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Non-thermal radio astronomy

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ABSTRACT

This presentation starts with Karl Jansky's discovery of cosmic radio emission in 1933 and notes the striking similarities to Hess's discovery of cosmic-rays in 1912. At first it was assumed that this radio emission was thermal but in 1939 Grote Reber discovered that it was stronger at longer wavelengths, requiring a non-thermal emission process. These discoveries had a revolutionary impact on astronomy and *radio astronomy* was born.

The interpretation of this non-thermal radiation as synchrotron emission from high energy particles in the interstellar medium did not occur until the late 1940s but then it provided the link between radio astronomy and cosmic-ray research. Ginzburg, in particular, saw that cosmic-ray astrophysics was now possible using radio waves to trace sources of cosmic-rays.

We discuss the discovery of extragalactic active galactic nuclei leading to the discovery of quasars and the first evidence for black holes in the nuclei of galaxies. We summarise the present status and future of some of the main radio telescopes used to image the non-thermal emission from external galaxies.

Finally, we include a short description of the use of radio signals for the direct detection of cosmic-rays and UHE neutrinos.

1. Beginning of radio astronomy

In the course of trying to identify the source of interference to trans-Atlantic telephone communications Karl Jansky, working at the Bell Telephone Laboratory, discovered cosmic radio emission in 1933 [1]. An unexpected source of noise (Jansky's Cosmic Hiss) was peaking each day but the peak signal arrived 4 min earlier each day and Jansky realised that this corresponded to sidereal (star) time and hence it must have extraterrestrial origins. The reaction from Bell Labs was underwhelming. As Grote Reber later remarked: "so faint it didn't even constitute an interesting source of radio interference!" Once he had determined that the interference was "of extraterrestrial origin" there was little support from the Bell Telephone Laboratory to further pin down the location in space. Sullivan [2] has noted that while a few astronomers expressed interest at the time, for the majority the engineers' world of decibels and superheterodyne receivers was too far removed from their world and Jansky had died before the importance of his discovery was appreciated. Although the scientists ignored Jansky's discovery, in December 1938 science fiction writer Edmond Hamilton wrote "The Cosmic Hiss" based on Jansky's observation of cosmic hiss [3].

1.1. Karl Jansky and Viktor Hess

There are some striking similarities between the discovery of cosmic-rays by Viktor Hess in 1912 and the discovery of cosmic radio emission by Karl Jansky 21 years later in 1933.

- Both Jansky and Hess started a new field of research.
- There was no equivalent to the residual radiation which was being explored by Viktor Hess and others so Jansky's role in the discovery of extraterrestrial radio emission was unambiguous.
- Karl Jansky was employed as an engineer; he had a physics background but was not an astronomer. Viktor Hess was an atmospheric electrician; he was neither a particle physicist nor an astronomer.
- Jansky deduced the extraterrestrial origin from his observations and showed that the emission was coming from the galaxy. Hess deduced the extraterrestrial origin of cosmic-rays and also showed they were not of solar origin.
- Both scientists were ignored, or even refuted, by most of the experts in their respective fields. In both cases there was no existing framework for the discovery. It was the wrong time!
- Both these discoveries were enabled by technology developments and both had built their own instruments and both had a deep understanding of the technical issues.

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- Both lived in the New York area for the latter part of their careers but since the connection between cosmic-rays and cosmic radio emission was not made until after Jansky died it is unlikely that they knew each other.

1.2. Non-thermal radio emission

In 1937 one successful amateur radio ham, Grote Reber, undertook the challenge to understand what Jansky had found. He built a home-made $2000 32 foot parabolic dish in his mother's backyard in Wheaton, Illinois, and started looking for the radio signals discovered by Jansky. At first he looked at shorter wavelengths than used by Jansky because the only type of natural radio emission known was thermal and thermal radio emission would be stronger at shorter wavelengths. But nothing was seen at the shorter wavelengths so Reber changed to longer and longer wavelengths until he finally detected a signal similar to that seen by Jansky [4]. This radio emission was stronger at longer wavelengths so had to be of non-thermal origin but there was no concept of non-thermal astronomical emission at any wavelength so things were even more puzzling. It was not until 13 years later in 1950, when the synchrotron radiation from high energy particles in space (cosmic-rays) was understood, (see Section 3) that these results could be integrated into the larger scientific world view and the strange world of extra-terrestrial radio noise became part of astronomy [5].

2. The story of the radio stars, quasars, and black holes

2.1. Cygnus A, strongest radio source in the sky

In 1946 Stanley Hey, one of the co-discoverers of radio emission from the sun in the UK during World War II (WWII), found that one of the strong sources of radio emission was fluctuating on time scales of 10–30 s [6]. He correctly concluded that the source must be small diameter. It was later realised that the fluctuations were ionospheric scintillations and not intrinsic but the small diameter argument was still correct [7]. This was the size of a star but there was no optical counterpart so what was it? Was all the Galactic radio emission the sum of such *radio stars*?

2.2. The cliff interferometer and the discovery of the radio galaxies

In 1946 at Dover Heights near Sydney a telescope was constructed on the cliff to measure the interference between the direct waves and those reflected by the sea (a Lloyd's mirror). This cliff interferometer was built to locate the origin of the solar radio emission and to identify the radio stars. The idea of a cliff interferometer came from multiple path interference already seen in shipborne radar in WWII and used to improve positional information. John Bolton and his colleagues [8] at CSIRO in Australia were able to measure positions accurately enough to identify three of the strongest of the mysterious discrete sources of radio emission which up until this time were thought to be radio stars. One was the Crab nebula, the remnant of a star that the Chinese had seen explode in 1054 AD. The other two were an even greater surprise. Centaurus A and Virgo A (strongest sources of radio emission in the constellations of Centaurus and Virgo) had conspicuous bright optical identifications which were galaxies – not stars! Galaxies, far outside our own milky way but undergoing such a violent explosion that they were among the brightest objects in the radio sky and became the most luminous sources known in the universe. This discovery, with some help from the now very enthusiastic optical astronomers at Mt Palomar in the US, led to the eventual identification of the strongest of all the radio sources, Cygnus A. It was found to be a very faint galaxy so distant that it was obvious that the radio telescopes were already probing the most distant reaches of the universe!

3. Synchrotron radio emission from cosmic-ray electrons

3.1. What was the non-thermal radio emission?

This is a very confusing story, and the misinterpretation of the early radio data added to the confusion. Some radio sources were thought to have small diameter [6] which was correct but it was incorrectly assumed that all the diffuse radio emission observed from the galaxy was the sum of all these *radio stars*. It was also assumed that the *radio stars* were like the sun but this was also incorrect; they were a mixture of galactic nebula (SNR) and extra galactic sources (AGN).

3.2. Synchrotron radiation

In 1949 Fermi had explained the acceleration of cosmic-rays particles in the interstellar medium [9] but at that time no one connected these high energy particles to the cosmic radio emission even though Langmuir had observed and explained the synchrotron radiation seen in the General Electric synchrotron in 1947 [10].

3.3. Synchrotron model for radio emission

In 1949 Unsold interpreted the anomalous non-thermal radio emission from sunspots as plasma oscillations [11]. Alfvén suggested that this anomalous radio emission from sunspots was synchrotron radiation [5] and in 1950 Kiepenhauer went further and suggested that the galactic radio emission could be generated by the synchrotron process in the interstellar medium (ISM) rather than in stars [12]. He recognised the existence of an interstellar magnetic field and assumed that cosmic-rays included relativistic electrons. This interpretation was mostly ignored in the West but enthusiastically embraced in Russia by Ginzburg and by Shklovsky since there was clear evidence for both the magnetic field and the cosmic-ray particles. At this time most astronomers in the West were unaware of the importance of cosmic-rays.

3.4. Linking non-thermal radio emission and cosmic-rays

Ginzburg argued in 1951 that synchrotron radiation by relativistic electrons in Galactic Magnetic fields "is very natural and attractive as an explanation for the general radio emissions of the Galaxy" [13]. In 1953 Shklovsky published his seminal paper explaining the radiation from the Crab nebula as radio and optical synchrotron emission [14]. In 1957 Burbidge noted that the jet in the radio galaxy M87 could be explained by synchrotron at radio and optical wavelengths [15]. By this time the radio synchrotron emission was well accepted for the galactic supernova remnants and for the extra-galactic sources so the pieces of the non-thermal radio synchrotron puzzle were falling into place.

3.5. Cosmic-ray astrophysics

Ginzburg [16] commented that cosmic-ray astrophysics was born in the early 1950s when it became possible to observe cosmic-rays far from the Earth using the non-thermal continuum radio emission from the synchrotron process [16]. The Crab Nebula and the first radio galaxies had been identified. Because radio waves propagate rectilinearly, the reception of cosmic radio emission provides a tool to obtain information about the electron component of cosmic-rays at a distance from the Earth, in our Galaxy,