The Discovery of Pulsars and the Aftermath[1]

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THE DISCOVERY OF PULSARS in 1967 is associated with the names of Anthony Hewish and Jocelyn Bell-Burnell, but the seeds of their achievement were sown long before during the exciting era when radio astronomy developed from a specialist pursuit of physicists and electrical engineers into a key area of contemporary astronomy.

After the Second World War, a number of university groups began the investigation of the nature of the cosmic radio emission, which had been discovered by Karl Jansky in 1933. The principal radio groups involved were those at Cambridge, Manchester, and Sydney. The Cambridge efforts were led by Martin Ryle, who assembled a brilliant team of young physicists, including Graham Smith, Tony Hewish, and Peter Scheuer, to attack these problems. The Cambridge efforts were largely devoted to the development of the technique of aperture synthesis as a means of obtaining high angular resolution and sensitivity by combining coherently the radio signals received by arrays of telescopes.

Hewish and the Scintillation of Radio Sources

As part of that effort, Hewish's research involved understanding the nature of the fluctuations, or scintillations, of the intensities of radio sources because of intervening moving plasma clouds. This research followed in the tradition of the Cavendish Radio Group, which, after the war, was led by Jack Ratcliffe, building on the pioneering ionospheric researches of Appleton. Just as stars twinkle even on the clearest nights, so point sources of radio emission are observed to scintillate, particularly at the long radio wavelengths, which were the focus of research in the early days of radio astronomy. The cause of the radio scintillations is the

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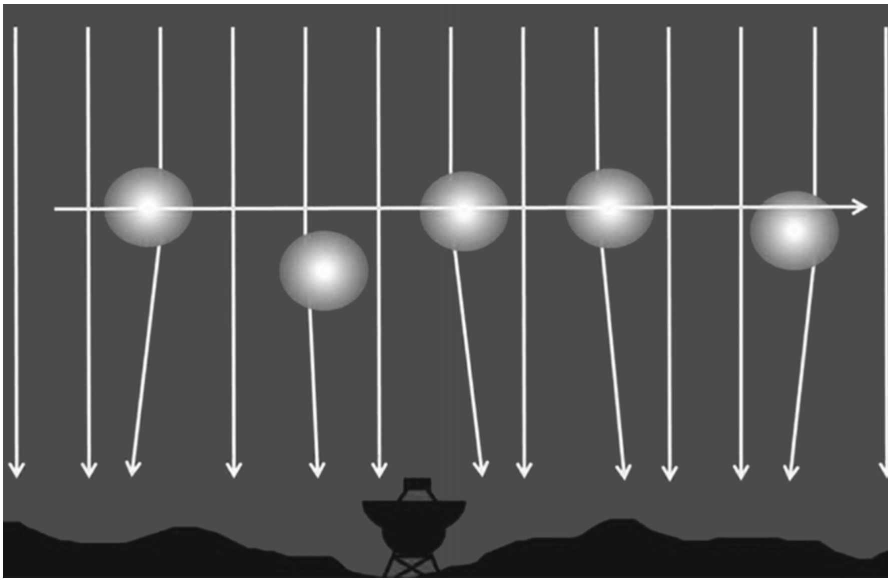

FIGURE 1. Illustrating the origin of ionospheric scintillation. Radio waves are deflected by density fluctuations in the Earth's ionosphere. The pattern of irregularities moves across the trajectories of the incoming waves, causing the observed intensity of radiation detected by the radio telescope to fluctuate.

deflections of radio rays when they pass through irregularities in the ionospheric plasma, as illustrated schematically in the diagram (fig. 1).

The theory of the process of scintillation was worked out in detail by Hewish in 1951 in a paper entitled "The Diffraction of Radio Waves in Passing through a Phase-Changing Ionosphere" (A. Hewish, *Proc. Roy. Soc.* 209 [1951]: 81–96). The paper sets out the theoretical background needed to understand the short-term fluctuations in the intensities of radio sources due to irregularities in an ionised plasma. The same concepts and techniques could be applied to the physics of fluctuations due to ionospheric, interplanetary, and interstellar electron density fluctuations. This theoretical paper was followed in 1952 by another entitled "The Diffraction of Galactic Radio Waves as a Method of Investigating the Irregular Structure of the Ionosphere" (A. Hewish, *Proc. Roy. Soc.* 214 [1952]: 494–514). Applying these concepts to observations of the fluctuating radio signals, Hewish showed that the scale of the irregularities ranged from 2 to 10 km, that the variation of electron content was about 5×10^9 electrons per cm^{-2}, and that the irregularities are at a height of about 400 km. These irregularities moved with a steady wind-like motion at a velocity of the order 100 to 300 m s^{-1}.

The same technique could be used to study the solar corona, the region of hot plasma surrounding the Sun. The radio source Taurus A (the Crab Nebula) was observed at varying angular distances from the Sun, and the variability of the signal could be accounted for by scattering because of the presence of fluctuations of the electron density in the solar corona. In his paper of 1955 "The Irregular Structure of the Outer Regions of the Solar Corona" (A. Hewish, *Proc. Roy. Soc.* 228 [1955]: 238–51), Hewish derived the sizes and electron densities of coronal irregularities in the distance range 5 to 15 solar radii.

The Controversy over the Radio Source Counts

During the 1950s, the first Cambridge catalogues of radio sources were produced, giving rise to the famous controversy concerning the excess of faint radio sources that was observed. Martin Ryle interpreted these data as evidence for an evolving Universe and inconsistent with expectations of steady state cosmology. The Cambridge survey had in fact significantly exaggerated the magnitude of the excess because of the phenomenon of source confusion, as pointed out by the Sydney radio astronomers. Relations between Martin Ryle, the Sydney radio astronomers, and the proponents of steady state cosmology became increasingly fraught.

Despite the controversy, it was clear that radio astronomy had the potential to provide new types of astrophysical and cosmological evidence. In 1956, the radio observatory moved from its site behind the university's rugby ground to a disused wartime Air Ministry bomb store at Lord's Bridge eight kilometres to the southwest of Cambridge. In acknowledgement of a grant of £100,000 from the electronics company Mullard Ltd., the new observatory was named the Mullard Radio Astronomy Observatory and formally opened in 1957.

Interplanetary Scintillation (IPS)

In 1954, Hewish had remarked in his notebooks that, if the angular sizes of the radio sources were small enough, they would illuminate the solar corona with a coherent radio signal and so give rise to rapid time variations in their intensities. This idea was forgotten until about 1962, when Margaret Clarke showed that two of the compact 3CR radio sources ($\theta < 2$ arcsec) were varying very rapidly in intensity. She left the problem unsolved, but Hewish realised that his old idea was the solution (fig. 2).

By 1964, a number of radio quasars were known and some of these radio sources had small angular sizes. With Paul Scott and Derek Wills, Hewish showed that the radio scintillations, shown in figure 2, were due to scattering of the radio waves by inhomogeneities in the ionised

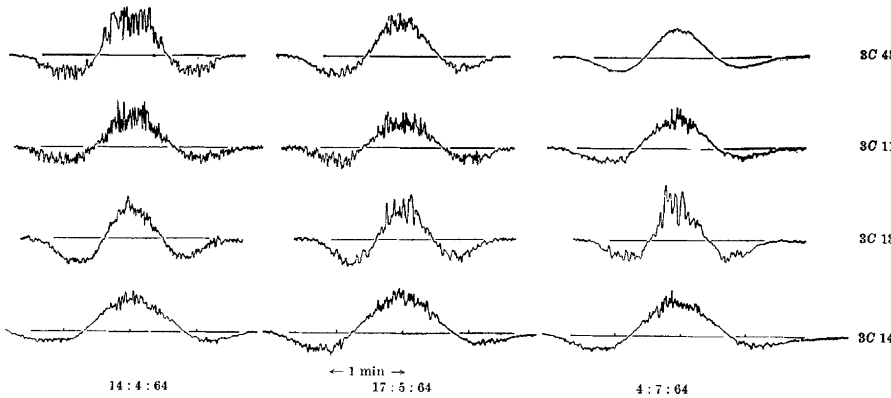

FIGURE 2. Illustrating the scintillation of compact radio sources as observed at different solar elongations (reprinted with permission from Macmillan Publishers Ltd.: A. Hewish, P. F. Scott, and D. Wills, "Interplanetary Scintillation of Small Diameter Radio Sources," *Nature* 203 [1964]: 1214–17).

plasma flowing out from the Sun, what is known as the solar wind. This wind had been predicted by Eugene Parker in 1958 and observed by the Soviet Luna satellites in 1959 and by the U.S. *Mariner*-2 satellite in 1962. The paper by Hewish, Scott, and Wills showed how radio source scintillations could be used to map the outflowing solar wind (A. Hewish, P. F. Scott, and D. Wills, *Nature* 203 [1964]: 1214–17).

Hewish realised that a large, low-frequency array dedicated to the measurement of the scintillations of compact radio sources would provide a new approach to the study of three important astronomical areas: (a) it would enable many more quasars to be discovered; (b) their angular sizes could be estimated; and (c) the structure and velocity of the solar wind could be determined. In 1965, he designed a large array to undertake these studies and was awarded a grant of £17,286 by the U.K. Department of Scientific and Industrial Research to construct it, as well as outstations for measuring the velocity of the solar wind. To obtain adequate sensitivity at the low observing frequency of 81.5 MHz (3.7 m wavelength), the array had to be very large, 4.5 acres (1.8 hectares) in area, in order to record the rapidly fluctuating intensities of bright radio sources on time-scales as short as one tenth of a second.

Jocelyn Bell joined the 4.5 acre array project as a graduate student in October 1965. She was involved in the construction of the telescope, including knocking the posts into the ground, and then became responsible for the network of cables connecting the dipoles. The telescope was commissioned during July 1967 with the objective of mapping the whole sky once a week so that the variation of the scintillation of the sources with solar elongation could be studied. The array consisted of

FIGURE 3. The 4.5 acre array (reprinted with permission from *40 Years of Pulsars —Millisecond Pulsars, Magnetars, and More*, edited by C. G. Bassa, Z. Wang, A. Gumming, and V. M. Kaspi. Copyright 2008, American Institute of Physics).

2,048 full-wave dipoles arranged in 16 rows of 128 elements. Each row was 470 m long and the north-south extent of the array was 45 m (fig. 3).

A key aspect of the array was that it had to be possible to measure the fractional scintillations of the radio sources in real time. Before the days of high-speed digital computers, this was achieved by electronic processing of the incoming signals, as illustrated in figure 4. On the strip chart, the top trace shows the intensity of the source as it passes through the beam of the telescope—note the fluctuating signal superimposed upon the shape of the telescope beam. This signal was then passed through a high-pass filter so that only the fluctuating component of the signal was registered, as seen in the central panel of figure 4. The noise power in the fluctuating component was then determined and plotted in the bottom trace.

While the array was being constructed, Leslie Little and Hewish had carried out a theoretical investigation of the strength of the scintillations as a function of heliospheric coordinates. They demonstrated how the angular sizes of the sources could be estimated from measurements of the amplitudes of the scintillations when sources were observed at

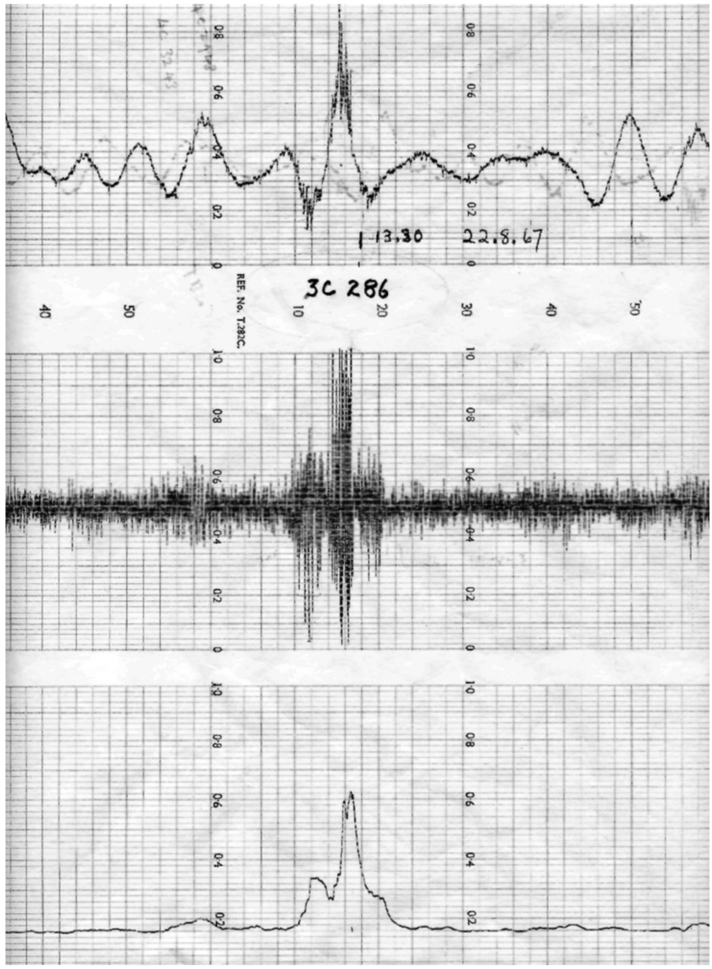

Figure 4. Illustrating the scintillations of the compact radio source 3C 286. The strong scintillations of 3C 286 can be compared with their absence in the other sources in the upper trace. The top trace shows the raw data, the middle trace the scintillating component, and the lower trace the power in the scintillations (reprinted with permission from *40 Years of Pulsars—Millisecond Pulsars, Magnetars, and More*, edited by C. G. Bassa, Z. Wang, A. Gumming, and V. M. Kaspi. Copyright 2008, American Institute of Physics).

different solar elongations (L. T. Little and A. Hewish, *Monthly Notices of the Royal Astronomical Society* 134 [1966]: 221–37). The key point is that the scintillations decrease to very small values when observed at large angles from the Sun, as they demonstrated in the plot of the scintillation index as a function of heliocentric coordinates. The term scintillation index means the ratio of the scintillating intensity to total intensity (fig. 5).

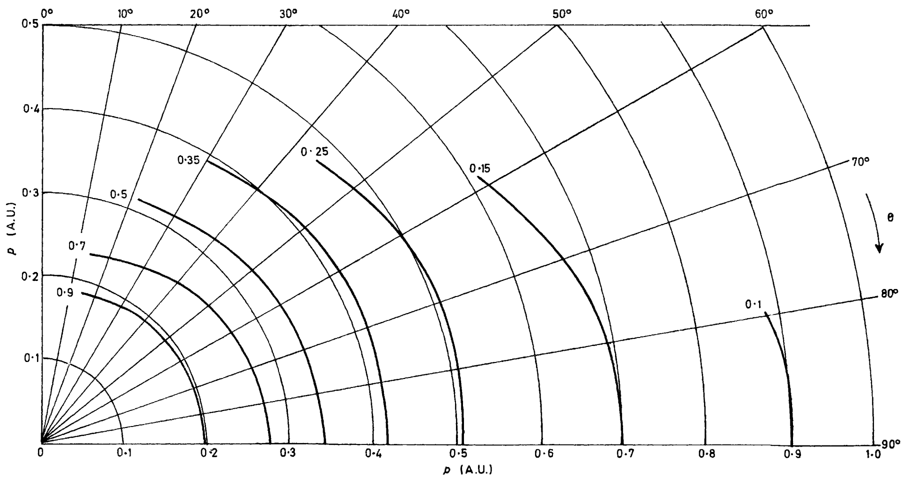

FIGURE 5. A plot showing the magnitude of the scintillation index as a function of heliocentric coordinates. The Sun is at zero coordinates in the radial direction (abscissa) and perpendicular to the ecliptic plane (ordinate) (L. T. Little and A. Hewish, *Monthly Notices of the Royal Astronomical Society* 134 [1966]: 221–37).

Hewish and Sam Okoye used the scintillation technique in 1964 to show that there is a compact low-frequency source in the Crab Nebula, very much smaller than the extent of the nebula itself (A. Hewish and S. E. Okoye, *Nature* 203 [1964]: 171). With the improved procedures developed by Little and Hewish, Bell and Hewish showed that the angular size and spectrum of the scintillating component could be determined (S. J. Bell and A. Hewish, *Nature* 213 [1967]: 1214–17). Remarkably, the compact source had an extremely steep radio spectrum, very much steeper than that characteristic of known radio sources. Although not known at the time, this compact source turned out to be the pulsar in the Crab Nebula.

Commissioning the 4.5 Acre Array and the Discovery of Pulsars

The commissioning of the 4.5 acre array proceeded through the summer of 1967. Hewish suggested that Bell create sky charts for each strip of the sky each day, noting all the scintillating sources. If the scintillating sources were present on successive weeks at the same astronomical coordinates, they were likely to be real sources, whereas if they were simply interference, for example caused by a nearby unsuppressed tractor, they would not recur at the same astronomical coordinates. This was a very demanding task requiring great persistence, patience, and

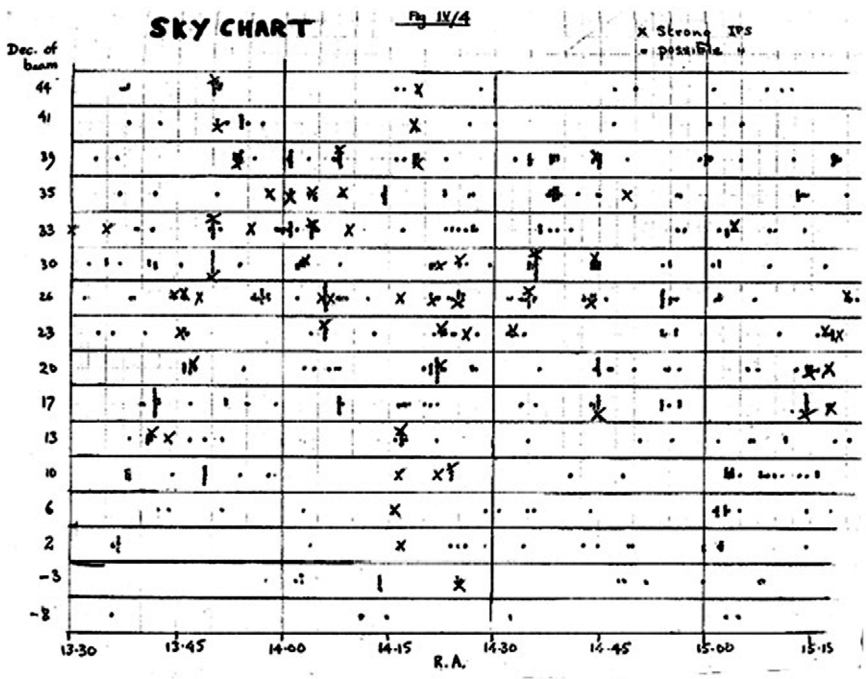

FIGURE 6. A example of one of Bell's maps of the sky showing the recurrence of genuinely scintillating sources (reprinted with permission from *40 Years of Pulsars—Millisecond Pulsars, Magnetars, and More*, edited by C. G. Bassa, Z. Wang, A. Gumming, and V. M. Kaspi. Copyright 2008, American Institute of Physics).

attention to detail on Bell's part since she had to keep up with the high rate at which the charts were being produced by the telescope (fig. 6).

The discovery of the pulsar CP 1919 was made by Bell on 6 August 1967 (fig. 7). The story of the discovery of pulsars is told in appendix 1 of Bell's Ph.D. dissertation, the first paragraph of which is shown in figure 8.

The remarkable feature was that the source was scintillating at roughly the 100% level in the anti-solar direction, quite contrary to the expectations of the scintillation models of Little and Hewish. Furthermore, the source was highly variable and not always present.

The source was not observed again until 28 November 1968, this time with a much shorter time-constant in the receiver system. With this improved time-resolution, the pulses were detected separately for the first time. To Hewish's astonishment, the signal consisted entirely of a sequence of pulses with repetition period 1.33 sec. This period was found to be stable to better than 1 part in 10^6.

The following two months were what Hewish described as the most

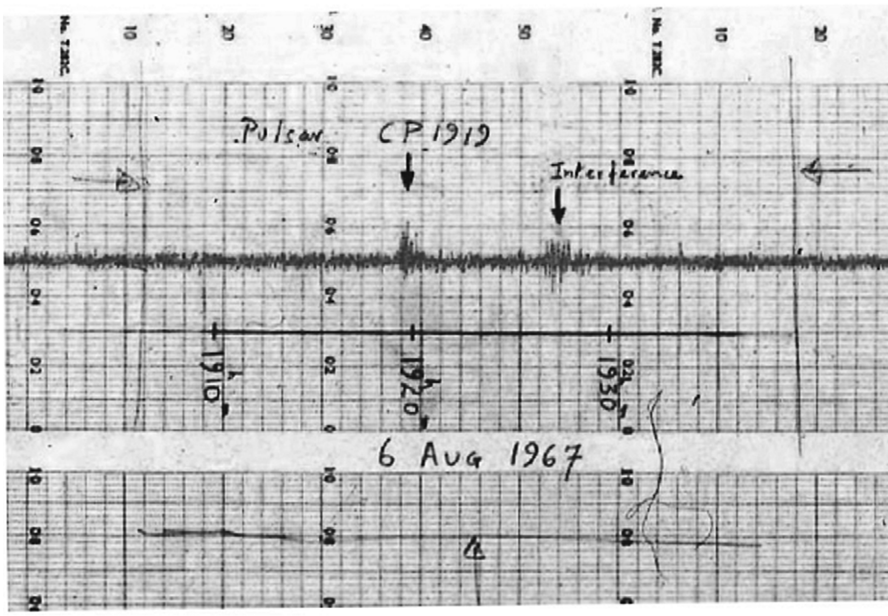

FIGURE 7. The discovery record of CP 1919 taken on 6 August 1967 (reprinted with permission from *40 Years of Pulsars—Millisecond Pulsars, Magnetars, and More*, edited by C. G. Bassa, Z. Wang, A. Gumming, and V. M. Kaspi. Copyright 2008, American Institute of Physics).

exciting of his scientific career. Nothing like this had been observed in astronomy before, and they had to be absolutely certain of the correctness of the observations. It was essential to carry out the following observations and experiments:

- All sources of terrestrial interference had to be excluded.
- If the source were associated with extraterrestrial emissions, including the notorious “Little Green Men” (LGM), the motion of a planet about the parent star would be easily detectable. The motion of the Earth about the Sun was observed, but no orbital motion of the source.
- The low-frequency signals displayed dispersion, the high-frequency signals arriving earlier than the low frequencies. This enabled a rough distance of 65 pc (about 200 light years) to be estimated for the source.
- Three other similar sources were discovered by Bell, including one with a period of only 0.25 seconds.

The discovery was kept under tight wraps until Hewish and his colleagues were absolutely convinced that they had discovered a new

Appendix 1. Pulsed Radio Sources.

Soon after preliminary analysis of the records started it was noticed that there appeared to be a source scintillating (interplanetary scintillation) on the declination 23° beam late at night. This was noteworthy because it was not expected that many sources would scintillate at such a great distance from the sun. If they did it would be because they were either strong sources (e.g. 3C sources) scintillating a little, or weaker sources with very small angular diameter, i.e. with high percentage scintillation. This was not a 3C source, so it was suspected that it was an extremely small angular diameter source (almost a point source). It is necessary to know the variation of percentage scintillation of a point source with distance from the sun for the measurement of angular diameters, and it was hoped that this source might provide this information.

FIGURE 8. The first paragraph of appendix 1 of Bell's Ph.D. dissertation (Cambridge University, 1968).

astronomical phenomenon. I was in the office next door to Hewish at the time as a member of the Radio Astronomy Group and I knew nothing about what was going on until he gave a lecture about the discovery in the week before the *Nature* paper was published. The paper, "Observation of a Rapidly Pulsating Radio Source," was submitted for publication in *Nature* on 9 February 1968 and published on 24 February 1968 (A. Hewish, S. J. Bell, J.D.H. Pilkington, P. F. Scott, and R. A. Collins, *Nature* 217 [1968]: 709–13).

Within a few months, Thomas Gold convincingly associated the pulsars with magnetised, rotating neutron stars. The radio pulses are caused by beams of very high-energy particles escaping from the poles of a magnetised rotating neutron star. When observations are made along the magnetic poles, an intense burst of radio emission is observed.

The Aftermath

Very soon after the discovery, large numbers of pulsars were discovered. By now, more than two thousand radio pulsars are known. They are of the greatest astrophysical importance as the last stable stars before collapse to a black hole ensues. The neutron stars represent matter in bulk at nuclear densities and offer many challenges for physicists and astrophysicists.

In 1972, neutron stars were discovered as the compact X-ray emitting sources in X-ray binary systems by Riccardo Giacconi and his colleagues from observations with the UHURU X-ray observatory. In these sources, the energy source is the accretion of matter from the normal primary star onto the poles of the neutron star.

In 1975, Russell Hulse and Joseph Taylor discovered that the pulsar PSR 1913+16 is a member of a binary neutron star system. This was a fabulous gift to relativists since it can be considered to be a perfect clock in a rotating frame of reference. The binary neutron star system loses energy by the radiation of gravitational waves. One of the great discoveries was the measurement of the speeding up of the binary due to this process. The remarkable agreement between theory and experiment shows that general relativity is the best theory of relativistic gravity we possess.

In PSR 1913+16, only one of the pair of neutron stars is observed as a pulsar, but in the remarkable binary system PSR J0737–3039, both neutron stars are observed as pulsars. This makes it possible to determine the parameters of their binary orbits very precisely. The binary period about the centre of momentum of the system is only 2.4 hours, so the effects of general relativity are even stronger than in PSR 1913+16. Thus, within a few years, this binary neutron star system will provide some of the most stringent tests of general relativity.

The discovery of the pulsars resulted in the award of the Nobel Prize to Hewish with Ryle in 1974. Hewish continued his outstanding work on the use of scintillation techniques to chart "interplanetary weather," work that is of the greatest current importance because of its impact upon the GPS system.

Bell has gone on to become a distinguished member of the U.K. scientific community. In June 2007, she was created Dame Jocelyn Bell-Burnell in the U.K. honours list. She is currently president of the U.K. Institute of Physics.