Chapter 1

Introduction

1.1 Measuring the Universe

Most human cultures have directed their attention towards the "heavens" very early during their development. From the daily practical aspects of this interest, astronomy emerged as the "exact science" of the early western civilization. The global and more abstract aspects of the interest for the sky, on the contrary, were mostly the realm of philosophy and religion. The desire to understand the physical characteristics of the Universe, however, led not only to many interesting cosmogonies and philosophical theories, but also to a number of remarkable scientific achievements that are to be considered the first examples of observational cosmology. Well known are the works of Aristarchus of Samos (4^{th} century BC), who measured the relative distances of the Sun and the Moon from the Earth, and their relative sizes; of Eratosthenes (3^{rd} century BC), who measured the Earth circumference; and of Hipparchus of Nicaea (2^{nd} century BC), who measured the precession of the equinoxes, and the absolute distance of the Moon from the Earth.

Cosmology nevertheless was not ready to become a science in its own right, and for a long time the only widely accepted description of the Universe was based on Ptolemy's abstract assembly of epicycles, equants and deferents, all enclosed into an Aristotelian sphere of fixed stars. Significant changes were introduced only during the period beginning in the middle of the 16^{th} century, with the Copernican revolution, and ending at the beginning of the 17^{th} century, with the invention of the telescope. The greatly enhanced light gathering power that the telescope provided over the naked eye opened the entire Galaxy to astronomical studies. The understanding of the physical properties of individual stars and of the entire Galaxy steadily improved during the following three centuries, and the first distances were measured outside the solar system (J. Michell obtained an estimate of the distance of Vega in 1784, and the first reliable parallax measurement was obtained by F.W. Bessel in 1838).

Finally, during the first three decades of the 20th century, with the help of astronomical photography, astronomy was able to move past our Galaxy and into the "realm of the nebulae". It was recognized that the so-called nebulae are galaxies comparable in size and mass with our own, and the first systematic attempts were made at determining redshifts and distances to those galaxies (E. Öpik obtained the first reliable estimate of the distance to M31 in 1922). At the same time A. Einstein was publishing his theory of General Relativity, and when the connection between astronomical observations (in particular the redshift measurements that pointed towards an expanding Universe) and Friedmann solutions of Einstein equations was recognized, modern cosmology was born.

A number of different cosmological models has been proposed during the last 60 years. Here we assume that an adequate description of the Universe is provided by the standard "Hot Big Bang" model. The main elements of this model are:
1) the mass distribution in the Universe is homogeneous in the large-scale average;
2) the Universe is expanding, as described by Hubble's law $dl/dt = H_\circ l$;
3) the dynamics of the expansion are described by the theory of General Relativity;
4) the Universe expanded from a hot dense state where its mass was not dominated by the baryonic component that is dominant instead at the present epoch.
The mathematical models that describe such a Universe are generally called Friedmann-Lemaître models. Another assumption we make, not necessarily implied by the Hot Big Bang model, is that organized structures in the Universe (galaxies, clusters and superclusters of galaxies) are formed and grow in time as the result of gravitational instability.

In the Friedmann-Lemaître models there are three free parameters, the Hubble constant $H_\circ$, the density parameter $\Omega_\circ$ (or the closely related deceleration parameter $q_\circ$), and the cosmological constant λ, that must be observationally derived, before a complete description of the Universe is obtained. Quite naturally, therefore, for a long time the main objective of observational cosmology was the determination of the values of $H_\circ$ and $\Omega_\circ$ (the possibility of a non-zero cosmological constant has been considered only in the more recent past). Then, over the last two decades, the focus of research has moved from the global picture of the Universe to its details. While the search for the values of $H_\circ$ and $\Omega_\circ$ is not yet completed, today's interests are centered on the processes of structure formation and evolution. In the standard cosmological scenario, small density fluctuations in the early Universe led to the gravitational collapse of galaxies, clusters, and superclusters of galaxies. This dynamical process resulted into an amplification of those fluctuations, and into large-scale motions of galaxies, because of gradients in the gravitational potential field. To understand this evolution we need to study the details of the mass distribution in the Universe. From the observational point of view this can be done using the cosmic microwave background (CMB) and the fluctuations in its intensity, redshift surveys, and redshift-independent distance measurements, with the closely related peculiar motion determinations.

The very existence of the CMB is the most important single element in support of the standard Hot Big Bang model. Presently, after the simple detection of the CMB has become almost a routine exercise, the efforts in this field are directed towards the measurement of fluctuations in the CMB intensity. The strongest of such fluctuations presents a clear dipole signature, and is generally interpreted as being the result of the motion of our Galaxy with respect to a reference frame in which the CMB intensity is isotropic. Much weaker fluctuations in the CMB intensity have been now detected (the COBE satellite providing the first unambiguous detection), and the study of these fluctuations carries great potential for accurate measurements of the cosmological parameters, and of the matter and radiation distribution in the early universe. So far the main limitation for this kind of studies has been in our technological development. The amplitude of the fluctuations is so minute that they escaped detection for almost 3 decades, and still their measurement is a formidable observational challenge. A new generation of satellites specifically devoted to CMB measurements (like the Plank Explorer currently under development) will be needed to fully exploit the potential of CMB fluctuations for cosmological studies.

Redshift surveys, after being instrumental in obtaining the knowledge that the Universe is expanding, are now being used to obtain detailed maps of the distribution of the luminous mass in the Universe. At the most elementary level, redshifts can be translated into distance measurements using Hubble's law, and they can therefore provide a first approximation three-dimensional map of the galaxy distribution. At higher levels of complexity it is possible to take into account deviations from the smooth and uniform expansion of the Universe that are produced by mass concentrations like clusters and superclusters of galaxies. Using an iterative scheme to correct the observed redshifts for the presence of peculiar motions, it is possible to derive both the density and peculiar velocity fields. It is also possible to use different approaches in the effort to quantify the characteristics of the spatial distribution of galaxies, measuring the so-called galaxy correlations functions (that measure the amount of clustering of galaxies), or the power spectrum of the galaxy distribution. The main limitation of redshift surveys is in that they are necessarily tied to the galaxy distribution, in a Universe that is believed to be dominated by dark matter not necessarily associated with galaxies.

Redshift-independent distance measurements were very important in establishing the modern cosmological ideas (providing both the final "proof" that the nebulae are galaxies like our own, and that fundamental cornerstone of observational cosmology that is Hubble's law). Their present importance is in the fact that they can be used to overcome the main limitation of redshift surveys. The combined use of redshifts and redshift-independent distances allows the measurement of deviations from the smooth and uniform expansion of the Universe, what we usually call peculiar motions or peculiar velocities. The origin of these peculiar velocities is thought to be related to inhomogeneities in the density field, and their amplitude is directly related to the amplitude of the density fluctuations. Therefore the peculiar velocity field can be used to obtain a map of the total (dark plus luminous) mass distribution in the Universe. The main limitations of redshift-independent distance measurements are the limited accuracy with which those distances can be measured, and the fact that they require a substantially bigger observational effort than pure redshift measurements.

1.2 Redshift-independent distance measurements

Ideally one would like to have some "standard candle" (or standard rod) to measure redshift-independent distances. A standard candle (rod) would be a class of objects easily detectable over a large range of distances, all with the same intrinsic luminosity (size), so that their apparent brightness (angular size) could be used to measure directly their distance. In the absence of perfect standard candles, a number of methods has been developed to climb the "cosmological distance ladder" with redshift-independent methods, out to cosmologically significant distances (see for example Rowan-Robinson 1985). The ideal method should provide high accuracy, i.e. it should exhibit small dispersion in the predicted distance, it should be applicable over a large range of distances, and it should have a well understood physical base. So far no method has been developed that satisfies all of the above requirements. Among the available methods (see Jacoby et al. 1992 for a review), those that have been most extensively utilized for the measurement of peculiar velocities are the Tully-Fisher (TF) relation (Tully & Fisher 1977) applied to spiral galaxies, and the $D_n - \sigma$ or Fundamental Plane (FP) relation (Dressler *et al.* 1987; Djorgovski & Davis 1987), applied to elliptical and lenticular galaxies.

These are similar methods, both based on the correlation between a photometric distance-dependent parameter (total magnitude for the TF, and galaxy size for $D_n - \sigma$ and FP) and a spectroscopic, distance-independent quantity (rotation velocity for the TF, stellar velocity dispersion for $D_n - \sigma$ and FP; a third distance-independent parameter, surface brightness, explicitly enters into the FP relation). Relative ease of application, fair accuracy (the uncertainty in the distance prediction of a single galaxy is 15 – 25%), and the fact that they can span a large distance interval (from the Local Group out to galaxies with redshift greater than 0.2; see for example van Dokkum & Franx 1996; Vogt *et al.* 1993, 1996) are a unique combination of positive characteristics that so far only TF, $D_n - \sigma$ and FP can offer, and this is the main reason behind the widespread use of these methods.

Although the TF and FP relations can be generically understood in terms of virial equilibrium, the astrophysical details of these relations are hidden behind the poorly understood processes of galaxy formation and evolution, and they are to be considered as empirical ones. In practice, distances are measured comparing single objects with a template relation, which is assumed to have universal validity. Also, because of the uncertainty on the value of the Hubble constant, and because the number of nearby galaxies that could be used for an absolute calibration of the template relations is small, these relations are most commonly used to derive only relative distances. In the following, the term distance is therefore often used as an abbreviation for "recession velocity corrected for peculiar motions", in a manner that should appear obvious within the given context.

The TF was originally introduced as a correlation between the total photographic (blue) magnitude of a spiral galaxy and its rotation velocity, as measured by the width of the HI 21 cm line (Tully & Fisher 1977). The latter has remained the favorite tool to derive the rotation velocity for TF diagrams, even though also optical (Hα) rotation curves have been successfully used for this purpose. Blue magnitudes have been generally abandoned, instead, in favor of magnitudes measured at longer wavelengths, where photometric measurements are facilitated by the smoother appearance of the disk of spiral galaxies, and also by the fact that dust extinction is somewhat less significant. Multiaperture H-band magnitudes were first introduced (Aaronson, Huchra & Mould 1979), but they were then substituted by R and I band magnitudes, because of the advantages offered by CCD photometry over photometric photometry.

For elliptical galaxies the path towards the best distance-indicator has been somewhat longer. Originally a relation between B-band luminosity and the stellar velocity dispersion was introduced (Faber & Jackson 1976), analogous to the TF. This relation presented a larger dispersion than the one typical of the TF, and was therefore less useful for distance measurements. Two improved relations were later proposed, the so-called $D_n - \sigma$ and FP relations (Dressler *et al.* 1987; Djorgovski & Davis 1987). These are two different ways to express the same relation among the parameters that characterize elliptical and lenticular galaxies. The FP is a correlation among the galaxy stellar velocity dispersion, effective radius (the radius within which is contained half the light of the galaxy) and effective surface brightness (the mean surface brightness within the effective radius). The $D_n - \sigma$ relation reunites the two photometric parameters into one, an isophotal radius measured at a fixed (but somewhat arbitrary) isophotal level. Stellar velocity dispersions are most often derived by measuring the broadening of the Mg Ib lines at $\lambda \simeq$5175 Å. Photometric parameters have been measured using most photometric bands, from the B-band in the optical, to the K-band in the near infrared, because early-type galaxies are almost dust-free and therefore extinction is not important in this case.

Because the $D_n - \sigma$ and FP relation are conceptually identical, it is possible to choose either one of them to measure redshift-independent distances for E and S0 galaxies. Here the choice is in favor of the FP relation, because of an easier statistical handling of measurement uncertainties and of bias effects.

1.3 Measuring distances and peculiar velocities with the TF and FP relations

1.3.1 Physical basis

Mass is certainly one of the most important parameters that regulate the processes of galaxy formation and evolution, and therefore also their present time appearance. As a result, there exist many correlations that link together parameters like galaxy luminosity (at all wavelengths), size, star formation (for spiral galaxies), metal and dust content, and many others, that are ultimately correlations with the galaxy mass. These "scaling relations" can be generally summarized saying that "bigger galaxies have more of everything" (Kennicutt 1989).

The TF and FP are examples of these scaling relations. Their physical basis is in the virial equilibrium (or quasi-equilibrium) of the galaxy components (see for example Djorgovski, de Carvalho & Han 1988). For a galaxy bound by Newtonian gravity, potential and kinetic energy are linked by the relation

$$\frac{GM}{< R >} = k_E \frac{< V^2 >}{2} \tag{1.1}$$

where M is the galaxy mass, $< R >$ a suitable mean radius, $< V^2 > /2$ the mean kinetic energy per unit mass, and k_E the virialization constant ($k_E > 1$ for a bound system, $k_E = 2$ for a system in virial equilibrium). We can relate the observed "size" of a galaxy (defined as the effective radius r_e of an elliptical galaxy, or the disk scale-length r_d of a spiral galaxy) with the mean physical radius $< R >$ through the relation $r = k_R < R >$. In the same way, the observed galaxy internal velocity V (the stellar velocity dispersion of an elliptical galaxy, or the maximum rotation velocity of a spiral galaxy) can be related to the mean kinetic energy as $V^2 = k_V < V^2 >$. The two parameters k_R and k_V thus reflect the density structure, including the coupling between dark and visible matter, and the kinematical structure of the galaxy. Finally, the relation among galaxy observed luminosity L, mean surface brightness I (the effective surface brightness of an elliptical galaxy, the central surface brightness of the exponential disk of a spiral galaxy), and size r is given by

$$L = k_L 4\pi r^2 I \tag{1.2}$$

If we substitute these relations into equation (1.1) we get

$$r = K_{FP} V^2 I^{-1} (M/L)^{-1} \tag{1.3}$$

where (M/L) is the global mass-to-light ratio of a galaxy, and the combination of structural parameters gives

$$K_{FP} = \frac{k_E}{8\pi G k_R k_V k_L} \tag{1.4}$$

If we square equation (1.3), and then substitute the luminosity-radius relation into it, we also get

$$L = K_{TF} V^4 I^{-1} (M/L)^{-2} \tag{1.5}$$

where the combination of structural parameters this time is

$$K_{TF} = \frac{k_E^2}{16\pi G^2 k_R^2 k_V^2 k_L} \tag{1.6}$$

The FP and TF relations have an empirical form

$$r_e \sim \sigma_v^\alpha I^{-\beta} \tag{1.7}$$

with coefficients $\alpha \simeq 1.25$ and $\beta \simeq 0.85$, and

$$L \sim V^\gamma \tag{1.8}$$

with a coefficient $\gamma \simeq 3$, respectively. In order for these relations to match equations (1.3) and (1.5), the products $K_{FP}(M/L)^{-1}$ and $K_{TF}(M/L)^{-2}$ must be power law functions of the explicit variables r, L, I, and V only, and the deviations of the empirical coefficients α, β, and γ from their "canonical" values of 2, 1, and 4, completely define these functions.

Clearly, the physical basis of the TF and FP relations is quite simple, but the astrophysical details behind their origin are complex, and involve the entire processes of galaxy formation and evolution. Because this is still a poorly understood subject, we adopt the TF and FP relations in their empirical realizations (equations 1.7 and 1.8). Certainly in the future the existence of well defined relations between the structural parameters and the global astronomical observables in both elliptical and spiral galaxies will provide important constraints for any theory of galaxy formation. At the moment, before any further progress towards the understanding of the astrophysical origin of the TF and FP relations can be made, an improved knowledge of how to link astronomical observables like luminosity or stellar velocity dispersion to physical quantities like mass and mean potential and kinetic energy is required. Therefore, even though the subject of the origin of the TF and FP relations in the long run might become the most interesting and the most far reaching one, its present development is still theoretically limited.

1.3.2 Observational requirements

Presently, we still face the basic problems of finding the "best" observables that could be used to build a TF or FP relation, and of defining the relations functional form (equations 1.7 and 1.8) avoiding the many observational biases that often hamper these efforts. From the observational view-point, the ingredients of the TF and FP relations are analogous, as both require a combination of photometric and spectroscopic data to be obtained. Photometric observations provide measurements of the galaxy total luminosity, its effective radius and effective surface brightness, and its inclination (for disk galaxies only). Crucial aspects of these measurements are the operational definition of total luminosity, and the absolute photometric calibration. Galaxies do not have hard-edges, and their peripheries fade gradually into the noise of the sky background. Therefore the accurate determination of that background, and the removal of any additional noise, other than the Poissonian fluctuations in its intensity, from CCD frames (the so-called flat-fielding) are very important steps of galaxy surface photometry work. Maximum tolerable uncertainties in the sky background are ~1–2%, while one order of magnitude less noise represents the mark for high quality data.

The smaller the uncertainty in the sky background, the higher the accuracy with which the galaxy radial luminosity profile can be measured, the fainter the limit up to which that measurement can be extended, and the smaller the extrapolation of the luminosity profile that is required to recover the true total luminosity of a galaxy. This extrapolation is generally based on an extension to infinity of a de Vaucouleurs $r^{1/4}$ (for elliptical galaxies) or exponential disk (for disk galaxies) profile, that is fitted to the galaxy observed luminosity profile[1]. The de Vaucouleurs profile fit is generally also used to derive effective radius and effective surface brightness for elliptical galaxies. The interval of radii where the exponential disk fit provides an accurate approximation of the true luminosity profile of a spiral galaxy is also the interval over which the galaxy ellipticity is measured, to provide an estimate of the galaxy inclination with respect to the plane of the sky.

High quality photometric measurements are only the first step towards building a TF or FP relation. Equally important is the set of corrections that must be applied to the measured parameters, before they can be used in the two relations. The most important of those is the correction for internal light absorption within spiral galaxies. Because dust in spiral galaxies is concentrated in a relatively thin layer in the disk, different viewing geometries of a given galaxy are affected by different amounts of dust extinction. Therefore the measured flux of a galaxy must be corrected to a standard viewing angle (generally the choice is face-on), before meaningful comparisons could be made. Other important corrections are those for the blurring effects of astronomical seeing. A galaxy luminosity profile, especially that of an elliptical galaxy, is strongly peaked at the center, and the effect of seeing is to redistribute the galaxy light more uniformly. As a consequence, the measured effective radius is broadened by seeing, and the measured effective surface brightness is dimmed. Also, seeing causes elongated objects to appear rounder, and therefore the measured ellipticity and galaxy inclination are smaller than the true values.

While the seeing corrections can be derived analytically, or with the help of simulations (see for example Saglia *et al.* 1993a), the correction for internal extinction must be obtained observationally from the same photometric data one is using for TF work, or a similar data-set (see for example Giovanelli *et al.* 1995). The accuracy with which it can be obtained is limited, because of the high degree of individuality displayed by spiral galaxies. Therefore, for TF work it is preferable to measure galaxy luminosities at

---

[1] The $r^{1/4}$ and exponential disk are empirical laws that in most cases provide a good description of the radial surface brightness profile of spheroidal and disk galaxies. The surface brightness is given by $\Sigma(r) = \Sigma_e \; exp\left(-7.67\left[(r/r_e)^{1/4} - 1\right]\right)$ and $\Sigma(r) = \Sigma_d \; exp\,(-r/r_d)$, respectively. When the surface brightness is expressed in magnitudes per unit solid angle, the two relations become $\mu(r) = 8.325\left[(r/r_e)^{1/4} - 1\right] + \mu(r_e)$ and $\mu(r) = 1.086\,(r/r_d) + \mu_\circ$.

red or near infrared wavelengths, where the total amount of extinction is reduced, rather than at blue wavelengths, where extinction is more significant. Another advantage of photometric observations in the red is the fact that in these bands spiral disks appear a lot smoother than they do in the blue (spiral arms are delineated primarily by very luminous and very blue star-forming regions), and this simplifies the fitting of an exponential disk profile to the galaxy light profile, and the measurement of the disk ellipticity. These are the main reasons for choosing the R or I photometric bands for TF work. Elliptical galaxies, on the contrary, are characterized by a smooth light distribution and negligible dust extinction. Therefore all photometric bands appear equally suitable for FP work.

Spectroscopic observations provide the measurements of the stellar velocity dispersion (elliptical and S0 galaxies) and of the disk rotation velocity (spiral galaxies). The crucial requirement for these measurements is the combination of high spectral resolution with high signal-to-noise ratio, two antithetical quantities. Single dish radio observations of the HI 21 cm line have provided so far the largest samples oh high quality rotation velocity measurements, because they can take advantage of the large radial extent of the HI disk in spiral galaxies, and because the flat rotation curve of these galaxies results into line profiles with sharp edges, that facilitate the measurement of the line width. Unfortunately these observations are limited to nearby galaxies (cz$\leq$10,000 km s^{-1}) by sensitivity and beam confusion problems. Measurements of the rotation curve of spiral galaxies, obtained with optical spectroscopy of the brightest emission lines from HII regions, appear to be the best alternative to the use of HI line widths.

No simple equivalent of HI observations is available for the determination of stellar velocity dispersions, and optical spectroscopy of strong absorption lines is the prevalent source of such measurements. These observations are more difficult than those aimed at obtaining rotation curves, because (a) the detection of absorption lines requires a spectrum with much higher signal-to-noise ratio than the one required by emission lines; (b) most of the strong absorption lines in the spectrum of early-type galaxies are multiple lines (Na D lines, Ca H and K lines, Mg Ib lines), whose separation is smaller or comparable to the broadening introduced by the stellar velocity dispersion, and therefore they appear blended in galaxy spectra; and (c) bright galaxies are not easier to measure than faint ones, because they have dimmer central surface brightness, and their large velocity dispersion translates into broader and shallower absorption lines, whose profile is difficult to measure accurately.

As in the case of the photometric parameters, the spectroscopic ones also require corrections, before they can be used in the TF and FP relations. Because redshifts can be used to measure only velocities along the line of sight, a measured rotation velocity needs to be corrected for projection effects to the value that would be measured in a perfectly edge-on galaxy. Also, when the rotation is derived from the width of the 21cm line, a correction is required to take into account turbulent motions within the HI disk. This second correction is particularly important for low luminosity objects, because the turbulent broadening can represent a significant fraction of the measured 21 cm line with. Stellar velocity dispersions need to be corrected for the so-called aperture effect. Because of radial gradients in the velocity dispersion within early-type galaxies, the measured dispersion depends on the size of the aperture within which the spectrum of a given galaxy was extracted. When spectra are obtained with a fixed aperture size (in arcseconds), this aperture covers regions of different physical size (in kiloparsec) on galaxies at different distances, and this produces biased velocity dispersion measurements. Therefore fixed aperture measurements must be corrected to a standard, distance independent, aperture size. It has also been suggested (see for example Saglia, Bender & Dressler 1993b) that a correction for systematic differences in the distribution of orbits (and therefore in the line-of-sight velocity distribution) between galaxies with different "shapes" (galaxies having so-called boxy or disky isophotes) might be required, but the evidence for this effect is still preliminary.

1.3.3 The TF and FP Template

After the photometric and spectroscopic measurements have been optimally corrected, they can be used for TF or FP work. The first and most important step of every such work is (or at least ought to be) to obtain a template relation. The empirical nature of both relations prevents the use of an a priori template, and both the "slopes" of the relations (the 3 coefficients α, β, and γ in equations 1.7 and 1.8), and their zero points must be obtained observationally. All aspects of the template fitting procedure are crucial to obtaining reliable redshift-independent distance measurements. A "wrong" template would result into spurious peculiar velocity determinations, and therefore an incorrect reconstruction of the peculiar velocity field. That could happen because (a) the template observationally derived does not reproduce accurately enough the "true" relation, or (b) the relation is not universal, and the template derived using one sample does not describe the galaxies in a different one.

Observational biases, biases introduced by the use of an inappropriate statistical procedure for the template fitting, and poor sample selection, all could lead to biased template determinations that differ significantly from the "true" template that describes a given galaxy population (see the discussion in Giovanelli *et al.* 1997b, hereafter G97b). A frequent approach in obtaining a TF or FP template is based on using a sample of galaxies that are all members of the same cluster to define it. The main advantage of this approach is that with such a sample all galaxies are effectively at the same distance from the observer, and their relative luminosities and diameters are not affected by peculiar velocities. It has also been argued that cluster samples for TF and FP work are almost bias-free, whereas field samples are not. Biased field samples are produced when a class of objects characterized by a distribution of intrinsic luminosities is used to build a magnitude-limited sample. Because of the cut in apparent magnitude, nearby objects are included in the sample for any value of their intrinsic luminosity, while for the more distant objects only the intrinsically bright ones are included. This distance-dependent bias is a variant of the well known Malmquist bias. It is avoided in field samples only when all galaxies above a given intrinsic luminosity are included (a so-called volume-limited sample). For cluster samples, composed of galaxies all at the same distance, the Malmquist bias is clearly avoided. However a different but equally important bias affects them. This is generally referred-to as the "cluster population incompleteness bias" (Teerikorpi 1987, 1990). Whenever a cluster sample that is preferentially missing faint objects is used for TF or FP work, this sample is described by a relation which is systematically different from the "true" relation that describes the corresponding complete sample. This bias depends on a sample degree of completeness[2], and therefore different

[2]The completeness of a sample is usually referred to the expected luminosity distribution of the galaxy population, and is given as the ratio of the number of galaxies of a given magnitude included in the sample with respect to the total number of galaxies of the same magnitude predicted by the

samples, drawn from the same cluster population but with different completeness, are fitted by different relations (see Sandage 1994a,b for a detailed description of the effects of this bias). This bias appears to be the most serious one affecting the measurement of redshift-independent distances for clusters of galaxies, but often it has been ignored in deriving TF or FP templates based on cluster samples, or in deriving cluster distances once a template had been obtained.

Poor sample selection, especially in terms of a rather loose definition of cluster membership, could also introduce significant biases. This is particularly important for the TF relation, because spiral galaxies are found preferentially at the cluster periphery, where the distinction between proper cluster members and field galaxies is sometimes difficult. Another likely source of bias often encountered in past TF and FP works is the rather arbitrary selection of just one cluster sample (often including no more than a dozen objects) for the definition of the TF or FP template, based only on the fact that a lower than average dispersion characterizes such a sample (all these effects are discussed in detail by G97b, and by Giovanelli 1997). Also the statistical exercise of finding the best fitting line or plane for a given sample might introduce some bias in the final template. The most commonly used linear regression algorithms are based on the assumption that the independent variables are measured with infinite accuracy, and only the dependent variable has an uncertainty associated with it. Because this is not the case with real data, the resulting "best fit" relation is a biased estimate of the true underlying relation. This bias becomes particularly important because it amplifies the effects of sample incompleteness previously discussed. Many discussions on the benefits of using the direct or the inverse fit (i.e. exchanging the role of the dependent and independent variables) to avoid incompleteness biases (see for example Strauss & Willick 1995) illustrate the attempts made towards the derivation of unbiased templates.

The best solution to this problem is to use algorithms that take properly into account the errors in all the variables involved in the fit (see for example Press *et al.* 1992). However these methods also have important limitations: they assume that the errors in the different variables are completely uncorrelated, and that the underlying correlation is a perfect one, without intrinsic dispersion. In practice errors are correlated. Magnitudes and rotation velocities in the TF relation both require corrections that depend on the measured galaxy inclination, and effective radius and effective surface brightness in the FP relation are derived from a single $r^{1/4}$ fit to the galaxy luminosity profile. Therefore any error in the inclination or in the $r^{1/4}$ fit produces correlated errors in the TF or the FP relation. Also, both relations appear to have intrinsic scatter. Only recently have the first efforts been made to understand the biases that might result from ignoring this intrinsic scatter and the error correlation in the fitting procedure (Akritas & Bershady 1996).

The use of cluster samples to derive TF and FP templates is based on the assumption that these relations are universal: all galaxies in all locations and environments have magnitude and rotation velocity, or effective radius, surface brightness and velocity dispersion that are related by the same relation, within measurement uncertainties and a possible intrinsic dispersion present in the TF and FP. If this were to be the case, biases would be the only obstacle to the accurate reconstruction of the peculiar velocity field. However, it is also possible that the environment might have an effect. For example,

appropriate luminosity function.

the template TF or FP relation might depend on the local density of galaxies, and thus differ among rich and poor clusters, and between clusters and the field. A number of environmentally-related effects that can systematically alter important galaxy properties are known to exist. First, and most important, is the so-called morphology-density relation (Dressler 1980a): elliptical and S0 galaxies are found preferentially in regions of high galaxy density, whereas spiral galaxies are found preferentially in regions of low galaxy density. Still unresolved is the issue of the origin of this phenomenon: are galaxies "born" different in different environments, or does some mechanism exist that is able to convert spiral galaxies into elliptical and S0 galaxies inside rich clusters? (See Dressler 1984 and Haynes, Giovanelli & Chincarini 1984 for reviews on this subject.)

Other important environmental effects include HI deficiency (spiral galaxies close to cluster cores have an HI content systematically lower than more isolated ones; see for example Giovanelli & Haynes 1985), the formation of cD galaxies and of cooling flows at the center of rich clusters, systematic enhancements in the metallicity (see for example Shields, Skillman & Kennicutt 1991; Skillman *et al.* 1996) and in the radio-continuum emission (see for example Gavazzi, Boselli & Kennicutt 1991; Scodeggio & Gavazzi 1993) of cluster galaxies. Still debated are possible effects on the amount of star formation activity and the mean age of the stellar population, and possible systematic alterations of structural characteristics like the bulge-to-disk ratio in disk galaxies. It is therefore possible that systematic differences might exist in the mass-to-light ratio of cluster and field galaxies, or in the detail of the light or mass distribution, that could affect the TF and FP relations, and make them non-universal. Certainly their universality cannot be taken for granted, but should be observationally verified. Some attempts have been made toward quantifying this issue (Aaronson *et al.* 1986; Djorgovski, de Carvalho & Han 1988; Guzmán *et al.* 1992; Jørgensen, Franx & Kjærgaard 1996), producing however conclusions of marginal clarity.

1.3.4 Peculiar velocity measurements

Once a template relation has been obtained, it defines the rest-frame against which peculiar motions are to be measured. Therefore when only relative distances are measured, there is some circularity in the logical foundation of the peculiar velocity determination process: in practice it is necessary to assume that the objects used for the template determination have on the average null peculiar velocity with respect to the CMB reference frame. An absolute motion of the observer with respect to this reference frame could be inferred, however, if the sky coverage of the objects used in the template determination is sufficiently uniform. Such a motion would in fact produce a dipole signature in the distribution of the positive and negative relative peculiar velocities. The best example of such an absolute motion detection, although one that was not obtained using peculiar velocity measurements, is that of the motion of the Local Group with respect to the CMB reference frame. In the standard theory of structure formation, this motion is the result of the gravitational pull of some mass concentration. The nearby Virgo cluster is certainly one such concentration, but there is general agreement on the fact that Virgo alone cannot explain the measured peculiar velocity of the Local Group, and some other mass concentrations must also be involved. The characteristics and spatial distribution of these other "attractors" are currently one of the hotly debated subjects in observational cosmology.

On one side there is the small-scale motions scenario, where peculiar motions are produced by local mass concentrations that extend their influence on scales of less than 40–50 h^{-1}Mpc (h is a dimensionless quantity, defined as $h = H_\circ/(100 \text{ km s}^{-1}\text{Mpc}^{-1})$, and is introduced because of the current uncertainty on the exact value of the Hubble constant). The so-called Great Attractor model proposed by Lynden-Bell *et al.* (1988), based on peculiar motion estimates for nearby bright elliptical galaxies obtained with the $\mathrm{D}_n - \sigma$ relation, is certainly the most famous example of such local models. In the large-scale motions scenario, instead, big mass concentrations extend their influence over regions of ~100 h^{-1}Mpc in size, or even larger. The evidence of bulk-flow motions presented by Mathewson *et al.* (1992), and by Courteau *et al.* (1993), based on TF peculiar motion determinations, and the evidence that the reference frame composed by the nearest 119 Abell clusters of galaxies is globally moving with respect to the CMB frame, presented by Lauer & Postman (1994), constitute the main support for the existence of very large-scale peculiar motions. An opposite result has been recently presented by Giovanelli *et al.* (1996): no bulk-flow signature is present in their large sample of TF-based peculiar velocity measurements.

The fact that the same techniques can be applied, using similar and at times partly overlapping samples, to derive very different pictures of the peculiar velocity field provides a measure of the limitations that are still present in our understanding of the TF and FP relations. Similar problems are found when different distance estimates for a given object are compared. A comparison of TF and FP distance estimates for a number of nearby clusters presented by Mould *et al.* (1991) shows differences between the two estimates for a given cluster that are significantly bigger than the uncertainties associated with the measurements. Most noticeable is the case of the cluster A2634, where the TF distance estimate obtained by Aaronson *et al.* (1986), and the $\mathrm{D}_n - \sigma$ distance estimate obtained by Lucey *et al.* (1991a) differ by ~3400 km s^{-1} (which is ≃40% of the distance to that cluster). The origin of these discrepancies is still unexplained. As briefly discussed in the paragraphs above, many possible biases can produce spurious peculiar motion signatures: erroneous membership assignments, sample incompleteness, inappropriate statistical procedures, or environmental effects could be the source for these biases. But already the task of demonstrating that those motions are spurious is a formidable one, in the absence of more reliable distance estimates than the ones under scrutiny. A detailed study on the reliability of TF and FP as distance-indicator relations, that combines high quality observational data, proper handling of the most important biases introduced by the sample selection and the statistical fitting procedures, and the capability of addressing the issue of universality of the two relations, is certainly needed before new efforts are directed towards more accurate and more detailed reconstructions of the peculiar velocity field.

1.4 High redshift applications

A new and different application of the TF and FP relations has been recently introduced in observational cosmology. From equations (1.3) and (1.5) we saw that the galaxy mass-to-light ratio is a hidden parameter in both the TF and the FP. Systematic changes in this ratio are expected to produce a change in the zero-point of the two relations, unless correlated variations in the structural parameters K_{TF} and K_{FP} conspire to cancel that out exactly, which is not impossible but certainly unlikely. Therefore, taking advantage of the possibility of obtaining TF and FP data for high redshift galaxies offered by the combination of large aperture telescopes (for the spectroscopy) and the Hubble Space Telescope (for the photometry), it is now becoming possible to study the time-evolution of the mass-to-light ratio of galaxies, by comparing the TF and FP relations obtained for galaxies at different redshifts (i.e. different look-back times). Pioneering efforts in this field were carried out by Franx (1993) for the FP, and by Vogt *et al.* (1993) for the TF. More recent works include Bershady (1996), van Dokkum & Franx (1996), and Vogt *et al.* (1996). This new topic of research will greatly benefit from the availability of large aperture telescopes like the two 10m Keck telescopes, the 10m Hobby-Eberly telescope, the two 8m Gemini telescopes, and the four 8m VLT telescopes, that will all be operational at the beginning of the next decade.

1.5 This work

Because redshift-independent distance measurements are the basic ingredient of the most direct and reliable methods for the reconstruction of the matter density field in the local Universe, it is very important that a satisfactory understanding of their properties and limitations is obtained. This understanding is even more crucial for the new high-redshift applications of these methods, where only objects with extreme properties (like very rich clusters, or very luminous galaxies) are generally observed. The goal of this work is therefore to study the reliability of one of the most commonly used distance-indicator methods, the FP relation, obtaining a quantitative estimate of its degree of universality. Long-term benefits of this work should be (a) a more accurate and reliable reconstruction of the local Universe peculiar velocity field, with the associated measurements of the mass density field and of $\Omega_\circ$, and (b) a more reliable application of the FP relation to high-redshift clusters to study the evolution of the galaxy population in those clusters.

The most direct way to test the reliability of a distance indicator relation is to compare its predictions with those of another independent, and at least equally reliable, method. The TF and FP relations provide the opportunity for such a comparison. They have similar accuracy, and they are totally independent methods, because they are applied to galaxies of different morphological type. Also, these galaxies populate different environments (E and S0 in the cluster cores, spirals preferentially at the cluster peripheries), and therefore it seems likely that, even in the case both the TF and FP might not be universal relations, they would be biased by different amounts by any environmentally-related mechanisms. Therefore a comparison between the two methods would still provide an opportunity to accurately quantify their universality.

Because of the limited accuracy of the distance estimates obtained with the TF and FP relation, a direct comparison of the two methods can be done only using clusters of galaxies, where large samples can be used to reduce the statistical uncertainty in the estimate of the cluster distances. Also, given the existing correlation between cluster richness and the properties of the intracluster medium (see for example Edge & Stewart 1991), the choice of a set of clusters with different richness offers the opportunity to perform the TF–FP comparison under different environmental conditions. In a recent work Giovanelli *et al.* (1997a,b) have obtained TF measurements for a large sample of cluster objects ($\simeq 750$ galaxies in 24 clusters). A sample of FP measurements of similar magnitude existed only for the Coma cluster (Lucey *et al.* 1991b). Before a TF–FP comparison could be made, it was therefore necessary to obtain a large sample of FP measurements. A sub-set of the clusters used by Giovanelli *et al.* (1997a,b) was chosen for this purpose, that includes a rich cluster like Coma, intermediate richness clusters like the spiral poor A2634 and the spiral rich A1367, rather poor clusters like A262 and Pegasus, and rich groups of galaxies like the NGC 507 and the NGC 383 groups, and the so-called Cancer cluster. All these clusters and groups have been extensively studied in the past, and large redshift surveys allow in all cases the derivation of reliable membership criteria. High quality photometric observations were obtained for large samples of early-type galaxies in all of them. This body of observations has been used to analyze in detail the relations between galaxy luminosity and effective radius and effective surface brightness, the two parameters that enter the FP relation. This has allowed a better understanding of the effects that the cluster population incompleteness bias has on the FP relation, a subject that was never discussed before in any FP work. Also, as a side result, these large samples have been used to study the reliability of alternative, more economical (in terms of observational requirements) distance-indicators. Because spectroscopic observations used to derive velocity dispersion measurements are more difficult to obtain than photometric ones, high quality spectroscopy was obtained only for a subset of the galaxies for which photometric measurements were available, consisting mostly of the brightest 20–30 galaxies in each cluster.

The template FP relation has been obtained combining the samples from the 6 best represented clusters and groups in the sample, under the assumption that, on average, these clusters and groups are at rest in the CMB reference frame. An extensive set of Monte Carlo simulations has been performed to reproduce as closely as possible the selection criteria of the final FP sample, and to quantify the effects of incompleteness on the parameters of the template FP relation. This allows for mostly bias-free peculiar velocity estimations for all the clusters in the sample. Therefore any difference in the comparison of the peculiar velocities derived here using the FP technique, with the similarly corrected peculiar velocities derived by G97b using the TF technique, should be produced solely by environmental effects within the clusters. Therefore the magnitude of those differences provides a direct estimate of the degree of universality of the TF and FP relations.

Chapter 2 presents a description of the 8 clusters used in this work, and of the membership criteria adopted to select the samples of early-type galaxies used to study the FP relation. An in-depth study of the cluster A2634 is used to illustrate the problems encountered in assigning cluster membership. In chapter 3 the photometric observations of 631 E and S0 galaxies are presented. In chapter 4 the spectroscopic observations of 212 of those galaxies are presented, together with 118 similar measurements collected from the literature. Chapter 5 presents a discussion of the many aspects of deriving peculiar velocity estimates from the FP relation. The derivation of the FP template, the statistical procedures used to obtain the “best fitting” plane, the bias corrections, the differences between individual clusters and groups, and the evidence for environmental effects, are discussed there. Chapter 6 presents a brief discussion on alternative “economical” distance-indicator methods, that require only photometric observations. Chapter 7 presents the results of the TF–FP comparison, and Chapter 8 a concluding discussion on the results of this work.