GRS SPECTROSCOPY OF INDIVIDUAL STARS IN R136a

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ABSTRACT

The installation of the Corrective Optics Space Telescope Axial Replacement (COSTAR) Instrument on the Hubble Space Telescope makes it possible to observe stars in very crowded regions with high spatial and spectral purity. To demonstrate this capability, we have used the Goddard High Resolution Spectrograph (GRS) to obtain spectra of two stars in the dense center of the 30 Doradus ionizing cluster: R136a5, and its nearest neighbor, R136a2, only 0.17 away. R136a5 is shown to be an O3f/WN star, while R136a2 is a WN4-w star. From both WFPC photometry and GRS, spectroscopy we estimate the following properties of R136a5: Teff = 42,500 K, R = 16.4 R⊙, Lbol = 8 × 105 L⊙, and M ≈ 50 M⊙—all indicating that, despite its spectral type, R136a5 is a massive, main-sequence O star. An astonishing aspect of these spectra is the high rate of mass loss in R136a5, as indicated by the strength of He ii λ1640 emission. The observed mass-loss rate, $\dot{M} = 1.8 \times 10^{-5} M_\odot$ yr$^{-1}$, is an order of magnitude higher than is assumed by current stellar evolutionary models. We argue that this high rate of mass loss will alter drastically the evolutionary path of R136a5. If so, evolutionary models for massive stars require substantial revision.

Subject headings: galaxies: star clusters — Magellanic Clouds — stars: early-type — stars: evolution — stars: individual (R136a5, R136a2) — stars: mass loss — ultraviolet: stars

1. INTRODUCTION

R136a, the nucleus of the 30 Doradus ionizing cluster, contains a very dense population of young, massive stars. Walborn (1991) and others have called it a "unique laboratory" for studying massive-star evolution, and the "Rosetta Stone" for interpreting starburst in distant galaxies. These accolades are well deserved. R136a is the only resolved cluster that is dense enough in very massive stars ($M \geq 40 M_\odot$) that it can define an empirical isochrone of young, massive stars. It is also the only resolved cluster dense enough that its initial mass function may be influenced by interactions with other stars or protostars. Like other star clusters in the LMC, R136a has a low metal content, and hence, represents a laboratory for exploring the effect of metal content on mass loss and evolution, when contrasted with clusters in the Galaxy.

In 1991, we obtained a GHSRS spectrum of R136a (Heap et al. 1992). Although the aperture subtended a region only 0.5 pc (2") across at the LMC, nearly 50 stars contributed light to the spectrum. Figure 1 shows the observed isochrone of R136a plotted in the Teff–Mv plane. Lacking spectroscopic temperatures, we used Mv to fit the stars to a theoretical isochrone of a cluster having an age of 3.2 Myr and an LMC metallicity (Z = 0.008; Schaefer et al. 1993). The GHSRS spectrum indicates that the dominant contributors are a mixture of O3f and WN-type stars with no detectable admixture of other spectral types. For example, there are no spectral signatures of mid-to-late O stars. The three brightest stars, R136a1, R136a2, and R136a3, are Wolf-Rayet stars (Campbell et al. 1992; Parker & Heap 1994), which helps to explain the W-R features in the spectrum. But the absence of stars brighter than $M_v = -7$ or stars with late-O or B-type spectra is puzzling. And if R136a is old enough to have formed W-R stars, then why are the dominant stars so hot (the temperature associated with an O3f star is at least 42,500 K)? Where are the cooler stars that should have evolved off the ZAMS to lower temperatures?

To answer these questions, we needed spectra of individual stars in R136a. This required the servicing of the Hubble Space Telescope (HST), which included the installation of the Corrective Optics Space Telescope Axial Replacement (COSTAR) Instrument. COSTAR corrects the spherical aberration in the beam from the HST primary mirror, and relays the corrected beam to the GRS and two other instruments.

Here we report the first ultraviolet spectra of individual stars in R136a, which were obtained with the GRS and COSTAR on 1994 April 2. Spectra were obtained of the V = 13.73 mag star, R136a5, and its closest neighbor, R136a2, located 0.16 to the southwest. We chose R136a5 for study because it could in principle be isolated by the GRS Small Science Aperture (SSA, 0.22 square), and because it was expected to be one of the brightest O stars in the core of R136a. WF/PC photometry (Malumuth & Heap 1994) yields an absolute magnitude for R136a5, $M_v = -6.0$ mag. For an assumed age of 3 ± 5 Myr (e.g., Heap et al. 1992; de Marchi et al. 1993), such a star is expected to have an effective temperature, $T_{\text{eff}} \leq 40,000$ (± 2000) K (cf. Fig. 1), a radius, $R \approx 15 R_\odot$, luminosity $L_{\text{bol}} \approx 6 \times 10^5 L_\odot$, and present-day mass, $M \approx 50 (\pm 5) M_\odot$. Current stellar evolutionary models, which make use of the compilation of observed mass-loss rates (de Jager, Nieuwenhuijsen, & van der Hucht 1988) scaled to the LMC, would assign a mass-loss rate, $\dot{M} = 0.9 \times 10^{-6} M_\odot$ yr$^{-1}$, to models for R136a5. Similarly, Kudritzki et al.'s (1989) theoretical "recipe" with the wind-force parameters of Pauldrach et al. (1994) yields a mass-loss rate, $\dot{M} = 2.9 \times 10^{-6} M_\odot$ yr$^{-1}$, and a

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terminal velocity, \( v_\infty \approx 2900 \text{ km s}^{-1} \). In short, R136a5 was expected to be a normal, if massive, O-type star.

Our analysis of the spectrum of R136a5 (de Koter et al. 1994) indicates that the star is indeed a hot (\( T_{\text{eff}} \geq 42,500 \text{ K} \)), massive star, still on the main sequence. To our surprise, it has a very high rate of mass loss, \( M \approx 1.8 \times 10^{-5} \text{ M}_\odot \text{ yr}^{-1} \), which is much higher than is assumed by modern evolutionary models (Schaerer et al. 1993; Fagotto et al. 1994) for that mass, temperature, and metal content. As a consequence, its evolutionary track should differ qualitatively from these models. We suggest that evolutionary models that assume a mass-loss rate enhanced by pulsational instability (Kiriakidis, Frick, & Glatzel 1993) may be more appropriate for stars in R136a and, at the same time, may solve some of the puzzling aspects described above.

2. THE OBSERVATIONS

Because of the extreme field crowding, acquisition of a particular star in R136a is a formidable undertaking. Our acquisition strategy was to use the GHR S flight software to acquire R136a in the Large Science Aperture (LSA, 1.74 square), peak up in the Small Science Aperture (SSA, 0.22 square), and then to make blind slews to position R136a2, and later R136a5, in the SSA and to get spectra of both stars. Since the relative coordinates of the stars were known (Malumuth & Heap 1994), the main problem was in predicting where in R136a the GHR S would autonomously center the LSA. Our simulations using a WFPC2 image of R136a (obtained for engineering purposes), illustrated in Figure 2 (Plate L22), suggested that the GHR S would most likely peak up between R136a1 and R136a2, which lies 0'08 to the east of R136a1. If this point were designated as R136a1, then precommanded blind slews to R136a2 and R136a5 would overshoot them slightly to the east, so that the spectrum of R136a2 would have minimal contamination from R136a1, and the spectrum of R136a5 should be uncontaminated by either R136a2 or R136a7.

The observations indicate that this strategy was successful and that the performance of COSTAR meets or exceeds expectations. A detailed map of the SSA made by the GHR S “focus diodes” at the time of observing R136a5 show no evidence of a second star in the aperture. Nevertheless, higher resolution WFPC2 images (0'043 pixels) obtained on the same day as the spectra show that one of the diffraction spikes from R136a2 intersects R136a5. Because of the diffraction spike and because one edge of the SSA came within \( \sim 0'05 \) of R136a2, we estimate that \( \sim 5\% \) of the flux of R136a2 was included in the GHR S SSA at the time of observing R136a5.

Figure 3 compares the normalized spectrum of R136a5 along with R136a2 and the pre-COSTAR spectrum of Melnick 42. All three spectra were obtained by the GHR S with the low-resolution mode (grating G140L, 0.6 Å resolution) with the target in the SSA. The UV spectrum of R136a5 is dominated by lines formed in the wind. Identifiable P Cygni features include N V \( \lambda 1240 \), O IV \( \lambda 1338 \), 1343, O V \( \lambda 1371, S V \lambda 1502 \), C IV \( \lambda 1549 \), He II \( \lambda 1640 \), and N IV \( \lambda 1718 \). When compared to the GHR S spectrum of R136a2, it is clear that the two spectra are different in detail: stellar SI IV \( \lambda 1393, 1403 \) is very weak, if present at all, in the spectrum of R136a5, but it does appear with P Cygni profiles in R136a2; He II \( \lambda 1640 \) line in the spectrum of R136a5 has an emission strength consistent with an early O of spectral type, while He II emission in R136a2 has a strength seen only in Wolf-Rayet stars; the edge velocity of the C IV \( \lambda 1549 \) doublet is higher in R136a5 than in R136a2.

Classification of the spectrum of R136a2 is not straightforward, because it must be contaminated by R136a1 only 0'08 away. We estimate that the observed continuous flux is two parts R136a2 to one part R136a1. We classify the spectrum of R136a2 as WN4-w (i.e., an early-WN spectrum with weak emission lines) because of its very high wind velocity for a WN star (\( V_\infty = 2600-2800 \text{ km s}^{-1} \)), the high ionization level of its spectrum, and the relative weakness of He II \( \lambda 1640 \). We attribute to R136a2, the general properties of WNE-w stars (Hamann, Koesterke, & Wessolowski 1993): \( T_\text{eff} = 30,000-40,000 \text{ K} \), log \( L_\odot = 4.5-5.5 \), and a composition enriched in nitrogen, although still containing hydrogen.

The spectrum of R136a5 strongly resembles that of Melnick 42, a very massive star also in 30 Doradus (Heap et al. 1991). Melnick (1985) classified the spectrum of Melnick 42 as O3f; more recently, Walborn et al. (1992) classified it as O3f/WN, with the clear implication that the star is in a direct, physical transition from an O-star to a WN-star. The major differences between R136a5 and Melnick 42 are that R136a5 is a magnitude fainter and, as shown in Figure 4a, has a higher wind
Fig. 2.—Target acquisition field of R136a. At left is the GHRS map of the 4" × 7 field made by the N2 mirror (pixel size = sample spacing = 0.711). The position and orientation of the Large Science Aperture (1" × 7") for the date of observation (1994 April 2) is shown. The image of the LSA projects onto exactly eight diodes as shown. Target acquisition in the LSA involves successive telescope pointings, first to center R136a in the "y" direction (along the length of a diode), and then in "x." At right is a WFPC2 image of R136a, also obtained on 1994 April 2. The pixel size is 0.44". At the distance of the LMC, 1" corresponds to 0.25 pc.

Heap et al. (see 435, L40)
velocity. SEI analysis (cf. Lamers, Cerruti-Sola, & Perinotto 1987) of the C IV λ1549 doublet gives \( V_{\infty} = 3200-3400 \) km s\(^{-1}\) for R136a5 versus \( V_{\infty} = 2900-3000 \) km s\(^{-1}\) for Melnick 42. A more subtle difference between the two spectra is in the profile of the C IV absorption trough. In fact, the rounded bottom of the C IV absorption trough in the spectrum of R136a5 is problematic: such a profile is not seen in other O stars; nor can it be fitted well by the SEI procedure. This problem is resolved if the spectrum is corrected for the suspected 5% contribution from R136a2, in which the C IV λ1549 absorption trough has a flat bottom. Although most other lines are unaffected by a 5% level of contamination, the He II λ1640 wind line does become somewhat weaker (Fig. 4b). Whether in original or corrected form, the He II λ1640 emission strength implies a very high mass-loss rate. De Koter et al. (1994) find that they can match the observed (corrected) strength of the He II λ1640 emission only for mass-loss rates as high as \( M = 1.8 \times 10^{-5} \) M\(_{\odot}\) yr\(^{-1}\). Such a high mass-loss rate is characteristic of W-R stars, not O stars. The derived high rate of mass loss appears to be robust despite a large uncertainty in the effective temperature of R136a5. De Koter et al. estimate a \( T_{\text{eff}} = 42,500 \) K for R136a5. They also reanalyzed the GHRS spectrum of Melnick 42 and derived a \( T_{\text{eff}} = 42,500 \) K. However, Pauldrach et al. (1994) estimate a \( T_{\text{eff}} = 50,500 \) K for Melnick 42; very likely, they would also assign a similarly high temperature to R136a5. While resolution of this discrepancy must await future computations (cf. de Koter et al. 1994), there is indirect evidence against such a high temperature for R136a5. First, only a star as massive as \( \approx 150 \) M\(_{\odot}\) can have a temperature as high as 50,500 K after 2–3 million years (Schaefer et al. 1993). Second, assigning such a high temperature to an O3f star only exacerbates the problem of explaining how O3f stars can co-exist with W-R stars in the R136a cluster. We therefore adopt the lower temperature, \( T_{\text{eff}} = 42,500 \) K, for R136a5. This temperature and \( M_{V} = -6.0 \) yield a stellar radius, \( R = 16.4 \) R\(_{\odot}\), and luminosity, \( L_{\text{bol}} = 8 \times 10^{6} \) L\(_{\odot}\). The corresponding mass is estimated to be \( \approx 50 \) M\(_{\odot}\).

While the observed mass-loss rate is relatively insensitive to temperature, the predicted mass-loss rate is quite sensitive. We have used the Kudritzki et al. (1989) mass-loss "recipe" with the wind-force parameters of Pauldrach et al. (1994): for \( T_{\text{eff}} = 42,500 \) K, we obtain a predicted mass-loss rate, \( \dot{M} = 2.9 \times 10^{-6} \) and terminal wind velocity \( V_{\infty} = 2900 \) km s\(^{-1}\); for \( T_{\text{eff}} = 50,500 \) K, we obtain a much higher mass-loss rate \( \dot{M} = 1.2 \times 10^{-5} \) M\(_{\odot}\) yr\(^{-1}\), almost in agreement with observation, but an unreasonably low wind velocity \( V_{\infty} = 1610 \) km s\(^{-1}\). We conclude that while the observed mass-loss rate seems well established, the ability for theory to reproduce the observed mass-loss rate hinges on the effective temperature: if \( T_{\text{eff}} = 42,500 \) K, the observed mass-loss rate is higher than can be explained by the CAK theory of radiatively driven winds; while if \( T_{\text{eff}} = 50,500 \) K, there is rough consistency between observations and theory. In any case, the observed mass-loss rate of R136a5 is much higher than is assumed by modern stellar evolutionary models (e.g., Maeder 1990; Schaefer et al. 1993) which adopt mass-loss rates given by de Jager et al. (1988) scaled to a LMC metallicity.

3. DISCUSSION

The theory of massive-star evolution is undergoing major upheaval. Improvements to the radiative opacities by the OPAL and Opacity projects (Iglesias, Rogers, & Wilson 1992; Seaton et al. 1994) recently led to substantial changes in the evolutionary tracks of massive stars (e.g., Schaefer et al. 1993 vs. Maeder 1990). More important, many of the models of hot, massive stars have been found to be violently unstable to pulsation, even while the star is on the main sequence (Kiriakidis et al. 1993). Such instabilities lead to enhanced mass loss, implying qualitatively different evolutionary tracks. Langer et al. (1994) explored the consequences of pulsation-enhanced mass loss for a \( M_{\text{ZAMS}} = 60 \) M\(_{\odot}\) star of Galactic composition. They find that while on the main sequence (i.e., the first 3.35 Myr), the model makes a small loop on the H-R diagram, returning to an effective temperature and luminosity near that at the ZAMS! Also during main-sequence evolution, a star loses half its mass, and the surface abundance of hydrogen (by mass) drops from \( X = 0.70 \) to 0.30. Subsequent evolution carries the star very briefly to lower temperatures, but at no stage does the star become as visually bright as models that do not allow for pulsation-enhanced mass loss. Langer et al. propose a new evolutionary sequence for massive stars: \( O \Rightarrow \text{H-rich WN} \Rightarrow \text{LBV} \Rightarrow \text{H-poor WN} \Rightarrow \text{H-free WN} \Rightarrow \text{WC} \Rightarrow \text{SN} \). With previous models, a star spends at least 80% of its lifetime on the main sequence (as an O star or H-rich WN star).

Langer et al. carefully pointed out that their findings may not apply to stars of other metallicities (e.g., stars in R136a) because both radiation-driven and pulsation-driven mass-loss rates are sensitive to the metal abundance (Kiriakidis et al. 1993). Nevertheless, their results are very useful in exploring the consequences of a very high mass-loss rate. For the case of R136a5, pulsation-enhanced mass loss may provide a physical
explanation for the observed high mass-loss rate. We therefore suggest that Langer's et al.'s evolutionary sequence applies to stars in R136a. In this scenario, both R136a2 and R136a5 are on the main sequence with the WN4 star, R136a2, being the initially more massive, and therefore, the more evolved star. R136a5 is an Of/WR star in transition to a WN star. Even R136a2 may not be a full-fledged WN star: the weakness of the emission lines and absence of $\mathrm{N\,iv}\lambda\,1485$ suggest that it too may be a transition object. Both stars undergo pulsation-enhanced mass loss, which leads to the signature $\mathrm{He\,ii}\lambda\,1640$ emission. Both stars also are very hot because main-sequence stars do not stray far from their ZAMS temperatures.

Although this hypothesis must be confirmed by a detailed grid of models for a LMC composition and by observations of more stars in R136a, it accounts for some of the puzzling aspects of R136a described above. The reason that there are no stars in R136a brighter than $M_v = -7$ mag is that, due to pulsation-enhanced mass loss, massive O stars evolve directly into H-rich WN stars like R136a2, and the subsequent LBV stage is extremely brief. Second, the reason why the integrated spectrum of R136a mimics that of an O3f star ($T \geq 40,000$ K) despite the presence of WN stars, is that massive stars retain their high temperatures throughout most of their lifetime. We plan to test this hypothesis by obtaining GHRS spectra of other stars in R136a and constructing an empirical isochrone for this cluster.

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REFERENCES


Heap, S. R., et al. 1992, in Science with the HST, ed. P. Benvenuti & E. Schreier (Garching, ESO), 347


Maeder, A. 1990, A&AS, 84, 139


Parker, J. W., & Heap, S. R. 1994, BAAS, 26, 908


Walborn, N. 1991, in Massive Stars in Starbursts, ed. C. Leitherer et al. (Cambridge: Cambridge Univ. Press), 145