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REVIEW ARTICLE

History of astronomical discoveries

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Abstract The wide diversity of routes to astronomical, astrophysical and cosmological discovery is discussed through a number of historical case studies. Prime ingredients for success include new technology, precision observation, extensive databases, capitalising upon discoveries in cognate disciplines, imagination and luck. Being in the right place at the right time is a huge advantage. The changing perspectives on the essential tools for tackling frontier problems and astronomical advance are discussed.

Keywords Astronomy · Astrophysics · Cosmology · Discovery · History

1 Introduction

The route to astronomical, astrophysical and cosmological discovery is often tortuous, but the essential ingredients are well known.

- New technology, including instrumentation,
- New ways of doing astronomy,
- Precision observation,
- Extensive databases,
- Capitalising upon discoveries in other disciplines,
- Relevant theory,
- Imagination,
- Luck.

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It is also an enormous advantage to be in the right place at the right time and to know that one is in that enviable position.

In my teaching of physics and astronomy to students fresh to University, I have presented an idealised overview of what can crudely be described as our ‘scientific method’—how we validate our theories by experiments and their interpretation. My favorite example is the route to the discovery of Newton’s laws of gravity and motion and the subsequent development of general relativity [15]. The sequence goes as follows:

1. *Experiment or Observation*. Tycho Brahe’s observations of the motions of the planets (1575–1595).
2. *Interpretation of the data*. Kepler’s laws of Planetary Motion (1605–1619)
3. *Development of Theory*. Newton’s law of gravity (1665)—circular planetary orbits.
4. *Comparison of Experiment/Observation with Theory*. Success, but the orbits are ellipses.
5. *Refinement of Theory*. Newton’s laws of gravity and motion (1687)—elliptical planetary orbits.
6. *Refinement of Experiment/Observation*. The advance of perihelion of Mercury discovered by Le Verrier (1855).
7. *Return to step 3*. Einstein’s General Theory of Relativity (1915).

If only it were that simple!

Once students reach the third or fourth year, one can adopt a more realistic model for the process of discovery. It cannot be better expressed than in the words of Douglas Gough [7]:

> ‘I believe that one should never approach a new scientific problem with an unbiased mind. Without prior knowledge of the answer, how is one to know whether one has obtained the right result? But with prior knowledge, on the other hand, one can usually correct one’s observations or one’s theory until the outcome is correct. However, there are rare occasions on which, no matter how hard one tries, one cannot arrive at the correct result. Once one has exhausted all possibilities for error, one is finally forced to abandon a prejudice, and redefine what one means by ‘correct’. So painful is this experience that one does not forget it. The subsequent replacement of an old prejudice by a new one is what constitutes a gain in real knowledge. And that is what we, as scientists, continually pursue.’

In fact, the process of astronomical discovery is much more eclectic than either of these models suggest. The really great discoveries which advance our real knowledge and change our perspectives are rarely without controversy and conflict. Once the breakthrough is achieved, however, the long task of assimilating the new discovery into its rightful place in the astronomical landscape begins. This is just as important as the initial breakthrough and is the route to further discoveries.

At this conference, it is fitting that we should begin with the observations of Galileo, as described in his *Sidereus Nuncius* (The Sidereal Messenger), surely one of the most amazing publications in astronomy—it appeared in March 1610, within weeks of his astronomical observations.[1] By the time of its publication, Kepler had established the first two of his laws of planetary motion, the first describing the elliptical orbits of the planets with the Sun in one focus and the second the areal law, that the radius vector from the Sun to the planet sweeps out equal areas in equal times. These laws were discovered as a result of his brilliant analysis of the observed motions of the planets detailed in the magnificent datasets bequeathed to him by Tycho Brahe. These reinforced his strongly pro-Copernican position.

Galileo's *Sidereus Nuncius* included day-to-day observations of the four bright satellites of Jupiter, Io, Europa, Ganymede and Callisto. Here was a scale model of the Copernican picture of the Solar System. Kepler published his own enthusiastic commentary on Galileo's achievement in his booklet *Conversation with Galileo's Sidereal Messenger*, including his interpretation of the significance of Jupiter's moons:

> 'The conclusion is quite clear. Our moon exists for us on Earth, not for the other globes. Those four little moons exist for Jupiter, not for us. Each planet in turn, together with its occupants, is served by its own satellites. From this line of reasoning we deduce with the highest degree of probability that Jupiter is inhabited.'

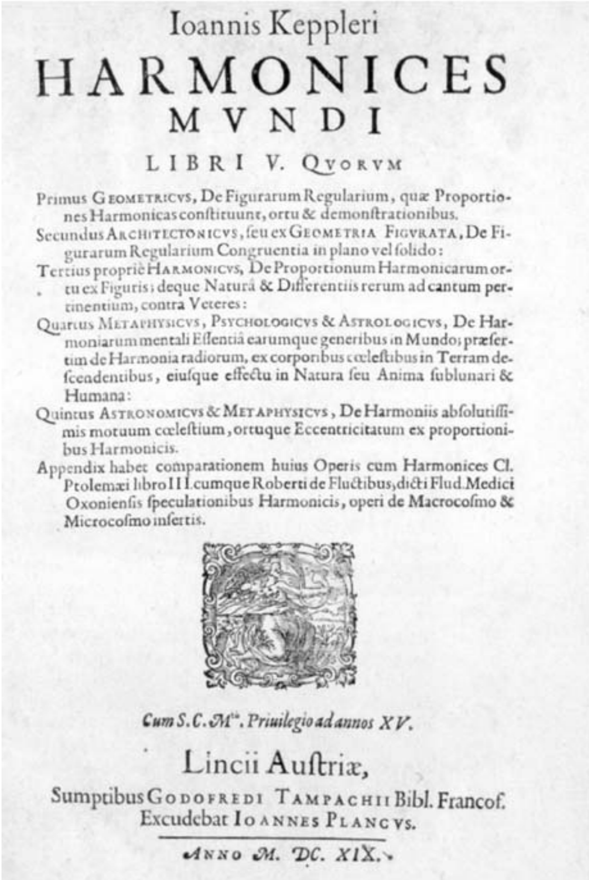
What is one to say? Kepler was simply allowing his imagination free rein in the interpretation of startling new observations. I invite readers to come up with contemporary examples.

Kepler was the most distinguished mathematician in Europe and in 1619 published his great *Harmonices Mundi* (The Harmony of the World). This was the Grand Unified Theory of its day, as can be seen from the contents page—geometry, architectonics, harmony, metaphysics, psychology, astrology, astronomy, and so on (Fig. 1). By this time, he had much more accurate values for the radii and periods of the orbits of the planets. Suddenly, when he had more or less completed the writing of his treatise, the crucial third law appeared from nowhere. These astronomical data were crucial in Newton's derivation of the law of gravity. Kepler's third law states that $v \propto r^{-1/2}$ and centripetal balance requires $F \propto v^2/r$. It follows that $F \propto r^{-2}$, Newton's law of gravity in its primitive form. Newton's genius was to show that the same force which caused apples to fall was the same as that which held the planets in their orbits.

The subsequent extraordinary success of Newtonian mechanics and dynamics had a profound effect upon the sciences and all branches of intellectual

[1] I have given many more details of the achievements of Tycho Brahe, Kepler, Galileo and Newton in my book *Theoretical Concepts in Physics* [15].

Fig. 1 The frontispiece and contents page of Kepler's *Harmonices Mundi*, the Harmony of the World, of 1619



Ioannis Keppleri

HARMONICES MVNDI

LIBRI V. QVORVM

Primus GEOMETRICVS, De Figurarum Regularium, quæ Proportiones Harmonicas conſtituunt, ortu & demonſtrationibus.

Secundus ARCHITECTONICVS, ſeu ex GEOMETRIA FIGVRATA, De Figurarum Regularium Congruentia in plano vel ſolido:

Tertius propriè HARMONICVS, De Proportionum Harmonicarum ortu ex Figuris; deque Naturâ & Differentiis rerum ad cantum pertinentium, contra Veteres:

Quartus METAPHYSICVS, PSYCHOLOGICVS & ASTROLOGICVS, De Harmoniarum mentali Eſſentiâ earumque generibus in Mundo; præſertim de Harmonia radiorum, ex corporibus cœleſtibus in Terram deſcendentibus, eiuſque effectu in Natura ſeu Anima ſublunari & Humana:

Quintus ASTRONOMICVS & METAPHYSICVS, De Harmoniis abſolutiſſimis motuum cœleſtium, ortuque Eccentricitatum ex proportionibus Harmonicis.

Appendix habet comparationem huius Operis cum Harmonices Cl. Ptolemæi libro III. cumque Roberti de Fluctibus, dicti Flud. Medici Oxonienſis ſpeculationibus Harmonicis, operi de Macrocoſmo & Microcoſmo inſertis.

Cum S. C. M^tis. Priuilegio ad annos XV.

Lincii Auſtriæ,

Sumptibus GODOFREDI TAMPACHII Bibl. Francof.
Excudebat IOANNES PLANCVS.

ANNO M. DC. XIX.

endeavour. It is salutary, however, to note the words of Hermann Bondi on Newton's achievement in deriving the laws of gravity and motion [2].

> 'Newton's solution of the problem of motion in the Solar System was so complete, so total, so stunning, that it was taken as the model of what any decent theory should be like, not just in physics, but in all fields of human endeavour…I regard this as profoundly misleading. In my view, most of science is not like the Solar System but much more like weather-forecasting.'

2 Stellar structure and evolution

The Hertzsprung-Russell diagram is a splendid example of discovery resulting from precision observation.[2] Russell's approach to stellar astrophysics

[2]Many more details of the discoveries discussed in the remainder of this essay are included in my book *The Cosmic Century: A History of Astrophysics and Cosmology* [16].

involved the difficult task of obtaining accurate distances for nearby stars. In collaboration with Arthur Hinks of the Cambridge Observatories, he perfected the techniques of determining photographic parallaxes. Accurate photometry and spectral types were provided by Pickering for the 300 stars for which parallaxes were available. These were the data which he used in the famous 'Russell diagram' of 1914 (Fig. 2). Hertzsprung's and Russell's achievements set the scene for the development of the mathematical theory of stellar structure and evolution.

It is intriguing that Russell's diagram included the very faint A star, *o*-Eridani, with absolute magnitude about +11 (see Fig. 2). The story of its discovery is delightfully told in Russell's memoirs [28]. As recounted above, Russell had suggested to Edward Pickering in 1910 that it would be useful to obtain the spectra of stars for which parallaxes had been measured. According to Russell:

> 'Pickering said 'Well, name one of these stars'. 'Well', said I, 'for example, the faint component of Omicron Eridani'. So Pickering said, 'Well, we make rather a specialty of being able to answer questions like that'. And

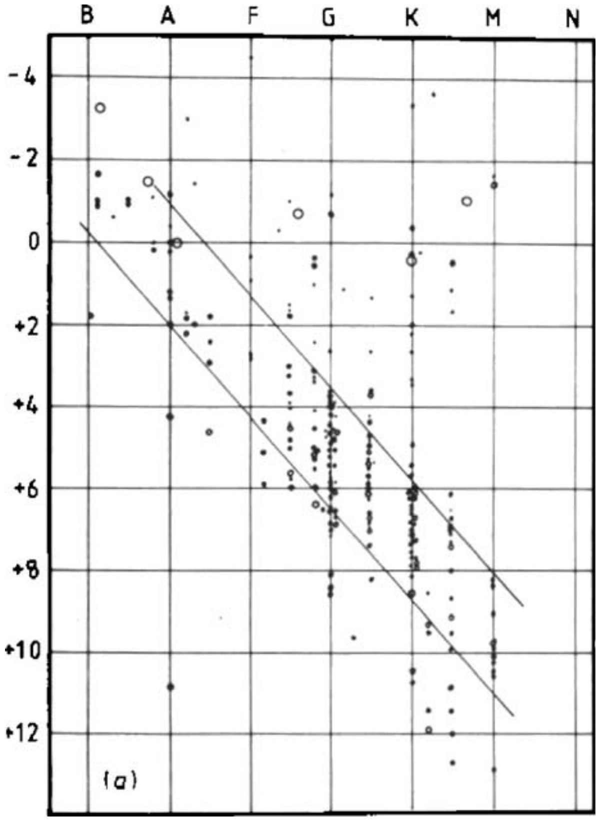


Fig. 2 Russell's original version of the Hertzsprung-Russell diagram of 1914 in which spectral type is plotted along the abscissa and absolute magnitude along the ordinate [25–27]

> so we telephoned down to the office of Mrs. Fleming and Mrs. Fleming said, yes, she'd look it up. In half an hour she came up and said, 'I've got it here, unquestionably spectral type A.' I knew enough, even then, to know what that meant. I was flabbergasted. I was really baffled trying to make out what it meant. Then Pickering thought for a moment and then said with a kindly smile, 'I wouldn't worry. It's just these things which we can't explain that lead to advances in our knowledge.' Well, at that moment, Pickering, Mrs. Fleming and I were the only people in the world who knew of the existence of white dwarfs.'

Even at that time, it was the general view that the sequence of stellar types was in some sense a temperature sequence. Hertzsprung had already applied Planck's law to understand the colours and sizes of the stars and so this 'white dwarf' was a truly remarkable object. The next white dwarf to be discovered was Sirius B by Adams in 1914. In 1926, Eddington used his theory of stellar structure to predict that the gravitational redshift of Sirius B should be 20 km s^{-1}. In the same year, the gravitational redshift of Sirius B was measured by Adams to be 19 km s^{-1} [4]. Eddington was jubilant:

> 'Prof. Adams has killed two birds with one stone; he has carried out a new test of Einstein's theory of general relativity and he has confirmed our suspicion that matter 2000 times denser than platinum is not only possible, but is actually present in the universe.' Douglas [3]

The story reads like a classic example of the combination of the genius of observation and theory. The only problem is that the best estimate of the gravitational redshift of Sirius B from recent HST observations is 80.42 ± 4.83 km s^{-1}. I invite the reader to reflect on this story. With hindsight, we can appreciate that the problem of scattered light from Sirius A may have confused the observations, and the bolometric corrections for a star like Sirius B was not well known. This story gives some substance to what in the 1960s we in Cambridge used to call *Bondi's Dictum* and *Redman's Theorem*:

> *Bondi's dictum* 'All observations are wrong.'
> *Redman's theorem* 'Any competent theorist can reconcile any given set of observations with any given theory.'

I would emphasise that this is the low point of this essay.

Eddington's great insights into the theory of stellar structure and evolution were not gained without considerable controversy. The physical data needed to construct stellar models were not then available. For example, the density and temperature dependence of the energy generation rate and the opacity of the stellar material were not known. Some sweeping approximations were needed to make progress and Eddington had the right qualities of fearless imagination and technical skill to make the problems tractable. For example, in order to simplify the mathematics of his standard stellar model, Eddington made what Leon Mestel refers to as the 'hair-raising approximation' that the radiation pressure is a constant fraction of the total pressure throughout the star. It is no surprise that the subject of the internal constitution of the stars provoked heated debate. In fact, Eddington was fortunate in that the form of the mass-luminosity relation for stars is remarkably independent of the precise processes of energy production and the opacity law. But, in the process of gaining this understanding, there were some fiery exchanges between Jeans, his principal adversary, and Eddington. The tone of the debates is faithfully recorded in the proceedings of the meetings of the Royal Astronomical Society in *The Observatory*. For example, in a letter to *The Observatory*, Jeans writes in 1926

> 'May I conclude by assuring Prof. Eddington it would give me great pleasure if he could remove a long-standing source of friction between us by abstaining in future from making wild attacks on my work which he cannot substantiate, and by making the usual acknowledgements whenever he finds that my previous work is of use to him? I attach all the more importance to the second part of the request because I find that some of the most fruitful ideas which I have introduced into astronomical physics—for example, the annihilation of matter as the source of stellar energy, and highly dissociated atoms and free electrons as the substance of the stars—are by now fairly generally attributed to Prof. Eddington.' Jeans [12]

3 The expanding universe

The velocity-distance relation for galaxies was the first of the great cosmological discoveries which were to provide the observational foundation of the present standard cosmological models. Expanding solutions of Einstein's field equations were implicit in Friedman's models of 1922 and 1924, although this did not attract any significant attention at the time [5, 6]. Friedman's solutions for uniformly expanding Universes were independently discovered by Lemaître in 1927 who derived the 'apparent Doppler effect' according to which the recession velocities of extragalactic nebulae were a cosmical effect of the expansion of the Universe. In 1928, Robertson found $v = cl/R$, where l is distance, and from the recession velocities of nearby galaxies he found the equivalent of a Hubble constant of 500 km s^{-1} Mpc^{-1}. These studies predated Hubble's paper on the velocity–distance relation for galaxies of 1929 [10].

The fact that most galaxies have recession rather than random velocities with respect to our own Galaxy was already known from the pioneering efforts of Vesto Slipher. He realised that it was not the size of the telescope which was important in measuring the spectra of faint diffuse objects such as galaxies, but the f-ratio of the spectrograph.

In 1921, Carl Wilhelm Wirtz searched for correlations between the velocities of spiral galaxies and other observable properties and concluded that, when the data were averaged in a suitable way,

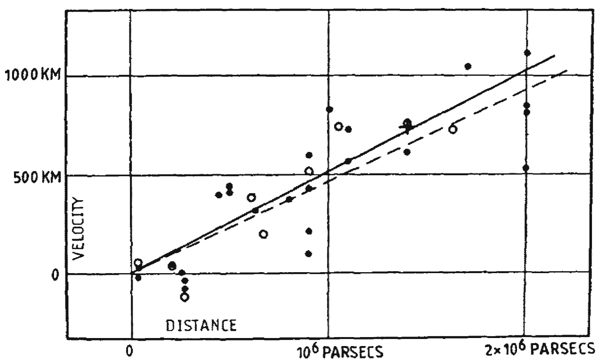
> '... an approximate linear dependence of velocity upon apparent magnitude is visible. This dependence is in the sense that the nearby nebulae tend to approach our galaxy whereas the distant ones move away ... The dependence of the magnitudes indicates that the spiral nebulae nearest to us have a lower outward velocity than the distant ones.' Wirtz [32]

It seems undeniable that this is the first enunciation of what became known as Hubble's law.

After Hubble had established beyond any doubt the extragalactic nature of the spiral nebulae in 1925, he published in the following year a wonderful paper in which he set out the basic types of galaxies, their masses and the contribution they made to the mass density of the Universe [9]. He was fully aware of the importance of his estimate of the mean mass density of the Universe since, according to Einstein's static model of the Universe of 1917, once this was prescribed, all the other properties of the Universe followed immediately.

By 1929, he had assembled data on the distances of galaxies for which velocities had been measured (Fig. 3). The distances of the nearest seven objects, all within 500 kpc, were the best determined and used the Cepheid variable technique; the distances of the next 13 objects were found by assuming that the most luminous stars in the galaxies had an upper limit of absolute magnitude $M = -6.3$; the last four objects, believed to be members of the Virgo cluster, had distances assigned on the basis of the mean luminosities of the nebulae in the cluster. As Hubble acknowledged, most of the velocities used in his 1929 paper were due to Slipher—of the 44 galaxy redshifts known in 1925, 39 of them had been measured by Slipher. From these meagre data, the velocity-distance relation shown in Fig. 3 was derived. It is remarkable that he found the relation from such a nearby sample of galaxies, given that we now know that the random velocities of galaxies are of the order of 300 km s^{-1}. He had, however, other evidence even at that time. In his brief paper, Hubble

Fig. 3 Hubble's original version of the velocity–distance relation of 1929 [10]



noted that Milton Humason had measured a velocity of 3,910 km s^{-1} for the galaxy NGC 7619, consistent with a extrapolation of the velocity-distance relation to greater distances.

4 The impact of the second world war

The Second World War had an enormous impact upon the whole of science. For astronomy, the most important legacy was the opening up of the electromagnetic spectrum for astronomical observation. Major advances in radio techniques had been driven by the need to enhance radar location, and the V2 rockets developed by the German scientists and engineers opened up the possibility of observations above the Earth's atmosphere. Scientific computing was on the horizon. Just as important were the major investments made in basic science, largely sponsored by the US military, recognising the enormous contributions which physics had played during the Second World War.

Many of the great astronomical discoveries of the subsequent decades can be traced to one or more of these wartime developments. But there was more to the new perspective than simply advanced technology. The scientists themselves had become used to carrying out huge programmes under enormous pressure on a scale far greater than in the pre-war years. As Bernard Lovell expressed it in 1987, the astronomers adopted an approach ...

> '...utterly different from that deriving from the pre-war environment. The involvement with massive operations had conditioned them to think and behave in ways which would have shocked the pre-war university administrators. All these facts were critical in the large-scale development of astronomy.' Lovell [17]

Astronomy was about to embark upon a course which would inevitably lead to it becoming one of the Big Sciences.

4.1 Radio astronomy and the origin of high energy astrophysics

Immediately after the War, a number of University Groups began to investigate the nature of the cosmic radio emission which had been discovered by Jansky in 1934. This radiation had been the subject of study by the UK Telecommunications Research Establishment during the War because the extraterrestrial noise could confuse radar signals. In the immediate post-War era, the principal groups involved in these studies were at Cambridge, Manchester and Sydney. The observations, which were carried out at long radio wavelengths, soon established the existence of populations of galactic and extragalactic radio sources.

By the early 1950s, the Australian radio astronomers had established that some of the extragalactic radio sources were associated with rather strange massive galaxies. For example, the source Virgo A was associated with the massive elliptical galaxy M87 which possessed a remarkable optical jet and

Centaurus A with the nearby massive 'colliding galaxy' NGC 5128. Thanks to an accurate radio interferometric position obtained by Ryle and Graham Smith, Baade and Minkowski were able to associate the brightest extragalactic radio source in the northern sky, Cygnus A, with a very distant galaxy [1]. In 1953, Jennison and Das Gupta at Jodrell Bank showed that Cygnus A had a double radio structure, what are now termed radio lobes, extending far beyond the confines of the associated massive galaxy [13]. The potential for new approaches to astrophysics and cosmology was apparent. By the mid 1950s, the nature of the radio emission was established as synchrotron radiation and so, to account for the properties of the radio emission, two major new components of the Universe were required—huge fluxes of ultrarelativistic electrons and large-scale magnetic fields. Both had to be ejected well beyond the confines of the parent galaxy.

During the 1950s, as the positional accuracy of the radio sources improved, several of the brightest radio sources were identified with bright giant elliptical or cD galaxies. These studies led to the discovery of the quasi-stellar radio sources 3C 48, 196, 286 by Matthews and Sandage in the early 1960s. The optical images of these objects were star-like but had spectra unlike those of any known type of star. The breakthrough came with the discovery of the quasar 3C 273. In 1962, Hazard's radio lunar occultation of 3C 273 led to an accurate determination of its position and radio structure, which in turn led to its identification as a quasar. The optical spectrum was obtained by Schmidt in 1963. The spectrum was again unrecognisable until he realised that it contained the characteristic lines of the Balmer series of hydrogen in emission, but with a redshift of 0.17 [29]. Once it was established that the quasars had large redshifts, the floodgates opened and many quasars were identified in the subsequent years, including the radio quiet variety in 1965. By the same year, the redshifts of the quasars had extended to values greater than 2.

In many ways, the quasars were discovered too early. Although Carl Seyfert had make pioneering spectroscopic observations of the compact, blue nuclei of a number of spiral galaxies, what we would now call Seyfert galaxies, these observations, published in 1943, were largely ignored [30]. The extreme luminosities and variability of the quasars were unprecedented in extragalactic astrophysics. It was quickly recognised that relativistic astrophysics must be involved in a central way in understanding their properties. At the closing dinner of the 1963 Texas Symposium, Thomas Gold summarised these new opportunities as follows:

> 'Everyone is pleased: the relativists who feel they are being appreciated, who are suddenly experts in a field which they hardly knew existed; the astrophysicists for having enlarged their domain, their empire by the annexation of another subject—general relativity.'

The remarkable upsurge of interest in general relativity in subsequent years was undoubtedly stimulated by the discovery of radio galaxies and quasars.

4.2 The discovery of pulsars

In March 1965, Antony Hewish was awarded a grant of £17,286 by the Department of Scientific and Industrial Research to construct a large radio array to study the 'twinkling' of radio sources with the joint objectives of discovering quasars, which were strongly scintillating sources, and studying the properties of the distorting screen, the interplanetary medium. To obtain adequate sensitivity at the low observing frequency of 81.5 MHz, the array had to be very large, $4\frac{1}{2}$ acres (1.8 ha) in area, in order to record the rapidly fluctuating intensities of bright radio sources on a time-scale of one tenth of a second. This was the key technological development which led to the discovery of radio pulsars.

A pulsating radio source was discovered during the commissioning observations in August 1967 by Hewish's graduate student Jocelyn Bell. It disappeared, but was observed with greater time resolution in November 1967—the pulses, once every 1.33 s, were individually resolved [8]. This was a totally unexpected discovery, although Franco Pacini had made the prescient suggestion that neutron stars might be observable as oblique rotators in 1967 [19]. Within months of their discovery, the parent bodies of the pulsars were identified with magnetised, rotating neutron stars, their masses being typically about 1.4 $M_{\odot}$, their radii 10 km and rotation periods 1 s.

The existence of neutron stars had been predicted by Baade and Zwicky in 1934, just two years after the discovery of the neutron. In the preface to his remarkable volume, *Catalogue of Selected Compact Galaxies and of Post-eruptive Galaxies* of 1968, Zwicky described how these ideas were received:

> 'In the Los Angeles Times of January 19 1934, there appeared an insert in one of the comic strips, entitled *Be Scientific with Ol'Doc Dabble*, quoting me as having stated
>
> 'Cosmic rays are caused by exploding stars which burn with a fire equal to 100 million stars and then shrivel from 1/2 million miles diameter to little spheres 14 miles thick',
>
> says Prof. Fritz Zwicky, Swiss Physicist. This, in all modesty, I claim to be one of the most concise triple predictions ever made in science. More than thirty years were to pass before the statement was proved to be true in every respect.' Zwicky [34]

The neutron stars were one of the key discoveries of modern astronomy. In these stars, general relativistic corrections are no longer small, but are central to understanding their stability. Relativistic stars really existed and their discovery had implications for understanding all types of explosive events, including the violent events occurring in active galaxies. At the Brighton General Assembly of the IAU in 1970, Iosef Shklovsky asked me to introduce him to Jocelyn Bell. He said, 'Miss Bell, you have made the greatest astronomical discovery of the 20th century'.

Once the initial discovery was made, the long process of discovering large samples of pulsars began and neutron stars rapidly became part of the furniture of modern astrophysics. As a result of the Arecibo surveys, the binary pulsar PSR 1913+16 was discovered by Hulse and Taylor in 1974 [11]. The existence of such systems initially came as a surprise to the astrophysical community, but their value as probes of relativistic theories of gravity was immediately appreciated. The more recent discovery of the short-period double pulsar PSR J0737-3039A and B promises even tighter constraints on relativistic theories of gravity.

4.3 X-ray astronomy

The early history of X-ray astronomy has been splendidly presented at this conference by Riccardo Giacconi. As in the case of radio astronomy, these unexpected discoveries revitalised many astrophysical disciplines and inaugurated others. From a global perspective, I would highlight the astrophysical significance of establishing accretion as an energy source for active systems, of providing a means for discovering solar mass black holes and of using hot gas as a tracer of the mass distribution in the Universe.

This bald statement disguises the problems of interpretation which the pioneers of X-ray astronomy faced. From Giacconi's famous rocket flight of 1962 to the launch of the UHURU satellite in December 1970, the picture was confused, largely because rocket flights only allowed about 5 min observation above the Earth's atmosphere. With the launch of the UHURU satellite, many of the strange results fell into place. For example, some of the most intense Galactic X-ray sources were associated with compact objects in binary stellar systems. The pulsating X-ray sources Centaurus X-3 and Hercules X-1 were of special importance, because, not only was the X-ray emission pulsed with pulse periods similar to those of the radio pulsars, but the orbital motions of the X-ray sources and their occultations by the primary star were observed. Combined with optical observations of the primary star, the masses of the X-ray sources could be determined. The pulsating X-ray sources were convincingly associated with systems in which matter is accreted onto neutron stars. In addition, a few of the binary X-ray sources did not display pulsations but rather extreme short time-scale variability. In a number of these cases, the masses of the X-ray emitters were found to be greater than three times the mass of the Sun, indicating that the parent bodies of the X-ray sources were solar mass black holes. A recent compilation of the masses of X-ray sources in binary systems is shown in Fig. 4. These sources provide laboratories for the study of the behaviour of matter in strong gravitational fields.

The first evidence for the presence of dark matter in clusters of galaxies was discovered in 1933 by Zwicky who made the first dynamical estimates of the masses of clusters of galaxies [33]. He found a mass-to-light ratio of 500 for the cluster as a whole, very much greater than the values of about 3 found in the visible parts of galaxies such as our own. All subsequent studies have confirmed Zwicky's key result. As discussed by Giacconi, the discovery of the diffuse

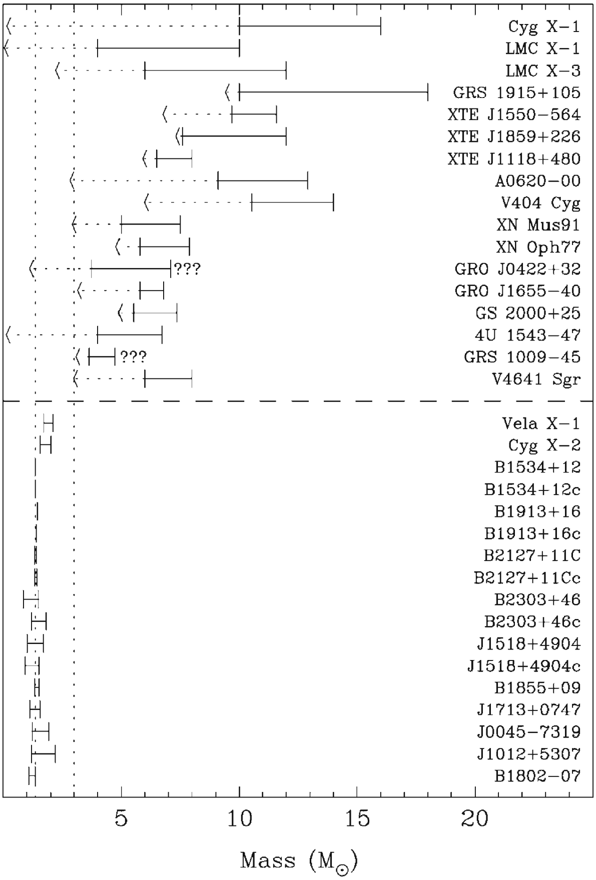


Fig. 4 A recent compilation of the masses of the parent bodies of X-ray sources in binary systems by Jerome Orosz (see http://mintaka.sdsu.edu/faculty/orosz/web/). The objects above the horizontal dashed line are black hole candidates, while those below the dashed line are neutron stars

X-ray emission of clusters of galaxies led to the realisation that the hot gas acts as a tracer of the underlying gravitational potential in which the galaxies move under the influence of the dominant dark matter. This in turn provides important constraints on the origin and evolution of large scale structures in the Universe.

The rapid variability of the X-ray emission from active galaxies indicated that the radiation must originate on very small scales. Just how small this region must be has been indicated by the observation of the line shapes of the 6.4 keV iron fluorescence line in the X-ray spectrum of the Seyfert galaxy MCG-6-30-15 which was first observed by the ASCA X-ray observatory [31] and subsequently by the XMM-Newton X-ray observatory. The line is highly asymmetric and broadened, the broadening being so great that relativistic phenomena must be involved. The most promising interpretation is that the X-ray iron fluorescence line is associated with matter in the accretion disc about a supermassive black hole, the largest redshifts being associated with matter close to the last stable orbit about the black hole.

5 Black holes—the story continued

No better example exists of the importance of new technology for astronomical discovery than the continued efforts to understand the astrophysics of black holes. As described by Reinhard Genzel in this volume, the combination of infrared array technology and adaptive optics enabled him and his colleagues to map out the motions of infrared stars orbiting the black hole in the nucleus of our own Galaxy with the Very Large Telescope in Chile. As he explained, these superb observations have enabled many key questions of black hole physics to be addressed observationally. It is unambiguous that there is a black hole in the centre of our Galaxy with mass $\approx 2.6 \times 10^6\ M_\odot$. One of the infrared stars passes within 17 light-hours of the black hole at its distance of closest approach.

Another unexpected surprise dates from the early days of VLBI when superluminal motions were observed in the radio structure of the core of the bright radio quasar 3C273—a radio component was observed to move out from the radio core at about ten times the speed of light [20]. The conventional picture is that this phenomenon is an optical illusion associated with the fact that jets of radio emitting material travel out from the core at speeds $v \sim c$ at an angle close to the line of sight. This preferred model was developed in a prescient series of papers by Martin Rees in the 1960s in the context of accounting for the extreme optical variability of the emission of quasars [23, 24]. Unexpectedly, Mirabel and Rodrigues discovered galactic counterparts of superluminal sources among X-ray sources containing stellar mass black holes [18]. These microquasars appear to have all the properties of the extragalactic variety but scaled down by a factor of about 1,000,000. This has the great advantage that, since many of the properties of active nuclei scale proportionally to the mass of the black hole, their evolution can be studied over a periods of weeks and months, rather than the time-scales of millions of years which would be required for the extragalactic black holes.

6 γ-ray astronomy

The history of discovery in γ-ray astronomy has been splendidly told by Gehrels in this volume and need not be repeated here. Undoubtedly, the most surprising discovery was that of γ-ray bursts, first noted in 1967 by the Vela surveillance satellites but only released publicly in 1973, by which time many of their properties were well characterised [14]. It proved to be a real challenge to determine their nature because the bursts only lasted from less than a second to several minutes. Observations of the γ-ray bursts over the lifetime of the Compton γ-ray observatory showed that they are uniformly distributed over the sky. The key observations which enabled their nature to be established were the afterglows at longer wavelengths which gave the ground-based observers time to turn their telescopes to the location of the burst. As a result, their extragalactic nature was convincingly established. To account for their extreme luminosities and the short timescales of their variability, both collimation of the γ-ray emission and relativistic beaming are required. These sources also have cosmological importance since they have been observed at redshifts greater than 6 and so can act as luminous cosmological probes of the reionisation and, potentially, pre-reionisation eras.

The spectacular discoveries of ground-based ultra-high energy γ-ray astronomy using the atmospheric Cerenkov technique are described by Heinz Völk in this volume. These have their origin in the development of array detectors combined with the stereoscopic capabilities of telescope arrays such as the High Energy Stereoscopic System (HESS) in Namibia. The spectacular maps of ultra high-energy γ-rays from supernova remnants constitute a wonderful discovery, providing direct evidence for the acceleration of cosmic ray protons in the shells of supernova remnants. Another key discovery has been the detection of the extreme variable sources Markarian 421 and 501 as ultra-high energy γ-ray sources. The understanding of the astrophysics of these sources involves a huge range of high energy astrophysical processes, including relativistic beaming of the high energy γ-ray emission.

The upshot of these many unexpected discoveries is that extreme high energy events must necessarily involve relativistically beamed emissions. The relativistic effects are not small corrections but are large and involve the motion of relativistic material in bulk moving at extreme relativistic speeds.

7 Optical and infrared astronomy

Optical and infrared astronomy have been revolutionised over the last thirty years in the approaches both to the construction of the telescopes and to their instrumentation. The history of the telescope has been dealt with extensively by many of the speakers at this meeting and the prospects for even larger telescopes in the medium-term future look distinctly promising, provided they are affordable. In parallel with the revolution in telescope design, the great innovation for optical and infrared astronomy has been the replacement of the photographic plate by digital detectors such as Charge-Coupled Devices (CCDs) and Infrared Arrays. Credit for the discovery of CCDs goes to Willard Boyle and George Smith of the Bell Telephone Laboratories who demonstrated the imaging capabilities of their patented CCD camera in 1974 (Fig. 5). Their objective was to develop a 'Picturephone' which would enable telephone callers to see each other. In my view, one of the most daring decisions of the Hubble Space Telescope programme in 1977 was to use CCD detectors in the Wide Field–Planetary Camera. At that stage, the prototype detectors were only beginning to be used on large ground-based telescopes. The decision more than paid off in the superb quality of the images obtained once the telescope optics had been corrected and full operations began.

It is salutary to look at what we said the HST would achieve in 1977 with what has actually been achieved. There is no question but that the HST has far exceeded our most optimistic expectations, both in terms of the quality and

Fig. 5 Willard S. Boyle (*left*) and George E. Smith, the inventors of the charge-coupled device (CCD), demonstrating the imaging capabilities of their patented CCD camera in 1974. (Courtesy of the AT&T Laboratories)

quantity of superb data which has been obtained. One of my favorite examples is the case of the Orion Nebula, the region of formation of massive stars closest to the Earth. This was observed by Robert O'Dell and resulted in the detection of protoplanetary discs about low-mass stars through the silhouettes which they cast on the bright background emission of the nebula. No-one had thought about this way of observing such discs until the observations themselves showed that this indeed occurs in nature. The fact that the discs typically have angular sizes of about 1 arcsecond meant that they could not be reliably observed with the ground-based technology available at that time.

The other major lesson of the Hubble Space Telescope programme is the enormous impact the images have had upon the public imagination. In the long term, I am certain this is as important as any scientific breakthrough for the long-term health of observational astrophysics. Ultimately, it is the tax-payer who will be supporting our ability to continue the process of astronomical discovery.

8 The discovery of the cosmic microwave background radiation

No discussion of discoveries in astronomy is complete without mention of the Cosmic Microwave Background Radiation by Penzias and Wilson in 1965 [22]. This salutary tale of prediction, neglect and discovery in modern astronomy is too well-known to require detailed discussion here, except to note the forthcoming book edited by Peebles, Page and Partridge entitled *Finding the Big Bang*, in which many of those involved describe their versions of that history [21].

I simply add one footnote to that story. The discovery was made with the Bell Laboratories 20-foot horn antennae which was designed for satellite communication at centimetre wavelengths. Penzias and Wilson had access to a 7.3 cm cooled maser receiver, with which they planned to undertake radio astronomical observations. The persistent background radiation which they

Table 1 Penzias and Wilson's detection of the cosmic microwave background radiation [22]

Signal	Noise signal T/K
Total zenith noise temperature	6.7 ± 0.3
Atmospheric emission	2.3 ± 0.3
Ohmic losses	0.8 ± 0.4
Backlobe response	≤ 0.1
Cosmic background radiation	3.5 ± 1.0

discovered wherever they pointed their telescope on the sky was a weak signal, as illustrated by the data presented in their discovery paper (Table 1). It will be noticed that their detection of the background amounted to a 3.5σ results. How often do we tell our students to beware of 3σ result. It is often remarked that Kepler's crucial discovery of the elliptical orbits of the planets about the Sun was based upon a 4-sigma result, the minimum deviation he could find from purely circular orbits. Penzias and Wilson did not do any better, but confirmation of their result flooded in through independent measurements over the next few years. Not all 3σ results are spurious!

The results of the Wilkinson Microwave Anisotropy Probe (WMAP) have been spectacular and we can expect a further roughly order of magnitude improvement in our knowledge of the properties of the Cosmic Microwave Background Radiation with the ESA Planck experiment. There is the possibility of the detection of primordial gravitational waves through the detection of the tensor component of the fluctuations on large angular scales, which would undoubtedly be one of the greatest achievements of observational cosmology.

9 The future

A good impression of the future of astronomy is provided by the document entitled *ASTRONET: A Science Vision for European Astronomy* which provides a comprehensive survey of the challenges and opportunities for future facilities for astronomy, astrophysics and cosmology (see http://www.astronet-eu.org/). The report highlights a number of 'essential' projects to build on the present momentum of European astronomy. Here is a list of some of these projects with a bias towards extragalactic astrophysics and cosmology, with my own interpretation of the principal areas of science which will benefit from them.

- Large X-ray Telescope: Tests of General Relativity in the strong field limit.
- Laser Interferometer Space Array (LISA): Search for low frequency gravitational waves. Tests of General Relativity.
- Extremely Large Telescope: Large redshift type 1a supernovae, γ-ray bursts, dark matter/dark energy probes, astrophysics of galaxies at very large redshifts, growth of perturbations during and after the reionization era, variations of fundamental constants with cosmic epoch.

- Square Kilometre Array: Neutral hydrogen redshifts out to $z = 2$, baryon acoustic oscillations, weak lensing, deviations from general relativity, huge samples of pulsars and tests of general relativity, astrophysics of normal galaxies and radio sources at early epochs.
- X-ray Survey Satellite: Large complete samples of X-ray clusters of galaxies, tests of the concordance model.
- Cherenkov telescope array.
- Very Long baseline interferometry at submillimetre wavelengths.
- Satellites for γ-ray bursts at very large redshifts.
- 4–8 m ultraviolet space telescope.
- 4–8 m infrared cooled space telescope.
- Euclid: Baryon acoustic oscillations, weak gravitational lensing, deviations from general relativity, huge samples of galaxies with colours and spectra.

This is undoubtedly a very exciting and ambitious programme, but it is seriously expensive. My parting shot is

'Don't forget the operating costs!'

In the steady state, operating costs are dominant. If the available budget for operations is x € per year and y% the percentage of the capital costs per year needed for operations, the total capital costs of operating facilities at any time cannot exceed $100x/y$ €. This is a very important equation for the effective construction, operation and continued exploitation of large scale facilities for science. For example, if $x = 100$ M€, $y = 10$, the cost of the capital facilities being operated at any time cannot exceed 1 B€. The ultimate scientific success of large facilities is crucially dependent upon the ability to operate them on behalf of the user community in an efficient and effective way, with adequate resources to provide new instrumentation and upgrades of the facilities in response to new scientific opportunities and technologies.

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