The Most Massive LMC Star Sk–66°41 Resolved

M. HEYDARI-MALAYERI, ESO[1]

Introduction

The upper limit to stellar masses constitutes one of the fundamental problems of astrophysics. Here I want to deal with Sk–66°41 (Sanduleak, 1969, other designation: HDE 268743), one of the most massive stars in the Large Magellanic Cloud. Sk–66°41, with its bolometric magnitude of −11.2, appears at the second position (along with HDE 269698) in the list of the most luminous stars in the LMC compiled by Humphreys (1983). As you may know from the ESO Press Release of last May 19, we have shown that Sk–66°41 is not a single star but a compact cluster of at least six components. This result has important implications for star formation theories and the distance scale in the Universe. This is a serious evidence against the existence of stars above 100 $M_{\odot}$.

The Associated H II Region N 11 C

We got interested in Sk–66°41 during our analysis of an H II region in the LMC as a part of the search and investigation of the high excitation compact H II blobs in the Magellanic Clouds. The knowledge of the physical characteristics of the associated H II region N 11 C (Henize, 1956) is important for understanding the nature of Sk–66°41. N 11 C is one of the several components (A to L, the latter being a supernova remnant) of the relatively isolated H II complex N 11 lying at ~4° NW of the "centre" of the LMC bar. This giant H II region, ~20′ in diameter corresponding to ~320 pc, is interesting in several respects related to massive star formation. Towards the eastern part of the main component, N 11 B (Heydari-Malayeri and Testor, 1983), there is a high excitation compact H II blob (Heydari-Malayeri and Testor, 1983, 1985) making this region attractive for star formation studies. A molecular cloud has been detected towards the eastern part of the complex, just east to N 11 C and E (Cohen et al., 1984).

The most luminous star Sk–66°41 lies nearly at the centre of component N 11 C which measures ~3′ (~50 pc) in diameter in the Hβ emission line (Fig. 1). The region is divided at the centre by a dark absorption lane. The most excited zones are the southern and northern boundaries of the nebula at both sides of the dark lane. The star lying at ~15″ SE of Sk–66°41, called Wo 599 (Woolley, 1963), is of particular interest as we will see below. Wo 600 and Wo 647 are late-type Galactic stars. N 11 C is a very young region, as shown by the

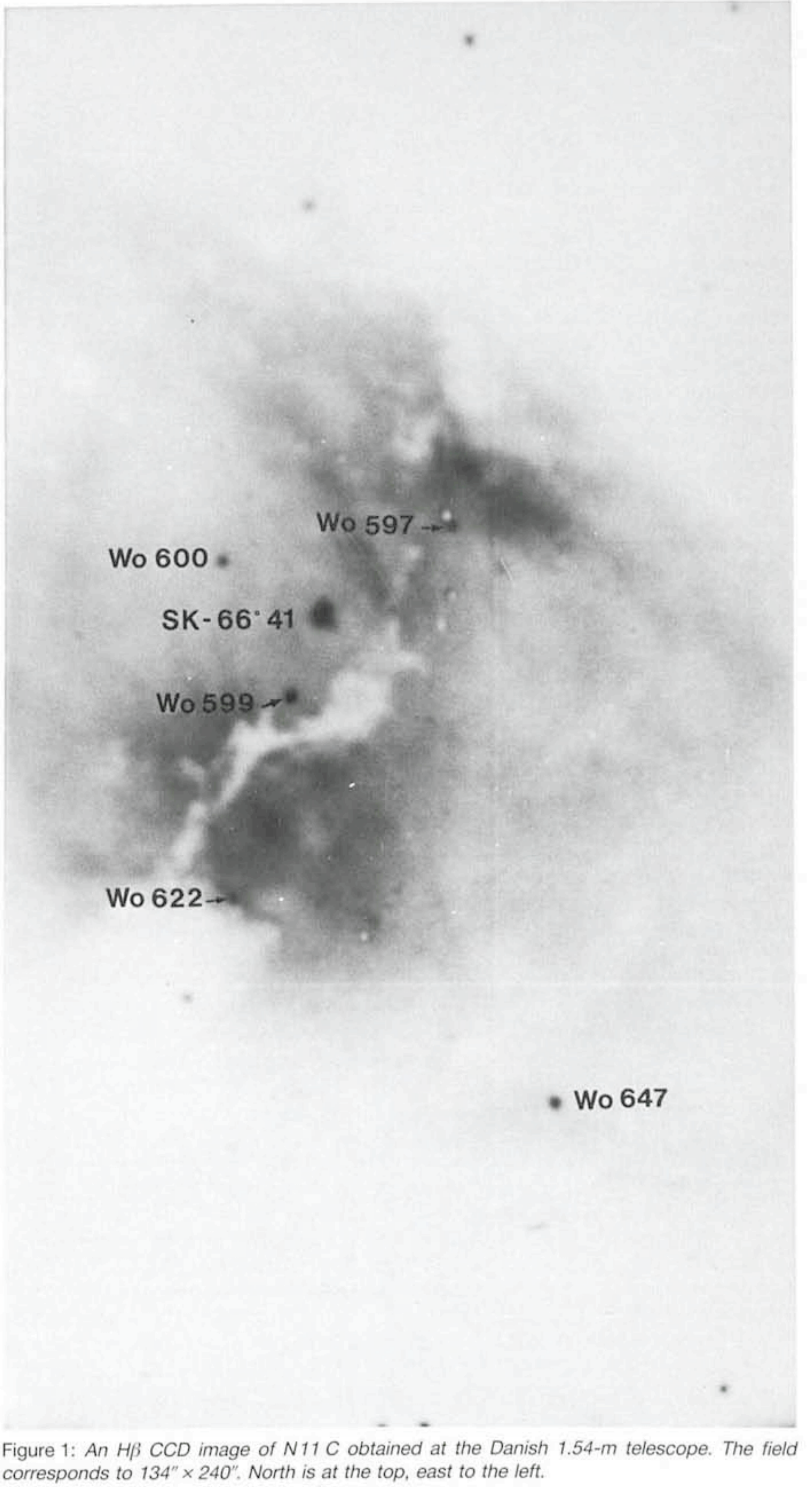

Figure 1: *An Hβ CCD image of N 11 C obtained at the Danish 1.54-m telescope. The field corresponds to 134″ × 240″. North is at the top, east to the left.*

[1] On leave from DEMIRM, Observatoire de Paris, Section de Meudon, France.

colour-magnitude diagram of the stars observed towards the region (Heydari-Malayeri et al., 1987, hereafter Paper I). The majority of the stars (~80%) lie clearly along a ZAMS centred at about B-V = −0.34 characterizing early O-type stars.

Physical Characteristics of N 11 C

The r.m.s. electron density in N 11 C is 20 cm^{-3}, while the highest value of the electron density amounts to ~350 cm^{-3}. The electron temperature derived from the [O III] lines is ~9200°K. The chemical abundances for He, N, O, Ne, S and Ar do not show significant discrepancy with respect to the corresponding mean values for the LMC.

The [O III] (4959+5007)/Hβ intensity ratio averaged over 166 points on the face of N 11 C is 4.1 (corrected for the reddening). The ratio is rather uniform on a fairly extended zone in the nebula. This suggests that N 11 C has several exciting sources scattered in it. The average value of the Balmer decrement Hα/Hβ derived for the same 166 points is 3.6. However, the extinction is not uniform towards N 11 C. For example, it shows a spectacular peak of ~7, corresponding to ~2.5 mag, along a N-S spectrum towards SE of Sk–66°41. Another remarkable feature of extinction is its enhancement northwards of N 11 C where the molecular cloud is detected. This is in agreement with the extinction behaviour southwards of N 11 E which lies north of N 11 C.

The total Hβ flux amounts to ~2.2×10^{-10} ergs $cm^{-1}s^{-1}$, while the radio continuum density flux is S(408 MHz) = 1.27 Jy (Clarke et al., 1976). From the latter value the number of the Lyman continuum flux is estimated to be N_L = 2.70×10^{50} ph s^{-1}, corresponding to an excitation parameter of ~200 pc cm^{-2} and an ionized gas mass of 4.10×10^4 $M_\odot$.

Energy Sources

We try to estimate the number of the exciting stars responsible for the above-mentioned N_L. We use stellar atmosphere models of Kurucz (1979) with the evolutionary tracks of Chiosi et al. (1978) for a ZAMS star with high mass loss. Several possibilities can be considered. For the reasons that will come up later we favour the following one: N 11 C may be excited by one star of 80 $M_\odot$ along with six stars of 60 $M_\odot$ and two stars of 40 $M_\odot$. This roughly means that we should find one star of type O4, six stars of O5 and two stars of O6 V in N 11 C.

Spectroscopic observations were carried out at the 2.2-m telescope of several stars sitting towards the H II region (Paper I). Wo 599 (Fig. 1) turned out to be very interesting. The spectrum of this star is dominated by the He II absorption lines characterizing O type stars. Wo 599 belongs to the dwarf luminosity class because the He II λ4686 Å line is strong in absorption. Using the equivalent widths criterion for He II λ4541 Å and He I λ4471 Å we classify Wo 599 as O4 V.

Several spectra were obtained of Sk–66°41. We classify this star as O5 V. Walborn (1977) assigned a spectral type of O6 to this star "uncertain by ± 1 subclass at least". Consequently, we already have an unexpected result. Contrary to what has been believed, the main exciting star of N 11 C is not Sk–66°41 but Wo 599.

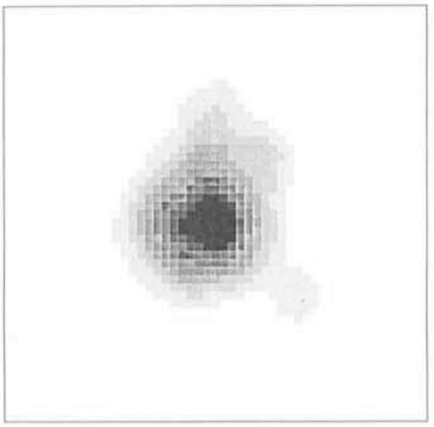

Figure 2: *The CCD R frame of Sk–66°41. The field, 51 × 51 pixels, corresponds to ~9" × 9" on the sky. North is at the top, east to the left.*

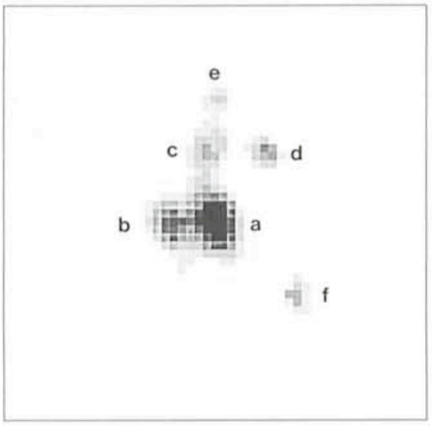

Figure 3: *Same image after deconvolution.*

Problem

The UBVRIJHK photometry of Sk–66°41 was carried out at the ESO 1-m telescope (Paper I). The UBV magnitudes V = 11.72, B-V = −0.12 and U-B = −0.92 agree very well with Brunet et al. (1973). Using a colour index of E(B-V) = 0.18 for the star and a distance modulus of 18.45 (Stift, 1982) the absolute visual magnitude turns out to be M_v = −7.3. From a bolometric correction of −3.9 (Humphreys and McElroy, 1984) a bolometric magnitude of M_b = −11.2 can be derived for Sk–66°41 corresponding to a luminosity of 2.63×10^6 $L_\odot$, an effective temperature of ~56,000°K and a mass higher than 120 $M_\odot$.

We see that there is obviously a problem. How can a main sequence star of type O5 get a mass > 120 $M_\odot$? According to star formation models the upper mass limit is inversely proportional to the metallicity, as first suggested by Kahn (1975). So, there are two possibilities: (i) Star formation mechanisms in a metal poor galaxy like the LMC have given rise to a peculiar very massive star, or (ii) Sk–66°41 is not a single star.

Compact Cluster

CCD images of SK–66°41 were obtained in March 1988 with the 3.6-m and 2.2-m telescopes at La Silla (Heydari-Malayeri et al., 1988, hereafter Paper II). At the 3.6-m telescope, the ESO Faint Object Spectrograph and Camera (EFOSC) was used. In both cases, the detector was a high resolution RCA CCD chip (type SID 503, 1024 × 640 pixels of 15 μm^2). Several images were obtained through the filters B, V and R with various exposure times. They were reduced using the MIDAS package and subsequently deconvolved using an improved version of a simple recursive restoration algorithm (Meinel, 1986) written by Magain (1988). The method was tested on several known objects and shown to lead to very reliable results (Magain, 1988). The image restoration was carried out on all the images.

A part of the R frame showing Sk–66°41 is presented in Figure 2. The exposure time was 30 seconds, the seeing 0."9 FWHM and the pixel size 0."176. The processed image after 10 iterations, shown in Figure 3, has a resolution of 0."5. It is clearly seen that Sk–66°41 is resolved into 6 components. The main components, stars (a) and (b), are separated by 0."8 (Fig. 4). From the analysis of the geometry and photometry of the system (Paper II) we find that component (a) has a bolometric magnitude of −10.5 corresponding to a star of ~90 $M_\odot$, whereas component (b), with a bolometric magnitude of −9.6, may have a mass of ~60 $M_\odot$ corresponding to an O5 star. The spectral

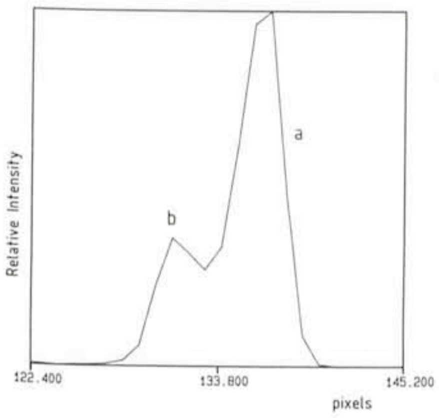

Figure 4: *An EW cross-cut through components (a) and (b).*

type of O5 derived for Sk–66°41 corresponds to the whole cluster. It is not possible that the fainter component, star (b), dominates the whole spectrum. Consequently, star (a) may itself be a multiple system. This is in agreement with the fact that the deconvolved image of star (a) shows a slight NS elongation, suggesting that it may consist of more than one component, in which case the estimated mass would of course decrease significantly.

The members of the cluster probably formed together. The fainter components (c-f) are probably early-type O stars, as the formation of low mass stars needs a longer time scale. This may be a general trend of massive star formation that they form in groups. Two recent results seem to confirm this impression. The first example is the central object of 30 Doradus (see below). The second one is provided by the star-like η Carinae which is one of the most luminous stars in our Galaxy. Recently, Weigelt and Ebersberger (1986) resolved it into four components lying within < 0″.03. It should be emphasized that the case of Sk–66°41 is of particular interest. In contrast to R 136 and η Carinae, it was not a mysterious exotic object. It was just an O-type star with a known spectral classification.

Implications

Towards 1960 it was believed that stars above a critical mass, the Ledoux-Schwarzschild-Härm limit of ~60 $M_\odot$, were unstable. Above this limit vibrational instability would set in entailing the destruction of the star. Vibrational instability occurs when the energizing processes in the core overcome damping in the envelope. Later on, it was found that vibrations produce shock waves in the star's gas which could damp down the vibrational instability. A non-linear treatment of vibrations showed that stars can get masses up to ~200 $M_\odot$ according to some models, especially those of Appenzeller (1970).

However, Larson and Starrfield (1970) and later Kahn (1974) took up the problem at an earlier stage, that is at the time of protostellar collapse. They found that dynamical effects due to radiation pressure can impede further infall of matter leading to an upper limit of ~60 $M_\odot$ for the star. Today the theoretical situation remains murky. In recent years several important effects have been taken into account, for example convective overshooting, turbulent diffusion incited by differential rotation, and mass loss (Maeder, 1983 and references therein) but the question of the upper limit to stellar masses remains open. On the basis of the luminosities, Maeder (1980) estimated that the initial mass spectrum extends up to a maximum mass of ~150–200 $M_\odot$ with no significant differences between the Galaxy and the LMC. However, recently, Maeder (1985) argues in favour of a critical mass near 100 $M_\odot$.

The mass of the famous R 136, the central object of the LMC giant H II region 30 Doradus, was in recent years subject of intense research. Feitzinger et al. (1980) suggested that the brightest and bluest of the three components, R 136a, might be a star of mass 250–1,000 $M_\odot$. Cassinelli et al. (1981) from the IUE data concluded that R 136a is a single supermassive star of ~3,000 $M_\odot$ emitting an extremely powerful wind of $10^{-3.5}$ $M_\odot$ yr^{-1} at 3,500 km s^{-1}. Today from the works of several workers (e.g., Moffat and Seggewiss, 1983; Melnik, 1983) we can rule out the possibility of these extreme masses for stars. In particular, Weigelt et al. (1985), showed that R 136a is a dense cluster of at least 8 stars embedded within a diameter of 1″. However, it should be stressed that the problem with R 136a as to the upper mass limit is not fully resolved. Walborn (1984), from an analysis of the magnitude and spectral characteristics of R 136a, finds that the main component should be ~250 $M_\odot$. *In this situation observational results are of invaluable help.*

In the classical method of star counts for deriving the luminosity function and then the initial mass function (IMF), the sample stars are usually taken from the published catalogues the majority of which have used low resolution techniques. The possible multiplicity of the sample stars, especially for the upper mass limit, which is dependent on a relatively small number of stars, can significantly alter the shape of the upper part of the IMF. Very roughly, one star in a billion may be above 60 $M_\odot$. The answer to the fundamental questions such as the universality of the IMF depends strongly on the problem of the multiplicity of the most luminous stars.

Several investigators have concluded that the high mass cutoff of the IMF increases with decreasing abundances of heavy elements. For example, Vangioni-Flam et al. (1980) found that the number of the luminous stars increases along the sequence the Milky Way-LMC-SMC-IZW 18, the latter being the most metal poor galaxy known. On the contrary, Humphreys (1983) finds that although the SMC and IC1613 have comparable metallicities, the lowest in the Local Group, their brightest blue supergiants have very different luminosities. This confusion may be due to the possible multiplicity of the observed luminous stars. Anyhow, before comparing the number of the brightest stars in different galaxies one should make sure that the sample stars are not multiple. Such a project requires the use of the VLT facilities.

Another consequence of the present result concerns the application of the brightest blue and red supergiants for intergalactic distance determinations (Hubble, 1926; de Vaucouleurs, 1978; Humphreys, 1983; Sandage, 1986). These stars, classified as secondary distance indicators, are used for distances up to ~10 Mpc. If the standard candles are multiple the distances are underestimated. This favours smaller values for the Hubble constant.

References

Appenzeller, I.: 1970, *Astron. Astrophys.* **5,** 355.

Cassinelli, J.P., Mathis, J.S., Savage, B.D.: 1981, *Science,* **212,** 1497.

Choisi, C., Nasi, E., Sreenivasan, S.R.: 1978, *Astron. Astrophys.* **63,** 103.

Clarke, J.N., Little, A.G., Mills, B.Y.: 1976, *Australian J. Phys. Astrophys. Suppl.* **40,** 1.

Cohen, R., Montani, J., Rubio, M.: 1984, in *Structure and Evolution of the Magellanic Clouds,* IAU Sympos. **108,** eds. S. van den Bergh, K.S. de Boer, p. 401.

de Vaucouleurs, G.: 1978, *Astrophys. J.* **224,** 14.

Feitzinger, J.V., Schlosser, W., Schmidt-Kaler, Winkler, Ch.: 1980, *Astron. Astrophys.* **40,** 50.

Henize, K.G.: 1956, *Astrophys. J. Suppl. Series* **2,** 315.

Heydari-Malayeri, M., Testor, G.: 1983, *Astron. Astrophys.* **118,** 116.

Heydari-Malayeri, M., Testor, G.: 1985, *Astron. Astrophys.* **144,** 98.

Heydari-Malayeri, M., Niemela, V.S., Testor, G.: 1987, *Astron. Astrophys.* **184,** 300 (Paper I).

Heydari-Malayeri, M., Magain, P., Remy, M.: 1988, *Astron. Astrophys. Letters,* in press (Paper II).

Hubble, E.: 1926, *Astrophys. J.* **64,** 321.

Humphreys, R.M.: 1983, *Astrophys. J.* **269,** 335.

Humphreys, R.M., McElroy, D.B.: 1984, *Astrophys. J.* **284,** 565.

Kahn, F.D.: 1974, *Astron. Astrophys.* **37**, 149.
Kahn, F.: 1975, in *Atomic and Molecular Physics and the Interstellar Matter*, eds. R. Balian, P. Encrenaz, J. Lequeux, North Holland, Amsterdam, p. 533.
Kurucz, R.L.: 1979, *Astrophys. J. Suppl.* **40**, 1.
Larson, R.B., Starrfield, S.: 1971, *Astron. Astrophys.* **13**, 190.
Maeder, A.: 1980, *Astron. Astrophys.* **92**, 101.
Maeder, A.: 1983, *Astron. Astrophys.* **120**, 113.
Maeder, A.: 1985, *Astron. Astrophys.* **147**, 300.
Magain, P.: 1988, in preparation.
Meinel, E.S.: 1986, SPIE, *Instrumentation in Astronomy* **627**, 715.
Melnick, J.: 1983, *The Messenger*, **32**, 11.
Moffat, A.F.J., Seggewiss, W.: 1983, *Astron. Astrophys.* **125**, 83.
Sandage, A.: 1986, in *Luminous Stars and Associations in Galaxies*, IAU Sympos. **116**, eds. C.W.H. de Loore et al., p. 31.
Sanduleak, N.: 1969, Cerro-Tololo-Inter-American Obs. Contr. **89.**
Stift, M.J.: 1982, *Astron. Astrophys.* **112**, 149.
Vangioni-Flam, E., Lequeux, J., Maucherat-Joubert, M., Rocca-Volmerange, B.: 1980, *Astron. Astrophys.* **90**, 73.
Walborn, N.R.: 1973, *Astrophys. J.* **179**, 517.
Walborn, N.R.: 1984, in *Structure and Evolution of the Magellanic Clouds*, IAU Sympos. **108**, eds. S. van den Bergh, K.S. de Boer, p. 243.
Weigelt, G., Baier, G., Ladebeck, R.: 1985, *The Messenger* **40**, 4.
Weigelt, G., Ebersberger, J.: 1986, *Astron. Astrophys.* **163**, L5.
Woolley, R. v. d. R.: 1963, *Roy. Obs. Bull.* No. **66.**

Age and Star Formation of the Radio Galaxy 0902 + 34 at Redshift z = 3.395: Constraints for Primeval Galaxies

B. ROCCA-VOLMERANGE
Institut d'Astrophysique, CNRS, Paris, and Université de Paris-Sud, Orsay, France

Introduction

Primeval galaxies are among the best test objects of observational cosmology. They will give an estimate of the density parameter of the Universe Ω_0 from a colour-redshift Hubble diagram observed to extreme values of redshifts. They also bring excellent constraints to models of formation and evolution of galaxies. In this sense, searching for distant galaxies becomes one of the first objectives of the new generation of telescopes.

On the basis of recent developments in galactic evolution (see review by Rocca-Volmerange and Guiderdoni, 1988a), it is possible to predict some of the most striking features which will be signatures of young galaxies. Moreover, the present set of observational data of faint galaxies, from deep counts (Tyson, 1988) until the most distant ($z \geq 3$) radio galaxies with a dominant stellar component (Lilly, 1988), is rapidly increasing. It can therefore now be confronted in detail with evolutionary models of galaxies. Due to high redshifts and current activity of these distant galaxies, models have to simulate the galactic evolution in extreme far-UV light, observed in the rest frame through the visible and infrared broad band filters. Scenarios of standard evolution based on a large sample of observations give template spectra. Corrections due to cosmological effect (k-corrections) and to intrinsic evolution of the galaxy (e-correction) are computed from template spectra to predict apparent magnitudes and colours at any redshift and age. Models also predict the nebular component emitted by the Lyman continuum photons N_{Lyc} absorbed by gas and the consequent gas content.

Up to now, to search for primeval galaxies from integrated colours through intermediate or broad band filters as well as from Lyα emission line through narrow band filters gave negative results and only fixed upper detection limits. The infrared and optical counterparts of radio galaxies at high redshifts ($z \geq 1.8$), the oldest stellar populations at about quasar distances, have recently been observed by Djorgovski et al., 1984; Lilly and Longair, 1984; Spinrad et al., 1985; Dunlop and Longair, 1987; Cowie, 1988, and others, from the 3CR or 1 Jy catalogues and the Parkes Selected Region Sample. One of these galaxies, 0902 + 34, was recently discovered by Lilly, 1988 at a redshift $z = 3.395$. According to its fluxes through the VIJK broad-band filters and Bruzual's models, 1983, this galaxy does not appear as a primeval galaxy; however, this result must be confirmed by other models including far-UV ($\leq$ 2000 Å) stellar spectra, nebular component and Asymptotic Giant Branch stars.

With the help of our Atlas of Synthetic Spectra of Galaxies (Rocca-Volmerange and Guiderdoni, 1988b (RVG)), based on the last version of our models (Guiderdoni and Rocca-Volmerange, 1987 (GRV)), we can give a possible age of this galaxy. In the galaxy frame, a burst of star formation is at present taking place but an older burst also happened about 3 Gyrs earlier.

The solution gives an epoch of galaxy formation at a redshift ≥ 10 and a resulting low value of the density parameter $\Omega_0 \leq 0.1$.

Signatures of a Young Galaxy

Due to the extreme distance of galaxies presumed primeval, any interpretation of their observations is a delicate problem. Simultaneous effects interact to modify apparent magnitudes and colours: cosmology, intrinsic evolution and likely environmental influences can affect their appearance in ways which are difficult to estimate with their respective weights. A classical Friedmann-Lemaître cosmological model gives a relation between the redshift z and the cosmic time t(z). This relation essentially depends on the cosmological parameters: the Hubble constant H_0, the density parameter Ω_0 and the cosmological constant Λ_0. Galactic evolutionary models coupled with cosmological models are the key to understand the respective importance of the various effects. For a galaxy observed at redshift z, the age estimated from evolution models constrains the epoch of galaxy formation and then the age of the Universe.

Some principles are used in building our models: limitation to a few free parameters, a time resolution sufficient to follow details of stellar evolution, input data preferentially observational. At least, results must simultaneously fit observational data on a large extent in wavelength range, gaseous content, emission lines, dust, etc. We proposed such models (Rocca-Volmerange et al., 1981, completed with cosmological effects by Guiderdoni and Rocca-Volmerange, 1987 (GRV) which is our present version) in which the star formation parameters are: (i) the start of the star formation process z_{for}, (ii) the time scale