SESSION 6.

LARGE STELLAR COMPLEXES IN GALAXIES.

Chairman : C. DE LOORE.

1. M.ROSA and S.D'Odorico : The Exciting Stars of Giant Extragalactic HII Regions.

2. P.HODGE: Systems of Stellar Associations in Galaxies.

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THE EXCITING STARS OF GIANT EXTRAGALACTIC H II REGIONS

Michael Rosa (1,*) and Sandro D'Odorico (2)
(1) The Space Telescope European Coordinating Facility,
European Southern Observatory, D-8046 Garching, F.R. Germany
(2) European Southern Observatory, D-8046 Garching, F.R.
Germany

ABSTRACT. Recent investigations of the stellar content of giant H II regions and star formation bursts in nearby galaxies are summarized. The preliminary results of a spectroscopic survey of 78 H II regions in 15 galaxies are presented. A minimum frequency of 30 percent is found for the occurrence of luminous Wolf-Rayet stars in such bursts of star formation. Observations of the positions of historical type II supernovae revealed the presence of WC stars, indicating very high ZAMS masses for the SN progenitors. The application of population synthesis models to the analysis of the integrated stellar spectra in terms of IMF parameters is discussed. An example of such an analysis for a giant H II region in Cen A is presented.

I. INTRODUCTION

Giant H II regions host significant portions of the population of the most massive stars in galaxies. The study of their exciting objects therefore provides direct insights into the mechanisms of star formation on large scales, the evolution of stellar associations, the evolution of the most massive stars and the chemical evolution of galaxies.

The stellar component in regions of star formation activity in spiral arms, irregular galaxies and blue compact galaxies (excluding nuclear activity) has been subject of a variety of investigations recently completed or under way. In going from nearby galaxies in the Local Group to remote objects as far as 50 Mpc, the observational material changes from the detailed investigation of single stars or groups of stars into spectra or photometry integrated spatially over areas measuring tens of parsecs up to several kiloparsecs in diameter. Walborn (this book), Moffat et al. (1985) and Melnick (1985) have obtained an amount of detailed photometry and spectral classification for some 100

(*) Affiliated to the Astrophysics Division, Space Science Department, European Space Agency

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stars in the 30 Doradus cluster, that allows one to construct realistic HR diagrams and to address the questions of stellar evolution, age and nature of the burst and the IMF parameters. The investigation of a large sample of giant H II regions in Local Group members and galaxies out to the M 101 distance is the subject of the remainder of this paper. On an even larger scale, both in distance and size or mass of the star forming complexes, the group Melnick, Terlevich, Campbell and Smith (see contribution in this book and references therein) is working on giant star formation bursts or "violent star formation" activity, mainly addressing objects where the mass and luminosity of the SF bursts is comparable with the remainder of the underlying galaxy. Recent studies on large samples of irregular, blue compact and dwarf galaxies have been presented by Gallagher and Hunter (1984) and Kunth and Joubert (1985). Though these objects show the presence of SF bursts of the 30 Dor type, the integrated light is dominated by a population in the age interval from a few 10^7 yrs to 10^8 yrs, thus giving clues on more global properties of long term SF activity on galaxy wide scales, dealt with in the contribution of J. Hoessel in this book.

From the above mentioned work it becomes clear that the terms star formation activity, and in particular star formation burst, are applied to a wide variety of phenomena in the parameter space of time, linear scale, mass involved and scales in relation to the underlying galaxy. All these objects contain considerable amounts of extreme population I stars with masses above 20 $M_\odot$, but for a varying degree of significance in relation to the whole stellar population. In the following we will present an overview of our investigations concerned with star formation activity on scales comparable to the 30 Dor cluster size and a few 10^6 years in age.

II. WOLF-RAYET STARS IN GIANT H II REGIONS

In the period 1980 to 1984 we have collected about 200 deep spectra of star formation bursts in nearby galaxies in order to detect the presence of WR stars through their characteristic broad emission features centered at 4650 Å and 5812 Å and to establish quantitative limits to the strengths of these emission bands. Data were obtained with Cassegrain spectrographs and IDS detectors at the 1.5 m and 3.6 m telescopes in the wavelength range 3600 to 7200 Å at a resolution of 5 to 10 Å and with the Lick 3 m telescope in the range 4000 to 6200 Å at a resolution of 3 Å. Data obtained till 1982 have been published in D'Odorico, Rosa and Wampler (1983). To complement the optical data, 14 regions have been observed with IUE and additional spectra have been collected from the IUE data bank. Most of the spectra have been presented in an atlas by Rosa, Joubert and Benvenuti (1984).

The sample of giant H II regions that we have surveyed is affected by a number of selection biases. Galaxies have been chosen which have conspicous H II regions (mainly Sc and Irr) or to which our intention has been drawn otherwise (e.g. Centaurus A). Within a galaxy we general-

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Table 1. Wolf-Rayet stars in giant H II regions

Galaxy	Type	Surveyed Regions	Regions with WR Stars	Reference
LMC	Irr	1	1	Walborn (this book)
NGC 55	Sc	8	2	
NGC 300	Sd	15	2	DRW 1983
M 33	Scd	2	2	DR 1981, CM 1981
NGC 625	IM	2	-	
NGC 4038	Sc	10	1	
NGC 4216	Sb	5	2	
NGC 5068	SBc	5	2	
NGC 5128	Epec	6	2	
M 83	Sc	8	3	
NGC 5253	pec	4	-	
NGC 5396	pec	1	-	
NGC 5408	pec	2	-	
M 101	Scd	7	5	DRW 1983
IC 4662	Irr	2	2	
Sum		78	24	(= 30 percent)

CM 1981 = Conti and Massey 1981
DR 1981 = D'Odorico and Rosa 1981
DRW 1983 = D'Odorico, Rosa, Wampler 1983

ly surveyed the H II regions in order of decreasing luminosity, though morphology and location of the H II complex within the host galaxy played a role as well. Finally, the signal to noise ratios in the stellar continua differ by large factors due to the gain obtained in repeated observations of more interesting objects. Table 1 summarizes the results of our survey. Details of the objects not covered by D'Odorico et al. (1983) will be given elsewhere.

As a detection we took those cases in which the WR emission, in particular the blue feature between 4580 Å and 4730 Å, is elevated above the continuum at least by 3 times the noise in the continuum and is broader than the nebular emission lines. Non-detections generally have equivalent widths of less than 10 Å. In summary, Table 1 contains 78 H II regions surveyed in 15 galaxies, out of which 24 regions (or 30 percent) showed detectable emission from WR stars. Among the population of the largest H II regions this probability of detection is actually a lower limit. The emission, when present, is not spread uniformly about the entire cluster of O stars but is concentrated in subgroups (D'Odorico and Rosa 1981a). A vivid example is R 136 in 30 Dor which emits more strongly in the WR features than all the remaining WR stars in 30 Dor combined (D'Odorico and Rosa 1981b). Figures 1 and 2 illustrate this effect on a vigorous star forming region in NGC 55 (cf.

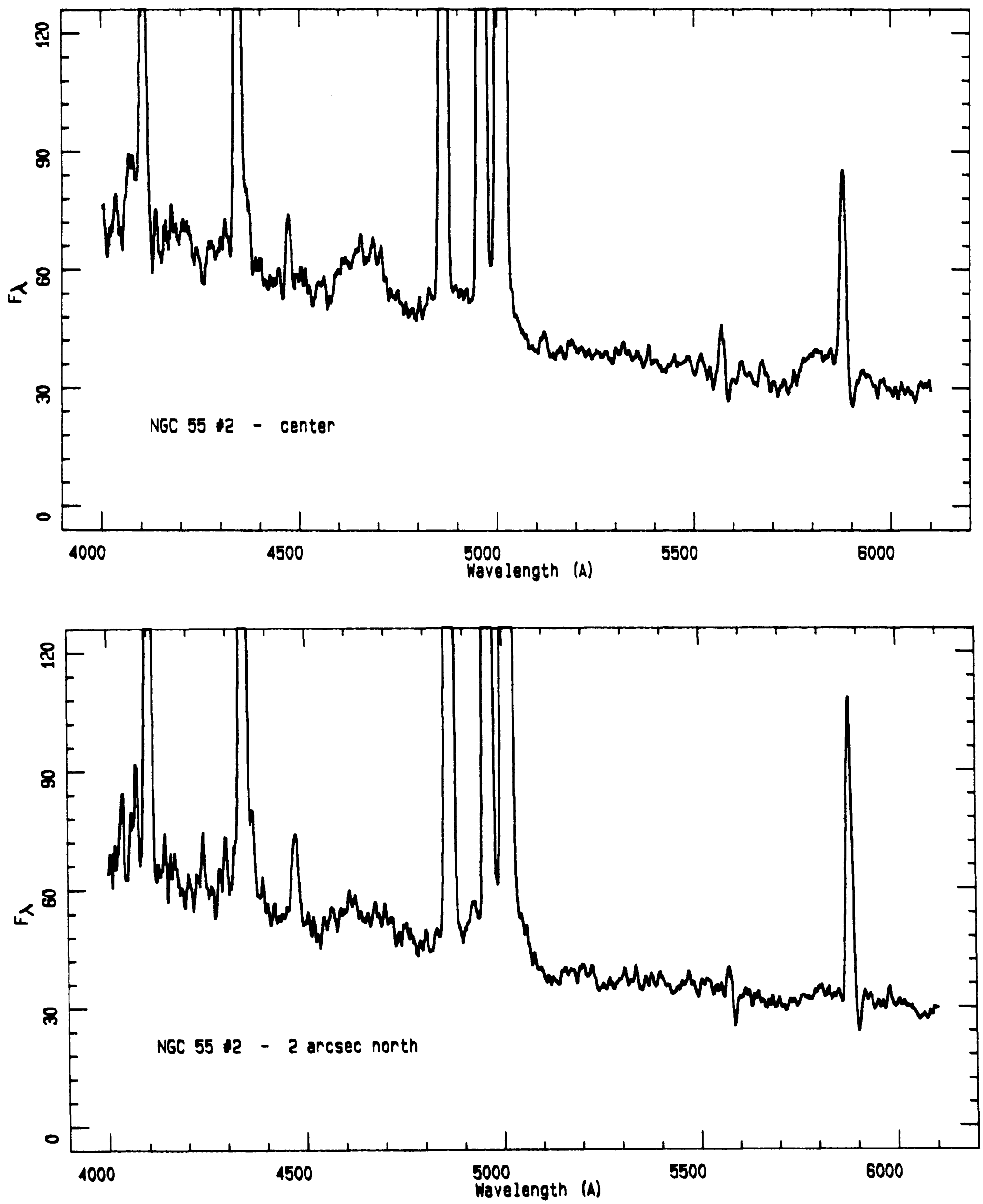

Figure 1 and 2. Spectra of a star burst in NGC 55, 6 arcsec in diameter. The 4 x 4 arcsec aperture was shifted by 2 arcsec between spectrum 1 and 2. Note the similarity of the continuum and nebular lines (shape and absolute scale) and the drastic change in the WR emission features between 4500 Å and at 5812 Å.

Graham 1979). The ionizing stellar cluster has a diameter of about 6 arcsec. The two spectra have been obtained through an aperture of 4 by 4 arcsec, No. 1 centered on the cluster, No. 2 offset by 2 arcsec or half the aperture width. Both spectra are surprisingly similar in shape and absolute scale, but for the reduced equivalent widths and shape of the WR emission bands. Spectrophotometry through apertures of constant size on similar objects will yield either non-detections or detections with rather large equivalent widths in nearby galaxies and a large detection probability but low equivalent widths in more remote galaxies. Qualitatively we can conclude that the presence of luminous WR stars in giant bursts of star formation is a common phenomenon.

The variety of shapes in the WR emission features observed can be seen in the spectra published by D'Odorico et al. (1983). All spectra are composite and the luminosity in the WR emission bands corresponds to rather large number of WR stars equivalent to the most luminous WR stars in the 30 Dor cluster, rendering a classification of WR spectral types difficult. Our previous finding that the luminous types WN 6, 7, 8 and (more rarely) WC 5 are the main contributors is in general confirmed and supported by the emission line spectra in the IUE UV range.

For the reasons discussed above, any quantitative assessment of our data sample in statistical terms is difficult and conclusions cannot be drawn without a detailed analysis of each individual object. Questions to be addressed to are for example the possible variation of WR to RSG number ratios with metal abundance, or the evolutionary sequence of WR spectral types.

Nevertheless, some interesting trends can be seen at this stage of the analysis already. Figure 3 shows a plot of the equivalent widths (EQW) of the WR emission (corrected for nebular contamination) versus EQW of Hβ for all "detections". The EQW of Hβ is a measure of the ratio of ionizing luminosity versus the luminosity in the visual wavelength range, depending on the IMF and the age of the cluster. Models of star formation bursts discussed below predict a decline of the EQW(Hβ) from above 300 Å at zero age to below 50 Å at about $6 \cdot 10^6$ yrs, a result of the rapid evolution of the most massive stars away from the main sequence. Consequently, one would expect an increase in the number of WR stars going hand in hand with the decrease in EQW(Hβ). Our data actually show the presence of WR stars at all ages with a factor 3 enhancement around $4 \cdot 10^6$ yrs, corresponding to WR stars stemming from 50 to 100 $M_\odot$ progenitors. In Figure 4 we plot the EQW(WR) versus the line ratio (4959+5007)/(3727), which is primarily a measure of the ionization in the H II region and hence the effective temperature of the ionizing radiation. This ratio depends however as well on the chemical composition and the gas density (Stasinska, 1980).

Our data indicate that WR stars are relatively more common in H II regions of high ionization. A straight forward interpretation of this effect would imply that the WR stars appear at an evolutionary phase of the cluster at which the ionizing radiation becomes harder. Synthetic

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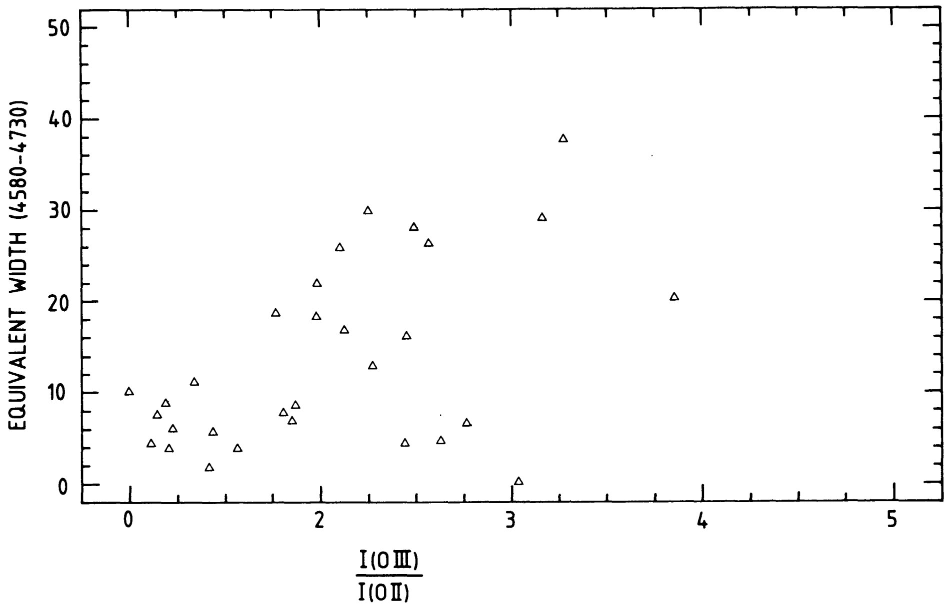

Figure 3. The equivalent widths of the WR emission versus EQW of nebular Hβ emission, which is sensitive to the age of the burst.

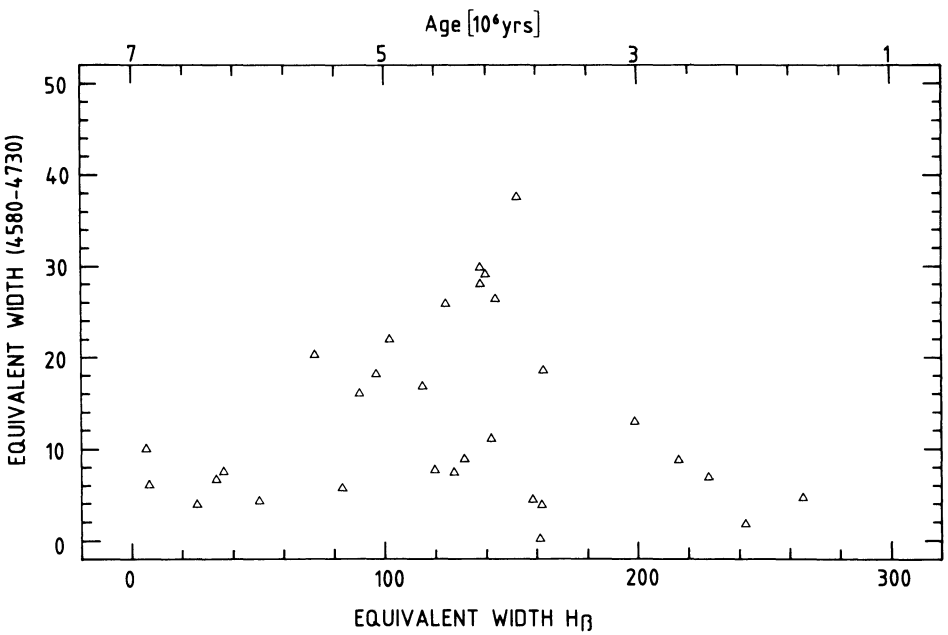

Figure 4. The EQW of WR emission versus the ratio of I(OIII) over I(OII) sensitive to the effective temperature of the ionizing radiation.

clusters (see below) using the (currently believed) low effective temperatures of about 30 000 K for WR stars will not show this effect. There are some indications from Non-LTE, extended atmosphere calculations (cf. contribution by Kudritzki in this book) for high and very high effective temperatures in the Lyman continuum of WR stars, but our data need a more thorough analysis of each individual spectrum in order to support the explanation by high effective temperatures of the WR stars. Such an analysis has been carried out on some objects and an example is described in section V.

III. SUPERNOVAE IN GIANT H II REGIONS

If the very massive stars in giant H II/OB complexes end their evolution in supernova explosions of the type II then a correlation between giant H II regions and the positions of historical type II SNe events has to be expected. Indeed, Richter and Rosa (1984) have shown that all historical SNe that could be classified as type II in M 83 and M 101 were located within the boundaries of giant H II regions. Surveys of SN remnants in nearby galaxies (e.g. D'Odorico et al. 1980) have revealed quite a number of objects located in giant H II regions, in spite of selection effects against finding non-thermal radio sources or faint emission objects on top of the high surface brightness H II region background.

Pennington et al. (1982) have estimated the progenitor masses of 2 historical SNe in M 83, based on an age and IMF analysis of the spatially integrated UBV colours of the underlying stellar population. As discussed below, IMF parameters of populations younger than 10^7 years determined from UBV data are subject to large errors stemming from the inability to completely separate the effects of reddening, age, shape and mass limits of the IMF and contributions of the underlying disk population. Accordingly, the lower mass limits of Pennington et al. (1982) are rather low (18 and 11 $M_\odot$).

In our search for WR stars in giant H II regions we took spectra of 8 regions in M 83, including those hosting the (certain or very probable type II) SNe 1923a, 1950b and 1957d (cf. Richter and Rosa 1984). We found WR emission features solely at the positions of those supernovae and no WR stars in the remaining 5 H II regions. This is a quite unexpected result in view of WR stars being found at random (with a 30 percent probability) in giant H II regions. Most interestingly, the spectra are among the very few in our large sample that unambiguously display the signatures of WC 5 stars. Figure 5 shows the combined spectrum of all 3 SN positions in M 83. The characteristic lines of WC 5 stars are indicated. We interpret our findings with a late (4 to 7 $\cdot 10^6$ yrs) evolutionary stage of the OB associations (WC 5 stars present in large numbers). If the progenitors of the SNe were coeval with those of the WC 5 stars, then they could have had ZAMS masses well above 30 $M_\odot$.

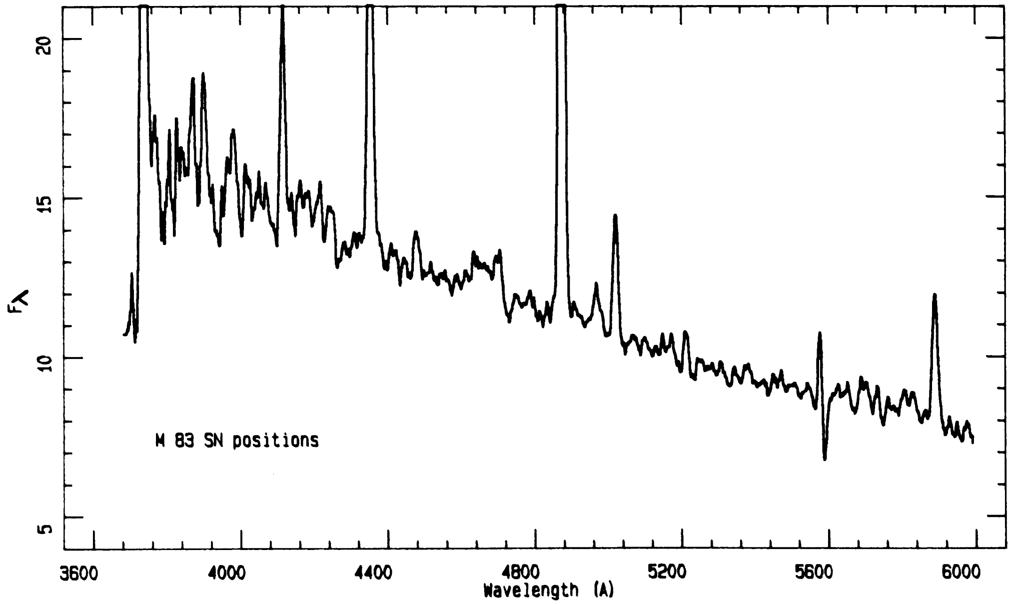

Figure 5. The combined spectrum of the positions of 3 historical SNe in M 83. The presence of luminous WC (5-6) stars is indicated by the broad emission lines of CIII/CIV at 4650 Å shortward of 5696 Å and at 5812 Å, WN 6 by NV at 4620 Å and HeII at 4686 Å.

IV. SYNTHETIC SPECTRA OF LARGE OB ASSOCIATIONS

The foregoing discussion of the observational material has been hampered mainly by the fact that the spectra are integrated over large assemblages of stars populating quite different parts of the HR diagram. A powerful method to disentangle the information from the integrated spectra is the synthesis of energy distributions using either observed spectra or model atmospheres together with evolutionary tracks and prescriptions of the IMF. An example of the straight forward modelling of an IUE spectrum with observed spectra has been presented by Benvenuti (1983). It does however not include a selfconsistent evolutionary scenario of an initial mass spectrum.

Melnick et al. (1985) have computed population synthesis models for the ionizing clusters of giant extragalactic H II regions. They are based on the model atmospheres of Kurucz (1979), evolutionary tracks with different metallicities and mass loss rates over a wide range of masses and power law initial mass functions. They assume single star burst without age spread, i.e. coevality of all stars in the HR diagram. Models are calculated for the zero age and the $3 \cdot 10^6$ yrs isochrone only, reasoning that the most massive stars do not contribute to the ionization after that stage any more. However, our observations show that luminous WR stars, hence evolved massive stars, are observed over a wide range in EQW(Hβ). In the models of Melnick et al. (1985) very low values of EQW(Hβ) are only reached under extreme assumptions on the IMF. We therefore extended their calculations to ages of up to $7 \cdot 10^6$ yrs, thus covering the entire lifetime of stars more massive than 30 $M_\odot$ and the core hydrogen exhaustion of stars more massive than 25 $M_\odot$, corresponding to O8 main sequence stars. The largest uncertainties in these population synthesis models arise from the combination of evolutionary tracks for the stellar core with model atmospheres in the late evolutionary stages, in particular WR stars for which self constistent model atmospheres do not exist at all and for which the luminosity in the Lyman continuum is essentially unknown.

The main results from the populations synthesis models concerning the analysis of integrated spectra of single bursts of star formation can be summarized as follows. In the age range from 0 to $7 \cdot 10^6$ years the main effect of the evolution of the massive stars is the decrease in the Lyman continuum luminosity, leading to a significant drop in the EQW of nebular Balmer lines, while the slope of the continuum between 1200 Å and 10 000 Å remains almost unchanged if evolution to the red supergiant phase is prohibited by stron mass loss. However, models at constant age with variations in the IMF parameters (slope and upper mass limit) and the evolutionary tracks produce energy distributions quite similar to those of clusters att different ages. Broad photometry is generally inadequate to separate out the effects of variations in age, upper mass limits and slope of the IMF. The combination of extreme values of these parameters produces and effect less than 0.2 mag in U-B or 0.8 mag in (1400 - 5500 Å) colours. Such an accuracy cannot be reached in view of the large uncertainties in interstellar extinction. The effective temperature of the ionizing cluster radiation, very sensitive to the composition of the upper part of the HR diagram, could in principle be used in diagnostic diagrams together with a long base line colour or the EQW(Hβ) to separate age effects from IMF parameters. However, the required accuracy of about 1000 K cannot be obtained from the analysis of the nebular spectrum (cf. Stasinska 1980, Mathis 1982). All these limitations are valid only for ages up to about 10^7 years. As soon as the intermediate mass stars evolve and low mass stars reach the main sequence the near UV and visual energy distribution is reflecting more significantly the composition in the HR diagram. At this stage, however, the O stars and giant H II regions are gone and the contrast of the star formation burst over the underlying populations in host galaxies starts to be lost.

A way out of this dilemma is the complete use of the large amount of information contained in the observable energy distribution, i.e. the spectra between 1100 Å and 10 000 Å. Comparison with model energy distributions over that wavelength range using the equivalent width of nebular lines, the strength and shapes of stellar absorption lines and the interstellar absorption features can in fact lead to a simultaneous solution for all the free parameters concerned, i.e. reddening, age and IMF parameters, as will be shown below. When applied to a large body of observations the method should permit to test additional parameters as

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for example duration and multiplicity of the burst of star formation and the validity of the theoretical evolutionary tracks.

V. THE STELLAR COMPONENT IN H II REGION NO. 13 OF CEN A

As an example of the combination of observations and modelling of the OB clusters in giant H II regions we outline here the main features of the analysis of the largest H II comples in Cen A (= NGC 5128), i.e. #13 in the notation of Moellenhoff (1981). The H II region is located just north of the nucleus of Cen A very close to the dust lane. Several properties make this object a prime candidate for the analysis of the integrated spectrum using synthetic energy distributions of star bursts. At the comparatively large distance the aperture sizes employed in the spectrophotometry cover the entire cluster of stars. The very low equivalent widths of Hβ results in a negligible contamination of the UV part by nebular continuum emission. The background at the position of Cen A #13 is composed of an old E galaxy population and a blue population with an age of about 1 to 4• 10^7 yrs (Dufour et al. 1979 and Pennington this symposium). And finally, our high signal to noise spectra allow for the spectral classification of the most luminous stars present. Figure 6 (upper curve) shows the combined dereddened spectrum of the object in logarithmic flux scale in the wavelength range 1100 Å to 3200 Å from IUE low dispersion observations and 3600 to 7200 Å from spectra obtained at the ESO 3.6 m telescope. The two parts have been adjusted using surface

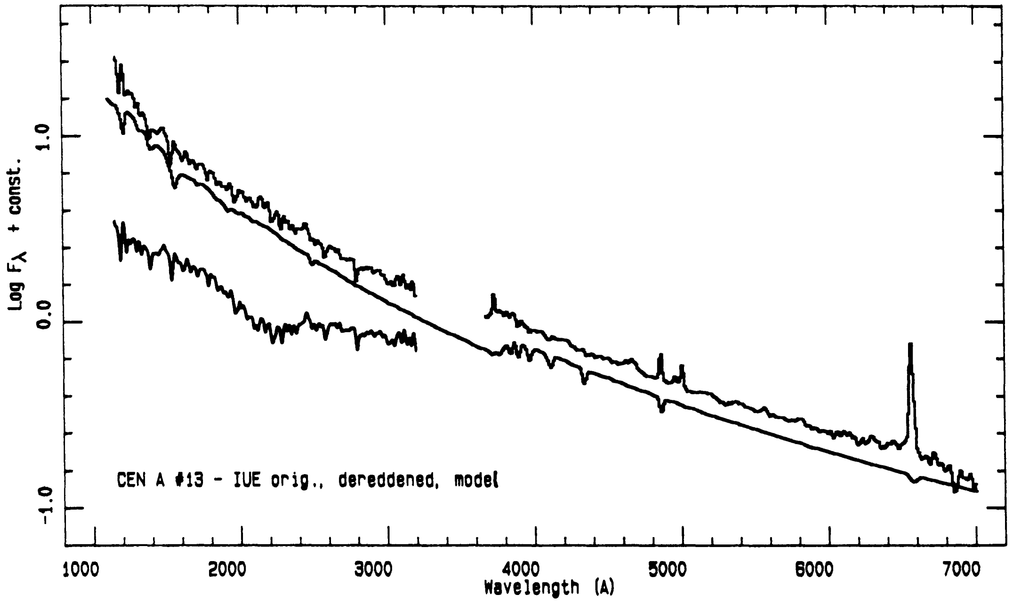

Figure 6. The observed (IUE part only) and the dereddened spectrum of the H II region Cen A #13 in logarithmic flux scale. Superimposed, shifted down 0.1 in log (Fλ) for clarity, is a population synthesis model (see text).

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photometry on CCD images to correct for the different sizes in apertures used and to scale the background spectra observed on either side of Cen A #13.

The prominent 2200 Å feature seen in the original UV spectrum (lower tracing) was used in combination with the constraints on the range of possible shapes of the IUE UV continua as deduced from the spectral synthesis to determine the amount of reddening in the spectrum of Cen A #13. Balmer decrements from the nebular emission are not useful because of contamination by stellar absorption lines and because the reddening of the nebula may not be applicable at all to the embedded stellar clusters. We found E(B-V) = 0.15 mag from a galactic extinction law and an additional E(B-V) = 0.08 from an LMC type law, in agreement with an average galactic foreground extinction for the galactic coordinates of Cen A and the idea that the northern ring of H II regions in Cen A may be located in front of the dust lane.

The smooth tracing offset by 0.1 in log $F\lambda$ from the dereddened spectrum is a synthetic spectrum that corresponds to a star burst with a solar neighbourhood IMF (Miller and Scalo 1979) with an age of 5 to 6 10^6 yrs. This corresponds to a current upper mass limit for fully evolved stars of about 40 to 60 $M_\odot$. The lowest mass limit depends very much on the assumptions made about the duration of the burst. If stars of all masses were formed within a few 10^5 yrs, then only stars with $M/M_\odot > 2$ can have reached the main sequence, otherwise the energy distribution would be consistent with an IMF extending down to 0.1 $M_\odot$. Using a distance of 6 Mpc to Cen A, the cluster contains 10^6 stars in the 2 to 50 $M_\odot$ mass range, 500 of which had ZAMS masses larger than 30 $M_\odot$. The latter group of stars contains about 300 WN, WC stars as estimated from the luminosity in the WR emission features. In the case of a small age spread in the burst, most of the flux in the red has to be provided by about 100 red supergiants with progenitors in the 30 to 60 $M_\odot$ mass range. Additional information on the composition of the upper HR diagram is provided by the analysis of the optical and UV absorption and emission line spectrum. In conclusion, the dominance of O9 to B2 supergiants in the blue spectrum, the presence of WN 7 and WC 5 stars and the numerical agreement with the numbers observed and required by the IMF solution for RSGs again indicate a Hydrogen core burning age of the cluster of 5 to 6 10^6 yrs with a very small age spread.

The example presented above demonstrates how much information can be obtained simultaneously on the star forming processes, stellar evolution and the IMF parameters from the analysis of the integrated spectra of extreme population I star bursts. The requirements are high signal to noise data at sufficient spectral resolution over a wavelength range as large as possible and, most important, the selection of regions of star forming activity well isolated in space and time (about $2 \cdot 10^7$ yrs) from other star formation activity in the underlying galaxies.

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Discussion : ROSA

PENNINGTON :

There is no question that population deconvolutions for HII regions can best be done using spectral synthesis. I would like to point out the usefulness of broad band colors for large scale mapping. The ages derived by Rosa for Mollenhoff's region 13 of $< 6 \times 10^6$ yrs is consistent with the results of digital surface photometry, $< 6.5 \times 10^6$ yrs. I would also like to point out that the necessary red continuum can very easily be due to the old stellar population of the elliptical component, both behind and in front of the dust lane, without requiring red supergiants.

The positions of two of the three SNe sites studied in M83 lie on the edges of HII regions, not in the cores. The inference that SN1957d was a type II is drawn only from its location on the edge of an HII region. The presence of a coincident radio point source with this position suggests that this may not have been a type II.

MASSEY :

I have a comment and a question : first off, why are the WC stars so absent? None of these seem to have strong WC features compared to HeII 4686A. Secondly, why use models for your synthesis? There are tons of IUE data on stars of all types, and Hunter and Jacoby have a very fine spectrophotometric atlas in this year's Ap.J.Suppl. (Jacoby, Hunter, Christian, 1985). You still would need models for fluxes, perhaps, but lines like OV in the UV must give you a very powerful handle.

SANDAGE :

In your spectral syntheses you need red stars added to the OB component to fit the observed I (..). Do you think these are red supergiants or main sequence G, K, M stars. The statement at this meeting by Humphreys and by Massey is that WR stars and RSG are anticorrelated, presumably because the WR star progenitors are more massive (younger) than the RSG progenitors. If so can we expect any red supergiants in those HII regions that show WR features?