Synchrotron radiation, a basis of modern astrophysics

Richard Wielebinski

Max-Planck-Institut für Radioastronomie, Bonn

The classical case of a relativistic electron emitting in a magnetic field was treated by G.A.Schott in 1912 already. Synchrotron emission was detected in the new electron accelerators in the 1940s as blue light seen when the beam entered the Earth's magnetic field. This led to considerable activity in the studies of synchrotron emission; notably by J.Schwinger in the USA. The serendipitous discovery of cosmic radio waves by K.Jansky in 1932 at first had no explanation. Also the extremely intensive Solar radio waves, observed by war-time radar stations, defied explanation. Only in the late 1940s the connection between cosmic radio waves and synchrotron emission could be established. This was preceded by the discovery of magnetic fields in the Milky Way. The synchrotron emission requires such magnetic fields and is observable as polarized emission. The rapid growth of radio astronomy is directly a result of the fact that cosmic objects emit intense radio waves through the synchrotron emission process. The radio waves come not just from nearby objects but from a huge variety of cosmic sources, many at the edge of the observable Universe. Radio galaxies are synchrotron sources emitting as a result of jets that are powered by active galactic nuclei interacting with the intergalactic medium. Supernovae leave remnants where the interaction of a magnetic field with the interstellar medium is obvious. The Milky Way is a giant synchrotron emitter. Quasars are often first identified as weak synchrotron radio sources before they are fixed in the distance by optical spectroscopy. In this lecture I will describe the most recent advances in our knowledge of the cosmic Universe, thanks to the synchrotron emission process.

Synchrotron radiation is the most important emission process in astrophysics, but it was a long and difficult way to make it acceptable to astronomers who were used to positional astronomy, stellar interiors and at most thermal emission from the interstellar medium. The detection of radio waves of extraterrestrial origin by K.Jansky in 1932 was widely publicized by the daily press but not taken up seriously by professional astronomers. The Bell Telephone Company engineer K.Jansky realized that the radio emission was connected in some way with the Milky Way. The next lone investigator, Grote Reber, followed up these early detections and started to investigate the radio emissions at different frequencies. Reber concluded that the observed radio emission could not be due to black-body (thermal) radiation from the interstellar medium. Reber also discovered that the maximum of the radio emission came from the direction of the constellation Sagittarius, some 30° away from the then accepted centre of the Milky Way. Solar radio emission was discovered by war-time radar station operators in the 1940s who were surprised at the intensity of the radio waves. It became also clear that solar radio emission was highly variable, correlated with visible eruptions and with the solar cycle. All the observed radio emissions called for a new interpretation.

The classical theory of an electron emitting in a uniform magnetic filed was treated by Schott in 1912 already. Synchrotron emission was detected in the new electron accelerators in the 1940s. The theory of synchrotron radiation was developed by J.Schwinger in the USA and a strong group of Soviet theoreticians. The theoretical explanation of the origin of the Solar radio emission was given by A.Unsöld who concluded that the steady radio emission of the Sun may be due to free-free (thermal) transitions in the solar corona and the chromosphere but the variable radio emission of the Sun must be non-thermal, some sort of 'plasma oscillation'. The radio emission of the Milky Way was to Unsöld of the same nature as the variable solar emissions. At this stage of observational progress 'radio stars', strongly emitting cosmic sources were discovered and it was suggested that this new population of celestial objects may be responsible for the cosmic radio emission. Theoretical considerations by H.Alfvén suggested that radio stars may be radio emission generated by electrons in magnetic fields, a suggestion that pointed to the presence of synchrotron radiation in cosmic sources. K.O.Kiepenheuer went into the details of possible scenarios, and concluded that radio stars are less likely to be a source of the 'background emission' but that interstellar space, when filled with magnetic fields, could generate the observed radio intensities. By 1950 the basic explanation was given and waited for observational confirmation. The understanding of polarization effects of synchrotron emission was paramount in the following development since it offered new ways of observing. The most concise reviews about synchrotron radiation in astrophysics are due to Viatli Ginzburg and A.G.Pacholczyk.

Magnetic fields have been detected in Solar sunspots by G.E.Hale in 1908 by observing the Zeeman splitting of optical spectral lines. Improved sensitivity allowed the detection of magnetic fields in 'magnetic' Ap stars using the same method. In 1949 optical polarization observations by W.A.Hiltner and J.S.Hall were published. In 1951 L.J.Davis & J.L.Greenstein developed an interpretation that suggested that the optical polarization was due to dust grains aligned by magnetic fields of the Milky Way. Thus one of the requirements for synchrotron radiation, the presence of cosmic magnetic fields, had been established.

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The Crab nebula played the crucial role in the progress of understanding the radio emission, a triumph of the synchrotron theory. I.Shklovskii suggested that the emission (optical and radio) of the Crab Nebula is due to the synchrotron process. This was motivated by observations of linear polarization of the Crab nebula optical emission made very early by Soviet astronomers. The search for the radio polarization was a logical consequence. After several negative attempts a detection of linear radio polarization at high radio frequencies was made in 1957. Another object that was important in the earliest days was Virgo A (M87). This is a peculiar galaxy with a jet and a very intense radio emission. G.R.Burbidge proceeded to interpret both the optical and radio emission to be a result of synchrotron radiation in strong magnetic fields. This object became the prototype of a 'radio galaxy' where due to an active galactic nucleus (AGN) intense radio (synchrotron) emission results in the outer lobes. To support this argument, the discovery of linear polarization in the radio galaxy Cygnus A in 1962 was most important. Further surveys of the polarization of radio sources were made, indicating the presence of synchrotron emission everywhere.

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The origin of the observed magnetic fields has been unknown. Early work of Ludwig Biermann in 1950 suggested a ‘battery’ mechanism for the generation of magnetic fields. However the intensity of ‘battery’ fields was negligible. The development of the Dynamo theory by Parker, Krause, Steenbeck and others offered the possibility of field amplification by substantial factors. One of the requirements of the theory, the existence of ‘seed fields’, was missing. Recent work suggests that the early cosmic universe or plasma instabilities may provide the seed field necessary to account for the observed field strengths in cosmic radio sources, thus closing the loop in interpretation. In addition extensive magnetohydrodynamic simulations became possible showing the effects of magnetic fields on interstellar matter.

The majority of radio sources in the cosmic universe emit by the synchrotron process, especially at the lower radio frequencies in the metre and cm wavelength range. Most of the sources are linearly polarized to a degree of 1% to 75%. The highest polarization is observed in thin regions away from depolarizing thermal clouds (depolarization due to the Faraday effect). The observations of linear polarization can be used to determine the magnetic fields in the emitting objects. The increase in the angular resolution and better sensitivity of modern radio telescopes helps in delineating the polarized regions. Circular polarization is much lower, 0.1% – 2%, seen in some special sources like BL lac objects, Active Galactic Nuclei, etc. Other forms of radio emission are thermal emission from hot gas clouds or from cold dust and maser emission in e.g. molecular clouds or pulsars. Synchrotron emission has been detected from the most distant quasars, implying the presence of magnetic fields in the early universe and making it the most important probe of cosmic evolution.

The data on the synchrotron radiation in astrophysics have gone through an enormous development. While at the beginning of observations in the 1950s angular resolution of the single dish radio telescopes was counted in degrees, we now have observations with the resolution of sub-arc seconds done with aperture synthesis arrays. Radio astronomers can compete in angular resolution with the Hubble Space Telescope. The technique of very long baseline interferometry (VLBI) has taken the angular resolution down to milli-arc seconds and is posed to improve this to micro-arc seconds. This allows radio astronomers to probe the inner nuclear regions of galaxies. The sensitivity of the radio observations, which started with the detection of sources of several JANSKY (1 Jy = 10^{-26} watts meter^{-2} Hz^{-1}), has trough improvements of the receivers and telescopes now reached the sensitivity in the microJy range. The frequency coverage of radio telescopes now spans a huge spectral range from meter to sub-mm wavelengths. New radio telescopes like the ALMA and LOFAR (under construction) or the SKA project (planned) will improve the angular resolution even further at the same time offering huge increase in sensitivity. We can expect more exciting observations as a result of these new instruments and the synchrotron emission process.