Modified Gravity in Cosmology and Astrophysics

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Why Modified Gravity?

The standard $Λ$CDM (Λ-Cold Dark Matter) cosmology uses a cosmological constant to give the current acceleration of the Universe. The energy stored in this constant is called dark energy, but the scale of magnitude of the energy density of this dark energy has no good explanation. Other models have therefore been proposed instead in order to explain the acceleration of the Universe.

Scalar field models

The Einstein equations of the $Λ$CDM cosmology can be derived from an action:

$$\int d^4x \sqrt{-g} \left( \frac{M^2}{2} R - \Lambda \right)$$

where $g$ is the determinant if the metric, $M^2$ is the Planck mass and $R$ is the Riemann trace. When a scalar field is included, the action becomes:

$$S = \int d^4x \sqrt{-g} \left( \frac{M^2}{2} R - \frac{M^2}{2} \phi^2 + V(\phi) \right) + S_m(A^i(\phi)g_{\mu\nu}, \phi)$$

Here $\phi$ is the scalar field, $V(\phi)$ is the potential energy and $A^i(\phi)$ gives the coupling to matter, as $S_m$ is the matter action. This type of model is determined by the specific choice of $V(\phi)$ and $A(\phi)$. The scalar field gives an effective potential

$$V_{\text{eff}} = V + (A - 1)\rho$$

where $\rho$ is the matter density. The field seeks to minimise this effective potential.

Scalar fields cause a fifth force to act between objects when the field is coupled to ordinary matter, which would have observable consequences.

Screening mechanisms

The Chameleon model: the field in dense environments is on the left, with the minimum of the field close to zero, and in less dense environments on the right.

For the model to be viable, it must not violate any of the results of observations we make— the fifth force caused by the scalar field must be too small to be noticed where we can make measurements.

Screening Mechanisms cont’d

Several models depend on the environment to achieve this. For the Chameleon model [1], the field is strongly coupled to matter, and the mass of the field is much larger in the laboratory so it will have little effect in comparison to it being almost massless on cosmological scales.

Another type of model is the environmentally dependent dilaton [2], where the coupling to matter $\beta = \frac{2\alpha}{\lambda}$ depends on the field, and turns off in high density environments. This is an example of the Damour-Polyakov mechanism which comes from string theory.

Particular model

The particular model is not environmentally dependent, so the screening mechanism works in a different way to above. It uses:

$$A(\phi) = 1 + \frac{\alpha}{2}\phi^2$$

$$V(\phi) = m^2 M^2 (1 + \frac{\lambda}{2}\phi^2)$$

There are several ways to check the model is a possibility.

Testing - Cosmology

The model must be experimentally viable. The first way check is to examine the cosmology of the model. The FRW metric for a spatially homogeneous isotropic universe uses a scale factor for the universe $a(t)$.

The modified Einstein equations derived from the action can be solved to find the Hubble constant $H = \frac{\mathbf{a}'}{\mathbf{a}}$.

Solar System Tests

There are several solar system tests which give bounds on the parameters:

- Testing- Cosmology

The spherical profile of the scalar field at a fixed time shows how the field changes with distance from a spherical object (such as the Earth or Sun). It useful to see how the field drops off away from the object. The graph below shows the field profile around such a spherically symmetric object, assuming the background is perturbed Minkowski space.

Conclusions

It is possible to find values of the parameters that satisfy these tests, and there are then more features of the model to examine, such as the behaviour near black holes.

References