R136: The Core of the Ionizing Cluster of 30 Doradus

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Introduction

I first read that R136 contained a supermassive object some time ago in the Sunday edition of the Chilean daily newspaper *El Mercurio,* where it was announced that ... "European astronomers discover the most massive star in the Universe!". Since *El Mercurio* is almost always wrong I did not take the announcement very seriously until the paper by Feitzinger and co-workers (henceforth the Bochum group) appeared in *Astronomy and Astrophysics* in 1980. More or less simultaneously with the publication of these optical observations, a group of observers from the University of Wisconsin, headed by J. Cassinelli (henceforth the Wisconsin group) reached the same conclusion on the basis of ultraviolet observations obtained with the International Ultraviolet Explorer (IUE).

After these papers where published, and since I have been interested in R136 for a long time, I started to consider the matter (a little) more seriously. I knew that R136 was in the centre of the 30 Doradus nebula but I had never heard of R136a before. Since, as you may imagine, 30 Doradus plays a crucial role in the whole story, I will give a brief description of this remarkable object.

The 30 Doradus Nebula and R136

The 30 Doradus nebula (thus named because it lies in the Constellation of Doradus) is an outstanding complex of gas, dust and stars in the Large Magellanic Cloud (LMC), the nearest galaxy to our own. Beautiful colour photographs of the LMC and the 30 Doradus region can be found in the December 1982 issue of *The Messenger.* The diameter of 30 Dor is several hundred parsecs and, although emission nebulae as large or larger than 30 Dor exist in other galaxies, none is found in our own. The visual light emitted by the nebula is produced almost entirely by hydrogen recombination lines and in order to maintain this radiation the equivalent of about 100 O4 stars (the hottest stars known have spectral type O3) are required. For comparison, the most massive stellar associations in our Galaxy, like the Carina nebula, for example, contain only a few such stars.

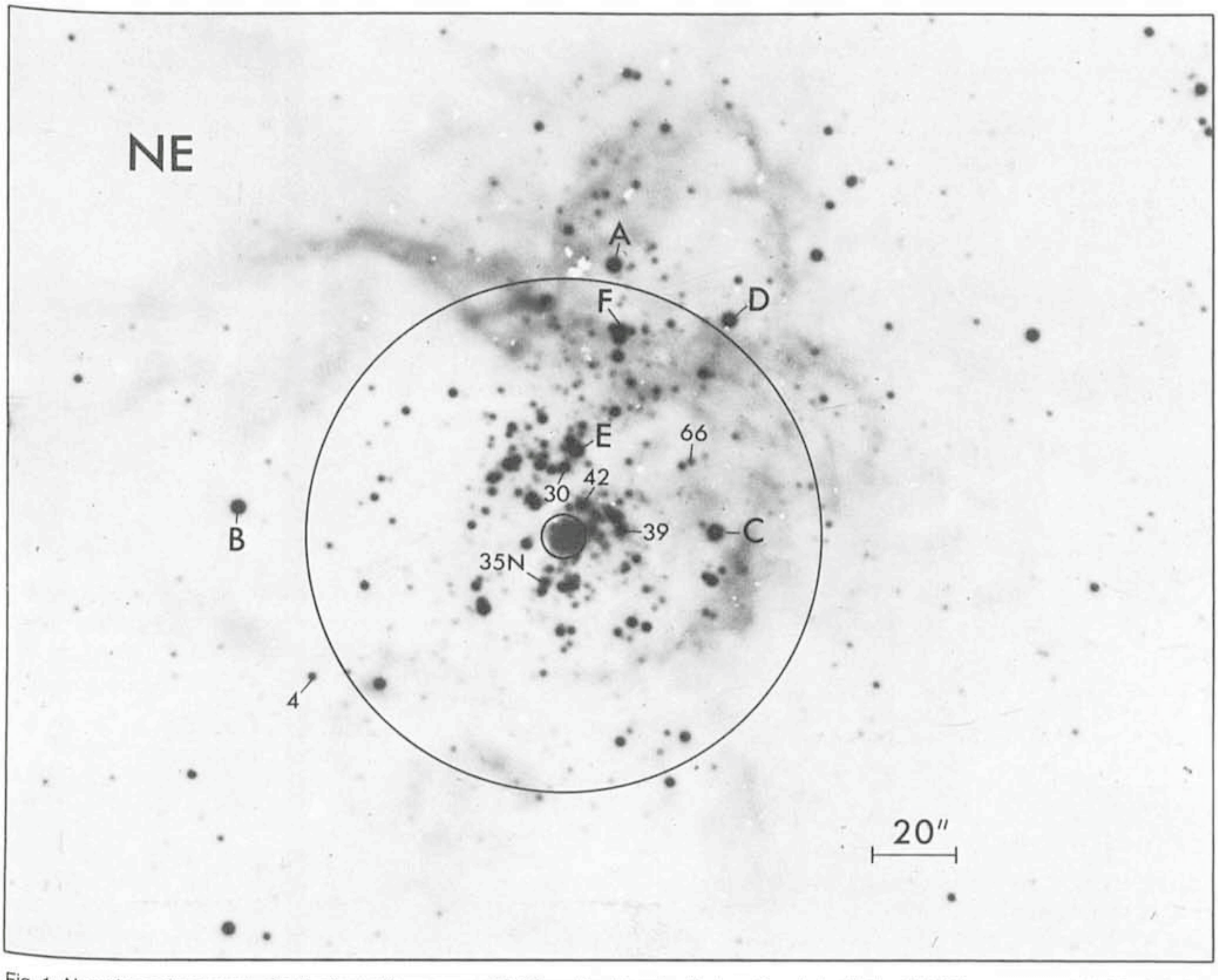

Fig. 1: *Negative enlargement of a 3-minute V exposure of 30 Doradus taken by Preben Grosbøl with the McMullan camera at the Danish 1.5 m telescope at La Silla.*

In Fig. 1 I have reproduced a visual electronograph of 30 Doradus exposed for 3 minutes with the Danish 1.5 m telescope at La Silla. The large circle in the photograph has a radius of one arc minute and marks the region I will refer to as the core of 30 Doradus as this region contains most of the central cluster stars as well as most of the nebular gas and dust. The diffuse object in the centre of the cluster is R136 (the 136th entry in the Radcliffe catalogue of LMC stars compiled in 1960 by Feast, Thackeray and Wesselink). Although R136 appears clearly non-stellar in the figure it looks almost stellar on small scale plates and this justifies its inclusion as an LMC star.

Some 10 years ago Nolan Walborn suggested that R136 was the unresolved core of the central cluster of 30 Doradus. This is why I was surprised when it was announced that R136 was or contained a single supermassive object. Using short-exposure photographs taken with the ESO 3.6 m telescope, the Bochum observers found that R136 contained three bright components (a, b and c), the brightest of which, R136a, is located more or less in the centre of the small circle drawn in Fig. 1. Components b and c lie NW of the centre and give R136 its "comma" shape.

A Supermassive Star

The distance modulus to the LMC is about 18.6 magnitudes. Thus, even if there was no extinction at all, it is clear that the brightest component of R136 must be extremely luminous since it is burned out even in the 3-min exposure reproduced in Fig. 1. In fact, the Bochum and the Wisconsin observers found that in the optical as well as in the ultraviolet the luminosity of R136a corresponds to the equivalent of more than 10 of the most massive O or Wolf-Rayet stars known. Thus, if R136a is a single object it must be extremely massive indeed.

Several other arguments have been presented in favour of the supermassive nature of R136a. I will not discuss these arguments in detail since all make the a-priori assumption that R136a must be a single object and/or that it must provide most of the energy required to ionize the 30 Doradus nebula. The crucial question therefore ist: What is the size of R136a?

Two groups have used the technique of speckle interferometry to determine the size of R136a. (A description of the speckle interferometry technique is given on page 23 of the *Messenger* No. 30, December 1982.) This is a very difficult experiment because, even when using the largest available telescopes, this technique can only be used for bright stars and because the interpretation of speckle observations for complex objects is somewhat subjective and therefore often ambiguous.

Gerd Weigelt from the Physikalisches Institut, University of Erlangen, used the ESO 3.6 m telescope and (in his latest unpublished result) finds that R136a is dominated by 2 stars separated by 0.46 arc-seconds surrounded by about 4 other fainter stars, all superposed on a complex background. On the other hand, J. Meaburn and collaborators from the University of Manchester, using the Anglo-Australian 3.9 m telescope find that R136a is a single object and thence that its size must be smaller than the diffraction limit of the AAT which, at the distance of the LMC, corresponds to about 1,000 AU. Interestingly enough, in a recent preprint, Moffat and Seggewiss have remarked in the astrometric observations made in 1927 from South Africa by Innes (who finds R136a to be a multiple system at the centre of which is a double star) a separation, position angle and magnitude difference almost identical to that found by Weigelt.

Before proceeding with the discussion of R136a I will present my own (previously unpublished) observations of R136 and the 30 Doradus cluster which (I hope) will make the R136a story clear.

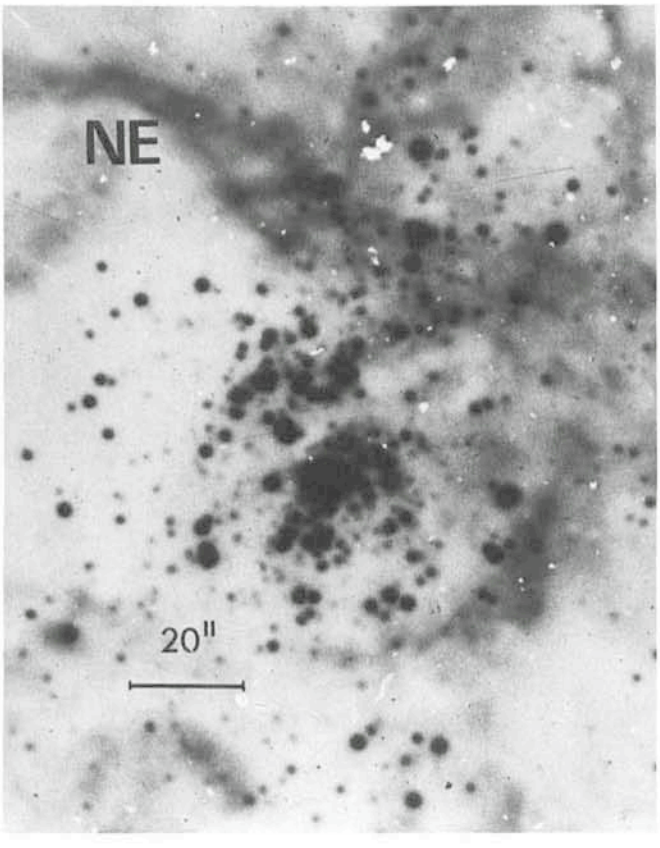

Fig. 2: *Contrast-enhanced version of Fig. 1.*

My Story

One of the principal motivations of the interest in R136 was the need to explain the energy source of the gigantic 30 Doradus nebula. In fact the effective temperature used in the early papers was derived assuming R136 produced most of the ionization of the nebula. Until recently, all that was known about the rest of the cluster was that it contained a large (in fact the largest known) concentration of Wolf-Rayet stars. However, most of these stars are late types (WN6–WN7), too cold to contribute significantly to the ionization of the nebula. Since WR stars are believed to be evolved O stars, it was considered that most of the stars in the cluster were too evolved to produce the large amount of ionizing photons required to account for the observed nebular emission.

In collaboration with Preben Grosbøl, I started a programme to obtain UBV electronographic photometry of a large number of stars in the core of 30 Doradus. Fig. 2 shows a contrast-enhanced print of our 3-min V exposure where the problems of doing photometry in 30 Dor are illustrated; a strong, highly inhomogeneous background and crowding. In fact photoelectric photometry is very difficult even far from the centre of the cluster because of the strong inhomogeneous background while photographic work is impossible because the nebular emission pre-flashes the plates. By comparison, the 40 mm McMullan camera at the Danish telescope combined all the features (good blue response – not available with most CCDs – fine grain, large dynamic range and linearity required for this project (and in fact for any photometry project). A set of programmes was incorporated into the ESO IHAP image processing system to handle this photometry which permitted to obtain reliable results down to about 15.5 magnitude (it is now possible, using point spread function fitting techniques, to go fainter but our U plates are not sufficiently exposed).

In order to interpret the photometry, it is necessary to correct the observed UBV colours for interstellar extinction. Even a casual inspection of Fig. 1 or 2 shows that the reddening varies significantly from place to place in the nebula so that one must determine individual values for each star. In principle this is easily done in the UBV system if the wavelength dependence of the extinction is known. The parameters required are R = Av/E(B-V, (Av being the total visual extinction and E(B-V) the colour excess), and r = E(U-B)/E(B-V).

Since an extremely hot O star (say O3) has the same UBV colours as a much cooler one, and since it was necessary to verify the extinction properties of the dust, with the collaboration of Phillip Massey from the Dominion Astrophysical Observatory in Canady, I started a programme to obtain spectral types for a significant number of stars in the core of 30 Doradus using the image tube spectrograph at the 4 m telescope of the Cerro Tololo Interamerican Observatory. Combining the spectroscopy with the UBV photometry it is possible to check on the reddening problem, as well as to test the accuracy of the electronographic photometry and our ability to assign spectral types of very early type stars on the basis of UBV magnitudes and colours.

Preliminary (just out of the oven) results are presented in Figs. 3 and 4 which show colour-colour and colour-magnitude diagrams for stars within 2 arc-minutes from R136. The photometry is complete to V=15.0. The solid lines represent the ZAMS, the locus of hydrogen burning unevolved stars, and the effect of reddening on an O4 star assuming r = 0.79. Considering the photometric errors, the r = 0.79 line is seen to represent well the effect of reddening on the cluster stars. Combining the UBV photometry with spectral types for about 25 stars, and assuming a distance modulus of 18.6 to the nebula, I find that r = 0.79 and R = 3.1 (i.e. the galactic and Orion values) represent adequately the extinction law in 30 Doradus. As in the case of the Orion nebula, the detailed visual extinction law may be very different from the normal galactic curve.

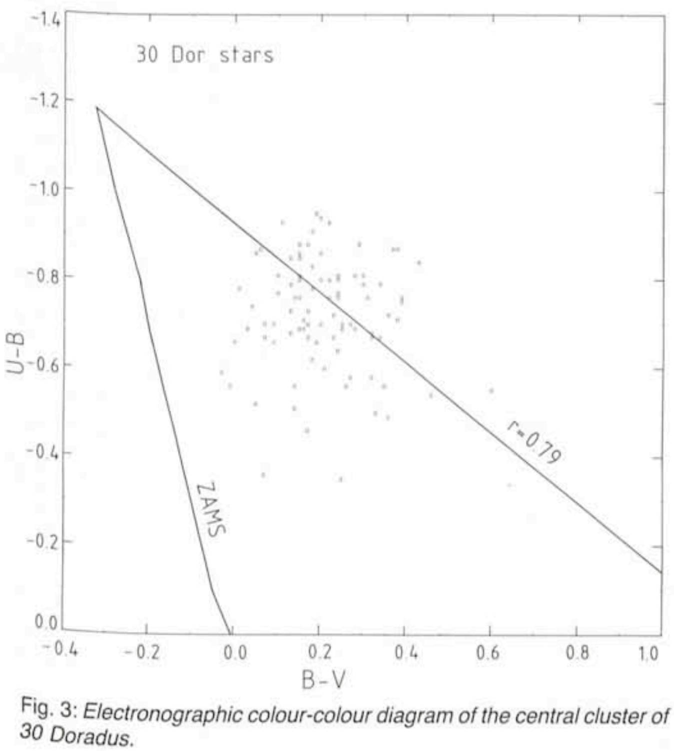

Fig. 3: *Electronographic colour-colour diagram of the central cluster of 30 Doradus.*

Fig. 4 shows the dereddened colour-magnitude plots. The line shows the ZAMS for early O-type stars taken from Schmidt-Kaler's review in Landolt-Bornstein. These plots show that most of the luminous stars in the nebula are early-type main-sequence stars. At first glance this may seem surprising, since the plot contains almost no ZAMS stars cooler than O3! In fact this is not so surprising. According to Schmidt-Kaler's review, an O4 ZAMS star has an absolute visual magnitude Mv = –5.2 which, for E(B-V)=0.6 corresponds to an apparent magnitude of 15.3, below the completeness limit of the photometry. I have marked in Fig. 1 a star of visual magnitude 14.3 (No. 4) which is classified as O3V from the slit spectrum and a star of V=15.0 (No. 66) classified as O3V(ZAMS) on the basis of its absolute magnitude and UBV colours. This illustrates the well-known (but apparently forgotten in 30 Doradus) fact that hot stars radiate very little at visual wavelengths.

Before returning to the discussion of the nature of R136a I would like to call your attention to the brightest stars in the core of 30 Dor. I have marked them A, B, . . ., F in Fig. 1 and I have listed in Table 1 their spectral types as determined from slit spectroscopy and their apparent magnitudes. Because these stars are too bright, giving saturation effects in the PDS scans, I have used published photoelectric observations.

TABLE 1

	Star	Sp. Type	V
A	R139	WN9 + O5	11.9
B	R145	WN6	11.9
C	R138	B0Ia	12.0
D	R137	B0.5Ia	12.1
E	R142	B0Ia	12.2
F	R140N	WC5	13.0

The important feature of the Table is that with the exception of R139 the brightest stars in the core of 30 Doradus are relatively cool OB or WR stars. I will return to these stars below. Now let us consider R136 once again.

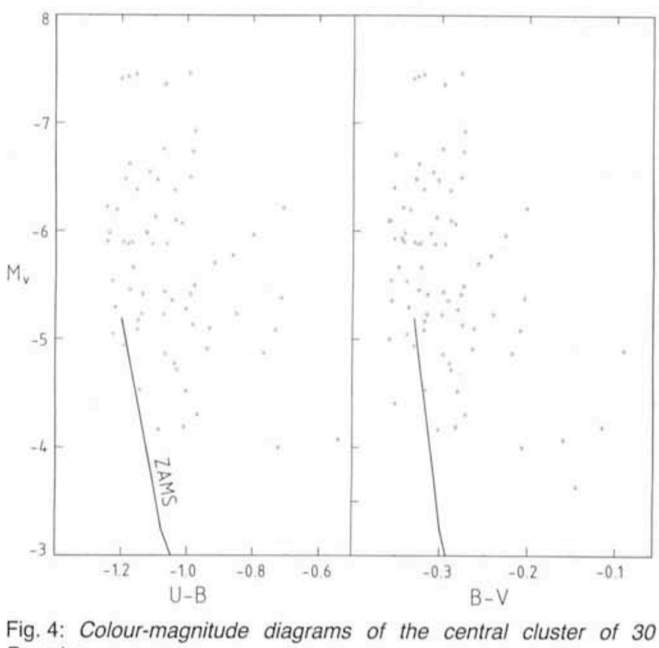

Fig. 4: *Colour-magnitude diagrams of the central cluster of 30 Doradus.*

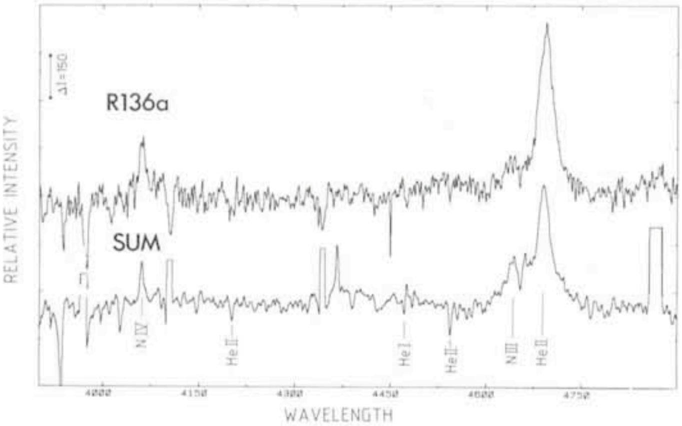

Fig. 5: *Comparison between the optical spectrum of R136a and the composite spectrum of the central arc-minute of the cluster.*

R136a: The Unresolved Core of the Ionizing Cluster of 30 Doradus

Most optical and all the ultraviolet observations of R136 have been obtained with apertures of 3 arc-seconds or larger. In fact most of the UV observations have been obtained through a 10 arc-second aperture. I have drawn in Fig. 1 a circle of 10 arc-seconds in diameter centered at R136a. Besides the components a, b and c, several other stars lie within this circle. Spectra of some of these stars obtained with the Intensified Reticon Scanner of the Du Pont telescope at Las Campanas on a night of magnificent seeing show that R136c and possibly R136b are WN7 stars while some of the others appear to be very early O stars. (Unfortunately, I have not yet received the data tapes, and these classifications are based on a quick look of spectra at the telescope.) It is, therefore, clear that, to be able to say something about R136a, we can only consider observations taken with a small diaphragm. This has been recognized by the Wisconsin workers who in a recent preprint have restricted their analysis to IUE observations taken with a 3 arc-second slit. Therefore in what follows, whenever I talk about R136a I will be explicitly referring to the central 3 arc-seconds of R136.

Because (as I mentioned above) the photometry is not complete down to ZAMS stars of types O4 and fainter, I will restrict the analysis to the central one arc-minute of the cluster. Also, since mass segregation may be important in 30 Doradus, it is more appropriate to compare R136 to the central part of the cluster.

Within one arc-minute from the centre, the mean colours of the cluster (excluding R136) are B-V = 0.16 and U-B = 0.72. The mean colour excess is E(B-V) = 0.46 identical to the value determined by the Bochum observers for R136. I am not aware of any photoelectric determination of the UBV colours of R136 with a diaphragm of 3 arc-seconds (or smaller); Using a 15 arc-second (diameter) aperture, Van den Bergh and Hagen give (U-B) = –0.75 and (B-V) = +0.14, slightly bluer than the mean colour of the rest of the cluster (although the difference is within the errors of the photoelectric observations). Thus if R136 is a composite object, it must contain a mixture of stars similar to that of the rest of the cluster. An independent check of this hypothesis may be obtained by comparing the spectrum of R136a with the sum of the spectra of the individual cluster stars. This is shown in Fig. 5. The spectrum of R136a is the sum of 24 Vidicon frames which I will discuss in detail below. The sum spectrum was obtained adding PDS tracings of the image tube spectrograms of each star, converted to intensity and weighted by the blue magnitude of the stars. The emission component of the composite spectrum is seen to be of slightly later spectral type than R136a while the converse is true for the absorption spectrum. The closest spectral type I can find for R136a is WN4.5+O6–7, in good agreement with the classification given by Conti and Ebbets from photographic spectra. The O6–7 type comes from the ratio of the He II λ 4542 to He I 4471 lines and is not affected by nebular emission since neither of these lines is present in our spectra of R136 out to a radius of 10 arc-seconds. The sum spectrum would have a type WN6+O5–6. Our classification for R136a differs from the type O3f given by Vreux and collaborators on the basis of their near infrared spectrum of R136a, and from the similar classification given by the Wisconsin observers from the UV spectrum. This indicates that R136a must be a composite object. The presence of the Si IV λ 4089 line in the optical spectrum of R136a is a further indication of its composite nature.

It is reasonable to assume, therefore, that R136a contains a mixture of stars similar to that found in the central arc-minute of the cluster. Using the UBV colours and the absolute visual magnitudes, I have estimated spectral types for all stars brighter than V_o=13.0 (visual magnitude corrected for extinction) in the central part of the cluster. From these, and the spectral types obtained from the image tube spectrograms, I find that there are about 30 O3–O5 stars and 10 WR stars in the core of 30 Doradus (this number is a lower limit since, as I mentioned above, the photometry is not complete for types O4V and O5V). The integrated apparent magnitude of the cluster is V=9.0; For R136a, the Bochum observers (also Moffat and Seggewiss) give V=10.8 corresponding to about 20 % of the cluster light since the extinction is similar in the two cases. Thus I conclude that R136a must contain more than 6 O3–O5 stars and more than 2 WR stars. The number of WR stars is uncertain because I cannot distinguish WR stars from late O and early B supergiants on the basis of the UBV photometry alone and I therefore have only counted WR stars observed spectroscopically.

The Wisconsin observers estimate that 10 to 15 of the most luminous known O or WN stars would be required to account for the observed UV luminosity of R136a. However, they have multiplied the observed fluxes " . . . by the standard factor of two to account for light losses in the (small) aperture". Since this correction is not appropriate for extended objects, only 5 to 8 stars are required, in excellent agreement with the number predicted above. But even 5 to 8 of these extreme stars would be quite extraordinary according to the Wisconsin workers

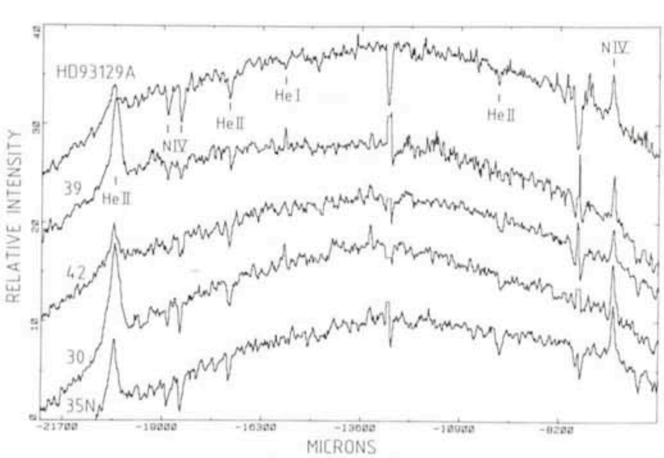

Fig. 6: *Optical spectra of very early supergiant O stars near R136. All stars shown have luminosities comparable to that of the most luminous star in the Galaxy, HD 93129A, also shown in the figure.*

since only two are known in the LMC. In Fig. 6 I show spectra of 4 very early O supergiant stars in the central part of the cluster very close to R136. I also show in the figure the spectrum of HD 93129A, which according to Conti and Burnichon is the most luminous star in our Galaxy. The 30 Doradus stars shown in the figure have bolometric luminosities similar to HD 9319A (some are even larger)! It is natural to expect more of these stars in R136a, especially if mass segregation effects are important.

At a distance of 53 kpc, 3 arc-seconds correspond to a diameter of about 0.8 pc, large enough to contain hundreds of stars. In fact galactic globular clusters have cores in this range of diameters. But, what about the speckle results?

The speckle interferometry results were obtained at optical wavelengths. As I have shown above, very hot O stars (which dominate the UV flux) are in fact very faint in the visible; as seen by the speckle, a compact group of these stars would not be resolved and may be what the speckle observers have called "complex background". In turn, later type O stars or late WN stars are much cooler and radiate much of their energy at optical wavelengths. This fact is illustrated in Table 1 where the most luminous stars in 30 Doradus in the visual band can be seen to be relatively cool compared to the hottest stars in the nebula. Thus, most likely, the speckle experiments have just detected one or two WN stars in the centre of R136a, probably the stars seen by Innes in 1927. After allowing for seeing effects, Moffat and Seggewiss find that within a diameter of 1.5 arc-second, R136a has a visual magnitude of V=12.1 even fainter than some of the stars listed in Table 1. Two of these stars (as seen by Weigelt and Innes) would then make up the optically (but not necessarily UV) brightest component. In order to test this hypothesis, in collaboration with Hernan Quintana from the Universidad Católica de Chile, I have obtained spatially resolved spectra of R136a with the 4 m telescope at CTIO. The slit was 0.5 × 3 arc-seconds centred in the brightest part (centre) one second of arc north (N) and one second south (S) of this position. Tracings of these spectra (each corresponding to an average of 8 Vidicon frames) are shown in Fig. 7. The spectrum is seen to vary significantly from north to south, particularily the emission line component (disregard the changes in the continuum which are due to atmospheric refraction. Also the zero point of the continuum has been shifted to separate out the components) changing from WN4.5 in the centre and N to WN7 in south. The asymmetry of the He II λ 4686 line may be due to absorption lines from early O-type stars (this is most prominent in S) which would imply that the O component of R136a is dominated by main-sequence stars.

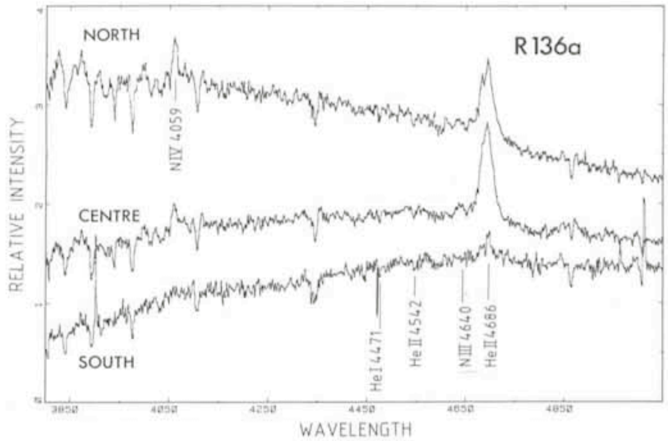

Fig. 7: *Spatially resolved spectrograms of R136a taken with a slit 0.5 arc-second wide and 3 arc-seconds long. The offset between centre and north or south is one arc-second.*

Epilogue

R136 is clearly the unresolved core of the ionizing cluster of the 30 Doradus nebula. It contains many very hot O stars which account for the observed UV luminosity and effective temperature. R136 also contains several late-type WR stars which account for the observed optical and infrared properties. The visually brightest of these WR stars, R136a, is the star (or 2 stars) found by the speckle interferometry. The luminosity, colour and infrared properties of this star are similar to that of other bright WR stars in the nebula. Most of the radiation required to ionize the nebula is emitted by stars outside R136. R136 itself contributes less than 30% of the ionizing flux.

In their recent preprint, Moffat and Seggewiss, using data complementary to those I have presented here, reach the same conclusion regarding the nature of R136a.

References

To make the text easier to read, I have not included formal references. Complete references to most of the papers I have mentioned can be found in the article on R136a by Schmidt-Kaler and Feitzinger published in the proceedings of the ESO conference "The Most Massive Stars". All other articles I refer to are preprints kindly sent to me by the authors.

Stellar Granulation and the Structure of Stellar Surfaces

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Convection in Stars

Stellar convection is a central but poorly understood parameter in the construction of stellar models and the determination of stellar ages, influencing both the energy transport through the atmosphere and the replenishment of nuclear fuels in the core. The motions in stellar convection zones probably supply the energy for generating magnetic fields, heating stellar chromospheres and coronae, driving stellar winds, and for many other nonthermal phenomena. The inhomogeneous structure of velocity fields on stellar surfaces complicates the accurate determination of stellar radial velocities. Further, the temperature inhomogeneities on stellar surfaces induce molecular abundance inhomogeneities and entangle the accurate determination of chemical abundances.

New diagnostic tools are now making stellar atmospheric convection accessible to direct study. From solar physics has come the realization that effects from solar granulation (Fig. 1) are visible also in the spectrum of integrated sunlight, i.e. the Sun seen as a star (Dravins et al. 1981). Consequently, also the effects of stellar granulation should be visible in stellar spectra. Theoretical models of inhomogeneous atmospheres, incorporating three-dimensional, radiation-coupled, time-dependent hydrodynamics of stellar convection, have been