The following is respectfully submitted in support of the comment that I filed earlier today on ET 02-135. It concerns the role that radio astronomy played in tranforming our knowledge of the universe. It was adapted from a section of a draft revision for Chapter 2 of the ITU Handbook on Radio Astronomy.

A Whisper of Noise

Radio astronomy as a scientific discipline became possible in 1932 when Karl Jansky discovered the existence of radio waves of extra-terrestial origin. By 1928, when Jansky began to work at Bell Telephone Laboratories, it was becoming obvious that short wavelengths (less than 200 m) were superior for radio telephony because of lower atmospheric noise, greater bandwidth availability, and physically smaller structures. So Jansky was assigned the task of understanding the sources of interference. Jansky worked systematically and discovered that one of the sources of noise was the Milky Way galaxy. His report was the first hint of a radically different perspective on the universe that would transform astronomy.

In the beginning, progress was slow. During this pre-war decade, various professional astronomers became interested in cosmic radio waves, either by proposing theoretical explanations or dedicated radio antennas (or both) without success.

It was in fact another electrical engineer, Grote Reber, who started his career as Jansky was making his epochal but little-noticed measurements, who took the next steps in advancing radio astronomy. After reading Jansky's paper and discussing with him the idea of a paraboloid antenna, he built a 31-foot dish in his backyard in the summer of 1937. Improved technology allowed him to attempt detections at 9 and 33 cm wavelength, without success. Operating at night to avoid automobile ignition static, he was able to detect the Galaxy at 187 cm. In 1941, an improved receiver allowed him to observe the sun and a strong radio source in Cassiopeia.

In general, World war II delayed further progress in radio astronomy. However, the war also produced some very talented radio research groups in Australia, Canada, England, and the United States, an abundance of new technology, and very suitable surplus military equipment.

One of the puzzles in astronomy during the mid-century was whether the universe was expanding (Doppler shifts of optical spectral lines of galaxies certainly appeared to indicate that) or whether it was static and timeless. In the former case, the universe was once in a compressed state similar to that found in nuclear explosions, the theory of which was being vigorously pursued. In 1946, such calculations led to the first prediction of the current brightness temperature of the cosmic background -- 10 K. The same year, a measurement was made to set an upper limit of 20 K. It would take almost two decades before radio receivers became sensititive enough to measure this cosmic noise.

During 1964, a group at Princeton was developing a 1.5-cm receiver to measure the cosmic background. Thirty miles away, at Bell Telephone Laboratories, Arno Penzias and Robert Wilson were trying to track down excess noise in a low-noise 7-cm receiver used for absolute calibration of radio sources. A persistent antenna temperature contribution of 3.5 K, independent of direction, could not be explained. Through colleagues at the Department of Terrestrial Magnetism in Washington, they became aware of the work at Princeton and, more importantly, the scientific driver. Their excess noise became a scientific blockbuster. In a charmingly gentlemanly fashion, their Princeton colleagues' confirmation (3.0 K) was published in the same journal issue.

In 1978, Penzias and Wilson were awarded the Nobel Prize in Physics "for their discovery of cosmic microwave background radiation."

The Sky Transformed

Dedicated radio telescopes were built during 50s and 60s, and many surveys were carried in an exuberance of exploration. It became quickly evident that the sky looked very different at radio wavelengths. Still one of the most famous of those surveys is the Third Cambridge Survey, which gave names to many sources, of which 3C84 and 3C273 played a special role.

The immediate and obvious thing to do with all these new radio sources was to identify them optically. This was a great challenge because the radio telescope beamwidths were so large as to include innumerable candidates. Two approaches were taken. In Australia, a program was begun in the late fifties to use the edge of the moon to measure the size and position of radio sources. At Caltech, a two-antenna interferometer was built to tackle the same problem in a different way. Starting in 1960, a number of radio sources were identified with with faint star-like objects whose optical spectra were unlike any known stars. Some had strong spectral lines of some apparently unknown element. They became known as quasi-stellar objects. Maarten Schmidt recalls that the moment of inspiration came to him on February 5, 1963. The mysterious spectral lines in 3C 273 were due to hydrogen, with a redshift of 0.16. His Caltech colleague Jesse Greenstein had the data for 3C 84, and within minutes its redshift was found to be 0.37. These radio sources, soon to be known as quasars, lay at the very edge of the detectable universe.

"Little Green Men"

As Cambridge was conducting its fourth survey, it was brought to the attention of Anthony Hewish that some of the radio sources appeared to be scintillating. The effect, similar to the twinkling of stars, had to be due to irregularities in the solar wind streaming out through the solar system. This offered two possibilities. One was to infer the sizes of radio sources by the degree of scintillation they showed. The other was to study the structure of the interplanetary medium. Hewish submitted a proposal to build a 4.5 acre radio telescope at 81.5 MHz for the purpose of studying interplanetary scintillation.

Part of the array became operational in 1967. A graduate student on the project, Jocelyn Bell, was the first to notice that some sources had an unexpected signature. Some months went by before they were able to capture the signal on a fast chart recorder, which showed a periodic pulse structure. At the time, the only known sources of such clock-like regularity were human, but that possibility was ruled out: Hewish quickly established that the phenomenon kept sidereal time (that is, followed the stars). Being apparently man-made but coming from the stars, it was perhaps inevitable that these sources were dubbed "Little Green Men". The new phenomenon was quickly published, though without this explanation. Even before the paper appeared Fred Hoyle, while listening to a seminar given by Hewish, calculated that these sources were supernova remnants.

In 1974, Hewish was awarded the Nobel Prize in Physics "for his decisive role in the discovery of pulsars." Credit for coining the term "pulsar is claimed by then science correspondent of the Daily Telegraph.

In the same year that Hewish was awarded the Nobel Prize, Joe Taylor and his graduate student Russell Hulse observing at Arecibo Observatory discovered a pulsar which from its timing signature was found to be in a tight binary orbit with another pulsar of approximately equal mass. They recognized this as an exceptional laboratory for studying Einstein's General Theory of Relativity. For example, by measuring the timing for just four years, it was found that the binary pulsar period slowed at a rate that agrees very well with the prediction that the system radiates gravity waves.

In 1993, Hulse and Taylor were awarded the Nobel Prize in Physics "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation."

Chemistry between the Stars

World War II stimulated theoretical astronomy in the Netherlands. In this low, cloud-covered country, observational astronomy requires foreign travel, which was restricted as to be essentially impossible. Jan Oort, the leading astronomer for many decades, made the suggestion that led student Henk van de Hulst to predict in 1944 that emission from atomic hydrogen (HI) should be detectable at 21 cm wavelength. Hydrogen was certainly far and away the most abundant element in stars and by any reasonable theoretical model should be the most abundant gas in the Galaxy. This led to a race to detect HI emission, won in 1951 by a narrow margin by a team at Harvard, followed within two months with a confirmation by a Dutch team.

HI proved to be enormously useful, providing us with the first image of our Galaxy as it appears from outside. Eventually, it would provide us with the first whiff of the still enigmatic "dark matter".

As early as 1940, there was a hint that there might be more than HI in the voids between the stars, in the possible association between CH radicals and a visual absorption line at 387.46 nm. Laboratory radio studies of molecules were already being carried at microwave wavelengths, so it was an obvious pursuit for radio astronomers. An attempt to detect OH was made as early as 1957, but unsuccessful because accurate laboratory-measured frequencies were not yet available. OH was detected in space in 1964. This heralded an avalanche. Water vapor was reported in 1968; ammonia and formaldehyde were reported in 1969; the first millimeter wavelength detection, of carbon monoxide, came in 1970. As of April 2002, 123 interstellar or circumstellar molecules were known.

The existence of such a rich variety of molecules in space gave rise to a new theoretical discipline of interstellar chemistry. However, even more amazing, it ultimately gave rise to a new field of laboratory chemistry.

In 1971, cyanoacetylene (HCCCN) had been detected. This intrigued English physical chemist Harry Kroto. While working in Canada, he and his colleagues undertook the production of longer carbon chains and measured their frequencies. He joined forces with a team of radio astronomers and in 1975 they detected cyanodiacetylene (HCCCCCN). In 1977, they found cyanohexatriyne (HCCCCCCCN). Cyano-octatetra-yne (HCCCCCCCCCN) was found later in the same year. HCCCCCCCCCCCN was found in 1982 in the envelope of a carbon-rich star.

In order to attempt to understand what other carbon species might form under such conditions, Kroto teamed up with another group of physical chemists who had equipment that could simulate such conditions. To their amazement they found spheroidal structures of carbon, starting with the spherical molecule consisting of 60 carbon atoms, which they dubbed "buckminsterfullerene". (Think of the vertices on the surface of a soccer ball). Because of the amazing properties of these materials (tensile strength greater than steel, for example), a new field of chemistry rapidly developed.

In 1996, Kroto, along with Robert F. Curl, Jr., and Richard E. Smalley, was awarded the Nobel Prize in Chemistry "for their discovery of fullerenes."