Primordial Cosmological Fluctuations on Galactic Scale

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**Abstract.** The galactic evolutionary theory is now sufficiently mature to provide information about the galaxy formation phase. From evolutionary models we establish a link between the present features of late type galaxies and the protogalactic density fluctuations. This link is used to estimate the fluctuation power spectrum amplitude at galactic scales. The agreement with the power spectrum derived from galaxy distribution and extrapolated to galactic scales, is satisfactory. Meanwhile, the comparison with respect to the standard cold dark matter power spectrum normalized to COBE satellite measurements reveals only a marginal agreement. Among the most interesting results, the Tully-Fisher relation and the constant central brightness pointed out by Freeman (1970) appear to be the natural consequences of the initial cosmological conditions.

1. Introduction

Modern cosmology offers the key concepts for understanding how, from an almost homogeneous sea of particles and radiation, the universe developed structures as complex as the galaxies, clusters and super clusters of galaxies that we observe today. At this point, it appears logical to question ourselves about the natural initial conditions that cosmology could provide for the astrophysical processes of galaxy formation and evolution. This question would result interesting only if the present structure of galaxies retained some information related to the cosmological physical conditions prevalent at the epochs when galactic seeds appeared; that is, if strong dissipative processes did not totally erase the initial cosmological conditions. If this were the case, the following question immediately arises: Is it possible to establish a link between cosmological models and the properties of galaxies seen today? It is the aim of this work to find precisely such a link, using for this purpose a galactic evolutionary theory.

The mayor ingredient relevant to the problem of structure and galaxy formation is the prediction from cosmology of an initial fluctuation type and distribution. The most popular cosmological approach, due to its simplicity and
predictive capability, is the inflationary Cold Dark Matter model (CDM) including their variants, and the usual assumption is that the primordial fluctuations have a Gaussian distribution (is it really a solid prediction of the inflationary models?), with a scale invariant density contrast.

Once a Gaussian nature is assumed for the density fluctuation field, its statistical properties can be determined in terms only of the fluctuation power spectrum ($P_S$). It has become customary to compare different cosmological scenarios at the level of their respective power spectra, linearly extrapolated to $z = 0$. In this way, at some epoch, say the recombination time, one has the initial conditions for structure and galaxy formation.

The normalization of this $P_S$ is not provided by the theory, and has been estimated on intermediate scales by the galaxy distribution and, more recently, at very large scales, by the temperature fluctuations of the cosmic microwave background radiation (CMB). The link we shall establish between cosmological models and the properties of galaxies, indeed offers a method to find the amplitude of the initial density fluctuations at the smallest cosmological relevant regions—the galactic scales. In this way, the different $P_S$ predicted by distinct cosmological models and normalized to the COBE CMB measurements, can be tested using galactic evolution, at the smallest scales, where maximal variations among them typically occur.

2. Galactic Evolution and the Epoch of Galaxy Formation

Our goal is to find the typical formation redshift $z_f$ of galaxies with a given mass $M$, using for this the galactic evolutionary theory. Here we treat galactic evolution within the framework introduced in Firmani et al. (1995). The global evolutionary models presented there are based on the local ones developed by Firmani & Tutukov (1992, 1994).

The initial conditions from which the global models start include a spherical distribution of $DM$, and depending on this, they predict the properties of a late type galaxy as seen today. We pay special attention to the Tully-Fisher relation and the constant central surface brightness pointed out by Freeman (1970), because they seem to be more directly related to the cosmological conditions.

It is very difficult to obtain an explicit solution to the problem of non-linear evolution of the primordial density fluctuations and the resulting $DM$ halo structures (see for example Flores & Primack (1994), Moore (1994), Klypin et al. (1995)). In order to avoid complicated dynamical calculations which in any case involve statistical uncertain primordial density fluctuation profiles, in the frame of our simplified approach, we assume that, during the non-linear evolution of the density fluctuations, a violent relaxation virializes the $DM$ halo to a truncated isothermal sphere with a core (Binney & Tremaine (1987), Bachall & Soneira (1980)). We also experimented with alternative halo profiles (e.g. Katz (1991)). The density profile parameters of the virialized halo can be easily related through energy conservation to the radius of the primordial fluctuation at the maximum expansion, if a $top-hat$ configuration is assumed for this phase. This relation reduces the degree of freedom of the virialized halo configuration to one, which we fix in order to obtain a flat rotation curve at the end of the
evolution. This simple procedure allows us to construct a virialized halo starting from $M$ and $z_f$.

One assumes that after the virialization of the $DM$ halo, all the baryonic gas trapped in it, cools and falls to the center forming a centrifugally supported disk where the stellar populations form, evolve, and interact with the interstellar medium. Here the disk mass fraction, in principle, may be assumed equal to the fraction of baryonic matter $\Omega_b$ which is well predicted by big bang nucleosynthesis (BBN). The initial angular momentum, measured by the dimensionless angular momentum $\lambda$, is taken from the tidal torque theory and numerical simulations (Peebles 1969, Fall & Efstathiou 1980, Efstathiou & Barnes (1987)), having an average value of $\lambda \approx 0.05$. We do not consider the possibility of major mergers after the galactic disk is formed. Since late type galaxies are typically field objects, or located at cluster peripheries, we think this last assumption is quite reasonable.

Now, given a total mass $M$ and following the above stated assumptions of a final flat rotation curve and a baryon content close to the BBN prescription, one selects those models which satisfy, through the galactic evolution, the Tully-Fisher relation (normalized to the Galaxy) and the Freeman law. This procedure fixes $z_f$ and $\lambda$ completely.

The results, obtained using an isothermal halo, $h = 0.5$ and $\Omega_b = 0.05$, are plotted in Fig.1 (continuous line). As shown in Fig.1, the mass roughly scales with $z_f$ as $M \propto (1 + z_f)^{-6}$ at galactic scales. On other hand, it is possible to estimate such a relation for the hierarchical models, using for this the Press-Schechter formalism (Press & Schechter (1974)). In Fig. 1 we also show the average $z_f$ of collapsed objects with masses $M$ for a COBE-normalized standard CDM power spectrum.

The rather good agreement found between our predictions of galaxy formation epochs and the Press-Schechter formalism applied to a standard CDM cosmology is quite encouraging of the validity of our approach. We feel it is now safe to state that the Tully-Fisher scale relationship and the constant central disk brightness found by Freeman are the fossil remains of the physical conditions prevalent during the epoch of galaxy formation. That the slope of the Tully-Fisher relation is related to the cosmological conditions was previously suggested (e.g. Faber (1981)), but the proportionality coefficient was not considered.

It is encouraging that we obtain the same value for $\lambda$ which the numerical simulations predict. Inverting the procedure, if we fix $\lambda = 0.05$, we can predict a disk mass fraction $\approx 0.05$, which results close to the value predicted by the BBN.

Several experiments with alternative halo profiles have been taken into consideration, with poor results in terms of final rotation curves.

3. The Normalization of Power Spectrum at Galactic Scales

From galactic evolution we were able to determine the formation redshifts of galaxies. Now, using the Press-Schechter formalism in reverse, and the spherical collapse model, it is straightforward to find the amplitude of the initial density fluctuations at galactic scales.
Figure 1. Formation redshift vs. mass from disk galaxy evolutionary models (solid line), and from the standard $CDM$ model (dashed line).

Figure 2. Calculated power spectrum in the galactic region, thick line, compared with the figure of Stompor et al. (1995), which shows various spectrum estimates from galactic distribution observations, as well as several theoretical power spectra.
In Fig.2 we plot the $P_S$ obtained from galactic evolution at wave numbers between 1 and $10 \, h \, Mpc^{-1}$. Also plotted are several observational estimates on larger scales and theoretical COBE-normalized power spectra (from Stompor et al. 1995). It is clearly seen that our results are a natural small scale extension of the $P_S$ estimated from galaxy distribution observations. Though it is still early to claim definitive results, we find our approach useful for constraining cosmological models at galactic scales. As was pointed out by Wambsganss et al. (1995), since cosmological models have an assumed $P_S$ that is normalized to pass through the region measured by the COBE satellite at very large scales, and given that the slope of the $P_S$ is a model-dependent feature, then the maximal variations among them naturally occur at the smallest scales (see Fig.2). The relevance of finding further estimates of the primordial fluctuation amplitude on scales as far removed as possible from the COBE measurements, for example galactic scales, is at this point obvious.

4. Conclusions

We can summarize the results of this work as follows:

1) The density fluctuation $P_S$ inferred from galactic evolutionary models defines a sequence in the range $1 < k < 10 \, h \, Mpc^{-1}$ which shows itself as the natural extension of the estimates obtained from the observations of galaxy distribution.

2) The Tully-Fisher relation (both, the slope and the proportionality coefficient) and the constant central brightness of late type galaxies appear to be consequences of the cosmological origin of galaxies. Both relations may be considered fossil information of the primordial density fluctuation field.

3) On the frame of a Gaussian distribution of the primordial density fluctuations, our results show in the fluctuation spectrum less power than the standard $CDM$ model, and lean slightly towards $CDM$ models with a non-vanishing cosmological constant.

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