Astrophysikalisches Praktikum

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SPECTRAL CLASSIFICATION

OF GALAXIES

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1 Introduction

Goal of this Praktikum is to give an overview of the main features and stellar population present in the spectra of galaxies. For emission line galaxies (spirals and active galactic nuclei) we also analyze the systematic behaviour of the nebular emission lines to learn about the gas ionization mechanisms and galaxy star formation rates.

What follows is not a comprehensive description of the morphological and physical properties of galaxies for which one should refer for instance to a general book like "Extragalactic astronomy" of Mihalas and Binney (1981).

Elliptical galaxies are nearly featureless tri-dimensional stellar systems with very little rotation and flattened by anisotropic velocity distribution. This means that the kinetic energy or mean squared velocity of the stars of an elliptical galaxy can be different in different directions, in contrast to the well known case of a thermalized gas, where the velocity distribution of the gas molecules is a gaussian function of the squared velocity. They appear as ellipses on the sky, with flattening $10 \times (1 - b/a)$ (where a and b are the semi-major and minor) ranging from 0 (round) to 7 (very flattened).

In contrast, spiral galaxies are two dimensional *disks*, rotationally supported, with a large fraction of cold (HI) and warm gas, and on-going star formation. Spirals have low central surface brightness compared to ellipticals. In their central parts on can find a *bulge*, or spheroidal component similar to an elliptical galaxy. As their name says, spirals show often bright spiral arms and/or barred structures. Spirals appear as circles if seen face-on (inclination angle $i = 0$) and ellipses more and more flattened as the inclination angle increases.

Between the two groups one finds S0 galaxies, which posses a large central bulge similar to an elliptical galaxy, a gasless disk and therefore no on-going star formation.

The morphological classification of galaxies is well correlated to their stellar populations content, i.e. their spectroscopic properties, that will be discussed in the next section.

The next pages are organized as follows. Section 2 gives an overview of the spectral properties of elliptical-S0 (2.1) and spiral galaxies (2.2). Spectra of active galactic nuclei are briefly discussed in (2.3). In Section 3 we learn how to distinguish between galaxies whose gas is ionized by stars and those in which the ionizing source is nonthermal (3.1). We then describe how to derive the ongoing star formation rate in spiral galaxies, considering the H_α and [OII]λ3727 emission line as star formation tracers (3.2) and taking into account the extinction caused by dust (3.3). A short description of the past and future star formation of spiral galaxies is given in Section 3.4. Section 4 describes how one should perform the Praktikum. The three Appendices provide more detail information about the mean star formation of spiral galaxies (A), the estimate of dust content and reddening correction (B), and the derivation of the ongoing star formation by means of the [OII]λ3727 line emission (C).

2 The spectral appearance of galaxies

The integrated spectrum of a galaxy is a powerful diagnostic of its stellar content and evolutionary properties. In most normal galaxies the *nuclear* regions contribute only a few percent or less of the integrated flux, in either the continuum or the emission lines, so in most cases the spectral appearance is dominated by the *disk* and the *bulge*. Therefore, the galaxy spectra must take into account the contribution of all these extended and external galactic regions to avoid that spatial undersampling introduces significant errors in the star formation rate determination.

In the following we distinguish between galaxies whose spectra are characterized by absorption features and those in which emission features are dominant. This difference is due to their stellar population properties.

2.1 Absorption line galaxies

Elliptical galaxie are dominated by an old, evolved stellar population, where all of the massive, bright and blue main sequence stars have died out, and have therefore red colours. They have a very low fraction of cold gas (but can have extended hot, X-ray emitting gas) and typically exibit little evidence of star formation. Most of them show no detectable emission lines at all, although faint [OII]λ3727 and [NII]λ6584 can be detected.

Elliptical galaxies show relatively homogeneous spectra, dominated by absorption features from cool giant stars like $\mathrm{Mg}_b\lambda$5175, Na D λ5892, Ca II K λ3933 and Ca II H λ3968.

NGC 4889 in Fig. 1 shows the typical spectrum of a bright elliptical. As a class the spectra of S0 galaxies are nearly indistinguishable from those of the elliptical galaxies and for both Hubble types the denomination early-type galaxies is commonly used.

A typical feature of early-type galaxies is the discontinuity in their spectral energy distribution around 4000 Å . This is due to the sudden onset of stellar photospheric opacity shortward of 4000 Å , to the Fraunhofer H and K lines of CaII and to a variety of elements heavier than helium in various stages of ionization. This discontinuity is called D_{4000} break index and can be simply visualized as the ratio of the mean fluxes in two windows above and below 4000 Å .

$$D_{4000} = \frac{\int_{\lambda_1^+}^{\lambda_2^+} F_\nu}{\int_{\lambda_1^-}^{\lambda_2^-} F_\nu} \tag{1}$$

where F_ν is the flux in erg s^{-1} Hz^{-1} and $(\lambda_1^-, \lambda_2^-, \lambda_1^+, \lambda_2^+)$ = (3750,3950,4050,4250) Å .

This index is insensitive to changes in metal abundance and to the absolute magnitude of the galaxies and its mean value for nearby early-type galaxies is 2.1±0.1 with a well defined upper envelope value of $\sim$ 2.3.

If the galaxy has a significant star formation the young and hot stars present will increase the flux in the ultraviolet spectral region below 4000 Å causing thus a decrease the D_{4000} break index. This sensitivity to the presence of young stars explain why this index has much lower values in spirals and generally correlates with the galaxy Hubble type and with emission features indicative of recent star formation (blue colors, [OII]λ3727 emission etc..).

2.2 Emission line galaxies

The stellar population of spiral galaxies is constantly refurnished by newly formed massive, bright and blue young main sequence stars, so that spirals have blue colours.

Most systematic studies of SFRs in disk and irregular galaxies are consistent with a common picture, in which the variation of the UV−visible colors and H_α emission properties of galaxies along the Hubble sequence can be attributed to underlying variations in their stellar birthrate histories. In this picture early-type galaxies (type S0-Sb) represent systems which formed most of their gas into stars on timescales much less than the Hubble time, while the disks of late-type systems (Sc-Im) have formed stars at roughly a constant rate since they formed (Fig.7).

In the following sections we will discuss the physical properties of the gas in star forming galaxies with the tools developed for the analysis of HII regions (Osterbrock, 1989). Clearly, a star forming galaxy is a system much more complex than an HII region. However, the well-spread evidence that star-forming galaxies generally follow relations expected for HII regions (Kennicutt, 1992) suggests that the integrated spectra of a galaxy could be used to roughly derive the characteristic ionization of its gas.

The source of energy that enables the gas of a galaxy to radiate is ultraviolet radiation from stars. Hot stars, with surface temperature $T_* = 3 \times 10^4$ K, inside or in the vicinity of a gas-rich region emit ultraviolet photons that tranfer energy to the gas by photoionization. Hydrogen is by far the most abundant element, and photoionization of H is thus the main energy input mechanism. Photons with energy greater than 13.6

eV, the ionization potential of H, are absorbed in this process, and the excess energy of each absorbed photon over the ionization potential appears as kinetic energy of a new liberated photoelectron. Collisions between electrons, and between electrons and ions, distribute this energy and maintain a Maxwellian velocity distribution with temperature T in the range $5000 < T < 20000$ K.

We summarize now shortly how *forbidden* and *permitted* lines form. For historical reasons, astronomers tend to refer to the chief emission lines of gaseous nebulae ([OII]λ3727,[OIII]λ5007, [OI]λ6300 etc.) as *forbidden* lines. Actually, it is better to think of the bulk of the lines as collisionally excited lines, which arise from levels within a few volts of the ground level and which therefore can be excited by collisions with thermal electrons. Although downward radiation transitions from these excited levels have very small transition probabilities, they are responsible for the emission lines observed. Indeed, at the low density of typical nebulae ($N_e \leq 10^4$ cm^{-3}) collisional deexcitation is even less probable.

So, almost every excitation leads to emission of a photon, and the nebula thus emits a *forbidden* line spectrum that is quite difficult to excite under terrestrial laboratory conditions.

In addition to the collisionally excited lines, the *permitted* lines of H I, He I, and He II are characteristic features of the spectra of spiral galaxies. They are emitted by atoms undergoing radiative transitions. Indeed, recaptures occur to excited levels, and the excited atoms then decay to lower and lower levels by radiative transitions, eventually ending in the ground level.

To give an overview of the main spectral features visible in the spectra of spiral galaxies we show in Fig.1 representative spectra for early$-$ to late$-$ and irregular types galaxies.

The spectra of early-type spirals such as NGC 2775 are dominated by late-type stars and differ only subtly from the spectra of E$-$S0 galaxies. The main changes are an increase of the flux in the blue, to which corresponds a decrease in the strength of the D_{4000} break and the appearance of weak H_α and [NII]λ6584 emission, at the level of a few Å or less in equivalent width (equation 2). Except for occasional weak [OII]λ3727 emission, no other nebular lines are detected in the integrated spectrum.

Intermediate$-$ to late$-$type spirals, illustrated by NGC 4750 and NGC 6181, are characterized by much higher blue flux, more prominent Balmer absorption lines and nebular emission features but lines at [SII]$\lambda\lambda$6717, 6731, [OIII]λ5007,H_β,[OII]λ3727 begin to appear.

As one progresses to the bluest spirals and Magellanic irregulars, as illustrated by NGC 4449, the integrated spectrum becomes increasingly dominated by the continua of B$-$A stars, and by strong nebular emission lines.

The smooth monotonic progression in both the emission and absorption spectra with galaxy type shows clear evidence of the systematic changes in stellar populations and star formation rates along the Hubble sequence.

Finally, we included the spectrum of NGC 7714, a nuclear starburst galaxy. Nuclear means that most of the starburst activity is concentrated in an H II region−like nucleus. Nuclear and global starburst galaxies possess very strong emission lines, with equivalent width of H_α+[NII] ranging from 70-200 Å ,3−10 times higher than in an average Sb or Sc galaxy. The stellar continua also resemble late−type, active star−forming galaxies.

2.3 Nonthermal sources

In addition to "extragalactic H II regions" or "H II-region galaxies" there are a few galaxies with ionized gas in their nuclei that is not associated with O and B stars. Examples are Seyfert galaxies, radio galaxies, quasars, collectively called active galactic nuclei (AGN).

To assess the effect of an active nucleus on the integrated spectrum of a galaxy we included in our galaxy sample a Seyfert 2 galaxy. We now briefly summarize the most relevant properties of this class of AGNs.

The narrow emission lines (Full Width Half Maximum $\sim 200 - 300$ km s^{-1}) observed in Seyfert 2 are much the same as the emission lines observed in H II regions and planetary nebulae, except that in the AGNs the range of ionization is considerably greater. The emission lines typically observed are the *forbidden*: [OII]λ3727, [OIII]$\lambda\lambda$4959, 5007 and [NII]$\lambda\lambda$6548, 6584 but also [OI]λ6300, [NeV], [FeVII] and frequently [Fe X]. In addition to the *forbidden* lines, *permitted* lines of HI, HeI and He II are moderately strong. All these narrow lines are emitted by a highly ionized gas, with roughly normal abundances of the elements.

The physical difference that distinguishes a narrow-line AGN from an H II region-like galaxy is the photoionizing continuum. In narrow-line AGNs the ionizing radiation is approximated by a power-law continuum $\nu^{-\alpha}$ with spectral index $\alpha \sim 1.0 - 1.5$ or by a combination of two such power laws, with $\alpha \sim 0.5$ at higher energies. So, in contrast with H II region-like objects, narrow-line AGNs have a significant fraction of their energy in the X-ray domain. These X-ray photons have important consequences for the gas ionization structure. Because the absorption cross section of H^0, He^0, He^+, and all other ions decrease rapidly with increasing energy, keV X-rays penetrate deeply into the predominantly neutral region. There they produce a large partly ionized zone, with characteristic fraction of ionized hydrogen $H^+/H \sim 0.2 - 0.4$. This extended zone of partly ionized H does not exist in H II regions photoionized by hot stars.

3 Informations obtainable from spectra

The analysis of a galaxy spectrum is typically based on the measurements of a set of line fluxes and equivalent widths *(EW)*

$$EW = \frac{\int_{\lambda 1}^{\lambda 2} (I_c - I_\lambda)\, d\lambda}{I_c} \tag{2}$$

where I_λ is the flux measured in the line and I_c is the flux in the continuum.
From these easily measurable quantities we can derive two relevant informations:

- Distinguish if the gas is ionized by hot stars or by nonthermal sources. In this way galaxies hosting AGN can be identified even if only an integrated spectrum is available (which is normally the case in high redshift AGN)
- Estimate of the ongoing and past galaxy star formation rate

3.1 Diagnostic diagrams

When interpreting the emission-line spectra, it is important to be able to distinguish emission produced by star-forming regions from other sources such as AGN. The conventional means for distinguishing between gas ionized by stars and nonthermal processes are diagnostic line diagrams.

They make use of reddening-corrected fluxes of the following line: [OII]λ3727, $H_\beta\lambda$4861, [OIII]λ5007, [OI]λ6300, $H_\alpha\lambda$6562, [NII]λ6584, [SII]$\lambda\lambda$6717, 6731. Fig. 2−4 show that appropriate ratios of these lines can clearly separate extragalactic H II regions from AGNs. We now try to give a qualitative explanation of why diagnostic diagrams work so well.

As we have seen, AGN are characterized by the existence of a partially ionized zone. In this partly ionized region, H^0, H, and free electrons coexist with neutral atoms of other elements, as well as with ions having an ionization potential similar to that of H. The dominant forms of O, S, and N in the partly ionized zone are O^0, S^+ and N^0, while smaller fractions of N^+ and O^+ are also present. Hot free electrons produced in this region by X-ray photoionization will increase the strengths of lines produced by collisional excitation. Important lines such [OI]λ6300, [SII]$\lambda\lambda$6716, 6713, [NII]λ6583 are of this type. Therefore, intensities of [OI]λ6300, [SII]$\lambda\lambda$6716, 6731 and [NII]λ6583 are larger with respect to H_α in narrow-line AGNs than in H II region-like objects because collisional excitation of these lines is more important in objects with extended partly ionized zones.

Since the ionization potential of O^0 matches the ionization potential of H very well we should expect a large difference between the [OI]$\lambda 6300/H_\alpha$ ratio of the H II region-like objects and that of narrow-line AGNs. The effect is also important for [SII]($\lambda6716 + \lambda6731$)/ H_α but the fact that S^+ can also exist within the H^+ zone of H II regions somewhat attenuates the difference between the two classes of objects.

Finally, O^{++} is produced predominantly by UV photons ($h\nu > 35$ eV) well inside the partly ionized zone and close to the ionizing source. The relatively larger numbers of photons that can ionize O^+ to O^{++} in the power-law type spectra generally make [OIII]$\lambda5007/H_\beta$ larger in the AGNs than in all but the highest H II region-like objects. Therefore, in trying to decide whether an object is an H II region galaxy or a narrow-line AGN, more weight should be given to the diagram of [OIII]$\lambda5007/H_\beta$ versus [OI]$\lambda6300/H_\alpha$ than to the other two diagrams.

3.2 Ongoing star Formation rate in normal galactic disk

In principle, measurement of the integrated photon flux in a Balmer line of a galaxy should provide a direct measurement of the Lyman continuum luminosity ($\lambda < 912\mathring{A}$) and the corresponding OB SFR in the galaxy.

The idea of this method is quite straightforward. If the galaxy as a whole is Lyman radiation-bounded, i.e. optically thick in the Lyman continuum, it will absorb all the ionizing photons emitted by the OB stars (the so called Case B recombination). Thus the total number of ionizations in the galaxy per unit time is just equal to the total number of ionizing photons emitted, and since the gas is in ionization equilibrium, these ionizations are balanced by the total number of recombinations per unit time.

However, to derive the SFR of a galaxy from the observed photon flux in a Balmer line one needs stellar evolution and photoionization models. The key ingredients in these models are: a) the stellar evolutionary tracks which describe the luminosity, effective temperature, and mass of a star as a function on initial mass and age, b) the atmosphere models which allow the trasformation from effective temperature and surface gravity to colors and ionizing photon production rates, c) the initial mass function (IMF) $\Phi(m)$ which gives the number of stars formed in the mass interval (m,m+dm) per total mass of stars that are formed.

The final result is the number of ionizing photons produced in the lifetime of a massive star. With appropriate weighting from the IMF these are summed to give the the ionizing output per mass of star formation, which can be then compared with the observations.

3.2.1 SFR indicator: H_α

Although the character of the integrated spectrum of a galaxy changes radically over the range of the Hubble sequence, a revealing result in Fig.1 is the subtlety of the changes in composite spectrum between Hubble types E and Sb. Most of the variance in spectral properties, especially in the blue region, occurs among Sc−Irr galaxies. The only exception is the H_α+[NII] emission feature, which is sensitive to stellar population over the entire range of types. This statement is quantified in Fig. 5 by the clear correlation between EW (H_α) and galaxy morphological type. Therefore, it is not surprising that H_α emission-line luminosity and equivalent width are the most widely adopted star formation tracers.

The H_α luminosity provides a direct measure of the global photoionization rate, which can be used in turn to reliably estimate the SFR in massive ($\geq 10M_\odot$) stars by means of the stellar evolution and photoionization models previously mentioned.

Extrapolation to a total SFR, integrated over all stellar masses, is accomplished by adopting a given IMF. Many IMFs can be approximated as power laws of the form $\Phi(m) \propto m^{-\alpha}$. In this notation the Salpeter (1955) IMF is a single power law with $\alpha =$ 2.35, while the Miller & Scalo (1979) function can be fitted by α =1.4 (0.1−1 $M_\odot$), 2.5 (1−10 $M_\odot$), and 2.3 (10−100 $M_\odot$).

The "extended" Miller-Scalo IMF adopted by Kennicutt (1983,1994) is similar to the Salpeter IMF above 1 $M_\odot$, but takes into account the rollover in IMF at lower masses observed in the solar neighborhood:

$$\Phi(m) \propto m^{-1.4} \qquad 0.1 \leq m \leq 1M_\odot \tag{3}$$

$$\Phi(m) \propto m^{-2.5} \qquad 1 \leq m \leq 100M_\odot \tag{4}$$

With this IMF the relationship between the star formation rate and the H_α luminosity of a galaxy reduces to a single constant:

$$SFR(\geq 10M_\odot) = \frac{L(H_\alpha)}{7.02 \times 10^{41} ergs^{-1}} \quad M_\odot yr^{-1} \tag{5}$$

$$SFR(total) = \frac{L(H_\alpha)}{1.12 \times 10^{41} ergs^{-1}} \quad M_\odot yr^{-1} \tag{6}$$

To derive with equations 5−6 a correct SFR we must consider several factors that can affect the H_α flux measured (see the Praktikum section):

- *the contamination of the H_α emission by nonthermal nuclear emission*

This is normally not relevant because nonthermal nuclear emission is negligible ($\leq$ 5%) in most of normal spirals.

- *the underlying stellar H_α absorption*

H_α absorption in the underlying red continuum should be small as well since the light at those wavelengths is dominated by G-K giant stars with a typical absorption *EW* of 1−2 Å.

- *the [N II]$\lambda\lambda 6548, 6584$ emission in the H_α+[N II] profile*

Average corrections for the larger effects of [NII] emission are normally applied taking into account that the [NII]/H_α ratio is fairly constant in spiral and irregular galaxies, spanning the range 0.75−0.95. In this Praktikum we analyze high resolution spectra (5−7 Å) of galaxies and we not need to apply this correction because both lines are well separated. Only for the Seyfert 2 galaxy we must take into account the contamination from [N II] and perform a gaussian decomposition of the H_α+[N II] line profile.

- *absorption by dust.*

Extinction is by far the most important source of systematic uncertainty in the SFR determination, whether measured from H_α or from modeling the broad-band colors. We will discuss this point in detail in another section.

3.2.2 SFR indicator: [OII]$\lambda 3727$

Although H_α is the best tracer to derive quantitative SFRs in galaxies, beyond z$\simeq 0.2 - 0.3$ H_α redshifts into the near infrared and for many applications it becomes more practical to measure the emission lines in the blue. Since the [OII]$\lambda 3727$ feature can be readily observed from the ground to redshifts of at least unity, it provides a powerful means of studying the systematics of galactic star formation to cosmological redshifts and lookback times. In Appendix A we discuss how the SFR can be measured using this emission line as SFR tracer.

3.3 Dust content and reddening correction

There is no doubt of the presence of dust in H II region galaxies and in Seyfert galaxies, nor that it modifies the spectra of these objects. However, to correct accurately for its extinction is difficult. Since very little is known of the properties of dust in these galaxies, the standard assumption is that the optical properties of the dust in emission-line galaxies are identical with the optical properties of dust in our Galaxy near the Sun. Therefore, the Whitford reddening curve as parameterized by Miller and Mathews (1972) is normally used (Tab.1).

Moreover, we have to to estimate the dust content of the galaxies. The most widely used method is based on the relative strengths of the lower Balmer lines, H_α and H_β. The observed Balmer decrement is invariably steeper than the calculated decrement and the difference is then assumed to be due to be due to interstellar extinction.

The effect of reddening on the ratio H_α/H_β can be written (see Appendix 2 for a derivation):

$$C = 3.1 \quad (\log \frac{F(H_\alpha)}{F(H_\beta)} - \log \frac{I(H_\alpha)}{I(H_\beta)}) \tag{7}$$

where C is the measure of the amount of reddening (E(B−V) = 0.77 C), I(λ) indicated the (unreddened) intrinsic flux and F(λ) the flux measured. For the intrinsic flux ratio for H II region-like objects we adopted the case B Balmer recombination decrement $I(H_\alpha)/\ I(H_\beta) = 2.85$ for T= 10^4 K and $N_e = 10^4$ cm^{-3}.

In AGN, however, the harder photoionizing spectrum results in a large transition zone in which collisional excitation is also important in addition to recombination collisional excitation (see Appendix 2). Therefore, for the intrinsic ratio for AGN we adopt $I(H_\alpha)/I(H_\beta)= 3.1$

The reddening correction at the different wavelengths can thus be obtained :

$$logI(\lambda) = logF(\lambda) + C \times f(\lambda) \tag{8}$$

3.4 Past and future star formation rate

Perhaps the most puzzling result from the studies of the SFR is the relatively short inferred timescale for gas consumption, on the order of a few Gyr. If this timescale is defined as

$$\tau_R = M_{gas}/SFR \tag{9}$$

where M_{gas} is the total mass content and SFR the ongoing star formation rate, most nearby spirals will exaust the gas in their star forming disk on times ranging from 0.1 to 0.6 of the Hubble time. This would suggest that we live in an epoch in which late−type spirals are being transformed into early-type systems, or alternatively that large amounts of infall may be needed to sustain the star formation in late−type disks. The resolution of this dilemma is the substantial effect that stellar gas recycling has on the disk lifetimes. Stellar gas recycling can be quantified by means of the return fraction R , i.e. the fraction of mass in a stellar generation that is returned to the disk over its lifetime. R is sensitive to several parameters, including the IMF but its mean value spans from 0.2 to 0.4. As a consequence of this additional, time delayed gas input the disk star formation extends by factors of 1.5−4.

4 Praktikum

In this Praktikum we will analyze high resolution (5−7 Å) spectra of the following galaxies: ngc4889, ngc2275, ngc4750, ngc6181, ngc4449, ngc7714.

The spectra, taken from the Kennicutt et al. (1992) Atlas, provide a basic set of continuum energy distributions and emission-line fluxes for a range of galaxy types as shown in Tabl.1.

Table 1

Name	**Spectral type**	**M(B)**
NGC 4889	E4	-22.1
NGC 2275	Sa	-19.9
NGC 4750	Sb	-20.2
NGC 6181	Sc	-20.7
NGC 4449	Sm	-17.9
NGC 7714	Starburst	-19.7
Mrk 3	Seyfert 2	-18.5

NOTE

These spectra have been obtained with a drift scanning technique for galaxies with diameters of $1'-14'$. This means that each measurement consisted of one or more integrations, during which the image of the galaxy was trailed across a long slit several times. As a result, the integrated spectrum takes into account the contribution of the light coming from the galaxy *nucleus*, *bulge* and *disk*.

Perform the analysis of each galaxy spectrum following these steps:

- 1) Plot the spectrum with the emission and absorption lines identified. Try to identify at least the lines marked with • in Table 2.
- 2) Calculate the redshift of the galaxy considering at least 3 lines.
- 3) Measure the *EW* and Fluxes for *at least* the following lines: [OII]λ3727,H_β,H_α, [OI]λ6300,[OIII]λ5007, [NII]$\lambda\lambda$6548, 6584.
- 4) Estimate the dust content and the reddening correction from the H_α/H_β ratio.

- 5) Correct for extinction the Fluxes of the lines specified in 3).
- 6) Plot and discuss the position of the galaxy in the 3 diagnostic diagrams showed in Fig.2–4.
- 7) Convert the observed H_α *(and optionally* [OII]λ3727) fluxes to the corresponding luminosities L_α *(and $L_{[OII]}$)* and calculate the SFR.
- 8) Plot and discuss the following correlation:

  -EW[OII] versus spectral type

  -D_{4000} versus spectral type

  -EW[OII] versus $EW(H_\alpha)$

NOTE:

- To facilitate the identification of spectral features we have summarized in Table 2 the main lines in emission or in absorption in the integrated galaxy spectra. The symbol • in the table indicates the most usual and strongest lines. The redshift of the galaxies is derived from:

$$\lambda_{ob} = \lambda_o(1+z) \tag{10}$$

  where λ_{ob} is the measured value and λ_o is the rest-frame value given in Table 2. All the galaxies are nearby and $0.001 \leq z \leq 0.021$.

- The spectra provided are in F(λ) and therefore a definition of the D_{4000} break slightly different from that given in equation 1 will be used here. Consider

$$D_{4000} = \frac{F_{4050-4250}}{F_{3750-3950}} \tag{11}$$

  where $F_{\lambda_1-\lambda_2}$ is the mean flux in the $(\lambda_1 - \lambda_2)$ wavelength range. While the absolute value of the index will differ from the standard one, its variations with the galaxy spectral types will remain unchanged.

- Measurements of EW and Fluxes are very sensitive to the continuum definition. Therefore, the students should repeat at least some measurements considering different continuum windows and evaluate the scatter in the results.

- For the conversion of the observed flux F_λ to luminosity L remember that

$$F_\lambda = \frac{L}{4\pi(cz/H_o)^2} \tag{12}$$

where (H_o = 50 km s^{-1} Mpc^{-1}; 1 Mpc = 3.08 $\times 10^{24}$ cm)

Commands for the spectral analysis

To start the program type: dipso.

Then type:

- **alaslins 3 2000** To define the lines to be read.
- **alasrd** *name file* and **push** To read one galaxy spectrum and store it in the current buffer.
- **sl** To see the content of all buffers
- **pop** *buffer number* To read a from a buffer position to the current buffer
- **dev xwindows** To create a graphic window
- **pm** *buffer number* To plot the galaxy spectrum in the specified buffer. Without specification the whole wavelength range will be plotted. If one wish to define a type **xr** *x start x end* and then **pm** again.
- **erase** To erase the plot on the screen.

Important

If one wishes a laser plot of the spectra type first **dev ps_l**, then **pm** , then **dev xwindows**. Postscript files with the gks*.ps, gks*.ps.1, gks*.ps.2 etc. names will be created in the working directory. After that, open another window on the screen with the command xterm &. From this window one can send the gks*.ps.* files to the laser with the command **lpr gks*.ps.***.

To identify emission and absorption lines :

- **xv** and click with the cursor. Use Table 2 to identify the absorption or emission lines (at least all those marked with •) and to measure the redshift.

To measure the D_{4000} break of a galaxy spectrum type:

- **rxr** *3750 3950* to select the appropriate wavelength range and **pm**
- **push** to store this wavelength region in a *buffer*
- **pop** *buffer number*
- **mean** to obtain the mean flux in this spectral region. Do the same for *4050 4250*.

To measure EW and Fluxes

- **xr** *xstart xend* to select a region around the line to measure
- *If the line has not a regular gaussian-like profile but is contaminated by another line, type* **snip** *and give with the cursor the limits of the region you want to ignore in the line profiles. A linear interpolation will be done. Then type* **push** *to store the "corrected" profile in a buffer and* **pop** *(buffer number) to read it.*
- **ew** To measure the EW of the lines. Mark one position on each side of the line.
- **flux** To measure the flux of the lines. Mark one position on each side of the line.

To deconvolve complex profiles (sometime necessary for the H_α+[NII] line complex)

- **rxr** *x start x end* to select only a region around the line to measure
- **yv** to measure the continuum value and **ysub** *value* to subtract it
- **push** to store the previous spectrum in a *buffer*
- **pop** *buffer number* to read the previous spectrum
- **elfinp** to define the number of gaussian components, the central wavelengths, and the FWHMs. A guess for the central Wavelength and Full Width at Half Maximum is required. Type **c1:***number* and **w1:***number*. More gaussian components can be given (**c2:***number* and **w2:***number*).
- **qelf** to return to dipso
- **elfopt** to run the optimization program. It gives center, width and line flux of the single gaussian components.

- **elfpush** [*n1, n2..*] to store the fit results in buffers. n1, n2 are the single gaussian components. Without specification only the total fitted profile will be stored
- In order to check the the reliability of the fit type **pop** *original profile* then
- **nb** to avoid to erase the screen
- **pop** and **pm** *single gaussian components*
- **pop** and **pm** *total fitted profile*
- To perform again the profile analysis type **elfnewc** to clean the input parameters of the previous fit and **erase**

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	Element	Wavelength	
	[Ne V]	3426.0	emission
1	•[O II]	3727.0	emission
	H_θ	3798.6	emission or absorption
	H_ϵ	3828.9	emission or absorption, in blend with He II 3843
	[Ne III]	3868.7	emission
	H_ζ+He I	3888.9	emission or only H_ζ in absorption
2	• Ca II K	3933.6	absorption
	[Ne III]	3967.5	emission
3	• Ca II H	3968.5	absorption
4	• H_ϵ	3970.1	emission or absorption in blend with Ca II H
	Fe I	4045.8	absorption
5	• H_δ	4101.7	emission or absorption
6	• Ca I, g band	4226.7	absorption
	Fe I	4271.7	absorption
7	• G band	4300.4	absorption
	Fe I	4329.7	absorption
	He II	4338.6	emission, in blend with $H\gamma$
8	• $H\gamma$	4340.5	emission or absorption
	[O III]	4363.2	emission
	Fe I	4383.5	absorption
	He I	4471.5	emission
	He II	4685.7	emission
9	• H_β	4861.3	emission or absorption
	Fe I	4920.5	absorption
10	•[O III]	4958.9	emission
11	•[O III]	5006.8	emission
12	• Mg I blend	5175.4	absorption
13	• Ca+Fe (E band)	5269.0	absorption
	[FeVII]	5721.0	emission
	He I	5875.6	emission
14	• Na blend	5892.5	absorption
	He II	5977.0	emission
	[FeVII]	6087.0	emission
15	•[O I]	6300.3	emission
	[Fe X]	6375.0	emission
16	•[N II]	6548.1	emission
17	• H_α	6562.8	emission
18	•[N II]	6583.4	emission
19	•[S II]	6717.0	emission
20	•[S II]	6731.3	emission
	B-band	6867−6919	absorption

APPENDIX A

The mean star formation of spiral galaxies

An important quantity related to SFR history of galaxies is the birthrate parameter b. It is defined as the ratio of the SFR at the current time to the past SFR averaged over the age of the disk

$$b = \frac{SFR}{< SFR >_{past}} = \frac{SFR \times \tau_d}{M_d} \ (1 - R) \tag{13}$$

where M_d and τ_d are the stellar mass and age of the disk, respectively, and R is the return fraction, i.e. the fraction of mass in a stellar generation that is returned to the disk over its timelife (Tinsley, 1980).

The main problem in the determination of b is that the stellar mass of a disk cannot be measured directly, but rather must be estimated using the disk luminosity and an average M/L ratio for galaxies of a given type.

Mean b values for different morphological types are given in Fig. 8. The average past SFRs has been determined with: a) the *disk* M_d/L_v ratio listed in Table 2 NOTE : The M/L ratios have been converted in *disk* M/L ratios using the mean buldge/disk ratio published for a given Hubble type; b) the observed V luminosity of each galaxy; c) a disk age of 10 Gyr; d) a mean value of 0.4 for the return fraction R.

The number of steps listed above emphasizes the considerable uncertainty in b derived with this method.

Nevertheless, Fig. 8 shows a clear trend. *A smooth progression in the star formation history with the Hubble type is visible, with the ratio of current to average past SFR increasing from 0.001−0.1 in Sa disks to 0.5−2 in a typical Sc disk.* Moreover, from these results we learn that the trend in integrated properties are primarily due to changes in the evolutionary properties of *disks*, rather than changes in the bulge/disk ratio. Between types Sc and Sa, for example the mean ratio of current to past SFR in the *disk* decreases by at least a factor of 20, whereas the disk fraction decreases by only 25%.

APPENDIX B

How to measure the dust content and reddening correction

In Section 3 we have already underlined the uncertainties related to the reddening corrections we must apply to take into account the presence of dust in spiral galaxies. First of all the assumption made about the reddening curve, assumed to be that of our

Galaxy.

We have seen that the most widely used method to estimate the dust content is based on the relative strengths of the lower Balmer lines, H_α/H_β. By taking the gas emission lines as dust tracer one assumes that the emission from the gas comes from the same place as the emission from the ionizing stars, which generally is not the case, since the gas in a spiral galaxy is situated in a plane. In general, we must admitt we have only a meager knowledge of the real distribution of dust in emission-line galaxies. It seems quite likely that it is patchy and irregular, and thus that the assignment of a single value for the "extinction" is only a crude first approximation.

Neglecting at first order these uncertainties one can write the effect of reddening on the ratio H_α/H_β as :

$$\frac{I(H_\alpha)}{I(H_\beta)} = \frac{F(H_\alpha)}{F(H_\beta)} \times 10^{C[f(H_\alpha)-f(H_\beta)]} \tag{14}$$

where C is the measure of the amount of reddening (E(B−V) = 0.77 C), f(λ) is the reddening curve, I(λ) indicated the (unreddened) intrinsic flux and F(λ) the flux measured. Note that only the difference in optical depths at the two wavelengths enters in this equation; so the correction depends on the form of the interstellar extinction curve (with arbitrary normalization) and on the amount of extinction (C).

If the Whitford reddening curve as parameterized by Miller and Mathews (1972) is used (see Tab. 1) one obtains

$$C = 3.1\ (\log\frac{F(H_\alpha)}{F(H_\beta)} - \log\frac{I(H_\alpha)}{I(H_\beta)}) \tag{15}$$

For the intrinsic flux ratio for H II region-like objects we adopted the case B Balmer recombination decrement $I(H_\alpha)/\ I(H_\beta) = 2.85$ for $T = 10^4$ K and $N_e = 10^4\ cm^{-3}$.

For AGN we must taken into account that the harder photoionizing spectrum results in a large transition zone, or partly ionized region, in which H^0 coexists with H^+ and free electrons. In this zone collisional excitation is also important in addition to recombination collisional excitation. The main effect of collisional excitation is to enhance H_α. The higher Balmer lines are less affected because of their large excitation energies and smaller excitation cross sections. For this reason $I(H_\alpha)/\ I(H_\beta) = 3.1$

APPENDIX C

SFR indicator for high redshift galaxies : [OII]λ3727

We discuss here several aspects of the [OII]λ3727 emission in nearby galaxies which are most relevant to their application in surveys of faint objects. Kennicutt (1983) calibrated the relationship between the integrated H_α luminosity and total SFR (equation 5-6) in disk galaxies, and the spectrophotometry presented in Kennicutt (1992) can be used to derive a corresponding relation between [OII]λ3727 flux and SFR.

Practically, the calibration between SFR and H_α luminosity can be trasformed to [OII] luminosity once a mean values for the [OII]/H_α and [NII]λ6584/H_α ratios are known. From the study of a homogeneous sample of normal galaxies Kennicutt (1992) found mean value [OII]/$H_\alpha = 0.3$ and [NII]λ6584/$H_\alpha = 0.5$ resulting in an extinction-corrected calibration

$$SFR(total) \simeq 2.0 \times 10^{-41} L([OII]) \;\; M_\odot yr^{-1} \tag{16}$$

where L is the observed emission line luminosity in units of ergs s^{-1}.

One drawback of this relation for applications to distant galaxies is that they require a photometric measurement of the [OII]. But absolute line fluxes are difficult to measure in faint galaxies. However, the strong correlation between [OII] and H_α+[NII] *EWs* (Fig. 6) suggests that [OII] *can be used as a quantitative indicator of the SFR in a distant galaxy, in much the same way that H_α is used in nearby galaxies.* Among galaxies dominated by stellar photoionization (solid points) the data follow a mean relation *EW*[OII] = 0.4 *EW*(H_α), with a rms dispersion of $\sim$ 50%.

Kennicutt (1992) showed that an approximate SFR can be derived if the *EW* and integrated broadband magnitudes are known.

$$L([OII]) \sim 1.4 \pm 0.3 \times 10^{29} \frac{L_B}{L_{B(\odot)}} EW([OII]) \;\; ergs^{-1} \tag{17}$$

where the B luminosity is expressed in units of the Sun.

However, Fig.6 clearly shows that *the* [OII] *versus H_α correlation breaks down for galaxies with luminous active galactic nuclei.* These galaxies fall indeed into two classes, those with abnormally strong [OII] emission, independent of Balmer line strength, and those with strong Balmer, [NII] and [OIII] emission but weak emission in [OII]. The former most often are Seyfert 2.