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The Stellar Population of R136

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Abstract. The luminous, compact star cluster R136 in the Large Magellanic Cloud is 300 times more spatially concentrated than a typical OB association and contains at least 39 O3 stars, the most massive of which is ~150 $M_\odot$. Yet, the stellar IMF for 2.8–120 $M_\odot$ is normal. The massive stars are 1–2 Myrs old, and Wolf-Rayet stars are not evolved.

1. Introduction

R136 is the luminous, compact star cluster at the center of the 30 Doradus nebula in the LMC. R136 is particularly interesting for several reasons. First, it is comparable to a very young version of a globular cluster. The half-light radius of R136 is 1.7 pc (Hunter et al. 1995) while that of globular clusters is 1–8 pc (van den Bergh et al. 1991), and the mass of R136 is 6×10^4 $M_\odot$ (extrapolating the stellar initial mass function [IMF] to 0.1 $M_\odot$) compared to 4–40$\times10^4$ $M_\odot$ for globulars (Illingworth 1976).

Secondly, R136 represents a region where many stars, especially massive stars, have formed in a very small space. Figure 1 compares the spatial concentration and richness of R136 with typical OB associations (Massey et al. 1995), and other star-forming regions (Hunter et al. 1996a,b; Dolphin & Hunter 1998). Compared to OB associations, R136 is ~ 300 times more spatially concentrated and ~ 10–100 times richer in stars. It has been suggested that the lower mass stars will be missing from regions where many massive stars have formed. R136 offers a place to test this idea. R136, while neither unique nor the most extreme among star clusters, is unique in being both very young and close enough to resolve into individual stars.

2. Early Stellar Population Studies of R136

R136 has intrigued astronomers for decades. It particularly gained notoriety in the early 1980's when people, puzzling over the prodigious UV output and spectra of the central object, postulated that R136a, the bright source in the center of R136, was a single star > 10^3 $M_\odot$ (Feitzinger et al. 1980; Cassinelli et al. 1981). The alternative explanation of a cluster of ~ 30 O3 stars seemed too unreasonable by comparison (but see Melnick 1985). However, ground-based speckle observations (Weigelt & Baier 1985; Neri & Grewing 1988) and then HST observations (Weigelt et al. 1991; Campbell et al. 1992; de Marchi et al. 1993; Elson et al. 1992) showed that R136a was a collection of a dozen stars. Ground-

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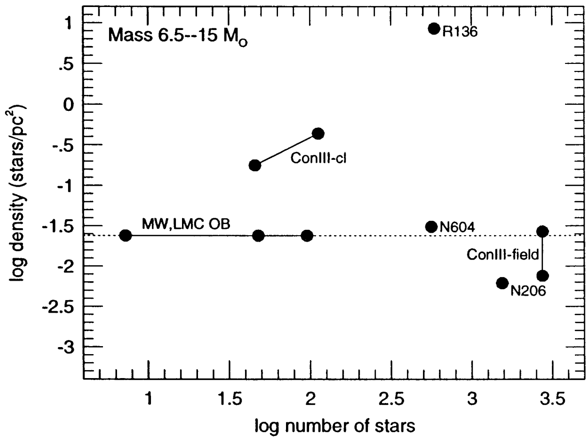

Figure 1. Richness of stars formed against their spatial concentration.

based (Walborn 1973; Moffat & Seggewiss 1983; Chu et al. 1984; Melnick 1985; Moffat et al. 1985) and HST observations (Campbell et al. 1992; Parker et al. 1995) also confirmed that R136 contained several Wolf-Rayet stars but no red supergiants. This plus stellar evolutionary models placed an age of 3–4 Myrs on the massive stars.

3. What WFPC2 Revealed

With WFPC2 on HST astronomers were finally able to measure a color-magnitude diagram for R136 (Hunter et al. 1995, 1996c), shown in Figure 2. This CMD showed a main sequence of intermediate mass stars—down to $\sim$2.8 $M_\odot$, and stars down to $\sim$1.1 $M_\odot$ on pre-main sequence tracks. Pre-MS stars have also been identified in ground-based near-infrared observations by Brandl et al. (1996). Isochrones show that stars on the pre-MS tracks are as young as 2 Myrs. This led to a very unexpected result: R136 did not fit the standard picture for cluster formation in which the lower mass stars form first and that, when the massive stars finally form, their strong winds disrupt the cloud and shut down star formation. On the contrary, in R136 some lower mass stars appeared to have formed 1–2 Myrs *after* the massive stars!

From the WFPC2 CMD we also learned that the intermediate mass stars were present in nearly normal proportions and that this IMF is independent of distance from the cluster's center. The lower mass limit is $\lesssim$ 2.8 $M_\odot$, although stars are also present to at least 1.1 $M_\odot$.

4. The Massive Stars

However, questions about the stellar population of R136 still remained: What is the IMF of the *massive* stars, and what is their age really? To answer these

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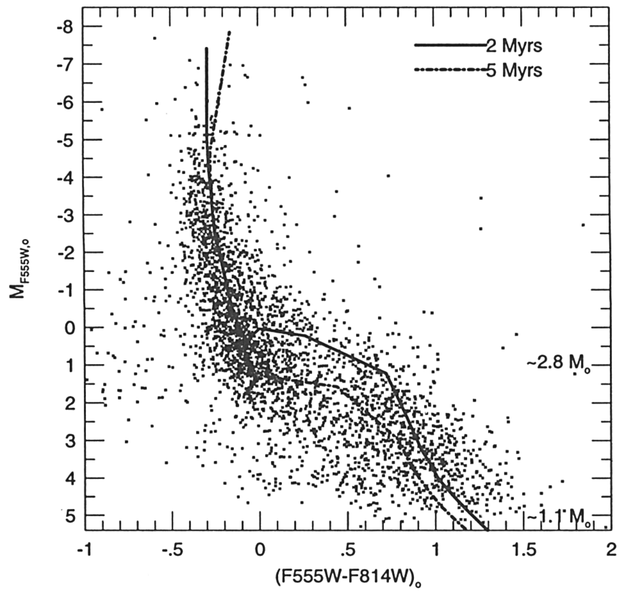

Figure 2. CMD for R136 to a radius of 5 pc from WFPC2 photometry.

questions requires spectroscopy of the individual stars, and Massey & Hunter (1998) did that. A hint of what was to come came from the results of de Koter et al. (1997) who obtained spectra of 3 stars in R136a. Two of these stars are Wolf-Rayet stars but turned out to be H-core burning.

Massey & Hunter (1998) obtained high signal-to-noise HST spectra of 65 of the bright, blue stars in R136 for the purpose of spectral classification. Including 2 of the stars observed by de Koter et al. (1997), one finds that 39 of 67 stars are O3 stars. The alternative explanation of R136 as a cluster of O3 stars was, in fact, correct! Furthermore, the highest luminosity stars turn out to be Wolf-Rayet stars that are 2.5 magnitudes too bright and are H-rich rather than H-poor. That is, as de Koter et al. found, the Wolf-Rayet stars are super Of stars rather than evolved objects. Furthermore, HR diagrams of the massive stars show that their age is 1–2 Myr, depending on which effective temperature scale for massive stars one adopts. Therefore, the massive stars are much younger than previously thought. Now R136 fits the standard scenario for star formation in a cluster: Star formation started $\geq$5 Myr ago with the lower mass stars and continued until the high mass stars formed most recently. The fact that the Wolf-Rayet stars in R136 are not evolved objects has implications as well for the "Wolf-Rayet galaxies" and their WR/O star ratio problem.

The most massive stars in R136 have masses of 140–150 $M_\odot$. These masses are based on extrapolating the mass–luminosity relationship from the Geneva evolutionary tracks, and so are conservative, but they are among the most massive stars known. Yet, surprisingly, the IMF slope is normal. So, the intense, rich environment of R136 did not produce an unusually shallow massive star IMF, but rather the IMF slope is just like those measured for OB associations.

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Therefore, we see that R136 has a normal stellar population for $\geq 2.8\ M_\odot$ and that this IMF applies over a range of 300 in spatial concentration from OB associations to globular-like clusters. Furthermore, finding such massive stars in R136 argues that the upper stellar mass limit observed so far in star-forming regions is statistical rather than physical in nature. R136 has such massive stars simply because it is very young and very rich in stars.

5. The Future

Several questions still remain about R136 to yet intrigue astronomers. First, what are the massess of the O3 stars really since the O3 class is degenerate? STIS observations are being analyzed to address this. Second, what is the stellar population $< 2.8\ M_\odot$ in R136? NICMOS observations are aimed at this question and is the subject of the talk by Zinnecker. So, it is possible that someday we may have a complete census of the stars in this remarkable star cluster.

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Discussion

Hans Zinnecker: How many 40-80 $M_\odot$ stars (early O-stars) are present in the NGC 2070/R136 cluster and how are they distributed spatially? Are they all near the cluster centre ($R < 2$ pc)? Please draw a map with the positions of the 100 most massive stars in 30 Doradus!

Hunter: There are $\sim$ 24 stars more massive than 80 $M_\odot$. They are scattered throughout the cluster and are not disproportionally concentrated toward the center. A picture showing the location of stars with masses $>$ 100 $M_\odot$ can be found on the NOAO web page under press releases.

Daniel Wang: You mentioned that R136 is young. Do you have a new estimate of its age?

Hunter: The massive stars appear to be $1 - 2$ Myrs old, depending on which temperature scale you use for the stars. Lower mass stars appear to be on pre-MS tracks that indicate ages of 2 Myrs and older.

Sally Oey: While the expectation value of the highest-mass star per cluster increases with N (the number of stars per cluster), it must approach the upper-mass limit if it exists. Are the observations of highest-mass star and numbers consistent with your claim of the upper-mass limit being statistical, not physical, especially for R136?

Hunter: In R136 the most massive stars that we see occur where the IMF peters out in numbers. So even in R136 we are not necessarily seeing a physical upper limit to the mass of a star that can form.