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Cosmological models and the brightness profile of distant galaxies

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Abstract. The aim of this project is to determine the consistency of an assumed cosmological model by means of a detailed analysis of the brightness profiles of distant galaxies. Starting from the theory developed by Ellis and Perry (1979) connecting the angular diameter distance obtained from a relativistic cosmological model and the detailed photometry of galaxies, we assume the presently most accepted cosmological model with non-zero cosmological constant and attempt to predict the brightness profiles of galaxies of a given redshift. Then this theoretical profile can be compared to observational data already available for distant, that is, high redshift, galaxies. By comparing these two curves we may reach conclusions about the observational feasibility of the underlying cosmological model.

Key words. galaxies: distances and redshifts; galaxies: structure; galaxies: evolution; cosmology: observations.

1. Introduction

The most basic goal of cosmology is to determine the spacetime geometry and matter distribution of the Universe by means of astronomical observations. Accomplishing this goal is not an easy or simple task, and due to that, since the early days of modern cosmology several methods have been advanced such that theory and observations are used to check one another. Detailed analysis of the cosmic microwave background radiation, galaxy number counts and supernova cosmology are just a few of the methods employed nowadays in cosmology, deriving results that complement one another. In this work we aim at discussing one of these methods, namely the connection between galaxy brightness profiles and cosmological models.

Thirty years ago, Ellis and Perry (1979) advanced a very detailed discussion where such a connection is explored. Their aim was to determine the spacetime geometry of the universe by connecting the angular diameter distance, also known as area distance, obtained from a relativistic cosmological model, and the detailed photometry of galaxies. They then discussed how the galaxy brightness profiles of high redshift galaxies could be used to falsify cosmological models as the angular diameter distance could be determined directly from observations.

Nevertheless, to carry out this program to its full extent, one would need detailed information about galaxy evolution. Without a consistent theory on how galaxies evolve, it is presently impossible to analyze cosmological observations without assuming a cosmological model. In addition, brightness profiles are subject to large observational errors, making it difficult to achieve Ellis and Perry's aim of possibly using the angular diameter distance determination to distinguish cosmological models.

This work is based on Ellis and Perry (1979) theory, although our aim is more limited in the sense that we do not seek to determine the underlying cosmological model by directly measuring the angular diameter distance, but to assume the presently most favored cosmology, deriving cosmological distances from it and seeking to discuss the consistency between its predictions and detailed observations of surface brightness of distant galaxies. Our goal is to obtain a theoretical brightness profile by means of the assumed cosmological model and compare it with its observational counterpart at various redshift ranges, and for different galaxy morphologies.

The outline of the paper is as follow. In §2 we introduce the cosmological distances and their connections to astrophysical observables. In §3 we describe the parameters that determine the surface brightness structure and in §4 we discuss the criteria for selecting galaxies, in view of the importance of evolutionary effects in galactic surface brightness.

2. Cosmological Distances

Let us consider that source and observer are at relative motion to each other. From the point of view of the source, the light beams that travel along future null geodesics define a solid angle $d\Omega_G$ with the origin at the source and have a transversal section area $d\sigma_G$ at the observer.

The flux F_G measured at the source considering a 2-sphere S lying in the locally Euclidean space-time centered on the source is related to the source luminosity by,

$$L = \int_S F_G d\sigma_G = 4\pi F_G \tag{1}$$

assuming that it radiates with spherical symmetry and locally this is a unit 2-sphere. If we consider now the flux F_r radiated by the source, but measured at the observer, the source luminosity is

$$L = \int_S (1+z)^2 F_r d\sigma_G, \tag{2}$$

where the factor $(1+z)^2$ comes from *area law* (Ellis 1971) and z is the redshift. This law establishes that the source luminosity is independent from the observer. So these two equations are equal, and we may write that,

$$L = \int_S F_G \, d\sigma_G = \int_S (1+z)^2 F_r \, d\sigma_G, \tag{3}$$

$$(1+z)^2 F_r \, d\sigma_G = const = F_G \, d\Omega_G \tag{4}$$

From the viewpoint of the source, we may now define the *galaxy area distance d_G* as,

$$d\sigma_G = {d_G}^2 d\Omega_G, \tag{5}$$

which considering eq. (4), becomes,

$$F_r = \frac{L}{4\pi} \frac{1}{(d_G)^2 (1+z)^2}. \tag{6}$$

The factor $(1+z)^2$ may be understood as arising from *(i)* the energy loss of each photon due to the redshift z, and *(ii)* the lower measured rate of arrival of photons due to the time dilation. With eq. (6) it is not possible to make any physics since we cannot measure the *galaxy area distance d_G*.

Considering a bundle of null geodesics converging to the observer, that is, light beams traveling from source to observer, they define a solid angle $d\Omega_A$ with the origin at the observer and have a transversal section area $d\sigma_A$ at the source. We may now define the *angular diameter distance d_A* by

$$d\sigma_A = {d_A}^2 d\Omega_A. \tag{7}$$

The *reciprocity theorem*, due to Etherington (1933; see also Ellis 1971, 2007) relates the d_G and d_A by means of the following expression,

$${d_G}^2 = (1+z)^2 {d_A}^2, \tag{8}$$

This relation is purely geometric, valid for any cosmology and contains information about spacetime curvature effects. Combining eqs.

(6) and (8), it is possible to connect the flux received by the observer and the *angular diameter distance* by

$$F_r = \frac{L}{4\pi {d_{_G}}^2} \frac{1}{(1+z)^2} = \frac{L}{4\pi {d_{_A}}^2} \frac{1}{(1+z)^4}. \qquad (9)$$

3. Connection with the surface photometry of cosmological sources

Galaxies are objects that can be used to measure cosmological parameters because they are located far enough in order to have significant spacetime curvature effects. The flux emitted by these objects and received by the observer depends on the surface brightness, which, by definition, is distant independent, although it is redshift dependent (Ellis 2007). Based on the reciprocity theorem, and bearing in mind that we actually observe in very restricted wavelengths, it is possible to connect the emitted and received *specific surface brightness*, respectively denoted by B_{e,ν_e} and B_{r,ν_r}, according to the following equation (Ellis and Perry 1979),

$$B_{r,\nu_r}(\alpha, z) = \frac{B_{e,\nu_e}(R, z)}{(1+z)^3} J[\nu_r(1+z), R, z]. \qquad (10)$$

Here J is the *spectral energy distribution (SED)*, R is the *intrinsic galactic radius*, ν_r and ν_e are respectively the *received* and *emitted frequencies*, and α is defined as the angle measured by the observer between the galactic center and its outer luminous limit, as below (Ellis & Perry 1979),

$$R = \alpha\ d_A(z). \qquad (11)$$

Note that d_A is given by the assumed cosmological model. Our aim is to compare the surface brightness observational data with its theoretically derived results calculated by means of eq. (10) and reach conclusions about the observational feasibility of assumed cosmological model.

To calculate the theoretical surface brightness, we have to assume some dependency between the surface brightness and the intrinsic galactic radius. Considering that a fundamental assumption in observational cosmology is that homogeneous populations of galaxies do exist, the structure and evolution of each member of such group of galaxies will be essentially identical. This assumption implies that *(i)* the frequency dependence of the emitted galaxy radiation does not change across the face of the galaxy, that is, it is R independent, and *(ii)* the radial variation of the brightness is characterized by an amplitude B_0, which may evolve with the redshift, i.e., $B_0(z)$, and a normalized radial functional form does not evolve $f[R(z)/a(z)]$. So, the emitted surface brightness can be characterized as (Ellis and Perry 1979),

$$B_{e,\nu_e}(R, z) = B_0(z) J(\nu_e, z) f[R(z)/a(z)]. \qquad (12)$$

Now, let us define the parameter β as being given by $\beta = R(z)/a(z)$, where $a(z)$ is the scaling radius. The redshift dependence in the parameters of the equation above is due to the galactic evolution. A detailed study of the parameters of eq. (refe5) and their evolution is fundamental to this work. Otherwise, we will not be able to infer if the difference between the observational data and the modeled surface brightness is due to the cosmological model or to a poor characterization of the brightness structure and its evolution.

3.1. Surface brightness profiles

The function $f[R(z)/a(z)]$ characterize the shape of the surface brightness distribution. There exist in the literature various different profiles. Some of them are one parameter profiles, like *Hubble* (1930), *Hubble-Oemler* and *Abell-Mihalas* (1966), characterizing the galactic brightness distribution quite well when the disk or bulge are dominant. They are given as,

$$B_{\mathrm{H},e}(R, z) = \frac{B_0(z) J(\nu_e, z)}{(1+\beta)^2}; \qquad (13)$$

$$B_{\mathrm{HO},e}(R, z) = \frac{B_0(z) J(\nu_e, z) e^{-R^2/R_t^2}}{(1+\beta)^2}; \qquad (14)$$

$$B_{\mathrm{AM},e}(R, z) = \frac{B_0(z) J(\nu_e, z)}{(1+\beta)^2}; \quad (\beta \leq 21.4); \qquad (15)$$

$$B_{\mathrm{AM},e}(R,z) = \frac{22.4 B_0(z) J(\nu_e,z)}{(1+\beta)^2}; \quad (\beta > 21.4). \tag{16}$$

Other profiles like *Sérsic* and *core-Sérsic* use two or more parameters, reproducing the galactic profile almost exactly (Trujillo et al. 2004).

$$B_{\mathrm{S},e}(R,z) = B_{eff} J(\nu_e,z) e^{\left\{-b_n\left[\left(\frac{R}{R_{eff}}\right)^{1/n}-1\right]\right\}} \tag{17}$$

$$B_{\mathrm{cS},e}(R,z) = B_b 2^{-\frac{\gamma}{\alpha}}\left[1+\left(\frac{R_b}{R}\right)^{\alpha}\right]^{\gamma/\alpha} \times \times\, e^{\left[-b\left(\frac{R^\alpha+R_b^\alpha}{R_{eff}^\alpha}\right)^{1/n\alpha}+b2^{1/\alpha n}\left(\frac{R_b}{R_{eff}}\right)^{1/n}\right]}, \tag{18}$$

where B_{eff} is the surface brightness at the effective radius R_{eff} that encloses half of the total light, B_b is the surface brightness at the core or break radius R_b. γ is the slope of the inner power-law region, α controls the sharpness of the transition between the cusp and the outer Sérsic profile and n is the shape parameter of the outer Sérsic. The quantity b is a function of the parameters α, R_b/R_{eff}, γ and n. The parameter b_n depends only on n.

4. Sample Selection Criteria

To analyze only the effect of the cosmological model in the surface brightness and minimize the effect of evolution, we assume that there exists a homogeneous class of objects whose properties are similar in all redshifts, allowing us to carry out comparisons at different values of z. Thus, galaxy sample selection follows this assumption. Choosing galaxies of different morphologies, we must consider the following requirements:

(1) The existence of different morphological populations at different redshift values. Due to the Hubble sequence we know that not all type of galaxies exist in all epochs. Therefore, it seems reasonable to choose early-type galaxies because they exist at different redshift values and have a lower star formation rate which could imply smoother evolution.
(2) The best frequency band to observe. If we consider all wavelengths, the theory tells us that the total intensity is equal to the surface brightness, so the chosen bandwidth should include most of the SED in the interval ν_e and ν_r.
(3) If the galaxies chosen are located in clusters or are field galaxies.

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