The X-ray Universe

Wallace Tucker y Riccardo Giacconi

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Chapter 2: The sensible world

“Our subject is the sensible world, not a world on paper.” Galileo put these words in the mouth of his character Salviatus more than 350 years ago. This contrast –between the “paper world” of natural philosophers in the Aristotelian tradition and the ”sensible world of observation”– was at the core of the scientific revolution of the seventeenth century.

Since that time the views of the Galilean-Newtonian school have prevailed: observations and experiments have been considered essential building blocks of theoretical structures. Indeed, at the end of the nineteenth century the pendulum had swung so far toward the observational-experimental approach that self-styled disciples of Galileo and Newton, misunderstanding their legacy, denied the validity of pure theory in solving problems in the real world. They even actively persecuted theoretical investigators. A famous disagreement between Lord Kelvin and Ludwig Boltzmann demonstrated in a tragic way that philosophical beliefs about method in science, as opposed to the actual way science is done, can have a profound impact on the conditions under which scientific research is carried out.

Lord Kelvin took the (by then) conservative Galilean-Newtonian point of view: “The true naturalist knows that the essence of science consists of inferring antecedent conditions, and anticipating future evolutions from phenomena which have actually come under observation.” On the other side of the debate, Boltzmann propounded pure theory as a way of understanding the physical world: “The more abstract the theoretical investigation, the more powerful it becomes; theory conquers the world.”

Boltzmann was challenged by Kelvin and Peter Tait in the field of applied mathematics. He was isolated among the atomists, who saw in his theories “inconvenient excesses of generalization and abstraction,” and he was attacked on philosophical grounds by Ernst Mach and Wilhelm Ostwald. At the 1895 Congress of Lubeck, he saw his view of the world and his scientific theories rejected by majority vote. This incident revealed more about the tenor of the times and the character of Boltzmann’s opponents than about the veracity of his ideas, but it affected him profoundly. Although later generations vindicated him and recognized that he had both laid the foundation and built the structure of much of statistical mechanics, in his own lifetime he was hounded by his academic colleagues. Finally, ill and depressed, he committed suicide in 1906.

Today this intolerance and doctrinaire certainty that only one approach to knowledge of the physical world is valid is no more than a musty skeleton in the closets of science. The need for different approaches to scientific research is hardly a matter of debate. A conflict between the observational and theoretical approaches to the natural sciences no longer makes any intellectual sense. Modern research in the history of science has shown clearly that scientists do not carry out their work in a straightforward logical procession in keeping with the steps of the scientific method as outlined by philosophers, but rather that they take a much more complex and tortuous path, influenced by a multitude of conditions that includes the society around them as well as their own intellectual baggage. Technologically advanced nations spend enormous sums of public money every year to support experimental investigations in all scientific disciplines. At the same time, the very powerful and abstract theories of Bernhard Riemann, Paul Dirac, Wolfgang Pauli, and Albert Einstein dominate our conception of the universe.

If all is well, why do we wave the Galilean flag? Because we share the concern of many scientists that experimental investigations that are truly new and can lead to great discoveries are being hampered by the structured approach to the conduct of science. This approach appears to result from the bureaucratic control of federal funding for research. It is difficult to say whether such structure has been adopted by the bureaucracies more from need or from preference. But it seems to us clear that it rests on a diffused and simplistic perception of how science is done, and that it is aided by a widening schism between theorists and experimentalists. This schism does not result from a reasoned difference in philosophy, but rather is the effect of misunderstandings brought about by social customs and by increased specialization.

There is a gencrally accepted view that science proceeds according to the scheme outlined by Thomas Kuhn in his book *Scientific Revolutions*. We believe this view has had a negative impact on decision making in science, especially through its influence on the bureaucracies that administer funds for scientific research in the United States. According to Kuhn a scientist approaches a problem with a mental picture developed over years of observing, hypothesizing, theorizing, and testing. Kuhn calls this mental picture, which the scientist shares with his colleagues, a “paradigm.” He asserts that the paradigms accepted by scientists at any given time guide them in their research and determine how they will perceive the world.

The existence of shared paradigms in a science denotes its maturity. It is only in the early stages of development of a new field that its practitioners fumble along without any conceptual framework. Kuhn says that a mature field of science exhibits alternating periods of “normal science” and “scientific revolution.” In times of normal science paradigms appear to work well, explaining new observations as they are obtained, and the observations tend to extend and consolidate paradigms. From time to time, however, observations are obtained that do not fit these neat pictures. Eventually, but only after much searching for a way out, the old paradigm is abandoned in favor of new ones. Such periods are Kuhn’s scientific revolutions.

Many historians of science consider Kuhn’s approach only a rationalization after the fact of the way science is really done. Notwithstanding this criticism, it is easy to see that the neat division into periods of normal science and scientific revolution could have great appeal to a government official pressured to make difficult decisions and to justify these decisions simply and quickly to his superiors. To decide what should be done next in a field of science, the official can simply form a committee of eminent scientists, typically but not necessarily theorists, the “keepers of the paradigms,” and ask them what should be the next step in a logical sequence of extending the validity of the paradigm.

But a paradigm is only a model on paper of the real world; it is not the real world. Outside the region illuminated by paradigms lies a whole world to be known. A discovery is by definition unpredictable from the limited point of view of previous knowledge. What then is to guide the scientist who wishes to embark on a voyage of discovery? Intuition, imagination, speculation, aesthetic considerations, a critical view of existing paradigms, intellectual arrogance, self-confidence, an almost childlike and mystical desire to know, a deeply held belief in the richness of nature. It would be difficult for a committee to defend its recommendations on the basis of reasons like these, yet often just such reasons motivate the leap of imagination and sustain the great effort that the would-be discoverer must dedicate to the pursuit of his vision.

The freedom to pursue an independent path has been more easily available to the theorists, whose traditional requirements have been pencil and paper (though nowadays they, too, often need considerable funding to pay for computer calculations), than to the experimentalists, who often need elaborate and expensive tools to carry out their work. This is certainly the case in elementary particle physics, where access to costly time at accelerators has to be carefully parcelled out, and in many areas of astronomy, where the proposals for use of the oversubscribed national observatories must go through a severe review procedure. The stifling of the independent spirit is an inevitable byproduct of these rigorous selection processes. This is of concern in any area of science where public funds are necessary to carry out the investigations, especially for those major undertakings which go under the label of "big science."

Several authors have claimed that the outstanding discoveries stem from relatively small enterprises carried out by a few individuals. For example, pulsars were discovered by a small group with a limited budget at Cambridge University, rather than by a big-science team. We believe that the problem has less to do with big versus small than with the restrictions that are inevitably imposed on big-science teams. It is extremely difficult for a big-science team to pursue the kinds of independent, innovative lines of research that often lead to major discoveries. If large amounts of public funds are to be spent, the expenditure must be justified, and for justification the government officials will turn to the keepers of the paradigms.

The schism in science today is not so much between the observer or experimentalist and the theorist as between the keepers of the paradigms and those who would follow a course that would take them outside the paradigms. A related problem is that the keepers of the paradigms often consider the observers or experimentalists to be merely technicians. This view ignores the personal and unique contributions that experimentalists can make in their search for new and unsuspected glimpses of nature's richness. These contributions do not come primarily from the execution of the task, however complex, but rather from seeing the problem in a new frame of reference and from posing questions that can be answered, so that we can probe in a new way the natural phenomena around us.

X-ray astronomy developed because creative scientists ignored the predictions of theorists that a search for cosmic sources of x-rays would be futile or of little interest, and invented ways to use this region of the electromagnetic spectrum to observe previously undetectable aspects of the universe. The result was the opening up of one of the most exciting fields of modern astrophysics.

Of course, x-ray astronomy did not begin in a vacuum, nor has it blossomed in isolation from the rest of astronomy. It emerged as part of a revolution that has occurred throughout the field of astronomy. This revolution began in the 1950s, when newly developed techniques for detecting radio waves were applied to the search for sources of cosmic radio waves. A series of spectacular discoveries came in rapid succession: first the discovery that the supernova explosion of a star generates a vast cloud of gas and high-energy particles; then the discoveries of radio galaxies and quasars, which led to the conclusion that explosive events that release a million times as much energy as a supernova explosion take place on a galactic scale; and finally the discovery of the microwave background radiation, which provided strong evidence that an explosive event, the Big Bang, encompassed and very likely gave birth to the Universe. By the end of the 1960s it was clear that violent events and high-energy processes play crucial roles in the universe.

As x-ray astronomy developed, it became apparent to many scientists that observations at x-ray wavelengths are uniquely suited to studying certain features of the high-energy universe. Neutron stars, the stellar remnants of supernova explosions, radiate large amounts of x-rays, as does the hot gas behind shock waves produced by supernova explosions. The central cores of galaxies, which may contain supermassive black holes, are also strong sources of x-radiation. On a much larger scale, regions of space where thousands of galaxies have clustered together are filled with vast clouds of hot gas that glows in x-rays.

The brief history of x-ray astronomy in many ways epitomizes modern science. It has the tension between experiment or observation and theory. It has the competition between groups to become the first to discover some new phenomenon, or for the opportunity to use a spacecraft; it has failures, misinterpretations of data, ventures down blind alleys, and also those golden moments when everything works, when everything comes together, theory and experiment, and we understand the universe a little better than we did before.