Part 1. Centenary Celebration Session (Plenary Presentations)

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100 Years of Astronomy, Astrophysics and Cosmology

A celebration of the centenary of the IAU

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Abstract. Astronomy, astrophysics and cosmology have changed out of all recognition over the last 100 years. The IAU has provided an essential means of fostering international collaboration in these disciplines including times of international tension. Developments will be highlighted which have profoundly changed our understanding and insight into the workings of our Universe.

Keywords. astronomy, astrophysics, cosmology, 100 years of IAU, history of astronomy

1. Introduction

My thesis is that the symbiosis between astronomy, astrophysics, cosmology, physics, chemistry, technology, computation and so on involves a huge set of multi-dimensional interactions between cognate disciplines. I regard these interdisciplinary interactions as the prime source of the incredible astronomical history of the last 100 years. I will concentrate upon the many great discoveries in astronomy, astrophysics and cosmology, recognising that, once discoveries are made, there is a long process of consolidation during which a breakthrough is converted into a new discipline with significant changes in perspective.†

It is salutary to recall the state of astronomy, astrophysics and physics in the years leading up to 1919, the year of foundation of the International Astronomical Union (Table 1). A list of significant events, discoveries, their indicative dates‡, the scientists involved and the countries in which research was carried out, as indicated by the current national flags, are indicated in Table 1, the physics advances being indicated by yellow cells. The table shows how the main thrust of astronomical achievement was in observational advances, with the beginnings of the application of astrophysical concepts to the study of the stars. The international nature of the advances in both observation and theory made the foundation of the IAU in 1919 a key initiative in bringing together what was already an international effort. But note crucially, quantum mechanics was not discovered until 1925 and so theorists had to do the best they could with the unsatisfactory old quantum theory.

What about technology and computing? Astronomy meant optical astronomy. Technologically, the innovations were dominated by developments in telescope and instrument design. The commissioning of the 100-inch Hooker telescope at Mount Wilson in 1917 represented the state-of-the-art in large telescope design and it was to play a

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† For more details and references, see my book *The Cosmic Century: A History of Astrophysics and Cosmology* (2006). For the high energy astrophysical aspects of the story, see also my book *High Energy Astrophysics* (2011).

‡ 'Indicative date' is generally the date of publication of the research, but occasionally the year in which the advance was made is given, if publication was delayed. Occasionally, it refers to the mean date when the research was carried out.

Table 1. Discoveries and innovations in astronomy, astrophysics, cosmology and physics to 1919. The flags indicate the countries in which these were made. The nationalities of the pioneers are not necessarily the same as the countries in which the breakthroughs were made and these are indicated as footnotes to the table.

Discovery-Event	**Date**	**Persons involved**	**Country**
Formulation of Boltzmann's – Gibbs' statistics	1880–90s	Ludwig Boltzmann, Austria; Josiah Willard Gibbs, USA	🇦🇹 🇺🇸
Validation of Maxwell's equations	1887	Heinrich Hertz, Germany	🇩🇪
Michelson–Morley experiment	1887	Albert Michelson and Edward Morley, USA	🇺🇸
Foundation of the Astrophysical Journal	1895	George Ellery Hale and James Keeler, California, USA	🇺🇸
Beginning of construction of the 100-inch telescope	1900s	George Ellery Hale	🇺🇸
Black-body radiation and the discovery of quantisation	1900	Max Planck, Germany	🇩🇪
Harvard Sequence of stellar spectra	1901	Annie Cannon, Cambridge Mass, USA	🇺🇸
Radiative transfer of energy in stars	1902	Ralph Sampson, UK; Arthur Schuster, Manchester UK; Karl Schwarzschild, Göttingen	🇬🇧 🇩🇪
Age of the Earth by radioactive dating	1904	Ernest Rutherford, McGill University, Canada [1]	🇨🇦
Discovery of quanta	1905	Albert Einstein, Switzerland [2]	🇨🇭
Special theory of relativity	1905	Albert Einstein, Switzerland [2]; Hendrik Lorentz, Netherlands; Henri Poincaré, France	🇨🇭 🇳🇱 🇫🇷
Emden gas spheres – polytropes	1907	Robert Emden, Munich, Germany	🇩🇪
Validation of the molecular hypothesis	1907	Jean Perrin, France	🇫🇷
Discovery of White Dwarfs	1910	Edward Pickering, Williamina Fleming Cambridge Mass, USA, Henry Norris Russell, Princeton, USA	🇺🇸
Measurement of stellar masses and diameters	1912	Henry Norris Russell and Harlow Shapley, Princeton, USA	🇺🇸
Period–luminosity relation for Cepheid variables	1912	Henrietta Leavitt, Cambridge, Mass, USA	🇺🇸
Hertzsprung–Russell diagram	1914	Hans Rosenberg, Göttingen, Germany; Ejnar Hertzsprung, Potsdam, Germany [3]; Henry Norris Russell, Princeton, USA	🇩🇪 🇺🇸
General theory of relativity	1915	Albert Einstein, Germany	🇩🇪
Mass–luminosity relation for stars	1915	Jacob Halm, Cape Observatory South Africa; Ejnar Hertzsprung, Potsdam, Germany [3]	🇿🇦 🇩🇪
Einstein's static model of the Universe - Cosmological Constant	1917	Albert Einstein, Germany	🇩🇪

Table 1. Continued

Discovery-Event	Date	Persons involved	Country
Shapley's model of the Galaxy using globular clusters	1918	Harlow Shapley, Harvard Observatory, USA	🇺🇸
Gravitational deflection of light by the Sun	1919	Arthur Eddington, Cambridge, UK	🇬🇧

Nationalities: [1] 🇳🇿 [2] 🇩🇪 [3] 🇩🇰

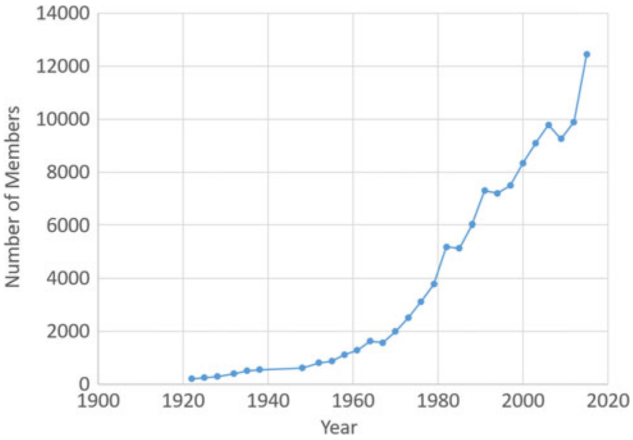

Figure 1. The growth in the number of members of the IAU from 1922 to 2015. Data up to 1965 from Blaauw, A. (1994). *History of the IAU. The birth and first half-century of the International Astronomical Union.* Dordrecht: Kluwer Academic Publishers. Later data from the published proceedings of the IAU General Assemblies.

dominant astronomical and cosmological role in the coming decades. Photographic plates were the recording elements for imaging and spectroscopy. The term 'computers' meant people who analysed all types of astronomical–astrophysical data. The most famous example of such computers was the remarkable team assembled by Edward Pickering to put order into the massive databases of stellar spectra they had assembled.

By the year of the First General Assembly of the IAU held in Rome in 1922, there were 19 adhering countries. This number increased essentially linearly over the years so that by the twenty-ninth General Assembly held in Hawaii in 2015, there were 79 adhering countries. But the numbers of IAU members grew dramatically since the early years of the IAU (Fig. 1). Following the steady growth in numbers during the interwar years, there was a huge increase in the numbers of members of the IAU, particularly from 1960 onwards. This can be attributed to a number of factors.

- The expansion of the observable wavebands for astronomical observation.
- The huge advances in technology, particularly in radio and electronic techniques and with access to space.
- Development of detector techniques, especially thanks to the semiconductor revolution.
- Major advances in physics and cognate disciplines.
- The exponential growth of computing power from the 1950s onwards.
- The impact of high energy astrophysics and general relativity as tools of the astronomer.

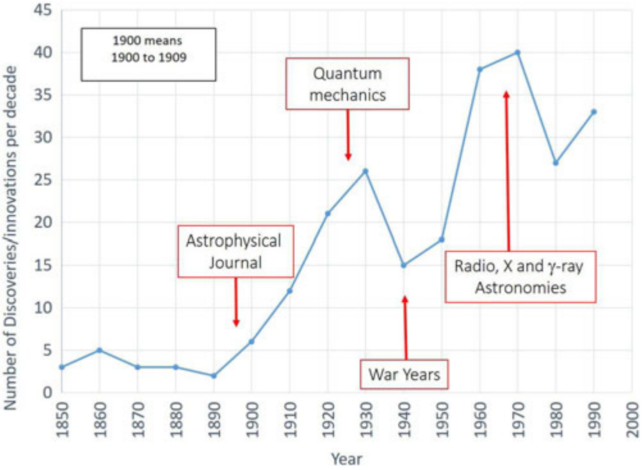

Figure 2. The number of key discoveries/innovations per decade from 1850 to 2000 with significant events indicated. The selections were made from my book *The Cosmic Century* and represent my personal judgements of key events. Tables 1, 2 and 3 are examples of my choices of discoveries and innovations.

These led to a huge increase in the volume of 'discovery space' and a corresponding increasing rate of discoveries and innovations. I have tried to encapsulate these effects in Fig. 2 which performs the same exercise as in Table 1, but now coming right up to the 21st century.

2. The Inter-War Years (1919-1939)

By the date of the 1938 IAU General Assembly in Stockholm, the numbers of IAU members had increased from 207 in 1922 to 554. Correspondingly, the number of adhering countries increased from 19 to 26. This represented a continued healthy growth of optical astronomy and astrophysical theory, but it was still a relatively small international community. Nonetheless, major advances were made and the seeds of what was to come were sown. The discoveries and innovations I have selected are listed in Table 2. Three important themes illustrate the state of understanding during these years.

2.1. *Eddington and the Theory of Stellar Structure*

This was the era when the internal structure of the stars was put on a firm physical and astrophysical basis. It is generally agreed that the key person in making this come about was Arthur Eddington.† When I was in the early stages of writing *The Cosmic Century*, William McCrea kindly read my draft of the events of this period and wrote to me in 1993 as follows:

> '[People] don't realise that before, say, 1916 astronomers simply had no idea what the inside of a star was like, and had no idea how to find out anything about this. The speed at which Eddington transformed the situation was incredible.'

But, Eddington's deep insights were not gained without considerable controversy. The physical data needed to construct stellar models were not available and so imaginative

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† See Chandrasekhar's tribute to Eddington and his contributions to stellar structure and evolution (Chandrasekhar 1983).

Table 2. Key discoveries/innovations during the interwar years, 1919 to 1939. Conventions as in Table 1.

Discovery-Event	Date	Persons involved	Country
Nuclear fusion as the energy source of the Sun	1920	Arthur Eddington, Cambridge UK	🇬🇧
Saha equation	1921	Megh Nad Saha	🇮🇳
Interferometric measurement of diameters of red giants	1921	Albert Michelson, USA	🇺🇸
Photoexcitation and photoionisation of the interstellar gas	1921	Russell (1921), Menzel (1926), Stromgren (1939)	🇺🇸 🇩🇰
Distribution of stars in the Galaxy and the mass density in the disc of the Galaxy.	1922	Jacobus Kapteyn, the Netherlands.	🇳🇱
Friedman world models	1922	Alexander Friedman, USSR (1922, 1924)	🇷🇺
Ionisation states of ions in stellar atmospheres	1923	Ralph Fowler, Cambridge and Edward Milne, Oxford, UK (1923–1924)	🇬🇧
The theory of stellar structure and evolution	1924	Arthur Eddington, Cambridge, UK (1916–1924)	🇬🇧
Discovery of Galactic rotation	1925	Bertil Lindblad, Sweden.	🇸🇪
Spiral nebulae are extragalactic systems	1925	Knut Lundmark, Sweden, Edwin Hubble, USA (1920, 1925)	🇸🇪 🇺🇸
Chemical composition of the stars	1925	Cecilia Payne (-Gaposhkin), Harvard, USA [1]	🇺🇸
Hubble classification of galaxies and their properties	1926	Edwin Hubble, Pasadena, USA	🇺🇸
Eddington-Lemaître world models	1927	Arthur Eddington, Cambridge, UK; Georges Lemaître, Belgium	🇬🇧 🇧🇪
Discovery of the differential rotation of the Galaxy	1927	Jan Oort, Leiden, the Netherlands	🇳🇱
Identification of nebulium lines as forbidden transitions	1927	Ira Bowen, California USA	🇺🇸
The theory of white dwarfs	1929	Wilhelm Anderson, Estonia; Edmund Stoner UK; S. Chandrasekhar, India (1929, 1931)	🇪🇪 🇬🇧 🇮🇳
Quantum barrier penetration in solar nuclear reactions	1929	Robert Atkinson, USA; Fritz Houtermans, Germany	🇺🇸 🇩🇪
Hubble and the recession of the nebulae	1929	Edwin Hubble, Pasadena, USA	🇺🇸
Discovery of interstellar extinction by dust	1930	Robert Trumpler, USA (1930), John Plaskett, John Pearce, Canada (1933); Alfred Joy, USA (1939).	🇺🇸 🇨🇦
Discovery of dark matter in clusters of galaxies	1933	Fritz Zwicky, Pasadena, USA [2]	🇺🇸

Table 2. Continued

Discovery-Event	**Date**	**Persons involved**	**Country**
Discovery of the radio emission of the Galaxy	1933	Karl Jansky, Bell Laboratories, New Jersey, USA (1933); Grote Reber, USA (1940).	🇺🇸
Theory of development of large scale structure in the Universe. Primordial fluctuation problem	1933	Lemaître (1933), Tolman (1934), Lifshitz (1946)	🇧🇪 🇺🇸 🇷🇺
Supernovae and their consequences for astrophysics	1934	Walter Baade, USA [3]; Fritz Zwicky, USA [2]	🇺🇸
Robertson-Walker metric	1935	Howard Robertson, Pasadena, USA (1935); Arthur Walker, Liverpool, UK (1936)	🇺🇸 🇬🇧
Discovery of the p-p chain	1936	Robert Atkinson, USA; Hans Bethe, USA; Charles Critchfield, USA	🇺🇸
Theory of interstellar dust extinction	1936	Schalen (1936), van de Hulst (1949)	🇸🇪 🇳🇱
Discovery of CNO cycle	1937	Robert Atkinson, USA (1931); Carl von Weizsäcker, Germany (1937), Hans Bethe, USA (1938)	🇺🇸 🇩🇪
The structure of Red Giants	1938	Ernst Öpik, Tartu Observatory, Estonia	🇪🇪
Upper limit to the masses of neutron stars	1938	Lev Landau, Moscow, USSR (1938); Robert Oppenheimer and George Volkov, USA (1939)	🇷🇺 🇺🇸
Inevitability of collapse to a Black Hole	1939	Lev Landau, USSR (1932); Robert Oppenheimer, Hartland Snyder, USA (1939)	🇷🇺 🇺🇸
Discovery of extensive air-showers	1939	Pierre Auger, France	🇫🇷

Nationalities: [1] 🇬🇧 [2] 🇨🇭 [3] 🇩🇪

leaps of the imagination were needed. For example, to make the equations of stellar structure soluble, Eddington made what Leon Mestel has referred 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 stellar structure provoked heated debate. In fact, Eddington was lucky, 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.

2.2. *Einstein, Friedman, Lemaître, Robertson and Hubble*

Once General Relativity was formulated, Einstein realised that he had the tools with which to derive the first fully self-consistent model of the whole Universe in 1917. At that time, the expansion of the Universe had not been discovered. He created a static Universe with closed spherical geometry by introducing the cosmological constant Λ.

The standard world models were discovered in 1922 and 1924 by the Soviet meteorologist Alexander Alexandrovich Friedman. The key realisation was that isotropic world models had to have isotropic space curvature everywhere at a given cosmological epoch. There was no reason why the Universe should be static. Georges Lemaître and Howard Robertson discovered independently the Friedman solutions of Einstein's equations for uniformly expanding Universes. In 1927, Lemaître derived the 'apparent Doppler effect where the receding velocities of extragalactic nebulae are a cosmical effect of the expansion of the Universe'. In 1928 Robertson found the theoretical relation $v = cl/R$, where l is the distance. For nearby galaxies he found the equivalent of a Hubble constant of 500 km s^{-1} Mpc^{-1}.

In 1921, Carl Wilhelm Wirtz had almost discovered the velocity–distance relation, the problem being the reliability of the distance estimates of the galaxies. In Hubble's iconic diagram of 1929, there are only 24 galaxies, most of the velocities having been measured by Vesto Slipher. Hubble's contribution was in making bold estimates of the distances of the galaxies out to the Virgo cluster using three types of distance indicator: Cepheid variables for nearby galaxies, then the brightest stars in galaxies for more distant galaxies and finally the mean luminosities of nebulae for galaxies in the Virgo cluster. By 1934, Hubble and Humason had extended the velocity–distance relation to 7% of the speed of light by assuming that the fifth brightest members of rich clusters of galaxies can be used as 'standard candles', or distance indicators.

2.3. *Zwicky and Dark Matter*

In 1933, Fritz Zwicky made the first dynamical estimates of the mass of the Coma cluster of galaxies and found a mass-to-light ratio of 500 for the cluster as a whole. This was very much greater than the values of about 3 found in our vicinity in the Galaxy. This was the beginning of the dark matter story, all subsequent studies having confirmed Zwicky's key result.

3. The Impact of the Second World War

It is often remarked that the First World War was a 'chemical' war, whereas the Second World War was a 'physics' war. The major advances in technology resulting from the war effort had a major impact on all astronomy and astrophysics. Primary among these was the opening up of the whole of the electromagnetic spectrum for observation. Radio astronomy benefitted from major advances in radio techniques, while access to rockets enabled observations to be made from above the Earth's atmosphere. The huge contribution made by physics to the war effort resulted in increased funding for science as it was appreciated how much innovative science had played during the war and subsequently for the benefit of society at large. Electronic computation was in its infancy, but the exponential growth in computing power was about to begin with huge impact upon all the sciences. All of these were contributory factors which led to astronomy becoming one of the 'big sciences'.

But there was also the psychological impact upon the scientists of working at breakneck speed on key military priorities during the Second World War. As Bernard Lovell wrote 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.'

3.1. *The technical legacy of the Second World War*

In Europe, there had been a huge effort supporting radar programmes, both for ground-based defence systems and for airborne radio location. After the War, the radio astronomers had access to high quality radio antennae, low loss coaxial cables, surplus quality radio equipment, and so on, much of it German war booty.

In space astronomy, the development of rocket technology opened up opportunities for space astronomy. The German V2 rocket was a remarkable technical achievement led by Werner von Braun who was to lead the US rocket programme. The Rand Report of 1946, led by Lyman Spitzer, outlined future possibilities for space astronomy and proposed a programme of space missions which was to lead to the various US space programmes of the 1960s. The launch of Sputnik in 1957 galvanised the US administration into creating the National Aeronautics and Space Administration (NASA) in 1958. This became all the more urgent with Yuri Gagarin's space flight in 1961. The USA had fallen behind the USSR – now the space race began in earnest.

Both the USA and the USSR pursued programmes to test general relativity in space. In 1961, Howard Robertson led the NASA Conference on *Experimental Tests of General Relativity* and the *First Soviet Gravitation Conference* was held in the same year in Moscow.

3.2. *The symbiosis between astronomy and defence programmes*

An important sub-plot to these developments was the symbiosis between defence science and its application for the benefit of astronomy. A spectacular example was the discovery of γ–ray bursts as part of the US programme to monitor atmospheric and space nuclear test explosions following the 1963 Partial Test Ban Treaty. The Vela 3 and Vela 4 satellites discovered the first of these in 1967, but the results were not published in the open literature until 1973, by which time a near-Earth origin could be excluded.

Another example is the symbiosis between the KH-11 Kennen high-resolution surveillance satellite and the Hubble Space Telescope.† Apparently, the KH-11 Kennen satellite was launched with electro-optical (CCD) detectors in 1976, one year before the approval of the Hubble Space Telescope project. It had an angular resolution on the Earth's surface of about 5 cm. It is suggested that the designers of the KH-11 Kennen satellite adopted concepts from the Space Telescope development programme. Both telescopes employed 2.4-m diameter mirrors.

Another key development for astronomy was the fabrication of infrared array detectors which had been deployed as guidance systems of cruise missiles. These necessarily involved very large development costs but, in the mid-1980s, the arrays became available to astronomers with remarkable results once they had been optimised for astronomical observation.

4. The 1960s and the Aftermath

It took some time for the potential of the new technologies to be realised, but a flood of innovations and discoveries took place during the 1960s. The topics listed in Table 3 illustrate what can only be called a miraculous decade in the history of astronomy. The table represents the beginnings of contemporary astronomy, astrophysics and cosmology. Each topic is worth an article on its own but I will develop only three themes in the following sections. In these themes, I will bring the story right up to the present day.

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† More information about the Kennen satellites can be found at https://en.wikipedia.org/wiki/KH-11_Kennen.

Table 3. Key discoveries/innovations during the 1960s. Conventions as in Table 1.

Discovery-Event	**Date**	**Persons involved**	**Country**
Discovery-Event	**Date**	**Persons involved**	**Country**
Stellar structure computations create detailed models of the interior of the stars	1960s	Among the pioneers were: Henyey, Kippenhahn, Iben and Christy	🇩🇪 🇺🇸
Leighton and colleagues measure 5-minute oscillations in the Sun	1960	Leighton *et al.* at Caltech, USA	🇺🇸
Determination of Hubble's constant and the age of the Universe	1960s	Sandage (1960s-1980s)	🇺🇸
Semiconductor detectors for infrared astronomy	1961	Johnson 1961, Low 1961	🇺🇸
Discovery of the Hayashi track	1961	Hayashi (1961)	🇯🇵
Horizon problem in cosmology	1961	Dicke (1961)	🇺🇸
Flatness problem in cosmology	1961	Dicke (1961), Peebles and Dicke (1969)	🇺🇸
Development of Earth Rotation Aperture Synthesis	1962	Martin Ryle, Cambridge, UK	🇬🇧
Discovery of X-ray sources and the X-ray background	1962	Giacconi et al, USA	🇺🇸
Exponential decay of light curve due to radioactive decay	1962	Pankey (1962), Colgate and McKee (1969)	🇺🇸
Discovery of interstellar molecular lines in radio waveband	1963	Weinreb *et al.* (1963)	🇺🇸
Kerr black hole solutions	1963	Kerr (1963) [1]	🇺🇸
Discovery of quasars	1963	Schmidt (1963) [2]	🇺🇸
Accretion model for the energy source of quasars and active galaxies	1964	Salpeter (1964), Zeldovich (1964), Lynden-Bell (1969)	🇺🇸 🇷🇺 🇬🇧
Problem of the cosmic helium abundance, origin of the light elements	1964	Hoyle and Tayler (1964), Wagoner et al (1967)	🇬🇧 🇺🇸
Discovery of the cosmic background radiation	1965	Penzias and Wilson (1965)	🇺🇸
Lyman-α clouds as cosmological probes	1965	Gunn and Peterson (1965), Scheuer (1965).	🇺🇸 🇬🇧
Baryon asymmetry problem	1965	Zeldovich (1965), Wagoner *et al.* (1967)	🇷🇺 🇺🇸
Detection of far-infrared sources in the Orion Nebula	1966	Becklin and Neugebauer (1966)	🇺🇸
Theory of superluminal motion	1966	Rees (1966, 1967)	🇬🇧
Development of Very Long Baseline Interferometry	1967	Broten *et al.*, Canada (1967); Moran *et al.* USA	🇨🇦 🇺🇸

Table 3. Continued

Discovery-Event	Date	Persons involved	Country
Violet relaxation of galaxies in clusters	1967	Lynden-Bell (1967)	🇬🇧
Baryogenesis Sakharov's rules	1967	Sakharov (1967)	🇷🇺
OSO-III and SAS-2 γ–ray missions detect the Galactic γ–ray emission	1968	Clark, Germire and Kraushaar (1968); Fichtel, Simpson and Thomson (1972)	🇺🇸
Discovery of radio pulsars as magnetised rotating neutron stars	1968	Hewish *et al.*, Cambridge, UK.	🇬🇧
Discovery of BL-Lac objects	1968	McLeod and Andrew (1968)	🇨🇦
Thermal history of the Universe, epochs of recombination and reioinsation	1968	Zeldovich *et al.* (1968), Peebles (1968)	🇷🇺 🇺🇸
Silk Damping	1968	Silk (1968) [3]	🇺🇸
Two point correlation functions for galaxies	1969	Neyman and Scott (1954), Totsuji and Kihara (1969), Peebles *et al.* 1970s	🇺🇸 🇯🇵
Hawking and Penrose singularity theorems	1969	Hawking and Penrose (1969)	🇬🇧

Nationalities: [1] 🇳🇿 [2] 🇳🇱 [3] 🇬🇧

5. High Energy Astrophysics

5.1. *Radio Astronomy*

In 1933 radio waves from our Galaxy were discovered by Karl Jansky at the Bell Telephone Laboratories. Grote Reber followed up this discovery with his home-made radio telescope resulting in the first radio map of the Galaxy in 1940. This pioneering effort made little impact upon the astronomical community, beyond the conclusion that the spectrum of the radiation could not be the thermal emission of hot gas clouds.

After the War, a number of University Groups began to investigate the nature of the cosmic radio emission. They were led by the physicists who had played a major role in the development of radar during the Second World War. The observations soon established the existence of populations of galactic and extragalactic radio sources. In 1951, the brightest extragalactic radio source in the northern sky, Cygnus A, was identified with a very distant galaxy. This was followed up in 1953 at Jodrell Bank by Jennison and Das Gupta who used intensity interferometry techniques to show that it had a strange double radio structure, centred on a massive galaxy in a cluster of galaxies. The radiation was identified with the synchrotron radiation of ultrarelativistic electrons gyrating in remarkably strong large-scale magnetic fields. The total energies involved were very large indeed – typically the energies in high energy particles and magnetic fields amounted to $10^6 M_\odot c^2$ and furthermore the particles and fields had to be ejected into intergalactic space, far beyond the confines of the host galaxy.

In 1963, 3C 273 was discovered through precise positional measurements with the Parkes telescope in Australia. It was the first radio quasar for which a redshift was obtained thanks to follow-up spectroscopy by Maarten Schmidt with the Palomar

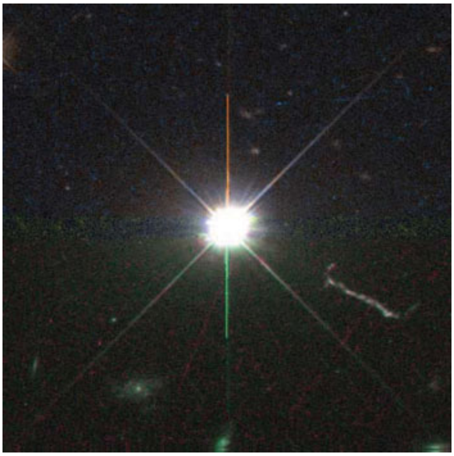

Figure 3. Hubble Space Telescope image of the radio quasar 3C 273 showing normal galaxies at the same redshift towards the bottom of the picture. The prominent jet emanating from the quasar nucleus is observed to the right of the quasar. (Courtesy of ESA, NASA and the Space Telescope Science Institute)

200-inch telescope. The HST image of 3C273 in Fig. 3 shows the quasar and normal galaxies at the same distance as the quasar towards the bottom of the picture. The floodgates opened and within a couple of years quasars with redshifts up to $z = 2$ had been discovered.† The First Texas Symposium on Relativistic Astrophysics took place in Austin, Texas in 1963 and these dramatic discoveries were centre stage. The extreme luminosities of the quasars and their rapid variability were unprecedented phenomena in extragalactic astronomy and it was quickly realised that these objects must involve strong gravitational fields. At the closing dinner of the Texas Symposium, Thomas Gold remarked:

> '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 was undoubtedly stimulated by the discovery of radio galaxies and quasars.

Continuing the theme of developments in radio astronomy, Martin Ryle pioneered the technique of Earth-rotation aperture synthesis as a means of obtaining high angular resolution and high sensitivity images of objects in the radio sky. The One-Mile Telescope at the Lord's Bridge Observatory in Cambridge was the first general purpose, fully steerable aperture synthesis radio telescope and was commissioned in 1965. I can remember vividly the excitement when the first maps of the radio galaxy Cygnus A and the supernova remnant Cassiopeia A came off the printer in the Cambridge Mathematical Laboratory – I was there! (Fig. 4). These were the predecessors of the spectacular images subsequently taken by the US Very Large Array.

In 1966, Antony Hewish began construction of a 4-acre low frequency radio array, also located at the Lord's Bridge observatory, to study the 'twinkling' of radio sources. The joint objectives of the project were the discovery of quasars, which were known to be strongly scintillating sources, and the study of the properties of the distorting

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† See Fig. 7 for a diagram showing how the largest redshift for quasars evolved over the subsequent years.

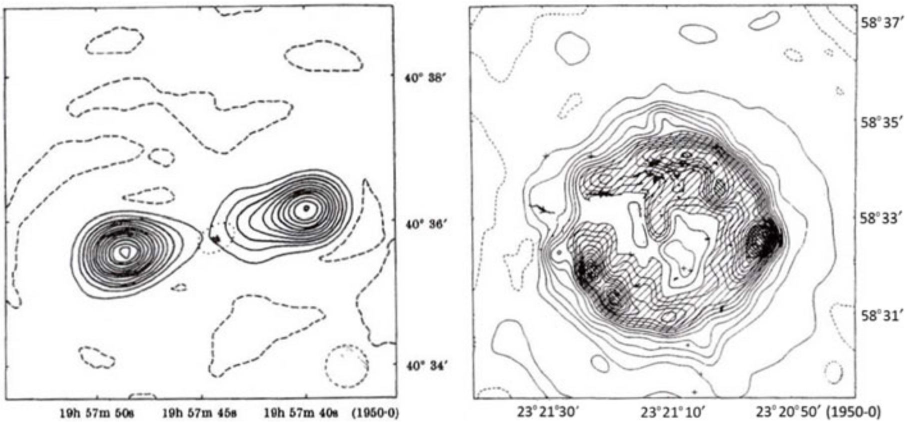

Figure 4. The first earth-rotation aperture synthesis radio maps of the bright extragalactic radio source Cygnus A (left) and the supernova remnant Cassiopeia A (right) made at 1.4 GHz with the Cambridge One-Mile Telescope. (Ryle, M., Elsmore, B. and Neville, A.C. (1965). *Nature*, **205**, 1259–1262).

screen causing the scintillations, in this case, the interplanetary medium. Jocelyn Bell was assigned the task of calibrating the array and keeping track of the scintillating sources over the whole northern sky, which was observed every week. In August 1967, a strange source was discovered consisting entirely of scintillations in a region of sky where they were expected to be rather weak. This was the pulsar CP1919, the first to be discovered.

The pulsars were soon identified with magnetised, rotating neutron stars, one of the key discoveries of modern astronomy – relativistic stars really do exist. Their discovery had implications for understanding all types of explosive events, including the violent events occurring in active galaxies. At the Brighton IAU in 1970, Iosef Shklovsky asked me to introduce him to Jocelyn Bell. He said to her:

> ‘Miss Bell, you have made the greatest astronomical discovery of the 20th century.’

Once the initial discovery was made, the long process of integrating pulsars into the infrastructure of astronomy and astrophysics began. As a result of the Arecibo surveys for pulsars, the binary pulsar PSR 1913+16 was discovered by Russell Hulse and Joseph Taylor in 1974. The existence of such systems initially came as a surprise to the astrophysics community, but their value as probes of relativistic theories of gravity was immediately appreciated. All the parameters of the binary orbit could be determined from precise timing and the energy loss due to gravitational radiation observed for the first time.

By the late 1960s, Very Long Baseline Interferometry (VLBI) enabled radio structures with milliarcsec angular resolution to be observed. By the late 1970s, the radio structure of the compact core of the radio source 3C273 was observed by VLBI over 3 years to 1980 – the components had separated by 25 light years over this period, over eight times the speed of light. This was one of the first examples of superluminal velocities. In fact, this phenomenon had been predicted by Martin Rees in his papers of 1966–67, showing that the superluminal velocities are an optical illusion involving jets travelling at $v \approx c$ at an angle close to the line of sight. Subsequent surveys by the US Very Long Baseline Array (VLBA) observed large numbers of superluminal velocities in compact radio sources, apparent separation velocities up to 32 times the speed of light being reported in a major paper of 2007.

5.2. *X-ray Astronomy*

The discoveries of X-ray astronomy have been pivotal in advancing understanding of many key astrophysical processes. The first detections of X-rays from celestial objects, other than the Sun, were made by the AS&E rocket flight of June 1962. In the seven minutes during which the rocket was above the atmosphere, the discrete X-ray source Sco X-1 and the intense X-ray background radiation were detected. For the next ten years, such short missions above the atmosphere were the principal means of studying the X-ray sky, but the picture was confused because of the variability of the sources.

The richness of the X-ray sky was revealed with the launch of the first satellite dedicated to X-ray astronomy, the UHURU X-ray Observatory, which was launched from Kenya in December 1970. The objects detected included active galaxies, clusters of galaxies and compact galactic X-ray sources. One of the key UHURU discoveries was that some of the intense Galactic X-ray sources display X-ray pulsations with periods similar to those of the radio pulsars. These sources were identified with neutron stars in binary star systems. The X-ray pulsar Her X-1 was the first example in which the binary nature of the source was deduced entirely from accurate timing of the X-ray pulses.

The masses of the compact stars in binary systems could be estimated by the techniques of classical astrometry. The X-ray pulsars turned out to have masses consistent with the upper mass limit for their stability as neutron stars. The masses of many of the non-pulsar X-ray sources turned out to have masses greater than three times the mass of the Sun and so were identified as stellar mass black holes (Fig. 5).

Digressing from the X-ray theme for a moment, mention must be made of the spectacular observations of the black hole in the centre of our Galaxy. Using infrared adaptive optics, the kinematics of stars orbiting the black hole have been measured. Among these, the star designated S2, shown in red in Fig. 6, has completed an elliptical orbit about the black hole with a period of 16 years. The black hole mass is estimated to be about 3.6×10^6 $M_\odot$. The upshot of many different types of observation is that most massive galaxies possess supermassive black holes in their nuclei.

A beautiful result from X-ray spectroscopy of active galactic nuclei is the observation of the 6.4 keV iron fluorescence line originating from the inner regions of the accretion disc about the black hole. Because of the combined effects of the gravitational and relativistic Doppler shifts, the line is broadened asymmetrically and shifted to lower X-ray energies. This phenomenon has been observed in the Newton–XMM spectrum of the active nucleus MCG-6-30-15. In this interpretation, the X-ray emission at the lowest detectable energies must originate close to the last stable orbit about the black hole.

The X-ray emission from clusters of galaxies has proved to be a key diagnostic for determining the total mass of the cluster and of the intracluster gas. The hot intracluster gas acts as a tracer of the gravitational potential within the cluster and the bremsstrahlung from the hot gas provides an estimate of the total gaseous mass. These observations of, for example, the Perseus Cluster provide compelling direct evidence for the presence of about 10 times more dark matter than baryonic matter in the cluster.

Another spectacular example of the power of combining different techniques to understand the dynamics of the baryonic and dark matter in clusters of galaxies is provided by the system known as the Bullet Cluster, which involves a collision between two clusters. The overall mass distribution of both clusters has been determined by the gravitational lensing of background galaxies and this distribution agrees with the distribution of galaxies. Since these are both composed of ‘collisionless’ particles, they pass through each other. But the diffuse baryonic matter in the clusters suffers a collision which results in the deceleration of these gaseous components and so accounts for the observed difference in location of the gaseous and dark matter distributions, as well as the ‘bow-shock’ appearance of the shocked gas.

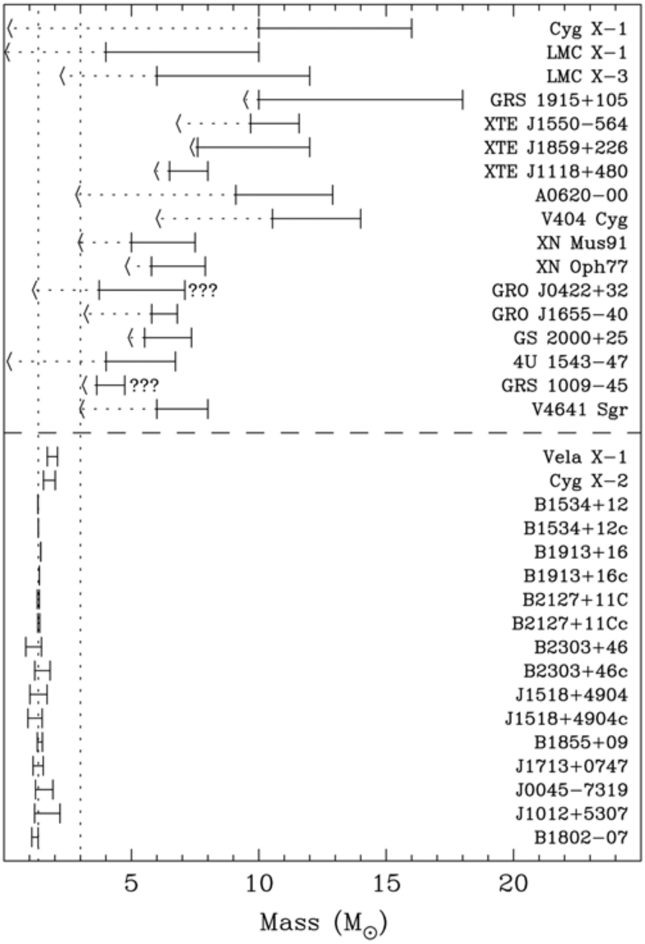

Figure 5. Masses of neutron stars and stellar mass black holes in binary systems as presented by Jerome Orosz in 2007 (Courtesy of Jerome Orosz).

5.3. *γ-ray Astronomy*

The nature of the γ-ray sky was gradually revealed through a series of small satellites. The existence of γ-rays of celestial origin was established in 1965 by the Explorer II satellite; γ-rays from the Galaxy with energies greater than 100 MeV were observed by the OSO-III satellite in 1967; in 1972, the SAS-II satellite, containing a spark chamber detector, detected discrete γ-ray sources; COS-B, also containing a spark chamber array, made the first map of Galactic Plane in γ-rays over the period 1975 to 1982. Finally, the Compton γ-ray Observatory, which flew in orbit from 1991–2000, made a definitive map of the γ-ray sky and detected many γ-ray bursts.

The observation of 2704 γ-ray bursts established that they are uniformly distributed over the sky. Observations of their afterglows at lower energies enabled their positions and redshifts to be measured and established their extragalactic origin. The γ-ray bursts are extremely luminous and last from a fraction of a second to several minutes. As a result, they must involve the most extreme form of relativistic beaming known. They can be observed at very large redshifts and have now almost reached the last stages of the epoch of reionisation. The dramatic rate at which the largest redshift γ-ray bursts have

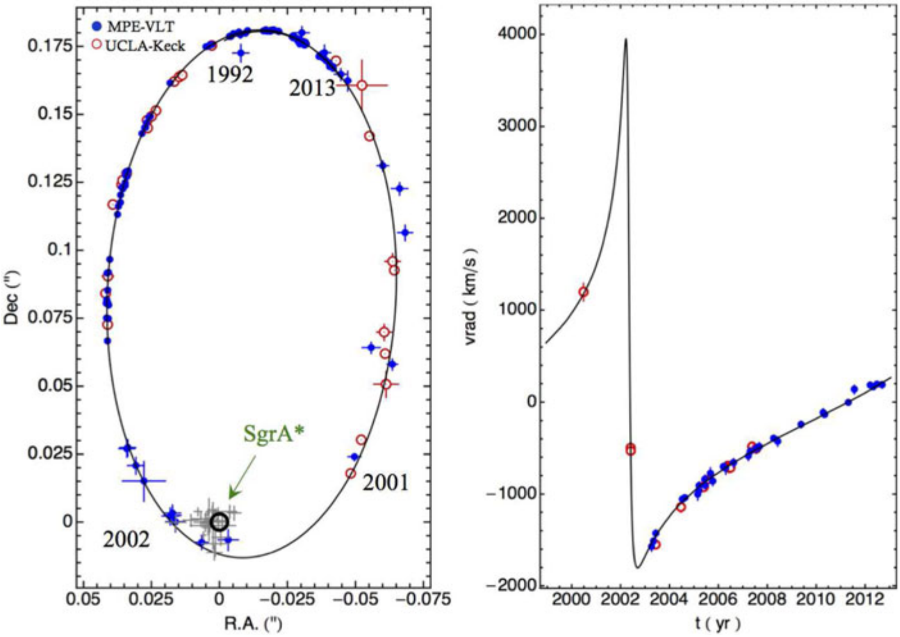

Figure 6. (left) The orbit of the star S2 around Sgr A*. The positions of S2 were measured by the New Technology Telescope (1992–2001), the VLT (2002–2012) and the Keck Telescope. (right) The corresponding radial-velocity data and best-fit relation. (Gillessen *et al.* (2009). Astrophysical Journal, **692(2)**, 1075.)

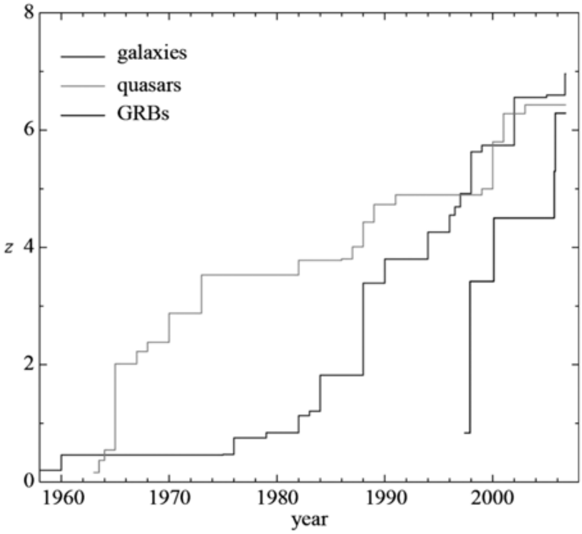

Figure 7. The rate of detection of the largest redshift objects for galaxies, quasars and γ-ray bursts (Tanvir, N.R. and Jakobsen, P., *Phil. Trans. R. Soc. A* (2007) **365**, 1377–1384).

been detected is compared with the more gradual observation of quasars and galaxies towards the reionisation epoch in Fig. 7.

To detect the very highest energy γ-rays, the atmospheric Cerenkov radiation technique has proved to be a great success. The incoming very high energy γ-rays induce electron-photon cascades which can be detected by γ-ray telescopes arrays such as the High Energy

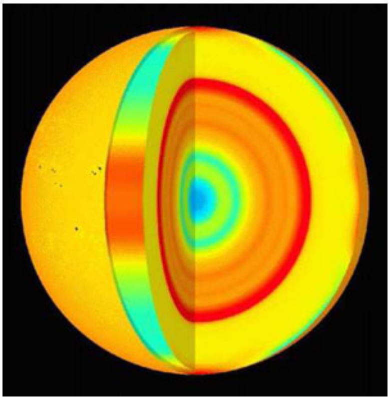

Figure 8. Regions inside the Sun which are hotter (red) and cooler (blue) than the temperature distribution expected according to the standard solar model are illustrated as a function of radius within the Sun. (Courtesy of ESA and the SOHO Science Team).

Stereoscopic System (HESS) in Namibia and similar telescope systems. I particularly like the HESS image of a supernova remnant observed in ultra-high energy γ-rays combined with X-ray observations by the Japanese ASCA X-ray Observatory, providing evidence for the acceleration of cosmic ray protons in supernova remnants.

The most active galaxies are also extreme γ-ray sources. The Compton γ-ray Observatory (CGRO) discovered that the superluminal radio sources are extremely luminous γ-ray sources and that the γ-ray emission must also be very strongly relativistically beamed to avoid degradation of the γ-rays within the source regions.

6. Stars, Star Formation, Planets and Life

6.1. *The Sun*

Probing the interiors of the Sun and the stars has been revolutionised by the discovery of solar oscillations and the subsequent development of the disciplines of Helioseismology and Asteroseismology. Of crucial importance for all astronomy has been the detailed study of the spectrum of solar oscillations by the SOHO Observatory. The dispersion relations for the different wave modes inside the Sun enable the speed of sound as a function of radius to be determined, in particular, into the very central regions where the nuclear reactions which power the Sun take place. An example of the remarkable precision which was achieved is shown in Fig. 8 which is a visualisation of the temperature distribution with radius inside the Sun. The combination of the MDI and VIRGO experiments showed the regions of the Sun which are hotter (red) and cooler (blue) than the temperature distribution expected according to the standard solar model. The deviations are all at less than the 2% level, even in the broad red band at the base of the convection zone. In addition, the velocity distribution inside the Sun has been determined, which is necessary to understand the transport of angular momentum in the Sun.

These observations were crucial in understanding the origin of the solar neutrino problem. A flux of electron neutrinos must accompany the nuclear reactions which power the Sun but, from the 1970s onwards, the flux of high energy neutrinos found by Raymond Davis in the Homestake Chlorine Solar Neutrino Experiment was consistently about a factor of three lower than predicted by the best solar models. This proved to be a longstanding, controversial result. It was beautifully confirmed by the Japanese Kamiokande experiments. To express it at its simplest, either the astrophysics or the nuclear physics of the solar interior was not quite right. The importance of the SOHO results was that,

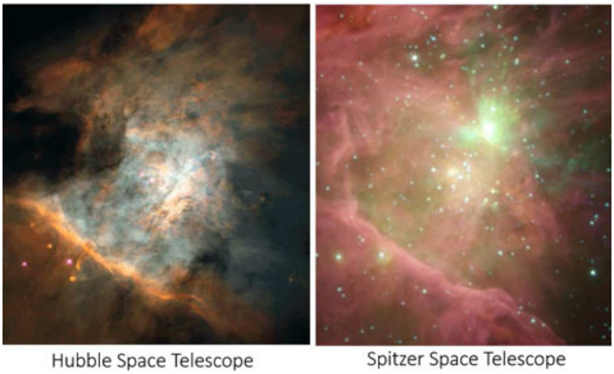

Figure 9. The Orion Nebula as observed (left) in the optical waveband by the Hubble Space Telescope and (right) in the mid-infrared waveband by the Spitzer Space Telescope. (Courtesy of NASA and the HST and Spitzer Science Teams.)

although there were small discrepancies with the standard solar model, the astrophysics was not the source of the problem – it had to lie with the nuclear physics.

A deficit was also found in the flux of the much more common low energy neutrinos from the first stage of the p-p chain in the GALLEX (1999) and SAGE (2002) experiments. The issue was finally resolved in 2002 by the detector at the Canadian Sudbury Neutrino Observatory (SNO) which was sensitive to all three neutrino species. The deficit of neutrinos was convincingly attributed to neutrino oscillations. These results are crucial for our understanding of the astrophysics of all types of stars.

6.2. *Star Formation*

One of the key discoveries of the 1960s was that stars form in the dustiest, most obscured regions of giant molecular clouds. At optical wavelengths, dust is strongly absorbing but the opacity of the grains decreases very rapidly with increasing wavelength so that by about $2-3\ \mu$m the dust becomes transparent. At wavelengths longer than about $3\ \mu$m, dust grains become strong emitters rather than absorbers of radiation. The dust grains radiate more or less like little black-bodies at the temperature to which they are heated. This is the means by which protostars get rid of their binding energy in order to form stars. This process is most beautifully illustrated by images of the region of massive star formation closest to us, the Orion Nebula (Fig. 9). The HST image shows the remarkable ionisation structures about the bright blue stars, known as the Trapezium stars, in the core of the Orion Nebula. In contrast, the mid-infrared image obtained by the Spitzer Space Telescope shows the dusty regions in emission and reveals the true extent of the cluster of young stars. Most impressive are the very luminous regions north of the Trapezium stars, as observed in the mid-infrared waveband – these are the very youngest stars in the Orion cluster and are still enshrouded in the dusty envelopes of the protostars from which they formed.

The dominance of the emission of heated dust grains continues into the submillimetre waveband, but in addition the emission lines of hosts of chemical species, which thrive under these cool conditions, begin to dominate the emission spectra. But the dust grains continue to be the ideal tracers of the material from which stars and planets form. These studies are one of the major scientific objectives of the Atacama Large Millimetre Array (ALMA). In 2015, soon after the completion of the array's commissioning phase, the spectacular image of the protoplanetary disc about the very young star HL Tau was observed (Fig. 10). The luminosity and effective temperature of HL Tau indicate that it

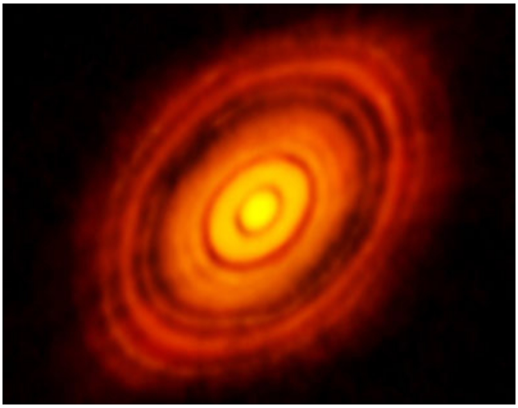

Figure 10. The ALMA image of the dusty protoplanetary disc about the nearby extremely young star HL-Tau (Courtesy of the ALMA Science Team, AURA, ESO and the JNAO).

is very young, less than 100,000 years old. The whole of the Solar System would occupy only the inner regions of the dusty disc about HL Tau. Note, however, the characteristic gaps in the disc, similar to those observed in the rings of Saturn and a key to how protoplanets are formed out of protoplanetary discs.

6.3. *Exoplanets and Life*

Since the first genuine exoplanet was detected in 1995, the subject has boomed. The successes of the radial-velocity observations and the occultation technique depended upon the development of extremely stable high resolution spectrographs and high precision photometry techniques. The numbers of exoplanets increased steadily until the first results of the Kepler missions abruptly increased their number by an order of magnitude. The diversity of the properties of the exoplanets is extraordinary and the study of their atmospheres is a very major growth area.

This is where the study of atmospheric chemistry comes into its own. Ultimately, we want to be able to characterise the processes which lead to the synthesis of amino-acids, the essential molecules for life, but that is a chemical challenge of very considerable complexity. HCN, water, light and molecules are needed to form complex molecules by gas phase interactions and surface chemistry. The result should be the 'amino-acids used by life.' In the meantime, a key objective is to detect the simpler molecules needed to synthesise these complex molecules. Then, we need to understand whether these really are present in planets which have the right atmospheric conditions for higher chemical synthesis to take place. But, even if we can detect biologically important light molecules such as oxygen, how can we be sure it is evidence of biological activity and the presence of water? This is the problem of 'false positives'. One of the further challenges for the observers is that the millimetre waveband is very crowded with molecular lines of the type needed for serious chemical synthesis of biological molecules. These questions are currently being taken very seriously and are wonderful challenges for the new generation of astrochemists and astrobiologists.

7. Cosmology

The discovery of the Cosmic Microwave Background Radiation by Arno Penzias and Robert Wilson in 1965 was a key event of modern cosmology. The Bell Laboratories 20-foot horn antennae was primarily to be used for satellite communication at centimetre wavelengths. While calibrating the telescope system, Penzias and Wilson discovered by

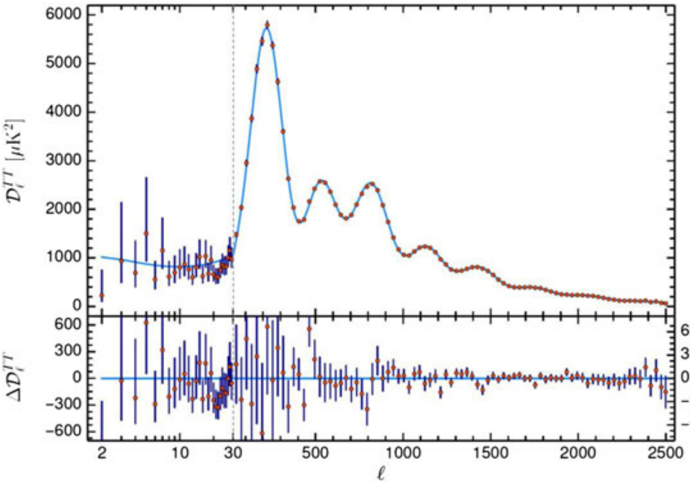

Figure 11. The scalar power spectrum of fluctuations in the Cosmic Microwave Background Radiation as observed by the Planck satellite (Courtesy of ESA and the Planck Science Team. (The Planck Collaboration, ArXiv e-prints 1807.06209 (2018))).

accident background radiation with radiation temperature 3 K wherever they pointed the telescope on the sky. It was soon convincingly demonstrated that they had discovered the cooled remnant of the hot early phases of the Universe. We need not rehearse the subsequent fifty years of increasingly sensitive and challenging experiment, but leap directly to the remarkable results of the Wilkinson Microwave Anisotropy Probe (WMAP) and the Planck satellite. These space missions have measured the properties of the Cosmic Microwave Background Radiation with unprecedented precision and set a benchmark for contemporary cosmology.

In Fig. 11, the red line shows the remarkable agreement between the observed fluctuation power spectrum and the best-fit 6-parameter model according to the standard ΛCDM model of structure formation. One of the more dramatic results of the Planck mission is that gravitational lensing of fluctuations in the Cosmic Microwave Background Radiation on the last scattering surface at redshifts $z \sim 1,000$ enables the power spectrum of dark matter perturbations on large scales to be determined. A map has been created of the distribution of dark matter on large scales and the features in it are correlated with the observed distribution of large–scale systems. The result is that the 6-parameter family of cosmological parameters can be determined entirely from observations of the CMB.

A consistency check is provided by the power spectrum of galaxies on the very large scales at the present epoch as defined by the Sloan Digital Sky Survey. The first peak in the Cosmic Microwave Background power spectrum is reflected in the correlation function of galaxies on a very large angular scales and the corresponding cosmological parameters are in excellent agreement with the value of $\Omega_{\rm b}h^2$ from the Planck power spectrum.

The large-scale properties of the Universe are summarised in Table 4. These show that the Universe is geometrically flat at the 0.002% level.

These are undoubtedly rather surprising values, but this is what the best observations we have ever made in cosmology are telling us. We live in a Universe dominated by Dark Energy and Dark Matter. The Dark Matter is a difficult problem and it is perhaps surprising that, despite extraordinarily impressive cryogenic experiments to detect the particles directly and searches for new types particles with the Large Hadron Collider, they have evaded detection. But, if the dark matter is a difficult problem, the origin of the dark energy is *very* difficult – it only makes its effects observable on large cosmological scales.

Table 4. The final (2018) values of cosmological parameters from the Planck mission. (The Planck Collaboration, ArXiv e-prints 1807.06209 (2018)).

Baryonic matter	$\Omega_{\mathrm{b}} h^2 = 0.02233 \pm 0.00015$
Cold Dark Matter	$\Omega_{\mathrm{c}} h^2 = 0.1198 \pm 0.0012$
Dark Energy	$\Omega_\Lambda = 0.6889 \pm 0.0056$
Spatial curvature	$\Omega_K = \Omega_{\mathrm{b}} + \Omega_{\mathrm{c}} + \Omega_\Lambda = 0.001 \pm 0.002$
Epoch of reionisation	$z_{\mathrm{reion}} = 7.64 \pm 0.74$
Hubble's constant	$H_0 = 100h = 67.37 \pm 0.54$ km s^{-1} Mpc^{-1}

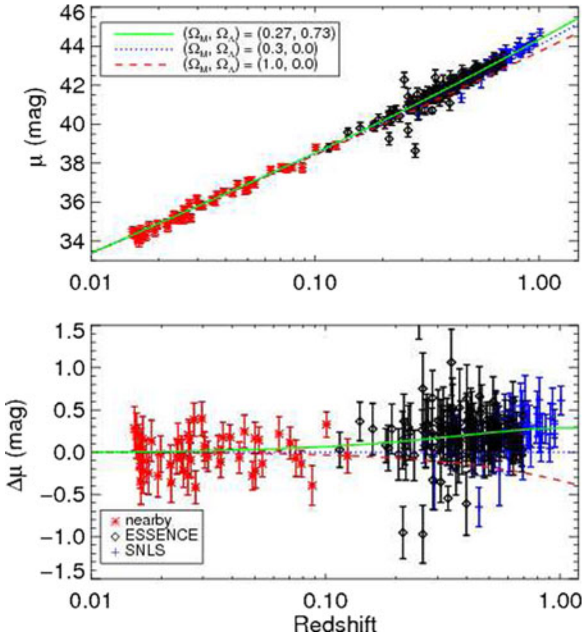

Figure 12. The redshift–magnitude relation for Type Ia supernovae from the ESSENCE project (Krisciunas, K., arXiv astro-ph 0809.2612 (2008)).

The good news is that these estimates of the cosmological parameters are in encouraging agreement with independent estimates. These include:

- Acceleration of the Universe – Type Ia supernovae;
- Value of Hubble's constant by independent routes;
- Mass density of the Universe from infall into large-scale structures
- The abundances of the light elements by primordial nucleosynthesis
- Age of the Galaxy, the ages of the oldest stars and nucleocosmochronology
- The statistics of gravitational lenses

The demonstration of the acceleration of the Universe through the observation of Type Ia supernovae has been a triumph for the classical route to the determination of the kinematics of the Universe. The ESSENCE project had the objective of measuring the redshifts and distances of about 200 supernovae. The observations are consistent with a finite, positive value of the cosmological constant (Fig. 12). The overplotted green lines are the expected relations for a ΛCDM model with $\Omega_{\mathrm{m}} = 0.27$ and $\Omega_\Lambda = 0.73$.

Now the debate has shifted to the issue of how well the parameters derived from the different routes are in fact in agreement. But we are now talking about discrepancies

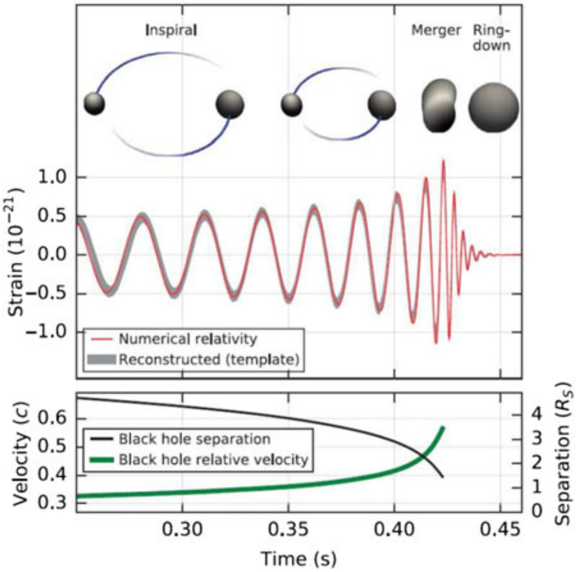

Figure 13. The signatures and observed signals from the two LIGO detectors of the event of 14 September 2015 (Abbott, B.P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) (2016). 'Observation of Gravitational Waves from a Binary Black Hole Merger', *Physical Review Letters*, **116**, 061102.

at less than roughly the 5% level at most. But, this is where the next generation of cosmological problems may lie.

8. Discovery of Gravitational Waves

Finally, we bring everything together with the recent detection of gravitational waves from inspiralling black holes. It was long recognised that this was one of the most promising routes for the detection of gravitational waves. The inspiralling of a pair of back holes and their coalescence to a single massive black hole has a very characteristic signature which can be calculated very precisely because the black holes are such simple objects. The minute strains expected from such a stupendous event are shown in Fig. 13, along with the signals observed at the two LIGO detectors located at Hanford, Washington and Livingston, Louisiana on 14th September 2015. The observation of the black hole coalescence signature is unambiguous.

The properties of the coalescing black holes involved in this event were as follows:

- The masses of the two black holes were both about 30 times the mass of the Sun before coalescence.
- They moved about each other at about half the speed of light just before coalescence.
- Three solar masses of the material of the black holes were converted into the energy of gravitational waves in less than a tenth of a second.

This is really serious high energy astrophysics.

Equally dramatic was the discovery of coalescing binary neutron stars on August 17 2017. In this case, a γ-ray burst was observed 2 seconds after the gravitational wave event. The resulting afterglows were followed up by a huge numbers of telescopes throughout the electromagnetic spectrum. The vision of multi-wavelength astronomy supported by outstanding technology, computation and theory had come about with a vengeance.

9. Conclusion

What is the message of this brief summary of some of the amazing successes of the last 100 years? The most obvious is the essential synergies between all the sub-disciplines of astronomy, astrophysics, cosmology, physics, chemistry, technology, computing and so on. The inter-dependences and international collaborations throughout all these disciplines are mandatory and the IAU has been, and will continue to be, at the heart of these endeavours.

What are the prime ingredients for advancing the discipline and making new discoveries? These are well known to all of us:

- New technology and instrumentation
- New ways of doing astronomy
- Precision observation
- Extensive databases and computational facilities
- Capitalising upon discoveries in other disciplines
- Cutting edge theory
- Imagination
- Perseverance
- Luck

Put these all together and astronomy, astrophysics and cosmology have a very bright future.

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