The Universe: Big and Small

Ashoke Sen

Harish-Chandra Research Institute, Allahabad, India

Bangalore, October 2016

Elementary particle physics

– study of the laws of the universe at tiny scales of order 10^{-17} cm and less

Cosmology

– study of the universe at large scales of order 10^{10} light years (10^{23} km) going beyond stars and galaxies.

The aim of this talk is to describe how these two subjects are intimately connected.

The small

Modern understanding of the ultimate constituents of matter

Molecules

$\downarrow$

Atoms

$\downarrow$

Nucleus Electrons

$\downarrow$

Protons Neutrons Electrons

$\downarrow$

Quarks Gluons Electrons

$\cup$

Zoo of elementary particles

These elementary particles interact via various kinds of forces.

1. Gravitational

2. Electromagnetic

3. Strong

4. Weak

These forces give rise to complicated interaction between elementary particles.

– measured by studying how the elementary particles scatter off each other.

Laws of quantum mechanics $\Rightarrow$ probing smaller distances requires higher energy particles.

– achieved in particle accelerators

For example large hadron collider (LHC) at CERN used high energy collision between protons to probe structure of matter at scales of order 10^{-17} cm.

– produced and discovered the Higgs particle in 2012.

It turns out that the effect of gravitational force between elementary particles is negligible compared to the other forces.

To see this one can compare the electrostatic force between two protons with the gravitational force between two protons at rest.

Result:

$$\frac{\text{Grav. Force}}{\text{Elec. Force}} = \frac{Gm_p^2/r^2}{e_p^2/r^2} \sim 10^{-36}$$

G: Newton's gravitational constant (6.67×10^{-8} $cm^3/gm\ sec^2$)

m_p: proton mass (1.67×10^{-24} gm)

e_p: proton charge (4.8×10^{-10} e.s.u.)

Similarly all other forces are also much larger than the gravitational force.

For developing a theory of elementary particles and their forces, we must remember two important points:

1. In typical experiments elementary particles move very fast.

   Hence we need to use special theory of relativity.

2. The elementary particles are very small.

   Hence we need to describe them using quantum mechanics.

There is a mathematical theory, known as the standard model, which describes all the elementary particles and their forces if we leave out gravity.

This theory is based on the principles of quantum mechanics and special theory of relativity.

In principle this theory can be used to calculate the result of any experiment that we wish to perform involving elementary particles.

So far the standard model has been extremely successful in explaining almost all observed experimental data.

List of elementary particles according to the 'standard model':

QUARKS

u^1, u^2, u^3 d^1, d^2, d^3 c^1, c^2, c^3

s^1, s^2, s^3 t^1, t^2, t^3 b^1, b^2, b^3

LEPTONS

(e, ν_e) (μ, ν_μ), (τ, ν_τ)

MEDIATORS

gluons: $g_1, \ldots g_8$ **Photon:** γ

W^+, W^-, Z

HIGGS ϕ

Despite these successes, the standard model <u>cannot</u> be the final story.

First of all there are some experimental results which do not agree with the predictions of the standard model

Example 1: According to the standard model, neutrinos have no mass.

Experiments during last two decades have shown that neutrinos have small but non-zero mass.

Example 2: Most of the matter in the universe exists in the form of 'dark matter' which has no explanation in the standard model.

However these can be explained by minor modifications of the standard model without giving up any of the basic principles.

In order to determine precisely what kind of modifications are needed, we need more experimental input

– better understanding of neutrino masses and dark matter.

Indian Neutrino Observatory (INO) could play a role if it ever gets built.

However, even with these modifications standard model will not be complete.

It does not contain one important force that we observe in nature, namely, the

GRAVITATIONAL FORCE

In all present day experiments gravitational force between elementary particles is extremely small and beyond measurement.

But any complete theory must account for all forces, however small.

Can we modify the standard model so as to include gravity?

The standard model is based on the principles of special theory of relativity and quantum mechanics.

$\rightarrow$ we need to first make the theory of gravity consistent with the principles of

1. special theory of relativity

2. quantum mechanics.

The first step – making gravity consistent with special theory of relativity – was carried out by Einstein in 1915.

$\rightarrow$ general theory of relativity

– tested in many experiments, including in the recent discovery of gravitational waves at LIGO.

The second step, – combining this with quantum mechanics – turns out to be extremely difficult.

The big

Cosmology

The universe we see is filled with stars, planets etc.

But there are two important properties of the universe which are not visible to the naked eye.

1. The universe is expanding.

2. The universe is filled with cosmic microwave radiation at a temperature of about 2.73K (-270°C)

Since an expanding radiation cools, the obvious conclusion is that the universe was hotter in the past.

The further back we go in time the hotter it would have been.

This leads us to the big bang theory of cosmology.

The universe started from a very high temperature state with a bang!

Since then it has been expanding and cooling, leading to the present state.

When the universe was very hot, it was filled with very energetic elementary particles colliding with each other

– described by the standard model.

This has many interesting predictions like the ratio of hydrogen to helium in our universe

– have been verified experimentally

However since we know that the standard model is not the complete story about elementary particles, we are unable to construct the full history of the universe.

For example we know that today the universe has much more matter than anti-matter.

There is no explanation of this in the standard model.

There is reason to believe that understanding better the origin of neutrino masses could answer this question.

But for this we need more experimental input.

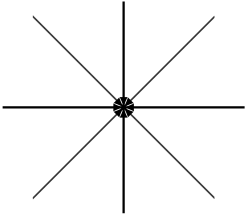
There is another big puzzle in cosmology

– homogeneity of the universe.

Even though the universe does not look uniform at the scale of the solar system, when we calculate average properties over large distances, the universe looks more and more uniform.

– same average density of matter in every part of the universe.

For example the cosmic radiation coming from different directions in the sky have equal temperature up to 1 part in 10^5.



Why is this so?

The radiation originated when the universe was about 400,000 years old (current age = 14×10^9 years)

If we consider two diametrically opposite points in the sky from which the radiation is coming, they are 28×10^9 light years apart today.

When the radiation originated, they were about 28×10^6 light years apart.

How did these points communicate with each other in 400000 years and make their temperature the same?

A possible answer: Inflation

Some time very early in the history of the universe it went through a very rapid expansion – at a rate much faster than that predicted by big bang theory.

During this rapid expansion tiny regions of the universe grew into gigantic regions.

Thus two regions which look very far apart today, were much closer in the past than what big bang theory would predict.

At that time they could have communicated and made their temperatures uniform, whose effect we see today.

What is responsible for such a rapid expansion of the universe?

Standard model <u>does not</u> predict such rapid expansion.

However, it is possible to find modifications of the standard model where such rapid expansions can take place.

We need more experimental input to decide on whether this is the correct understanding of nature.

Moving forward . . .

Summary of main points so far:

Standard model has been able to explain most features of the observed universe.

There are some features which are not explained by the standard model, but can be explained by some of its modifications.

The only place where such modifications fail is in incorporating the force of gravity.

Can this be giving us a clue?

Since gravity is so difficult to incorporate, perhaps there is a unique quantum theory that contains gravity.

If so, then this quantum theory must incorporate not only gravity but everything else that we see in nature

– top-down approach.

String theory is such a proposal.

Basic ingredients of the standard model and its modifications

1. Special theory of relativity

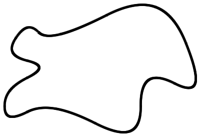
2. Quantum mechanics

3. Elementary constituents of matter are point particles

String theory gives up the last postulate

Basic postulate of String Theory

Elementary constituents of matter are not zero dimensional point particles but one dimensional strings.



Typical size of a string $\sim 10^{-33}$ cm

This is much smaller than the length scale that can be probed by any present day experiment ($\sim 10^{-17}$ cm.)

Thus to a present day experimentalist the states of the string will appear to be particle like objects.

Different vibrational states will have different properties and will appear as different elementary particles.

It turns out that one of the vibrational states of the string acts as the mediator of gravitational force.

– strings automatically exert gravitational force on each other.

String theory is automatically a quantum theory of gravity!

Furthermore the requirement of mathematical consistency completely fixes the underlying laws of string theory.

In other words there is a unique string theory.

This is to be contrasted with the theory of point particles where there are infinite number of consistent theories.

Standard model is one of these consistent theories favoured by experimental results.

The uniqueness of string theory, and the fact that it incorporates quantum theory of gravity, makes this a strong candidate for the theory that describes the fundamental constituents of matter and their forces.

To confirm this we need to verify that string theory also explains the origin of electromagnetic, strong and weak forces.

– not completely straightforward

The difficulty in doing this is related to the existence of many different phases of string theory.

Analogy: The single theory, describing the H_2O molecules and the force between them has different phases in the form of ice, water and steam.

Similarly string theory has many phases, even though the theory itself is unique.

Just as the environment inside ice, water and steam are very different, similarly the environments in different phases of string theory are very different.

Even the 'fundamental constants of nature' like the number of elementary particles and their masses and charges appear to be different in different phases.

For some phases of string theory the environment is very similar to what we observe in nature.

– have elementary ‘particles’ and forces similar to what we observe in nature.

However there are also other phases of string theory which have very different environment.

– even the dimension of space can be different in these phases taking values all the way up to 10 instead of 3.

Is there a phase of string theory that describes exactly the universe in which we live?

Search for such a phase is still on, but we have not yet found one.

Even if we find such a phase, we need to explain why nature exists in one particular phase and not in any other phase.

Both issues are currently under active investigation by many researchers.

Summary

Study of the universe at small and large scales is an exciting subject.

We have already learned a lot about this subject $\cdots$

$\cdots$ but a lot is yet to be learned.