A New Stellar Generation in 30 Doradus

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Abstract. The increasing evidence for current star formation within the 30 Doradus Nebula is reviewed and illustrated. A new stellar generation appears to have been triggered by the massive central cluster (R136), in and just beyond the surrounding, curved nebular filaments. These filaments appear to be 'star-formation fronts' moving into the dense dust clouds beyond. The evidence consists of IR continuum and H_2 sources, an H_2O maser, early O dwarfs embedded in dense nebular knots, and intricate bright and dark nebular structures in HST/WFPC2 images which are signatures of star-formation activity. 30 Doradus is the nearest and hence most highly resolved extragalactic starburst; an understanding of its complex structure and evolution is essential for interpreting the integrated properties of more distant, unresolved starburst regions. Two-stage starbursts, in which an initial massive, centrally condensed generation subsequently triggers a secondary event around its periphery, may be characteristic of star formation on this scale.

1. Introduction

The 30 Doradus Nebula in the Large Magellanic Cloud is the largest H II region in the Local Group and the nearest extragalactic starburst. The degree to which its stellar content and nebular structures can be resolved make it a paradigm for the interpretation of more distant starbursts. Nevertheless, at the LMC $1''$ subtends 50 000 AU, and the internal structure of 30 Dor is turning out to be surprisingly complex, involving several discrete star-formation epochs. Hence, the highest possible spatial resolution is essential to unravel the vital information it offers about the evolution of massive stars in dense concentrations.

Several recent and current investigations with large ground-based telescopes and HST are providing qualitatively new information about the structure and evolution of 30 Dor. WFPC2 images of the dense, central cluster core have been analyzed by Hunter et al. (1995a, 1996, 1997), who measured several thousand stars and found a normal IMF down to $2.8M_{\odot}$. These results answer two basic questions about starbursts, namely the nature of the upper IMF and the formation (or inhibition) of lower masses. Massey & Hunter (1998a, b) and Heap et al. (1998; see also de Koter 1998) have followed up with spatially resolved HST spectroscopy in and near R136, finding from both the optical and UV spectra that 40 of the 65 brightest stars are of type O3! Despite this unprecedented concentration of the most massive and hottest stars, the results continue to be consistent with a normal IMF. Brandl et al. (1996) performed ground-based IR observations with adaptive optics and detected potential lower-mass stars in R136, as well as a possible variation of the IMF with radius. H. Zinnecker et al. are conducting a Cycle 7 HST/NICMOS programme to do deep imaging of R136 in the H band, in order to investigate the IMF to yet smaller masses.

Walborn & Blades (1997) discussed ground-based optical classification spectrograms of 106 OB stars within the 30 Dor Nebula, and they identified five distinct spatial and/or temporal structures among the stellar content: (1) the O3/WN core cluster, including R136, of age 2–3 Myr; (2) a surrounding triggered generation, represented in these data by subluminous early-O dwarfs embedded in dense nebular knots, age <1 Myr; (3) a 'field' of OB supergiants throughout the region, ages 4–6 Myr; (4) an OB association of similar age surrounding the recently discovered Luminous Blue Variable R143 in the southeast part of the nebula; and (5) a 10–20 Myr old cluster containing red supergiants to the northwest of R136. They pointed out that this entire complex would subtend less than $1''$ at the Virgo Cluster.

2. Evidence for Current Star Formation in 30 Doradus

Several recent investigations support the inference of a current, triggered star-formation event in and just beyond the bright nebular filaments centred on R136, primarily toward the northeast and west. Whiteoak & Gardner (1986) discovered an H_2O maser located near the northeast filament. Hyland et al. (1992) and Rubio et al. (1992) reported a number of obscured IR sources in the same localized regions. Four of the Rubio et al. northeast sources and one of the Walborn & Blades (1997; see also Walborn & Blades 1987) embedded O stars lie within the maser positional error circle. Most of the IR sources to the west are aligned along the bright nebular filament there. Moreover, these regions show intricate filamentary structure in WFPC2 [S II] images, and they are replete with bright and dark nebular microstructures characteristic of star-formation activity, some of which have been discussed by Hunter et al. (1995b). Recently, H_2 knots and filaments in 30 Dor have been reported by Probst & Rubio (1997). The morphology of the H_2 is quite different from that of the ionized gas, with the most intense H_2 emission again to the northeast and west of R136, but for the most part non-coincident with the ionized filaments. The emerging interpretation is that the ionized filaments are 'star-formation fronts' powered by the stellar winds (and possibly SN events?) from the spectacular R136 cluster core, currently moving into the dense dust and molecular clouds which surround it.

The detailed relationships between the optical nebular structures and the IR sources in 30 Doradus are remarkable. Figure 1 is from archival WFPC2 [S II] images including the west filament, and Fig. 2 is a sum of WFPC2 F555W images containing the northeast filament (no narrow-band images of this region are available). In the figures the Rubio et al. IR sources and Knots 1–3 with embedded O stars of Walborn & Blades are marked with circles.

In Fig. 1, Rubio IR source 2 coincides with a bright nebular knot, while source 4 consists of a stellar object with possible bipolar nebulosities. IR source 5 is adjacent to a bright nebular structure. IR source 6 coincides with an optical

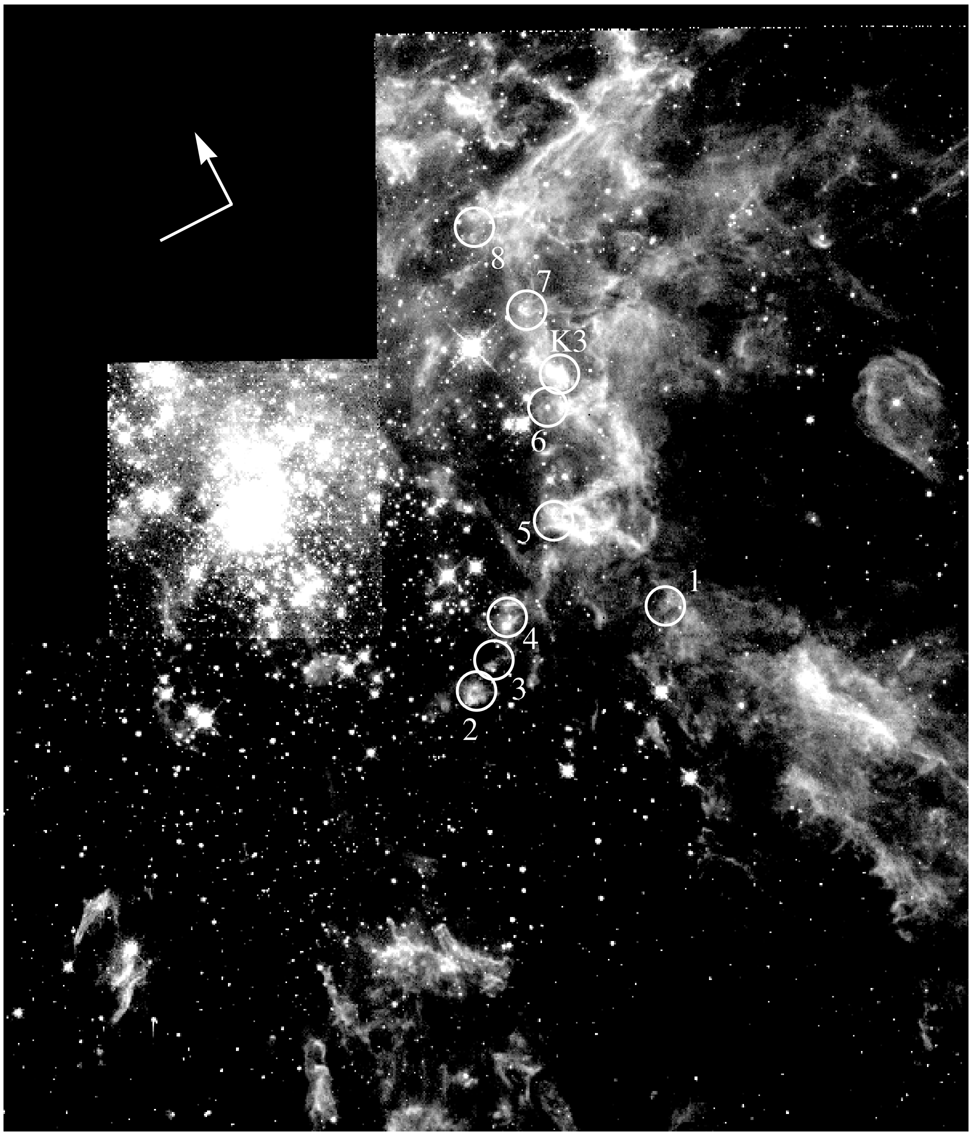

Figure 1. WFPC2 [S II] image of fields W and S of R136; the latter is centered in the PC chip. This image is a sum of two 500s exposures through the F673W filter, from programme No. 5589, PI J. Trauger. The cardinal indicators are 10″ in length. The circles mark Rubio et al. (1992) IR sources (plain numbers) or Walborn & Blades (1987, 1997) early O stars embedded in nebular knots (K numbers). Another view of part of this region is shown in the frontispiece to this volume [p. x].

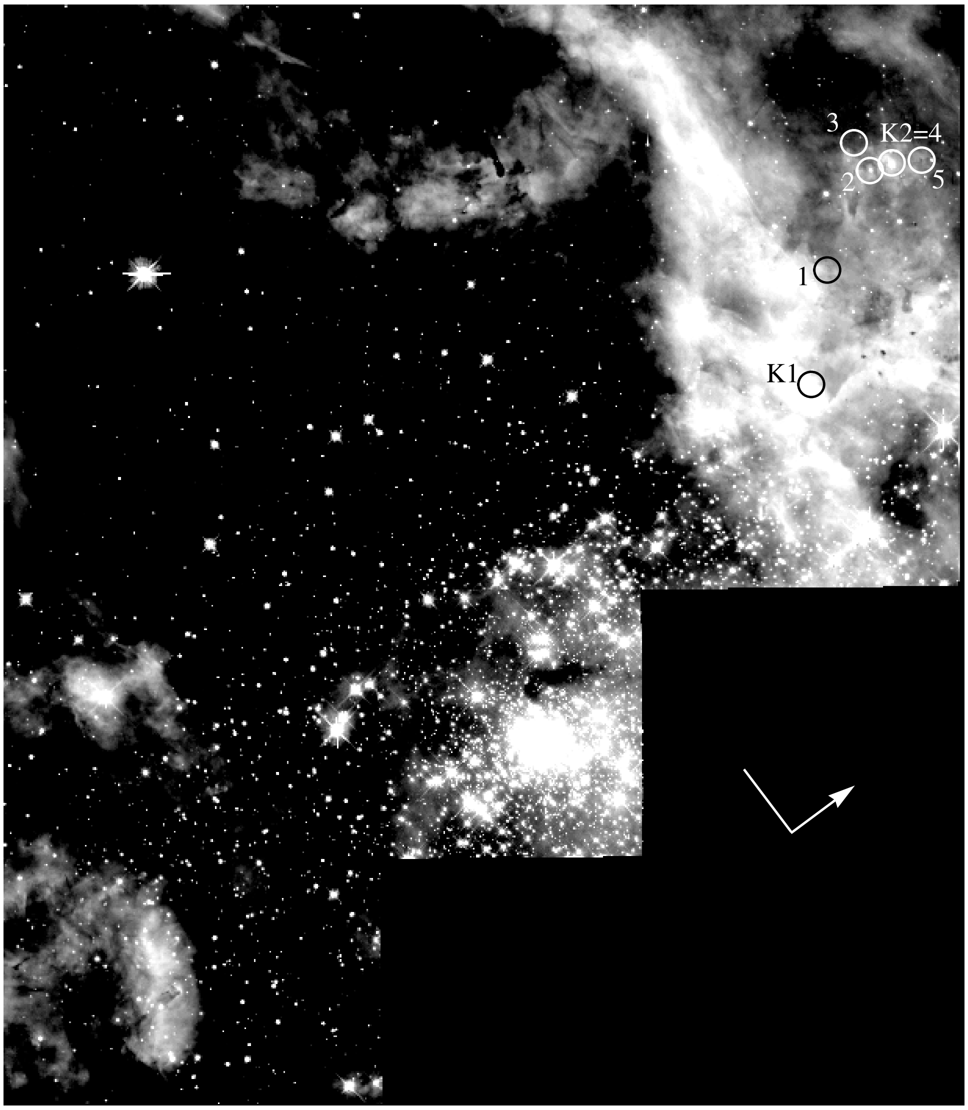

Figure 2. WFPC2 F555W image of fields S and NE of R136; the latter is again centered in the PC chip. This image is a sum of ten 23s exposures, from programme No. 5514, PI J. Westphal. The symbols are as in Fig. 1.

star, while source 7 is the tip of a large dust pillar with bright edges. Walborn Knot 3 is very prominent, as are the intricate filamentary [S II] structures throughout this region. The circular nebula to the west with a bright central star is probably not a young structure, because Walborn & Blades (1997) found an unremarkable spectral type of O8–9 III for the star. On the other hand, a relatively small, apparently active region about 1′ south of R136 contains bright nebulosity and dust pillars very similar in morphology and size to those found in HST images of M16 by Hester et al. (1996).

This last region is also included in Fig. 2. Similar structures are seen in the 'loop' just over 1′ east of R136, where dark pillars are superimposed on bright nebulosity. Knot 1 is the brightest of several compact nebulosities in the region; Hunter et al. (1995b) show annular nebular structures surrounding the stars within Knot 1. Several very dark, small globules, three of which are also (unnumbered) Rubio et al. IR sources, can be seen near the north edge of the field. The clustering of Knot 2 and IR sources 2–5 at the northeast edge lies within the positional error circle of the H_2O maser. IR sources 6–8 are just beyond the boundary of Fig. 2 to the north. It is likely that formation of the triggered generation in 30 Dor is not yet complete, since the star-formation fronts appear to be still moving into the surrounding dust clouds.

3. Concluding Remarks

Walborn & Parker (1992) compared 30 Dor to the giant shell H II region N11, also in the LMC, pointing out that the age *differences* between the cores and peripheral regions are essentially identical in the two objects, but that the *absolute* ages are 2–3 Myr greater in N11. As noted above, the core cluster of 30 Dor has an age of 2–3 Myr, while the surrounding, triggered generation must be <1 Myr old; in N11 the core is about 5 Myr old, while the peripheral clusters are 2–3 Myr old. That is, N11 may be interpreted as an evolved 30 Dor. The structure of NGC 604 in M33, as revealed by HST images, is virtually identical to that of N11. Two-stage starbursts, in which a second generation is subsequently triggered around the periphery by an initial central concentration, may be characteristic of massive star formation on this scale. To investigate this hypothesis, further information is needed about the extent and content of the current star-formation event in 30 Dor, which must be obtained in the IR with high spatial resolution.

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Discussion

Kaper: You showed N11 with a ring of star formation; how does that work? You said it was induced, but what induces the star formation?

Walborn: Well, the stellar winds and supernovae in the inner region. The energetics were studied some time ago by J. Meaburn et al. [A&A, 225, 497, 1989], and more recently by M. Rosado et al. [A&A, 308, 588, 1996]. The morphology shows that the central region very likely triggered star formation in the outer regions, and the age difference of 2–3 million years can be understood in that context. Full understanding will come only through physical analyses, but while we have so many uncertainties and approximations in the models, I believe we do well to be guided by the morphology.

Langer: You showed a WC star in one of your regions; if it belongs to the central cluster, would that contradict your age estimates?

Walborn: That's a very interesting question. There are two WC stars in 30 Dor, one quite close to R136 and one a little further out. There are at least three possible explanations. One is that they belong to the population of OB supergiants which also exists in 30 Dor; another is that they've reached the WC stage through a binary mass-transfer process; and the third is that maybe these very massive stars do have a WC stage. In giant H II regions we observe almost entirely luminous WN stars with few or no WCs; maybe the WC stage is so brief that we need a very rich population of massive stars to see any in that condition. I don't know which of those three explanations applies.

Langer: The second one cannot apply, as even in a binary you need to wait 3 million years to get get core-helium burning started.

Walborn: My thinking was that the binary interaction might accelerate or enhance the stripping process, with respect to single-star evolution.

Kudritzki: It would be interesting to do a differential study of Balmer lines to see if the youngest generation in 30 Dor has higher surface gravities for a given spectral type.

Walborn: We're trying to do some work along those lines with Nidia Morrell and Roberto Mendez. There's obviously a sequence up from compact H II regions, but you can observe stages in early-O stars which are clearly different from typical class-V stars. You have to look in very young regions to find them. θ^1 Ori C is an example of a class of nearly zero-age main-sequence stars: it may be subluminous, and it has excessively broad Balmer lines and peculiar, variable emission in He II λ4686.

There's another class of stars in 30 Dor and N11 which I've called Vz (for 'zero-age' main-sequence). Those stars have λ4686 absorption which is much stronger than any of the other helium lines; a possible explanation, which should be investigated quantitatively, is that slightly more evolved main-sequence stars have λ4686 already somewhat filled in by emission, by the same effect which brings that line into emission in more luminous stars. Curiously, the heavily embedded O3–6 V stars in general do not show λ4686 stronger than the other He lines. Perhaps they have weak emission effects unrelated to luminosity, as in θ^1 Ori C. We may therefore be able to recognize at least two or three sequential stages of optically observable, massive main-sequence stars.