The Top Ten Astronomical “Breakthroughs” of the 20th Century

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Summary

Astronomy was revolutionized in the 20th century. The electron was discovered in 1897 and this transformed spectroscopy and introduced plasma and magnetohydrodynamic physics and astro-chemistry. Einstein’s $E = mc^2$, solved the problem of stellar energy generation and spawned the study of elemental nuclear synthesis. Large telescopes led to a boom in astronomical spectroscopic and photometric data collection, leading to such cornerstones as the Hertzprung-Russell diagram and the mass-luminosity relationship, and to the realization that the Universe contained a multitude of galaxies and was expanding. Radio astronomy was introduced and the advent of the space age saw the astronomical wavelength range expand into the ultraviolet, X-ray and gamma-ray regions, as well as the infrared and millimetre. We also started wandering around roaming the Solar System instead of merely glimpsing its members from the bottom of our warm, turbulent atmosphere. Astronomical “breakthroughs” abounded. We have asked astronomers to select their “top ten” and these are listed and discussed in this paper.

Introduction

The progress of astronomy leapt forward when astrophysics was added to its sub-disciplines. The science of astrophysics essentially started in the early 19th century and has advanced at a great pace, especially so in the last century. In fact we might suggest that the 20th century was an epoch of enlightenment, in which our understanding of the Universe was revolutionized. As with many of today’s sciences, we might wonder whether this rate of progress will continue.

Science advances in two ways. On the one hand we have the gradual accumulation of knowledge and data. There are many examples of this in astronomy. Just think of the slow and painstaking accumulation of accurate stellar distances, masses, luminosities, temperatures and spectra. On the other hand, we have “breakthroughs”. These are major paradigm shifts, the realization that we have actually been ‘barking up the wrong tree.’ Here, our concept of the astronomical Universe changes dramatically over a relatively short period of time. The Earth’s cosmic position is a good example. In the 15th century the vast majority of thinkers placed the Earth at the centre of the Universe. By the 17th century our understanding of the cosmos had changed dramatically and Earth was demoted to being a mere planet. The Sun then became the centre of the Universe, but even this view did not last long.

In this paper we aimed to recognize the major astronomical breakthroughs that occurred in the 20th century. These stand out as landmarks in the progress of astronomical history. Our subtext is the implicit suggestion that the breakthroughs of the twentieth century might have been better and more numerous than the breakthroughs of previous centuries. We are also asking the reader to consider whether it is it possible that a similar number of major changes and impressive breakthroughs might also occur in the next century. Perhaps the rate of astronomical advance is slowing down.

Let us start by being pedantic, and define the word “breakthrough”. In the context of astronomy this can be thought of in terms of **parameters, processes,** or **objects**. To illustrate this we will provide examples in each category.

(i) Parameters. A typical astronomical parameter would be “the distance between the Earth and nearby stars”. Here, we stray away from the 20th century. In the early part of the 19th century we knew the Earth-Sun distance, some 150×10^6 km (1 au), but that was the extent of our precise knowledge of the cosmic distance scale at the time. To quote John Michell (1767)

> *“[T]he want of a sensible parallax in the fixed stars, is owing to their immense distance.”*

An understanding of the relationship between stellar brightness and apparent magnitude, coupled with an understanding that the flux from a specific star decreased as a function of the inverse square of the distance from that star, would provide a clue as to typical interstellar spacings. The fact that the Sun is about 10^{11} times brighter than the next ten brightest stars in the sky, coupled with a guess that all stars might have luminosities similar to the Sun’s (a rather optimistic assumption, given that the median absolute magnitude of the fifty closest stars to the Sun is 11.85, indicating a median luminosity of $L_\odot/640$), leads us to the suggestion that typical interstellar distances in the galactic disc are around $\sqrt{10^{11}} = 300{,}000$ au $=$ 1.5 pc. This means that when we are trying to measure the “sensible” stellar parallax of the nearest stars we are attempting to measure angles that are at best about 1/1.5 arcsecond in size. These parallax angles had been hunted for since the days of Nicolaus Copernicus and his promotion of the heliocentric Solar System in 1543. Only by the 1830s had telescopes improved sufficiently for the first stellar distance to be measured. The star was 61 Cygni, and the measurement was made in 1838 by Friedrich Wilhelm Bessel. (The distance of this star is now given as 3.496±0.007 pc.) This was the astronomical breakthrough, as it confirmed astronomers' suspicions as to the enormity of the Milky Way. As the 19th century progressed, more and more stellar distances were measured, this leading to the assessment of stellar luminosities and stellar masses, and eventually the foundation of astrophysics.

Distance is only one of a host of physical and chemical astronomical characteristics. Think briefly of the parameter "velocity". Albert Einstein regarded the Universe as static. Then along came Edwin Hubble and his discovery that clusters of galaxies have non-random velocities, and that the Universe is expanding. This was a breakthrough; the concept of the Universe was revolutionized.

Consider the age of astronomical objects. Many thought of the Earth as being created in a Biblical fashion some 6000 years ago. Then, we subsequently discover that the Earth is actually around 4,570,000,000 yr old (see for example Faul, 1966; Brush, 1996.) This was clearly a major paradigm shift and thus another breakthrough.

In the early 19th century we had no idea as to the composition of the Sun. Even in the 1920s Sir Arthur Eddington thought that the solar composition was similar to that of the Earth. Along came Cecelia Payne (later Payne-Gaposchkin), who discovered that the solar mass is about 74% hydrogen, 24% helium and 2% metals; another breakthrough. Here, we are reminded of a further episode in the history of our subject, when, like Aristotle, we regarded the heavens as "perfect" and made of some "quintessence" completely unlike the mundane terrestrial earth, fire, air and water. The breakthrough was due to the development of spectroscopy and the discovery that the heavenly bodies consisted of exactly the same elements as the Earth beneath our feet.

(ii) Processes. An example of the "process" breakthrough would be the mechanism of stellar energy generation. As soon as astronomers had been convinced that the constant-luminosity Sun was more than 6000 years old, they started worrying about its energy source. Was it burning? Was it shrinking? Was it gaining mass (and kinetic energy) by cometary and meteoritic accretion? Was it radioactive and thus decaying? All these mechanisms proved to be inadequate. Then in 1905 Einstein introduced $E = mc^2$. Mass, m, could be converted into energy, E, the discovery of this process being a breakthrough. All that then remained was to decide what specific mass was being used. It was soon realized that atoms and electrons were not being annihilated but merely converted from one form into another. Hydrogen was transformed into helium, helium into carbon, carbon into oxygen, and so on. These ideas eventual led to our detailed understanding of the proton-proton and CNO cycles. Stellar energy generation was also transformed from being a mere fuelling process. Not only were we producing energy, we were also manufacturing new, and heavier, elements. The over-abundance of stellar helium was explained by processes that occurred in the Big Bang. The metallicity of the Universe was explained by Burbage, Burbage, Fowler and Hoyle (1957), evoking nuclear synthesis in stellar interiors and during supernova explosions. Here we have another breakthrough; the chemistry of the Universe was no longer a complete mystery.

(iii) Object breakthroughs can be divided into "new" and "similar" objects. So you might flag a breakthrough if you discover something completely new, something that you had no idea existed. Examples might be Uranus, white dwarf stars, Cepheid variables, quasars and gamma-ray bursters. Then you have the objects that are predicted theoretically but take a considerable effort to find. Neptune, Pluto, asteroids, pulsars, black holes, the cosmic microwave background and the 21 cm radiation, spring to mind.

In the context of "similar" objects one can think of galaxies. Astronomers spent the first few thousand years of their scientific endeavour being convinced that there was but one galaxy, the one that contained our Sun and Solar System. Then, in 1928, there was a breakthrough. The Universe did not just contain a single galaxy; there were actually huge numbers of them. (1999 Hubble Space Telescope observations led to an estimate of about 125 billion, and more recent modelling programs indicate that the number might be as high as 500 billion.) A second surprise was the realization that our Galaxy was not very special but was rather similar to many other large (non-dwarf) galaxies.

Turn to the Solar System. As soon as the Earth had been demoted from its geocentric cosmic elevation, the normality of the Sun and the profusion of planets led astronomers to suggest that planetary systems were commonplace. The breakthrough came when, in the mid-1990s, other planetary systems were detected, by radial velocity measurements and transit observations. A subsequent surprise was the realization that our Solar System was rather unusual and might be way off the Gaussian mean when it came to the distribution of planetary system characteristics. Many of the newly discovered planetary systems had large Jupiter-like planets very close to the central star (see, for example, Croswell, 1997; Goldsmith, 1997).

Perhaps the term "object" can be stretched slightly. In Newtonian times astronomers were convinced that space was Euclidean, and that light always travelled in straight lines from emitter to observer. We now realize that this is far from the case, and the discovery of gravitational lenses has led to an interesting breakthrough, in essence showing that massive bodies affect the geometry of the surrounding space, this leading to the bending of the rays of light that pass close by. Also in the 19th century, with the exception of the "aether", astronomers were convinced that space was empty. The 20th century discovery that space contained considerable amounts of dust and gas, and the discovery of the influence of missing mass ("dark matter") was a considerable breakthrough.

Notice that we do not count techniques and instruments as breakthroughs, even though new types of instruments and bigger and more sensitive examples of old ones might lead to breakthroughs. The invention of the telescope, the spectroscope, the photographic process and the silvering of glass mirrors are not breakthroughs, and neither is the construction of, say, the 100 inch (2.54 m) Hooker Telescope, or the Lovell radio dish at Jodrell Bank, or the microwave horn antenna at Bell Telephone Company, Holmdel, New Jersey, USA, or the Hubble Space Telescope, or the Saturn rocket that took men to the Moon. The use of these certainly resulted in a number of breakthroughs, such as the discovery of planetary rings, asteroids, external galaxies, stellar composition, interstellar hydrogen and dust, the exansion of the Universe and the cosmic microwave background, but they are not breakthroughs in themselves.

The Time Period

In this paper we restrict ourselves to the 20th century. Let us review a few of the changes that occurred in this 100 year time interval.

In 1900, astronomical calculations were carried out using logarithm tables and slide rules, but by 2000 we had the laptops and supercomputers. In 1900, it took three weeks to calculate a cometary orbit from a limited data set. By the year 2000 the job could be done in less than three minutes. In 1900, we had no idea what was inside the atom. The electron and neutron had not been discovered, quantum mechanics had not laid the foundation for the study of spectroscopy and electromagnetic radiation, there was no special or general relativity, no $E = mc^2$, and no understanding of nuclear fusion or fission.

In 1900, we were still wedded to the refracting telescope, and Lord Rosse's reflecting Leviathan, in the middle of Ireland was regarded as somewhat of an oddity. The great Yerkes refractor, near Chicago, with its 40 inch (1.01 m) lens, was a 'thrusting research tool' when it was commissioned in 1897. The largest reflecting telescope effectively working on astronomical research in 1900 was Ainsley Common's 36 inch (0.91 m) Crossley reflector, this being the telescope that the Lick Observatory had bought in 1885. In the first decade of the 20th century the Americans were hard at work trying to fund and built the 60 inch (1.5 m), Ritchey and the 100 inch (2.5 m) Hooker telescopes at Mount Wilson, California. The former started to be used in 1908 and first light hit the Hooker in November 1917 (Edwin Hubble joined the Mount Wilson staff in 1919). By the year 2000 we had a 2.5 m telescope orbiting our planet, 600 km up, and giant 8 and 10 m telescopes in both hemispheres. Instrumentation had been further augmented by the replacement of the

20th Century Top Ten Breakthroughs

Listed using the Eurovision Song Contest approach to positioning

1. Expanding Universe
2. The multitude of galaxies
3. Cosmic microwave background
4. Exotics (quasars/AGN)
5. Stellar energy sources and evolution
6. Hertzprung-Russell diagram and stellar diversity
7. Exoplanets
8. Stellar chemical composition
9. Dark matter
10. Galaxy mapping and structure

20th Century Top Ten Breakthroughs

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9. Exoplanets
10. Solar probing using neutrinos/helioseismology

photographic plate by the much more efficient charge-coupled device, and by the introduction of adaptive optics.

In 1900, with the exception of a small incursion into the infrared using blackened thermometers and bolometers, all astronomy was restricted to the limited visual wavelength range. By 2000, the surface of the Earth was dotted with radio telescopes and a legion of gamma-ray, X-ray, UV and IR telescopes had been placed above the atmosphere in low Earth orbit.

In 1900, if we wanted to travel, we caught a railway train or a ship. By 2000, everyone was flying and twelve men had walked on the Moon (albeit in the 1969-72 time period). The space age had also seen craft flying by all the planets except for Pluto (although NASA's New Horizon mission is expected to fly by Pluto and its satellite Charon in July 2015), going into orbit around Venus, Mars Jupiter and Saturn, and actually landing and roving about on Mars.

In 1900, the world boasted around 2000 active astronomers, working in around 100 observatories. This dropped to about 1000 after the ravages of the First World War. By the year 2000, the world groaned under the efforts of around 20,000 astronomers, each publishing, on average, 2 research papers a year. Today, the world has 32 telescopes with mirror diameters, D, in the range $2.0\ \mathrm{m} < D < 3.0\ \mathrm{m}$, fourteen in the range $3.0\ \mathrm{m} < D < 4.0\ \mathrm{m}$, eight in the range $4.0\ \mathrm{m} < D < 8.0\ \mathrm{m}$ and eleven with $D > 8.0\ \mathrm{m}$.

The Process

In our original letter to Astronomy & Geophysics (de Grijs & Hughes, 2006), we overviewed the huge advances in enlightenment and instrumentation that had occurred in the 20th century, and pointed to some of the ways in which the understanding of our planetary, stellar and galactic neighbours had changed between AD 1900 and 2000. We then decided to ask both the readers of Astronomy & Geophysics and our colleagues at the University of Sheffield to produce lists of what they considered to be the significant astronomical and astrophysical breakthroughs that had occurred in this time interval, and to place these breakthroughs in order of significance.

Many contributions were received and the suggested breakthroughs were then analysed and ordered in two ways. All the breakthroughs suggested by all the respondents were considered, even though some respondents put forward fewer than the ten requested. First choices were given ten points, second choices nine, third choices eight and so on. List 1 shows the results using the Eurovision Song Contest approach. Here, the points given to each breakthrough are added up, and the breakthrough with the most points wins, the one with the next highest tally coming in second, and so on. In this approach all the "judges" considered all the "entries".

The second approach is rather like the "betting form" of a horse when entering a new race. Here, we wish to know the position it obtained in the previous races that it entered. And not entering a race does not count. In this method, all the points allocated to a breakthrough are added up, but this number is then divided by the number of times that that breakthrough has been chosen, and the results are then listed in order, giving List 2.

Both lists indicate that galaxies win clearly. The top two places in both lists go to the discovery that the Universe actually contains a huge number of galaxies, as opposed to just the single one (ours!), and the discovery that the galactic distribution was not static, but ever expanding. The galaxy/cosmology party then try to dominate List 1 by having the cosmic microwave background in third place, the emphasis here being on the Big Bang theory and its conclusions as to the age of the Universe. The galactic bias is further underlined by the high position of the astronomical "exotics". Much is made of quasars, active galactic nuclei, galactic accretion discs and galactic central black holes, all of which are powered by a range of highly energetic physical processes, these being observed over a multitude of wavelengths from the gamma- and X-ray end of the spectrum through to the long wavelength radio.

The middle orders of both our final lists are dominated by stellar astrophysics. There is considerable agreement in the ordering of these breakthroughs. The most important was the discovery of the sources of stellar energy. The fact that there is a variety of nuclear "fuels", coupled with the possibility of simply utilizing potential energy, means that there are a range of different star types. So the second major "stellar" breakthrough concerns the division of the stellar population into dwarf stars, giant stars and white dwarf stars, exemplified by their positions on the Hertzsprung-Russell diagram. This advance was extremely fruitful, leading as it did to the recognition of both a mass-dependent stellar evolutionary sequence and a host of subspecies stellar types. The final "stellar" breakthrough concerned composition. Maybe we can couple this with physical state too. Clearly, we are dealing with a triumph for the spectroscopists and a transition from an era when we had no idea what a star was made of or how stellar structure and composition varied from surface to centre to today's deep understanding of elemental nuclear synthesis and stellar interiors.

It is interesting to note the lowly position of planetary astronomy in both Lists 1 and 2. Despite the dawn of the space age, no characteristic of our Solar System makes the top ten. Exoplanets have a somewhat contentious breakthrough status considering that the discovery of well over a hundred planets orbiting stars other than the Sun simply underlines that fact that we really have little idea where our Solar System came from, or how cosmogonical processes fit in with general star birth.

A More Detailed Consideration of the Breakthroughs

1. The Milky Way is not the only galaxy in the Universe. Many of the fuzzy nebular blobs that Charles Messier (1730-1817) charted in the mid-18th century are actually distant star systems just like our own. The breakthrough occurred in 1923, when Edwin Hubble (1889-1953) used the 100 inch Hooker reflector and discovered a Cepheid variable in M31 (later published in Hubble, 1929a). By 1924 he had discovered twelve more. Using the calibrated Magellanic Cloud Cepheid data obtained by Henrietta Leavitt (1868-1921), see Leavitt & Pickering (1912), he realised that M31 was 900,000 light years away, nine times further than the outer edge of our Milky Way galaxy. Soon it was realized that the Universe contained over 10^{11} galaxies and not just the one. This is a marvellous example of an astronomical breakthrough and paradigm shift. Astronomers did not just double the number of galaxies, or change it by a factor of ten. A single unique entity, our Galaxy, suddenly, in the late 1920s found itself to be merely one among over 125 billion. Some change!

2. The Universe is expanding. This entry relies somewhat on the previous one. The stars in the Galaxy are clearly orbiting the centre of mass, and astronomers envisaged a stellar system of a specific size, with a nuclear bulge at the centre and an edge beyond which there were very few stars. It was a great leap to introduce another 10^{11} or so galaxies. And Einstein's view was that the Universe was static. The realization that, on average, the galaxies seemed to be moving away from us was a major paradigm shift. And this was bolstered by the discovery that the recessional velocity increased with distance. Again, the 100 inch Hooker telescope was responsible. This huge instrument had been used to take spectra of galactic radiation. Vesto Slipher (1875-1969) measured redshifts, as did Edwin Hubble. These Doppler velocities were reasonably accurate. Hubble estimated galactic distances using Cepheids, for the close ones, and then magnitude and size comparisons for the more distant. Needless to say, the assumption that galaxies of a specific type all had similar absolute magnitudes and diameters led to errors in the estimated distances. By 1929, however, Hubble had obtained 46 values of both velocity and distance.

A graph indicated that velocity was proportional to distance (see Hubble, 1929b). The gradient was 500 km s^{-1} Mpc^{-1}, this positive value indicating that the Universe was smaller in the past. It was noted at the time that the inverse of the gradient (assuming no retardation) gave the time since the expansion started. Astronomers could thus measure the age of the Universe, or at least the time since it was all "squashed" into a primeval "atom". Initially this worryingly revealed that the Universe was younger than the Earth, but cosmologists speedily reassessed the "Hubble constant", whose present value, combining WMAP with other cosmological data, is around 71 ± 4 km s^{-1} Mpc^{-1} (see http://map.gsfc.nasa.gov/m_uni/uni_101expand.html). So the Universe is about $(13.8\pm0.8) \times 10^9$ yr old, about three times older than planet Earth.

Another breakthrough discovery associated with Hubble's early work was the realization that the Universe looked very similar in all directions. This led to the suggestion that the Universe would look similar from the vast majority of places inside it, and thus that the formative Big Bang must have been amazingly homogeneous and isotropic.

3. The generation of stellar energy. The next three breakthroughs indicate just how little we knew about stars in 1900 and how the first few decades of the 20th century led to a major transformation of our views. In 1900, astronomers realized that stars were old, well over a billion years old, and that they were very luminous for much the greater part of their life. But astronomers did not know how the huge amounts of stellar energy were produced. The breakthrough was triggered by Albert Einstein's 1905 paper on special relativity and the introduction of mass-energy equivalence, this being exemplified by the iconic equation $E = mc^2$. Clearly, mass is not converted into energy under normal physical conditions. Before $E = mc^2$ could be embraced, astrophysicists like Sir Arthur Stanley Eddington (1882-1944) had to show just how extraordinary the centre of a star was. Eddington was one of the first to realize that stars were gaseous throughout, and that stars owed their stability to the balance between the force exerted by gravity and the opposing pressure exerted by gas and radiation. This led to the mass-luminosity relationship, which was vital for the understanding of stellar evolution. For example, the main sequence luminosity of a star is proportional to $mass^{3.5}$ and the main sequence lifetime of a star is proportional to $mass^{-2.5}$. These relationships enabled astronomers to estimate such important characteristics as stellar cluster masses and ages.

Eddington (1926) intimated that the density of the gas at the centre of the Sun was well over a hundred times that of water, and that the temperature of this region was higher than 10^7 K. Stellar interiors were certainly hot enough for the nuclear reaction rate to be non-negligible. But what was the form of the mass that was being destroyed? Luckily, at about the same time (1920), Francis William Aston (1877-1945) was using a mass spectrometer (an instrument that he invented) to measure the masses of certain atoms and isotopes. He realized that four hydrogen atoms were heavier than one helium atom. Others at the time (see later) were hinting that hydrogen and helium were the major components of stellar composition. These factors combined to solve the stellar energy generation problem. But one had to show exactly how it worked. Hans A. Bethe (1906-2005) did this in 1939, when he proposed the carbon-nitrogen-oxygen (CNO) cycle. Later on he introduced the proton-proton cycle. Interestingly, these processes were extremely slow, so stars spent long periods of time on the main sequence, gently converting hydrogen into helium. During this period, their luminosity changed very little.

The recognition of the source of stellar energy led eventually to the general solution of the stellar evolution problem, an endeavour that took about 35 years.

4. There are only two common types of stars. Slightly before our understanding of how stellar energy was gained came the realization that the vast majority of stars are essentially of just two types, the so-called "dwarfs" and "giants". This is rather surprising nomenclature for objects that typically have diameters of around 10^6 and around 20×10^7 km respectively. The year 1910 saw certain astronomers drawing up lists of stellar luminosities and surface temperatures (as time went by these lists were extended to included radii and masses). Hertzprung (1911) plotted graphs showing the apparent magnitude as a function of spectral type for stars in specific open clusters (i.e. nearby "moving groups" of closely related stars), such as the Pleiades and the Hyades. Russell (1914) took full advantage of recent parallax work and plotted absolute magnitude (i.e. luminosity) as a function of spectral type (i.e. log[surface temperature]) for stars in general. Both Hertzprung and Russell found that there were two main types of stars. By far the commonest were the "dwarfs"— approximately Sun-sized stars occupying a "main sequence" along which luminosity was proportional to temperature to the power of approximately 6.7. Less common were the "giants". Here, we had stars with absolute magnitudes of around zero. (As time went by more stellar classes were added. One class was the faint Earth-sized white dwarfs, with absolute visual magnitudes between 10 and 14 and spectral types around B and A, and the other, the rarer supergiants with absolute visual magnitudes in the -5 to -8 range.)

5. We now understand the composition of the baryonic matter in the Universe. In 1900, the general consensus was that stars were made of "earth". Since 1925 astronomers started to realize that stars are predominantly made of hydrogen and helium, this clearly being a major paradigm shift. Cecelia Payne led the way, in her famous Harvard PhD thesis Stellar Atmospheres, A Contribution to the Observational Study of High Temperature in the Reversing Layer of Stars, a thesis that led to her 1925 Radcliffe College (Cambridge, Massachusetts) doctorate. She used the 1920 equation developed by Meghnad Saha (1894-1956) to convert spectroscopic line strengths into atomic number counts and eventually stellar photospheric compositions. A second important breakthrough in this field was the realization that stars come in two main compositional sorts; metal rich Population I and metal poor Population II. This was discovered by Walter Baade (1893-1960) in 1943 (see Baade 1944), using photographic plates that he had taken of the M31, The Andromeda Galaxy, with the Hooker, under the conditions of the wartime blackout. A third breakthrough was the explanation of why the stars actually had the compositions that they did, and how that composition varies with time. There were two components to this breakthrough: first the explanation of the initial 75%:25% hydrogen helium mix produced just after the Big Bang, and second the 1957 breakthrough due to the work of Margaret Burbidge, Geoffrey Burbidge, William Fowler and Fred Hoyle. This takes the nuclear e-process that converts hydrogen into helium and extends the sequence on to the production of carbon and oxygen, silicon, sulphur, argon and calcium, and ending with the iron peak. These four scientists then showed how the r-process takes over in supernova explosions and moves the composition on towards gold, platinum and uranium.

6. Exotics. In 1900, the "Universe" consisted of planets, other minor members of the Solar System, stars and a single Galaxy. The objects known at that time were relatively mundane. But there is a special class of astronomer who yearns for the exotic, and the last century has provided such celestial bodies in abundance. The exotics, by their very nature, stretch cosmic physics to extremes, and it is this that leads to the breakthrough. First one has the stellar exotics. Typical examples are found at the end points of stellar evolution. Low-mass stars evolve into Earth-sized white dwarfs, bodies governed by the laws of degenerate matter. Neutron stars were predicted by Subrahmanyan Chandrasekhar (1910-1995) in 1930 to be the evolutionary endpoint of stars more massive than 1.4 solar masses. Many of these are produced by supernova explosions, as suggested by Walter Baade and Fritz Zwicky (1898-1974) in their joint 1933 paper. The radio wave observations of of Jocelyn Bell (now Bell-Burnell) and Anthony Hewish in 1967, showed that pulsars were just rotating neutron stars. Finally, one has the black holes, these being the endpoints of the evolution of stars more massive than three solar masses.

Another addition to the tally of exotic breakthroughs was the1963 discovery of the quasi-stellar object 3C 273 by Maarten Schmidt. Here, we were confronted by a strong radio source, at a redshift of 0.158, which visually looked just like a 13th magnitude star moving away from Earth at 16.6% of the velocity of light. Subsequently, radio-quiet quasars were found, as well as quasars that varied in brightness over timescales of a few weeks. Soon, quasars were being equated to accreting discs around 10^7 to 10^8 solar mass black holes, these being the very active nuclei at the centre of distant (and thus young) galaxies. Seyfert galaxies (first described in 1943) are thought to be a specific class of quasars with rather low luminosity. They are near-normal spiral galaxies with reasonably active nuclei Quasars/AGN are perfect examples of late 20th century exotics, lending themselves to multi-wavelength investigation.

7. The Microwave Background Radiation. It is one thing to suggest that the Universe started with a “big bang” (a derogatory term coined by Fred Hoyle (1915-2001) in a BBC broadcast, see Hoyle, 1950), but it is another to prove it. It is one thing to measure an expanding Universe, but it is another to work out what made it expand. Robert Henry Dicke et al. (1965) realized that a Big Bang (the term quickly became capitalized) would not only accelerate matter away from a singularity but would also produce extremely hot radiation that would cool as the Universe expanded. If the Universe was 13,000,000,000 yr old it should have a radius of 13,000,000,000 light years, and the radiation should now have a temperature of only a few K. This corresponds to an energy emission maximum at a wavelength of a millimetre or so. Dicke planned to search for this microwave maximum, but was pipped at the post by a serendipitous discovery. Arno Penzias and Robert Wilson of Bell Telescope Laboratories detected the 3.1±1 K background radiation (λ_{max} = 0.93 mm) in 1965 when trying to eliminate static that was interfering with their satellite communication system. Their 4080 MHz horn antenna was about as big as a house. This breakthrough immediately converted cosmology from a vibrant exciting subject with two flourishing and competing theories, into a boring dirge where everyone sings from the same “Big Bang” hymn sheet and the “steady state” theorists are cast into outer darkness. Interestingly, in whichever direction one looked from Earth, the radiation was very close to the same temperature of 3.1 K. More recent refinements have indicated that this radiation, in the rest-frame of the Universe, is isotropic down to 1 part in 105. Huge amounts of money have been expended in launching satellites such as COBE (1992) and WMAP (2001) to investigate the isotropy on ever smaller scales.

8. Dark Matter. Most of the Universe seems to consist of material that we cannot see. The “luminous”, radiating, bodies in our Universe only make up about 4% of the total mass. This strange and still unexplained phenomenon was first discovered by Fritz Zwicky (1937). The application of the virial theorem to the Coma cluster of galaxies indicated that it contained 400 times more mass than that indicated by the visible parts of the galaxies.

Galaxies are more massive than they look. We can count all the stars and add up their masses, and then include the gas and the dust. But it is still not enough. Vera Rubin showed that the velocity curve of a typical galaxy indicated that the velocity of rotation did not decrease significantly as a function of distance from the galactic spin axis (see Rubin, 1978, 1983). Everyone was expecting most of the galactic mass to be in the nucleus. If this were the case, the rotation velocity would decrease as the inverse square root of distance from the massive central body (as happens in the Solar System). The typical spiral galaxy actually has a massive halo, which has a density that decreases as a function of the inverse square of the distance from the spin axis. The composition, or form, of the “missing mass” in this halo is not known. Some of our contributors to the breakthrough listings suggested that the discovery of “dark matter” should only achieve breakthrough status when the actual physical form of the dark matter has been identified. This is somewhat unfair. One of the great joys of modern astronomy and astrophysics is the host of mysteries that abound.

9. Exoplanetary systems. In 1900, there was one known planetary system — the one we inhabit. As the century progressed certain astronomers, such as Peter van de Kamp (1975), hinted that the slight astrometric wobble of the celestial paths of certain nearby stars indicated that they had planetary companions. By the end of the 1900-2000 period, the planetary floodgates had opened. The Doppler shift of a planet’s parent star could now be monitored accurately. A profusion of planetary discoveries were reported (see, for example, Mayor & Queloz, 1995, who used the telescope at the Haute-Provence Observatory in France, and Butler & Marcy, 1996, who confirmed the discovery using the telescope at the Lick Observatory in California, USA). Later on, some of these discoveries were confirmed by the observation of stellar transits. This was a fascinating breakthrough. Our Solar System was proved not to be the only one in the Galaxy. Rather unexpectedly, however, the vast majority of these newly discovered planetary systems are nothing like the system that we live in. Instead of having Jupiter-like planets orbiting the central star every decade or so, their “hot Jupiters” are in Mercury-like orbits. The observations of a host of other planetary systems were expected to provide clues as to the origin of our own system. They have not.

A side issue to the breakthrough discoveries of many exoplanetary systems is the realization that we are still alone. Life seems to be rare; and intelligent, inquisitive, communicating life, rarer still. Look though we may, we have found absolutely no evidence of life having broken out on other planets in our system. Even though we listen diligently, we have intercepted no incoming radio signals from “extraterrestrials”.

10. Solar neutrinos and helioseismology. We cannot “see” inside a star. Our vision of the solar photosphere extends to a depth of about 500 km, but, in comparison with the solar radius of around 700,000 km, this still leaves a very long way to go. Until recently, the stellar interior was the realm of the theoretical astrophysicist. Two breakthroughs have occurred in the last 50 years. The first was the detection and monitoring of solar neutrinos, these being produced by the host of nuclear reactions that convert hydrogen into helium. Raymond Davis Jr and his huge tank of ^{37}Cl in the mine at Homestake, South Dakota, measured at least a few of the 6.5 x 10^{14} neutrinos m^{-2} s^{-1} that pass through the Earth. This experiment started in 1968. Detectors using gallium started operation in 1991 (see, for example, Stix, 2002).

The second breakthrough was the observation of seismic waves on the solar surface. As waves of different frequency penetrate to different depths, they can be used to estimate spin rates in the solar interior as well as the position of the region where radiative energy transport changes to convective energy transport. Helioseismic oscillations were discovered in 1960 and reported by Leighton et al. (1962). The detailed structure of the five-minute evanescent oscillations were reported in 1975 (Deubner, 1975) and the lowest wavelength modes were observed in 1979 (see Claverie et al. 1979).

Discussion and Conclusions

The timing of the breakthroughs is rather informative. Those relating to stars occurred rather early on in the 20th century. The stellar energy problem was well on the way towards a solution in 1905; stellar diversity was indicated by the 1911-14 Hertzprung-Russell diagrams; and stellar composition was reasonably well understood by 1925. The two huge extragalactic breakthroughs, the discovery of galactic multiplicity and the expansion of the Universe, both occurred at the end of the 1920s. The year 1937 saw the discovery of dark matter. So six out of ten of our breakthroughs occurred in the first 37 years of the 20th century. Three more occurred in the 1960s: the discovery of quasars in 1963, the cosmic microwave background in 1965 and the detection of solar neutrinos in 1968. The mid-1990s saw the discovery of exoplanets.

With the exception of quasars and the microwave background, the visual portion of the electromagnetic spectrum dominates the breakthrough scene. It is also rather interesting to note that the 100 inch Hooker telescope provided two of the breakthroughs, and larger telescopes have not helped a great deal in providing the remainder. Perhaps there are a host of future breakthroughs awaiting the next generation of large telescopes, but this is rather unlikely. Computers seem to have led to no top-ten breakthroughs at all. Neither has space exploration. The later is rather unexpected. Maybe the discoveries of the planetary flyby probes, orbiters and landers, discoveries such as magnetic fields around Mercury, impact craters on Venus, thick crusts on the non-Earth facing hemisphere of the Moon, great canyons on Mars, smooth sandblasted asteroids, kilometric dirty snowball nuclei at the centre of comets, active volcanoes on Io, huge subsurface water oceans on Europa, lakes of liquid methane on Titan, large blue spots on Neptune, etc. might have crept into the top thirty, but not the top ten. There again, maybe the bodies in the Solar System turned out to be very much as we expected, and there were few major surprises.

Breakthroughs come in two main categories; (i) the completely unexpected, and (ii) the solution to a longstanding problem. Considering lists 1 and 2 it is clear that nobody predicted the existence of quasars before they were found, or had suggested that the vast majority of the material in the Universe was “dark”. Also, the expectation was that the space between the stars and galaxies was well behaved, empty and flat. The discovery of interstellar dust and gas by Robert Julius Trumpler in 1930, and the consequent light absorption, together with the discovery of 21 cm radio waves emitted by neutral atomic hydrogen in the Universe, put paid to the second of these assumptions. The gravitational flatness disappeared with the introduction of General Relativity by Albert Einstein in 1916. The “proof” of space curvature came with Eddington’s observations of the starlight from the Hyades cluster during the totality of the 29 May 1919 solar eclipse, followed, more importantly, by the detection of the gravitational lensing introduced by super-massive galaxies as observed by Dennis Walsh et al. (1979).

Likewise, if one combs through the research papers of the 19th century the possibility of there being a multitude of galaxies was hardly mentioned, and when this multitude was discovered, again, the expectation was that they would be orbiting their centre of mass as opposed to rushing away from the Big Bang.

These “completely unexpected” breakthroughs sometimes depended on the invention of a completely new type of scientific instrument. Often, the “new instrument” started life having very little to do with astronomy. Just consider these possible statements and consequences.

- *‘I have invented a two-lens telescope that brings distant things closer, and reveals bodies too faint for the eye to see, marvellous for army and navy use and for spotting your enemies when a long way away. Blast, an astronomer has usurped the device and used it to show that the Moon has mountains, Venus goes round the Sun, and Jupiter has satellites . . .’*
- *‘I have invented a prismatic instrument that splits light into its different colours, and when I look at Sun-light I see lots of dark lines, at specific wavelengths, just the job to help my physicists measure the refractive index variations of glass. Blast, an astronomer has developed the instrument, fitted it to a telescope, and measured the chemical composition of the Universe, stellar surface temperatures, the radial velocities of stars and planetary surfaces . . .’*
- *‘I am using a new-fangled millimetre wave radio horn antewweiver to pick up messages from submarines and am trying to reduce the background noise. But I am not going to pass this interesting noise data on to an astronomer. I shall publish the results myself and thus prove that the Universe started with a Big Bang.’*

Those breakthroughs associated with ‘the solution to a long-standing problem’ usually arose from a combination of instrumental advance, prolific data collection or theoretical enlightenment. The “chemical composition of the cosmos” is a perfect example, relying, as it did, on the invention of the spectrometer, the analysis of spectral lines, the discovery of the electron and the theoretical work of Menghnad N. Saha. The Hertzprung-Russell diagram is another. Here we have a “discovery” whose time had arrived. If Ejnar Hertzprung (1873-1967) and Henry Norris Russell (1877-1957) had not reached for the graph paper, others would have done the job in the next year or so. A similar situation arose with a mini-breakthrough around the same time, this being the discovery of the Cepheid period-luminosity relationship. Henrietta Swan Leavitt’s work in 1912 was ground-breaking, as was the calibration and use of the relationship by Ejnar Hertzprung and Harlow Shapley (1885-1972) to measure the 94,000 light year distance to the Small Magellanic Cloud. But again, if these astronomers had not done the job some one else would have, soon after.

Let us conclude by hinting at some of the breakthroughs that we are still waiting for. Some of these concern astronomical bodies that are embarrassingly close to planet Earth. Consider the second brightest object in the sky, our Moon. Do we know where it came from? The short answer is, no. Some contemporary researchers hint that a Mars-sized asteroid simply knocked a chunk off the Earth’s mantle and that this ejected material subsequently condensed and accumulated to form our Moon. But it would be most unusual if there was just the one large impact in the history of our planet. In those times there were many asteroids, and many big ones, so similar impacts should have occurred quite a few times. If our Moon were the result of an impact it is rather surprising that we do not have quite a few moons, as opposed to just the one. And Mars, Venus and Mercury should be blessed with satellite families too.

Another serious “yet-to-come” breakthrough concerns cosmogony. It is fair to say that we have a very tenuous understanding of how our planetary system formed, and why there are only eight planets in it, and why it essentially ends at Neptune. The discovery of planets around other stars simply has not helped. The majority of these systems have Jupiter-sized planets in Mercury-like orbits. In fact, many of the new systems are nothing like the system that we live in and were probably formed in different ways.

And then we have the problem of the origin of the Universe. Many astronomers are rather uncomfortable about the *creatio ex nihilo* aspects of the Big Bang. And the addition of the spice of inflation, dark energy and dark matter does little damp down their suspicions that we might not yet be on exactly the right track.

We also worry that angular momentum still seems to be rather too difficult a topic for astronomers. As university lecturers we have always been somewhat embarrassed by being unable to explain to our students why, for example, the Sun and Venus are spinning so slowly and the Universe is not thought to be spinning at all.

One of the great joys of astronomy is the simple fact that, even though breakthroughs abound, and occur at a fairly regular rate, there is a vast amount of evidence indicating that there are still a huge number of breakthroughs yet to come.

Finally, let us mention some general points. Before starting this exercise we thought that different types of astronomers might come up with completely different lists of breakthroughs. Surprisingly, this was not the case. There was considerable agreement between such diverse groups as, for example, the cosmologists, planetary astronomers, stellar theoreticians and astro-historians. Many alluded to the temporal nature of our quest. What we today (in 2007) regard as being the great breakthroughs of the 1900-2000 period might differ somewhat from what astronomers in 2107 would regard as the significant breakthroughs. And clearly the breakthroughs of 1900-2000 bear scant relationship to the breakthroughs of 1800-1900 and 1700-1800.

It was also interesting to compare the speed with which certain breakthroughs became recognized. One can well imagine that the discovery of the cosmic background radiation was realized to be a breakthrough in about half an afternoon. The elevation of the HR diagram to breakthrough status clearly took a couple of decades.

One also feels sorry for the topics that did not quite make it. The 20th century was the era of astronomical ages. At the beginning, we did not like to talk about such a delicate topic as age, such was our uncertainty. At the end, planets, meteorites, stars, stellar clusters, galaxies, and even the Universe itself, had well known ages. It was also the century of interiors. Stellar and planetary interiors were mysterious places in 1900. By 2000, these had been successfully modelled and we had a detailed understanding of the variability of pressure, density, temperature and composition, and the origin of such characteristics as heat and magnetism. Temperature ranges also expanded hugely during the century. The expansion of the observed wavelength bandwidth enabled us to investigate the high temperatures of such places as the solar corona and the surfaces of neutron stars, and such freezing spots as the centres of giant molecular clouds and the midnight regions of Pluto. The century has also been a period when the isolation of the Earth was lessened. In 1900 the only magnetic field that we could measure was the field at the surface of our planet. By 2000, we had measured magnetism in such diverse places as the centres of sunspots and the surfaces of white dwarfs. We were also beginning to appreciate and understand the influence that solar magnetic variation had on terrestrial characteristics. The century, which started only three years after J. J. Thomson discovered the electron, was also a period when the significance of plasma was first appreciated.

The expression ‘the textbooks will have to be rewritten’ is often overused in modern media discussions of scientific progress. But in the case of “breakthroughs” it often turns out to be true.

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Bios

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