On the Origin of the most massive stars around R136

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Abstract. We discuss the signature of a peculiar constellation of very massive stars at a projected distance of 2-3 pc around R136a. We discuss various scenarios for its possible origin, such as independent clusters, triggered star formation, supernovae, and ejections via dynamical interactions. If the latter scenario were the correct one this would have significant implications on the way to probe the conditions in dense stellar cores, and on the evolution of massive clusters in general.

1. Observational findings

1.1. Introduction

The 30 Doradus region in the LMC is the largest and most massive H II region in the Local Group at a distance of 53 kpc. Within a diameter of 15' (200 pc) it contains more than $8 \times 10^5 M_\odot$ of ionized gas (Kennicutt 1984). The inner 60 pc contain the stellar cluster NGC 2070 with about 2400 OB stars, which are responsible for about 1/3 of the total ionizing radiation of the entire 30 Doradus region (Parker 1993). The dense center of NGC 2070 is called R136 (HD 38268). With a bolometric luminosity of $7.8 \times 10^7 L_\odot$ (Malumuth & Heap 1994) in the inner 4.5 pc R136 is often considered the closest example of a starburst region.

1.2. Observational peculiarity

Figure 1 shows the projected distribution of emission line stars in the central part of NGC 2070. For the purpose of this study their exact spectral classification is rather subordinate; what is important here, however, is that these stars are very massive O-stars (see Table 1). The stars labeled in Fig. 1 either have been classified as Wolf-Rayet stars (Parker 1993) or X-ray sources, presumable HMXBs (Portegies Zwart et al. 2002).
Figure 1. HST image of R136, the central portion of the 30 Doradus region (Massey & Hunter 1998). The exposure time was 26 s with filter F336W (centered on 3344 Å and with a 381 Å bandpass) using WFPC2. The Wolf-Rayet stars identified by (Parker 1993) are indicated by squares, and the ellipses give the locations of the Chandra X-ray sources. The sizes of the ellipses give the 1σ positional accuracy for the Chandra sources (Portegies Zwart et al. 2002).

Table 1 lists the projected distance and spectral types for these stars. About one third of them is located within 4″ of R136a, close to another third is spread across the entire region, with distances ranging from 16″...135″. But more than one third of these massive stars in 30 Dor appear to be located in a shallow sphere of \( r \approx 8″ - 13″ \) (although even more of the massive stars, which we attribute to the core region, may be actually located in the sphere behind or in front of R136a).

Could this be just a statistical fluctuation? For a core radius of \( r_c \approx 1″ \) (Brandl et al. 1996) and under the assumption that the stellar density distribution follows roughly a standard cluster King profile, we would expect

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\int_{8″}^{13″} \frac{I_0}{1 + ((r/c)^2)} dr = I_0 r_c \left[ \ln(r + \sqrt{r^2 + r_c^2}) \right]_{8″}^{13″} = 2.2 \text{ stars},
\]

in the projected sphere, while we find 9 (±3) emission line stars – well above a random statistical fluctuation! Thus we conclude that their apparent location must have a physical origin.
2. Discussion of various scenarios

2.1. The stars were born at their observed location

*Independent smaller clusters*  Generally, massive stars do not form in isolation but in clusters and associations. For a Salpeter IMF [Salpeter 1955], one would expect about 65 stars with $m \geq 4 \, \text{M}_\odot$ for each star of $m \geq 60 \, \text{M}_\odot$. Are the massive stars around R136 surrounded by increased stellar density, relative to the overall cluster density profile, or do they appear to be isolated?

Figure 2 shows the local luminosity functions, derived from WFPC2 data in the V (F555W) and I (F814W) filter bands [Hunter et al. 1996], for 16 randomly chosen test fields and the 9 emission line stars. There is no noticeable enhancement in stellar density around the peculiar emission line stars that would support the presence of smaller clusters. However, we note the possibility that smaller associations could have dissolved within only a couple of million years to a level, which is below the detection limit.

*Triggered star formation*  Sequential star formation has been found to have triggered the LMC associations LH9 and LH10 [Parker et al. 1992] as well as N144 and N158 [Lortet & Testor 1988] in the vicinity of the 30 Doradus nebula. Several sites of ongoing star formation, such as Hodge 301 and R143, are located only 3 arcminutes from R136. However, the peculiar emission line star are located very close to R136, in a region of very little extinction where the gas has been mostly cleared out [Brandl et al. 1993]. No gaseous filamentary structures, often associated with triggered star formation, are present in the inner parts. Most importantly, the emission line stars around R136 are likely of the same age than the stars within R136. The core of R136 still appears to be the most recent site of massive star formation within 30", making a second generation of massive stars in its vicinity rather unlikely.

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Table 1. Emission line stars in and near R136. The spectral type is based on determinations by [Massey & Hunter 1998].
2.2. The stars were born within R136 and moved outwards

Supernova explosions  Runaway OB stars, i.e., apparent field stars with high relative velocities of $\geq 40$ km/s have been known for a long time — a prime example are AE Auriga and $\mu$ Columba both moving at 100 km/s away from Orion (Blauuw & Morgan 1954). Unfortunately, relative velocities are difficult to determine for the stars around R136. Although it would only take them 0.3 Myr to reach the observed location from the cluster core, even at a runaway velocity as low as 10 km/s the corresponding proper motion would only be $0.001''$ over a 20 year baseline. Radial velocity studies are in progress, but complicated by the energetic winds from these stars.

At any rate, some of the emission line stars are O-star binaries, which cannot be explained by supernova explosions. Most importantly, with an age of less than 4 Myr, R136 is unlikely to have yet produced such a large number of supernovae, and even more so when taking the kinematical age, i.e., the “travel time” from the birthplace to the observed locations, into account.

Stellar interactions  One can estimate that the timescales for global mass segregation of R136 are about $10^8$ yr (Brandl et al. 1996). However, the relaxation time for the high mass ($m_H$) stars alone is significantly shorter than for the low mass ($m_L$) stars by a factor $\frac{m_L}{m_H} \left(1 + \frac{\sigma_H^2}{\sigma_L^2}\right)^{\frac{3}{2}}$, where $\sigma_L$ and $\sigma_H$ are the velocity dispersions for the low and high mass stars, respectively. Hence, even in the simplified analytic framework, which assumes point-like, identical particles and no binaries, the relaxation time for the high mass stars can easily be 1–2 orders of magnitude shorter.
Recently, Portegies Zwart et al. (2004) performed N-body simulations of a much more realistic situation: 130,000 stars with a mass distribution given by a Salpeter IMF, a cluster half-mass radius of 1.2 pc, and an initial binary frequency of 30%\(^1\). The initial conditions used in the simulations are similar to the conditions in R136. The high central density, existence of binaries, finite stellar sizes and realistic mass spectrum allow the cluster to undergo significant dynamical evolution early on – provided that the core density is sufficiently high. Figure 3 shows the evolution of the cluster core radius for different concentration parameters. In the most extreme case, core collapse happens at less than 1 Myr. At those high stellar densities dynamical processes (binary-binary, or binary-single star interactions) can account for numerous ejections of massive stars from R136.

\[ \text{Figure 3. Evolution of the cluster core radius with time for different concentration parameters (} r_c/r_{hm} \text{). The densest systems (large } W \text{ numbers) show dramatic variations (Portegies Zwart et al. 2004).} \]

### 3. Open questions

**Can massive binaries be ejected and become bright X-ray sources?** Whether an ejected binary can become a luminous X-ray source depends on its orbital separation. For a total mass of R136 of \(5 \cdot 10^5 \, M_\odot\), a mean stellar mass of \(0.5 \, M_\odot\), and a half-mass radius of 1.2 pc a binary of mass \(m_b = 40 \, M_\odot\) and a binding energy \(E_{\text{bind}} = 2000 kT\) will have an orbital separation of \(d = 222 R_\odot\), which is a typical separation for an X-ray binary.

**Why is this signature not observed in NGC 3603?** Although NGC 3603 has been referred to a Galactic clone of R136 (Moffat 1994) there are significant

\(^1\)The binary frequency of stars, in particular high mass stars, is a very difficult problem to attack, both observationally and theoretically. Studies in the Orion cluster by Preibisch et al. (1999) using speckle interferometry indicate a large number of 1.5 – 4 companions per primary OB star – about 3 – 8 times higher than the frequency of low-mass companions.
differences. Most relevant here is that NGC 3603, with an age of about 1 Myr (Brandl et al. 1999), is significantly younger than R136. Given the strong dependency on central density and quick evolution (see Fig. 3), a few hundred thousand years can make a big difference.

Why should all ejected stars be observed at the same distance? First, the tidal radius of R136 is about 21′′ (Meylan 1993). If the stars are still bound to the cluster potential they are in elliptical orbits around R136 and most likely to be found at the apocenter. Second, most of the dynamical interactions, which have led to an ejection of a massive star, have occurred within a narrow time window, namely after the core has reached a critical density. Third, even spherically uniform distributions tend to appear ring-like in projection.

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