On the nature of early-type galaxies

Krajnović, D.

Citation

Krajnović, D. (2004, October 12). *On the nature of early-type galaxies*. Retrieved from https://hdl.handle.net/1887/575

Chapter 1

Introduction

1 Understanding the world

THE urge to comprehend and describe the world is a defining characteristic of mankind. One remarkable illustration of this urge is shown on the cover of this thesis. This ceramic vessel, with an ordered sequence of different symbols, is approximately 4500 years old. It was created by a craftsman of the *Vučedol* culture and excavated in 1978 in the town of Vinkovci in eastern Croatia. The classical Vučedol culture belongs to the European Neolithic period and was created by newly arrived Indo-European people. This widespread European culture was named after its central site on the river Danube in eastern Croatia. The meaning of the symbols on the vessel was a mystery until recently when Durman (2000) suggested they represent the different stellar constellations which dominated the Vučedol sky five millennia ago. The half-broken pot from Vinkovci is very likely the oldest European calendar, used by the people of Vučedol for the organisation of their every-day life [1].

Five thousand years ago, stock-raising people of the Panonic plane were looking at the night sky. They noticed regularities and formed an elaborate system to measure the passing of time. In this way, they were able to describe a crucial aspect of the world using primitive but straightforward astronomical observations. Nowadays, astronomy is a science, having undergone the process of transformation from *predicting the future* by early astrologers to *explaining the facts* by modern astronomers observed with telescopes and instruments using the laws of physics. Still, at the centre of the science of astronomy lies the same wish that led the Vučedol people: to comprehend, describe and tame the world around us.

Our methods are much more sophisticated, but the astronomical themes have changed as well. Astronomy had a profound influence on the Vučedol people giving them the calendar. It produced valuable information relevant for life. Unlike some other sciences in the present times, astronomy does not directly influence our everyday life anymore. Modern astronomical research is focused on processes that shape the Universe, starting from our Sun, its neighbours, the Milky Way, and other galaxies, to distant quasars and relics of the Big Bang. In a broader sense, the astronomy of today is an idealised pursuit of knowledge of the Universe. Complementary to this, astronomy also records mankind's perception of the world. The advances in astronomy are reflected in changes in philosophy and culture. In the 1960s the size of the Universe

---

[1] An in-depth description of the Vučedol culture and particularly the oldest European calendar is given in the exhibition catalogue The Vučedol Orion (Durman 2000).

was changing almost on a daily basis with discoveries of ever more distant quasars (e.g. Schmidt 1963). It seems a matter of time only before the first Earth-like planet outside the Solar system[2] will be discovered. The next step will be to search for life on such a planet. Our lives do not directly depend on astronomy anymore, but it does have a long term influence on the human society. Astronomy is our window into the complexity of the Universe. This thesis focuses on a particular aspect of astronomy: the formation and evolution of galaxies.

2 Galaxies of the early type

Galaxies were perhaps most elegantly described by Immanuel Kant in the 18th century as “island universes”. Neither he nor anybody else until the astronomers of the early 20th century knew what these island universes, that appeared like nebulae on the sky, actually were; what they were made of, or even how far they were from Earth. Observations with the Mount Wilson 100 inch telescope provided the first clues about the nature of galaxies. They are made of stars and they are at a great distance from our own “island universe”, the Milky Way. Galaxies come in different flavours and they are usually classified in four distinctive groups according to their apparent shape (see Fig. 1 of Nederlandse Samenvatting or Hrvatski sažetak). This classification scheme was introduced by Hubble (1936) and it is known as the Hubble sequence of galaxies (Hubble diagram or Hubble tuning fork are also frequently used terms). The sequence starts with *elliptical* galaxies that seemingly have little or no structure. At the other end are disc galaxies, very different with prominent spiral arms. They are usually called *spirals* emphasising their eye-catching structure. *Lenticular* galaxies (also simply called S0s) look like transition objects between ellipticals and spirals: they have a prominent disc without a significant spiral structure embedded in a nearly spherical distribution of stars. The fourth group of galaxies consists of all galaxies without a regular shape, appropriately called *irregulars*. When constructing the diagram, Hubble was led by the idea of galaxy evolution. Spiral galaxies with their complicated and easily visible structure were natural candidates for complex and evolved systems, while elliptical galaxies were obvious examples of simpler systems. Lenticulars were seen as a stage between the two classes. Although such reasoning is not valid anymore and galaxy evolution should be viewed the other way around (e.g. Kormendy & Bender 1996), the ellipticals and lenticulars are still called early-type galaxies and the spirals are, hence, known as late-type galaxies.

Galaxies are not made only of stars. They also contain gas and dust in different amounts that change with Hubble type: late-type galaxies are observed to have more gas and dust than early-types. A big discovery of the 1970s is that spiral galaxies are embedded in dark matter halos (Rubin & Ford 1970; Rogstad & Shostak 1972; Ostriker et al. 1974). It is believed that all galaxies have dark halos, but the observational evidence for dark halos around elliptical galaxies is not as decisive (Romanowsky et al. 2003). The nature of the dark matter is, however, still unknown, but the observations clearly show that most of the matter in the Universe ($> 90\%$) is non-baryonic, dark matter. Any theory of the formation and evolution of galaxies has to take this into account

---

[2] More then a hundred Jupiter-like gas giants orbiting other stars have already been found.

and explain the variety of morphologies and specific characteristics observed. Unfortunately, the timescales over which galaxies evolve is not comparable to the life span of an astronomer, who must act as a detective looking for evidence of the processes that shaped the observed galaxies. These processes are easily masked by frequent and intensive starformation which is common in late-type galaxies. By contrast, early-type galaxies are particularly well suited for investigation because they do not contain much gas and dust, and, having no recent star formation, retain fossil records of their formation history. Specifically, nearby ($<$ 50 Mpc) early-type galaxies are very interesting, since we are able to obtain accurate, spatially-resolved information (unfortunately not the individual stars, which is currently possible only for the nearest[3] galaxies).

Although generally fairly simple and uniform in appearance, early-type galaxies show a rich structure on a closer look. High-resolution observations are necessary to provide data that can be used to construct theoretical models of early-type galaxies. The observations can be from ground- or space-based telescopes, each contributing in a particular way. The goal is to construct theoretical models and test their description of the processes that shape galaxies with state-of-the-art observations. Indeed, the connection between theory and observations is very important because only by combining their different approaches it is possible to ascertain the nature of the early-type galaxies.

3 A brief guide through the formation and evolution of galaxies

Galaxies originate from fluctuations in the dark matter density of the early Universe. An area of higher density accretes material through gravitational interaction until the system becomes unstable and collapses dissipating energy into a small-scale object ($\sim 10^6$ $M_\odot$). According to the hierarchical scenario of galaxy formation (e.g. Press & Schechter 1974; Kauffmann & van den Bosch 2002) small systems merge to form larger and larger objects. These objects are made of gas, but are gravitationally dominated by the dark matter distributed in halos. The temperature of the gas (infalling or already present) is crucial. Stars can form only from cold gas, but gas is easily heated by several processes: motion in the gravitational potential of a galaxy, heating by the new-born stars and supernovae, and interaction with already heated (virialised) gas (e.g. Binney 2004). Heated systems are pressure supported and have a spheroidal structure, but in certain cases cold gas can fall into the equatorial plane forming stars and creating what can be observed today as disc galaxies (e.g. White & Rees 1978).

Early-type galaxies are thought to be formed in mergers of disc galaxies (Barnes & Hernquist 1996). The gas content of the resulting galaxy can be replenished by accretion from larger gaseous structures. This may result in formation of a new disc, renewed star formation and restoration of the galaxy into a late-type. However, each merger will heat the stellar component and form spheroidal structures. These pro-

---

[3] Nearby is a relative term in astronomy. About 40 galaxies (Courteau & van den Bergh 1999), of which only one (the Andromeda galaxy) is comparable in size to Milky Way, make up the *Local Group* of galaxies and are our nearest neighbours, within approximately 1 Mpc. Galaxies discussed in this thesis, which we consider “nearby”, are at distances of 5 to 40 Mpc, but astronomers use the term “nearby” for object which are up to a few times further. Beyond that begins the far Universe.

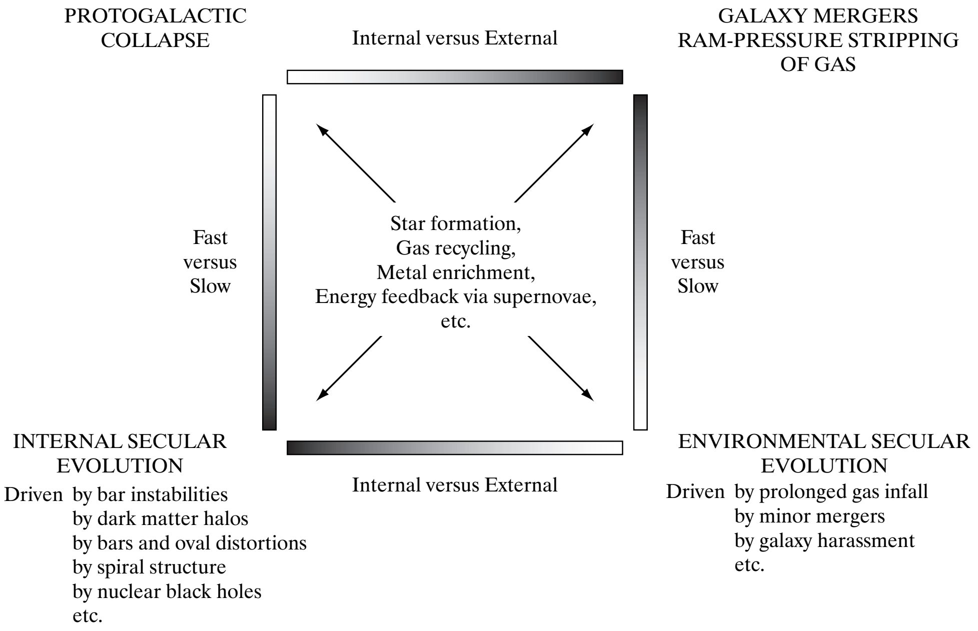

Figure 1 — Morphological box of processes of galactic evolution (from Kormendy & Kennicutt 2004). Processes are divided horizontally into internal (left) and external (right); and vertically into fast (top) and slow (bottom). Fast processes happen on a dynamical time scale, while slow processes last several rotation periods. The processes at the centre happen in all types of galaxy formation scenarios.

cesses can repeat several times depending on the environment thus changing the shape of galaxies. Confirmation of this scenario comes from ever-improving N-body simulations (e.g. van Albada 1982; Navarro et al. 1996; Naab & Burkert 2003) and observations that in the dense cluster systems there are more early-type than late-type galaxies. Similarly, at higher redshifts ($z \sim 0.5$), the relative contribution of disc galaxies in clusters is larger (e.g. Combes 2004). In this way the Hubble sequence of galaxies should be interpreted from right to left, starting from spiral and finishing with elliptical galaxies.

Galaxy evolution, however, is not restricted to the relatively fast processes of galaxy mergers and interactions. They also evolve on longer time scales. This secular evolution of galaxies is driven by a number of internal and external conditions and by slow processes including: bar instabilities (see Section 8.2 for more details), the shape of the dark matter halos, the presence of supermassive nuclear black holes, supernova winds, spiral structures, gas infall, minor mergers, etc. An instructive classification of the different processes that operate in galaxy formation and evolution is presented in Fig. 1, taken from Kormendy & Kennicutt (2004). As stressed by these authors, in the present-day Universe, both short and long timescale processes are important, although the secular evolution will dominate in the future (expanding) Universe.

A theory of the formation and evolution of galaxies has to be able to explain all observational facts. Early-type galaxies are our probes into the distant past of the Universe and their observed properties can be used to constrain and validate the theoretical models of the processes that shaped the galaxies. For example, N-body simulations of hierarchical galaxy formation produce galaxies that have triaxial dark halos (Frenk et al. 1999). By contrast, observations of the luminous parts of elliptical galaxies show that, although there are true triaxial galaxies, the majority are only mildly triaxial, almost consistent with axisymmetry (Franx et al. 1991; see also Fig. 2 for preliminary results from `SAURON` observations). This dark versus luminous matter discrepancy is a stimulus to both theoretical models and observations in search for the true answer. Galaxy formation and evolution is complex and consists of many pieces that have to be well understood individually and assembled together into a coherent picture. Each chapter of this thesis is devoted to a somewhat distinct issue of galaxy evolution. Details on each aspect are given in the following section.

4 Activity in early-type galaxies

The centres of many early-type galaxies emit non-stellar radiation. This so-called 'activity' is confined to a region within a few parsecs from the centre, and such centres are usually called *active galactic nuclei* (AGN). The same acronym is often used to also specify the whole host galaxy. AGN are sometimes even called *monsters* (Gunn 1979), because they radiate enormous amounts of energy into the surrounding space (e.g. E $\sim 10^{61}$ erg in total). Generally, AGN appear to be very diverse, and a classification according to their properties is very broad. The bestiary of AGN includes radio-loud and radio-quite quasars, optically violent quasars, broad and narrow line galaxies, Seyferts (of type 1 and 2) and low-ionisation narrow-line regions (LINERs)[4], each with different defining characteristics (e.g., Krolik 1999). However, there are also many similarities and properties that lead to a unification scheme and a paradigm that the activity of all AGNs is produced by matter falling onto a supermassive black hole that resides at the bottom of the galaxy's potential well (Hoyle & Fowler 1963; Lynden-Bell 1969). Different species of AGN are then the manifestation of the same process viewed from different angles and under different conditions.

Distant AGN are on average several orders of magnitude stronger than the AGN residing in the nearby galaxies. Quasars and most of the radio-loud AGN are found at higher redshifts (the population peaks at redshifts of 2-3) while the local population of AGN consists mostly of Seyferts and LINERs. Most quasars reside in early-type galaxies which look similar to normal nearby elliptical galaxies (Ho et al. 1997; McLure et al. 1999, 2000). Still, some amount of activity is present among many of the nearby galaxies, although often of barely detectable intensity: about 40% of all nearby galaxies show some AGN activity and $\sim$ 60% of nearby early-type galaxies show AGN characteristics (Ho et al. 1997). In a somewhat limited sample of nearby galaxies we found that 47% of early-type galaxies are active at the level of 0.1 mJy (Chapter 2, Krajnović & Jaffe 2002).

If some nearby galaxies are direct descendants of high-redshift quasars and other AGN, the supermassive black holes should still be present in the nuclei of many galaxies (Soltan 1982). This is now largely accepted and confirmed by the search for black holes in nearby galaxies over the last two decades. The success of the hunt for supermassive black holes was largely the result of the unprecedented spatial resolution offered by the HST. Masses of about thirty supermassive black holes ranging between $10^6 - 10^9$ $M_\odot$ have been measured to date (e.g. Tremaine et al. 2002). A tight correla-

---

[4] LINERs are, however, not necessarily connected to AGN.

tion between black hole mass and velocity dispersion (of the central spheroidal part of the galaxy) suggests that the formation and evolution of supermassive black holes and their host spheroids are connected (Haehnelt et al. 1998; Richstone et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Monaco et al. 2000). Perhaps most galaxies go through a violent quasar period that starts with intensive accretion of (cold) gas which falls towards the black hole in the centre of the galaxy. The violent process that creates the quasar's light also increases the mass of the black hole, which can reach the observed values in a few times 10^9 years (for details see Yu & Tremaine 2002). However, as mentioned before, in nearby galaxies, the supermassive black holes are dormant or barely emitting radiation. The activity then, clearly, has to be connected to the existence of fuel material that can be accreted by the supermassive black hole.

Large-scale dust and gas are not often seen in early-type galaxies (but more often in lenticulars than in ellipticals), and the amount of available fuel is less compared to the high-redshift objects. However, higher-resolution imaging by means of the HST shows that dust is common on smaller scales in nearby early-type galaxies (van Dokkum & Franx 1995; Verdoes Kleijn et al. 1999; Rest et al. 2001; Tran et al. 2001). Dust indicates the presence of gas: the fuel for the AGN engine. An immediate question arises: how is the presence of dust and gas connected to the activity in nearby early-type galaxies? Observations presented in this thesis (Chapter 2) suggest that although galaxies without dust have a somewhat lower probability of AGN activity, the existence of dust in HST images is certainly not a necessary condition for the existence of an AGN. On the other hand, a recent study (Kauffmann et al. 2003) showed that, although the AGN host galaxies morphologically look very similar to present-day ellipticals, they often have a young stellar population component and in this way differ dramatically from nearby ellipticals. There might be more subtle differences between the nearby normal and AGN host galaxies.

There are many processes at play that determine the activity in galactic nuclei. Major mergers and interaction between galaxies (more common at higher redshifts) act as reservoirs of fuel for starving central engines. Minor mergers and motion of gas in the gravitational potential of a galaxy perturbed by bar instabilities can have a crucial role in transporting gas to the bottom of the potential well and the black hole. The amount of gas and the specific physics of accretion will define the resulting AGN (quasar, radio galaxy with jets, LINER, etc), as well as the influence of the AGN on the evolution of the whole galaxy. Detailed observational and theoretical studies of the accretion processes in galactic nuclei as well as secular evolution are still needed to understand the nature of the activity in galaxies.

5 Nuclear stellar discs in early-type galaxies

The central regions of galaxies are not easily observed from the ground because of the limiting influence of atmospheric seeing on the observations. Early-type galaxies often look simple and featureless on ground-based images. High-resolution observations with HST have revolutionised our knowledge of the nuclear regions (approximately inner 1 kpc) of early-type galaxies (Jaffe et al. 1994; van den Bosch et al. 1994; Lauer et al. 1995; Carollo et al. 1997a; Carollo et al. 1997b; Rest et al. 2001). Among several discoveries, these observations revealed the existence of small nuclear stellar discs, with sizes of the order of 1″. These discs can be remarkably thin (30 pc compared with 300 pc of disc in our galaxy) and are often related in some way to the large scale discs, but are not necessarily connected to them since outer discs often have an inner cut-off radius (Scorza & Bender 1995; Scorza & van den Bosch 1998; van den Bosch 1998; Chapter 3 of this thesis). These features clearly point to a complex formation scenario, possibly involving secular evolution. Studies of larger samples of galaxies showed that they occur in about 50% of early-type galaxies, and since discs are easily found only if seen near to edge-on (Rix & White 1990), they might be very common features.

Discs are generally dynamically simpler than spheroids. They are very flattened axisymmetric structures dominated by rotation which can be used to determine the galaxy's potential (assuming circular motion of stars in the disc). It is easy to determine the inclination of a disc and correct for its effects. As a result, nuclear stellar discs can be used to measure the mass of the black hole in the centre of the galaxy. Perhaps the most interesting consequence of the existence of nuclear discs is the fact that they can be used as probes of galaxy evolution scenarios.

There are two likely scenarios for nuclear disc formation. Discs could be the end result of a minor merger of galaxies. In this scenario a satellite galaxy interacts with the bigger host galaxy and the captured gas is transported to the centre where it settles in (one of) the principal planes of the host galaxy. Frequently the infalling gas has enough angular momentum to form a disc. Interaction with the black hole can result in an AGN, but also stabilises the disc leading to the formation of stars (Loeb & Rasio 1994). An alternative scenario, that, unfortunately, can result in similar observational properties, invokes the secular evolution of galaxies, where bar instabilities play a critical role in transporting gas towards the centre of the galaxy, creating a nuclear disc (e.g. van den Bosch & Emsellem 1998). Discriminating between these two very different scenarios (positioned in opposite corners of Fig. 1 - upper right and lower left) is difficult. However, it is probably a combination of both scenarios that occurs in galaxies leaving signatures in the observed structures. Generally, the different formation paths of a nuclear stellar disc and the rest of the galaxy, are expected to result in differences in the age and metallicity of their stellar component.

In edge-on galaxies, where nuclear stellar discs are most easily detected, the effects of bar instabilities are hard to observe. A range of different observations, including imaging and spectroscopy are necessary to investigate the effects of the above mentioned processes. Chapter 3 presents such a comprehensive observational study of galaxies with four previously-known nuclear stellar discs. Assembling all observational evidence from Chapter 3, there are no clear proofs of bar-driven evolution in any of the observed galaxies, although some are strong candidates. Our long-slit spectroscopic data are of high resolution, but they cover only a small fraction of the nuclei and discs. Additional observations of the two-dimensional kinematic properties and their connection to the distribution of line-strengths (metal content and age of stellar populations) would probably offer decisive insight in the formation of the nuclear stellar discs.

6 Integral-field spectroscopy

Recent developments in instrument design have introduced a new acronym in the astronomical jargon, IFU (integral-field unit), specifying an instrument capable of producing simultaneous spectroscopic measurements over an area (field) rather than along a slit. There are several possible ways to construct an IFU. All IFUs have a mechanism for separating the light coming from the sky, whilst retaining the information of the sky coordinates from which each separated light beam has originated. In this way, it is possible to observe an extended astronomical object, as with traditional imaging, but at the same time to extract spectral information from different parts of the object. An alternative is to stack a number of long-slit measurements together, but since the spectra are not taken simultaneously it is generally not considered to be an IFU measurement, nor it is anywhere near being efficient in time. Due to the time limitations, the multiple-slit approach has been used for only a few galaxies (e.g. Statler & Smecker-Hane 1999). The final observational product of an IFU is a three-dimensional data-cube with spatial and spectral information (x, y, λ). These data can be presented as two-dimensional kinematic and line-strength maps[5], bringing a wealth of spatially-resolved information of observed objects (e.g. Bacon et al. 1995, 2001).

The true power of IFUs is revealed when observing objects with complicated morphologies whose properties cannot be accurately measured with just one or two long-slits. Galaxies of all types, and merging objects, are typical examples. Astronomical objects, in general, are three-dimensional structures, but we see them only as two-dimensional projections onto the sky. With an IFU we can efficiently observe the projected distribution of light and obtain spectra integrated along the line-of-sight. This gives valuable additional information for understanding and constraining the internal structure of the observed objects. Chapters 4 and 5 of this thesis analyse the integral-field observations of early-type galaxies showing their advantages and usefulness for the study of internal structure of galaxies.

IFU observations are currently mostly used to observe nearby galaxies (e.g. the `SAURON` project de Zeeuw et al. 2002), with the purpose to construct dynamical models of galaxies, and constrain the distribution of their stellar content. The diversity of the science done with IFUs is, however, continuously growing: solar system bodies, planetary nebulae, young stellar objects, supernova remnants, extragalactic supernovae, merging galaxies, gravitationally-lensed galaxies and deep-field studies to name a few (e.g. Swinbank et al. 2003; Bower et al. 2004). The next generation of IFUs mounted on 8-10m telescopes with a wide field coverage and assisted with adaptive-optics systems, will be capable of observing objects at higher redshifts, probing earlier stages of galaxy formation and evolution.

7 Two-dimensional kinematic maps

Assuming there are no objects in front and behind an observed stellar system, spectroscopic observations can be used to constrain the system's kinematic properties. Each

---

[5] It is important to note that radio astronomers have observed two-dimensional velocity fields for more then thirty years. The IFU technology is, however, a relative novelty in optical astronomy.

(unresolved) star will contribute to the observed spectrum. Its absorption lines will be Doppler shifted according to the star's line-of-sight (LOS) velocity. Generally, stars have different velocities and directions of motion which are reflected in the integrated spectrum as a broadening of the (combined) absorption lines. The distribution of stellar velocities along the line-of-sight can be described by a *broadening function*, usually called the line-of-sight velocity distribution (LOSVD)[6]. Commonly, the LOSVD is decomposed into orthogonal functions, e.g., as a *Gauss-Hermite series*. This expansion exploits the fact that LOSVDs are to first order well-approximated by a Gaussian, so that the deviations can be described by a small number of Gauss-Hermite terms. The spectra of bright nearby galaxies can be used to extract the first four terms of the Gauss-Hermite series measuring: the mean velocity V, the velocity dispersion σ, and two Gauss-Hermite coefficients, h_3 and h_4. These coefficients measure the asymmetric (h_3) and symmetric (h_4) departures of the LOSVD from a Gaussian (van der Marel & Franx 1993; Gerhard 1993).

Observing nearby galaxies with an IFU provides two-dimensional kinematic maps, i.e., maps of their kinematic moments V, σ, h_3, h_4. The maps offer a wealth of information important for understanding the shape and properties of a galaxy, as well as for constructing dynamical models that describe its internal structure. However, the important information has to be extracted efficiently from the maps. A simple and straightforward approach is to use a harmonic expansion along concentric annuli to describe each two-dimensional map. The result is a set of coefficients describing the amplitude and orientation of the kinematic moments. These parameters are related to the intrinsic properties of the observed galaxy. A similar approach is used in photometric analysis of optical surface brightness images (e.g. Lauer 1985; Jedrzejewski 1987). Chapter 4 presents a general method for analysing and describing two-dimensional kinematic maps of early-type galaxies. Due to the similarities with the surface photometry of early-type galaxies, we called our technique *kinemetry*[7].

The internal kinematic moments of stationary triaxial systems show a high degree of symmetry. Following these symmetries we distinguish between even and odd moments. This is reflected in the symmetries of the observed kinematic maps. Generally, maps of even moments are *point-symmetric* [$\mu_e(r, \theta + \pi) = \mu_e(r, \theta)$], while maps of odd moments are *point-anti-symmetric* [$\mu_o(r, \theta + \pi) = -\mu_o(r, \theta)$], where μ_o and μ_e are arbitrary odd and even moments of the LOSVD, respectively, with dependence on radius r and angle θ. As a consequence, the terms of the harmonic expansion will behave accordingly: the even terms will be nearly zero for maps of odd moments and the odd terms will be nearly zero for maps of even moments. Alternatively, the observed symmetry of kinematic maps makes it possible to ascertain the symmetry of the density distributions and kinematics of the observed galaxy. If all kinematic maps of a galaxy show an additional signature of *mirror-(anti)-symmetry* [$\mu_e(r, \pi - \theta) = \mu_e(r, \theta)$ for even and $\mu_o(r, \pi - \theta) = -\mu_o(r, \theta)$ for odd moments] the galaxy will be consistent with being intrinsically axisymmetric. An example of the application of kinemetry on velocity maps is shown in Fig. 2. Using kinemetry we analysed velocity maps of 48

---

[6] Sometimes, the broadening function is simply called the velocity profile (VP)

[7] Again, radio astronomers pioneered a similar although less general technique (Begeman 1987; Schoenmakers et al. 1997)

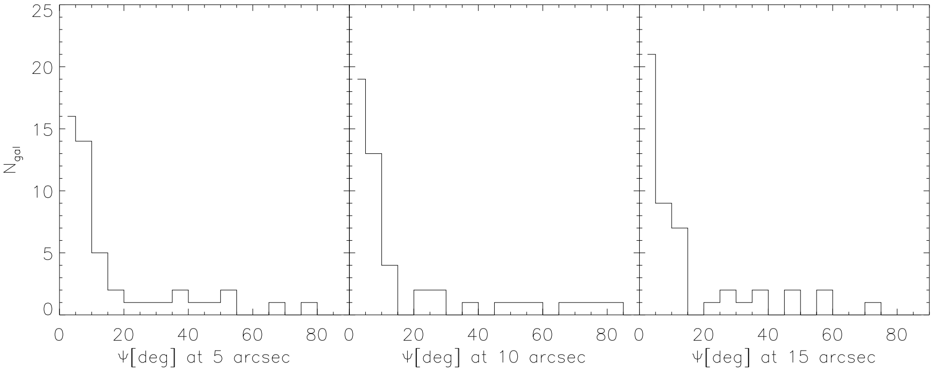

Figure 2 — Histogram of the kinematic misalignment angle ψ measured for a sample of 48 E/S0 galaxies from the `SAURON` survey (de Zeeuw et al. 2002). The angle ψ is the angle between the photometric and kinematic axes (Franx et al. 1991). The kinematic major axes were measured using *kinemetry* (Chapter 4) at radii of $5''$, $10''$ and $15''$. The photometric major axis was determined using the inner $15''$ of the galaxy. About 35% of galaxies have small misalignment angle ($< 5^\circ$) and are consistent with axisymmetry at the given radii. The measured number of galaxies consistent with axisymmetry increases with radius, showing that the central regions are often very different from the rest of the galaxy.

galaxies from the `SAURON` survey, extracting the position angle of the maps, the so-called *kinematic angle*. Comparing this angle with the photometric position angle, the position angle of the light distribution, we can measure the apparent (projected on the sky) misalignment between the two angles, which constrains the intrinsic shape of the galaxy (Franx et al. 1991).

Kinemetry is a powerful tool for describing and analysing kinematic maps, but it can be also used as a noise filter. Its most obvious usage is on the mean velocity maps which were already studied theoretically (e.g. Franx et al. 1991; Statler 1991, 1994a; Statler & Fry 1994; Statler 1994b; Arnold et al. 1994), but, as presented in Chapter 4, kinemetry can also be applied to higher moment maps. Kinemetry can hence be used to extract useful information from the observed objects, and so to serve as a bridge between observations and theoretical modelling.

8 Dynamical models

A full understanding of the intrinsic shape and structure of galaxies can only be obtained through detailed dynamical modelling. Construction of such models is a theoretical undertaking which is based on the general laws of physics and incorporates ideas and assumptions about the investigated objects (or processes). However, only models which can reproduce the observations (experiments) can be considered as physically meaningful. Theoretical constructions are limited only by the inventiveness of the human mind, but the natural world around us is unique. In order to explain it, theory must agree with the observations.

8.1 Stellar dynamical models

The structure and dynamical properties of a collisionless stellar system are fully specified by its phase space density or distribution function, $f = f(\vec{x}, \vec{v}, t)$, where $\vec{x}$ and $\vec{v}$ label the position and velocity of stars at a time t. The distribution function must be non-negative, must satisfy the continuity equation and if it describes a system in a steady state (no changes with time), it does not depend on the time variable t. The distribution function, however, cannot be measured directly because individual stars are resolved only in the nearest stellar systems and observations cannot be expected to be complete. The distribution function can be partially constrained by observations of the object's surface brightness, which is the line-of-sight projection of the density of the system. Unfortunately, the deprojection of the surface photometry is non-unique (Williams 1981; Rybicki 1987) and the density itself does not fully constrain the possible orbits of stars. On the other hand, the projected kinematics (two-dimensional observation with large coverage of the object) provide a significant additional constraints on the stellar distribution function.

The six-dimensional phase-space $(\vec{x}, \vec{v})$ dependence of the distribution function can be substituted by, in the most general case, a dependence on only three conserved quantities. The Jeans theorem (Jeans 1915; Lynden-Bell 1962) states that f is a function of the *isolating integrals of motion*, functions of $\vec{x}$ and $\vec{v}$ that are constant along every orbit in a given gravitational potential. The reduction from six to at most three variables is a significant simplification. The actual number of integrals of motion depends on the symmetry of the potential. Spherical potentials, with an isotropic velocity distribution, correspond to a one-integral distribution function: $f = f(E)$ having energy E as the integral of motion[8]. Axisymmetric potentials conserve the energy and the one component of the angular momentum, L_z, but most of the orbits in a realistic potential are regular and also conserve an effective third integral of motion, I_3 (Contopoulos 1960, Ollengren 1962). This quantity is non-classical in the sense that it cannot be analytically known, except in the rather special, but instructive case of Stäckel potentials (Kuzmin 1956; de Zeeuw 1985a), so we expect $f = f(E, L_z, I_3)$. The most complicated is the case of the triaxial potential. Non rotating triaxial potentials[9] conserve energy and two non-classical integrals, I_2 and I_3 (Schwarzschild 1979; de Zeeuw 1985b).

In Chapter 5 we construct axisymmetric models that conserve two- and three-integrals of motion, (E, L_z) and (E, L_z, I_3) respectively. Two-integral models can be constructed following the Hunter & Qian (1993) method. Since both integrals are analytically known, it is possible to derive a distribution function, $f = f(E, L_z)$. On the other hand, the distribution function of the three-integral models, cannot be computed directly due to the nature of the unknown third integral, I_3. An elegant numerical method for the construction of three-integral dynamical models, however, was introduced by Schwarzschild (1979, 1982). In this method, the galaxy is built as an ensemble of stellar orbits, that are assumed to be independent. Each orbit contributes with

---

[8] In spherical potentials it is also possible to construct models of the form $f = f(E, \vec{L})$ and $f = f(E, L^2)$. The former have a preferred axis and are usually not considered, while the latter conserve the amplitude of angular momentum, but not its direction.

[9] Bars provide examples of rotating triaxial systems. Although there is lack of observational evidence, elliptical galaxies are generally considered to have nearly stationary figures.

certain mass and kinematic properties. Determining a superposition of orbits that best reproduces the observed galaxy (surface brightness and kinematics), one obtains an orbital representation of the galaxy. Since the method results in a superposition of orbits, specified by the integrals of motion (E, L_z, I_3), it is possible to construct an equivalent form of the distribution function, $f = f(E, L_z, I_3)$, describing the galaxy. The three-integral method is more general than the two-integral method and produces more realistic models of the observed galaxies. The finite number of orbits, however, is much smaller than the number of stars and even sometimes than the number of observables used to constrain the model (10000 orbits vs 10^{11} stars vs ~ 5000 kinematic observables in the case of integral-field data), and the effects of the discreteness of the method have to be properly understood. Schwarzschild's method has been successfully applied in a number of cases to recover the mass of central black holes, the mass-to-light ratios, and to describe the internal (kinematic) structure of the modelled galaxies (e.g van der Marel et al. 1998; Cretton et al. 1999; Cretton & van den Bosch 1999; Cappellari et al. 2002; Verolme et al. 2002; Gebhardt et al. 2003).

Properties of the observed galaxies are not known *a priori*, and we do not know whether the models recover the true galaxy parameters and its correct orbital structure. One way of testing the modelling results is to construct artificial models of galaxies for which one knows all details to arbitrary accuracy. Two-integral models are useful for this purpose and one can use them as inputs to the three-integral models. Comparing the results with known inputs, one can attach confidence levels to the three-integral models. The physics of stellar motion belongs to classical Newtonian dynamics, but the observed galaxies are complex systems with innumerable stars. A proper understanding of the dynamical structure of galaxies continues to pose a challenge.

8.2 Dynamical models of gas

In the interstellar medium of galaxies some of the gas, if present, is ionised by the radiation of stars or an AGN and gaseous emission-lines are often easily observed. In an axisymmetric potential, gas eventually settles in a disc in the equatorial plane of the galaxy. Gas is said to be dynamically *cold* if it is observed in a disc configuration where non-selfintersecting clouds of gas move in circular orbits in the equatorial plane. This situation is observed in galaxies such as M87 (van der Marel 1994) and NGC 7052 (van den Bosch & van der Marel 1995), but gas is often observed with irregular morphologies and disturbed kinematics. In these cases the treatment of gas needs to go beyond gravitational forces, by including hydrodynamical effects. There are also intermediate cases[10] when gas is observed in a regular disc but its velocity dispersion is high (gas is not cold) and is comparable with the measured rotation velocity.

The velocity dispersion of a settled (cold) gas disc is expected to be $\sim 10\,\mathrm{km\,s^{-1}}$ (Osterbrock 1989) due to its temperature ($\sim 10^4$K in galaxies without any or with low ionisation activity). However, the measured velocity dispersion is often larger for reasons that are presently not well understood. In some cases it is possible to assume

---

[10] The gas disc can also display spiral structure, which happens when the mass of gas is large and self-gravity becomes important, or, generally, as a result of a perturbation in the potential, like a bar-instability or interaction with a neighbour galaxy.

that the velocity dispersion is the result of *local turbulence* which does not disturb the bulk flow of gas rotating at nearly the circular velocity (e.g. van der Marel & van den Bosch 1998; Verdoes Kleijn et al. 2000) and the gas bulk motion is explained with cold gas disc models. Alternatively, the non-thermal component of the velocity dispersion comes from collisionless gravitational motion of the gas: gas clouds act as stars moving on self-intersecting orbits. In this case one can use the epicyclic approximation[11] to the motions of gas clouds and evoke the so-called asymmetric drift correction to the circular motion of collisionless gas clouds (Cinzano & van der Marel 1994; Cretton et al. 2000; Barth et al. 2001; Aguerri et al. 2003; Debattista & Williams 2004; Chapter 5 of this thesis). Neither of these approaches are entirely physically justified, although these approximations often do reproduce observations.

Flattened potentials are prone to perturbations which disrupt their shape. An example of such a perturbation is the bar instability, which is typical for disc systems (roughly two thirds of disc galaxies have bars). Bars are triaxial structures that rotate with a *pattern speed*, Ω_p. Stars, having their own rotation speed, Ω, feel the gravitationally pull of the bar potential which perturbs their orbits. This effect is seen in the existence of several resonances in the galaxy, one of which happens when the rotational speed of the bar (pattern speed, Ω_p) matches the speed of the stars and it is called *corotation* (CR, $\Omega_p = \Omega$). Other strong resonances are: *Inner Lindblad* (ILR, $\Omega_p = \Omega - \kappa/2$), *Outer Lindblad* (OLR, $\Omega_p = \Omega + \kappa/2$) and *Ultra-Harmonic* (UHR, $\Omega_p = \Omega + \kappa/4$), where κ is its radial epicyclic frequency. The allowed orbits are aligned with the bar between the ILR and CR, and perpendicular to the bar between the CR and OLR. Each time a resonance is crossed stellar orbits change direction perpendicularly(Binney & Tremaine 1987; Athanassoula 1992).

The existence of resonances will also shape the gas disc pushing gas away from corotation towards the Inner and Outer Lindblad resonances. Unlike stars, gas can collide and the orbits of cold gas change smoothly between resonances. In strong bars this will result in the formation of gas rings, followed by starformation. On the other hand weak bars do not betray their existence so easily and are hard to detect. Often they are not visible on images of galaxies. Twists of velocity contours on two-dimensional maps are, however, likely signatures of bars. For an in-depth review of bars see Sellwood & Wilkinson (1993) and Kormendy & Kennicutt (2004).

Observations of gas kinematics in many galaxies is simpler than measuring the stellar kinematics, because the gas emission-lines are bright and easier to detect than stellar absorption lines. Dynamical models of gas discs can be used to determine the properties of the gravitational potential, its symmetry, inclination as well as mass of the central black hole. Gas particles move in the same potential as the stars and so dynamical models of gas and stars should give the same results, or at least can be used to verify each other and their underlying assumptions. Observation and models of gas shed light on the evolutionary stage of the observed host galaxy.

---

[11] The epicyclic approximation is valid in the limit of small radial oscillations.

9 Outline of this thesis

The research presented in this thesis deals with different aspects of galaxy formation and evolution. It is based on observations with ground- and space-based telescopes, in the radio and optical wavelength range. The work focuses on nearby early-type galaxies and their properties, ranging from nuclear structures and activity to global kinematic and dynamical properties. A short outline of each chapter is given here.

Chapter two presents a survey of an optical/IR selected sample of nearby E/S0 galaxies with and without nuclear dust structures on the HST images. The observations were obtained with the Very Large Array radio interferometer at 3.6 cm to a sensitivity of 100 μJy. The Radio Luminosity Function (RLF) of the observed galaxies down to $\sim 10^{19}$ W Hz^{-1} shows that $\sim 50\%$ of these galaxies have AGNs at the surveyed level. The space density of these AGN equals that of starburst galaxies (at the same luminosity). The main result of the survey is that several dust-free galaxies have low-luminosity radio cores, and their RLF is not significantly less than that of the dusty galaxies. This implies that the existence of dust visible with the HST is not a necessary requirement for the existence of an AGN in nearby early-type galaxies.

Chapter three discusses observations of four nearby early-type galaxies with previously known nuclear stellar discs. The galaxies were observed using two instruments on-board the Hubble Space Telescope. The Wide Field Planetary Camera 2 observed NGC 4128, NGC 4621 and NGC 5308. The Space Telescope Imaging Spectrograph observations also included NGC 4570. Numerous nuclear colour features were detected, such as: a red nucleus in NGC 4128, a blue nucleus in NGC 4621, and a blue disc in NGC 5308 only 30 pc thick. Additionally, a blue disc-like feature with position angle $\sim 15^\circ$ from the major axis in NGC 4621, possibly related to the kinematically decoupled core discovered by Wernli et al. (2002), was found. In NGC 5308 there is evidence for a blue region along the minor axis. A blue transient on the images of NGC 4128 at a position of $0\farcs14$ west and $0\farcs32$ north from the nucleus was discovered. The nature of the transient is not certain, although it could have been a supernova.

The extracted kinematic profiles belong to two distinct groups: fast (NGC 4570 and NGC 5308) and kinematically disturbed rotators (NGC 4128 and NGC 4621). The discovery of a kinematically decoupled core in NGC 4128 is also reported. Galaxies have mostly old (10-14 Gyr) stellar populations with a large spread in metallicities (sub- to super-solar). In this chapter possible formation scenarios are discussed, including bar-driven secular evolution and the influence of mergers, which can explain the observed colour and kinematic features. The available evidence unfortunately cannot entirely distinguish between the two cases, and it is likely that a combination of processes may have shaped the galaxies.

Chapter four describes a general method for analysing and describing two-dimensional kinematic maps of galaxies observed with integral-field spectrographs. The method is based on the harmonic expansion of kinematic maps along concentric annuli in the plane of the sky similar to those used in observations of cold gas (e.g. Begeman 1987; Franx et al. 1994; Schoenmakers et al. 1997) and in the surface photometry approach to broad-band imaging, but without assuming any *a priori* knowledge of the galaxies (Lauer 1985; Jedrzejewski 1987; Franx et al. 1989). We call it *kinemetry*. Using symmetries of the kinematic moments (even moments are point-symmetric and odd moments are point-anti-symmetric) it can be used to parametrise trends and detect properties of the host galaxies and as a diagnostic tool of underlying symmetries of the gravitational potential. Kinemetry is also a powerful filter. The method is presented, tested and applied to model maps of kinematic moments as well as actual `SAURON` observations of a few galaxies. An interesting, preliminary, finding is that the velocity maps of nearby early-type galaxies are very similar to the velocity maps of discs. This is somewhat unexpected since early-type galaxies are (flattened) spheroidal systems, and warrants a detailed study of a larger sample of two-dimensional velocity maps of early-type galaxies.

Chapter five contains a detailed dynamical study of the E4 galaxy NGC 2974. The observations include ground- and space-based imaging and integral-field spectroscopy with `SAURON` , which were used to extract stellar and gaseous kinematics. The kinematic maps are quantified with *kinemetry* and the large-scale kinematics show only small deviations from axisymmetry (which are, however, visible in the central $3''$ of the gas kinematic maps). General axisymmetric dynamical models for the stellar motions are compared to the observations of the galaxy. The three-integral models ($f = f(E, L_z, I_3)$) presented here are based on Schwarzschild's orbit superposition method. The models are constructed to determine the mass-to-light ratio, Υ, and inclination, i, of the galaxy, as well as its internal orbital structure. The best fitting parameters are $\Upsilon = 4.5 \pm 0.1$ $\mathrm{M}_\odot / \mathrm{L}_\odot$ and $i = 65 \pm 2.5°$.

The results of the stellar dynamical modelling are tested on the gas kinematics. The inclination of the gas disc can be obtained from its velocity field. The measured value, $i = 58 \pm 5°$, is close to the stellar dynamical value. The observed gas disc was modelled with the asymmetric drift approximation in the potential derived from the stellar models. The gas models are able to accurately reproduce the large-scale kinematic structure, but fail to do so in the inner $3''$, which are influenced by the non-axisymmetric perturbations.

A large section of Chapter 5 is devoted to tests of the three-integral method, as well as the importance of the two-dimensional maps for constraining models of observed galaxies. The robustness of the method is tested against two-integral models with analytic DF ($f = f(E, L_z)$). We used these models to test: (i) the influence of the radial coverage of the kinematic data on the internal structure, (ii) the recovery of the test model parameters (Υ,i), and (iii) the recovery of the test model DF.

Results show that increasing the radial coverage of the kinematic data from $1r_e$ to $2r_e$ does not change the internal structure within $1r_e$. The results of the dynamical models of the `SAURON` observations of NGC 2974 would not change if the radial coverage would be increased by a factor of 2. Also, three-integral models can accurately recover the mass-to-light ratio. Although the models are also able to constrain the inclination of the test model formally, the apparent differences between the models are very small (as in the case of real observations). Under a careful examination, it is possible to choose the best model by eye, but the decisive kinematic features are below (or at) the level of the systematics in the data (e.g. template mismatch) and might be influenced by uncertainties in the models (e.g. regularisation or variations in the sampling of observables with orbits). This suggests a degeneracy of models with respect to the recovery of inclination. More general tests on other galaxies and theoretical work is needed for a better understanding of this issue. Finally, three-integral models are able to recover the true input DF, to the level of the discreteness effects in the models.

10 Future prospects

Basic concepts of galaxy formation and evolution, as well as the cosmological background, are generally agreed upon and can be used as a working paradigm of modern astronomy. We believe we understand the processes that shape and control the nature and nurture of galaxies. N-body simulations and three-integral Schwarzschild models are able to simulate interactions and create representative models of observed galaxies, respectively. We may even boast that we understand the global picture and certainly it is true that observations and theory are starting to agree. However, there are a number of loose ends to be tied and questions to be answered.

The advent of integral-field units opens a detailed view into the structure of galaxies. Two-dimensional spectroscopic observations are clearly very important in constraining the models (kinematic maps), but also complementary to the photometric observations for distinguishing the stellar populations of galaxies (maps of line-strength indices). This is shown by the results of the `SAURON` survey of nearby galaxies (Verolme et al. 2002; Emsellem et al. 2004; Chapter 5 of this thesis; McDermid et al. 2005; Kuntschner et al. 2005; Cappellari et al. 2005, Sarzi et al. 2005). The next natural step is to look back in time, using new two-dimensional spectroscopic glasses that are being commissioned on the 8-10 meter class telescopes, towards higher redshifts and earlier epochs when interactions between galaxies were more frequent and galaxies look different from today. Comparing the properties of galaxies at redshifts between 0.5 and 1, when the Universe was between three-quarters and half its current age respectively, with the properties of nearby galaxies will show the actual evolution of galaxies.

Another approach is to observe (with the same new instruments on the largest telescopes) nearby objects that were not often studied up to now due to technical limitations. One such class of objects are small galaxies with low-surface brightness. These galaxies are interesting because they have not yet participated in merger events (in a way they are real fossils of Universe), they have experienced only limited starformation, and clearly reside in different potential wells than large luminous galaxies. Dynamical models of dwarf galaxies will also give low-redshift constraints to cosmological models.

There are possible advances on the modelling front. Firstly, models of triaxial galaxies which also fit the observed kinematics will soon be ready (van den Ven et al. in prep). They are more complex than axisymmetric models, due to the large parameter space that describes a triaxial body. On the other hand, models of real galaxies must include both kinematic and line-strength information, because, after all, galaxies are not made of one population of stars and a true distribution function is dependent on the age and metallicity of stars. The modelling approach here differs from the conventional approach: instead of fitting LOSVDs, new models will directly fit observed spectra giving simultaneous information about the kinematics and distribution of stellar populations (Cappellari et al. in prep.).

The impact of the Hubble Space Telescope on modern astronomy cannot be properly acknowledged in a single paragraph (nor in a much thicker book!), however, at this moment of its uncertain future and perhaps even a premature demise, and, here, thinking of the next steps, it is important to remember its profound role in the increase of our understanding of the Universe. Discoveries related to the nearby early-type galaxies are numerous, some of which are presented and discussed in the following chapters. Modern ground-based telescopes are almost an order of magnitude larger than HST and have a huge advantage in the collecting power: very important in astronomy where every photon counts. The new technology of adaptive optics with natural or laser guide stars is almost completely able to correct for atmospheric seeing (although currently at longer wavelengths only) and scientific observations from the ground are entering a promising new era. From this point of view we can be satisfied and encouraged because new observations will surely bring new excitements. Still, HST will remain a unique human eye into the vastness of the Universe.

References

Aguerri J. A. L., Debattista V. P., Corsini E. M., 2003, MNRAS, 338, 465

Arnold R., de Zeeuw P. T., Hunter C., 1994, MNRAS, 271, 924

Athanassoula E., 1992, MNRAS, 259, 328

Bacon R., Adam G., Baranne A., Courtes G., Dubet D., Dubois J. P., Emsellem E., Ferruit P., et al. 1995, A&AS, 113, 347

Bacon R., Copin Y., Monnet G., Miller B. W., Allington-Smith J. R., Bureau M., Marcella Carollo C., Davies R. L., et al. 2001, MNRAS, 326, 23

Barnes J. E., Hernquist L., 1996, ApJ, 471, 115

Barth A. J., Sarzi M., Rix H., Ho L. C., Filippenko A. V., Sargent W. L. W., 2001, ApJ, 555, 685

Begeman K. G., 1987, Ph.D. Thesis, University of Groningen

Binney J., 2004, astro-ph/0407238, to appear in Phil. Trans. Roy. Soc.

Binney J., Tremaine S., 1987, Galactic Dynamics. Princeton, NJ, Princeton University Press, 1987, 747 p.

Bower R. G., Morris S. L., Bacon R., Wilman R. J., Sullivan M., Chapman S., Davies R. L., de Zeeuw P. T., et al., 2004, MNRAS, 351, 63

Cappellari M., Verolme E. K., van der Marel R. P., Verdoes Kleijn G. A., Illingworth G. D., Franx M., Carollo C. M., de Zeeuw P. T., 2002, ApJ, 578, 787

Carollo C. M., Franx M., Illingworth G. D., Forbes D. A., 1997a, ApJ, 481, 710

Carollo C. M., Danziger I. J., Rich R. M., Chen X., 1997b, ApJ, 491, 545

Cinzano P., van der Marel R. P., 1994, MNRAS, 270, 325

Combes F., 2004, astro-ph/0406306

Contopoulos G., 1960, Zeitschrift fur Astrophysics, 49, 273

Courteau, S., van den Bergh, S., 1999, AJ, 118, 337

Cretton N., de Zeeuw P. T., van der Marel R. P., Rix H-W., 1999, ApJS, 124, 383

Cretton N., Rix H-W., de Zeeuw P. T., 2000, ApJ, 536, 319

de Zeeuw P. T., Bureau M., Emsellem E., Bacon R., Carollo C. M., Copin Y., Davies R. L., Kuntschner H., et al.,2002, MNRAS, 329, 513

de Zeeuw P. T., 1985a, MNRAS, 216, 273

de Zeeuw P. T., 1985b, MNRAS, 215, 731

de Zeeuw P. T., 2001, in Black Holes in Binaries and Galactic Nuclei, p. 78, eds. Lex Kaper, Edward P. J. van den Heuvel, Patrick A. Woudt, Springer

Debattista V. P., Williams T. B., 2004, ApJ, 605, 714

Durman A. 2000, The Vučedol Orion, Exhibition Catalogue, Zagreb 2000

Ferrarese L., Merritt D., 2000, ApJ, 539, L9

Franx M., Illingworth G., de Zeeuw P. T., 1991, ApJ, 383, 112

Franx M., Illingworth G., Heckman T., 1989, AJ, 98, 538

Franx M., van Gorkom J. H., de Zeeuw P. T., 1994, ApJ, 436, 642

Frenk, C. S., White, S. D. M., Bode, P., Bond, J. R., Bryan, G. L., Cen, R., Couchman, H. M. P., Evrard, A. E., Gnedin, N., et al. 1999, ApJ, 525, 554F

Gebhardt K., Bender R., Bower G., Dressler A., Faber S. M., Filippenko A. V., Green R., Grillmair C., et al., 2000, ApJ, 539, L13

Gebhardt K., Richstone D., Tremaine S., Lauer T. R., Bender R., Bower G., Dressler A., Faber S. M., et al., 2003, ApJ, 583, 92

Gerhard O. E., 1993, MNRAS, 265, 213

Gunn J. E., 1979, in Active galactic nuclei, Cambridge, Cambridge University

Haehnelt M. G., Natarajan P., Rees M. J., 1998, MNRAS, 300, 817

Ho L. C., Filippenko A. V., Sargent W. L. W., 1997, ApJ, 487, 579

Hoyle F., Fowler W. A., 1963, MNRAS, 125, 169

Hubble E. P., 1936, The Realm of Nebulae, Yale University Press

Hunter C., Qian E., 1993, MNRAS, 262, 401

Jaffe W., Ford H. C., O'Connell R. W., van den Bosch F. C., Ferrarese L., 1994, AJ, 108, 1567

Jeans J. H., 1915, MNRAS, 76, 70

Jedrzejewski R. I., 1987, MNRAS, 226, 747

Kauffmann G., Heckman T. M., Tremonti C., Brinchmann J., Charlot S., White S. D. M., Ridgway S. E., Brinkmann J., et al., MNRAS, 346, 1055

Kauffmann G., van den Bosch F., 2002, Scientific American, 286, 36

Kormendy J., Bender R., 1996, ApJ, 464, L119

Kormendy, J., Kennicutt, R, C., 2004, astro-ph/0407343, ARAA, in press

Krajnović D., Jaffe W., 2002, A&A, 390, 423

Krolik J. H., 1999, Active galactic nuclei : from the central black hole to the galactic environment, Princeton, N. J. : Princeton University Press, 1999

Lauer T. R., 1985, MNRAS, 216, 429

Lauer T. R., Ajhar E. A., Byun Y.-I., Dressler A., Faber S. M., Grillmair C., Kormendy J., Richstone D., et al., 1995, AJ, 110, 2622

Loeb A., Rasio F. A., 1994, ApJ, 432, 52

Lynden-Bell D., 1962, MNRAS, 124, 1

Lynden-Bell D., 1969, Nature, 223, 690

McLure R. J., Dunlop J. S., Kukula M. J., 2000, MNRAS, 318, 693

McLure R. J., Kukula M. J., Dunlop J. S., Baum S. A., O'Dea C. P., Hughes D. H., 1999, MNRAS, 308, 377

Monaco P., Salucci P., Danese L., 2000, MNRAS, 311, 279

Naab T., Burkert A., 2003, ApJ, 597, 893

Navarro J. F., Frenk C. S., White S. D. M., 1996, ApJ, 462, 563

Ollongren A., 1962, Bull. Astron. Inst. Neth., 16, 241

Osterbrock D. E., 1989, Astrophysics of gaseous nebulae and active galactic nuclei, University Science Books, 1989, 422 p.

Ostriker J. P., Peebles P. J. E., Yahil A., 1974, ApJ, 193, L1

Press W. H., Schechter P., 1974, ApJ, 187, 425

Rest A., van den Bosch F. C., Jaffe W., Tran H., Tsvetanov Z., Ford H. C., Davies J., Schafer J., 2001, AJ, 121, 2431

Richstone D., Ajhar E. A., Bender R., Bower G., Dressler A., Faber S. M., Filippenko A. V., Gebhardt K., et al., 1998, Nature, 395, A14

Rix H., de Zeeuw P. T., Cretton N., van der Marel R. P., Carollo C. M., 1997, ApJ, 488, 702

Rix H., White S. D. M., 1990, ApJ, 362, 52

Rogstad D. H., Shostak G. S., 1972, ApJ, 176, 315

Romanowsky A. J., Douglas N. G., Arnaboldi M., Kuijken K., Merrifield M. R., Napolitano N. R., Capaccioli M., Freeman K. C., 2003, Science, 301, 1696

Rubin V. C., Ford W. K. J., 1970, ApJ, 159, 379

Rybicki G. B., 1987, in IAU Symp. 127: Structure and Dynamics of Elliptical Galaxies, p 397, ed. P. T. de Zeeuw (Reidel, Dordrecht)

Schmidt M., 1963, Nature, 197, 1040
Schoenmakers R. H. M., Franx M., de Zeeuw P. T., 1997, MNRAS, 292, 349
Schwarzschild M., 1979, ApJ, 232, 236
Schwarzschild M., 1982, ApJ, 263, 599
Scorza C., Bender R., 1995, A&A, 293, 20
Scorza C., van den Bosch F. C., 1998, MNRAS, 300, 469
Sellwood J.A., Wilkinson A., 1993, Rep. Prog. Phys., 56, 173
Soltan A., 1982, MNRAS, 200, 115
Statler T. S., 1991, AJ, 102, 882
Statler T. S., 1994a, ApJ, 425, 458
Statler T. S., 1994b, ApJ, 425, 500
Statler T. S., Fry A. M., 1994, ApJ, 425, 481
Statler T. S., Smecker-Hane T., 1999, AJ, 117, 839
Swinbank, A. M., Smith, J., Bower, R. G., Bunker, A., Smail, I., Ellis, R. S., Smith, G. P., Kneib, J.-P. et al., 2003, ApJ, 598, 162
Tran H. D., Tsvetanov Z., Ford H. C., Davies J., Jaffe W., van den Bosch F. C., Rest A., 2001, AJ, 121, 2928
Tremaine S., Gebhardt K., Bender R., Bower G., Dressler A., Faber S. M., Filippenko A. V., Green R., et al., 2002, ApJ, 574, 740
van Albada T. S., 1982, MNRAS, 201, 939
van den Bosch F. C., 1998, Ph.D. Thesis
van den Bosch F. C., Emsellem E., 1998, MNRAS, 298, 267
van den Bosch F. C., Ferrarese L., Jaffe W., Ford H. C., O'Connell R. W., 1994, AJ, 108, 1579
van den Bosch F. C., van der Marel R. P., 1995, MNRAS, 274, 884
van der Marel R. P., 1994, MNRAS, 270, 271
van der Marel R. P., Cretton N., de Zeeuw P. T., Rix H-W., 1998, ApJ, 493, 613
van der Marel R. P., Franx M., 1993, ApJ, 407, 525
van der Marel R. P., van den Bosch F. C., 1998, AJ, 116, 2220
van Dokkum, P. G., Franx, M., 1995, AJ, 110, 2027
Verdoes Kleijn G. A., Baum S. A., de Zeeuw P. T., O'Dea C. P., 1999, AJ, 118, 2592
Verdoes Kleijn G. A., van der Marel R. P., Carollo C. M., de Zeeuw P. T., 2000, AJ, 120, 1221
Verolme E. K., Cappellari M., Copin Y., van der Marel R. P., Bacon R., Bureau M., Davies R. L., Miller B. M., et al., 2002, MNRAS, 335, 517
Wernli F., Emsellem E., Copin Y., 2002, A&A, 396, 73
White S. D. M., Rees M. J., 1978, MNRAS, 183, 341
Williams T. B., 1981, ApJ, 244, 458
Yu Q., Tremaine S., 2002, MNRAS, 335, 965