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# The present-day galaxy population in spiral galaxies

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**Abstract.** Although there are many more stellar population studies of elliptical and lenticular galaxies, studies of spiral galaxies are catching up, due to higher signal to noise data on one hand, and better analysis methods on the other. Here I start by discussing some modern methods of analyzing integrated spectra of spiral galaxies, and comparing them with traditional methods. I then discuss some recent developments in our understanding of the stellar content of spiral galaxies, and their associated dust content. I discuss star formation histories, radial stellar population gradients, and stellar populations in sigma drops.

**Keywords:** Galaxies: spiral,Galaxies: stellar content, Galaxies: bulges
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## INTRODUCTION

Spiral galaxies are complicated systems, with a number of morphological components, and several types of stellar populations. With their, at times, violent star formation, with sometimes large amounts of dust extinction, and with relatively low surface brightness, they are difficult objects to study the stellar populations using integrated light. Studies of spiral galaxies are important, though, since our own Milky Way belongs to this class.

Important questions to study are: When did those galaxies form? Did galaxies form quickly, at high $z$, as is believed for massive elliptical galaxies? Or did star formation take a long time. Did bulges form first, in the same way as elliptical galaxies, before the disk? Or did they form from disk material? For a review see Kormendy & Kennicutt (2004).

Most of our knowledge about the stellar populations in spiral galaxies until recently has come from studies of our own Galaxy, from broadband color studies (e.g. de Jong & van der Kruit (1994), Peletier & Balcells 1996), from studies of ionized gas (see Kennicutt 1998) and from a few absorption line studies (e.g. Proctor & Sansom 2002). In recent years, though, many more studies are becoming available, increasing rapidly our knowledge about the stellar populations in spiral galaxies (e.g. Ganda et al. 2007, Peletier et al. 2007, Jablonka, Gorgas & Goudfrooij 2007, Moorthy & Holtzman 2006, Morelli et al. 2008, MacArthur et al. 2009).

In this short review I will discuss a few of the issues related to stellar populations in spiral galaxies. I will discuss their ages, their star formation histories, and the relation between the so-called sigma-drops and their stellar populations. I will also discuss extinction maps of a few late-type spirals. To start, I will address methods how people can obtain stellar populations information from unresolved spectra in an optimal way. Is it better to use Lick-style indices, or is it more efficient to directly fit the observed

spectra?

# HOW TO ANALYZE OPTICAL SPECTRA?

Stellar population synthesis of galaxies traditionally has been done using absorption line indices of e.g. the Lick system (Worthey et al. 1994). Ages, metallicities and abundance ratios of integrated spectra are determined by comparing indices with stellar population models. In recent years, however, the availability of full spectral energy distributions for the models (Vazdekis 1999, Bruzual & Charlot 2003) has made it possible to use the full spectral energy distribution. Some recent papers using full spectrum fitting are Koleva et al. (2008), Koleva (2009) and MacArthur et al. (2009). An important advantage of this method is that emission lines can be separated very well from the absorption line spectrum, making the assumption that the absorption line spectrum has to resemble a linear combination of stellar population models, convolved with an appropriate line of sight velocity distribution (LOSVD) (see Sarzi et al. 2006 for more details). This means that Balmer absorption lines, which are often accompanied by Balmer emission lines, can be determined much more accurately than before. But although it seems obvious that the latter method is preferable, one can still make arguments for using indices.

- Indices are easier to publish and to compare with literature values. It is a lot easier to compare 2 numbers than to compare 2 fits-files.
- It is much harder to understand a fit to a continuous spectral energy distribution than an index-index diagram. A nice example is given in Section 4 of MacArthur et al. (2009), where a misfit is seen between a galaxy spectrum and the models in the wavelength region from 5150-5450Å. This could be due to a flux calibration problem, or to the fact that the galaxy has a non-solar [Mg/Fe] abundance ratio. However, when plotting the same models in an index-index diagram of Mg b vs. an Fe index, one directly sees that the misfit is caused by a non-solar abundance ratio.
- The fits are ultimately limited by the quality of the models. So, if the parameter space covered by the models does not cover the parameters of the galaxy, unsatisfactory results are being obtained. At the moment, we don't have a reliable set of full model spectral energy distributions with a range in age and metallicity, but also in [Mg/Fe] abundance ratios. Models are available, however, for the line indices of the Lick system, from Thomas et al. (2003). For this reason some people prefer to use indices, rather than SED's. Even without models with non-solar abundance ratios, approximations for abundance ratios can be obtained, see e.g. Yamada et al. (2006). People, however, are working on making full model spectral energy distributions with variable abundance ratios, using synthetic spectral libraries, such as the one of Coelho et al. (2005).

To me the most important achievement of the full SED fitting method is that it is possible to obtain reliable star formation histories with multiple bursts. This requires a large wavelength range, an accurate treatment of the effects of velocity broadening, and excellent single age/metallicity (SSP) stellar population models. Koleva (2009) showed that she needs a combination of up to 4 SSP's per galaxy to fit the spectra of a sample of dwarf elliptical galaxies. Similar star formation histories are obtained if she fits these

spectra using a completely different and independent way, using STECKMAP (Ocvirk et al. 2006). Similar quality results are obtained by MacArthur et al. (2009) for a sample of spiral galaxies. Using indices, on the other hand, it is already difficult to determine whether the galaxy contains one or two SSP's (e.g. Serra & Trager 2007).

## STAR FORMATION HISTORIES AND RADIAL STELLAR POPULATION DISTRIBUTIONS

Thomas & Davies (2006) claim that small bulges of galaxies, with central velocity dispersions smaller than 100 km/s, have extremely low ages, sometimes smaller than 2 Gyr. Here it should be understood that they mean luminosity-weighted ages. On the basis of this they conclude that these bulges have been rejuvenated with at least 10-30% of the mass having recently formed. This result is questioned by MacArthur et al. (2009), who, with their more accurate stellar population modeling from full SED fitting, find a considerable old stellar population in all of their 8 galaxies ($\geq$ 70% in mass, bust mostly more than 80 or 90%. For galaxies with $\sigma_c \sim$ 60 km/s, the latter find an average luminosity-weighted age of 6 Gyr, much higher than Thomas et al. (2005). Ganda et al. (2007), for a sample of Sb-Sd galaxies, modeled their Lick-indices in the context of an exponential star formation history. Converting their best-fit e-folding time scales into average ages, MacArthur et al. (2009) showed that they correspond also to luminosity-weighted ages of $\sim$ 6 Gyr at $\sigma_c \sim$ 60 km/s.

Independent evidence of a large range in ages in bulges of spiral galaxies is given by the SAURON results of Peletier et al. (2007). In their sample of Sa and Sab galaxies they find objects for which the bulges are uniformly old, objects with young stellar populations in a small central region, others with young stars across the whole bulge, and bulges that contains rings forming large amounts of stars. Current wisdom in the literature is that there are two modes of star formation (Kennicutt 1998). The first manifests itself by a strong relation between the morphological type and the amount of star formation, as measured from H$\alpha$. This causes the average star formation rate to increase monotonically with morphological T-type. The second mode can be found in the circumnuclear regions of many spiral galaxies, which harbor luminous star-forming regions. The physical conditions in the circumnuclear star-forming discs are distinct in many respects from the more extended star-forming discs of spiral galaxies. The circumnuclear star formation is especially distinctive in terms of the absolute range in SFRs, the much higher spatial concentrations of gas and stars, and its burst-like nature (in luminous systems) (Kennicutt 1998).

Although the picture described above was derived primarily from H$\alpha$ images, Peletier et al. (2007) see exactly the behavior described above. The galaxies, all early-type spirals, and most of them of type Sa, show a much larger range in age than ellipticals and S0s, derived both from the index-index diagrams and from the Mg (or H$\beta$ )- $\sigma$ diagram. Also spatially, one sees that the younger stellar populations are concentrated near the center or in annuli suggestive of resonance rings (e.g. Byrd et al. 1994). The picture in these early-type spirals is consistent with all star formation taking place in the disc, and close to the center. In a different study, of a sample of edge-on S0-Sc galaxies, Jablonka et al. (2007), from minor axis spectra, find that outside the plane of the galaxy,

which they cannot investigate because of dust extinction, the stellar populations are very similar to those in ellipticals and S0's, with metallicity decreasing outward, and ages somewhat younger near the center of the galaxy. Putting together all the evidence from the different samples, it seems that the central regions of spiral galaxies consist of a spheroidal component (a classical bulge), with elliptical-like stellar populations, and a disk-like component (a pseudo-bulge), with a lower scale height, and generally younger stellar populations.

A galaxy population that has not been studied often has been the stellar populations in galactic bars. Martin & Roy (1994) concluded from ionized gas studies that global abundance gradients of spiral galaxies with bars are in general shallower than gradients of normal galaxies. No studies of gradients of absorption lines in reasonably-sized samples have been published until the recent work of Pérez et al. (2008), who show some interesting results: They find three different types of bars according to their metallicity and age distribution as a function of radius: 1) Bars with negative metallicity gradients. These show young/intermediate luminosity-weighted average ages ($< 2$ Gyr), and have amongst the lowest central stellar velocity dispersions. 2) Bars with zero metallicity gradients. These galaxies, without any gradient in their metallicity distribution along the bar, have negative age gradients (i.e younger populations at the end of the bar). 3) Bars with positive metallicity gradients, i.e. that are more metal rich at the ends of the bar. These galaxies are predominantly those with higher velocity dispersions and highest average ages.

## DUST EXTINCTION IN LATE-TYPE SPIRALS

When determining stellar populations, it is often also important to determine the amount of extinction in spiral galaxies. Given the recent renewed interest in this subject (Driver et al. 2007, Graham & Worley 2008) Ganda et al. (2009) decided to calculate central extinction maps of a number of Sb-Sd galaxies by combining SAURON Mg b absorption line maps, which are basically independent of extinction, with broad band HST $V - H$ color maps. The combination of color and line strength gives the color excess $E_{V-H}$ in a model-independent way, which can easily be converted to $A_V$. This method is in principle very powerful, but has not been applied much in the literature, because of the lack of well-calibrated line strength data. They find that the central $A_V$ ranges from 0 to 2 mag, with many galaxies being optically thick in the optical. The $V - H$ profiles show a lot of structure, mostly due to extinction, with much larger gradients than are generally displayed by early-type galaxies. One can conclude from this that in general color gradients cannot be used to determine stellar population gradients. I show the extinction maps of 5 of their galaxies in Figure 1.

## STELLAR POPULATIONS AND SIGMA DROPS

Galaxies with local velocity dispersion minima in their center (so-called sigma-drops) are found to be increasingly common. Current wisdom is, that they are relatively cold stellar disks that formed through secular processes in the disk. In a review in 2006,
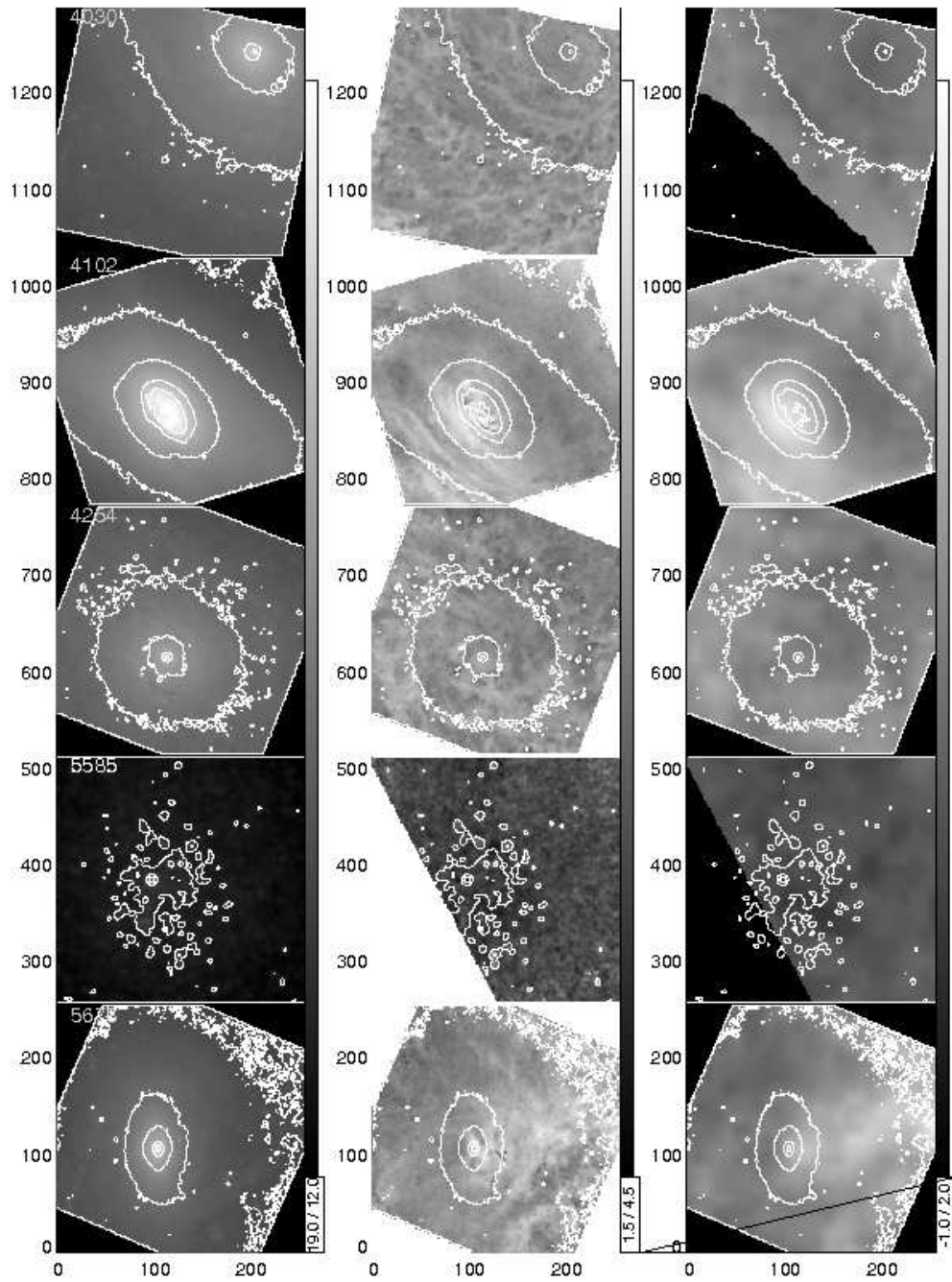
**FIGURE 1.** Extinction distribution for 5 of the 10 galaxies from Ganda et al. (2009) with HST in F606W and F160W. Left: surface brightness distribution in H. Middle: calibrated V-H color maps. Right: extinction maps from $V - H$ and Mg b. The ranges of the plots are shown in the lower right of each column of plots.

Emsellem (2006) gives a list of 25 spiral galaxies with sigma-drops. In the SAURON-papers of Ganda et al. (2006) and Peletier et al. (2007) another 21 are given out of a total combined sample of 42, indicating that about 50% of all spirals contains sigma-drops, first detected by Bottema (1989). As a comparison, Chung & Bureau (2004) revealed a sigma drop frequency of about 40% in a sample of 30 nearly edge-on S0-Sbc galaxies, which is consistent with the previous number of 50%. The 2-dimensional data of SAURON clearly confirm that the $\sigma$ drops are caused by central discs. In the 2-dimensional area where $\sigma$ is lower, the stars are always rotating faster than at larger radii.

The fact that we observe so many sigma-drop galaxies must imply that these disks are long-lived. These discs are formed as dynamically cold systems, and slowly heat up. As long as they are cold, and are responsible for a significant fraction of the light, they will produce $\sigma$ drops at any inclination, if they are dominating the light. This interpretation is consistent with N-body and SPH simulations of, e.g., Wozniak & Champavert (2006), who form discs from gas inflow towards the central regions of the galaxy and subsequent star formation.

The SAURON data offer a nice possibility to check whether these central disks are indeed long-lived, by measuring their stellar population ages. In Figure 10 of Peletier et al. (2007) the square root of the quadratic difference between the maximum and central velocity dispersion is plotted. This is a measure of the size of the central dip. If no dip is present this parameter is equal to zero. Here we see that, although the fraction of $\sigma$-drops for young galaxies is larger, very old central discs exist as well. They conclude that indeed central discs can survive long. McDermid et al. (2006) shows the age distribution of kinematically-decoupled cores (KDCs) in the SAURON/OASIS sample of early-type galaxies. All large-scale KDCs ($\sim$1 kpc), present in slow-rotating galaxies, appear old, while most small-scale KDCs ($\leq$ 300 pc), present in fast-rotating galaxies, appear young. Their interpretation is that they are also discs, which like any stellar population will slowly fade, until the surface brightness is low enough to be totally overcome by the main galaxy body. The sigma drops of spiral galaxies discussed here are extended (size $> 5''$), and mostly older than 1 Gyr. They might be similar to objects such as the central discs in giant ellipticals (for more discussion see McDermid et al. 2006).

## SUMMARY

In this short review I have discussed a number of recent developments in our under-standing of the stellar content of spiral galaxies, and their associated dust content. Here I briefly state the conclusions.

- Instead of using Lick-style indices, more and more people using full SED fit-ting methods to analyze galaxy spectra. These methods are becoming increasingly mature, and are clearly superior to the old methods for most applications. Using full SED fitting accurate detailed star formation histories can be determined. One should continue to realize that problems with the current stellar population models, such as the non-availability of SSP-models with non-solar abundance ratios, also

apply to the SED fitting method.

- The central regions of spiral galaxies show several components: a spheroidal component containing similar stellar populations as in elliptical galaxies and S0's, and a disk-like component, with complex star formation histories. About 50% of the galaxies contain central inner, fast rotating disks, that cause sigma-drops. The stellar populations in these inner disks can be both old or young.

- The comprehensive study by Pérez et al. of stellar populations along bars shows that there are 3 kinds of bars: those with negative metallicity gradients, those with positive metallicity gradients, and those with zero metallicity gradients, along which the age becomes younger towards the end of the bar.

- Using calibrated HST color maps and SAURON Mg b absorption line maps, Ganda et al. (2009) have made extinction maps that are almost model-independent. They show that Sb-d galaxies have central $A_V$ that ranges from 0 to 2 mag, with many galaxies being optically thick in the optical. The $V - H$ profiles show a lot of structure, mostly due to extinction, with much larger gradients than can be attributed to stellar population gradients.

## ACKNOWLEDGEMENTS

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