Ionization Structure in the 30 Doradus Nebula as seen with HST/WFPC-2

P.A. Scowen\textsuperscript{1}, J.J. Hester\textsuperscript{1}, R. Sankrit\textsuperscript{1}, J.S. Gallagher \textsuperscript{2}, G.E. Ballester\textsuperscript{3}, C.J. Burrows\textsuperscript{4}, J.T. Clarke\textsuperscript{3}, D. Crisp\textsuperscript{5}, R.W. Evans\textsuperscript{5}, R.E. Griffiths\textsuperscript{6}, J.G. Hoessel\textsuperscript{2}, J.A. Holtzman\textsuperscript{7}, J. Krist\textsuperscript{4}, J.R. Mould\textsuperscript{8}, K.R. Stapelfeldt\textsuperscript{5}, J.T. Trauger\textsuperscript{5}, A.M. Watson\textsuperscript{9} and J.A. Westphal\textsuperscript{10}

accepted for publication in \textit{The Astronomical Journal}, July 1998

\textbf{ABSTRACT}

Using the Hubble Space Telescope and WFPC2 we have imaged the central 20\,pc of the giant H II region 30 Doradus nebula in three different emission lines. The images allow us to study the nebula with a physical resolution that is within a factor of two of that typical of ground based observations of Galactic H II regions. We present a gallery of interesting objects within the region studied. These include a tube blown by the wind of a high velocity star and a discrete H II region around an isolated B star. This small isolated H II region appears to be in the midst of the champagne flow phase of its evolution.

Most of the emission within 30 Dor is confined to a thin zone located between the hot interior of the nebula and surrounding dense molecular material. This zone appears to be directly analogous to the photoionized photoevaporative...
flows that dominate emission from small, nearby H II regions. For example, a column of material protruding from the cavity wall to the south of the main cluster is found to be a direct analog to elephant trunks in M16. Surface brightness profiles across this structure are very similar to surface brightness profiles taken at ground based resolution across the head of the largest column in M16. The dynamical effects of the photoevaporative flow can be seen as well. An arcuate feature located above this column and a similar feature surrounding a second nearby column are interpreted as shocks where the photoevaporative flow stagnates against the high temperature gas that fills the majority of the nebula. The ram pressure in the photoevaporative flow, derived from thermal pressure at the surface of the column, is found to balance with the pressure in the interior of the nebula derived from previous x-ray observations.

By analogy with the comparison of ground and HST images of M16 we infer that the same sharply stratified structure seen in HST images of M16 almost certainly underlies the observed structure in 30 Dor. 30 Doradus is a crucial case because it allows us to bridge the gap between nearby H II regions and the giant H II regions seen in distant galaxies. The real significance of this result is that it demonstrates that the physical understanding gained from detailed study of photoevaporative interfaces in nearby H II regions can be applied directly to interpretation of giant H II regions. Stated another way, interpretation of observations of giant H II regions must account for the fact that this emission arises not from expansive volumes of ionized gas, but instead from highly localized and extremely sharply stratified physical structures.

Subject headings: (ISM:) HII regions; ISM: individual (30 Doradus); ISM: structure; galaxies: ISM; (galaxies:) Magellanic Clouds

1. Introduction

30 Doradus is a giant ionized complex in the Large Magellanic Cloud (LMC), located at a distance of 51.3 kpc (eg. Panagia et al 1991). The nebula is centered on a dense cluster of newly formed stars, the most dense component of which is called R136. The nebula itself is more than 180 parsecs across, qualifying it as a smaller member of the elite class of nebulae termed Giant Extragalactic H II Regions (GEHR’s). If 30 Doradus was placed at the distance of the Orion Nebula from the Earth, it would appear to be more than 20 degrees across, and would fill more than 4% of the night sky.
The central cluster is very dense and is comprised of several hundred OB stars with a small number of W-R stars (Hunter et al 1995b). The integrated ultraviolet flux from this cluster is intense: more than fifty times that being produced in the center of the Orion Nebula (Campbell et al 1992). Radiation from the cluster combined with strong stellar winds from the most massive stars in the cluster has eroded a large cavity in the nearby molecular complex, producing the nebula we see today.

Hunter et al 1995b showed that the majority of the stars in the cluster were formed in a single star formation event more than 2-3 million years ago. The census performed yielded a “head count” of more than 3000 stars with more than 300 OB stars capable of producing the intense UV radiation and strong stellar winds responsible for forming and shaping the H II regions we observe in galaxies. The level of star formation exhibited by the 30 Doradus region and the neighboring LMC complex are the closest example of starburst-like star formation. As such we are getting a unique view of the star formation environment in the middle of an ongoing starburst.

The average reddening along the line of sight to the Large Magellanic Cloud and 30 Doradus is very low (Panagia et al 1991). However, within several H II complexes in the LMC comparison between optical and radio measurements suggest a large variation in the local reddening. Kennicutt & Hodge 1986 found a variation in these estimates between 0 and 1 magnitude in $A_V$. Hunter et al 1995b also found substantial variation in the reddening across the face of the 30 Doradus nebula, and derived a mean estimate for this reddening of 1.4 magnitudes in $A_V$ at 555 nm, and 0.8 magnitudes at 814 nm. For the purposes of this paper we will adopt an extinction of 1 magnitude in $A_V$ for the emission lines we observe.

The 30 Doradus nebula plays a key role in our understanding of H II regions. Nearby regions are close enough for the physical processes at work within the nebula to be studied in detail. The work by Hester et al 1996 (hereafter H96) on M16, for example, shows that emission within the nebula arises predominantly within a narrow region at the interface between the H II region and the molecular cloud. They follow Hester 1991 in describing this thin region as a photoionized photoevaporative flow. However, an H II region like M16 is tiny in comparison with giant H II regions, and no giant H II regions are close enough to allow the stratified ionization structure of the photoevaporative flow to be studied directly. 30 Doradus alone offers an opportunity to bootstrap the physical understanding of small nearby H II regions into the context of the giant regions seen in distant galaxies.

In this paper we present Hubble Space Telescope images of the ionization structure we observe around the central cluster R136. The wealth of spatial information contained in these pictures is daunting to consider, but we attempt to summarize the most telling
points by selecting and presenting several examples of distinct structures around the field of view that provide insight into how the interface with the local gas and dust is evolving. In §2 we discuss the observations themselves and the general structure of the nebula, as well as presenting full-field mosaics of the data. In §3 we discuss the conditions apparent in the ionized hydrogen along the walls of the H II region cavity, as well as comparing the ionization structure we observe with models we derive from the Hα surface brightness.

2. Observations and Data Processing

Observations of 30 Doradus were obtained on January 2, 1994 using the Wide Field and Planetary Camera 2 (WFPC-2). Details of the observations are presented in Table 1. Results of the stellar content of R136 derived from the broad-band images in this set have been published by Hunter et al. 1995b. Here we present narrow-band observations of [O III] λ5007, [S II] λλ6717+6731, and Hα λ6563 emission from the nebula itself. Images in a relatively line-free continuum band (F547M) were also obtained to distinguish between line emission and stellar reflection luminosity.

The data were processed in the standard way for WFPC-2 (Holtzman et al. 1995), including subtraction of DC offsets, bias frames, and the flat field correction. Time dependent hot pixels were subtracted using maps derived from on-orbit dark frames from that general time frame. Cosmic rays were removed using standard anti-coincidence techniques for each pair of images. The images were mosaicked using the appropriate astrometric solution from Holtzman et al. 1995.

Figures 1-4 presents the four datasets used in this paper as surface brightness mosaics: Figure 1 being the Hα, Figure 2 the [O III], Figure 3 the [S II], and Figure 4 the F547M. The location of the WFPC-2 field is superimposed on a CTIO R-band image of 30 Doradus in Figure 5. Figure 6 presents the full field color image of the 30 Doradus nebula. In producing the color image the following steps were taken: (i) all stars were masked off and filled, (ii) the [S II] image was included as red, the Hα as green and the [O III] as blue, and (iii) the F170W image was used to replace the hottest stars also in blue. As presented the position angle of the field of view for these data is 62° east of north. One WFC pixel represents a linear scale of $7.7 \times 10^{16}$cm or 0.025pc, at the assumed distance of 51.3 kpc to the nebula.
2.1. General Appearance of the Nebula

Our field of view is at the very heart of the 30 Doradus Nebula and positions the cluster R136 on the Planetary Camera. As such our field extends to a radius of 15-20pc around the center of the nebula, with WF2 to the SE, WF3 to the SW and WF4 to the NW (cf. Figure 1). The structure of the nebula is dominated by the ionizing flux from the large number of Wolf-Rayet and early O stars known to be in the cluster (Hunter et al 1995b). Very close to the center of the cluster there is very little nebulosity, except for a component that can be seen between the cluster stars. This emission could originate either in front of the cluster or behind it, but it does not lie within the interior of the cluster. Intense UV and stellar winds have cleared the cluster itself of dense gas.

Almost all of the nebulosity we observe is concentrated into bright arcs or edges located along the walls of the cavity. Bright rims such as these are commonplace in photoionized nebulae in our own Galaxy. They represent the boundary between the ionized volume and the nearby neutral and molecular gas from which the young cluster was born. The presence of significant xray emission within the interior of the nebula and the strongly limb-brightened appearance of these edges suggests that the more diffuse nebulosity arises in such interfaces, but instead seen more face-on.

At a radius of about 5pc there is a bright circular rim centered on the cluster. This marks the first major interface between the cluster radiation and the nebula wall. To the WSW from R136 this rim is very bright and is littered with finger-like structures that all appear to point toward the cluster. Outside of this rim the brightness of the nebula dims significantly.

One very bright rim is located directly south of the cluster and stands out as a bright ridge set against a relatively darker region. As such we contend that this ridge is directly exposed to the ionizing radiation from the central cluster.

The nature of the photoionized interface at the boundary of a molecular cloud has been discussed in the literature. Heating by UV radiation incident on the interface drives a photoevaporative flow away from the interface (Bertoldi 1989, and references therein). This flow is then photoionized by the same radiation responsible for driving it. Such photoionized photoevaporative flows are characterized by sharply stratified ionization structure (Hester 1991; H96). The overall thickness of the resulting emissive region is typically of order $10^{17}$ cm, while the observed scale for stratification at the boundary of the cloud can be much less.

By using emission lines arising from species with different ionization states it is possible to probe the structure of this region. High ionization lines such as [O III] $\lambda 5007$ arise in
the part of the flow furthest from the interface where the ionization parameter is high and
the radiation field contains enough high energy photons to reach such ionization states.
Emission from species such as [S II] $\lambda\lambda 6717 + 6731$ are brightest beyond the hydrogen
ionization edge where the gas density is high and the radiation field is depleted of photons
with energies in excess of 13.6 eV. In M16 there is a clear distinction between the peak of
the [S II] zone and the peak of the H$\alpha$ zone, but the two are separated by only of order $10^{15}$
cm. H96 found that this structure can be reproduced in detail by photoionization models
using a steeply falling density distribution.

Manipulation of photoionization models has revealed that the physical extent of
the emission zones and their relative strengths and separations can vary substantially.
Factors that can affect these distributions include the steepness of the particle density
gradient toward the ionization front, the intensity of the incident ionizing radiation, and
the “hardness” of the ionizing radiation (the fraction of photons that fall shortward of the
Lyman edge)(H96, and references therein).

While 30 Doradus is too distant to allow resolution of the separation between the H$\alpha$
and [S II] peaks, it is close enough to see the difference between the highly localized [S II]
emission and the thicker zone in which much of the H$\alpha$ and all of the [O III] originates.

In 30 Doradus, our images have been taken in the three emission lines mentioned
above. Comparing Figures 1-3 we notice that while the images differ in several ways but
are also quite similar in many others. In the majority of locations across the nebula the
general appearance in the distribution of [O III] emission is almost identical to that of the
H$\alpha$ emission. The nebula looks very different in [S II] $\lambda\lambda 6717+6731$ but since these lines
are brightest outside of the ionized volume, they trace structure that [O III] and H$\alpha$ cannot.

Most of the physical structures we observe in 30 Doradus exhibit bright emission in
all three of the lines allowing us to trace a consistent picture of the ionization structure in
those locations. Several regions appear only bright in H$\alpha$ and [S II] indicating that the
emission from those regions is characteristically of lower excitation.

In the rest of this section we are going to visit and describe individual locales in
the wall of the nebula. Each will be featured as a morphological prototype for a host of
other structures we observe across the field but that we do not have the space to address
individually here. The approach we will use employs the three emission lines to compare
and contrast the observed physical structure in each line and uses these clues to make some
statement about the physical nature of each object.
2.2. Objects of Interest in the Field

2.2.1. A high proper motion star?

Toward the upper left corner of Figures 1-4.6 is a long tube-like structure, especially visible in [S II], that runs approximately E-W. It is rather dim and so has been reproduced in some detail as Figure 7a-7c. In Figures 7-9 the sets of 3 panels observe the same convention: the top panel represents [O III], the middle represents H α, and the bottom represents [S II].

This object is composed of a long (1.5pc) limb-brightened tube of emission that is bright in [S II] and is visible in H α but not [O III]. There is one part of the tube that does show up in [O III] (in the upper left) and this corresponds to regions where the H α and [S II] are brightest. The wall of the tube is also thickest in this region. Elsewhere the wall is close to being unresolved, and appears broken and discontinuous in many locations. The lower right end of the tube appears to widen to a more spherical shape where a faint star is seen at the heart of the cavity. The very end of the cavity is very fragmented in appearance, and has a radius of about $7 \times 10^{17}$ cm. The center volume of the tube and cavity are relatively dark contributing little emission. The low ionization tube lies within a more extended region of diffuse higher ionization emission. The intensity of the emission from the tube does not depend on distance from the star at its head, indicating that it is ionized externally rather than by the visible star.

The appearance of the system is one of a tube with a relatively dense wall, that provides enough local electron density and column depth to make it brighter in both H α and [S II] relative to the background nebula. The walls appear to have a resolvable thickness in places but this appearance might also be produced by limb brightening of an unresolved surface. The apparent “width” of the wall in the upper left is about 1.3 WFC pixels or $10^{17}$ cm. We infer that the center of the tube is less dense because of the lower emission in that region. The tube is seen to narrow with increasing distance from the star.

We suggest that this structure might be the result of a high proper motion star that has a stellar wind. This star appears to be ploughing its way through a cloud of gas of intermediate density. Around the star itself the wind establishes a balance with the thermal pressure of the local gas and produces the observed cavity. As the star moves through the cloud, from upper left to lower right in our image, the leading edge of the cavity continues to be pushed into the local gas. On the trailing edge the wall of the cavity persists to leave a channel or tube through the nebula gas.

If we balance the thermal pressure in the main nebula, obtained from xray observations
(Wang & Helfand 1991) to be about $10^{-10}$ ergs cm$^{-3}$, with the kinetic energy of the material of material in a wind, then we can infer the density of the material in that wind. The typical velocity of a stellar fast wind is about $10^3$ km s$^{-1}$, which implies a wind particle density of about $10^{-2}$ cm$^{-3}$. This corresponds to a mass loss rate of about $10^{-7}$ M$_\odot$ yr$^{-1}$ when integrated across a sphere of radius $7 \times 10^{17}$ cm. At the point where the wind kinetic energy balances the thermal pressure in the nebula, i.e., at the bubble wall, if the gas is at a temperature of $10^4$ K and using the known pressure, we calculate a local particle density of about 50 cm$^{-3}$.

This is a fairly low density, and one would expect there to be significant [O III] and H$\alpha$ emission except that the surrounding material provides enough shielding. This calculation simply balances the momentum in the wind with the thermal pressure of the local nebula gas. If the star does indeed have a significant proper motion then the mass loss rate and the gas density in the wall are both lower limits.

This tube will collapse in time as the gas in the tube cools and the surrounding nebula gas moves to fill the void under thermal pressure. The speed of this collapse would be something like the local sound speed. Using the canonical temperature for photoionized gas of $10^4$ K we estimate the local sound speed to be of order 12 km s$^{-1}$. We measure the opening half-angle of the tube to be 3 degrees. If all the transverse velocity is produced by the collapse of the tube at the sound speed, the 3 degree angle implies that the forward proper motion of the star is of order 230 km s$^{-1}$, which is equivalent to an angular proper motion of 0.95 mas yr$^{-1}$.

If this is a star with a substantial proper motion, then its path appears to take it directly toward the center of the cluster. If we take the mass of the cluster to be $10^6$ M$_\odot$ then at the apparent distance of the tube from the cluster center of about 20 pc the escape velocity of the cluster is about 20 km s$^{-1}$. We have calculated an apparent proper motion that is an order of magnitude greater than this. Therefore the star is not bound, and is therefore not on a return orbit. The fact that its velocity vector appears to coincide with the cluster is coincidence.

2.2.2. Overlapping bubbles or a single cavity?

Towards the center of WF2 in Figures 1-4,6 are a couple of overlapping arcs. The arcs are shown in Figure 7d-7f, and are visible to varying degrees in all three emission lines. The sharpest structure is seen in the [S II] image. Both arcs are covered or masked by appreciable levels of foreground H$\alpha$ and [O III] emission. The arcs themselves appear quite
sharp-edged, and appear to brighten towards their edges suggesting that they are probably thin sheets that are limb brightened, implying that they are seen in projection from one side.

At the distance we adopt to the nebula the arcs have a radius of about 1.5 parsecs with a peak surface brightness of 0.022 ergs cm\(^{-2}\) s\(^{-1}\) Sr\(^{-1}\), or \(5.1 \times 10^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\).

Each of the arcs appears to open toward one of the two bright stars seen in the figure. The lower of these two stars has been identified in the ground-based census of stars in the region of the R136 cluster published by Parker 1993, and subsequently included by Walborn & Blades 1997. The other star has not been previously identified, but does appear from our data to be redder and therefore later in spectral type than the first star. The lower star is classified as a B 0.5 type Ia star by Parker 1993, implying the existence of a possible massive wind associated with it. We therefore assume that the lower star is the one responsible for the origin of the arcs, with the upper star being a line of sight coincidence with the structures. Recent work by Aufdenberg et al 1998 has shown that conventional atmosphere models of early B stars have underestimated the hydrogen-ionizing flux they are capable of producing, in some cases by as much as a factor of two. The helium-ionizing flux may be underestimated by an order of magnitude. As such it is entirely possible that the lower of these two stars could produce enough flux to ionize the local gas and cause a lot of the diffuse H\(\alpha\) we see spread across the foreground of this object. The wind from the star might also have been sufficient to sweep up enough material from the region around the star to produce the thin shell of gas we observe. This shell was then ionized by the flux from the same star.

2.2.3. Finger-like column in the molecular wall of the cavity

Immediately to the south of the R136 cluster is an isolated region of very bright emission in all three emission lines we observed. Figure 8a-8c illustrate the structure in the previous manner. Central to the overall morphology of the region are a number of finger-like structures that stick out from the wall of the cavity directly at the main cluster. The main column is about a parsec long and about 0.25 parsec wide. The \([\text{O III}]\) and \(\text{H}\(\alpha\)\) emission are again very similar, while the \([\text{S II}]\) is quite different being concentrated to a narrow region that hugs the wall of cavity. As such these structures bear a striking resemblance to the columns of dense material observed in M16, the Eagle Nebula, in our own Galaxy and recently studied in high detail with photoionization modelling by H96. The main column we observe in 30 Doradus is directly comparable to the largest column in M16.
Considering the physical scales found to be important in the modelling of the structure observed in M16, we know that these scales are hopelessly unresolvable in the 30 Doradus nebula at a distance some 25 times further away than M16. Direct comparison between the two nebulae also shows a difference in presentation - with the Doradus finger being viewed more obliquely and through much more foreground emission than M16. Since the visible face of the column is bright in both Hα and [S II] we can state that the near face of the column is directly exposed to the radiation from the cluster. As such we can also state that the column is therefore on the far side of the tangent plane that passes through the cluster, and that therefore the finger is sticking out of the back wall of the nebula rather than a feature of the near wall.

We place the finger on the back wall but not too far into the back since the foreground emission is not as bright as some regions in the nebula. By doing this we can infer very low levels of intrinsic reddening within the nebula, but we will still adopt our conservative estimate of 1 magnitude of extinction in A_V.

Based on the similarity in the morphology of the two systems, we explicitly compare M16 with the Doradus finger in the Discussion section below and derive limits on the physical conditions in the nebula despite our much poorer physical resolution at the distance of the LMC. For more details about the structure of this object refer to that section.

2.2.4. A low excitation H II region

At the bottom of the field in Figures 1-4,6 is a well-defined bubble-like structure about 2-3 pc in diameter. This structure is depicted in the usual way in Figure 8d-8f. It is characterized by bright emission in both Hα and [S II]. At the geometric center of the region is a bright star not catalogued by any previous surveys of the region. Around this star is some very faint diffuse [O III] emission.

These morphological hallmarks when combined with the absolute levels of the ratio of [S II]/Hα (ranging from less than 0.1 in the center to peaks around 0.3 at the edge) and [O III]/Hα (only ranging between 0 and 0.4 across the bubble) point to a low-excitation H II region centered on the star. This view is supported by the fact that the peak in the lower-energy emission lines [S II] occurs exterior to that of the higher line Hα - a known morphological hallmark of a photoionized region. We observe the peak Hα surface brightness to be 0.004 ergs cm⁻² s⁻¹ Sr⁻¹, or 9.1 x 10⁻¹⁴ ergs cm⁻² s⁻¹ arcsec⁻².

The lack of any appreciable [O III] emission in the main body of the small H II region, particularly around the star itself, implies that the ionizing radiation from the star is
not very “hard”. However, there is still enough flux coming out of the star to ionize an appreciably large volume of gas. This would suggest an early B star as the culprit rather than a late O star. In addition the lower left end of the bubble appears open-ended and may represent some type of over-pressure blowout from the cavity into a lower density region. Further observations would be needed to clarify the exact physical nature of the system.

An excellent collection of Galactic H II regions was catalogued by Sharpless 1953, chosen for their strong line emission. Many objects from this sample have been observed by Hester et al 1992 as part of a morphological atlas of line emission from H II regions. After comparing this bubble-like object with several of the nebula in this collection, the best analog found was the nebula S-104. The observed line ratios and overall shape were very similar. We assume that the two nebulae are also similar in the source and strength of their ionizing sources, allowing us to assume that they are the same physical size based on Strömgren sphere considerations. To make the observed diameter of S-104 the same as that of the bubble nebula it would have to be placed at a distance of about 50kpc. This confirms that the bubble nebula is located in the LMC.

It is difficult to place the bubble along the line of sight with respect to the 30 Doradus nebula. Some of the structure observable in the 30 Doradus nebula can be seen through the bubble, suggesting that the bubble might be closer to the observer than the main nebula. However, as we stated above, we do know that the bubble nebula is part of the LMC and is therefore more local to 30 Doradus than to our Galaxy.

2.2.5. Two views of the edge of the main cavity

Examination of the images in Figures 1-4,6 show a remarkably circular edge to the main cavity - that part of the inner nebula immediately centered on the R136 cluster. This region has a radius of about 8pc and in our field is characterized by a bright rim to the SW with numerous large elephant-trunk-like structures. In Figure 9 we present two sets of panels focussing on two particular areas around this bright rim.

Figure 9a-9c depicts a region WSW of the cluster with a dark ridge that runs as a chord from rim edge to rim edge. Scattered along the outside of this ridge are several blob-like structures with fairly long tails. At this distance our view of these objects is not good, but we can determine some morphological properties. The objects are bright in both Hα and [O III], with the latter appearing marginally sharper around the edge of the objects. In [S II] the objects appear smaller and fainter. These structures are about 2-3 WFC pixels across (2 × 10^17 cm, 13000 AU, 0.06 pc) and have tails as long as 10-12 pixels.
(7 – $10 \times 10^{17}$ cm, 65000 AU, 0.3 pc). The distribution of emission suggests that the [S II] emission comes from a central core, with the Hα and [O III] emission coming from a bright sheath surrounding the core.

As such these objects could represent smaller versions of the finger-like column, mentioned above. These structures could also be protruding from the cavity wall or could even be separated from the wall. It is not uncommon to find large globules of this kind floating free in Galactic H II regions (we have found examples in M8 and M17 from the collection of H II regions by Hester et al 1992), and so it should not be surprising to find analogs in this nebula.

A little further out from the cluster is the main inner cavity edge – seen as a large circular interface around the PC/WFC boundaries in Figures 1-4,6. The brightest part of this region is depicted in Figure 9d-9f. In this field we have two remarkable structures. The lower, darker feature has many common morphological traits with outflows observed in our own Galaxy associated with HH objects and the like. A good physical analog might be HH47 except that HH47 is only about 0.6 pc long (Heathcote et al 1996), whereas the “flows” we observe in 30 Doradus are as long as 1.2 pc. The flow is composed of dense, non-optically-emitting gas and appears to broaden into a bow-shock-like interface at its end. The narrow end of the structure could be the outflow source and appears to be buried in the cavity wall.

Immediately above this is another structure which appears quite ghostly in Figure 9d-9f. It is another tall column of material, but its shape and the limb brightened emission in all three emission lines suggest that it is more like the finger-like structure we considered above. This column measures about a parsec in length and so is very comparable in size to M16 and the Doradus finger. Buried in the head of this column is a stellar object that may or may not be associated with the column. This object is very close to one of the bright IR sources found in the 30 Doradus nebula by Hyland et al 1992, and noted in passing in WFPC-1 images of the region by Hunter et al 1995a. The accuracy of the position published by Hyland could place either of these two column-like objects within the positional error bars.

The second column is veiled in very bright foreground emission making clear definition of the structure hard. When we compare the emission line profiles across the edge of this structure, we see similar ionization structure characteristics to those found across simple photoionized interfaces. The [O III] and Hα are more extended and appear to be limb brightened only on the side of the column closest to the central cluster. The [S II] emission is much more concentrated towards the very edge of the column and is spread thinly across the face of the column as well. Due to the bright foreground emission in both [O III] and
Hα we cannot accurately determine how bright the front face of the column really is in these two lines.

Across this particular field we also see many smaller globules and finger-like structures that exhibit similar physical morphology in the three emission lines as do the prototypes we have already discussed. In light of what was learned about photoevaporation in M16 by H96, we expect the majority of the remaining structures in the field to be somewhat denser than their surroundings, and might harbor new stars that are in the process of forming.

The remarkable thing about the emission along this cavity edge is the total lack of any emission to the upper left (toward the cluster) from this edge. This is apparent too in Figures 1-4,6. The volume of the very inner cavity appears totally devoid of any detectable line emission - a direct result of a very low local electron density driving down the emission measure for these lines. The only line emission seen in this region is visible between the stars of the cluster. Estimates for particle densities in the main cavity of 30 Doradus based on diffuse xray background emission (Wang & Helfand 1991) suggest number densities around $0.2 \text{ cm}^{-3}$. The same paper also noted several regions or pockets of very hot xray emitting gas associated with “holes” in the optical Hα emission seen from the ground. These regions are probably filled with gas that has been even more strongly shock excited than the majority of the cavity and may be associated with some of the Wolf-Rayet stars discovered by Hunter et al 1995b.

3. Discussion

3.1. Hα Surface Brightness and Photoevaporative Flow

In §2.2.3 we describe an elephant trunk structure that is a remarkable analog to the structures in M16. Located about $10^{18}$ cm from the head of this structure and another nearby elephant trunk are two arcuate emission features. We interpret these features as bow socks where the diverging photoevaporative flow stagnates against the pressure in the hot gas that fills most of the volume of 30 Doradus. (A similar interpretation was offered by H96 for faint filaments in M16).

Since the interface at the end of the column in 30 Doradus is concave to the pillar, we assume that the flow is spherically divergent and obeys a $1/r^2$ law for density with distance.

We observe that the surface brightness of this concave bowshock is $3 \times 10^{-4}$ ergs cm$^{-2}$ s$^{-1}$ Sr$^{-1}$ above the bright background, which is equivalent to an emission measure of 1400 cm$^{-6}$ pc. The observed “width” of the bowshock is very thin indeed. It appears to be a
limb-brightened shell that has little or no transverse thickness. We put an upper limit on
the width of the interface at 2 WFC pixels or 0.05 parsecs ($1.5 \times 10^{17}$ cm). If we assume
we are looking at a tangent through a shell of this thickness then the characteristic line of
sight through the wall of that shell will be of order $10^{18}$ cm. Using the emission measure
we observe for the shell wall this implies a local electron density of about $70 \text{ cm}^{-3}$. This is
a lower limit. If this shell is in fact thinner than we can resolve, which is quite likely, then
the actual electron density will be higher. If the shell is a factor of 3 thinner (which is the
sort of shell thickness observed in Galactic wind blown bubble nebulae such as NGC 7635
and NGC 6888) then the implied electron density is more like $260 \text{ cm}^{-3}$. We observe the
radius of curvature of the bow shock to be about 24 pixels, with the end of the column at a
radius of about 7 pixels. This implies a factor of 1/12 drop in the flow density from the end
of the column to the bowshock, assuming a $1/r^2$ divergence. Therefore the density at the
end of the column must be about $3000 \text{ cm}^{-3}$.

The thermal pressure at the end of the column drives the divergence of the gas away
from the interface. At the bowshock the pressure of the photoionized gas is given by:

$$P = nkT_e = 2n_e kT_e = 2 \cdot 260 \cdot k \cdot 10^4 \sim 7 \times 10^{-10} \text{ erg cm}^{-3}$$ (1)

We need to determine the character of the material in the cavity of 30 Doradus. If
it is simply a volume filled with photoionized/photoevaporated material then the typical
electron temperature is something like $10^4$ K. However, if the interior gas has been shock
heated by the strong stellar winds from the dozen or so Wolf-Rayet stars found in the
cluster (Hunter et al 1995b), combined with the possible effects of supernovae that have
occurred in the cavity since it was formed, then the typical electron temperature is probably
in excess of $10^6$ K. Wang & Helfand 1991 presented observations of the diffuse gas in the
nebula made with the Einstein Observatory. They found a diffuse x-ray component with
a characteristic temperature of about $5 \times 10^6$ K. From their observations of the x-ray
luminosity they presented a relation between the electron density in the x-ray bright gas
and the overall cavity size. In their paper they assumed that the photoionized gas pressure
was more like $1 \times 10^{-10}$ ergs cm$^{-3}$, instead of the higher value we calculated by divergence
above.

If we balance the divergent $\rho v^2$ flow calculated above with the thermal pressure of an
x-ray bright gas at $5 \times 10^6$ K, we predict an electron density of $0.5 \text{ cm}^{-3}$ for the hot diffuse
gas that fills most of the nebula. This number compares well with the implied estimate by
Wang & Helfand of $0.2 \text{ cm}^{-3}$. This is good agreement considering how disparate the two
approaches are and the assumptions that have been made.
Next we turn to the emission we see across the top of the column itself. The brightness of the emission at the end of the column allows us to make some statement about the physical conditions in the region where the emission is most intense. Hunter et al. 1995b quote an ionizing flux of lyman continuum photons of $2 \times 10^{51}$ photons sec$^{-1}$ within 93 pc of the cluster center. This number was in good agreement with calculations made by Kennicutt & Hodge 1986 if an internal reddening of 1 magnitude in $A_V$ is assumed. Here we will adopt this value for the ionizing flux incident on the elephant trunks since this close in to the center of the nebula the ionizing flux is dominated by the radiation from R136.

If $Q$ is the ionizing luminosity in units of photons sec$^{-1}$ coming out of the cluster, then we can express the incident ionizing flux at the elephant trunks as:

$$q = \frac{Q}{4\pi R^2} = \frac{2 \times 10^{51}}{4\pi \cdot (5 \times 10^{19} \text{cm})^2} = 6 \times 10^{10} \text{photons cm}^{-2} \text{sec}^{-1}$$  \hspace{1cm} (2)

where $R$ (= 15 pc) is the distance from the ionizing stars. This estimate is made in the plane of the sky and could be much larger if the finger is located on the back wall of the nebula cavity. Assuming that objects such as these are randomly distributed throughout the cavity we can assess this uncertainty by introducing a factor of $\sqrt{2}$ in our estimate of the distance from the ionizing source. The fraction of these incoming photons that produce a visible H$\alpha$ photon is given by the ratio of the recombination coefficient for the H$\alpha$ transition to the total recombination rate for hydrogen as a whole. From Osterbrock 1989, Table 4.2, we find that the recombination rate for H$\alpha$, $\alpha_{H\alpha}$ (in units of cm$^{-3}$ sec) is:

$$\alpha_{H\alpha} = \alpha_{H\beta} \cdot \frac{j_{H\alpha}}{j_{H\beta}} \cdot \frac{E_{H\beta}}{E_{H\alpha}} = (3.03 \times 10^{-14}) \cdot (2.87) \cdot (1.35) = 1.17 \times 10^{-13} \text{cm}^{-3} \text{sec}$$  \hspace{1cm} (3)

where $E_{H\alpha}$ is the photon energy for H$\alpha$, $E_{H\beta}$ is the photon energy for H$\beta$, and all numbers are quoted for conditions of $10^4$ K. This predicts that the fraction of H$\alpha$ photons emerging versus incoming hydrogen ionizing photons is:

$$\Im = \frac{\alpha_{H\alpha}}{\alpha_B} = \frac{1.17 \times 10^{-13}}{2.59 \times 10^{-13}} = 0.453$$  \hspace{1cm} (4)

Using equations (2) and (4) we calculate that the expected H$\alpha$ flux emerging from the end of the column should be $3 \times 10^{10}$ photons cm$^{-2}$ sec$^{-1}$. If we include the statistical factor of $\sqrt{2}$ for the projection along the line of sight, this could fall as low as $2 \times 10^{10}$ photons cm$^{-2}$ sec$^{-1}$. This is the emission we expect to be emerging from the end of the column, but
we need to factor in the adopted extinction to make an estimate of the expected surface brightness we would measure. Doing this, using 1 magnitude of $A_V$, we end up with an estimate of $1 \times 10^{10}$ photons cm$^{-2}$ sec$^{-1}$.

We need to estimate the size of the emitting region, but lack one of the dimensions. We can measure the transverse width across the column, and the depth of the zone along the radial vector from the cluster, both measured in the plane of the sky. The third dimension, the transverse depth of the emitting zone across the column but perpendicular to the plane of the sky, is unknown. Using our observations we will constrain this depth. If we assess what the emission per unit length across the top of the column is in the plane of the sky, we can use the observed surface brightness to calculate how deep the emission zone must be to produce that level of emission.

The first step is to place an aperture across the top of the column and integrate it across the short dimension of the column. This takes the measured surface brightness in units of ergs cm$^{-2}$ s$^{-1}$ pixel$^{-1}$ and produces an emission per unit length along the top of the column in units of ergs cm$^{-2}$ s$^{-1}$ pixel$^{-1}$. This is now essentially an integrated profile of the emission across the interface at the end of the column. From this profile we need to choose the value and location that corresponds to the thin emission zone at the top of the column, which we know to be unresolved in our data. When we do this we measure a value of $2 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ in the one pixel that represents the width of the emission zone at the top of the column. Converting this to H$\alpha$ photons, we get a flux of $7 \times 10^{-3}$ H$\alpha$ photons cm$^{-2}$ s$^{-1}$ in one pixel. This flux needs to be corrected for the 1 magnitude of extinction we have assumed, increasing the flux estimate to $2 \times 10^{-2}$ H$\alpha$ photons cm$^{-2}$ s$^{-1}$ in one pixel.

We next need to take out the effect of the inverse square law by integrating the flux we observe over a sphere of radius 51.3 kpc. This yields a flux of $5 \times 10^{44}$ H$\alpha$ photons s$^{-1}$ in that one pixel. The width of that one pixel is $7.7 \times 10^{16}$ cm at the distance we are assuming for 30 Doradus. Dividing out the physical extent of the pixel along the top of the column we end up with a flux per unit length of $6 \times 10^{27}$ H$\alpha$ photons cm$^{-1}$ s$^{-1}$. Our estimate of the expected H$\alpha$ flux from the top of the column was $1 \times 10^{10}$ photons cm$^{-2}$ sec$^{-1}$. If we divide the two quantities we arrive at an estimate for the depth of the emitting region into the plane of the sky. This depth is $6 \times 10^{17}$ cm, or about 8 WFC pixels. This dimension is very close to the observed transverse width of the column in the plane of the sky, so it is appropriate to think of the column as being cylindrical.

Now that we know the dimensions of the emitting region at the end of the column, we can use the observed surface brightness to make an estimate of the local electron density in the emitting region, and compare it to the estimate of 3000 cm$^{-3}$ made independently using the observed bow shock around the end of the column.
The conversion between observed surface brightness and emission measure (EM) is:

\[
EM(\text{cm}^{-6}\text{pc}) = 2.41 \times 10^3 T_0^{0.92} S(\text{H}\alpha)
\]

where S is the surface brightness expressed in units of ergs cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) (Peimbert et al 1975).

We measure the mean surface brightness per pixel to be \(1 \times 10^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\), or \(4 \times 10^{-3}\) ergs cm\(^{-2}\) s\(^{-1}\) Sr\(^{-1}\). Correcting for an extinction of 1 magnitude raises these numbers to \(2 \times 10^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\) arcsec\(^{-2}\), or \(1 \times 10^{-2}\) ergs cm\(^{-2}\) s\(^{-1}\) Sr\(^{-1}\). This measurement was made across the brightest region of emission at the top of the column, after having the bright background/foreground subtracted. The corresponding emission measure is \(1 \times 10^5\) cm\(^{-6}\) pc. Using the derived path length through this emission zone of \(6 \times 10^{17}\) cm, or 0.2 pc, we obtain an electron density of about 700 cm\(^{-3}\).

When considering the emission at the end of this column we have to assess the impact of our lack of sufficient resolution. We have calculated that if you take the observed flux and the observed extent of the emitting region we derive a mean electron density of about 700 cm\(^{-3}\). In M16, H96 shows that the H\(\alpha\) bright emission zone is of order \(2 \times 10^{15}\) cm which would be unresolved in our data. Using the data from the HST observations of M16 we estimate that the ratio between the observed mean electron density for the region and the value derived from where the emission peaks is about a factor of 1/3. We also have to assess the difference in path length through the emitting gas. The path length of the line of sight through the region where the emission peaks will be shorter than the path length through the extended emission (since it is further out from the interface). We estimate this difference in path length to be about a factor of 5 (or a factor of \(\sqrt{5}\) in electron density since it is proportional to the square root of path length). Combining these two corrections yields a potential increase in our electron density estimate to about 4700 cm\(^{-3}\). This is an average assessment of the impact of the two effects, and it is entirely possible that slightly different factors should be used in the case of 30 Doradus. Given this uncertainty this estimate compares well with our earlier independent estimate of 3000 cm\(^{-3}\) based on the bowshock. A summary of the numbers we have calculated is included in Table 2 along with numbers calculated for M16 from H96.

In Figure 10 we compare the finger in 30 Doradus with the columns of gas in M16. In addition we present measured profiles for the three emission lines to illustrate the similarities between the two objects. There are definite differences between the two cases, however, which we will address below.

In conclusion, we have shown that the observed characteristics of the H\(\alpha\) emission at the edge of the 30 Doradus nebula are well explained by the existence of a photoevaporative
flow. We resolve a bowshock transition between the photoevaporative flow and the shock heated tenuous gas that fills most of the 30 Doradus cavity. The apparent brightness of this interface gives us an independent estimate of the conditions at the head of the column and agree well with our estimates based purely on the apparent surface brightness coming from the column itself. The column in 30 Doradus is a good morphological analog for the columns observed in M16 by others, but upon closer examination the conditions in 30 Doradus are slightly different.

3.2. Stratification of the Ionization Structure

At the distance to the Large Magellanic Cloud (51.3 kpc) our linear resolution in 30 Doradus is $7.7 \times 10^{16}$ cm, or about 5000 AU. This compares to the typical resolution achieved by ground-based observations of Galactic H II regions of about $3 \times 10^{16}$ cm, or about 2000 AU. With the HST we can study the ionization structure in 30 Doradus in the same way that we have been used to studying the structure in local objects.

We cannot, of course, achieve the kind of resolution that was achieved with HST imaging of M16 (H96) – that allowed successful modelling of the observed structure of the photoionized gas using the known incoming ionizing radiation and the observed density profile of the ionized gas across the edge of the H II region. It is, however, instructive to compare what information we can extract from these data with the picture reached in M16.

The method used to model the structure in M16 started with the observed H$\alpha$ profile. For a constant path length through the emitting gas, the surface brightness of H$\alpha$ emission is proportional to the square of the local electron density. This fact allows us to map the local density of neutral gas, which in turn allows a self-consistent photoionization calculation to be made of the observed structure using photoionization codes such as CLOUDY (Ferland et al 1996). The results achieved in M16 with HST were impressive and represented the first time this type of model had been compared directly with observation.

To pursue this approach we need a clean view of an ionization front, and the structure depicted in Figure 10 is again the best choice in our field. We imaged the nebula in three emission lines, each characteristic of a different photoionization energy. The structure of the ionization front in an H II region is predicted by theory to be layered with [O III] emission originating interior to the interface, the H$\alpha$ emission being concentrated toward the interface and peaking there (by definition), and finally the [S II] is predicted to peak just outside the ionization front (since it has an ionization potential just less than 13.6 eV) with an emitting zone that is very narrow.
When profiles of sufficient resolution are taken across the bright edges of H II regions these emission line zones form “strata” where the emission from each line forms a distinct peak. These peaks are usually separated since the conditions for the emission to be maximized for each line differ in terms of the local electron density and the emissivity of the appropriate species.

In Figure 11a we show the background subtracted profiles from the column in 30 Doradus plotted as a function of linear distance. The H$\alpha$ and [O III] peaks are essentially coincident. The [S II] peak is separated from the other two by as much as $10^{17}$ cm. Employing the density distribution derived from the square root of the H$\alpha$ profile in Figure 11a, we ran a model of the expected photoionization structure at the interface between the H II region cavity and the bounding molecular gas. The other input to this model is the expected hydrogen-ionizing flux from the cluster (calculated above, Hunter et al 1995b). The appropriate mix of stellar continua was made using the spectral type distribution inferred by the results of Hunter et al. It should be noted that the resulting photon distribution was harder than the continuum employed for the M16 models in that it had a higher proportion of high energy photons shortward of the Lyman edge (at 912 Å).

Figure 11b depicts the results of this model convolved to the linear resolution of our observations. The n(H) plotted is the self-consistent solution from the model, which took as input the profile from Figure 11a. At lower radii there are departures from the input profile due to the nature of the fit employed and the boundary conditions placed on the model. In the region where the H$\alpha$ emission is strong, the resulting n(H) closely tracks the observed profile.

Comparison of Figures 11a and 11b reveals a pretty good match. The H$\alpha$ and [O III] peaks merge, as we observe, and the narrow [S II] peak becomes more separated from the H$\alpha$ peak. Thus we have done a reasonable job of reproducing what our observations show as far as the distribution of emission in the three main lines. It is unclear, however, how unique this solution is.

Figure 11c is a reproduction of Figure 10d - it depicts the same set of line profiles that we have extracted in 30 Doradus, but this time from ground-based observations of M16, which have been observed at essentially the same linear resolution. Figure 11d shows a set of profiles for M16 taken from the best fit models used in H96, except that this is the model used for column I (their paper presented models calculated for column II). It is included for direct comparison with Figure 11c.

What these 4 graphs show is the remarkable similarity between the structure we observe in 30 Doradus and the structure we observe from the ground in M16. We have matched
our observations in 30 Doradus with a model calculated using the same approach as that used by H96. Most of the morphological features are well reproduced - peak separation, approximate zone width, ordering, and so on. However, the critical issue is that while this appears to be a good fit it has been calculated using parameters that we know are incorrect - we know that the actual width of the emitting zones are far narrower than we can resolve. This problem is well illustrated in Figures 11c and 11d. From the ground we can extract profiles that are very comparable to 30 Doradus and could calculate a similar model in the same way. However, from the model presented in Figure 11d we know that the emitting zones for each emission line are very much narrower than we can see from the ground.

Turning this around, it does allow us to make an important statement about the structure we observe in 30 Doradus. Throughout this section we have shown in a variety of ways that a picture of a photoevaporative flow is consistent with all the observations we have made. The calculations we have performed by several different methods have yielded the same physical parameters and together the data support the case for the emission we observe in 30 Doradus to originate in a photoionized photoevaporative flow. By comparing Figures 11c and 11d, and then comparing Figures 11b with 11a we can make the statement that the structure we see in 30 Doradus is almost certainly composed of emitting zones far narrower than we can resolve, but that appear the way we would expect them to given the resolution we can achieve. The structure and emission we observe in 30 Doradus is well explained by exactly the kind of structure observed with HST in M16.

There are differences between 30 Doradus and M16 but they are not great. The most significant difference between the two sets of profiles is that in 30 Doradus the Hα and [O III] peaks coincide whereas in M16 they are well separated. We have already stated that the ionizing flux is more intense in M16, but this should not affect the separation of the Hα and [O III] peaks very much. What is different about the two objects is that the ionizing continuum in 30 Doradus is much harder than it is in M16 due to the presence of more very massive O stars and a handful of W-R stars. The effect of hardening the ionizing continuum is to compress the [O III] zone toward the ionization front since more photons of high enough energy will get through to those regions. This would, by inspection of Figure 11, shift the [O III] peak toward the right making it more coincident with the Hα peak. The picture is still consistent.

4. Conclusions

We have presented high resolution narrow-band imagery of the 30 Doradus nebula. There are many interesting localized structures within the nebula, a number of which appear
to be associated with winds and UV from stars that are not part of the main 30 Doradus cluster. However the majority of the emission from the nebula is due to photoionization by the flux from the central cluster. This emission is largely concentrated in thin regions located at the interface between dense molecular material and the shock-heated interior of 30 Dor.

At the resolution of the $HST$ data we find that the structure in 30 Doradus is remarkably similar to what is seen in ground-based observations of nearby H II regions. This similarity is not surprising given that despite an overall difference in scale, locally the physical conditions in 30 Doradus are not much different than those found in smaller H II regions. We demonstrate this point above by focussing on one particular region in 30 Doradus and showing that it is a very direct analog of the Galactic H II region M 16. Taking this same argument a step further we are lead to the conclusion that underlying the observed structure in M 16 is the same sort of extremely localized and sharply stratified structure seen in the $HST$ images of M 16. Thus, even though the 30 Doradus nebula spans hundreds of parsecs, the emission from this giant H II region arises largely in the same sorts of sharply stratified photoionized photoevaporative flows seen in nearby H II regions.

The 30 Doradus nebula is a crucial case. The fact that at $HST$ resolution 30 Doradus is so similar to ground based images of nearby H II regions has allowed us to bootstrap our physical understanding based on detailed study of nearby regions into the physical context of a giant H II region surrounding a massive young cluster. Similarly, preliminary analysis of $HST$ images of more distant giant H II regions suggests that they compare favorably with 30 Dor when that nebula is viewed at the same physical resolution. This indicates that conditions in 30 Doradus are probably typical of those found in these distant H II regions as well. Bootstrapping first from nearby H II regions to 30 Doradus in this paper, and we anticipate from 30 Doradus to more distant regions in later work, we are approaching the conclusion that the emission from giant H II regions megaparsecs distant is determined by the physics of photoevaporative flows in which relevant physical scales can be as small as 100 AU or less.

The significance of this work lies in the conclusion that the detailed study of nearby, well-resolved H II regions is directly applicable to distant giant H II regions in much the same way that an understanding of radiative shocks that is tested in nearby supernova remnants can be applied in a variety of contexts in which the shock itself is not resolved. Viewed from a different perspective, interpretation of observations of distant giant H II regions must take into account the fact that much of this emission arises not in vast expanses of ionized or even clumpy gas, but instead in well defined and highly stratified photoevaporative flows localized to the surfaces of molecular clouds.
This work was supported by NASA grant NAS5-1661 to the WF/PC ID T and NASA contract NAS7-1260 to the WFPC2 IDT. This work was supported at ASU by NASA/JPL contracts 959289 and 959329 and Caltech contract PC064528.

REFERENCES

Aufdenberg, J.P., Hauschildt, P.H., Shore, S.N. and Baron, E. 1998, ApJ, 498, accepted

Bertoldi, F. 1989, ApJ, 346, 735

Campbell, B., Hunter, D.A., Holtzman, J.A., Lauer, T.R., Shaya, E.J., Code, A., Faber, S., Groth, E.J., Light, R.M., Lynds, R., O’Neil, E.J., Jr., Westphal, J.A. 1992, AJ, 104, 1721

Ferland, G.J. 1996, Univ. of Kentucky, Dept. of Physics & Astronomy Internal Report

Heathcote, S., Morse, J.A., Hartigan, P., Reipurth, B., Schwartz, R.D., Bally, J., Stone, J., 1996, AJ, 112, 114

Hester, J.J. 1991, PASP, 103, 853

Hester, J.J., Scowen, P.A., Sankrit, R., Lauer, T.R., Ajhar, E.A., Baum, W.A., Code, A., Currie, D.G., Danielson, G.E., Ewald, S.P., Faber, S.M., Grillmair, C.J., Groth, E.J., Holtzman, J.A., Hunter, D.A., Kristian, J., Light, R.M., Lynds, C.R., Monet, D.G., O’Neil, E.J., Jr., Shaya, E.J., Seidelmann, K.P. and Westphal, J.A. 1996, AJ, 111, 2349 (H96)

Holtzman, J.A., Hester, J.J., Casertano, S., Trauger, J.T., Watson, A.M., Ballester, G.E., Burrows, C.J., Clarke, J.T., Crisp, D., Evans, R.W., Gallagher, J.S. III, Griffiths, R.E., Hoessel, J.G., Matthews, L.D., Mould, J.R., Scowen, P.A., Stapelfeldt, K.R. and Westphal, J.A. 1995, PASP, 107, 156

Hyland, A. R., Straw, S., Jones, T. J., & Gatley, I. 1992, MNRAS, 257, 391

Hunter, D.A., Shaya, E.J., Scowen, P.A., Hester, J.J., Groth, E.J., Lynds, R., and O’Neil, E.J., Jr. 1995a, ApJ, 444, 758

Hunter, D.A., Shaya, E.J., Holtzman, J.A., Light, R.M., O’Neil, E.J. and Lynds, R., 1995b, ApJ, 448, 179

Kennicutt, R.C. and Hodge, P.W. 1986, ApJ, 306, 130

Osterbrock, D.E. 1989, “Astrophysics of Gaseous Nebulae and Active Galactic Nuclei”, University Science Books

Panagia, N., Gilmozzi, R., Machetto, F., Adorf, H.-M., & Kirshner, R. P. 1991, ApJ, 380, L23
Parker, J.W. 1993, AJ, 106, 560
Peimbert, M. et al 1975, Revista Mexicana, 1, 189
Sharpless, S. 1953, ApJ, 118, 362
Walborn, N.R. and Blades, J.C. 1997, ApJS, 112, 457
Wang, Q. and Helfand, D.J. 1991, ApJ, 370, 541
5. Tables and Figures

Table 1: Details of observations made of 30 Doradus

| Image Root Numbers     | Filter | Exp. Time | Date Taken |
|------------------------|--------|-----------|------------|
| u25y0101t, u25y0102t, u25y0103t, u25y0104t | F336W  | 10.0s     | 2 Jan 1994 |
|                        |        | 100.0s    |            |
| u25y0105t, u25y0106t, u25y0107t, u25y0108t, u25y0109t, u25y010at | F555W  | 4.0s      | 2 Jan 1994 |
|                        |        | 40.0s     |            |
|                        |        | 200.0s    |            |
| u25y0201t, u25y0202t, u25y0203t, u25y0204t | F547M  | 5.0s      | 2 Jan 1994 |
|                        |        | 100.0s    |            |
| u25y0205t, u25y0206t, u25y0207t, u25y0208t | F814W  | 5.0s      | 2 Jan 1994 |
|                        |        | 100.0s    |            |
| u25y0209t, u25y020at, u25y020bt, u25y020ct | F170W  | 10.0s     | 2 Jan 1994 |
|                        |        | 100.0s    |            |
| u25y0301t, u25y0302t | F502N  | 500.0s    | 2 Jan 1994 |
| u25y0303t, u25y0304t | F656N  | 500.0s    | 2 Jan 1994 |
| u25y0305t, u25y0306t | F673N  | 500.0s    | 2 Jan 1994 |
Table 2: Table comparing the derived properties for the photoevaporative flow from the column in 30 Doradus with published numbers from H96.

| Parameter                                      | M16 (HST) | 30 Doradus |
|------------------------------------------------|-----------|------------|
| Dimensions of Column (pc)                      | 0.3 × 1.03| 0.2 × 1    |
| Incident Ionizing Flux (photons cm\(^{-2}\) sec\(^{-1}\)) | 4 × 10\(^{11}\) | 6 × 10\(^{10}\) |
| Total Ionizing Flux in Cluster (photons sec\(^{-1}\)) | 2 × 10\(^{50}\) | 2 × 10\(^{51}\) |
| Mean H\(\alpha\) Surface Brightness (ergs cm\(^{-2}\) sec\(^{-1}\) Sr\(^{-1}\)) | 6 × 10\(^{-2}\) | 1 × 10\(^{-2}\) |
| Depth of Low Resolution H\(\alpha\) Emission Zone (cm) | 5 × 10\(^{17}\) | 6 × 10\(^{17}\) |
| Depth of High Resolution H\(\alpha\) Emission Zone (cm) | 6 × 10\(^{16}\) | unresolved |
| Mean Electron Density in H\(\alpha\) Bright Zone (cm\(^{-3}\)) | 4000 | 3000 |
Fig. 1.— Mosaic of the WFPC-2 field of the center of 30 Doradus, seen in Hα λ6563 emission. The field orientation is indicated. The core of the cluster and in particular the cluster of stars R136 are centered on the PC. The field is characterized by regions of very bright emission from thin interfaces, with a broad diffuse component that covers the face of the nebula. The names of the four WFPC-2 chips are included for the unfamiliar reader.

Fig. 2.— Mosaic of the WFPC-2 field of the center of 30 Doradus, seen in [O III] λ5007 emission. The field orientation is indicated. The core of the cluster and in particular the cluster of stars R136 are centered on the PC. The [O III] emission follows the Hα emission very closely and only departs from it in subtle places.

Fig. 3.— Mosaic of the WFPC-2 field of the center of 30 Doradus, seen in [S II] λλ6717+6731 emission. The field orientation is indicated. The core of the cluster and in particular the cluster of stars R136 are centered on the PC. Since the [S II] emission is confined to the regions just exterior to the ionization fronts at the walls of the cavity, only the edges of the nebula show up bright in these lines.

Fig. 4.— Mosaic of the WFPC-2 field of the center of 30 Doradus, seen in broad band F547M emission. Note the lack of any line emission from the intense nebula. This frame is used to continuum subtract the line images. The field orientation is indicated. The core of the cluster and in particular the cluster of stars R136 are centered on the PC. Many stars are seen in the nebula with some small amount of dust scattering evident in the regions of brightest line emission.

Fig. 5.— CTIO CCD Image of the 30 Doradus Nebula. The WFPC-2 FOV presented in this paper is indicated at the heart of the object. Note the large size of the overall ionized volume. North is up.

Fig. 6.— Three-color image of the 30 Doradus Nebula. This is a composite of four sets of data: in the nebula emission blue being [O III] λ5007, green being Hα, and red being [S II]λλ6717+6731; while the stars are replaced with the F170W images as blue. Scale and orientation are indicated.

Fig. 7.— Tube-like structure found to the SE of the main cluster. (a) View seen in [O III], (b) view in Hα, (c) view in [S II]. Double arcs located SSE of the main cluster. (d) View seen in [O III], (e) view in Hα, (f) view in [S II].
Fig. 8.— Finger-like structure found directly south of the main cluster, and discussed at length in the text. (a) View seen in [O III], (b) view in Hα, (c) view in [S II]. Low excitation H II region located SSW of the main cluster, that appears to be a foreground object unrelated to the main 30 Doradus cavity. (d) View seen in [O III], (e) view in Hα, (f) view in [S II].

Fig. 9.— Smaller blobs of material seen in emission against the bright nebula. These are located close to the cluster and the inner rim of the cavity. (a) View seen in [O III], (b) view in Hα, (c) view in [S II]. Close-up view of main rim in inner cavity. Several outflow-like structures are visible. (d) View seen in [O III], (e) view in Hα, (f) view in [S II].

Fig. 10.— (a) Picture of the region south of R136 selected to perform ionization structure analysis. The bowshock used in the text is indicated on this picture, along with another one just to the NE of it. An arrow indicates the direction the cut illustrated in (c) has been taken. (b) The most obvious physical analog to (a) is M16 in our Galaxy. This ground-based image of the Eagle Nebula shows the same finger-like morphology and provides a direct comparison for the derived ionization structure from 30 Doradus. Note the physical scales for (a) and (b) are the same, but the angular scales are very different. Overlaid are the extracted apertures for each dataset. An arrow indicates the direction the cut illustrated in (d) has been taken. (c) Derived emission line profiles for the aperture indicated on (a). Note the broad tails on most of the profiles. (d) Derived emission line profiles for the aperture shown on the M16 image.

Fig. 11.— (a) Extracted emission line profiles for the aperture shown in Fig. 10 in 30 Doradus. The Hα and [O III] peaks coincide, while the [S II] is markedly separated. The physical scale is indicated in the legend. (b) Model of the ionization structure in 30 Doradus using the n(H) from (a) and convolved to the same linear resolution as (a). The peak separations are reproduced as well as the coincidence of the overall profiles between Hα and [O III]. (c) Reproduction of Figure 10(d) showing the ground-based resolution profiles - note how similar they are in width to those seen in 30 Doradus. (d) A model of the structure observed in M16 by H96. This shows how the ground-based data does not represent the true width of the emitting zones. This is also what is happening in 30 Doradus.
This figure "Scowen.fig1.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9803301v1
This figure "Scowen.fig2.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9803301v1
This figure "Scowen.fig3.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9803301v1
This figure "Scowen.fig4.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9803301v1
This figure "Scowen.fig5.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9803301v1
This figure "Scowen.fig6.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9803301v1
This figure "Scowen.fig7.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9803301v1
This figure "Scowen.fig8.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9803301v1
This figure "Scowen.fig9.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9803301v1
This figure "Scowen.fig10.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9803301v1
This figure "Scowen.fig11.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9803301v1