He I $\lambda 10830$ (crosses), hydrogen Pa$\beta$ (thin line), and H$_2$ v = 1 – 0 S(1) $\lambda 21218$ (thick line). All fluxes have been corrected for extinction and reddening with $E(B-V)=0.37$ and $R=4.8$, as shown in Figure 6. In each filter, a constant value was subtracted corresponding to the emission from the background H II region far from the globule. Note that the weaker lines of [S II] and H$_2$ have been multiplied by factors of 5 and 25, respectively, for more effective comparison. The horizontal axis shows spatial position relative to the peak of the [S II] emission, adopted as the nominal location of the ionization front. The star symbol in panel (e) marks the position of a star (see Figure 7).

Positions a through d all have the same ionizing source, and Table 4 indicates that all these positions have roughly the same incident flux of ionizing photons, with an average of $\log_{10}(\Phi) = 11.04$ s$^{-1}$ cm$^{-2}$. Position e has a lower incident UV flux, with $\log_{10}(\Phi) \approx 10.7$ s$^{-1}$ cm$^{-2}$. The disagreement between the values of $\Phi$ for positions a through d compared to e is consistent with the apparent morphology in Figure 2, where position e seems to have a different UV source.

The shape and relative intensities of various lines in Figure 8 can also be used to constrain the spectral type of the ionizing star, by comparison to detailed emission models of photoevaporative flows. Sankrit & Hester (2000; SH hereafter) modeled ionized photoevaporative flows as seen in the same optical emission line tracers as we observed with HST. SH found that while the maximum density at the IF depends on the total ionizing flux but not on the shape of the incident continuum, the ratio of [O III] to H$\alpha$ is sensitive to the spectral type of the ionizing star. In Table 4 we list spectral types of the ionizing stars inferred from values of the peak [O III]:H$\alpha$ ratio for positions a through e, corresponding to the models of SH with $\log_{10}(\Phi) \approx 11$ s$^{-1}$ cm$^{-2}$ for positions a through d, and $\log_{10}(\Phi) \approx 10.7$ s$^{-1}$ cm$^{-2}$ for position e (see their Figure 8). We regard these characteristic spectral types as very rough estimates; they should be taken as representing the approximate ratio of photons with $h\nu > 35$ eV to those with $h\nu > 13.6$ eV, rather than the actual spectral type of a main sequence star (SH also noted that the derived properties differed depending on the type of model atmosphere used). This is especially relevant to

4 When interpreting the characteristic spectral types, one should
the possibility of WR25 as the ionizing source, as it is not a main-sequence star and has a strong wind ($\dot{M} = 10^{-4.4}$ $M_\odot$ yr$^{-1}$; Crowther et al. 1995). Also, these characteristic spectral types may underestimate the actual hardness of the source energy distribution, since hard photons may be absorbed in the ambient material between the star and the Finger or by dust in the photoevaporative flow itself. In general, the peak [O iii] $\lambda$5007/H$\alpha$ ratios for positions $d$ through $e$ are consistent with a characteristic spectral type of $\sim$O7 or O7.5, according to the models by SH, while position $e$ requires a source with a spectral type later than B0 (an [O iii] peak is weak or non-existent at position $e$).

Figure 9 shows the hydrogen-ionizing photon luminosity $Q_H = 4\pi R^2 \Phi$ that would be required at a distance $R$ to produce a flux of $\log_\odot(\Phi)=11.04$ s$^{-1}$ cm$^{-2}$ at the surface of the Finger. This is compared to the actual values of $Q_H$ and $R$ for stars that are potential sources of the UV flux evaporating the Finger. $Q_H$ values are taken from Smith et al. (2002) for the corresponding spectral type. For WR25 we adopted $Q_H$ from the models by Crowther et al. (1995; Crowther, private comm.; models by Smith et al. 2002 and Crowther et al. 1995 include line blanketing.) The positions of these candidate source stars are identified in Figure 1 and their properties are collected in Table 5. Figure 9 shows two values for $R$: the separation on the sky given in Table 5, and a value that is a factor of $\sqrt{2}$ larger to account for a possible projection effect. From Figure 9 we conclude that the dominant source of ionization for the Finger is the WNL star WR25 (Crowther et al. 1995) or the neighboring O4 If star Tr16-244 (star number 257 of Massey & Johnson 1993) — or perhaps both working together. It is somewhat unsettling that the thin Finger appears to point toward a slightly skewed position angle of $\sim$208°, while WR25 is found at P.A.$=219^\circ$ and Tr16-244 is at P.A.$=215^\circ$, relative to the Finger; one might expect a feature like the Finger to point directly toward its UV source. However, other factors may affect the appearance of photoionized columns as well (see Williams et al. 2001; Cantó et al. 1998). The Finger does point almost exactly at CPD $-59^\circ 2574$, but as an early B star, it does not even come close to providing the required ionizing flux (Figure 9). Located directly south of the Finger, the massive hot stars HD 93204 and HD 93205 also provide insufficient ionization.

One further complication, however, is that the ionizing continuum striking the Finger appears to be softer than that produced by either WR25 or Tr16-244. The spectral type inferred from the [O iii] $\lambda$5007/H$\alpha$ ratio at the IF is only about O7 (Table 4), whereas both likely UV sources have much earlier spectral types. We have not considered the effect of the strong X-ray flux from WR25 (e.g., Raassen et al. 2003; Seward et al. 1979). Since there are no other plausible sources of ionization in this direction, this suggests that the incident radiation field is softened as it passes through the nebula and the IBL on its way to the Finger. From the spectrum of the IBL we would derive an earlier spectral type from the [O iii] $\lambda$5007/H$\alpha$ ratio than in the thin IF itself (Figure 5 and Table 2).

### 5.3 Mass-Loss Rate and Lifetime

From $^{12}$CO (2-1) observations, Cox & Bronfman (1995) estimated a characteristic mass for the Finger of $\sim 6$ $M_\odot$, but because the emission sampled mostly the warm surface of the cloud, they noted that the total mass of the globule is probably 10 to 20 $M_\odot$. This mass provides the reservoir for future photoevaporation, and allows us to estimate a likely evaporation timescale for the cloud. If the evaporation of the cloud is dominated by the brightest southern IF, and if the geometry can be approximated as a cylinder illuminated on one side, the mass loss rate is given roughly by

$$\dot{M} \simeq \pi r^2 m_H n_H v$$  \hspace{1cm} (3)
where \( r \) is the characteristic radius of curvature of the cloud appropriate for the apparent size of the IF (\( \sim 10^{17.3} \) cm), and \( v \) is the speed of the evaporative flow through the IF. The electron density at the main evaporating surface (positions \( c \) and \( d \)) is \( \sim 4000 \) cm\(^{-3} \) (Table 4), while right at the IF itself we typically have \( n_n \approx 0.7n_H \) because the gas is not fully ionized (e.g., SH). If we assume that the material expands away from the ionization front at the isothermal sound speed \( (v \approx 10 \) km s\(^{-1} \)), then \( \dot{M} \approx 2 \times 10^{-5} \) M\(_{\odot} \) yr\(^{-1} \). In that case, the remaining lifetime of the entire cloud is \( 10^{5.3} \) to \( 10^6 \) years; about 15% to 30% of the age of the nebula. The Finger and other associated molecular clumps probably represent the last vestiges of the original molecular cloud core that spawned Tr16, while significant reservoirs for future star formation exist in the neighboring giant molecular cloud (Grabelsky et al. 1988).

### 6 STAR FORMATION IN THE FINGER?

In addition to the emission-line images described above, near-IR images in the \( J \), \( H \), and \( K \) broadband filters were obtained. A few reddened sources with \( m_K \approx 14 \) were detected within the boundaries of the globule, but these were positioned randomly and could easily be chance alignments of background sources (these point sources can be seen in the 2.122 \( \mu \)m H\(_2\) image in Figure 3c). A few of these \( K \)-band sources seem preferentially located near the limb-brightened edges of the globule, but no reddened stars were detected near the southern ionization front or inside the thin “finger” protruding from it, as one might have expected. However, that doesn’t necessarily mean that no stars are currently forming here or that no stars will form in the future. Below we estimate the amount of extinction in the Finger and the \( K \)-band source that could be hidden, as well as other pertinent quantities like the column density and mass in the Finger and its associated globule. Then we discuss implications for current and future star formation in this globule.

#### 6.1 Extinction and Dust Mass

The Finger globule is seen as a silhouette in \([\text{O} \text{ III}]\), H\(_\alpha\), He 1 \( \lambda 10830 \), and Pa\(_{\beta}\), so tracings through the globule in these emission lines can be used to estimate the optical depth, mass column density, and total mass of the globule. Figure 10 shows representative cross-cuts through the middle of the globule and through the thin finger (perpendicular to tracing “a” in Figure 7). Differences in spatial resolution between the HST and ground-based data aside, it is clear that the minimum emission intensity in the center of each tracing \( I_3 \) increases with wavelength. Thus, the globule becomes translucent at the longer near-IR wavelengths. Interpreting these tracings is not entirely straightforward, however, because the Finger is not a simple silhouette blocking light from a background source — instead, it is a bright-rimmed globule suspended inside the H\(_\text{II} \) region. Thus, some fraction of the observed minimum intensity originates along our line-of-sight to the Finger or near its surface. For example, it would not be unreasonable to assume that roughly half the intensity for each line in Figure 10 is foreground emission. Since the globule has a flat-bottom profile and negligible limb brightening in \([\text{O} \text{ III}]\), we can make a crude correction for this foreground emission if we assume that the globule is optically thick and “black” in the \([\text{O} \text{ III}]\) line. Then, the effective transmission at a given wavelength is given by \([I_3 - I_{3o}]/(1 - I_{3o})\), where \( I_{3o} \) is the minimum flux in the \([\text{O} \text{ III}]\) line in the middle of the globule. Contamination from the IBL is probably worst in H\(_\alpha\) and Pa\(_{\beta}\), so using the He 1 \( \lambda 10830 \) line, we estimate an effective transmission through the middle of the globule of roughly 30%, and a corresponding optical depth \( \tau \) of \( \sim 1.2 \) at a wavelength of 1.08 \( \mu \)m. Similarly, for the thin finger we estimate a slightly higher \( \tau \) of \( \sim 1.5 \) at 1.08 \( \mu \)m. The dust-mass column density is given by

\[
m_{\text{DUST}} \approx \frac{4a \rho \tau}{3 Q_{\text{abs}}} \tag{4}\]

where \( a \approx 0.1 \) \( \mu \)m is the assumed grain radius (large grains dominate the opacity), \( \rho \approx 1 \) g cm\(^{-3} \) is the average grain mass density, and \( Q_{\text{abs}} = 0.04 \) is the extinction coefficient at 1.08 \( \mu \)m (e.g., Draine & Lee 1984). Then, with \( 1.2 \leq \tau \leq 1.5 \) at 1.08 \( \mu \)m, we have characteristic dust-mass column densities of 4 to \( 5 \times 10^{22} \) g cm\(^{-2} \). If we integrate over the entire projected area of the globule, and assume a typical gas:dust mass ratio of 100:1 (this is the dominant source of uncertainty), then we find a total mass for the Finger globule of 6 to 8 M\(_{\odot}\). Likewise, the mass of the small clump at the end of the thin finger is of order 0.1 to 0.2 M\(_{\odot}\). The corresponding hydrogen column density through the globule is \( N_H \approx 2 \) to \( 3 \times 10^{22} \) cm\(^{-2} \).
The excellent agreement with the mass of 6 M$_\odot$ derived for the globule by Cox & Bronfman (1995) is fortuitous, given the large inherent uncertainty in the assumed gas:dust mass ratio. In fact, just as Cox & Bronfman noted that their value was an underestimate because the CO emission was dominated by warm outer layers of the globule, ours is probably an underestimate because some parts of the finger may be optically thick even at 1 to 2 $\mu$m and may hide additional mass.

In our images, the K-band detection limit for point sources projected against the uneven background emission associated with the Finger globule is $m_K \simeq 17$. The extinction estimated above could then hide an intrinsic $m_K \simeq 15.5$ source from detection. At 2.3 kpc, this corresponding to an absolute $K$ magnitude of roughly 3.5 to 4, or a young star of roughly 0.3 to 0.5 M$_\odot$. (Note that this is comparable to the minimum mass of dust and gas within the end of the thin finger.) Considering our detection limit we cannot rule out the possibility that a low-mass star has already formed at the end of the finger, so deeper $JHK$ images with high spatial resolution are desirable.

6.2 Future Star Formation in the Finger?

Even though we have found no direct evidence for newly-formed stars within the Finger, this globule and others like it in Carina may still be likely sites of future star formation. In §5.3 we found that the remaining lifetime before the globule evaporates away is of order $10^5$ to $10^6$ years, which is longer than the average free-fall time for the whole globule, and is plenty of time to allow a dense clump to collapse and form a protostar that would survive exposure to the interior of the H II region. Thus, it is worth a closer look at the physical conditions within the globule and its advancing IF. In particular, we ask whether the formation of a star may be triggered by radiation-driven implosion. We consider two cases: the main southern IF working on the body of the globule, and the end of the thin finger protruding from it.

6.2.2 The Thin Finger

The thin finger protruding from the IF presents a somewhat different case, because it is smaller and denser than the main globule. One might expect that it was much denser than its initial surroundings, and that it has come into pressure equilibrium with the IF, since it has obviously resisted evaporation more than adjacent areas of the initial cloud (see also Williams et al. 2001). We approximate the end of the thin finger as a spherical globule with radius $5 \times 10^{16}$ cm, a mass larger than 6 M$_\odot$, and again, we find it plausible that the dense clump may be in the process of collapsing to form a star — especially if 0.2 M$_\odot$ is an underestimate of the clump’s mass because of high optical depth as noted earlier. Following the analysis above, we find $P_{IF}/P_0 \approx 1.4$. This is considerably more uncertain than for the main globule above, because turbulence dominates the internal pressure, and we do not know to what extent the value of $\sigma$ used above applies to the small fingertip (this uncertainty also precludes a meaningful estimate of the magnetic field needed to halt collapse). Thus, the most likely scenario may be that the fingertip is in pressure equilibrium, and that a slowly-advancing D-type (dense) IF is eating into the fingertip, and the shock from the IF has long ago passed through the clump. If a star is to form here, the process should already be underway. The fingertip may contain a faint low-mass protostar that has escaped detection in our images, or it may have a very young Class 0 protostar. In the latter case, thermal IR emission from a dense hot core would be difficult to detect, as it would be masked by thermal emission from the adjacent warm IF and PDR.

6.2.1 The Main Ionization Front

With a characteristic radius of $\sim 10^9$ or $\sim 3 \times 10^{17}$ cm, the Jeans mass for the whole globule is $\sim 2 M_\odot$ (T/10 K). Thus, with a temperature of 10 - 40 K (e.g. Cox & Bronfman 1995), a mass larger than 6 M$_\odot$ makes it plausible that the globule can collapse to form stars — or at least, one could argue that the globule is on the verge of collapse under self gravity, neglecting rotation and magnetic support. Thus, external pressure may play an important role in the globule's future.

When evaluating if radiation-driven implosion is important, we must consider pressure balance between the ionization front ($P_{IF}$) and the pressure inside the neutral globule ($P_0$). We have

$$ P_{IF} = n_e kT_e + m_H n_e v^2 $$

$$ P_0 = \frac{\rho_0}{\mu m_H} kT + \rho_0 \sigma^2 + \frac{B^2}{8\pi} $$

where \(m_H n_e v^2\) is the back pressure from the photoevaporative flow launched from the IF (roughly equal to \(n_e kT\)), \(\rho_0\) is the mass density, \(\mu\) is the mean molecular weight, \(\rho_0 \sigma^2\) is the inferred turbulent pressure of the molecular gas, and the last term in equation (6) is the magnetic pressure inside the cloud. The electron density and temperature of the IF are roughly 4000 cm$^{-3}$ and 10$^4$ K (Tables 3 and 4), respectively, the average mass density $\rho_0$ inside the cloud is $\sim 2 \times 10^{-19}$ g cm$^{-3}$ (see §6.1), and $\sigma$ is roughly 1.1 km s$^{-1}$ inferred from CO linewidths of 2.7 km s$^{-1}$ (Cox & Bronfman 1995). If we neglect magnetic fields\(^5\), we find $P_{IF}/P_0 \approx 5$. Thus, a significant external overpressure may be causing the globule to collapse. If magnetic pressure is to support the globule, the perpendicular component of the magnetic field that would be required is $\sim 5 \times 10^{-4}$ G. Interestingly, in their analysis of the pillars of the Eagle Nebula, White et al. (1999) find a similar field of $B \simeq 5.4 \times 10^{-4}$ G (in fact, many of the physical parameters of the Finger resemble those estimated for the M16 pillars). However, as noted by those authors, a field of this strength would broaden the observed line width to $\geq 4$ km s$^{-1}$ because of Alfvénic motions, which is broader than the CO linewidth of 2.7 km s$^{-1}$ reported by Cox & Bronfman (1995) for the Finger. Thus, we find it likely that radiation-driven implosion at the IF may be triggering the formation of low-mass stars in the globule.

\(^5\) Note that turbulence dominates over thermal pressure, and we have neglected rotation because the straight edges of the thin finger protruding from the globule suggest that it has maintained the same orientation for its evaporation timescale of $10^5$ years.
7 CONCLUSIONS

We have presented optical narrow-band HST/WFPC2 images, ground-based optical spectra, and near-IR images of the “Finger” – a photoevaporating molecular globule in the core of the Carina Nebula. The main conclusions of this work are the following:

1. The Finger globule exhibits an interesting morphology, with a thin extended middle finger apparently pointing toward its source of ionizing photons. The spatially-resolved structure of the stratified ionization fronts are consistent with the interpretation of the Finger as an optically-thick photoevaporating molecular globule, similar to structures often seen in HST images of H II regions.

2. Quantitatively, electron densities and the corresponding flux of ionizing photons incident upon the southward-facing ionization fronts of the Finger indicate that the dominant UV source is either WR25 (a late-type Wolf-Rayet star), Tr16-244 (O4 If), or perhaps both. This is reassuring, since the finger points to within a few degrees of these stars.

3. The mass-loss rate for the main evaporating surface of the globule is of order $2 \times 10^{-5} M_{\odot}$ yr$^{-1}$.

4. From extinction measurements, we estimate an average hydrogen column density of a few times $10^{22}$ cm$^{-2}$ through the globule, and a total mass (assuming a gas:dust mass ratio of 100:1) of at least 6 $M_{\odot}$, in agreement with independent estimates from molecular studies. This is an underestimate if the globule contains clumps that are optically-thick in the near-IR.

5. The remaining lifetime of the globule before it is evaporated away is of order $10^3$ to $10^6$ years.

6. Several reddened stars are seen projected within the boundaries of the Finger globule, but whether or not these sources are newly-formed stars that are physically associated with the globule is uncertain. No reddened star is seen at the apex of the thin protruding finger or immediately behind the main ionization front, down to a limit of $m_K \approx 17$.

7. Considering the properties of the advancing ionization front, it appears likely that stars are currently forming or will soon form in the globule, triggered by radiation-driven implosion. At the main ionization front we find an external overpressure of a factor of $\sim 5$, and a smaller overpressure ($\approx 1$) at the end of the thin finger.

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