The Physics of Galaxies

Observations versus Theory

From the Early Universe to the Present

Part 1

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XX. Heidelberg Physics Graduate Days

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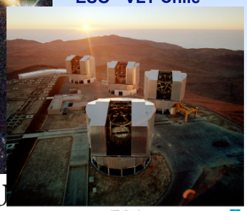
Large groundbased Telescopes & **Hubble Space Telescope** & **Satellites**

large mirrors & fields of view — high spatial resolution & γ-ray, X-ray, UV-wavelengths

➜ nearby galaxies in enormous detail
➜ distant galaxies in large numbers
➜ explosion in galaxy research

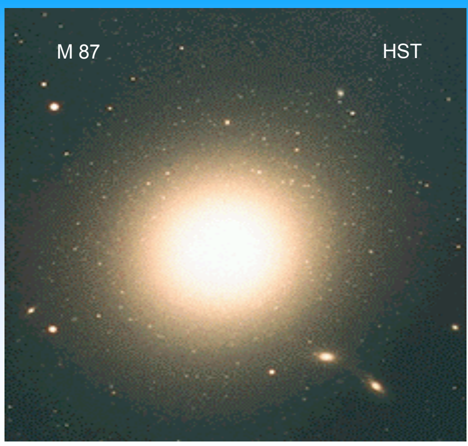
over the full spectral range γ-rays . . . radio

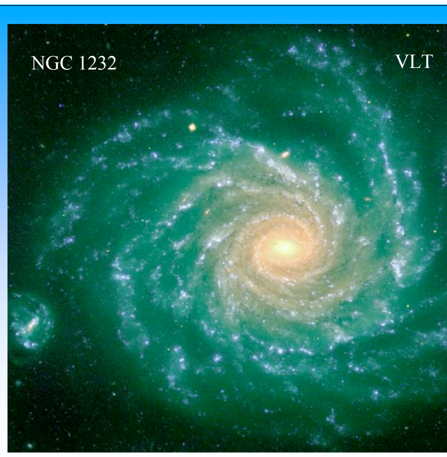
ESO - VLT Chile

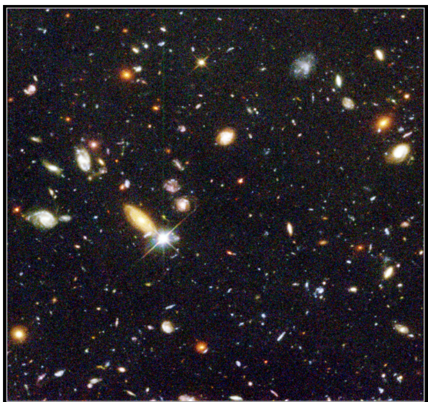


HST

GALEX



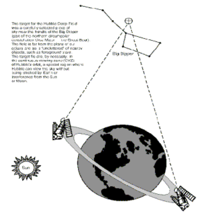




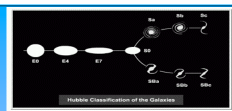
Hubble Deep Field
Hubble Space Telescope • WFPC2

PRC96-01a • ST ScI OPO • January 15, 1996 • R. Williams (ST ScI), NASA

Area 1/100 Full Moon
~ 3000 Galaxies
Faintest galaxies : 29 mag
↳ candle at D_{moon}
Multi – band imaging
UV – NIR
WFPC2 + NICMOS



(E. Hubble 1923ff)



Cosmic Microwave Background :
Universe at z=1000 extremely homogeneous & isotropic

? Splendid manifold of local galaxies ?

? Relation of distant galaxies to local ones ?

Observations = snapshots

Evolution of galaxies ↔ numerical models

Program

- Introduction & basics
- Local Galaxies : overview

- Modelling the formation & evolution of galaxies
- Chemical, spectral & dynamical evolution

- The Milky Way and the Local Group
- Resolved stellar populations vs integrated light

- Starbursts & interacting galaxies
- Galaxy transformation in clusters

- Towards the highest redshifts
- Galaxy formation scenarios
- Open question & future perspectives

Galaxies consist of Stars

& eventually of gas (in several coexisting phases)
& dust

The sun is "our" star. The Earth is one out of 8 planets orbiting the sun. Light from the sun travels 8 min. to reach the Earth, 4 h to reach Neptun.

The nearest star is Proxima Centauri, ~4.2 Lyr away.

$1 \text{ Lyr} = c \cdot \pi \cdot 10^7 \text{ km} = 300.000 \cdot \pi \cdot 10^7 \text{ km}$

[km/s] [s/yr] $= 9 \cdot 10^{12}$ km

The Sun

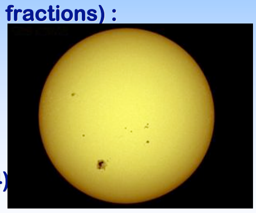
= "our" star, is a gaseous sphere, ~ 4 billion yr old, produces energy by nuclear fusion

$H + H + H + H \rightarrow {}^4He + 2e^+ + 2\gamma + 2\nu_e + 26.7$ MeV

has diameter 1.4×10^6 km, mass $1\ M_\odot \sim 2 \times 10^{30}$ kg, mean density 1408 kg/m^3

& chemical composition (mass fractions) :

H	74%
He	24%
C, O, Fe, \	
Ni, Si, S, Mg,	〉~2%
Ne, Ca, Cr /	



from Fraunhofer's lines (1814)

Astrophysical "semantics" : metals or metallicity Z := everything heavier than H and He $Z_\odot \sim 0.02$

The Sun

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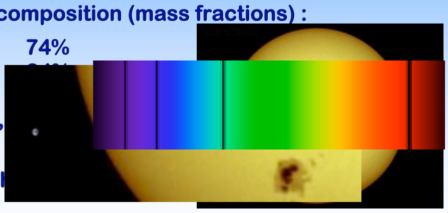
has diameter 1.4×10^6 km, mass $1\ M_\odot \sim 2 \times 10^{30}$ kg, mean density 1408 kg/m^3

& chemical composition (mass fractions) :

H 74%
He
C, O, Fe,
Ni, Si, S, Mg,
Ne, Ca, Cr



from Fraun

Astrophysical "semantics" : metals or metallicity Z := everything heavier than H and He $Z_\odot \sim 0.02$

Galaxies consist of ~ 10 … 1000 billion stars

& eventually of gas (in several coexisting phases)
& dust

Stars are born in cooling and collapsing gas/dust clouds, they live & evolve & die.

Stars are social, they are always born in groups or clusters.

Most clusters disperse before stars become visible after blowing away their natal dust cocoon
--> field stars

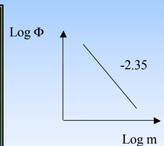
New stars first appear in the NIR, which can penetrate the dust.

Stars are born with widely different masses but with a universal mass distribution

→ Stellar Initial Mass Function (Salpeter 1955, Kroupa+ 93, …)

lower mass limit : $m_l \sim 0.04\ M_\odot$ hydrogen burning limit,
below $0.04\ M_\odot$: Jupiters & brown dwarfs

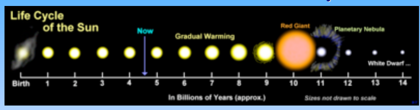
upper mass limit : $m_u \sim 140\ M_\odot$? $(1\ M_\odot \sim 2 \times 10^{30}$ kg)



Normalisation :

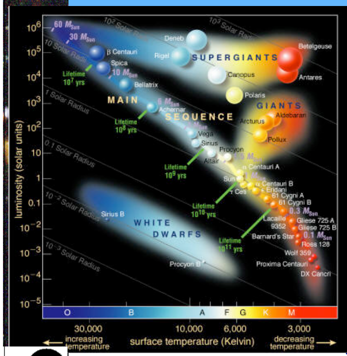
$\int_{ml}^{mu} m \cdot \Phi(m) dm = 1$

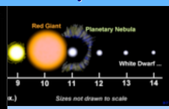
Stars evolve & die
-- depending on their initial mass
& chemical composition



The magic diagram of stellar evolution :
Hertzsprung - Russell (1910) diagram (HRD)
Stellar evolution & stellar nucleosynthesis
= input physics for galaxy evolution

Stars evolve & die
-- depending on their initial mass
& chemical composition





evolution :
diagram (HRD)
cleosynthesis
put physics for galaxy evolution

Stars evolve & die
-- depending on their initial mass
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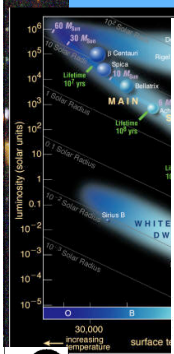
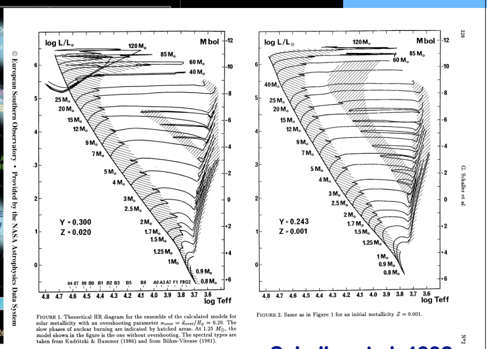
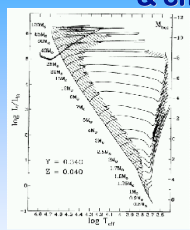
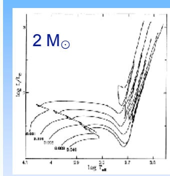




Schaller et al. 1992

Stars evolve & die
-- depending on their initial mass
& chemical composition





Crude rule of thumb:
metal-poor stellar populations are bluer (in the optical) & brighter than metal-rich ones.

Stellar lifetimes (total & in various phases/positions in the HRD) depend on chemical composition. E.g.

solar abundance $Z=0.020$ $\tau(1\ M_\odot) \sim 10\times10^9$ yr, $\tau(100\ M_\odot) \sim 2\times10^6$ yr

low metallicity $Z=0.004$ $\tau(1\ M_\odot) \sim 7\times10^9$ yr, $\tau(100\ M_\odot) \sim 3\times10^6$ yr

Stars evolve & die
-- depending on their initial mass
& chemical composition

Stars end their life -- depending on their initial mass:
$M_\star < 8\ M_\odot$: in the ejection of a planetary nebula (PN)
➜ Remnant : white dwarf = naked degenerate CO core, initially very hot but faint, cools and fades:
➜ white dwarf cooling sequence
Limiting upper mass of a white dwarf : $1.4\ M_\odot$
(e- degeneracy pressure vs. grav. collapse: Chandrasekhar 1931)

Stars evolve & die
-- depending on their initial mass
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Stars end their life -
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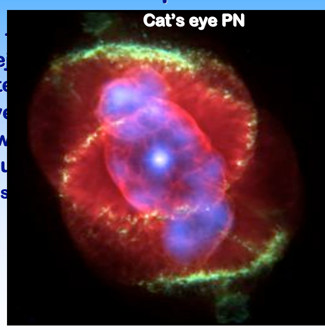
➜ Remnant : white ... ore,
initially v
➜ w
Limiting u ... $M_\odot$
(e- degeneracy press ... 931)



Stars evolve & die
-- depending on their initial mass
& chemical composition

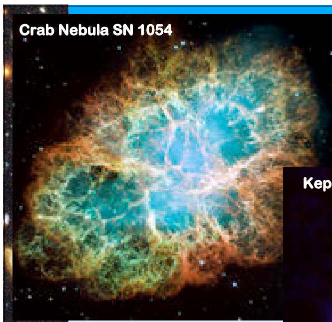
Stars end their life -- depending on their initial mass:

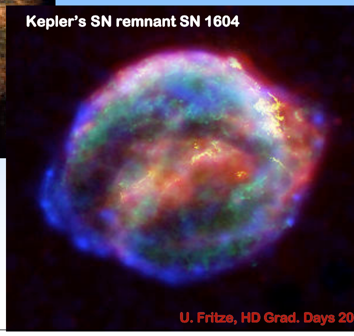
$M_{☆} \geq 8\ M_{\odot}$: in a supernova explosion (SN)

10^{53} erg ~ 10^{44} J ?

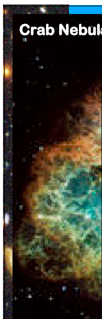
➜ Remnant : neutron star of (stellar) black hole

volve & die
n their initial mass
al composition
nding on their initial mass:



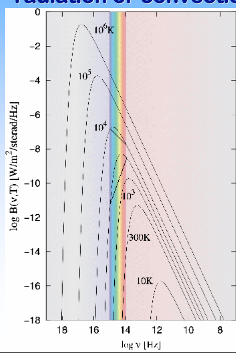


volve & die



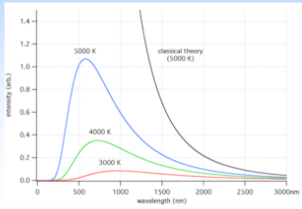
Stars are gaseous spheres

they produce energy through nuclear fusion, transport it to their surface (photosphere) by radiation or convection & radiate like black bodies

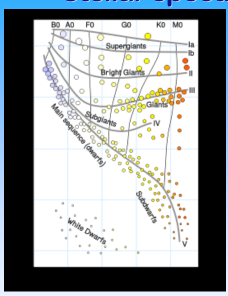


➜ Boltzmann's & Wien's laws

+ > 50 million absorption lines



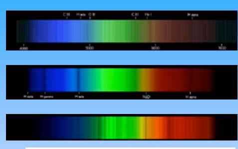
Stellar spectra and spectral types

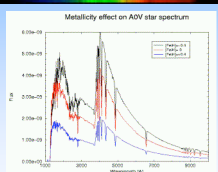


O

A

K





Stellar spectra depend on

☛ stellar mass & evolutionary stage (i.e. on temperature & luminosity)

spectral classes : O B A F G K M,
luminosity classes : V (main sequence), III (giants), I (supergiants)

☛ on chemical composition: absorption lines

Stellar nucleosynthesis

Big bang formed H, He, traces of Li.

All other elements have beed produced by nuclear fusion in the cores of stars.

Stars lose mass (=gas) in

☆ stellar winds in late evolutionary phases
heavily dependent on stellar mass and metallicity $\dot{M}_{wind} \sim Z^4$

☆ PNe
winds & PNe : H, He, C, N, O

☆ SNe
SNe type II : O, Ne, Mg, Si, S, Ar, Ca, Ti
(= α - elements)

in/after explosion: rapid & slow neutron capture
r- & s-process elements (Ti, Cr, Fe, Ni; Sr, Ba, Pb)

SN type Ia : Ni ➝ Fe

New stars are then formed out of more enriched gas …
➜ cosmic cycle.

Brief History of Galaxy Rese

☛ 1923 Edwin Hubble, Mt. Wilson Obs. :
Cepheids in M31 = Andromeda nebu
➜ M31 = external galaxy

Henrietta Swan Leavitt 1912: period luminosi
for Cepheid variables.

Cepheid with P=3 d has 800 × luminosity of the sun.
Cepheid with P=30 d has 10.000 × luminosity of the su

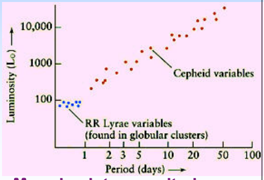
Absolute luminosities of Milky Way Cepheids from parallax distances

$M_V - M_{V\odot} = -2.5 \log L_V/L_{V\odot}$ [mag]

$L_{V\odot} = 3.8 \times 10^{33}$ erg/s, $M_{V\odot} = 4.83$ mag

$$M_v = -2.81 log(P) - (1.43 \pm 0.1)$$

$$5 \log_{10} \frac{D}{\text{kpc}} = m - M - 5,$$



M_V : absolute magnitude
m_V : apparent magnitude

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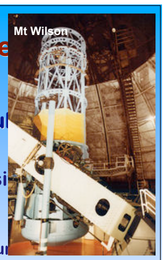


inosity of the sun.
× luminosity of the su

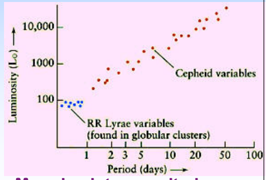
ky Way

mag]

mag

± 0.1)

kpc



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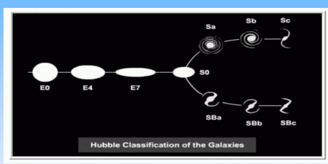
Brief History of Galaxy Research

☛ 1923 - 1925: Hubble sequence of galaxies



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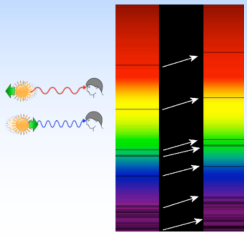
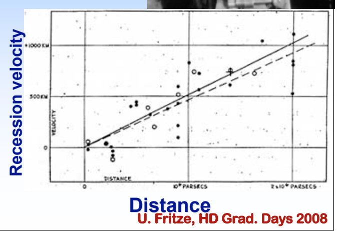
Brief History of Galaxy Research

☛ 1929 E. Hubble, Mt. Palomar 5m :
galaxy redshifts





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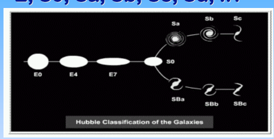
Local Galaxies

Normal (= big) galaxies : Hubble sequence
E, S0, Sa, Sb, Sc, Sd, Irr



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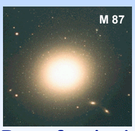

Dwarf galaxies : dE, dSph, dI
Low surface brightness galaxies : E, disk, dwarf
Starburst galaxies, interacting galaxies, radio gals,
AGN, ULIRGs, SCUBA gals, Lyman Break Gals, . . .

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Observations at different wavelengths → complementary information

X-rays : hot gas, binary stars

UV : young, hot, high-mass stars
→ star formation (=SF)

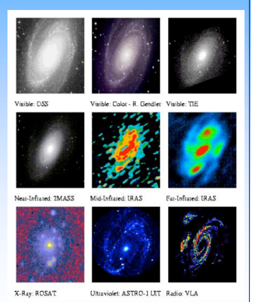
opt. : solar-type, intermed. mass stars

NIR : old, cool, low mass stars
→ galaxy mass

mid- & FIR : dust - therm. emission

sub-mm : cold, molecular gas
→ 1. order reservoir for SF

Radio : neutral hydrogen gas
→ 2. order reservoir for SF



Spiral galaxy M81

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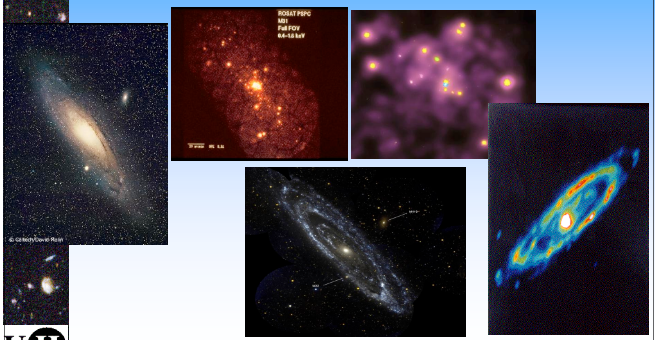
Observations at different wavelengths → complementary information

M31 Caltech – ROSAT – Chandra – GALEX – IRAS



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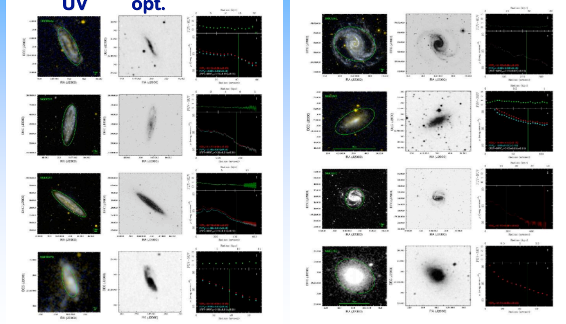
Observations at different wavelengths → complementary information

GALEX – SDSS (Gil de Paz+06)

UV opt.



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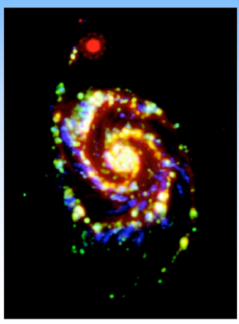
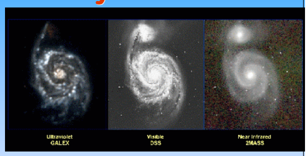
Observations at different wavelengths → complementary information

GALEX M51 (Johnson+06)





GALEX – optical – Spitzer

UV mid-IR

FUV : blue 6" resol.

Hα : green degraded to 6"

24 μm dust : red 6" resol.

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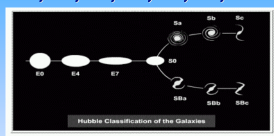

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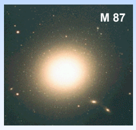

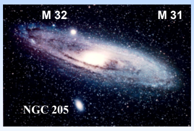

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Starburst galaxies, interacting galaxies, radio gals,
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Local Galaxies

Normal (= big) galaxies : Ellipticals

~ spheroidal e:= 1-b/a, 0 ≤ e ≤ 0.7

stellar densities : not measurable
→ surface brightness

de Vaucouleurs r$^{1/4}$-surface brightness profile

R_e := effective radius
= half light radius
I_e := intensity within R_e

$$I(R^\star) = I_e \exp\left(-7.67 \cdot \left[\left(\frac{R^\star}{R_e}\right)^{\frac{1}{4}} - 1\right]\right)$$

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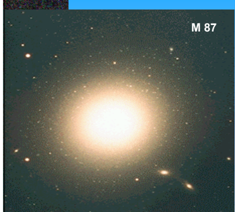
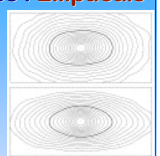
Local Galaxies

Normal (= big) galaxies : Ellipticals



disky – boxy Es
low-L – high-L



old, low-mass stars

K-star type spectrum, red colours

no HI, no molecular gas, no SF

wide range in luminosities : $-25 \le M_B[\text{mag}] \le -12$
cD . . . . dE

$M_V - M_{V\odot} = -2.5 \log F_V/F_{V\odot}$ [mag]

$10 \le M/L \le 100$ (in solar units $[M_\odot/L_\odot]$)

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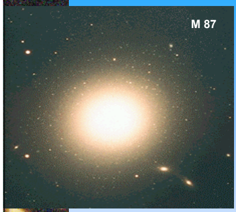
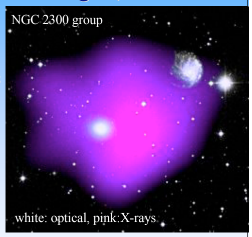
Local Galaxies



Normal (= big) galaxies : Ellipticals

no HI, no molecular gas, no SF

But :
extended
> 400 kpc
X-ray halos
gas $10^{6 \dots 7}$ K
~ 5% M_{tot}

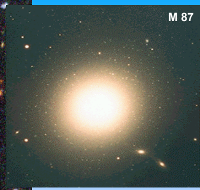


if X-ray gas is bound ➜ mass estimate : Dark Matter !

wide range in mass : $10^9 \dots 10^{14}\ M_\odot$

$10 \leq M/L \leq 100$ (in solar units $[M_\odot/L_\odot]$)

Local Galaxies



Normal (= big) galaxies : Ellipticals

no/slow rotation (big/dwarf Es)

dynamically hot : high stellar velocity dispersion $\sigma \gg v_{rot}$

velocity dispersion σ := rel. veloc. of stars against each other

extended systems of Globular Clusters < 200 kpc, (0 - few in dEs, 100 - 1000 in Es, 10.000 in cDs)

gradients in colour & metallicity

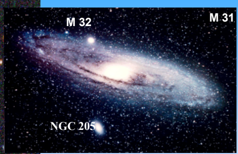
1. boxiness, counter-rotating cores, ripples & shells in ~ 50% Es,
2. circumnuclear molecular gas & SF in some Es,
➜ past/recent interaction

➜ Initial Collapse vs. hierarchical accretion scenarios for formation of elliptical galaxies

Local Galaxies

Normal (= big) galaxies : Spirals Sa, Sb, Sc, Sd

B/D light ratio ↘ for Sa . . . Sd



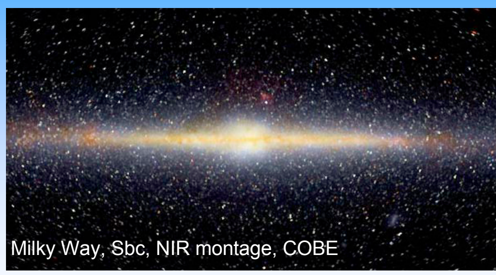
narrow range in luminosities
$-21 \leq M_B[\text{mag}] \leq -16$

bulge + disk + halo
B D H

Bulge : spheroidal E0 - E4, old (+young ?) stars
Disk : stars, gas, dust, SF, young star clusters
Halo : old metal-poor stars & old Globular Clusters

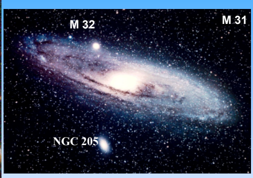
Local Galaxies

The Milky Way : Sbc

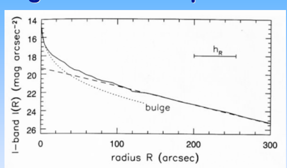


Local Galaxies

Normal (= big) galaxies : Spirals Sa, Sb, Sc, Sd



bulge - disk decomposition



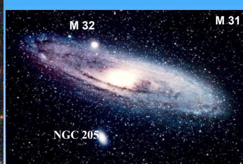
Stellar disks : exponential luminosity profile
$\mu(r) = \mu_o \exp(-r/r_o)$ (Freeman 70)

μ_o : central surf. brightness ~ 145 $L_\odot$ /pc^2 narrow range !
r_o : scale length ~ 2 . . . 5 kpc

Stellar disks end @ Holmberg radius R_H : $R_H \sim 5\ r_o$
$\mu(R_H)$= 26.5 mag arc sec^{-2} ~(1 - 2)% night sky

Local Galaxies

Normal (= big) galaxies : Spirals Sa, Sb, Sc, Sd



disks dynamically cold : $\sigma \ll v_{rot}$

subject to instabilities
➜ bar formation

HI : neutral hydrogen gas
HII : ionized hydrogen gas

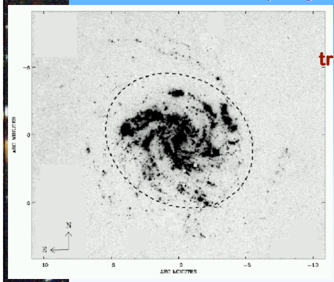
HI disks 3 × more extended than stellar disks
molecular gas (thin disk) CO
dust disks 1.5 × more extended than stellar disks

SF ongoing in disk/spiral arms
SF more extended than stellar disk
(Hα: Ferguson+98,van Zee+98, GALEX-UV: Thilker+07)

➜ Stellar disks grow from inside out

Local Galaxies

Ferguson+98 : Hα emission from HII regions (➜ star formation) beyond the optical radius in spirals



Hot gas : HII : emission lines

trace physical & chemical conditions

N_e, T_e abundances

H : Lyman, Balmer, Paschen, ...
UV opt. NIR series
Hα, Hβ, Hγ,Hδ,...

lines from all elements & ionisation stages

also forbidden* lines, e.g. [OII]

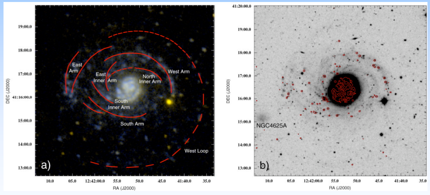
F(Hα) [erg/s] ~ SFR_o [$M_\odot$/yr]

* collisionnally de-excited under terrestrial conditions, but not in Hyper-UHV in space

Local Galaxies

Thilker+07, Gil de Paz+05 : Galex UV emission from hot young stars beyond the optical radius in spirals

E.g. NGC 4625
Galex: FUV deep B-band



Observations at different wavelengths → the GALEX Surprise

GALEX – SDSS (Gil de Paz+06)

Some galaxies appear much more extended in the UV than in the optical, HI, and Hα

Star formation extends far beyond the optical disk !

(= far beyond where the stars are)

➜ inside out formation of disks but :

Reservoir ???

HII regions ??? (but see Ferguson+04)

IMF ??? (cf. Kotulla & Fritze, in prep.)

Observations at different wavelengths → the GALEX Surprise

GALEX – SDSS (Gil de Paz+06)

Some galaxi... V
than...

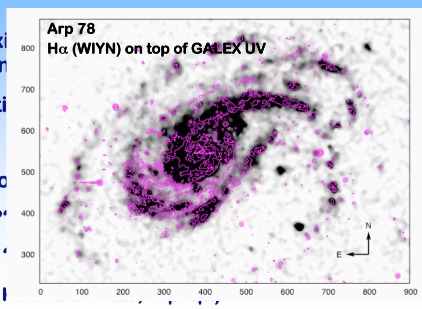
Star formati...

➜ inside o...

Reservoir ?...

HII regions ...

IMF ??? (cf. ...



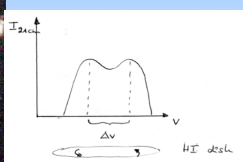
Local Galaxies

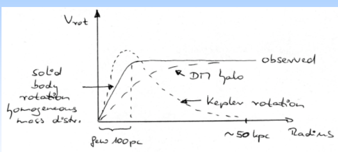
Normal (= big) galaxies : Spirals Sa, Sb, Sc, Sd

differential rotation

120 km/s ≤ v_{rot} ≤ 240 km/s

rotational velocity ➜ total (= dynamical) mass





rotation curves ➜ Dark Matter halos

Local Galaxies

Normal (= big) galaxies : Spirals Sa, Sb, Sc, Sd

disks : gradients in
- color
- extinction
- metallicity
- stellar age

difficult to disentangle

Spiral Galaxies

Spirals Sa, Sb, Sc, Sd:

Masses within 1 R_H : $9 \cdot 10^{11} \ldots 3 \cdot 10^{10}\, M_\odot$

Sa		Sb		Sc		Sd
SFRo(Sa)	<	SFRo(Sb)	<	SFRo(Sc)	<	SFRo(Sd)
G/(S+G)(Sa)	<	G/(S+G)(Sb)	<	G/(S+G)(Sc)	<	G/(S+G)(Sd)
~0.05		~0.15		~0.3		>0.5
Z(Sa)	>	Z(Sb)	>	Z(Sc)	>	Z(Sd)
(B-V)(Sa)	>	(B-V)(Sb)	>	(B-V)(Sc)	>	(B-V)(Sd)
M/L(Sa)	>	M/L(Sb)	>	M/L(Sc)	>	M/L(Sd)
~6.2		~4.4		~2.6		(Rubin+82)

MW : M_B= -19.4 mag, M31: M_B= -20.5 mag,
LMC: M_B= -18.1 mag, SMC: M_B= -16.6 mag

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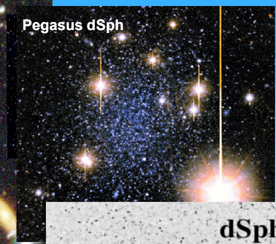
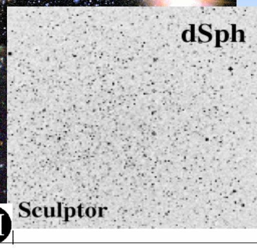
Galaxies beyond the Hubble Sequence





Dwarf galaxies : dE, dSph, dI

M32, NGC 205 - LMC, SMC

dE : mini-E $10^7 \ldots 10^9\, M_\odot$
red, old, metal-poor

dSph : mini-S0
red, ?old?, ?metal-poor?

dI : irregular : HI, CO, SF
blue, young stars
low metallicity

dwarf galaxies : by far the dominant population of galaxies (by number) -- in particular in clusters

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Galaxies beyond the Hubble Sequence

Low surface brightness galaxies : Es, disks, dwarfs

parallel sequence to Hubble sequence

LSB Es, dEs : old stellar pops, no gas (diff. to detect)
Sagittarius, Canis Major

LSB disks and irregulars : very gas-rich, low SFR,
Malin-1 young stellar pops, low metallicity
? old stellar component ?
? formation epoch ?
? late formation or slow evolution ?
? why ?

in isolation or low gal. dens. environm. !

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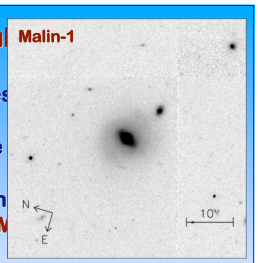
Galaxies beyond the Hu



Low surface brightness galaxies

parallel sequence to Hubble

LSB Es, dEs : old stellar pops, n
Sagittarius, Canis M

LSB disks and irregulars : very gas-rich, low SFR,
Malin-1 young stellar pops, low metallicity
? old stellar component ?
? formation epoch ?
? late formation or slow evolution ?
? why ?

in isolation or low gal. dens. environm. !

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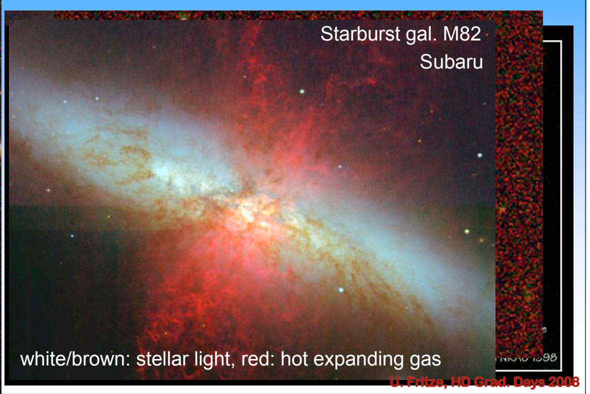
Galaxies beyond the Hubble Sequence

Starbursts, Seyfert galaxies, radio galaxies, quasars



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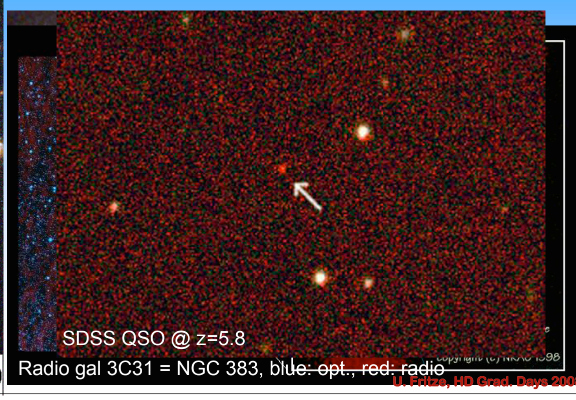
Galaxies beyond the Hubble Sequence

Starbursts, Seyfert galaxies, radio galaxies, quasars



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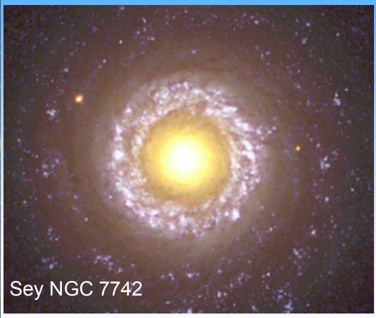
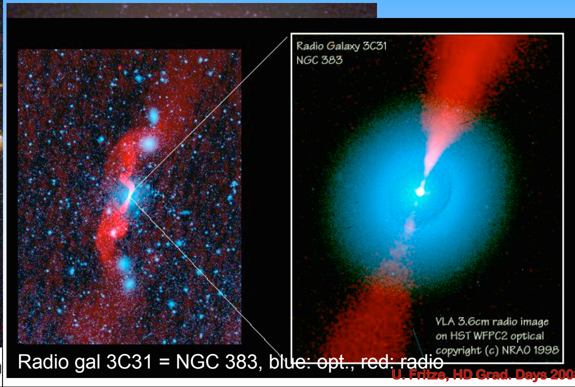
Galaxies beyond the Hubble Sequence

Starbursts, Seyfert galaxies, radio galaxies, quasars



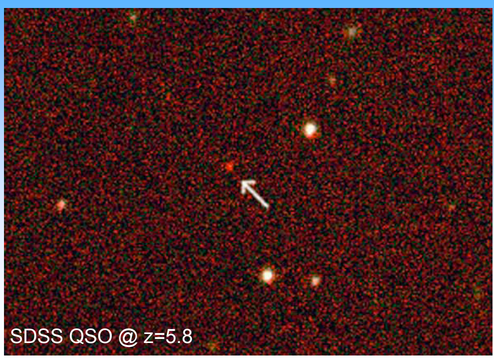
Galaxies beyond the Hubble Sequence

Starbursts, Seyfert galaxies, radio galaxies, quasars



Galaxies beyond the Hubble Sequence

Starbursts, Seyfert galaxies, radio galaxies, quasars



Galaxies beyond the Hubble Sequence

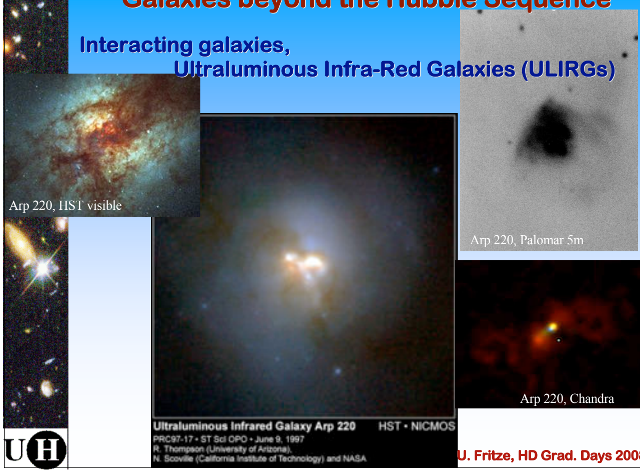
Interacting galaxies, Ultraluminous Infra-Red Galaxies (ULIRGs)

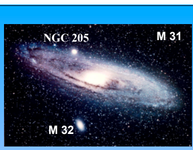
Galaxies beyond the Hubble Sequence

Interacting galaxies, Ultraluminous Infra-Red Galaxies (ULIRGs)

Galaxies beyond the Hubble Sequence

Interacting galaxies, Ultraluminous Infra-Red Galaxies (ULIRGs)





Splendid manifold of local galaxies :

? How & when did they form & how did they evolve ?

? nature vs. nurture ?

2 approaches :

☛ study distant galaxies : identify progenitors

high redshift

☛ study nearby galaxies in detail : traces of their history

astro-archeology

Observations = snapshots

Evolution of galaxies ↔ numerical models

3 Aspects of Galaxy Evolution

Spectral — Bruzual '83ff

Observational relations

Chemical — Tinsley '68ff

Dynamical — Toomre '72ff

Originally modelled one by one independently.
Now attempting to couple consistently : **GALEV models***

S : formation & evolution of stars +/- gas +/- dust
C : formation & nucleosynthesis of stars; infall/outflow of gas
D : internal & external gravitation, stars + gas + DM

*2003 Hertha-Sponer Research award DPG

Local Galaxies

Fundamental relations for Ellipticals & dEs :

Color – magnitude relation : brighter Es are redder
Luminosity – metallicity relation : brighter Es are more metal-rich
Faber – Jackson relation : central velocity dispersion increases with luminosity
➜ distance determination
Kormendy's relations :
brighter Es have large effective radii
brighter Es have lower (average) surface brightness

Sphs (and GCs) do not follow Kormendy's relations

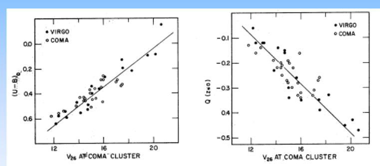
Fundamental Plane relations : effective radius – surface brightness – luminosity – central velocity dispersion
➜ M/L increases with L

Local Galaxies

Fundamental relations for Ellipticals & dEs :

Color – magnitude relation : brighter Es are redder

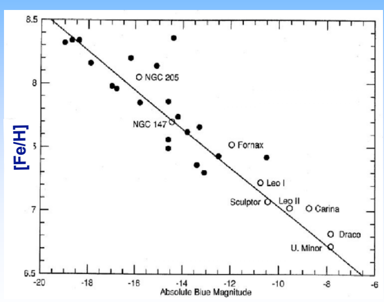
(de Vaucouleurs 61, 72, fffff)



Local Galaxies

Fundamental relations for Ellipticals & dEs :

Luminosity – metallicity relation : brighter Es are more metal-rich*



Vader 86,
Bica & Alloin 87,
Skillman 89

Local Galaxies

* how to measure stellar abundances/metallicities in ellipticals/S0s/star clusters:

from absorption lines !

The stronger the absorption line of a given atom or molecule in a stellar spectrum, the more of it must be in the stellar photosphere (c.f. ionization corrections, etc.).

In integrated spectra of galaxies it's more complicated: luminosity weighted mean stellar abundances/metallicities

~ 20 Lick indices, measured in extenso in stellar spectra with dependencies on [Fe/H]*, Teff and surface gravity studied in detail (e.g. Mg2, Mgb, NaD, Fe52, …, TiO, …)

Local Galaxies

* how to measure stellar abundances/metallicities in
from absorption lines !

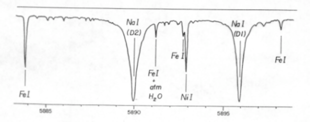


Fig. 3.2. Portion of the solar spectrum in the neighbourhood of the sodium D-lines. Adapted from L. Delbouille, G. Roland & L. Neven, *Spectrophotometric Atlas of the Solar Spectrum*, Liège, 1973.

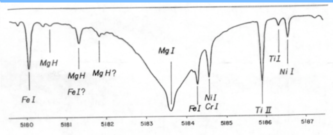


Fig. 3.9. A very strong absorption line of Mg I in the solar spectrum, dominated by damping wings. Adapted from the Liège Atlas (Delbouille *et al.* 1973).

* what the hell is [Fe/H] ?

[Fe/H] : Log stellar metallicity or (luminosity weighted mean) metallicity of a stellar population

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Gaseous & stellar metallicities

☛ Metallicity: chemical composition

metallicity Z := mass fraction of everything > ^{4}He
solar (photospheric) metallicity $Z_\odot = 0.02$
metallicity dominated by O, …, C, …, N, ……, Fe, …

Metallicity of the stellar population : [Fe/H]
luminosity-weighted stellar metallicity from stellar absorption lines in the integrated spectrum

$[Fe/H] := \log (X_{Fe}/X_H) - \log (X_{Fe}/X_H)_\odot$

X_i := mass fraction of element i

[Fe/H] = 0 : solar
[Fe/H] = -1 : 1/10 solar
[Fe/H] = -2 : 1/100 solar

[Fe/H] = +0.4 : 2.5 solar

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Stellar & Gaseous Metallicities

Metallicity of the Inter Stellar Medium (= ISM): Z

measured from HII region emission lines (!), expressed in terms of

12 + log (O/H)

$O/H := N_O/N_H$ number(!) densities

Transformation into [O/H] requires mass number

12 + log (O/H) = 8.9 for solar abundance $Z_\odot$
12 + log (C/H) = 8.6 for $Z_\odot$
12 + log (Mg/H) = 7.6 for $Z_\odot$
. . . . .
12 + log (O/H) = 7.9 for 1/10 $Z_\odot$

Solar photospheric abundances
→ B. Pagel : Nucleosynthesis & Chem. Evol. of Galaxies

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Local Galaxies

Fundamental relations for Ellipticals & dEs :

Faber – Jackson relation : central velocity dispersion* increases with luminosity
(Faber & Jackson 76)

➜ distance / mass determination

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Local Galaxies

How to measure velocity dispersion*

E.g. elliptical galaxy : integrated spectrum of all its 2 - 2000 billion stars
~ 2 - 2000 billion × K-star spectrum

K-star spectrum : absorption lines with intrinsic width

Elliptical galaxy spectrum : absorption lines are broadened by stellar velocity dispersion
(= random motions of stars)

Comparison of galaxy spectrum with star spectrum
➜ stellar velocity dispersion

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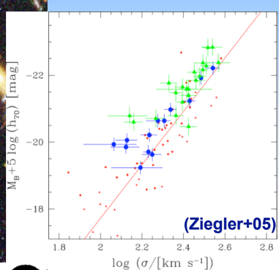
Local Galaxies

Fundamental relations for Ellipticals & dEs :

Faber – Jackson relation : central velocity dispersion increases with luminosity

(Faber & Jackson 76)

➜ distance / mass determination



$L_V \sim \sigma^\varepsilon$, σ: central veloc. disp.

$M_r \sim \sigma^4 / (\rho_r\ r)$

➜ M/L increases with L

luminous Es have older stellar populations and/or more Dark Matter

ε~ 4 for bright gals
ε~ 3.2 for faint gals
ε~ 5.4 for cD gals

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Local Galaxies

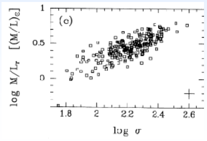
Fundamental relations for Ellipticals & dEs :

Fundamental Plane relations : effective radius – surface brightness – luminosity – central velocity dispersion

3 global parameters enough to describe structure of normal ellipticals, 2-dimensionally correlated: plane

$L_V \sim \sigma_e^a \, I_e^b \qquad r_e \sim \sigma_e^c \, I_e^d$

	a	b	c	d
Dressler+87	2.65	-0.65	1.33	-0.83
Djorgovski & Davis 87	3.45	-0.86	1.39	-0.90



➜ M/L increases with L

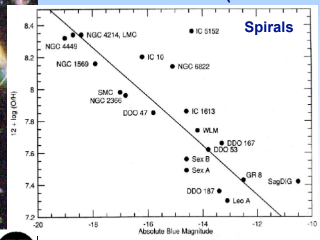
Local Galaxies

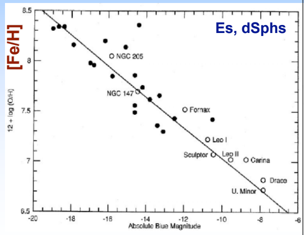
Fundamental relations for Spirals :

Luminosity – metallicity relation : for spirals and Irrs: brighter Sps/Irrs have higher ISM metallicities

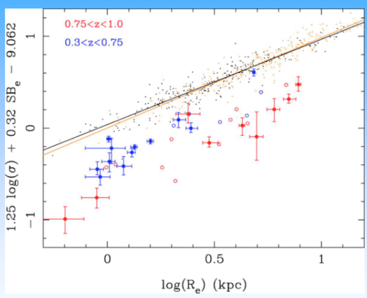
similar to relation for ellipticals (stellar metall.)

(Skillman 89)





Redshift Evolution of Fundamental PLane



Redshift evolution

Local Galaxies

Galaxy mix :

in the field : normal (=big) galaxies >70% Sps
~20% Es
<10% S0s

in galaxy clusters : <10% Sps
~20% Es
>70% S0s

dwarf-to-normal galaxy number ratio in clusters much higher than in the field

Galaxy clusters form continuously through infall of field galaxies

➜ transformation of galaxy types

Local Galaxies

Luminosity function for galaxies : Schechter 1976

Schechter LF : $\Phi(L) = (\Phi^*/L^*)(L/L^*)^\alpha \exp(-L/L^*)$

L^* : characteristic luminosity

$M_B^* = -19.7 + 5 \log h, \quad h := H_o/100$

$L_B^* = 9 \cdot 10^9 \, h^{-2} \, L_\odot \sim 2 \cdot 10^{10} \, L_\odot$ for $H_o = 70$

Φ^* : (local) normalisation = $1.6 \cdot 10^{-2} \, h^3$ Mpc^{-3}

difficult to determine !

α : faint end slope

$$\phi(L)dL = \phi^* \left(\frac{L}{L^*}\right)^\alpha exp\left(-\frac{L}{L^*}\right)\frac{dL}{L^*}$$

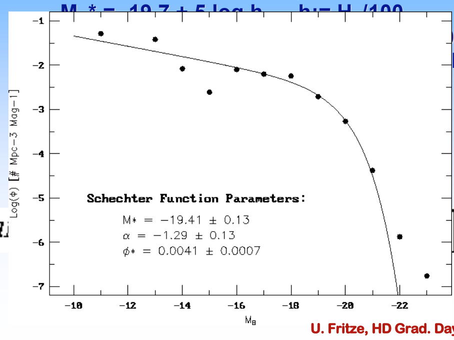
$$\phi(M)dM = \frac{2}{5}\phi^*(ln10)\left[10^{\frac{2}{5}(M^*-M)}\right]^{\alpha+1} exp\left[-10^{\frac{2}{5}(M^*-M)}\right]dM$$

Local Galaxies

Luminosity function for galaxies : Schechter 1976

Schechter LF : $\Phi(L) = (\Phi^*/L^*)(L/L^*)^\alpha \exp(-L/L^*)$

L^* : characteristic luminosity



Local Galaxies

Local luminosity functions for galaxies :

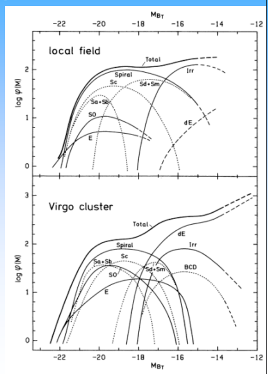
field galaxies
break-down
into types

faint end slope $\alpha \sim -1.1$

($N_{gal} \rightarrow$ inf. for $L_B \searrow$)

cluster galaxies:
steep faint end slope

faint end slope $\alpha << -1.1$



Local Galaxies

Luminosity function for galaxies : Schechter 1976

Schechter LF : $\Phi(L) = (\Phi^*/L^*)(L/L^*)^{\alpha} \exp(-L/L^*)$

L^* : characteristic luminosity
$M_B^* = -19.7 + 5 \log h$ $\quad h := H_0/100$
Φ^* : (local) normalisation = $1.6 \cdot 10^{-2}\ h^3\ Mpc^{-3}$
difficult to determine !
α : faint end slope

low luminosity galaxies dominate by number
high luminosity galaxies dominate the light
in the local universe

M_B^* (E) < M_B^* (Sa) < M_B^* (Sb) < M_B^* (Sc) < M_B^* (Sd)
-21.5 -19.7 -18.9 -18.8 -17.7
with considerable overlap in Virgo (Sandage+85)

Local Galaxies

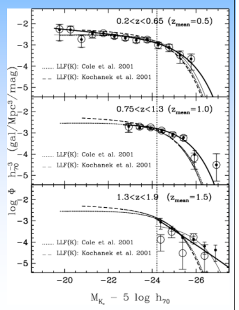
Schechter LF : $\Phi(L) = (\Phi^*/L^*)(L/L^*)^{\alpha} \exp(-L/L^*)$

Φ^* : (local) normalisation = $1.6 \cdot 10^{-2}\ h^3\ Mpc^{-3}$
difficult to determine !

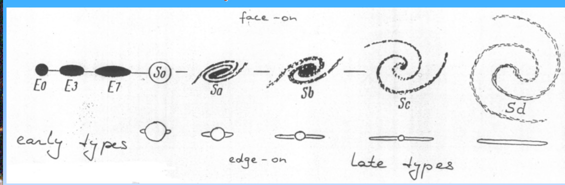
large volume : bright galaxies ok,
faint galaxies incomplete

small volume: faint galaxies
complete,
bright galaxies poor
statistics

redshift evolution : clues to
galaxy evolution



The Hubble Sequence of Normal Galaxies

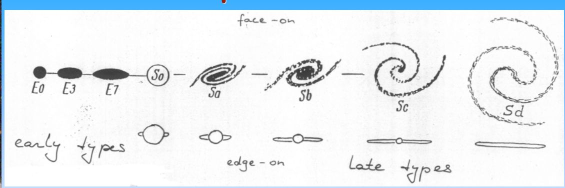


early type
old stars
no/little HI, H_2
dust
no SF today
red colours
K-star absorption line

late type galaxies
young + old stars
plenty HI, H_2, HII,
active SF today
blue colours
hot star + emission line

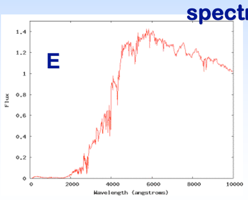
spectrum

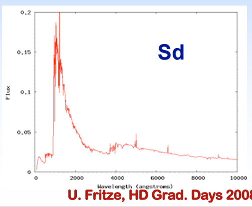
The Hubble Sequence of Normal Galaxies



early type late type galaxies

spectra





Trends along the Hubble Sequence

- ☛ Morphology : Bulge/disk light ratio (by definition)
- ☛ Colours
- ☛ Spectra
- ☛ SFR_0*
- ☛ Luminosities
- ☛ Composition: stars, gas, dust
- ☛ Metallicity: chemical composition

? how to explain ?

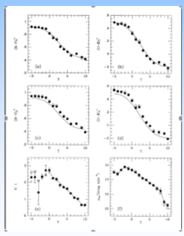
Trends along the Hubble Sequence

☛ Colours : RC2 (de Vaucouleurs et al. 1977), RC3 (Buta et al. 1995)

<elliptical> . . . . <Sd/Irr>

T = – 5 . . . T = 8, 10

red . . . blue



Trends along the Hubble Sequence

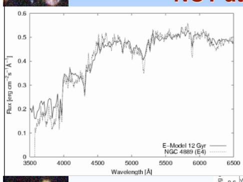
☛ Spectra : Kennicutt 1992, Kinney et al. 1996

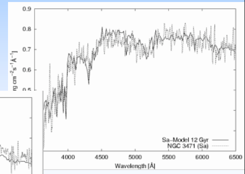
Template spectra of different galaxy types

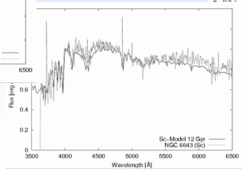
Spectral type ↔ morphological type

in the local universe ✔

NOT at high redshift !



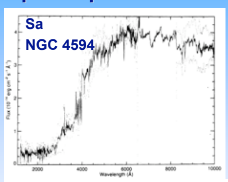


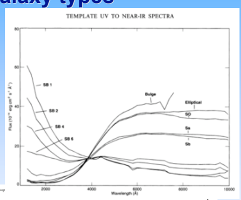


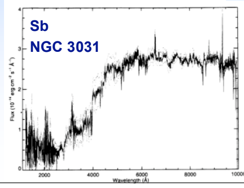
Trends along the Hubble Sequence

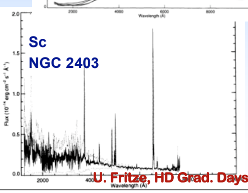
☛ Spectra : UV(IUE) + optical(KPNO) : Kinney et al. 96

Template spectra of different galaxy types









☛ SFR_0* : how to measure SFRs ?

from emission line strengths !

Stars are formed with IMF, most massive stars are hot enough to emit ionizing photons. These ionize the surrounding gas : HII region, which emits radiation: continuum & emission lines.

Massive stars are short-lived ($10^{5\text{-}6}$ yr)

emission lines trace present/very recent SFR.

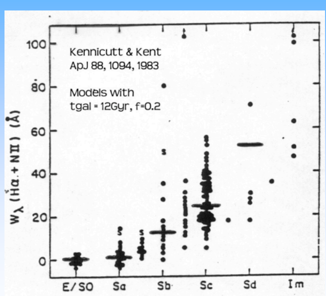
Hydrogen emission line strength Hα is a measure of SFR_0 (more accurately of $\langle SFR \rangle_{10\,Myr}$).

For galaxies at higher redshift, shorter wavelength lines have to be used, e.g. [OII].

UV flux also measures SFR, but rather $\langle SFR \rangle_{100\,Myr}$ since stars of somewhat lower mass & longer lifetimes contribute to the UV flux.

Trends along the Hubble Sequence

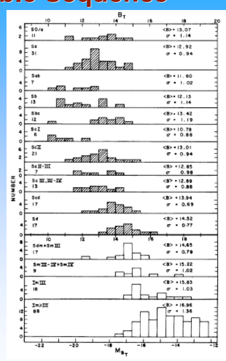
☛ SFR_0 : Kennicutt & Kent 1983



Trends along the Hubble Sequence

☛ Luminosities :

Sandage et al. 1985a, b



M_B* (E) < M_B* (Sa) < M_B* (Sb) < M_B* (Sc) < M_B* (Sd)

-21.5 -19.7 -18.9 -18.8 -17.7

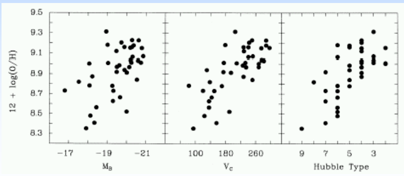
Trends along the Hubble Sequence

- Metallicity: Zaritzky et al. 1994

  trend of HII region metallicities among spiral types

  radial gradients in HII abundances across disks
  ➜ compare metallicities at 1 R_e

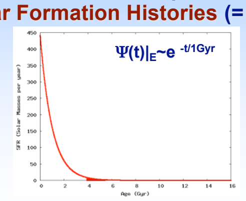
Sd/Irr Sa

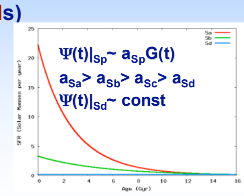


Trends along the Hubble Sequence

- Morphology : Bulge/disk light ratio
- Colours
- Spectra
- SFR_0
- Luminosities
- Composition: stars, gas, dust
- Metallicities: chemical composition

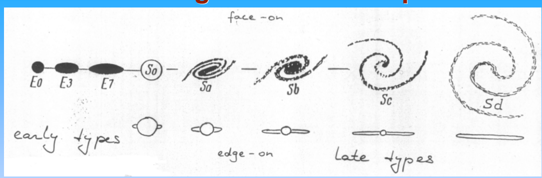
All trends can be explained by differences in the Star Formation Histories (= SFHs)



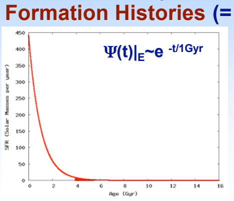


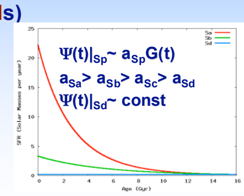
SFR = Star Formation Rate; SFH = SFR(t)

Trends along the Hubble Sequence



All trends can be explained by differences in the Star Formation Histories (= SFHs)



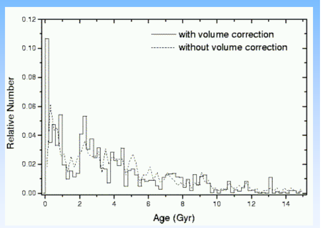


SFR = Star Formation Rate; SFH = SFR(t)

The Star Formation History of the Milky Way
Sbc galaxy

Rocha-Pinto+2000, Rocha-Pinto & Maciel 1997, 1998

from individual star age and metallicity determinations



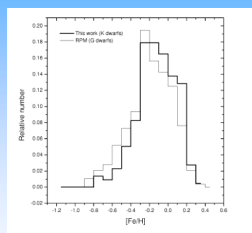


Fig. 2. Comparison between the metallicity distributions for K dwarfs (this work) and G dwarfs (RPM).

Decrease by factor ~4 since the beginning + short-term (10^8yr) fluctuations by factor < 2 around simple model SFH

Broad (>factor 10) stellar metallicity distribution
$\langle[Fe/H]\rangle < 0$ subsolar