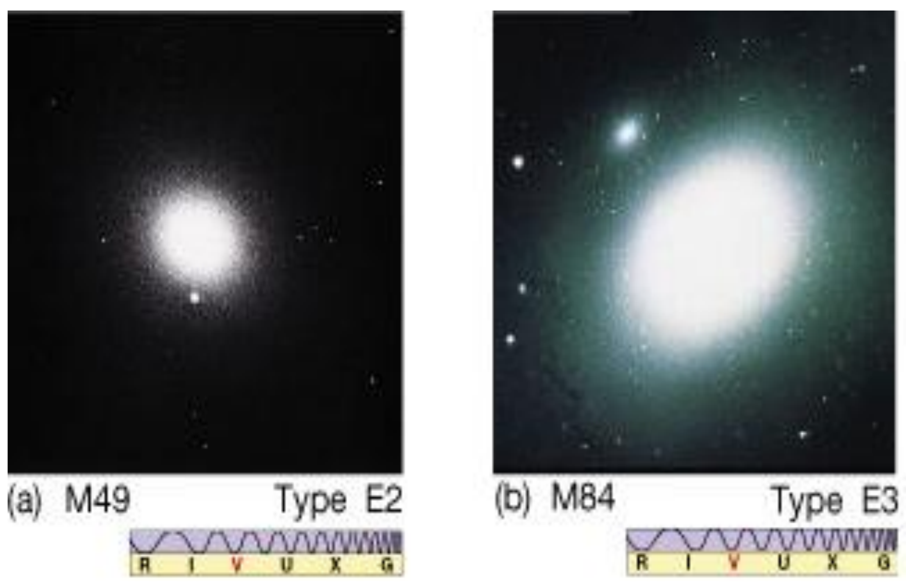
GALAXY FORMATION THROUGH THE COSMIC TIME

THAIS IDIART

IAG/ São Paulo University

ELLIPTICAL GALAXIES



ELLIPTICAL GALAXIES CAN BE USED AS STANDARD CANDLES?

It is usually thought Ellipticals were formed in high redshifts, in a short time range and are quite quiescent until today. So, simple models should be enough to estimate their sizes and luminosities.

GALAXY FORMATION THEORIES

MONOLITHIC COLLAPSE (Eggen et al. 1962; Larson 1974)

- Gaseous material is assembled in the form of a unique cloud inside dark matter halos
- The bulk of stars are formed at high redshifts (z ~ 8-10) in a short time scale, so E galaxies present old mean stellar populations

HIERARCHICAL SCENARIO (Toomre 1977; White & Rees 1978)

- galaxies form from successive non-dissipative mergers of smaller halos of dark and baryonic matter
- galaxies of smaller masses are formed first and can merge to form the most massive and luminous galaxies
- massive E galaxies are assembled at low redshifts (~ z=1.5) and present younger mean stellar populations

KEY QUESTIONS:

1) WHEN THE BULK OF STARS WAS FORMED ?
2) ELLIPTICALS EVOLVED PASSIVELY OR WERE MODIFIED BY INTERACTIONS WITH ENVIRONMENT (MERGING) ?

AGE DISTRIBUTION OF STELLAR POPULATIONS IN E GALAXIES IS ESSENCIAL TO UNDERSTAND THEIR ORIGIN AND EVOLUTION.

OBSERVATIONAL TOOLS:

- INTEGRATED COLORS
- INTEGRATED METALLICITY INDICES

INTERPRETATION OF DATA REQUIRES THE USE OF MODELS

THE EVOLUTIONARY MODEL

Galaxy formation and chemical evolution is a function of successive generations of stars

Age and abundance distribution

Successive formation of star clusters of a given age and abundance (metallicity)

Distribution of single stellar populations (SSPs)

FIRST STEP

Evolutionary synthesis of integrated colors and spectral indices.

Build a library of colors and spectral indices for SSPs with different ages, chemical abundances (Z) and initial mass functions (IMF).

Evolutionary synthesis of integrated colors and spectral indices

Integrated colors for a SSP

$$L_{filter}(age,Z,\gamma)=\int_{m_{inf}}^{m_{sup}}\varphi(m)\times L^{i}_{filter}\,dm \quad (1)$$

IMF

Luminosity or absolute magnitude in a given spectral band *filter* of a star of mass **m** and evolutive stage **i**

Spectral indices for a SSP

Spectral index of a star of mass **m**, evolutive stage **i** weighted by a luminosity fraction in a given spectral band

$$I(age,[Fe/H],\gamma)=\int_{m_{inf}}^{m_{sup}}\frac{L^{i}_{filter}}{L_{filter}}\times\varphi(m)\times I^{i}(T_{ef},\log g,[Fe/H])\,dm \quad (2)$$

Integrated colors and spectral indices of galaxies (composite spectra)

To obtain the stellar contribution for a given spectral index, we selected from the literature a sample of stars from a homogeneous set of stellar atmospheric parameters and chemical abundances of various nuclear species.

Star formation rate at a given time **t**

$$L^{tot}_{filter}\ \text{or}\ I^{tot}=\frac{\int_{t_{inf}}^{t_{sup}}\frac{df_*}{dt}(t)\times[L_{filter}(age),I(age)]\,dt}{\int_{t_{inf}}^{t_{sup}}\frac{df_*}{dt}(t)\,dt}$$

Luminosity or spectral index of SSPs born in time **t** (obtained by (1) and (2)), in a galaxy of age T_{for}: **age=T_{for}- t**

A complex problem arises:

there is not a theory of star formation $\frac{df_*}{dt}(t)$

SFR IS A FUNCTION OF GAS MASS IN A GALAXY

HAVE TO FOLLOW THE EVOLUTION OF INTERSTELLAR MASS

SECOND STEP

THE EVOLUTION OF THE INTERSTELLAR MASS IN E GALAXIES

Main assumptions:

- One zone model
- Galaxy formed by accretion of gas: continuum infall or by mergers in different epochs
- Supernova (SN) feedback:
  a) creates a two phase interstellar medium (IM) hot and cold, whose stars are formed only in cold gas regions
  b) generates galactic winds (mass loss by the galaxy)

EQUATIONS OF MASS CONSERVATION

Evolution of the Total Gas Mass

$$f=\frac{mass}{total\ \ mass\ M_{GAL}(gas+stars)}$$

$$f_g=f_{hot}+f_{cold}$$

$$\frac{df_g}{dt}=\frac{df_{infall}}{dt}-\frac{df_{\star}}{dt}+\frac{df_{ej}}{dt}-\frac{df_{wind}}{dt}$$

ACCRETED GAS

$$\frac{df_{infall}}{dt}=C\times e^{-t/\tau_{infall}}$$

τ_{infall} = time scale of galaxy formation

C = normalization constant

STAR FORMATION RATE

$$\frac{df_{\star}}{dt}=k\times f_{cold}$$

k = star formation efficiency (Gyrs^{-1})

EJECTED GAS BY STARS EVOLUTION

$$\frac{df_{ej}}{dt}=\int_{m(t)}^{m_{sup}}(m-m_r)\varphi(m)\underbrace{\frac{df_{\star}}{dt}(t-\tau_m)}_{k\times f_{cold}(t-\tau_m)}dm$$

$\varphi = A\times m^{-(1+\gamma)}$ is a IMF

m_r = mass of remnant star

the star formation rate is calculed at the retarded time **(t - τ_m)**, where τ_m is the lifetime of a star of mass **m**.

WIND RATE

$$\frac{df_{wind}}{dt}=\frac{f_{hot}}{\tau_W}$$

The rate at which the hot gas of the galaxy is removed by the galactic wind

τ_W= wind time scale : estimated by hydrodynamical models considering galaxy mass and mechanical energy released by supernova per time unit.

HOT GAS FRACTION

$$\frac{dN_{ion}}{dt}=N_q-\frac{\alpha N^2_{ion}}{V_{gas}}$$

- N_{ions} = ions per time unit
- N_q= ionization rate = ions created by time
- $\alpha\ N_{ions}\ N_e$ = ions that recombine with electrons (gas cooled)
- α = recombination coefficient (cm³/s)

In a cloud of H we assume : N_{ions}=N_e

Ions (hot gas) generated per time unit:

- Supernova explosions
- Ejected gas by stars at the end of their evolution

Evolution of the Hot Gas

$$\frac{dN_{hot}}{dt}=N_{ph}\nu_{SN}+(1/m_H)\frac{dM_{eject}}{dt}-\alpha\frac{N^2_{hot}}{V_{gas}}$$

Number of ionizing fotons emitted by SN

Hot gas fraction returned by stars to the IM

Gas fraction cooled by recombination

SYSTEM OF TWO INTEGRO-DIFFERENTIAL EQUATIONS:

TWO VARIABLES TO DETERMINATE : x_{hot} e f_g

Evolution of Total Gas Mass

$$\frac{df_g(t)}{dt}=-k\ f_g(1-x_{hot})+\int_{m(t)}^{msup}(m-M_R)\ \varphi(m)\ k\,[f_g(1-x_{hot})](t-\tau_m)\ dm+Ce^{-(t/\tau_{inf\,all})}-\frac{x_{hot}f_g}{\tau_W}$$

Evolution of the Hot Gas Mass

$$\frac{dx_{hot}(t)}{dt}=\frac{m_H\varepsilon\ (E_{SNII}\nu_{SNII}(t)+E_{SNIa}\nu_{SNIa}(t))}{M_{GAL}\,f_g(t)<h\nu>}+(1/\ f_g(t))\frac{df_{eject}}{dt}-\frac{\alpha\ M_{GAL}}{m_H V_{gas}}\times f_g(t)\times x^2_{hot}(t)-\frac{x_{hot}(t)}{f_g(t)}\times\frac{df_g(t)}{dt}-\frac{x_{hot}}{\tau_W}$$

THIRD STEP

EQUATIONS OF CHEMICAL EVOLUTION

Mass abundance of a given chemical element i $X_i=f_i/fg$

Mass abundance of accreted gas

$$\frac{df_i}{dt}=-X_i[kf_{cold}(t)]+\frac{df^{i}_{eject}}{dt}+X_{inf\,all}C'e^{-t/\tau_{inf\,all}}-X_i\frac{f_{hot}}{\tau_W}$$

EQUATIONS OF CHEMICAL EVOLUTION

$$\frac{df^{i}_{eject}}{dt}=SNII+SNIa+\int_{m(t)}^{msup}X_i(t-\tau_m)(m-M_R)\varphi(m)kf_{cold}(t-\tau_m)dm$$

SUPERNOVA TERMS:

$$SNII=\int_{\min f}^{msup}m_i\varphi(m)kf_{cold}(t-\tau_m)dm$$

m_i = yields for a range of SNII progenitor mass

$$SNIa=<m_i>_{Ia}\ \nu_{Ia}(t)$$

m_i = mean yield for a SNIa event

OBSERVED PROPERTIES PREDICTED BY THIS EVOLUTIONARY MODEL

STELLAR POPULATION :

- Integrated absolute magnitudes and colors
- Integrated stellar spectra

GAS PROPERTIES:

- Amount of gas (hot and cold) in the galaxy
- Amount of gas in the intergalactic medium (wind)

OUTPUT OF THE MODEL:

MEAN AGE AND MEAN ABUNDANCE OF THE DOMINANT STELLAR POPULATION

BEST FITTINGS OF INTEGRATED PROPERTIES

Free parameters:

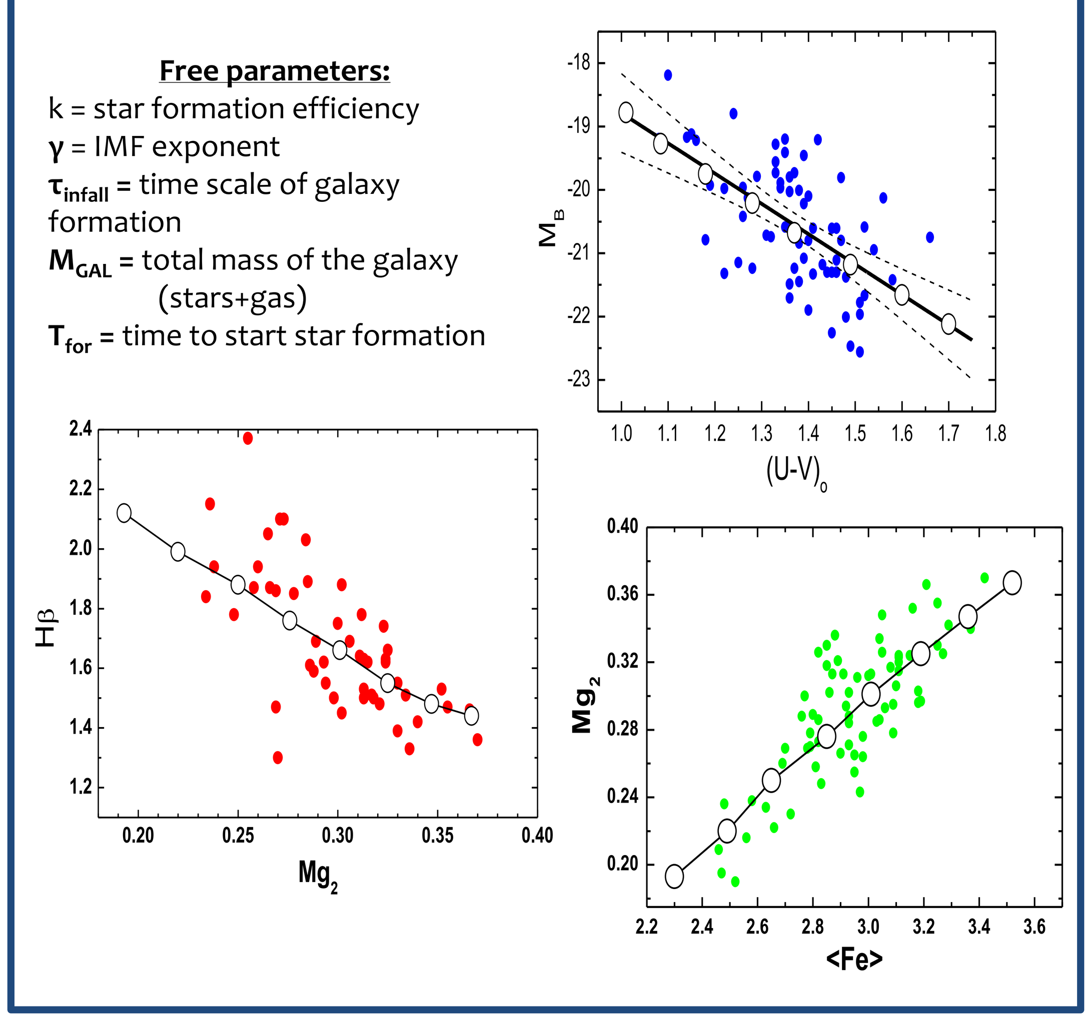
k = star formation efficiency

γ = IMF exponent

τ_{infall} = time scale of galaxy formation

M_{GAL} = total mass of the galaxy (stars+gas)

T_{for} = time to start star formation



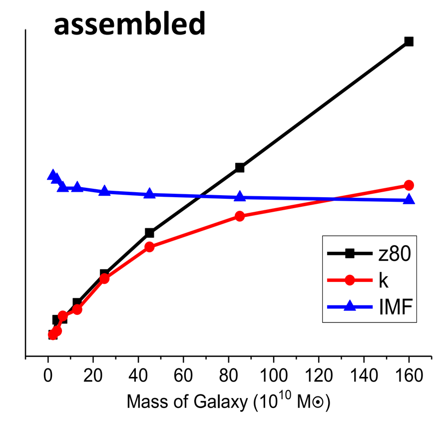
SOME RESULTS FOR THE BEST FITTINGS

Model	M (10¹⁰M⊙)	z80	K (Gyrs⁻¹)	IMF	fg (10-3)
1	2.2	0.73	0.73	2.43	5.9
2	4.0	0.89	0.77	2.39	6.2
3	6.6	0.90	0.93	2.30	6.7
4	13	1.07	1.00	2.30	6.3
5	25	1.38	1.33	2.26	5.6
6	45	1.82	1.67	2.23	6.1
7	85	2.52	2.00	2.20	7.3
8	160	3.87	2.33	2.17	8.9

Downsizing effect

- Massive Es are formed earlier
- Massive Es have bigger star formation efficiency
- The star formation rate is relatively high
- Massive Es have IMF that favours massive stars formation (flatter IMF)

z80 = redshift at which 80% of the mass was assembled



CONCLUSIONS

- On the average, massive E galaxies form earlier than Es of smaller masses.
- Stellar populations of E galaxies of bigger masses are older than the smaller ones.

These two results seem to be against the hierarchical model that predicts smaller structures forming first in a cold dark mater scenario.

- Stellar formation efficiency k increases with galaxy mass.

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