UV TO IR MODELS OF GALAXY EVOLUTION AND COSMOLOGY

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Abstract

Recent improvements of spectrophotometric evolutionary models are described. New stellar libraries in the near-infrared (JHK) allow extension of the synthetic spectral Atlas of galaxies down to 10μm. From analyses in the far-UV and visible, observed colors and counts of faint galaxies are fitted by modelling a standard luminosity evolution and a low value of $\Omega_0(\simeq 0.1)$ while, in a Ω_0=1 Universe, models only fit data with a standard luminosity evolution and a number density evolution $\simeq (1+z)^{1.8}$: such a modelling is simulating a merging process. Another solution would be a tidally triggered star formation rate in a model in which galaxies form by hierarchical clustering of a dominant dark matter component. From evolution of M/L ratio, these models allow to link observed luminosity functions with mass distributions predicted from galaxy formation models and then to significantly connect evolution to formation models. Nevertheless these two models are not sufficient to fit some observational data such as the Hubble diagrams and faint galaxy counts in the near-infrared, the bright galaxy counts in visible and the Extragalactic Background Light. So new evolution scenarios are needed implying other constraints for cosmological parameters.

1. Introduction

Early evolution of galaxies makes up the keystone of cosmology : a link between the observable Universe and predictions from initial fluctuations. For the first time, a large variety of distant galaxies marks out with light or matter the way to the primeval phases. Individual sources or galaxy populations discovered through narrow pencil beams at distances up to now never reached, explore deep into the structures and likely test evolution. Galaxies turn up as stellar populations with typical spectral, dynamical and chemical signatures. However their appearance is depending on the geometry of the Universe and a model of galaxy evolution is needed to deconvolve the respective effects of evolution and cosmology. Such a model based on the physical processes driving birth and evolution

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of stars or triggering emission of gaseous components, has to simultaneously interpret signatures of intervening, absorbing and diffusing matter. Significant results are essentially depending on three conditions : i) input data have to be mostly observational, ii) evolution scenarios fit various observational samples at z=0 on a large wavelength range (far-UV to IR) iii) when it is possible, details of data processing are taken into account in modelling. Several models have been built. Mostly they have similar basic principles and essentially differ from their input data. We shortly review some of them and their recent improvements. Then we show that at the present time the most convincing interpretation of the large redshift samples corresponds to luminosity and number density evolution which could be a phenomenological simulation of the merging process. However, as some observables are not well fitted by these models, our conclusion is a perspective of a better understanding of galaxy evolution by a simultaneous fit of observations from the far-UV to the infrared.

2. Present status of models

Historically these models were built in two phases. The first models of evolving stellar populations were simultaneously proposed by Tinsley, 1972 and Searle, Sargent et Bagnuolo, 1973. Respectively based on isomass tracks and isochrones following evolution of stars in the Hertzsprung-Russell diagram, they interpreted blue galaxies with bursts of massive stars. These photometric models were improved with nebular emission lines (Huchra, 1977) and with far-UV colors and metallicity effects (Rocca-Volmerange et al, 1981). Some recent models are still photometric, most of them take into account a simplified chemical evolution (Arimoto and Yoshii, 1986, Franceschini et al, 1991)

A second generation of models appeared when atlases of spectra replaced stellar colors as input data (Bruzual, 1983, Guiderdoni and Rocca-Volmerange, 1987 (GRV)), down to the far-UV from the IUE atlases (Wu et al, 1983, Heck et al, 1984). From then, several improvements were taken into account:
i) Recent improved stellar tracks have been published by Maeder and Meynet, 1988. Time duration phases may increase by a factor 3 compared to the Yale tracks, due to the overshooting of convective cores. Mass loss rates and opacities given by the most recent determinations (de Jager et al, 1988). Maeder's models essentially fit massive stars, typically $M \geq 1.5\ M_\odot$ (Maeder, private communication). Low mass stars are from Vandenbergh, 1985. These new tracks were introduced in our models by 1988 and the integration time step was refined down to 10^5 yr for calculating burst models. Most of recent results on ages of radiogalaxies (Rocca-Volmerange and Guiderdoni, 1990) and faint counts (Guiderdoni and Rocca-Volmerange, 1991) are based on these new input data. Maeder and Meynet, 1988 tracks were recently introduced in Bruzual's model (Charlot and Bruzual, 1991) and a more refined integration is carried out from a large ($\simeq$ 150) number of interpolated isochrones as used by Searle et al, 1973. Another model (Yoshii and Takahara, 1988) based its calculations in the far-UV from "so-called template" galaxies, observed with the ANS or IUE satellites. So their calculations of evolution in the far-UV are not explicit. This could explain why this model needs the help of a cosmological constant to fit Tyson's, 1988 observations in a low density universe (Fukugita et al, 1990). Detailed models with recent data of massive stars were proposed by Olofsson, 1989, Leitherer, 1990. Some models are extended in the near-infrared by

using stellar photometry or consistent black-body emission of stellar effective temperatures (Franceschini et al, 1991, Rocca-Volmerange and Gros, 1991).

ii) An extinction correction is proposed assuming stellar emitters mixed with gas. The optical depth through a spiral disk depends on inclination, gas content and metallicity (GRV).

iii) A nebular component (continuum plus lines) is calculated by estimating the number of Lyman continuum photons from stellar models (Clegg and Middlemass, 1987, Kudritski, 1990) and the current radiation field.

iv) The metallicity effect is taken into account in stellar evolutionaty tracks (Maeder and Meynet, 1991, in preparation). It corresponds to an increase of age with metallicity due to an increase of opacities. As a consequence, at a given age, the giant/dwarf number ratio is lower in metal-rich galaxies since giants take more time to reach the giant branch phase (Guiderdoni and Rocca-Volmerange, 1984). For other effects of increasing metallicity (lowering effective temperature and blanketing effect), Arimoto and Yoshii, 1986 gave rough estimates. Most uncertain are the evolutionary parameters of the Asymptotic Giant Branch (AGB) and post-AGB phases. If luminosities and effective temperatures can be derived from observations (Mould, this conference), phase duration can vary from 10^6 to 10^8 yrs according to models (see Renzini this conference).

3. Extension to the near-infrared

To extend spectrophotometric models to the near-infrared, two complementary libraries of stellar spectra have been observed and compiled:

i) Our far-UV and visible stellar library has been linked to the near-IR with observational infrared colors in the JHK bands. The caracteristics of this library are a wavelength range from 200Å to 10μm and a resolution $\Delta\lambda$ =10Å below 1μm. An extension of our Atlas of synthetic spectra of galaxies (Rocca-Volmerange and Guiderdoni, 1988, RVG), based on scenarios of evolution for 8 morphological types intends to reproduce colors of the Hubble Sequence: an example is shown on Figure 1. These spectra are used to calculate cosmological and evolutionary corrections (respectively k- and e- corrections) needed to predict apparent magnitudes and colors of distant galaxies according to:

$$\begin{aligned} m_\lambda(z) &= M_\lambda(0) + (m - M)_{bol}(z) + k_\lambda(z) + e_\lambda(z) \\ C_\lambda(z) &= C_\lambda(0) + k_{\lambda,c}(z) + e_{\lambda,c}(z) \end{aligned}$$

with $M_\lambda(0)$ and $C_\lambda(0)$ respectively intrinsic magnitude and color at the present epoch. The important point is all the spectral UV to IR stellar data are observational, they cannot be the origin of the discrepancy between observations and model predictions in the near-infrared and so evolution scenarios for the Hubble sequence have to be revised.

ii) To study in more details the stellar populations of nearby and distant galaxies, Rocca -Volmerange and Maillard observed a new library of high resolution stellar spectra ($\simeq$40 dwarfs, giants and supergiants) with the Fourier Transform Spectrograph (FTS) at C.F.H.T. by 1989, 1990 through a large filter covering the H and K bands and with a high spectral resolution (2-3 Å) showing typical signatures of CO and H_2O bands, Brackett lines and many others. Data have been processed; an example of such spectra is given on figure 2 (Lancon et al, 1991).

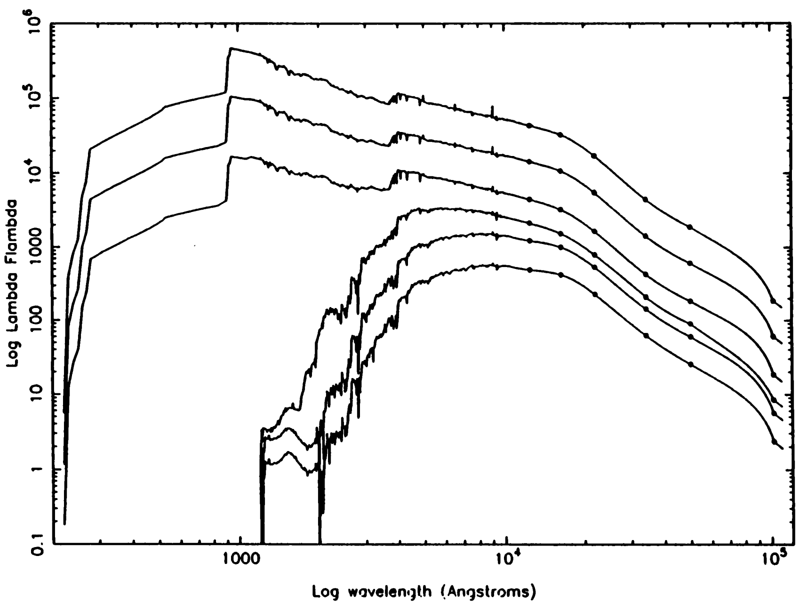

Fig. 1: Examples of synthetic spectra of galaxies extended from the far-UV (200Å) to the IR ($\simeq 10\mu m$) calculated with an updated version of our model (Rocca-Volmerange and Gros, 1991).

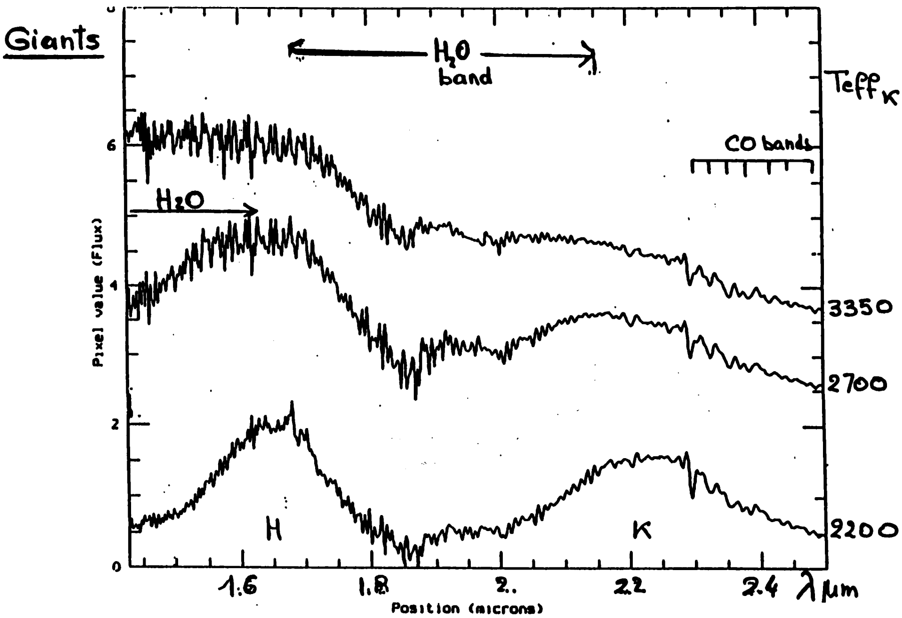

Fig. 2: High resolution spectra of the stellar library observed with the FTS instrument at C.F.H.T. through an H+K filter. Signatures of CO bands and H_2O bands are strongly varying with temperatures (Lançon et al, 1991).

4. Evidences of galaxy evolution

From the pionneer works of Butcher and Oemler, 1978, these last ten years confirmed a star formation evolution for distant galaxies providing vital clues to the process of luminosity evolution. Related to a starburst phenomenon, it has been firstly analysed in the optical from extremely blue colors (Searle, Sargent and Bagnuolo, 1973) and recently in the far-IR from the IRAS satellite (Sanders et al, 1988). In these last cases, an extreme evolution of the ultraluminous starbursts is associated to a dynamical interaction (Mirabel, 1991). At a lower level, the star formation activity in cluster galaxies has been related to dynamical processes to explain the morphological segregation (Dressler, 1980) and the discovery of A stars in elliptical galaxies (Dressler and Gunn, 1983).

The recent deepest surveys of faint counts of galaxies (Tyson, 1988, Cowie et al, 1990) strongly constrain scenarios of galaxy evolution and/or cosmological parameters. Evolution models fit number counts, redshift or color distributions on a large dynamic range down to $B \simeq 27$ (Guiderdoni and Rocca-Volmerange, 1990, see also Guiderdoni, this conference). As number counts are strongly depending on the size of the covolume element, they give constraints on cosmological parameters: standard evolution models reproduce the data in a low density Universe while, by adding a number density evolution, data are compatible with models in a $\Omega_0 = 1$ Universe (Rocca-Volmerange and Guiderdoni, 1990, Guiderdoni and Rocca-Volmerange, 1991). However a large-scale structure survey of bright galaxies (the APM survey by Maddox et al, 1990) gives results in number counts, correlation functions, and other large scale properties in disagreement with the current models of galaxies. In particular, the evolution of galaxy number density between $m = 14$ and 19 is higher than predicted by models. Similar conclusions were given by Broadhurst et al, 1988 followed by Colless et al, 1990 who suggested a new population of blue galaxies vanished at the present time; we prefer another solution which would be new evolution scenarios, relaxing our initial hypotheses (Rocca-Volmerange and Gros, 1991).

Other signatures of galaxy evolution are given from the optical and infrared counterparts of powerful radiosources. The two most distant radiogalaxies: 0902+34 at $z = 3.395$ (Lilly, 1988) and 4C41.17 at $z = 3.8$ (Chambers et al, 1988) show signatures of stellar populations. Their typical features are: i) a large gap (up to a factor 10) of the observed flux from the far-UV plateau to the visible (rest frame) ii) the alignement of the radio and far-UV axes in most cases iii) an enormous Lyman-α (1215Å) line with an equivalent width of roughly 1000Å, implying a considerable star formation rate, about 1% of the total mass(Rocca-Volmerange and Guiderdoni, 1990) iv) different morphologies according to the wavelength range v) a narrow relation in the K-z Hubble diagram.

According to different authors, estimated ages spread from $\simeq$ 0.3Gyr to about 1.5 Gyr (Lilly, 1988, Rocca–Volmerange, 1988, Chambers and Charlot, 1990). In fact, arguments leading to a unique solution are not sound (Rocca–Volmerange and Guiderdoni, 1990) first because stellar evolutionary data of respectively supergiants, asymptotic giant branch stars and giants are not well established. Second, present status of observational data show that current star formation erases most of spectral features which could give a significant age (figure 3). Third, the infra-red emission associated to the radio jet (Joy et al, 1991) and possibly a dust contribution of these distant radiogalaxies could partly mask the stellar emission to be dated. Relative to the number density evolution, there is some evidence that radiogalaxies with $1 < z < 3.8$ are objects undergoing a rapid merging of the available clumps, as suggested by Djorgovski et al. 1988. The 16 3C radiogalaxies carefully imaged with sub-arcsecond seeing at the Canada-France-Hawaii Telescope all show a number of clumps, from 2 to 5 (Le Fèvre et al, 1988). Zepf & Koo,1989, used a deep survey of distant galaxies to estimate the relative frequency of close pairs at faint magnitudes ($B \leq 22$) relative to that for nearby bright galaxies. A statistically significant excess of faint pairs is consistent with an increase in the frequency of interactions $f = (1+z)^{4.0\pm2.5}$.

5. Star Formation in merging-driven evolution models

Among models of galaxy formation, more or less dissipative collapses (Larson 1975,1976) of clumpy turbulent protogalaxies with anisotropic stellar velocity (Carlberg, 1985) reproduce disks and spheroïds. On the other hand, dynamical friction acting on two or more building blocks could result in a merging process forming a condensed galaxy (Toomree and Toomree, 1972). Many observations favor, with a more or less high degree, a merging scenario. Fundamentally, a merging process is dynamical depending on the mass distribution of intervening blocks. For high masses of interacting components, a starburst strongly emits in the far-IR and/or in the far-UV. However such extreme cases are rare and the essential question is: what star formation rate (SFR) is induced by the bulk of interactions predicted by galaxy formation models? Likely it depends on intrisic and relative dynamical properties of components (mass, velocity,..) but we ignore on what way. Moreover the classical modelling $(1+z)^{\eta}$ increases the confusion because it is not clear if luminosity or number density are in fact multiplied by this factor.

According to the simultaneous approach of distant radiogalaxies and faint galaxy counts, Rocca-Volmerange and Guiderdoni, 1990, Guiderdoni and Rocca-Volmerange, 1991 proposed an unifying model in which all galaxies form from the merging of building blocks for which the spectral evolution is computed. The following scenario is suggested: the collapse and cooling of gas in the potential wells of dark-matter haloes lead to fragmentation into a number of clumps, say $N \simeq 10$ with a characteristic mass of an order of magnitude below the total baryonic mass. These clumps are the gas reservoir for star formation. The general rule for field galaxies would be that star formation begins at relatively high redshift in these clumps (z_{for}=10 to 5, derived from the colour distribution of faint galaxies as well as from the radiogalaxies). The clumps also "slowly" merge according to an 'average' $(1+z)^{\eta}$ law. Star formation continues in the merged objects from the residual gas. These objects would essentially be those observed in faint galaxy counts. Dynamical friction could be the process regulating merging and number evolution. In a small fraction of the massive, high-redshift objects, the merging of the available clumps could be more rapid, simply as a Poisson fluctuation. Since the clumps would then still be gas-rich, the star formation would be stronger, and the large amount of gas could also feed some central compact object and initiate the radiogalaxy phenomenon. The small number of high-redshift, active objects could be found from a search of radio sources, but would have no significant effect on faint galaxy counts. Finally, the subsequent growth of these objects is impeded by the large cooling time of very massive haloes (see e.g. Evrard, 1989). This scenario is compatible with most observations of radiogalaxies and faint galaxy counts and it has the essential property to save Ω_0=1 because the pure luminosity evolution models only fits the data in a low Ω_0 Universe incompatible with inflation. The number density evolution varies as $(1+z)^{1.8}$ and the luminosity evolution roughly follows our standard scenarios.

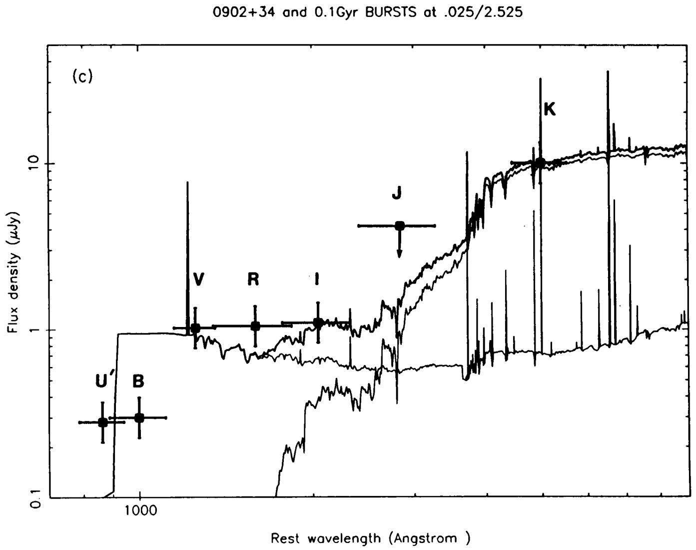

Fig. 3:Fit of the spectral energy distribution of 0902+34 in the U'BVRIJK bands at z=3.395. The spectra of two 0.1 Gyr and 2.5 Gyr are superimposed. Most of the evolution signs in the old burst are cancelled by the current ones.

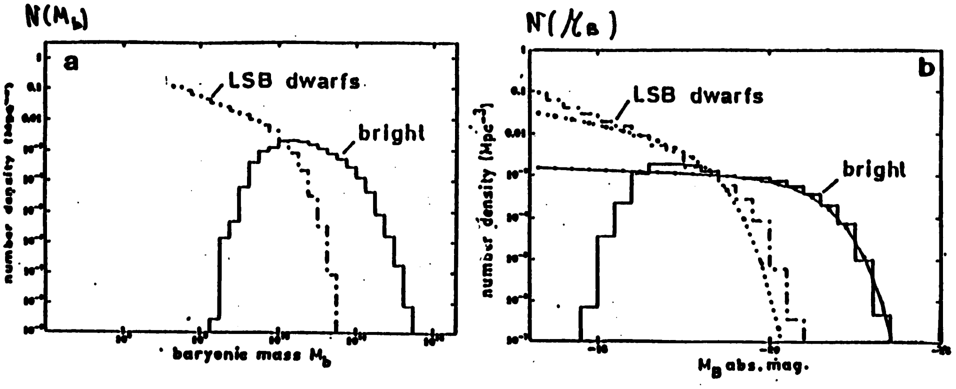

Fig. 4: Distribution of baryonic masses (a) compared to the corresponding luminosity functions (b) computed for bright galaxies and low-surface-brightness dwarf galaxies. The galaxy formation model and refinements of our evolution model are described in Lacey et al, 1991.

Another solution is a model in which galaxies form by hierarchical clustering of a dynamically dominant dark matter component and in which the rate of star formation is controlled by the frequency of tidal interactions with neighbouring galaxies. This has been proposed by Lacey and Silk, 1991. Owe to the mass-luminosity ratio M/L as a fruitful output of evolution models, luminosities, colours, surface brightnesses and circular velocities of nearby bright galaxies as well as distributions of redshifts, colours and numbers of distant faint galaxies are analysed with our spectrophotometric model (Lacey et al, 1991). Several constraints for the scenarios of galaxy evolution result from this complete study which will be extended to other galaxy formation models. Figure 5 shows the relation of mass-luminosity used in this model by adding a dwarf population. Early winds induced by supernovae explain their low surface brightnesses and the reason why this population is not detected at the present time (Silk, this conference).

These last solutions are compatible with the recent observations of bright galaxies (Maddox et al, 1990) only at a low level. Moreover, the blue (B) and red (K) number distributions are not fitted with the same models (Cowie et al, 1991). As a confirmation, we show in Rocca-Volmerange and Gros, 1991, that the JHK Hubble diagrams are not so well fitted that the corresponding blue diagrams. At evidence, new populations or new basic hypotheses of evolution scenarios have to be proposed. And only a significant confrontation of the blue and red will be avalaible to find the solution.

An excellent compilation of the present status of EBL measurements is given by Mattila,1991. These observational results can be compared to theoretical predictions for the background light due to galaxies. Evolution of galaxies has been calculated with a standard luminosity evolution in various cosmologies (Ω_0=0.1 and 1) and various redshifts of formation (z_{for}=2 or 30). All these curves are an order of magnitude lower than the observational values or upper limits in the UV, optical and IR. The important point is that merging models with number density evolution give roughly similar fits since we assume that the total comoving mass density is conserved. Similar conclusions were derived from Bruzual models and Yoshii and Takahara results. Figure 6 presents a strong near-IR emission due to a current starburst and two different extinction factors E_{B-V}=0.1 and 0.5, added to the global galaxy emission. the SED of the burst corresponds to a (1+z)λ shift with 1+z=10. As an example, this population could be a solution for the EBL which has to be constrained by the new scenarios of galaxy evolution .

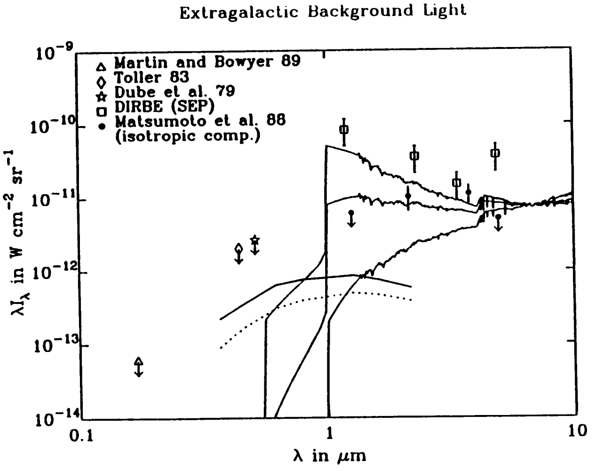

Fig. 5: Predictions of the global emission of galaxies with evolution (full line)and without evolution (dotted line) are far below observations. The contribution of a synthetic burst formed at z=9 with various extinction factors would fit the near- infrared recent data from DIRBE or Matsumoto et al, 1988.

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Questions: J. Ostriker: You presented two quite different pictures. In the first, you had $\Omega_0=0.1$ and $z_{for} \geq 10$. In the second, you had $\Omega_0=1$ and $z_{for} \leq 3$ with extensive mergers. Am I free to believe either model? If so, I prefer the models without much recent merging since there are physical arguments against the latter. Recent merging would heat Sp disks too much. **B.R.V.**: Many observational arguments are in favor of old galaxies (high z_{for} and low Ω_0) even if merging is possible. Observations of large samples of galaxies at intermediate z will give nearly the answer.

G. Bruzual: I got the impression that you include chemical evolution in the evolutionary tracks but not in the stellar libraries. Could you comment on this point? **B.R.V.**: This is a current work.

A. Chokshi: Two comments and a question: i) 0902+34's K band data from Lilly is wrong. P. Eisenhardt's K band photometry drops the K-band data by about 1 magnitude. Given that I band data is an upper limit, the spectrum of 0902+34 is much flatter now. ii) The Hubble diagram is fairly insensitive to galaxy evolution models. iii) Can you list the key parameters, according to their importance for galaxy evolution models, if you try to reproduce the photometric properties of low z galaxies? For example, can one play off M_{high} in IMF versus amount of dust extinction or is it not allowed? **B.R.V.**: The question of key parameters is fundamental and not yet clearly solved. Your suggestion is difficult because of the predominant role of supernovae winds needed by most models. However the emission lines are correlated to the M_{high} and anticorrelated to the dust amount.

P. Whitelock: It has been known for a long time that M giants have strong H_2O absorption. However it is only the most luminous AGB stars-the Miras. Jay Frogel has told us that we don't expect these luminous AGB stars to make a significant contribution to the near-IR spectra of old metal-rich systems. If you find you need to include such objects in your spectral synthesis it would be very interesting as it would mean that the contribution from luminous AGB stars was much larger than predicted. **B.R.V.**: I agree that, for the first time, the H+K filter of the F.T.S. instrument allows a detailed estimate of the AGB stellar population in galaxies.