*RevMexAA (Serie de Conferencias)*, **8**, 161–169 (1999)

# MASSIVE STARS IN 30 DORADUS: THE NEXT GENERATION[1]

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RESUMEN

Hay una evidencia muy amplia de que actualmente existe formación de estrellas de gran masa en la Nebulosa de 30 Doradus. Dichas estrellas se estarían formando en y más allá de los filamentos gaseosos curvados que rodean al núcleo R136. Estos filamentos parecen ser "frentes de formación estelar" moviéndose a través de densas nubes de polvo. Esta evidencia proviene de la intercomparación de observaciones en el continuo IR, $H_2$ y Br$\gamma$ de la parte interna de la Nebulosa de 30 Doradus, realizadas desde observatorios terrestres, y observaciones de banda angosta y ancha efectuadas con *HST*/WFPC2. Muchas estrellas de gran masa que se hallan sumergidas en el material nebular han sido descubiertas en o cerca de los filamentos nebulares al Oeste y Noreste de R136, y su localización está íntimamente conectada con estructuras nebulares brillantes u oscuras. Además, la clasificación espectral en el rango óptico de estas estrellas tempranas de tipo O en densos nudos nebulares, así como observaciones de líneas de CO, contribuyen al cuadro emergente, el cual sugiere que una nueva generación estelar está naciendo en la periferia de R136, siendo ésta producto de la actividad energética del cúmulo central, compuesto por decenas de estrellas de gran masa, sobre las nubes moleculares circundantes.

ABSTRACT

There is ample evidence for current star formation within the 30 Doradus Nebula, in and just beyond the curved nebular filaments surrounding R136. These filaments appear to be "star-forming fronts" moving into the dense dust clouds beyond. This evidence comes from the intercomparison of groundbased IR continuum, $H_2$, and Br$\gamma$ observations with *HST*/WFPC2 narrow and broadband images of the inner 30 Doradus Nebula. Numerous heavily embedded massive stars have been discovered in or near the bright nebular filaments West and Northeast of R136, and their locations are intimately connected with bright and dark nebular structures. Optical spectral classifications of early O stars in dense nebular knots and CO data also contribute to the emerging picture, which suggests that a new stellar generation is being triggered by the energetic activity of the massive central cluster around its periphery.

*Key words:* **GALAXIES: STARBURST — H II REGIONS — ISM: INDIVIDUAL (30 DORADUS) — ISM: MOLECULES — MAGELLANIC CLOUDS — STARS: FORMATION**

## 1. INTRODUCTION

The 30 Doradus Nebula in the LMC has been one of the most observed objects in the entire sky. Each time that a new telescope or astronomical device is put to work in the Southern Hemisphere or in space, some of the first light collected comes from that nebula. The 30 Doradus region (1 kpc across, Walborn 1991a) is

[1]Based in part on observations with the NASA/ESA *Hubble Space Telescope* obtained from the archive at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

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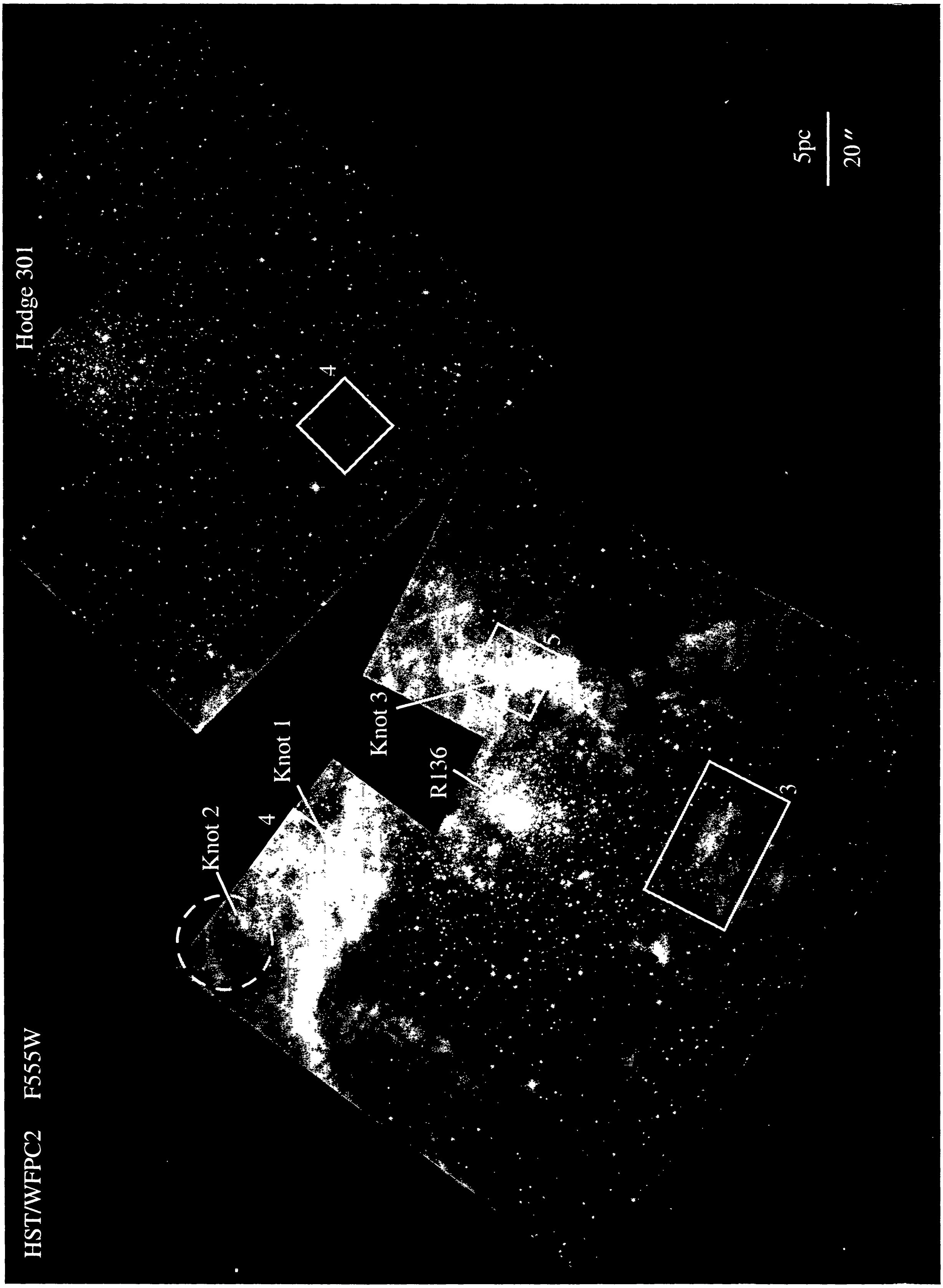


Fig. 1. WFPC2/F555W moisac of 30 Dor Nebula. Labeled rectangles correspond to enlarged areas shown in following figures, whose numbers are marked. Knots 1, 2, and 3 are embedded early O stars. The water maser locus is marked with a 26″ circle.

TABLE 1

STELLAR POPULATIONS IN THE 30 DORADUS NEBULA (FROM WALBORN & BLADES 1997)

| | Population | Distribution | Phase | Age |
|---|---|---|---|---|
| a | O3/WN Stars | Core cluster: R136 | Carina | 2–3 My |
| b | Subluminous Early O Dwarfs | Close to Nebular Filaments | Orion | < 1 My |
| c | Field LMC OB Sg | Uniform | Sco OB1 | 4–6 My |
| d | Open Cluster Ho 301, with A-M Sg | 3′ NW of R136 | h+$\chi$ Per | 10–20 My |
| e | OB Assoc. around the LBV R143 | 2′ SE of R136 | Sco OB1 | 4–6 My |

the largest and most massive H II complex in the Local Group, dominated by the 30 Dor Nebula (200 pc in diameter), which harbors the 30 Dor ionizing cluster of early O stars (40 pc in diameter), which in turn has a dense core of very luminous and massive stars known as R136 (2.5 pc in diameter). An understanding of the gaseous structure and stellar content of the 30 Dor region is an essential prerequisite for interpretation of more distant, similar objects known as Starburst[4] regions. Walborn (1991a) applied the term *Rosetta Stone* to emphasize the importance of 30 Doradus as a necessary step to understand more distant, unresolved starbursts.

Also, there are several important astrophysical problems related to knowledge of the stellar and gas content in massive star-forming regions like 30 Dor. Among those problems, it is possible to enumerate: How is a massive star formed? What are the accretion processes in a massive protostar and which is their relationship to the powerful stellar winds when they turn on? Is there an upper mass limit for a newborn massive star? Is the formation of low-mass stars in such regions inhibited? Do the gas dynamics and chemical enrichment in giant H II regions differ with respect to more modest ones?

The 30 Doradus region has been observed in almost all wavelength ranges from X-rays to radio. It is our interest to focus attention on those wavelengths where the signatures of a new massive-star generation become evident.

### 1.1. *On the Stellar Content Beyond the Core*

Recently, the *Hubble Space Telescope* has made fundamental contributions to the study of 30 Doradus, when the core, named R136, was resolved into tens of massive stars (e.g., Campbell et al. 1992). After that, several investigations focused on the initial mass function (IMF) problem; for example, Hunter et al. (1995, 1996) counted 3600 stars in the inner 4.7 pc around the core, reaching a limit of $M > 2.8\ M_{\odot}$, that is, approximately a main-sequence A2 star, and finding a normal IMF down to that limit. A huge *HST*/FOS spectroscopic effort was made by Massey & Hunter (1998). This work brought a spectacular increase in our knowledge of the stellar content in the core of the 30 Dor starburst. They obtained spectrograms of the 65 bluest and most luminous stars in R136, finding that 39 of them are O3 stars! Another striking result is the discovery of four double-lined spectroscopic-binary candidates with early O-type spectra, which are very valuable to provide accurate masses of massive O stars in an early stage of evolution. Finally, *HST*/GHRS and FOS observations of the most luminous stars in R136 demonstrated them to be very hot and massive stars with Wolf-Rayet-like features in their spectra, and with O V UV lines developing wind profiles, again a signature of the O3 spectral type (de Koter, Heap, & Hubeny 1997).

The 30 Doradus core is encircled by impressive nebular filaments, mimicking the appearance of a large spider; for this reason it was named the *Tarantula* Nebula. Figure 1 shows a mosaic of current *HST*/WFPC2 coverage of the nebula in the light of filter F555W (similar to Johnson $V$). In spite of the gap just north of R136, the filamentary structure around the core is the distinctive feature. Also, it can be appreciated that a population of bright stars is spread around the core, close to the filamentary structure and beyond it, and that some of them are concentrated in an open cluster, Hodge 301, about 3′ northwest of R136.

[4]A definition in Spanish of *Starburst* might be: es como la primavera en alguna región de una galaxia pero en vez de brotar flores, brotan estrellas.


Fig. 2. Superposition of CO contours on an $H_2$ 2.12$\mu$m minus Br$\gamma$ image. Light and dark tones indicate $H_2$ and Br$\gamma$ emission, respectively. A large "white spot" is a subtraction artifact due to an M supergiant, as marked. Also, Knots 1, 2, and 3 are marked.

Efforts to establish the nature of the stellar content of 30 Doradus beyond the core through spectroscopic observations of many stars were made by Melnick (1985) and Walborn (1986); additional spectroscopy and a complete photometric survey were done by Parker (1993). The latter author was the first to combine groundbased *UBV* CCD photometry plus spectroscopy of an extensive sample of stars. Further detailed progress was made by Walborn & Blades (1997), who showed evidence for discrete epochs of massive-star formation within the 30 Dor Nebula, comprised by five different populations that cohabit now in the starburst, namely (Table 1): a) a very young population of massive stars concentrated in and around the R136 core; b) a still younger population of massive stars close to the nebular filaments; c) an older population of late O and B supergiants spread throughout the entire area; d) an evolved open cluster 3′ to the northwest of the core; and e) an OB association near the LBV star R143 (Parker et al. 1993).

Populations (c), (d), and (e) perhaps are not directly related in origin to populations (a) and (b), because the former are likely part of the more extensive LMC field population of OB, WR, and red-supergiant stars and associations projected onto and around the 30 Dor Nebula, but not part of the perturbation that gave rise to the core. The populations (a) and (b) perhaps are physically related through the sequential formation of (b) due to the effects of outflow activity from (a) on the neighboring molecular clouds. It is our interest to focus on population (b), that is, on the youngest population and its relationship with the nebular environment.

## 2. OBSERVATIONS

Throughout this paper we use observations obtained at different telescopes and wavelengths. Near-IR broadband observations were obtained in *J*, *H*, and *Ks* filters (for the definition of the *Ks* filter see Persson et al. 1998) with the 2.5-m Du Pont Telescope at Las Campanas Observatory by M.R. in 1993 (see Rubio et al. 1998 for further observational details). Near-IR narrowband observations at 2.12 $\mu$m ($H_2$), 2.16 $\mu$m (Br$\gamma$), and 2.14 $\mu$m (continuum) were obtained by Probst & Rubio (1999) using the CTIO 1.5-m telescope. Archival images obtained with the *HST*/WFPC2 were used to investigate the morphological relationships between IR sources and stellar objects or gaseous structures in the nebula. These WFPC2 data are from three sets of images obtained in January 1994 (Proposal 5589, PI J. Trauger), September 1994 (Proposal 5114, PI J. Westphal), and

September 1995 (Proposal 6122, PI Y.-H. Chu). Images in the first and last sets were obtained with broadband filters F336W, F555W, and F814W and narrowband filters F502N ([O III]), F656N (H$\alpha$), and F673N ([S II]). The remaining set contains images only in the broadband filters. Further discussion about the relationships between the IR and WFPC2 observations is presented by Rubio et al. (1998).

## 3. TRACERS OF MASSIVE-STAR-FORMING REGIONS

The 30 Dor nebula itself is clear evidence for recent massive-star-formation processes, but the question is whether these processes have now stopped or slowed down, or whether they are currently ongoing on a large scale within the nebula. Evidence for massive-star formation may be manifested in many distinct ways, but its true significance is appreciated only when all the morphological information about star-formation tracers gathered during recent years is interrelated. For example, the presence of CO emission by itself is not a guarantee of current star formation, but when it is spatially associated with $H_2$ emission, IR sources, compact gaseous globules, and very young massive stars embedded in dense nebular knots (among other tracers), then the presence of CO emission is more relevant and reinforces the idea of current massive-star-formation activity. Among these *tracers* of star-formation activity we can enumerate:

— *Molecular clouds: CO and $H_2$ emission.* Recent CO observations with a resolution of 20″ by Johansson et al. (1998) show four molecular clouds just beyond the bright filamentary nebulosity around the 30 Dor core, namely 30Dor-10, 30Dor-12, 30Dor-13, and 30Dor-15. This molecular gas emission traces the coldest regions in the nebula. Figure 2 shows a superposition of CO contours on a subtracted $H_2$ minus Br$\gamma$ image. The CO emission is found only far away from the primary ionizing source (the 30 Dor core) and just beyond the ionized front mapped by Br$\gamma$ emission. $H_2$ emission presents maxima in the same positions as those of CO, and also shows a clumpy distribution, associated with dark patches, lanes, and pillars throughout the entire nebula (Rubio et al. 1998). Furthermore, evidence of $H_2$ emission associated with jet-like structures on the West nebular filament is presented by those authors.

— *Gas morphology.* WFPC2 images reveal in great detail that the nebular filaments have many bright and dark microstructures, characteristic of star-forming activity. Also, these images show extensive dark clouds. It is possible to enumerate the presence of the following kinds of microstructures:

- *Nebular knots.* These are very bright nebulosities with sizes of a few tens of arcseconds with or without embedded optical stellar sources, that may be interpreted as compact H II regions. Among the most important are Knots 1, 2, and 3 (Walborn & Blades 1987; Walborn 1991b), which have embedded early O stars. Knot 1 is in fact the brightest optical nebulosity in the entire filamentary structure of 30 Doradus.

- *Pillars and fingers.* WFPC2 images reveal beautiful bright and dark dusty structures spread along the nebular filaments, which point toward R136. Their formation is due to the carving activity of energetic outflows from the core, producing photo-evaporative processes in the interfaces between the molecular clouds and the interior of the H II region. Many of these pillars present strong $H_2$ emission in their heads and one of them contains one of most powerful IR sources of the 30 Dor Nebula (IRSW-30, Rubio et al. 1998; see also Fig. 5 below). A distinctive example of such structures is a complex of pillars 1′ south of R136 that resembles the M16 pillars (Hester et al. 1996), both in morphology and size (Fig. 3).

- *Bok globules.* These are dusty dark globules with elliptical shapes, very noticeable against the bright background. Figure 4 shows several of them in the NE filament. Their sizes range from 0.″3 to 1″ (0.075–0.25 pc), that is, they are resolved in WFPC2 images.

- *Partially ionized globules (PIGS).* These are isolated globules but in this case they appear bright against the background (Fig. 4). They present a variety of shapes, most of them cometary, others with more amorphous contours, perhaps due to the association of several globules not completely separated yet. Perhaps these latter composite globules will give rise to Trapezium-like systems of early O stars, similar to the neighboring system P294–P304 (Barbá & Walborn 1999). The common feature of these globules is that each presents a bright face pointing toward R136, analogously to the "proplyds" in the Orion Nebula (O'Dell & Wen 1994), but the striking feature is that the globules in 30 Dor are at least 50–100 times larger in diameter (0.1–0.3 pc) than their more modest counterparts in Orion ($3\,10^4 - 0.05$ pc). These globules are comparable in size and morphology to similar features reported in the galactic giant H II region NGC 3603 by Dottori et al. (1999).

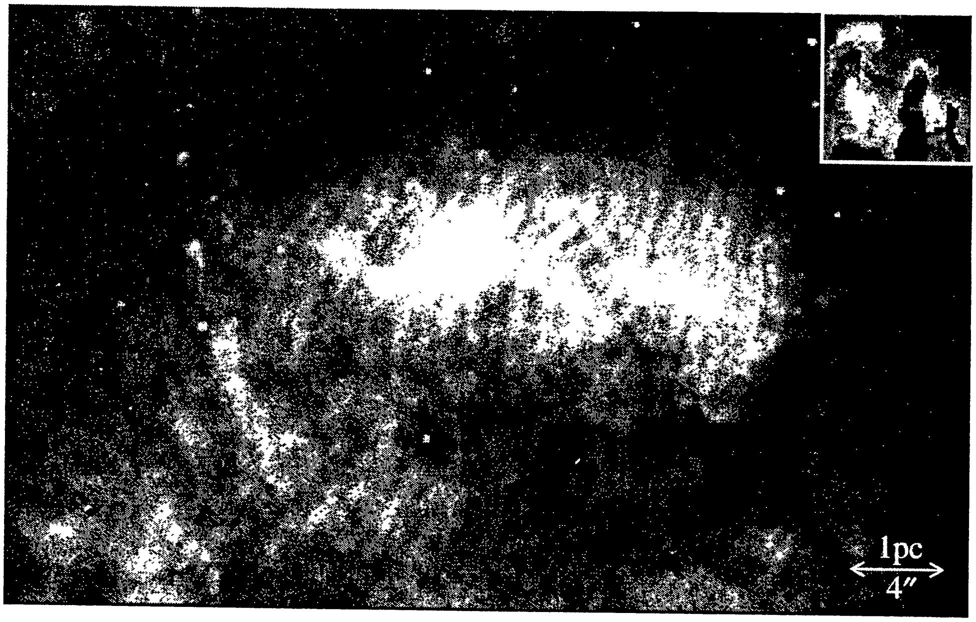


Fig. 3. WFPC2/F656N (H$\alpha$) view of "30 Dor Southern Pillars", a dusty structure 1′ to the S of R136 that resembles the M16 Pillars. The inset in the upper right corner shows an M16 image (from Hester et al. 1996) scaled to the LMC distance.

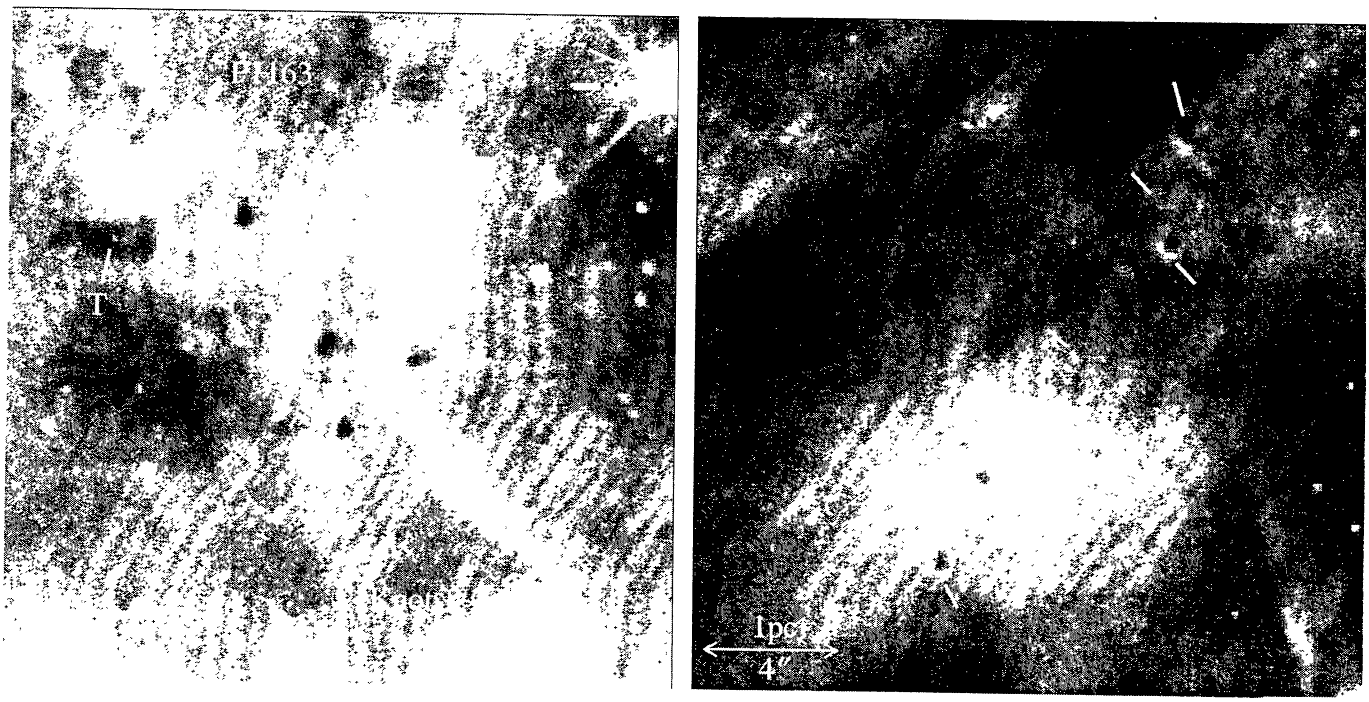


Fig. 4. Left: detailed view of WFPC2/F555W image of NE filament. B marks prominent Bok globules, T an "elephant trunk", P numbers are from Parker's (1993) catalog. Right: detailed view of WFPC2/F656N (H$\alpha$) image of a sector relatively empty of strong nebulosity, just 2′ NW of R136. Lines mark the brightest PIGS.

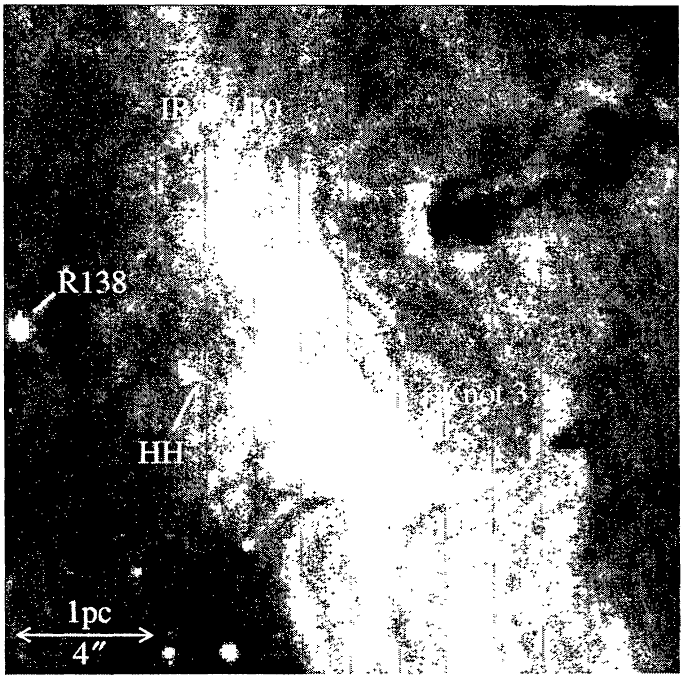


Fig. 5. Enlargement of WFPC2/F656N (H$\alpha$) image of the W filament in the neighborhood of Knot 3. The jet-like structure resembling galactic Herbig-Haro objects is marked with "HH". IRSW-30 (from Rubio et al. 1998), in the head of a bright-rimmed pillar, is one of the most luminous IR sources in the whole 30 Dor Nebula. R138 is an A supergiant field star not related to the young structures.

- *Jet-like features and Herbig-Haro objects.* WFPC2 images reveal a very complicated hyperfine nebular structure where it is very hard to identify stellar jets or features similar to galactic Herbig-Haro objects. In spite of that, close to Knot 3 (Fig. 5) there appears a jet-like structure that resembles galactic HH objects like HH 203–204 (O'Dell et al. 1997), with associated $H_2$ emission (Rubio et al. 1998). This jet-like feature could originate inside the nebulosity where Knot 3 is located.

- *Infrared sources.* Recent groundbased IR observations have provided evidence that there is a current star-formation event in and just beyond the bright nebular filaments centered on R136. Hyland et al. (1992) discovered four bright IR sources in the 30 Dor Nebula. Rubio, Roth, & García (1992) reported an additional number of bright IR sources, establishing a spatial association with nebular filaments and knots. Walborn & Barbá (1998) showed a remarkable and detailed relationship between the optical nebular structures in *HST*/WFPC2 images and these IR sources. Our latest *JHKs* survey reveals several tens of new IR sources, most of them inside of or beyond the nebular filaments (Rubio et al. 1998). Some IR sources may be explained as heavily reddened early O stars ($A_V > 20$!), but several show intrinsic IR excesses because their IR luminosities are equivalent to several tens of reddened early O stars. Also, some O stars (like P409 in Knot 3) present anomalous IR colors.

- *Embedded O dwarf stars in or near nebular filaments.* These stars are optical sources identified spectroscopically, which excite the nebular knots where they are embedded. They are perhaps at the final stages of their birth, when they are emerging from their original cocoons. Walborn & Blades (1987, 1997) and Walborn (1991a) discovered eleven early O dwarf stars embedded in bright nebular knots. These stars have a preferential distribution near or in the nebular filaments that surround the core. Also, all of these stars present a spatial association with IR sources and some of them are IR sources themselves, reinforcing the idea that they are very young objects (Rubio et al. 1998). Walborn & Blades (1997) suggested an age less than one million years for them.

- *A water maser.* Whiteoak & Gardner (1986) discussed a water maser just beyond the NE filament. In the 26″error circle (Fig. 1) of the maser position, Knot 2 (Walborn & Blades 1987) and several bright IR sources (Rubio et al. 1998) are located. Also in that region there are a CO emission peak and strong $H_2$ clumps.

## 4. CONCLUSIONS AND NEXT STEPS

The comprehensive observational evidence presented in this paper clearly demonstrates that massive stars are forming now in the 30 Doradus Nebula at a significant rate, precisely where such activity is most probable: in the nebular filaments and molecular clouds. In the filamentary structure, all of the ingredients expected in an active star-forming region are present: large molecular concentrations; bright IR sources preferentially located close to the interfaces between the molecular clouds and the inner H II region ionized by the radiation from the core; in the same locations, a "zoo" of different nebular microstructures like elephant trunks, dark and bright pillars, dark globules, PIGS, knots, fingers, and jet-like features; a water maser; early O stars embedded in their nebular birthplaces. Some of these interstellar microstructures found in the 30 Dor Nebula are perhaps the first extragalactic example of such features, which are very common in star-forming regions of the Milky Way; therefore, a new possibility to compare star-forming regions in environments of different metallicities is opened. The action of UV radiation and stellar winds from the massive core, carving and compressing the surrounded molecular clouds, has triggered a new massive-star generation in the filamentary structure that may now be seen as star-forming fronts *eating into* those clouds. Walborn & Parker (1992) called attention to the morphological similarities between 30 Doradus and the giant shell H II region N11 in the LMC, describing the latter as an evolved 30 Dor, with an evacuated central cavity containing an older association, and a younger population around the periphery ionizing the nebula. This general mechanism (also suggested by NGC 604 in M33), in which an initial massive cluster triggers a second generation of massive-star formation was named a *two-stage starburst* by Walborn & Parker (1992), and it appears to be characteristic of massive-star formation on this scale.

Disentangling 30 Doradus is the *key* to understanding other, more distant starbursts. All of the stellar and nebular complexities described above would subtend only 0.″5 at the distance of the Virgo Cluster. The next steps toward extending our knowledge of 30 Dor at IR wavelengths are being taken with *HST*/NICMOS by Zinnecker et al. and Walborn et al. The study of the optical stellar content in the filamentary structure of 30 Dor is being pursued with *HST*/WFPC2 archival images by Barbá & Walborn (1999).

Support for this work was provided by NASA through grants GO-6032.01-94A, GO-6508.01-95A, and AR-7545.01-96A from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555. R.H.B. thanks the SOC for inviting him to do this review talk and the LOC, especially the students, for the warmth and pleasure included in the organization of this workshop. M.R. wishes to acknowledge support from FONDECYT(CHILE) grant 1960926.

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