

The Physics-Astronomy Frontier

JAYANT V. NARLIKAR

Tata Institute of Fundamental Research, Bombay 400 005

Introduction

Astronomy may rightfully claim to be the oldest branch of physics. Philosophical speculations apart, a systematic approach to understand the cosmos seems to date as far back as the Greek civilization of more than two thousand years ago.* The observations of Hipparchus and Ptolemy and the latter's masterpiece 'the Almagest' describe the sophistication achieved by the Greeks in the study of stars and planets. Although much of that work was based on the wrong premise of 'a fixed Earth and a moving cosmos' the geometrical constructions employed and the approach of the theoretician to explain the observations by a model both indicate the same spirit that guides today's scientists.

Even after the fall of the epicyclic geocentric theory of the Greeks, astronomy continued to dominate the scientific scene till well into the seventeenth century. The first of the four fundamental interactions of physics to be discovered owes its discovery to astronomy. It was not the falling apple (an unsubstantiated legend) that led Newton to the inverse square law of gravitation; the law was indicated only by its astronomical applications. Starting from Kepler's laws of planetary motion and Halley's prediction of the return of the comet (subsequently named after him) in 1758, to Laplace's masterpiece on the solar system, called the 'Mecanique Celeste' published in Napoleon's regime, we see how detailed astronomical observations led to the general belief in the law of universal gravitation. Indeed it was the success of the Newtonian inverse square law that prompted Coulomb to postulate a similar law for electrostatic attraction and repulsion.

However, during the eighteenth and nineteenth centuries and the first half of the present century other branches of science outpaced astronomy. The 'laboratory experiment' with its advantages of control, repeatability, accuracy and nearness to the observer took precedence over the 'mere observations of remote heavenly bodies'. Astronomical theories began to be considered too speculative to be of scientific interest and from the position of the head of the household, astronomy found itself relegated to the status of a poor relation.

However, thanks to many factors converging the fortunes of astronomy have brightened. This article examines how today the frontier between astronomy and physics is thriving with excitement, how astronomical observations have made the best use of modern technology and, last but not the least, how astronomy may hold the clues to the validity of the ideas in fundamental physics.

The law of gravitation

In chronological order, gravitation is the oldest known interaction of physics. We have already indicated how astronomy played the leading role in establishing the validity of this interaction over vast cosmic distances, out to billions of kilometres, that characterize our solar system. In the nineteenth century J. C. Adams in England and U.J.J. LeVerrier in France both used perturbation techniques based on Newtonian gravitation to deduce the existence and location of a new planet in the vicinity of Uranus. The planet was found where indicated and was named Neptune.

The discovery of Neptune was prompted by the desire to account for the observed irregularity

*It is often stated that advanced sciences were known to our vedic ancestors. I am willing to accept this claim provided it is substantiated with a mathematical and unambiguous account of any scientific experiment/observation from the vedic literature. So far I have not seen any such account.

in the motion of Uranus. Was the irregularity a signal that Newtonian gravitation breaks down? Placing their faith in the Newtonian theory Adams and LeVerrier independently argued that the irregularity was due to a hitherto unknown planet—and so Neptune was discovered in 1845.

The same approach did not work two decades later when LeVerrier tried to account for the observed precession of the perihelion of Mercury's orbit with the hypothesis of a new intramercorial planet which he tentatively called Vulcan. No Vulcan was found and its nonexistence was confirmed. Where was the source of this apparent irregularity? Where in this context did Newtonian gravitation stand then? It could explain all but a small amount of precession rate 43 seconds of arc per century.

The discrepancy between theory and observations was resolved in 1916 with a new theory of gravity—Einstein's general theory of relativity. Although the motivation and the fundamental postulates of general relativity (GR) were totally alien to Newtonian concepts, its predictions agreed with the Newtonian theory in the limit of weak gravitational fields. It was the small difference between the two theories that could account for the observed discrepancy.

The theoretical difference may be understood in the following way. In addition to the inverse square force per unit mass

$$F_N = \frac{GM_\odot}{r^2}$$

with which the sun (mass $M_\odot$) attracts Mercury at a distance r in the Newtonian theory, GR predicts an additional force of attraction

$$F_{GR} - F_N \propto 1/r^4$$

which has inverse-fourth power dependence on r .

The extra term is small and negligible for outer planets and produces marginal effects on inner planets, the most significant being Mercury. Mercury's orbit precesses at the rate of about 43 seconds of arc per century—exactly the rate needed to account for the observed advance of the perihelion.

In this century several experimental tests have

confirmed the reality of the difference between GR and Newtonian gravity—in each case the outcome has favoured GR. All tests are astronomical in origin and it is not difficult to see why.

The characteristic parameter that indicates the order of magnitude of the difference is

$$\alpha = \frac{GM}{c^2 R}$$

where R is the distance from the gravitating mass M . Clearly α is largest at the surface of the body so we may set R equal to the radius of the mass, assumed spherical. If ρ is the mean density of the object we may write

$$\alpha = \frac{4\pi G}{3c^2} \rho R^2$$

Now terrestrial objects have densities not exceeding $\sim 20 \text{ g. cm}^{-3}$. Measuring R in metres we get

$$\alpha \cong 5 \times 10^{-24} R_{\text{metres}}^2$$

Thus in characteristic terrestrial experiments the value of α is $\sim 10^{-25}$ as compared to $\alpha \sim 2 \times 10^{-6}$ on the surface of the Sun. The large masses provided by astronomy are much more useful for verifying these subtle gravitational effects than any terrestrial masses.

It is not surprising therefore that the concept of the black hole (for which $\alpha = \frac{1}{2}$) and its remarkable properties have originated in astrophysical contexts. By acting as a powerful attractor of matter in its environment the black hole is potentially a large reservoir of energy. It has the added advantage that the energy is concentrated in small volumes of space. Wherever the astronomer sees manifestations of concentrated pockets of energy he is naturally tempted to use black holes as energy machines. So the rapidly fluctuating X-ray sources in binary stars, the active nuclei of galaxies and the powerful but very compact quasistellar objects are assumed to derive energy from black holes in most of the popular scenarios being discussed today. Thus so far as gravity is concerned astronomy has vastly enriched the storehouse of physics.

Electromagnetic theory

It was the second of the four fundamental interactions, the electromagnetic interaction, that boosted laboratory physics at the expense of astronomy in the eighteenth and nineteenth centuries. Nevertheless in the present century astrophysicists have gained considerably by the laboratory knowledge of electromagnetic radiation, the various mechanisms that give rise to it and the way it is absorbed by different kinds of matter at various wavelengths.

It was the spectral analysis of light from stars that gave such important information as their surface temperatures and the nature of matter in their outer envelopes. By examining the reddening of interstellar light it is possible to guess what is the interstellar dust that absorbed or scattered it. Processes like synchrotron emission and the inverse Compton scattering have been applied successfully by the theoreticians to study and explain the observed features of cosmic X-ray and radio sources.

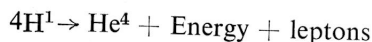
These applications of electromagnetic radiation to astronomical problems are given here to indicate not only how astronomers have gained from basic physics, the gain has flowed in the reverse direction also. For, in the astronomical systems we encounter environments so different from what can be simulated in the laboratory. Thus the successful applications described above illustrate how the basic electrodynamic theory is valid over situations far wider than those under which it was tested in the laboratory. It is through astronomy therefore that the physicist acquires confidence in the universality of the laws of physics.

Strong and weak interactions

Although gravity and electromagnetic theory may be considered relevant to astronomy because they are long-range interactions, even the short range strong and weak interactions are important to understand the nature of astronomical objects.

The most important applications of these theories are, of course, to the understanding of stellar structure and evolution. Why do stars shine? The answer comes from nuclear energy—the energy of fusion. It was in the 1920s that the

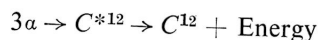
astronomer Eddington proposed the idea (based on J. Perrin's suggestion) that fusion of hydrogen to helium



releases nuclear energy in quantities sufficient to keep the Sun shining for billions of years. Eddington had estimated the temperatures in the stellar cores to be as high as 10 to 40 million degrees (K). At these temperatures Eddington believed fusion to be possible.

Although the nuclear physicists of his time thought the process impossible, a decade later Eddington was vindicated. Hans Bethe successfully completed a theoretical model of the Sun in which the primary energy source was nuclear fusion of hydrogen to helium.

In the 1950s, it was another astrophysicist, Fred Hoyle who successfully forecast the triple-nuclear reaction:



In this reaction three α particles (i.e., helium nuclei) are fused together in a resonant reaction to generate an excited state of the carbon nucleus (C^{*12}) which decays into an ordinary carbon nucleus (C^{12}) to produce energy. Hoyle had conjectured that such a process was bound to exist if stars were to keep shining after exhausting their hydrogen fuel. Again, nuclear physicists were skeptical at first but then they found that such a reaction indeed exists.

These instances demonstrate the valuable inputs astrophysicists have made to the understanding of the atomic nucleus. White dwarf stars, neutron stars, etc., are examples of stars in which matter is strongly compressed with densities in the range 10^6 – 10^{15} g. cm^{-3} —far exceeding normal matter we see here on the earth. How do such bulk concentrations behave? This question can only be answered through astronomical studies.

Towards unification of physics

One of the most fashionable frontier areas currently is the unification of all basic physical interactions. The approach using gauge theories, which Abdus Salam and Stephen Weinberg successfully employed

to unify the electromagnetic and weak interactions, is being tried further to incorporate the strong interaction also. Eventually, it is hoped that all four interactions will be unified into a single one.

To test the Salam—Weinberg theory it was necessary to study the interactions of particles which have been energized to ~ 100 GeV. The accelerator ($p\text{-}\bar{p}$ collider at CERN) was able to generate such high energy particles. Attempts are being made to raise the energy limit by one or two orders of magnitude. Perhaps with future technologies the limit may be raised by two or three orders of magnitude more.

However, even these prospective limits fall far short of the energies needed to verify the so-called grand unified theories (GUTs) that seek to unify the strong interaction with the already unified electroweak interaction. The particles taking part in GUTs must be energized to 10^{15} GeV—some thirteen orders of magnitude higher than the energies at which the electroweak theory was tested. How can we expect a verification of GUTs? A laboratory test is not on the cards.*

Again astronomy provides the clue. The currently popular model of the universe as a whole leads us to the concept of its origin in a gigantic explosion—the so-called big bang. It is believed that the universe exploded into existence about 15 billion years ago. Starting our cosmic clock from this instant we may relate the characteristic linear size S of the universe to the time elapsed t by a simple relation

$$S \propto t^{1/2}$$

The universe can be ascribed a temperature T which behaves as

$$T \propto t^{-1/2}$$

Thus at $t = 0$ the temperature was infinite. It rapidly declined thereafter.

Now temperature is a measure of the average energy per particle. And that energy also declines from infinity to the presently observed very low values.

It is clear therefore that at some time soon after the big bang there was an epoch when the typical particle energies were as high as 10^{15} GeV. Detailed calculations place this epoch at $\sim 10^{-36}$ second! Thus there were a few fleeting moments soon after the big bang when GUT had a role to play.

Of course it is not possible to catch those moments of history now. But we can examine the aftermath. If there were some permanent relics left by the GUT then we should be able to examine them and try to verify the GUT thereby.

Such relics are expected to be the type and quantity of matter (seen and unseen) as well as radiation that is found in the universe today. GUTs and the Super-Symmetry (SUSy) theories are many and they make different predictions. By examining the nature of visible and dark matter and how it is distributed, how galaxies are formed, etc., we can perhaps tell which GUT or SUSy is consistent with the overall scenario. Thus, by a strange twist of fate theories about the microscopic structure of matter are to be decided by theories of the large scale structure of the universe!

Conclusions

These ideas indicate how the science of astronomy can make valuable contributions to fundamental physics. That laws of fundamental physics help the astronomer's understanding of the heavenly bodies is readily appreciated. What is not so obvious but is equally valid is the fact that by such applications the physicist gains confidence about how universal the applicability of those laws is. This two-way interaction is what makes the physics-astronomy frontier so exciting.

*The proton decay experiment tests are consequence of GUTs but not their full dynamical implications.