Astronomy 330

Lecture 19

12 Nov 2010

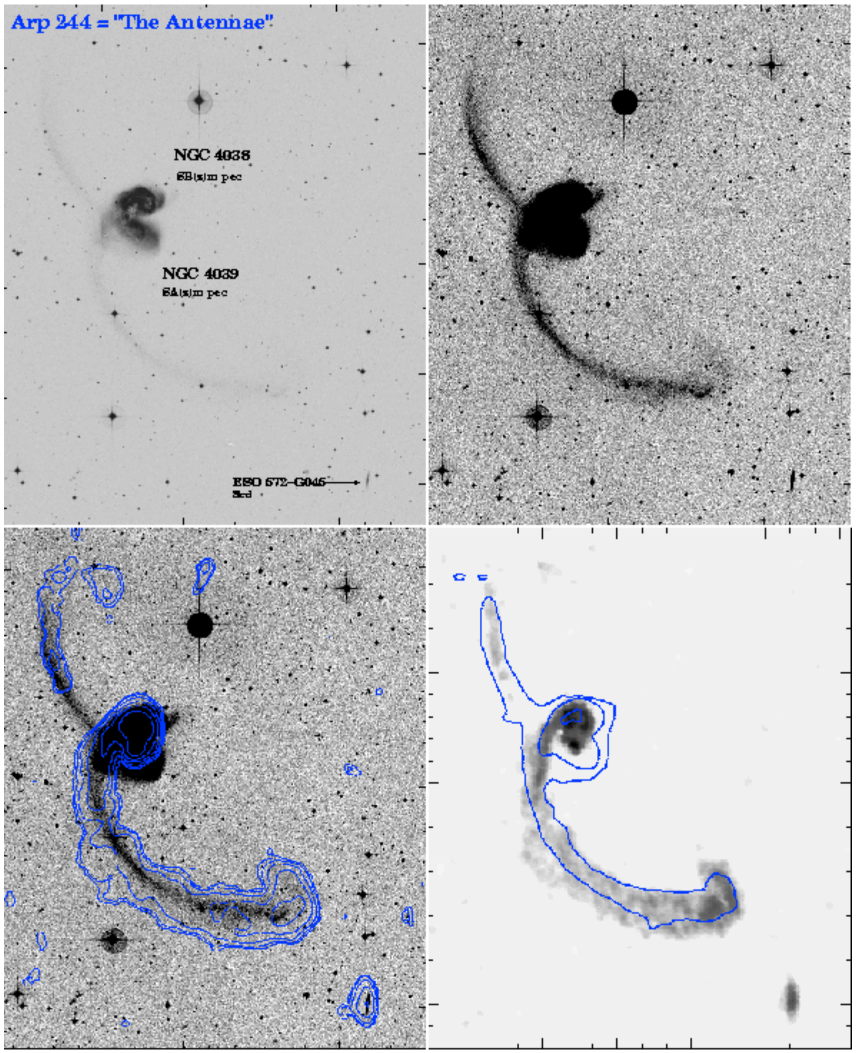
Outline

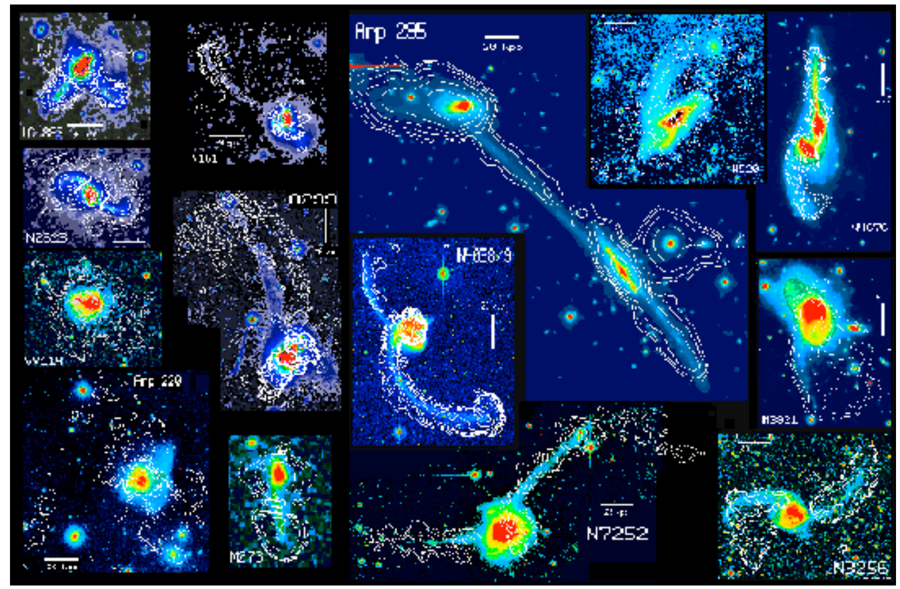
- Ellipticals:
  - Formation
    - Quenching of star-formation
    - Mergers and heating
- Stellar populations
  - Fuel consumption theorem
    - Dominant phases with time
    - M3
  - Direct approach (Pickles)
  - Modern SPS (BC03)
  - Spectra vs age and SFR
  - Simple models

Formation of Elliptical galaxies

- Mergers
  - Tails and bridges result of tidal forces
  - Two galaxies approach on parabolic orbits
    - Systems pass, turn around, but leave tails behind them
    - Ultimately the systems merge
- Simulated merger remnants follow $r^{1/4}$ law
- Observationally….
  - E+A galaxies look like merger remnants
  - Ellipticals reside in high density environments

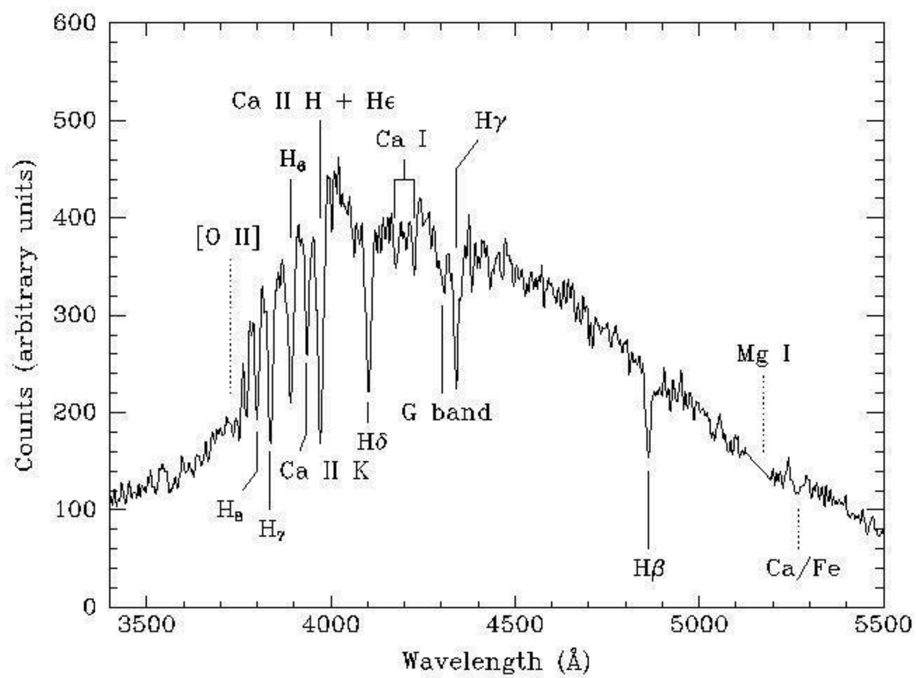
Gallery of interactions





HI Rogues Gallery, J. Hibbard

E+A galaxies: Quenching of star-formation?



Zabludoff et al.

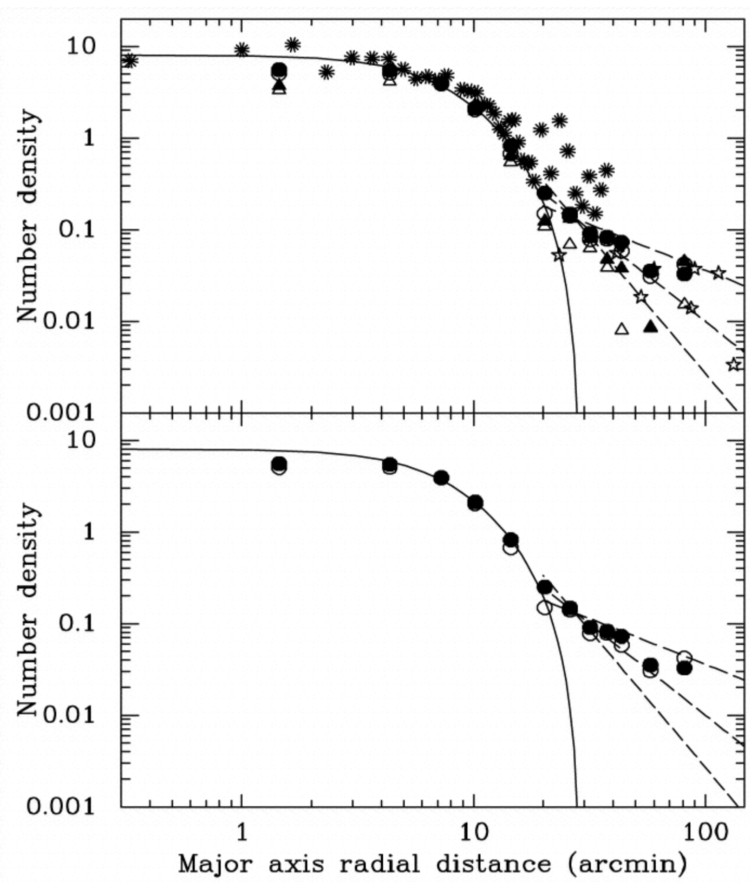
Galactic Cannibalism

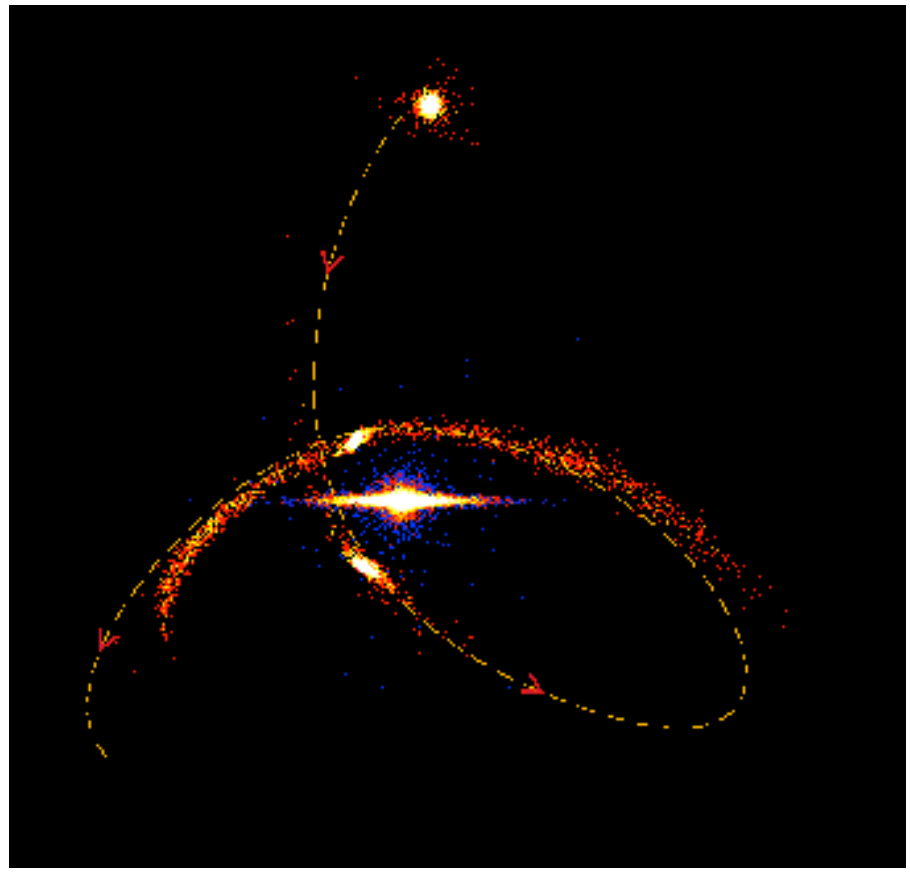
- "dynamical friction" induced cannibalism turns a normal elliptical into a cD giant ➔ some E's have multiple nuclei
- Dynamical friction = braking of some massive body via large numbers of weak gravitational interactions with a distribution of smaller masses (i.e. stars)
  - ➔satellite, M, deflects stars into building a trailing concentration of stars, increasing the gravitational drag, slowing down the satellite
- Applications:
  - Growth of elliptical galaxies
  - Milky Way is swallowing a number of its satellites
    - could the halo be comprised entirely of tidally stripped stars?

Galactic Cannibalism (continued)

- Consider:
  - Satellite with mass, M
  - Stars with mass, m
  - Relative velocity, v_0
  - Impact parameter, b
  - Angle of deflection, θ
- "reduced particle"; μ =mM/(m+M)
- Change in velocity parallel to the initial motion
  - $\Delta v = (2mv_0/M+m)[1+(b^2v_0^4/G^2(M+m)^2]^{-1}2\pi b\, db$
  - Then you integrate over impact parameter and some velocity distribution

Growth of the MW Halo?



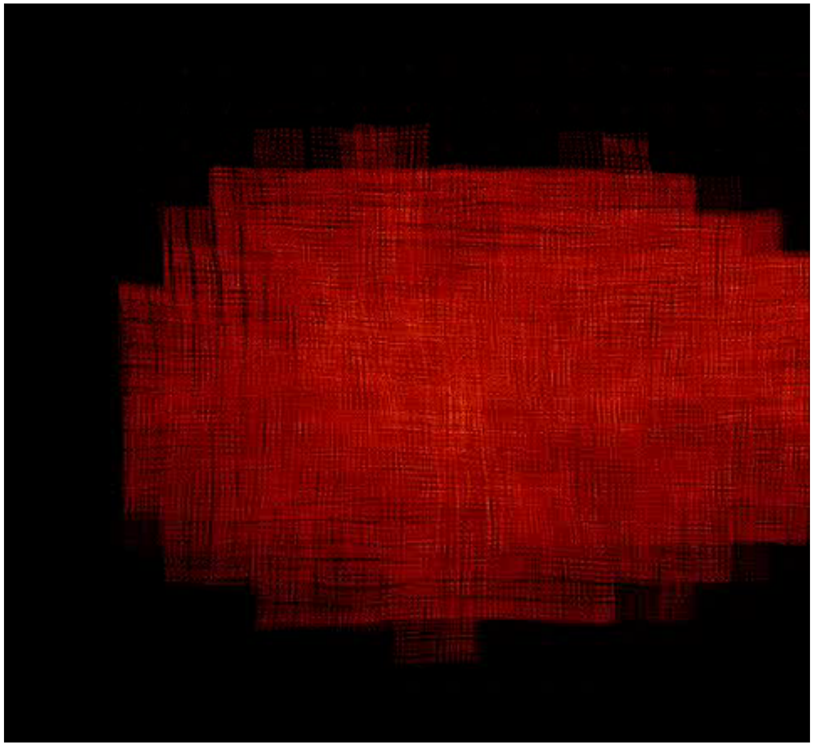


Majewski – real data

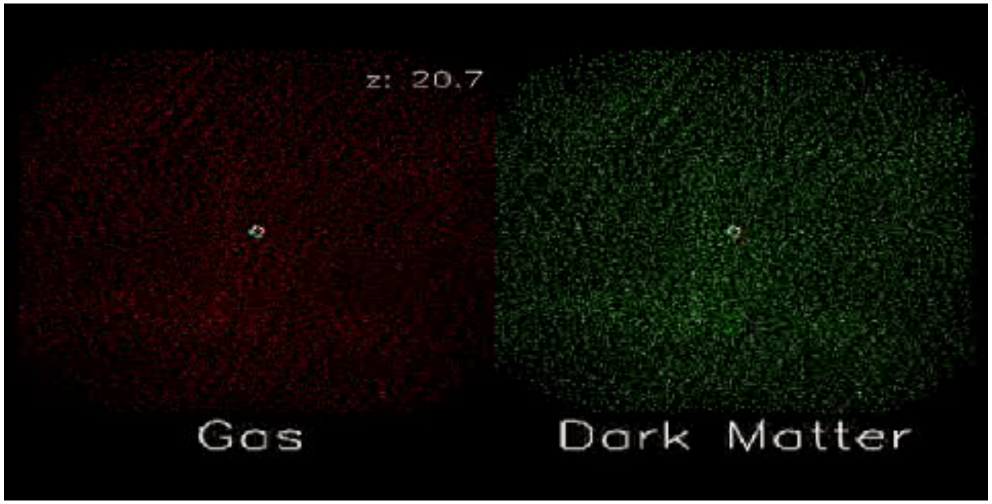
Johnston - simulation

Making galaxies

elliptical

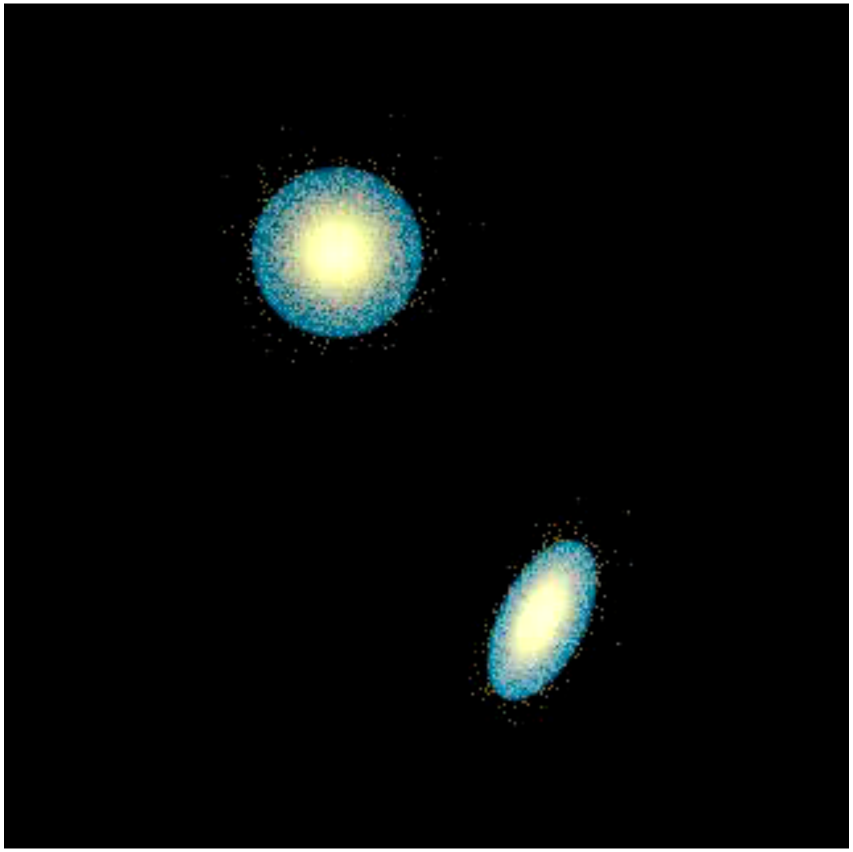


spiral



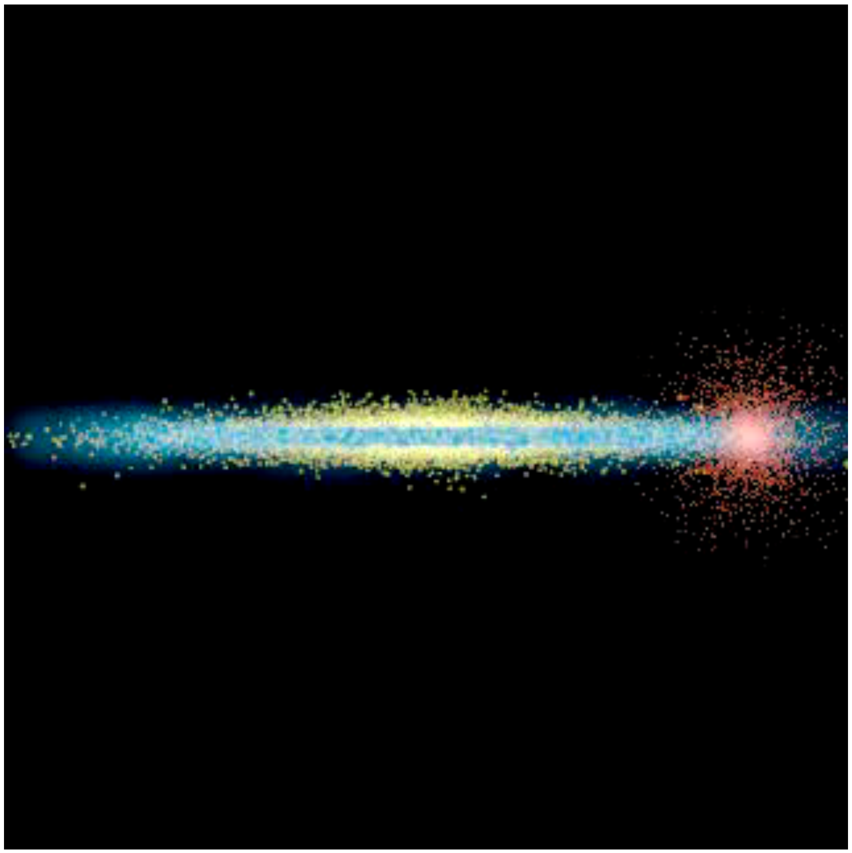
Steinmetz

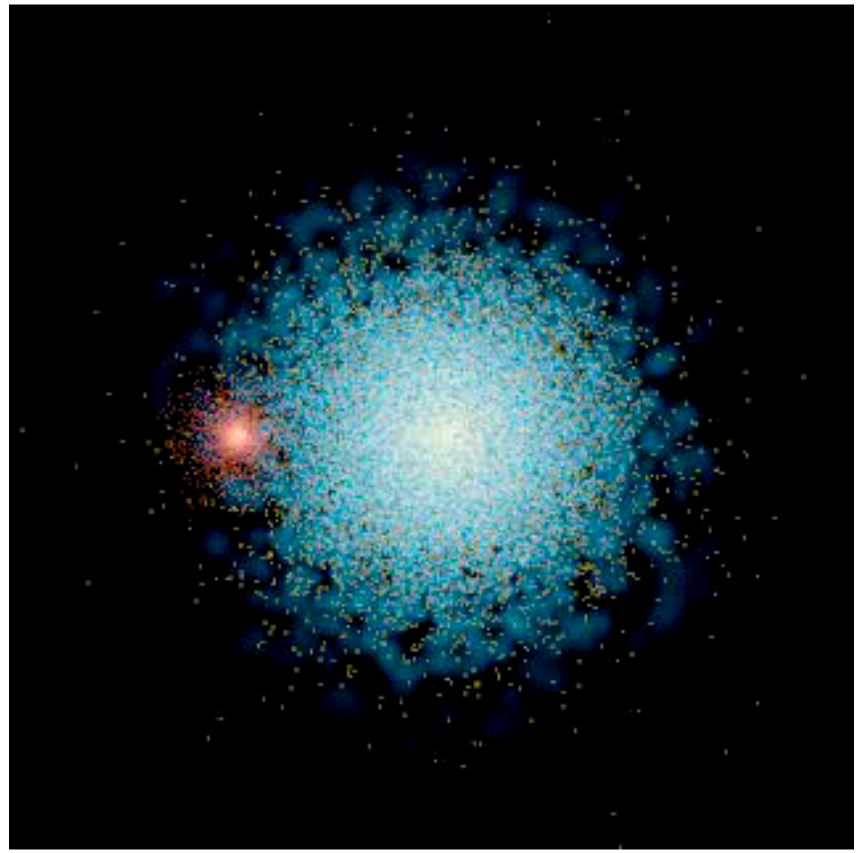
Major mergers



Mihos & Herbquist

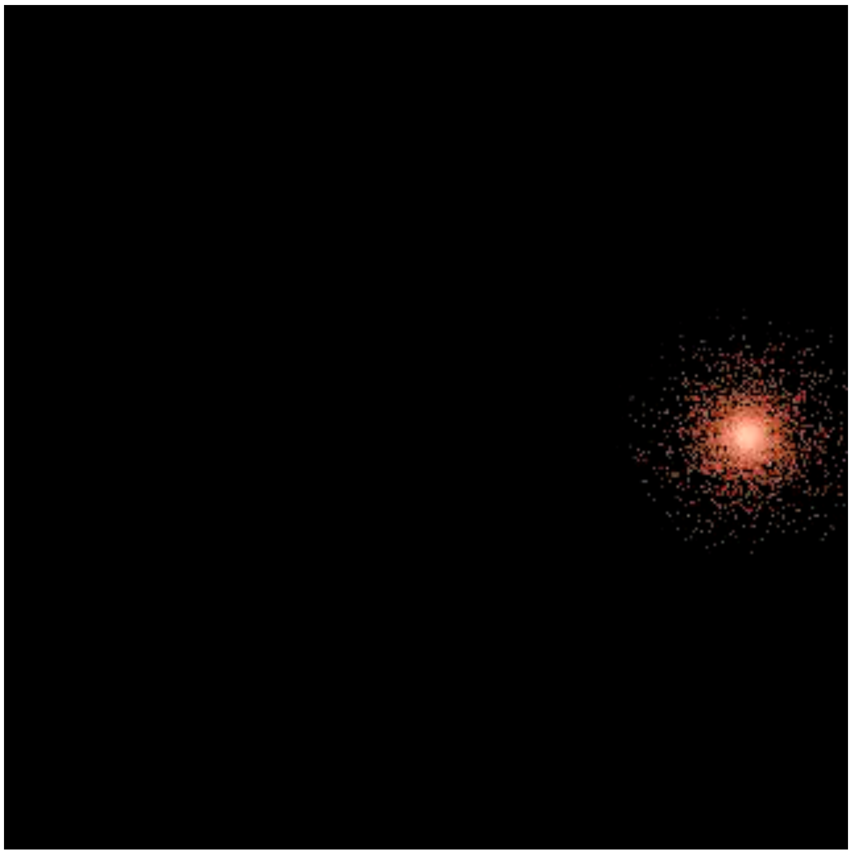
Minor merger

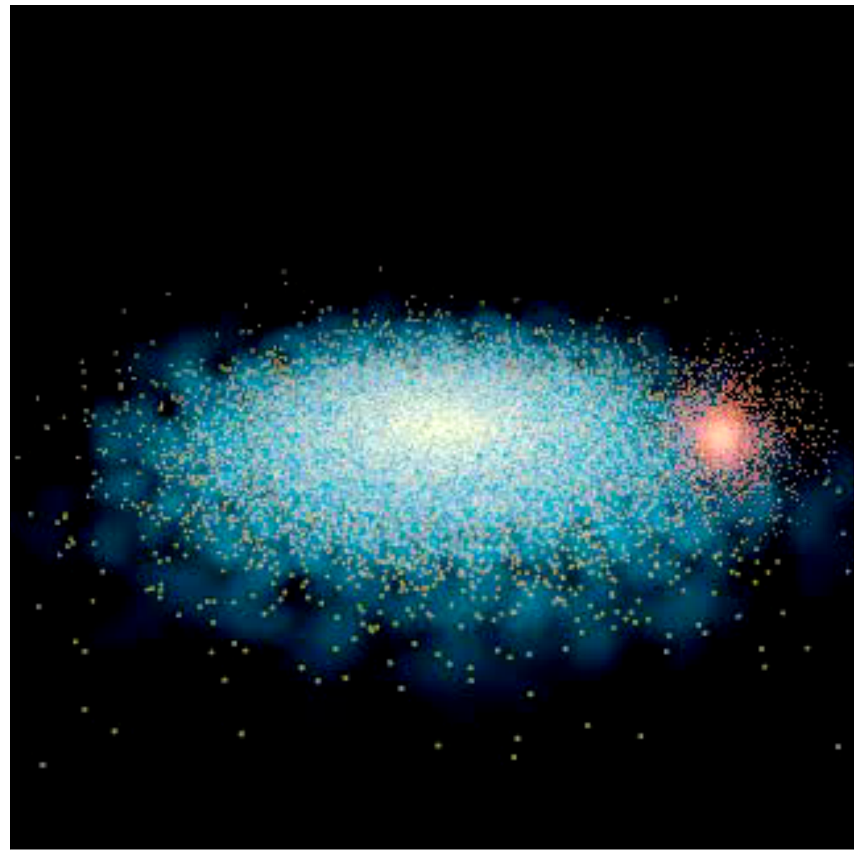




Mihos & Hernquist

Minor merger





Mihos & Hernquist

Stellar populations

- Fuel Consumption theorem
  - The relative *bolometric* contribution of stars (L_j) in any evolutionary phase (j) is equal to the relative amount of fuel (F_j) that each evolving star burns during that phase

$$L_j/L_T = \sim 9.75 \times 10^{10} B(t) F_j,$$

Amount of fuel burned by stars of turn-off mass $M_{TO}(t)$:

$$F_j = \Delta M_j^{\mathrm{H}} + 0.1 \Delta M_j^{\mathrm{He}}$$

He fusion liberates only 10% energy per unit mass compared to H

Total (integrated) luminosity

Number of stars in any post-main sequence stage of duration t_j:

$$N_j = B(t) L_T t_j,$$

Death-rate per unit luminosity, i.e., the specific evolutionary flux; *B(t)* ranges from 0.5×10^{-11} to 2×10^{-11} stars per year per L as age increases from 10^7 to 10^{10} yr

Renzini & Pecci (ARAA, 1988, 26, 199)

Fuel-consumption *continued*

- FC theorem particularly useful for old stellar populations
  - For $t \geq 10^{10}$ yr, $B(t) \sim 2.2 \times 10^{-11}$ stars $L_{\odot}^{-1}$ yr^{-1}

$$\frac{L_j}{L_T} \simeq 2 \times F_j[M_{\mathrm{TO}}(t)] \, .$$

  - Accurate to about 10%

Examples: M3 and 47 Tuc

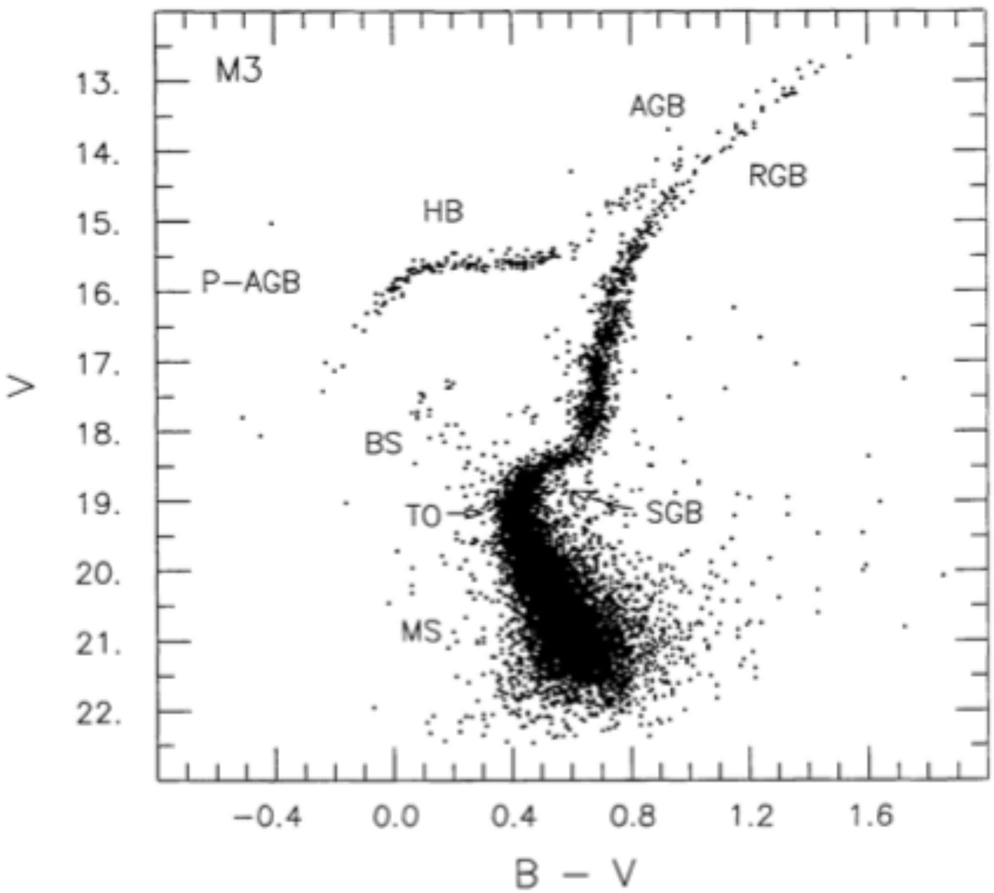


Figure 1 The CMD of the cluster M3 (Buonanno et al. 1986a, 1987). In this diagram, 10,637 stars are plotted, 9879 from a sample that is complete down to $V = 21.5$ and totals $\sim 30{,}000\ L_\odot$ of cluster light, while the remaining 758 stars are drawn from a sample that is complete down to $V = 18$ and totals $\sim 50{,}000\ L_\odot$ of cluster light. The stars brighter than $V = 18$ therefore belong to a sample totaling $\sim 80{,}000\ L_\odot$ of cluster light ($\sim 30\%$ of the total luminosity of M3). More information on this diagram can be found in Table 2. The following classification has been adopted for the various evolutionary stages: 1. main sequence (MS)—core hydrogen-burning phase; 2. blue stragglers (BS); 3. subgiant branch (SGB)—shell hydrogen-burning phase, from the MS turnoff (TO) to the Hayashi line; 4. red giant branch (RGB)—shell hydrogen-burning phase along the Hayashi line, until helium ignition in the core; 5. horizontal branch (HB)—core helium-burning phase; 6. asymptotic giant branch (AGB)—shell hydrogen- and helium-burning phase; 7. post-AGB (P-AGB)—final evolution from the AGB to the white dwarf (WD) stage.

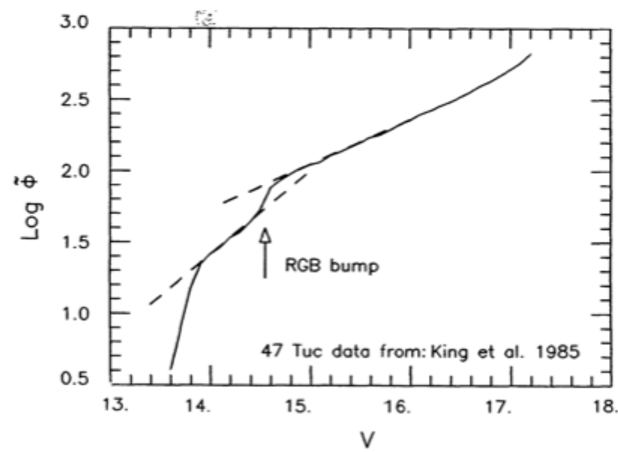
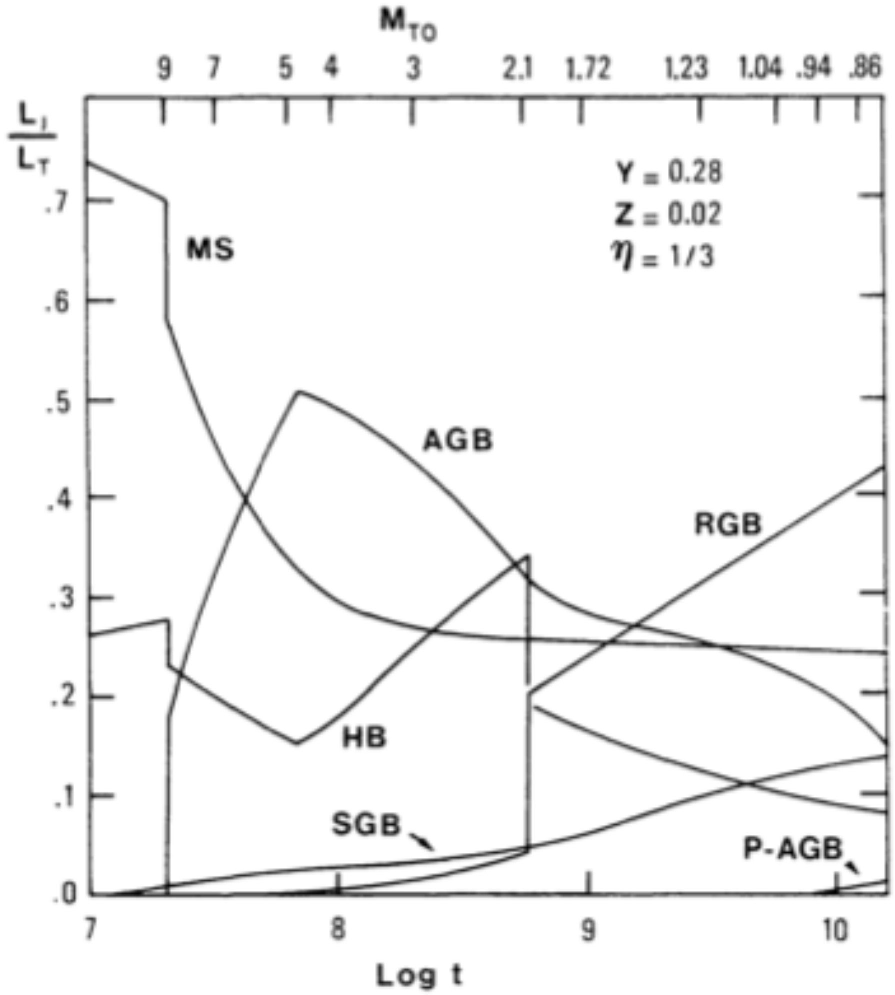


Figure 4 The cumulative luminosity function $\tilde{\Phi}$ for the RGB stars of the cluster 47 Tuc, obtained from Figure 4 of King et al. (1985). The RGB bump and the associated change in slope are clearly visible.

- RP88

Bolometric contributions by time and phase



- RP88

Contributions by time, phase, and λ

- Updated with modern stellar population synthesis (SPS)

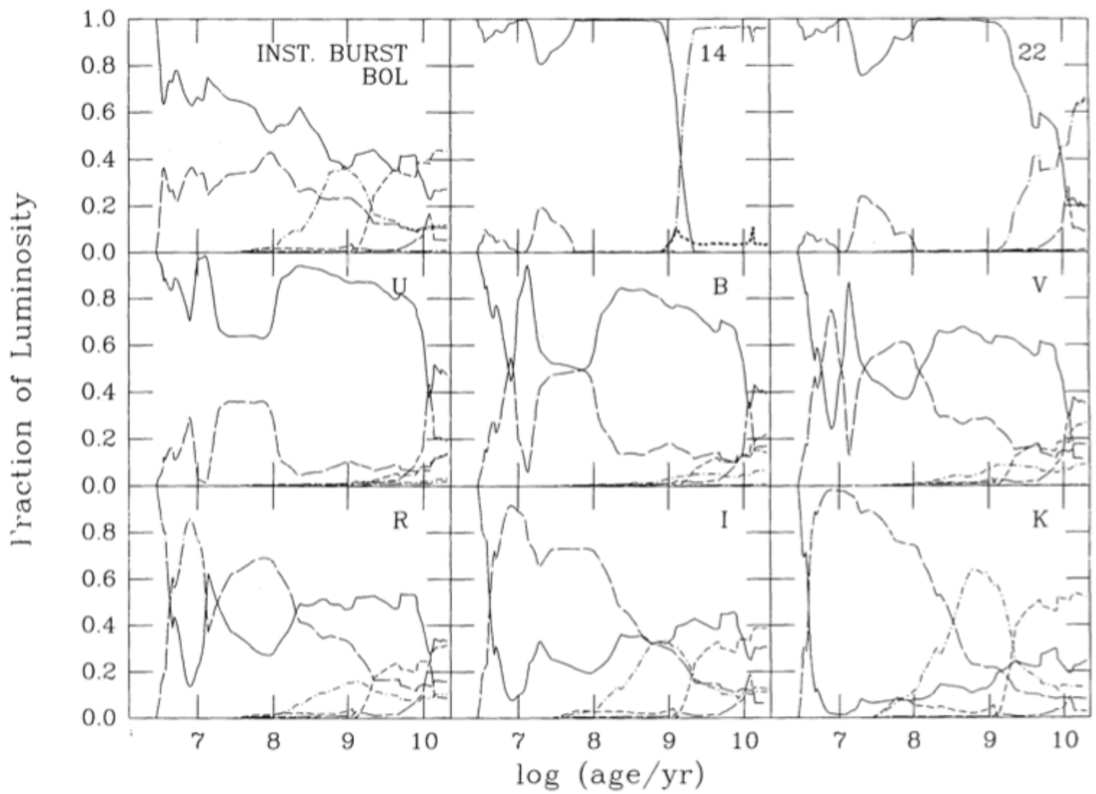
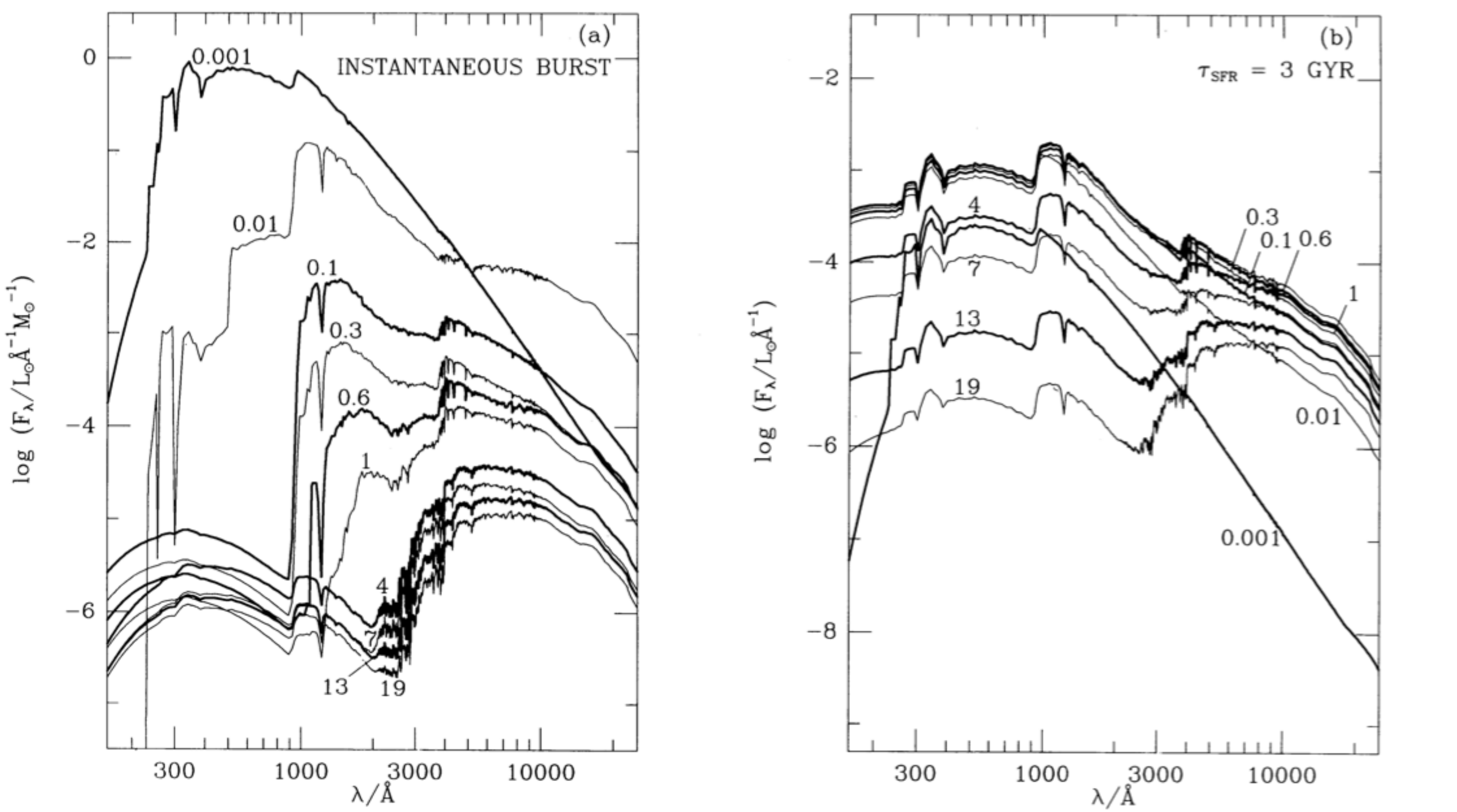


FIG. 2.—Fractional contribution to the integrated light of an instantaneous-burst population by the various stellar evolutionary stages, as predicted by the present model of spectral evolution (isochrone synthesis). The nine panels indicate the contributions to the bolometric light, to the fluxes at 1400 and 2200 Å, and to the broad-band *UBVRIK* fluxes. In each panel the different curves correspond to the following stellar evolutionary stages (acronyms defined in § 3.5): main sequence (*solid line*), SGB (*short-dash–long-dash line*), RGB (*dashed line*), CHeB (*long-dashed line*), AGB (*dot–short dash line*), PNN (*dot–long dash line*), and WD (*short-dashed line*).

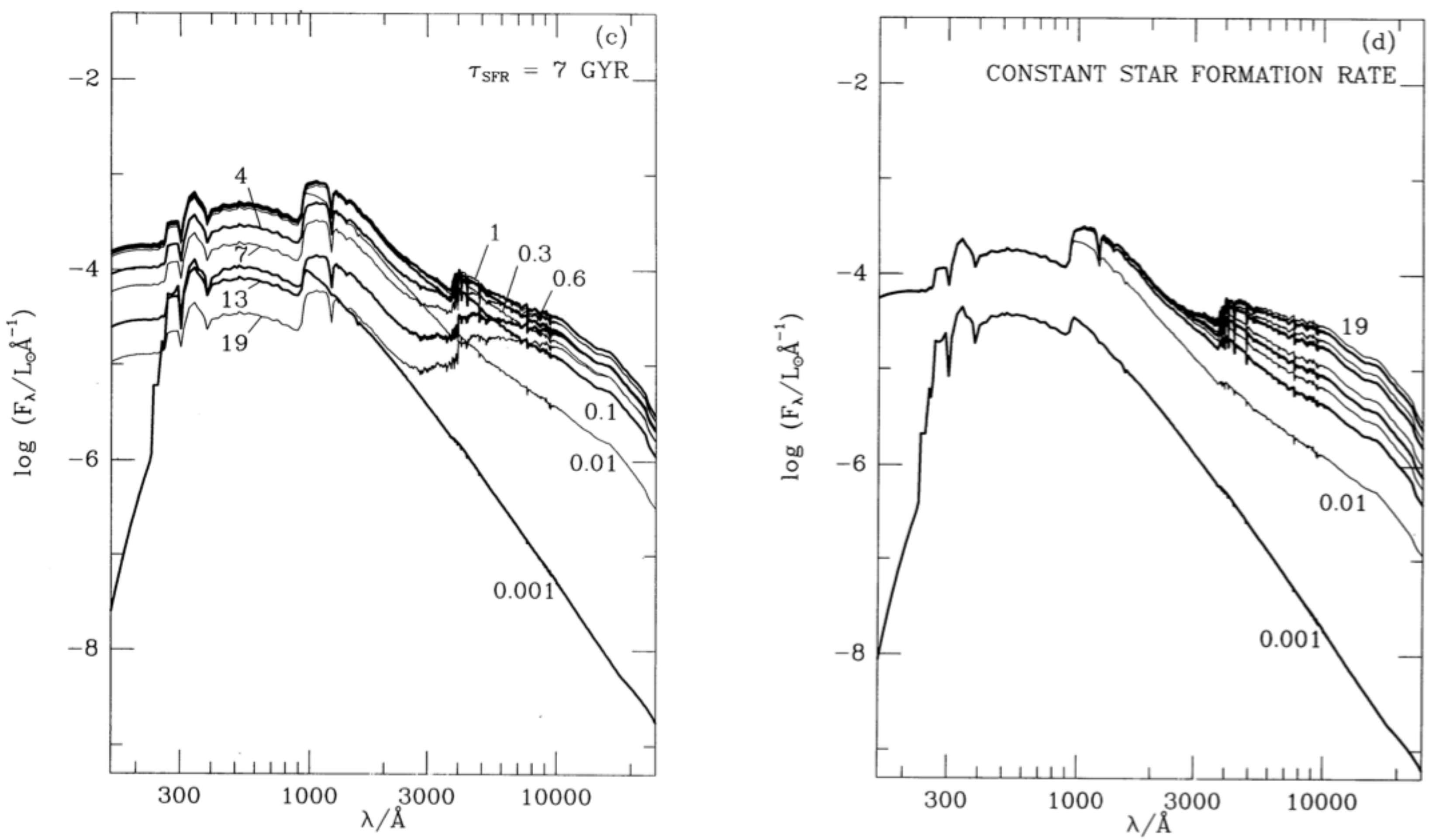
- Bruzual & Charlot (1993, ApJ, 405, 538); Bruzual & Charlot (2003, MNRAS, 334, 1000)

SPS Evolution: early star-formers



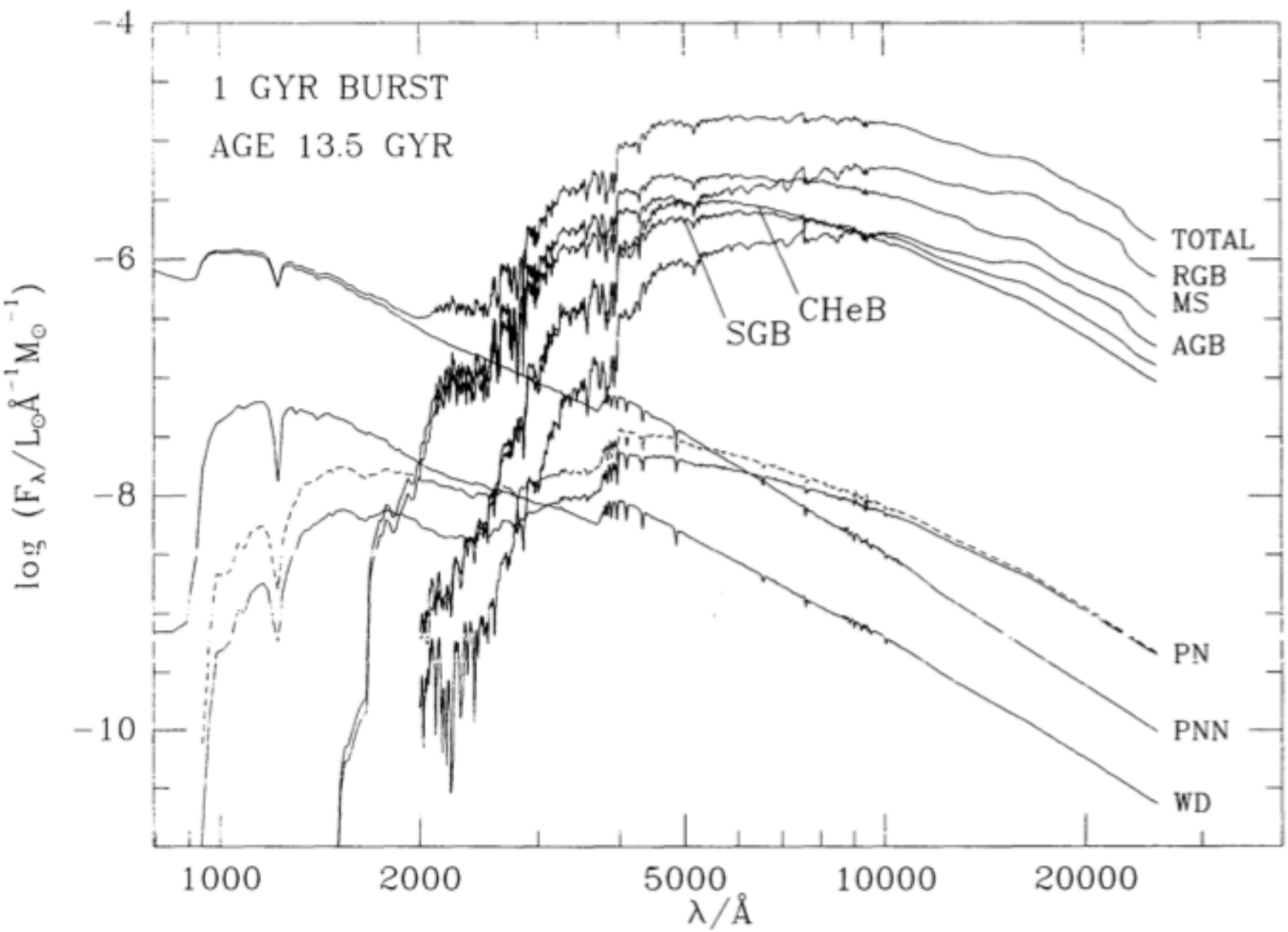
- BC93

SPS Evolution: on-going star-formers



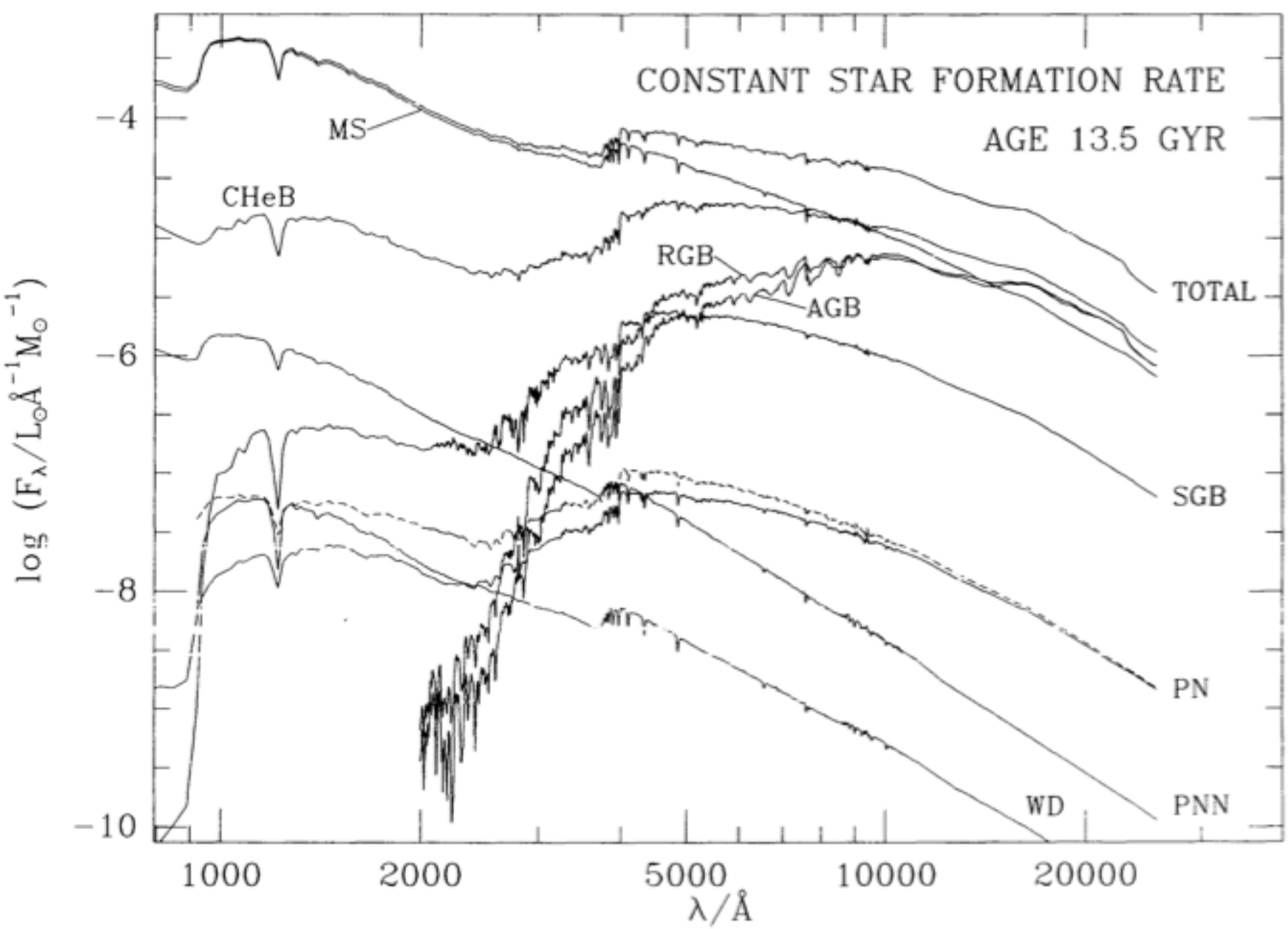
- BC93

SPS Contributions today: early star-formers



- BC93

SPS Contributions today: on-going star-formers



- BC93

Differential populations synthesis

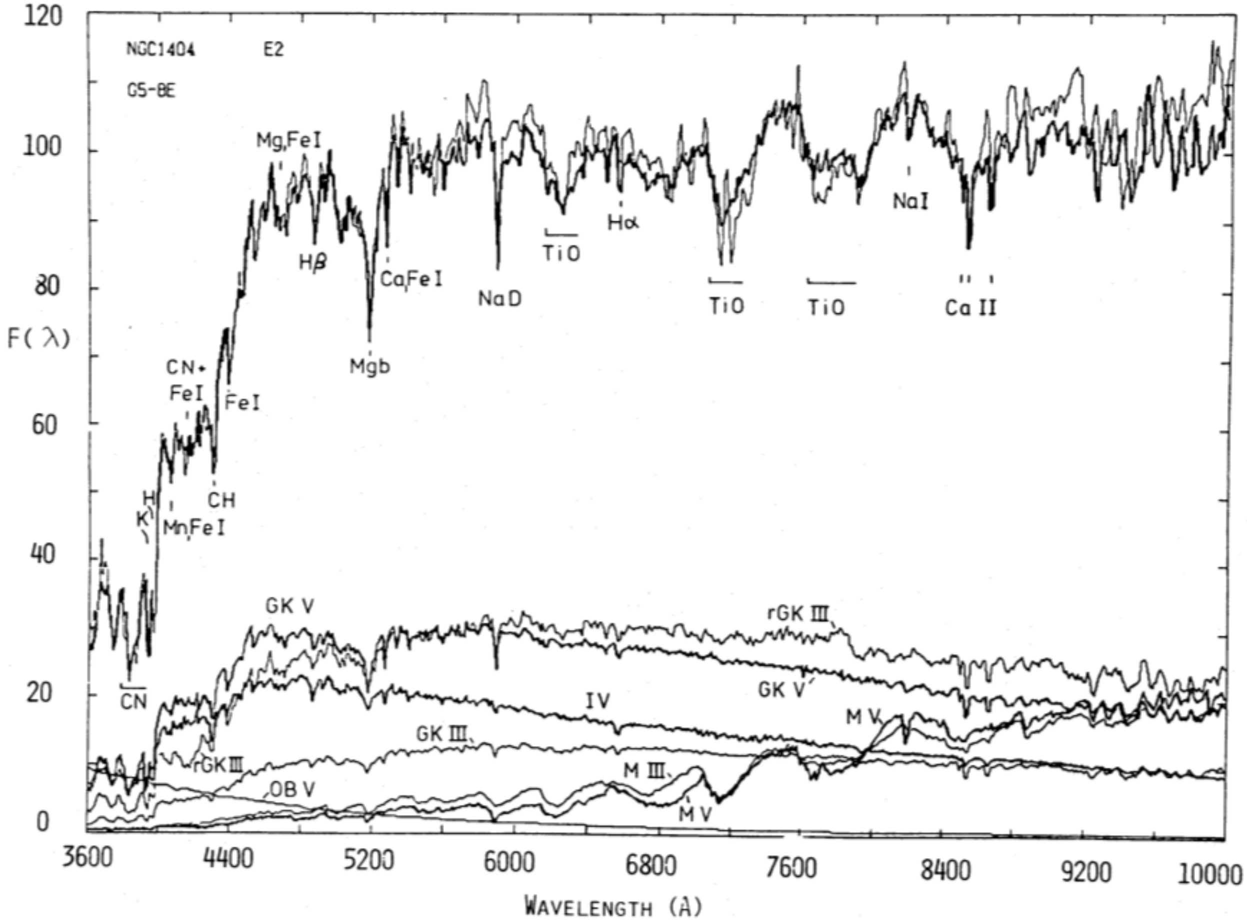
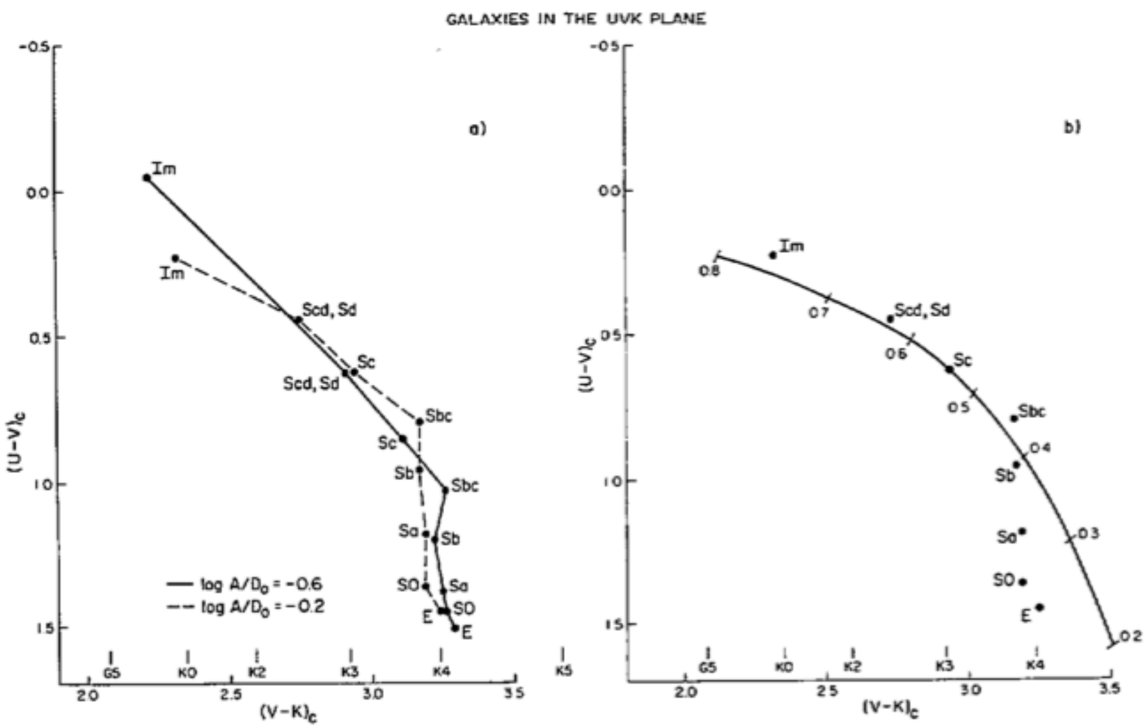


FIG. 2a

- Pickles 1985 (ApJ, 296, 340)

Stopped here

Simple population synthesis: the UVK plane

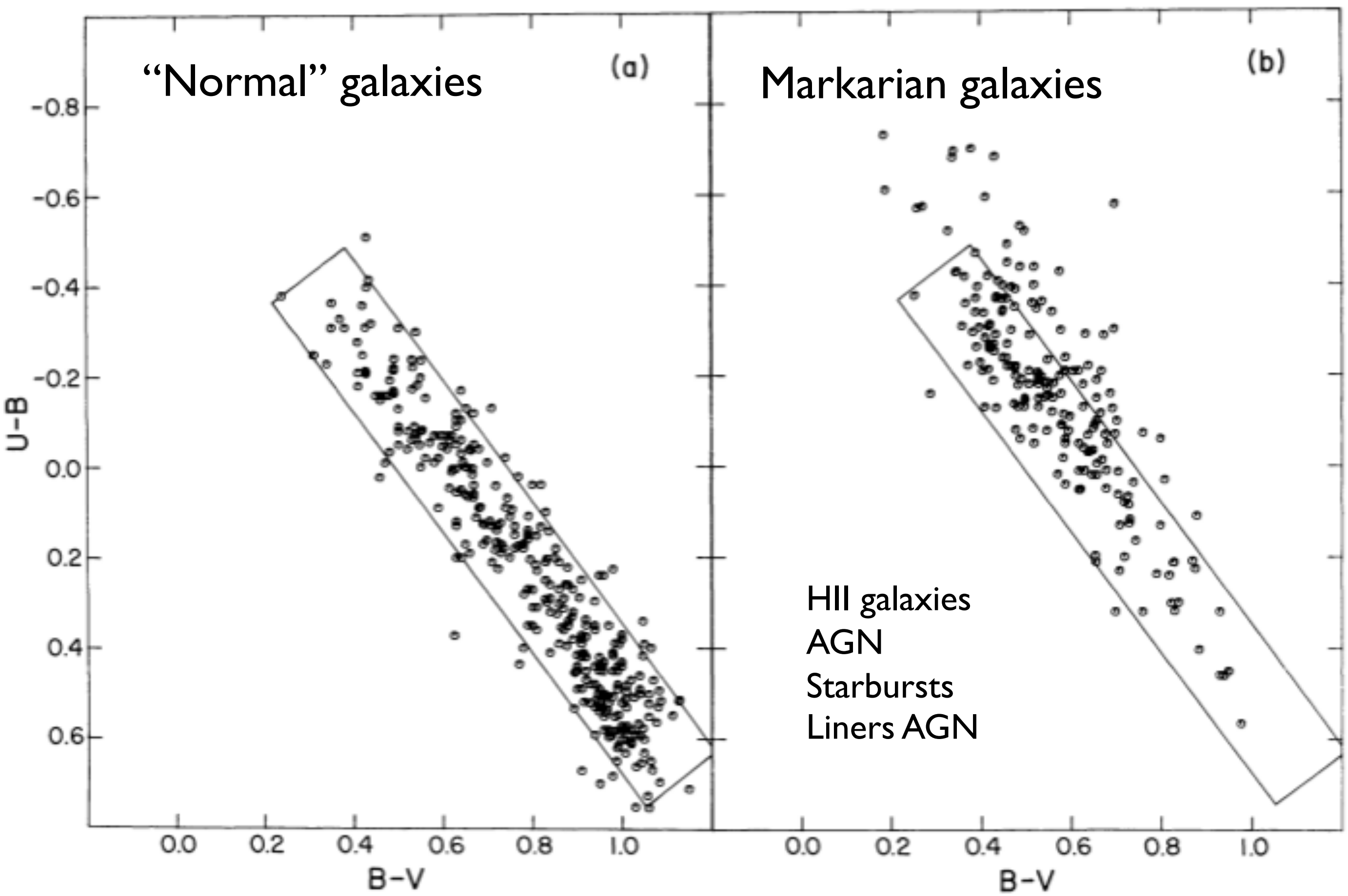


U: 370 nm
V: 550 nm
K: 2200 nm

Galaxies can be well-modeled by an admixture of A0V and M0III in U-V vs V-K

- Aaronson 1980 ApJ, 221, L103

Galaxies in the UBV plane



Markarian:
Russian astronomer

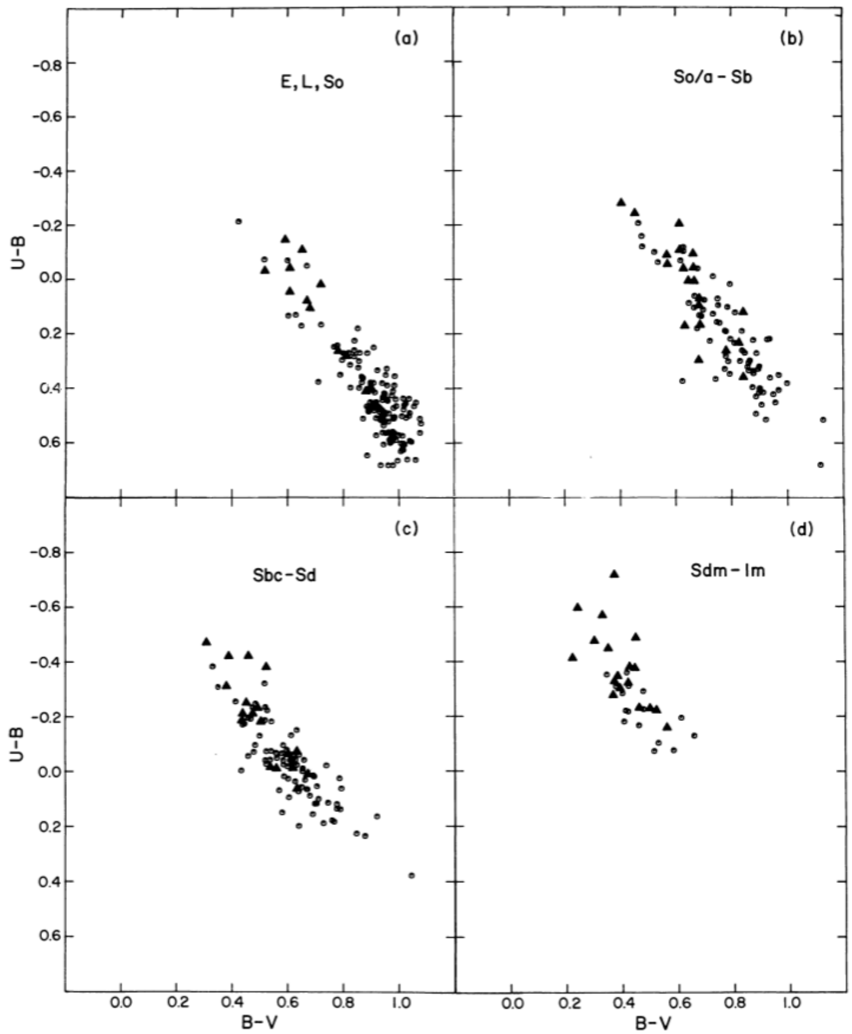
U: 370 nm
B: 440 nm
V: 550 nm

What's the color of an A0V?

What does this tell us about Aaronson's simplification of A0V+M0III for the UVK plane?

- Huchra 1977, ApJS, 35, 171

Galaxies in the UBV plane by Type



U: 370 nm
B: 440 nm
V: 550 nm

What's the color of an A0V?

What does this tell us about Aaronson's simplification of A0V+M0III for the UVK plane?

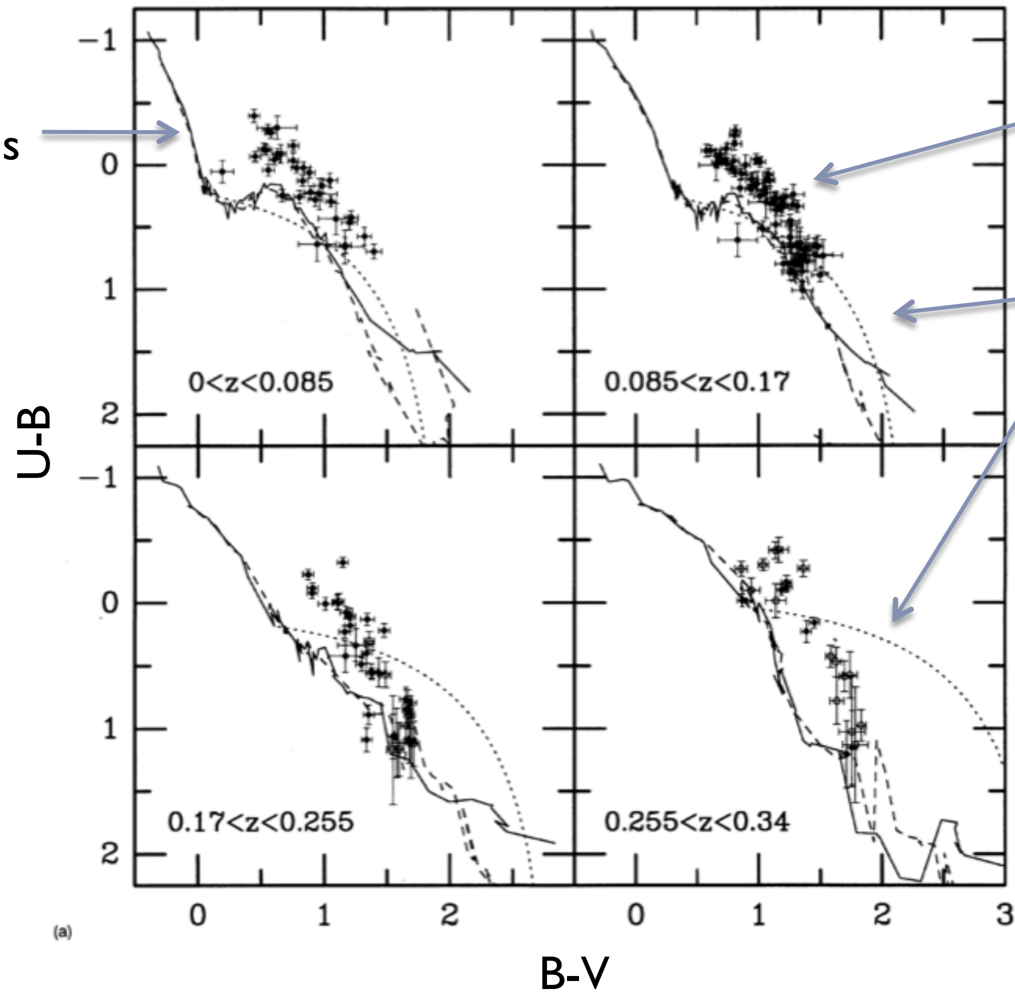
Why is it more complicated when you look in more detail in the blue? (U-V ➔ U-B,B-V)

What are the implications for spectra?

- Huchra 1977, ApJS, 35, 171

Galaxies: UBVRIK multi-colors

Stellar locus



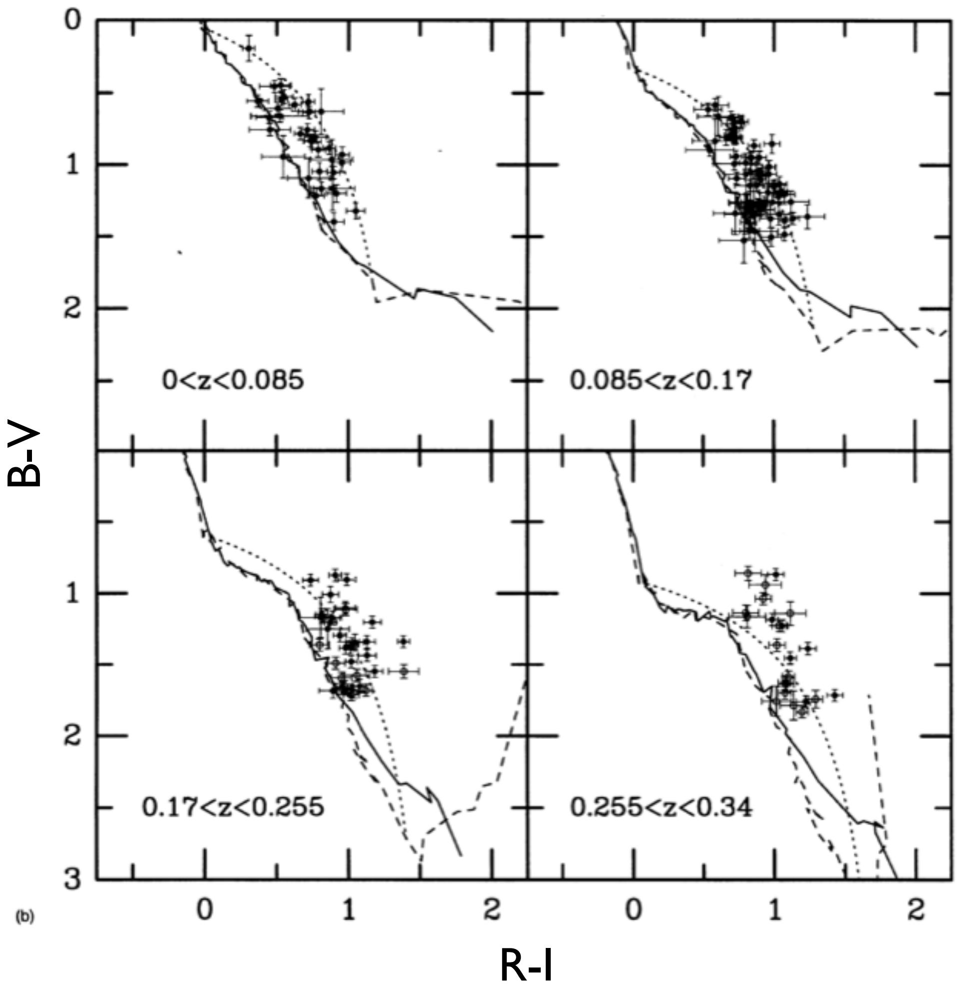
Individual galaxies

Aaronson's A0V+M0III model

The effect of redshift:
By z ~ 0.3 UBV samples 280, 330, 420 nm (near-UV)

- Bershady 1995, AJ, 109, 97

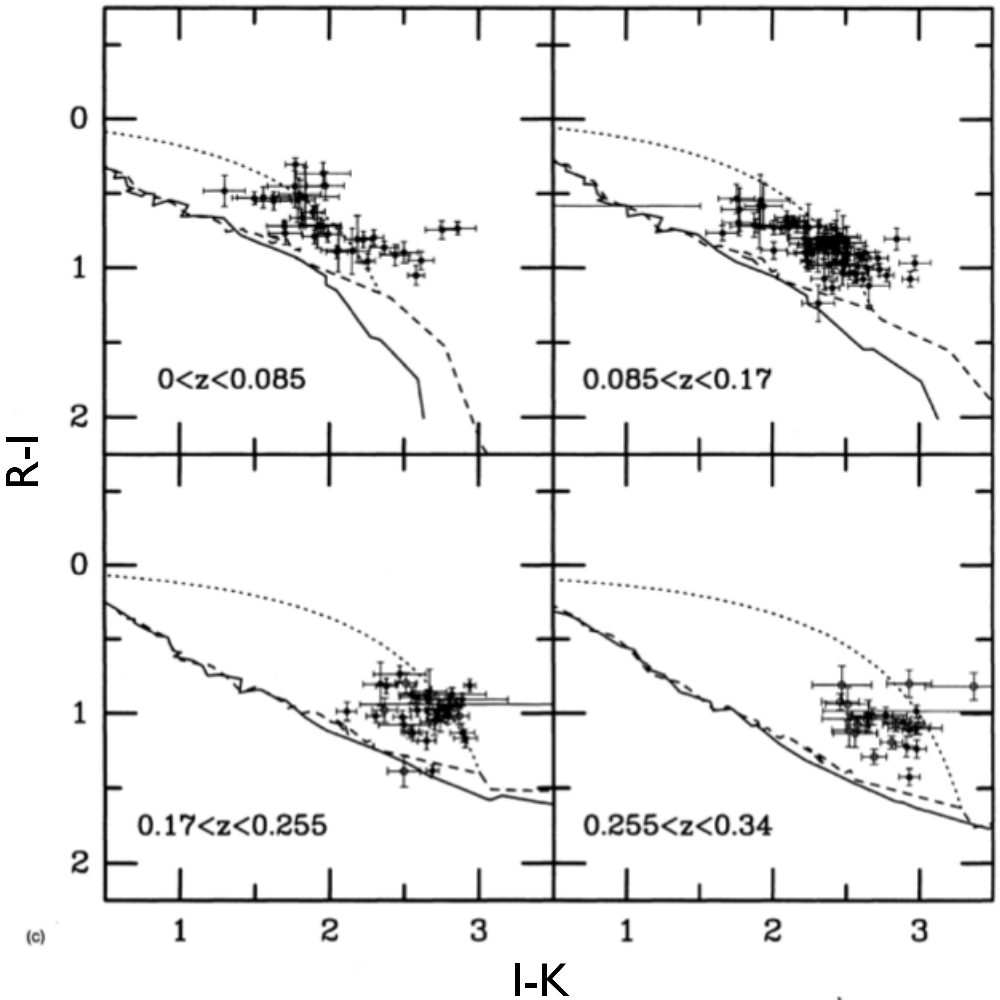
Galaxies: UBVRIK multi-colors



R: 650 nm
I: 800 nm

- B95

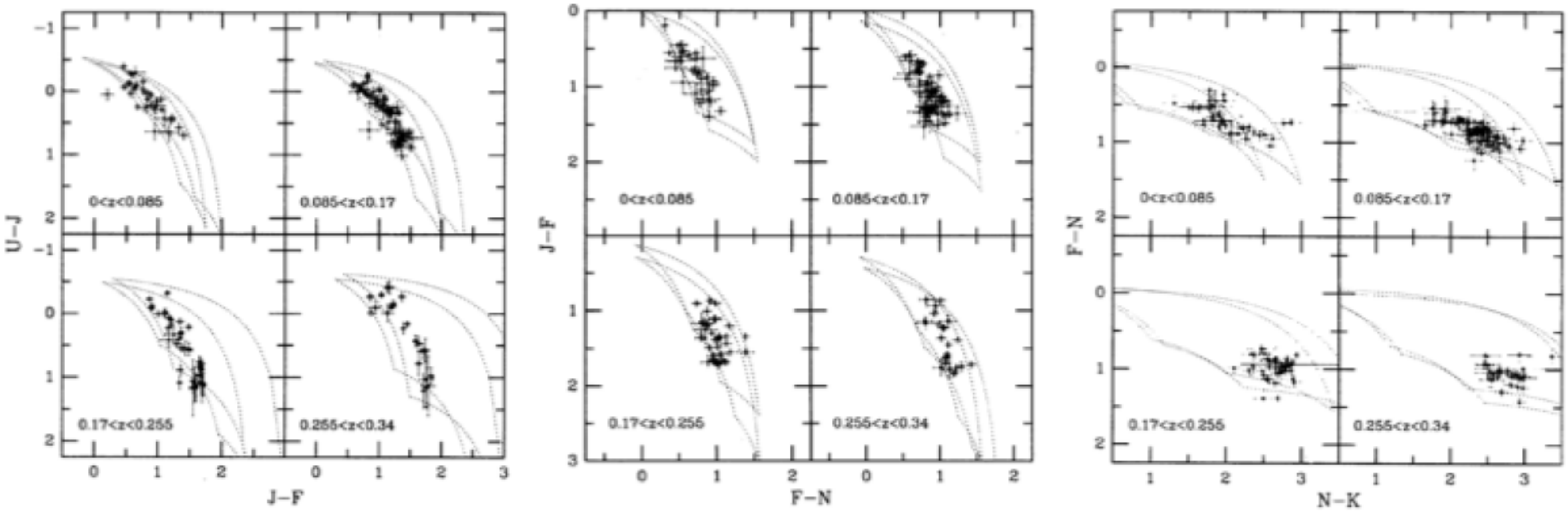
Galaxies: UBRIK multi-colors



- B95

Simple model: 4 stars in UBRIK

Linear combinations of B V, G V, K III, M III



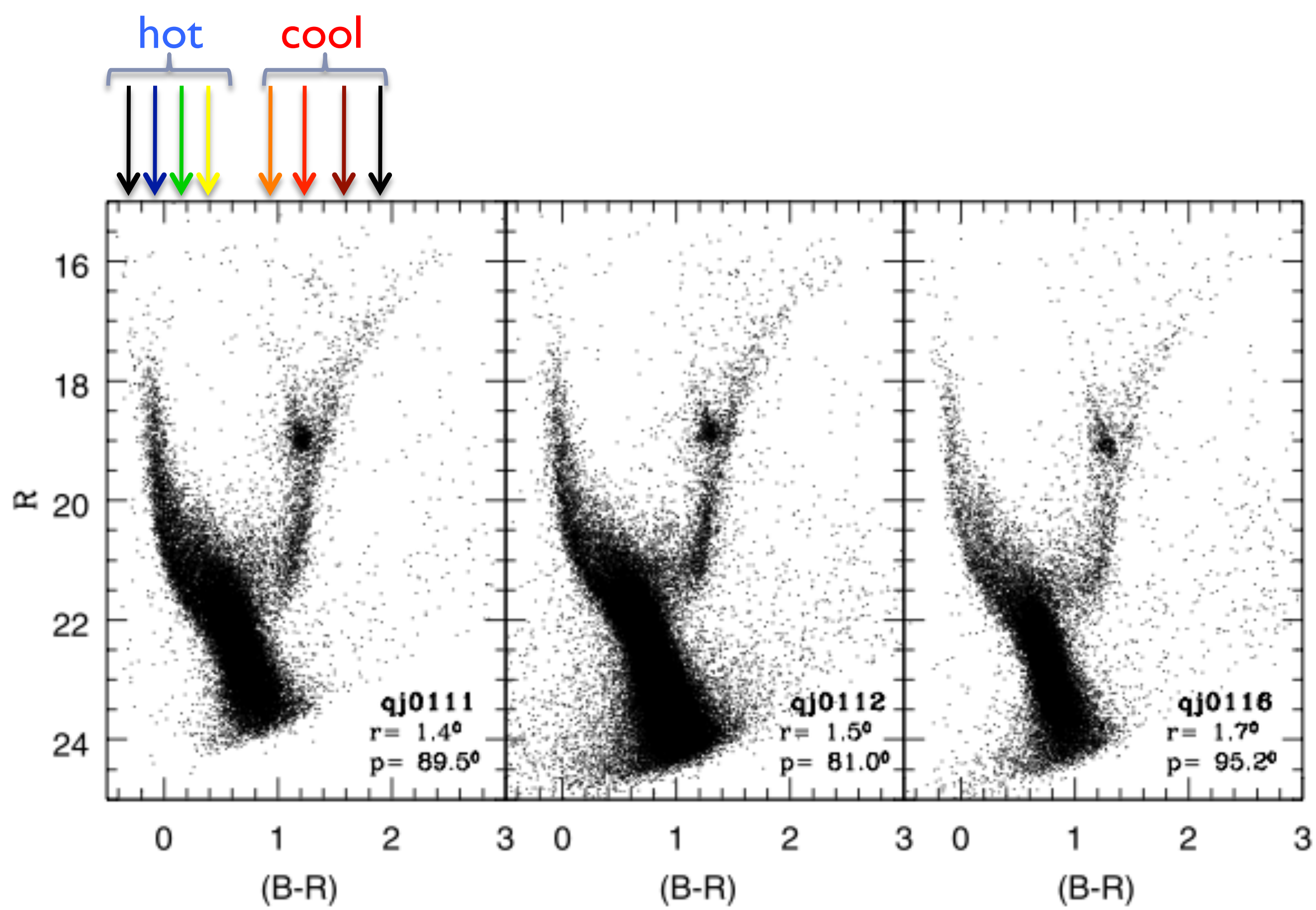
Alternatively, use linear combinations of 2 stars, but don't fix type:

○ One star is hot (ranging from B to G) – assume luminosity class V

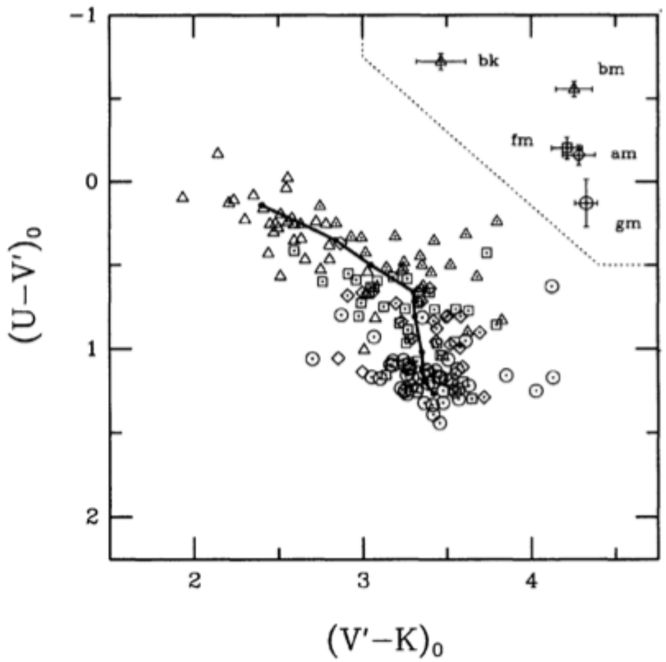
○ The second star is cool (ranging from G to M) – assume luminosity class III

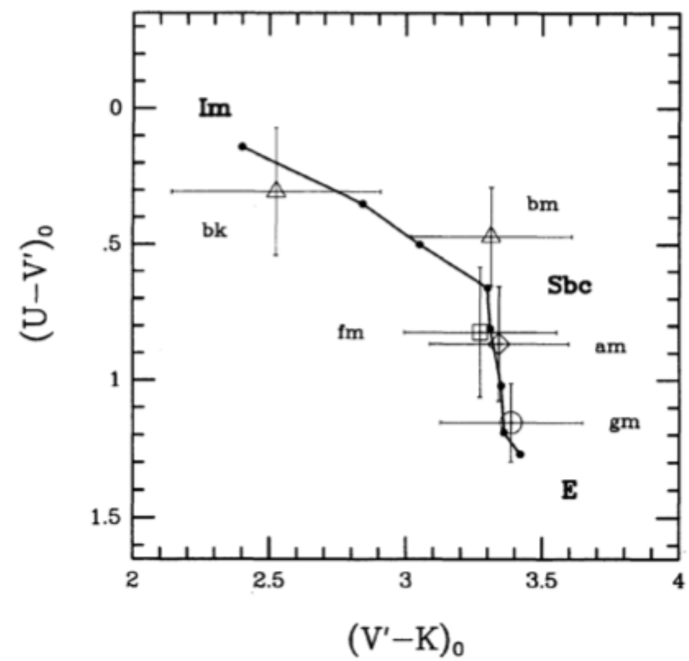
Thinking in terms of CMDs, why does this make sense?

CMD for the SMC at 60 kpc OMG



UVK plane revisited





- Galaxies classified by two-star models required to fit UBVRIK multicolors
- Reminiscent of Morgan spectral-types, extended to red and NIR