Testing Dark Energy with HI Surveys:

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Introduction

One of the key problems in cosmology today is to identify the source of the late-time acceleration of the universe. Is it an anti-gravity field called dark energy? If so, what kind of dark energy - vacuum energy (the cosmological constant) or a dynamical scalar field (quintessence) or a field that interacts with dark matter? Given the lack of a fundamental theory for dark energy, an alternative is that the acceleration is driven by a relative weakening of gravity on large scales - i.e. a breakdown of general relativity in the infrared. Radio surveys of the HI signal provide a new frontier for putting these theoretical ideas to the test, complementing the current use of optical galaxy surveys. The MeerKAT HI survey will have a fairly small volume, but will be useful to testing techniques. LOFAR will provide large volumes, and the SKA will take this much further. Theoretical work needs to be done to prepare for implementing tests of models with data from these surveys.

The Background Evolution

We obtain two equations to describe evolution of the background universe, they are:

\[
\Omega_\Lambda = 1 - \Omega_m \quad \Omega_m = \frac{3}{8}\Omega H_0^2
\]

The Perturbed Equations

We start with the perturbed metric in the Newtonian Gauge [2]:

\[
d\tau^2 = -a^2(\delta \omega^2 + \delta x^2) dt^2 + a^2 \delta x^2 + \delta \omega^2
\]

and the energy momentum tensor for perfect fluid with zero anisotropic stresses:

\[
T^{\mu\nu} = (-\rho + p)u^\mu u^\nu + p g^{\mu\nu}
\]

and obtain, the perturbation equations from the perturbed Einstein Field equations (see e.g.1):

\[
\delta \phi' - 3H\delta \phi + \mathcal{H} \phi = 4\pi G\rho\delta \omega
\]

\[
\delta \phi' - 3H\delta \phi + \mathcal{H} \phi = -4\pi G\rho\delta x
\]

where \( \mathcal{H} = \frac{1}{a} \frac{da}{d\tau} \)

and the conservation equations:

\[
\delta x' - k^2 \delta x = 3H^2 a
\]

\[
\delta x' - k^2 \delta x = 0
\]

follow from the vanishing covariant derivative of the energy momentum tensor (3). The dimensionless background and perturbation equations

We transform the background evolution equations (1) and the perturbation equations (2) into the ordinary differential equations in redshift space:

\[
d\delta a = \frac{3}{2}(1 - \Omega_\Lambda) \delta a
\]

\[
d\omega a = \frac{3}{2}(1 - \Omega) \omega a
\]

\[
d\mathcal{H} a = \frac{3}{2} \mathcal{H} a
\]

\[
d\delta \omega a = \frac{3}{2} \delta \omega a
\]

\[
d\delta x a = \frac{3}{2} \delta x a
\]

and using equation (4) obtain the dimensionless relativistic Poisson equation:

\[
\frac{\delta \phi'}{\mathcal{H} \phi} = \frac{3}{2} \delta x' + 3H^2 a
\]

where \( b = \frac{\delta \omega}{\omega} + \frac{\delta x}{x} \) and \( u = H_0 a \) are dimensionless variables and \( H_0 \) is the Hubble rate today.

The Growth Rate

Defining the comoving density contrast as:

\[
\delta = \delta_0 \quad \delta_0 = \mathcal{H} \delta_m
\]

we can derive the formula:

\[
\delta' = 2H_0 \delta + 4\pi G\rho \delta_0 = 0
\]

This implies that:

\[
\Delta(k, a) = D(a) \Delta(k, a_0)
\]

where \( D(a) \) is the growth function and \( a_0 \) is the initial value of the scale factor \( a \). Now, since the rate of growth of galaxies is given by

\[
f = \frac{d}{da} D
\]

we can test dark energy models by comparing the growth function \( f(a) \) with observations from HI surveys.

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References


