

STRUCTURE OF GALAXIES

CONTENTS OF THE COURSE

1. Structure, kinematics and dynamics of the Galaxy
2. Stellar populations, classification, surface photometry
3. Luminosity distributions and component analysis
4. Photometric parameters and evolution
5. Kinematics of galaxies
6. Dynamics of galaxies
7. Structure of galaxy disks
8. Absorption, chemical evolution
9. Elliptical galaxies
10. Formation of galaxies

WEBSITE, TEXTBOOKS AND CONTACTS

The Website of this course is part of my honepage. See:

[www.astro.rug.nl/~vdkruit/#Structure of galaxies](http://www.astro.rug.nl/~vdkruit/#Structure%20of%20galaxies).

The beamer presentations of the course are available there.

Further reading material on the subjects covered in these lectures can be found in the textbooks:

- King, Gilmore & van der Kruit (KGK): “*The Milky Way as a Galaxy*”
- Binney & Merrifield (BM): “*Galactic Astronomy*”

The following chapters are relevant:

In BM chapters **1.2** (*A brief history of galactic astronomy*), **4.1** (*Morphological classification of galaxies*) and **8.2** (*The interstellar medium in disk galaxies*).

From **KGK** my five chapters: **5** (*Photometric components in galaxies*), **10** (*Kinematics and mass distributions in spiral galaxies*), **12** (*The distribution of properties of galaxies*), **14** (*Chemical evolution and disk-galaxy formation*) and **15** (*The Milky Way in relation to other galaxies*).

My chapters in “*The Milky Way as a Galaxy*” are available as pdf’s on the website of the course.

These are now more than twenty years old and much of the discussion on what we know is out of date. However, the basic methods and principles are still relevant.

Below I list some background literature and two exercises (which are NOT required for the exam!).

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BACKGROUND MATERIAL AND LITERATURE

♣ PRIMARY TEXTBOOKS:

Gilmore, King & van der Kruit: *The Milky Way as a Galaxy* (1990)

Binney & Merrifield: *Galactic Astronomy* (1998)

Pagel: *Nucleosynthesis and Chemical Evolution of Galaxies* (1997)

Binney & Tremaine: *Galactic Dynamics* (1988)

Sparke & Gallagher: *Galaxies in the Universe: an Introduction* (second edition 2007)

♣ OTHER USEFUL MATERIAL:

Van der Kruit & Gilmore: *Stellar Populations* (IAU Symposium **164** (1995)

Tinsley: *Evolution of the Stars and Gas in Galaxies*, (1980: Fun. Cos. Phys. **5**, 287-388)

de Jong: *Island Universes: Structure and Evolution of Disk Galaxies* (2007)

♣ BOOKS WITH HISTORICAL PERSPECTIVES:

Hubble: *The Realm of the Nebulae* (1936)

Shapley: *Galaxies* (1943)

Baade: *Evolution of Stars and Galaxies* (1963)

Blaauw & Schmidt: *Galactic Structure, Stars and Stellar Systems, Vol. V* (1965)

Sandage, Sandage & Kristian: *Galaxies and the Universe, Stars and Stellar Systems, Vol. IX* (1975)

Berendzen, Hart & Seeley: *Man discovers the Galaxies* (1976)

van der Kruit & van Berkel: *The Legacy of J.C. Kapteyn: Studies on Kapteyn and the Development of Modern Astronomy* (2000)

♣ ATLASSES:

Many of these are available online using the **NASA/IPAC Extragalactic Database**, see: nedwww.ipac.caltech.edu/level5/catalogs.html

Also consult the beautiful pictures on the website by Hogg: **SDSS images of selected RC3 galaxies**, at cosmo.nyu.edu/hogg/rc3/.

Sandage: *The Hubble Atlas of Galaxies* (1961)

Arp: *Atlas of Peculiar Galaxies* (1966)

Takara, Kodaira & Okamura: *An Atlas of Selected Galaxies* (1984)

Arp & Madore: *A Catalogue of Southern Peculiar Galaxies and Associations, Vol. II: Selected Photographs* (1987)

Tully & Fisher: *Nearby Galaxies Atlas* (1988)

Wray: *The Color Atlas of Galaxies* (1988)

Sandage & Bedke: *Atlas of Galaxies Suitable for Measuring the Cosmic Distance Scale* (1989)

Sandage & Bedka: *The Carnegie Atlas of Galaxies* (1994)

♣ CATALOGUES:

Many of these are available online using the **NASA/IPAC Extragalactic Database**, see: nedwww.ipac.caltech.edu/level5/catalogs.html

de Vaucouleurs, de Vaucouleurs, Corwin, Buta, Paturel & Fouqué: *Third Reference Catalogue of Bright Galaxies* (1991, in 3 Volumes)

Nilson: *Uppsala General Catalogue of Galaxies* (1973)

Sandage & Tammann: *A Revised Shapley-Ames Catalogue of Bright Galaxies* (1981)

Lauberts: *The ESO/Uppsala Survey of the ESO(B) Atlas* (1982)

Arp & Madore: *A Catalogue of Southern Peculiar Galaxies and Associations, Vol. I: Positions and Descriptions* (1987)

Tully: *Nearby Galaxies Catalog* (1988)

Lauberts & Valentijn: *The Surface Photometry Catalogue of the ESO/ Uppsala Galaxies* (1989)

♣ OTHER MATERIAL

There are two further texts on my homepage that I prepared to help you for more detailed information and background, namely

- A Review of Galactic Dynamics
(<http://www.astro.rug.nl/vdkruit/jea3/homepage/dynamics.pdf>).
- Theory of Chemical Evolution
(<http://www.astro.rug.nl/vdkruit/jea3/homepage/chemical.pdf>).

The second text is necessary if you want to make the second of the two following exercises.

STRUCTURE OF GALAXIES: EXERCISE I

PHOTOMETRIC EVOLUTION

In this exercise we will develop a simple analytic model to calculate the luminosity- and color evolution of galaxies. It adapted from and an extension of the work of Tinsley (*Ap.J.* **186**, 35; 1973).

1. Color- and luminosity evolution of a single star cluster.

The “*initial mass function*” IMF is the distribution of the number of stars of mass M , formed during star formation:

$$\Phi(M)dM = CM^{-(1+x)}dM$$

for

$$M_L \leq M \leq M_U.$$

Take the solar mass as unit, so $M_\odot = 1$.

a. Calculate the proportionality constant C by integrating the IMF over all masses and then normalising Φ . Take for this $M_L \ll M_U$ and $x > 0$.

We will assume that stars on the main sequence have a luminosity $L = M^\alpha$ with L in L_\odot and M in M_\odot . We take care of colors by letting the α 's differ for U , B and V . Assume that the time a star spends on the main sequence can be expressed as $t_{\text{MS}} = M^{-\gamma}$ (so the unit of time of t_{MS} is that which applies for a star of a solar mass, which is $\pm 10^{10}$ years). We assume that after that *each* star becomes a giant with a luminosity L_g for a time interval t_g , where again L_g is different for U , B and V .

Take a “*single burst*” (SB), in which the total number of stars that are formed is Ψ_0 . After a time t all those stars have evolved from the main sequences for which $M > M_t = t^{-1/\gamma}$. The total luminosity of the main sequence is then

$$L_{\text{MS}}(t) = \int_{M_L}^{M_t} \Psi_0 M^\alpha \Phi(M) dM.$$

b. Explain this equation and solve it for $M_t \gg M_L$. This then gives $L_{\text{MS}}(t)$ as a function of M_t (so with t only as implicit variable).

The number of giants N_g at time t then is (for $t_g \ll t$)

$$N_g(t) = \Psi_0 \Phi(M_t) \left| \frac{dM}{dt_{\text{MS}}} \right|_{M_t} t_g.$$

c. Explain this equation and solve it. This then gives $N_g(t)$ as a function of M_t .

The total luminosity of the cluster is then

$$L_{\text{SB}}(t) = L_{\text{MS}}(t) + N_g(t)L_g.$$

We now need some numerical values:

$$\begin{aligned} \alpha_U &= 4.9 & \alpha_B &= 4.5 & \alpha_V &= 4.1 \\ (L_g)_U &= 35 & (L_g)_B &= 60 & (L_g)_V &= 90 \\ U_\odot &= 5.40 & B_\odot &= 5.25 & V_\odot &= 4.70 \\ \gamma &= 3.0 \\ M_L &= 0.1 & x &= 1.35 & t_g &= 0.03 \end{aligned}$$

Note The main sequence is of course not accurately described with a single set of α 's. This has been "corrected" by choosing slightly incorrect values for the colors of the sun and somewhat high values for M_L . The L_g 's are roughly those for a K0III-star, but again slightly adapted since not all stars will follow the same giant branch.

d. Use this to calculate $L_{SB}(t)$. In order to do this change from M_t as variable to t and calculate L both in solar luminosities and in magnitudes. Also calculate $(U - B)$ and $(B - V)$. Do this for $t = 0.01, 0.1$ and 1 . What is the effect of the fact that we have effectively taken M_U to be infinite?

2. Colors of different types of galaxies after 10 Gyr

Take a galaxy to be a superposition of SB's of which the strength is a function of time. This strength is the *Star Formation Rate* SFR

$$\begin{aligned} \Psi(t) &= \Psi_0(1 - at) & \text{voor } t &\leq 1/a \\ \Psi(t) &= 0 & \text{voor } t &\geq 1/a \end{aligned}$$

We can see that for $1/a = 0$ we recover the SB and for $a = 0$ we have a constant star formation. (*Note.* An exponential form for the SFR would give better results but that case cannot be solved analytically). The total luminosity at time t can now be calculated with

$$L(t) = \int_0^t \Psi(t - t') L_{SB}(t') dt'.$$

e. Explain this equation and write down an equation for $L(t)$ with the equations above for the SFR. Do this for $1/a > t$.

We will now normalise the results to a system that has turned $10^{11} M_\odot$ into stars. So

$$10^{11} = \int_0^t \int_{M_L}^{M_U} \Psi(t') \Phi(M) M dM dt'.$$

f. Derive the formula for Ψ_0 for $1/a \geq t$ by doing the double integral. If we use this in $L(t)$, we get with this normalisation the luminosities and colors for any galaxy.

You will note (I hope) that the integrals for $L(t)$ will diverge for times $t \leq 1/a$, since we took M_U to be infinite. Introduce after all a M_U of $32 M_\odot$.

g. Now calculate $(U - B)$, $(B - V)$ and M/L for $t = 1$ and $a = 0, 0.8, 0.9, 0.95$ and 1 . We have the case $1/a = 0$ already from part 1 (except M/L). Compare this with observed colors of galaxies as a function of Hubble type:

Irr :	$(U - B) = -0.3 \pm 0.2,$	$(B - V) = 0.4 \pm 0.1$
Sc :	$(U - B) = -0.1 \pm 0.2,$	$(B - V) = 0.5 \pm 0.1$
Sb :	$(U - B) = +0.1 \pm 0.2,$	$(B - V) = 0.6 \pm 0.1$
Sa :	$(U - B) = +0.3 \pm 0.2,$	$(B - V) = 0.7 \pm 0.1$
S0 :	$(U - B) = +0.4 \pm 0.2,$	$(B - V) = 0.8 \pm 0.1$
E :	$(U - B) = +0.5 \pm 0.2,$	$(B - V) = 0.9 \pm 0.1$

STRUCTURE OF GALAXIES: EXERCISE II

CHEMICAL EVOLUTION IN THE SOLAR NEIGHBORHOOD

In this exercise we will analytically calculate the chemical evolution of the solar neighborhood. It is based on the work of Tinsley (Ap.J. **216**,548; Ap.J. **198**,145; Ap.J. **250**,758). The background and the fundamental equations have been written up separately (“Theory of chemical evolution”). This description is available at www.astro.rug.nl/~vdkruit/jea3/homepage/chemical.pdf.

The most important formulae that you will need are the three fundamental equations on the last page of that document. The boundary conditions are the observed properties at present, that is to say at $t = T$, or deduced from observed distributions. We can only do such analysis locally, but the results and methods are illustrative for extragalactic situations. We will take $R=0.2$ en $T = 15 \times 10^9$ years. The boundary conditions are:

- a. When the disk formed the abundance was small and the upper limit is that of the oldest stars, namely $Z_0 \leq 0.008$. $Z(t)$ has varied little (a factor 2 at most) over the last 50% of the age of the disk.
- b. The inflow of unenriched (pristine) material at present is less than $f(T) \leq 5M_\odot \text{ pc}^{-2} \text{ Gyr}^{-1}$.
- c. The star formation rate (SFR) $A(t)$ was a slowly decreasing function of t , but within the uncertainties it could have been constant.
- d. Of the G-K dwarfs in the disk a fraction of about 10% has an abundance of $Z < 0.3Z(T)$.
- e. From cosmonucleochronology it follows that the heavy elements had an average age of $(3 - 7) \times 10^9$ years at the time $T_\odot = 10.5 \times 10^9$ years when the solar system formed.
- f. The composition of the disk at present is as follows: total surface density $M_{\text{tot}}(T) = 80M_\odot \text{ pc}^{-2}$, of which $M_g = 8M_\odot \text{ pc}^{-2}$ is in the form of gas and its abundance is the same as that of the sun, namely $Z(T) = 0.025$.

We will calculate four specific models for the solar neighborhood and then will compare these to the boundary conditions above. For each model we will need to solve the three fundamental equations in order to find the following properties:

- the mass in heavy elements $Z(t)$,
- the SFR $A(t)$,
- the mass in gas $M_g(t)$,
- the yield P_Z ,
- the fraction $S(< Z_1)$ of stars with an abundance less than Z_1 (the mass in stars

at time t' follows from an integration of $A(t)$ from $t = 0$ to $t = t'$ and the fraction $S (< Z_1)$ then follows by dividing the masses at $t = t_1$ and $t = T$),

- the average age \bar{t} of heavy elements at the time T_\odot , when the solar system was formed,
- the time at which all the gas will be used up in star formation.

Condition **f.** should be used as input parameters and therefore cannot be used to test the models.

A. The “Simple Model”.

For this model we have $g(t) = f(t) = 0$ and $Z_0 = 0$. Assume that the SFR is proportional to the gas mass; not all conditions depend on that, but indicate which ones do. It is best for the solution of the differential equation not to take the time t as variable, but

$$g = \ln \left(\frac{M_{\text{tot}}}{M_g(t)} \right).$$

B. “Prompt Initial Enrichment”.

Again we have here that $g(t) = f(t) = 0$, but now Z_0 has a positive value. In practice this can come about in two ways: (1) There was much nucleosynthesis in the halo, after which the disk was formed with gas with $Z \neq 0$. (2) After the formation of the disk there was a brief period during which only massive stars were formed (no stars will then be left now of that generation), which gave rise to a substantial enrichment. Use $Z_0 = 0.008$.

C. “Extreme Infall Model”.

We now assume an inflow of unprocessed material (so $Z_f = 0$). Assume that M_g is constant and $A(t)$ is proportional to M_g . Now we take again $Z_0 = 0$. Use again another variable instead of time t , namely

$$\mu = \frac{M_{\text{tot}} - M_g(0)}{M_g(0)}.$$

The solution of the differential equation

$$\frac{df(x)}{dx} = a - f(x)$$

is

$$f(x) = a \left(1 - e^{-x} \right).$$

D. “Mixed Model” or “Simple Model with Bells en Whistles”.

In order to find a more realistic solution we will assume that M_g is constant and $Z_0 = 0$. We will replace this with $f(t) = \beta A = \text{constant}$ (with of course $\beta/(1 - R) < 1$). Take $\beta = 0.6$ and $Z_0 = 0.004$.

The solution of the differential equation

$$(1 - cx) \frac{df(x)}{dx} = a - bf(x)$$

is

$$f(x) = \frac{a}{b} - \left[\frac{a}{b} - f(0) \right] (1 - cx)^{b/c}.$$

You will also need the following integral

$$\int x(1 - ax)^{-4} dx = \left[\frac{x}{2a} - \frac{1}{6a^2} \right] (1 - ax)^{-3}.$$

Summarize the conclusions from the four models in a table and produce graphs of $Z(t)$ and $S(< Z_1)$. Finally present a general discussion.