The Characteristics of (Normal) Pulsars

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Abstract. Pulsars have now been studied for 34 years. We know of the existence of some 1500 objects at radio frequencies. Many of the characteristics of pulsars such as pulsar period, period derivative, spectrum, polarization, etc., have been catalogued for many objects. Still we do not know the details of the pulsar emission mechanism. The present review will give an up-to-date description of the characteristics of (normal, slow) radio pulsars. Millisecond pulsars will be dealt with by M. Kramer (this volume).

1. Introduction

The discovery of pulsars by Hewish et al., made at the low radio frequency of 81.5 MHz, stunned the astronomical community. In the discovery paper the authors speculated already on the possibility that we had either white dwarfs or neutron stars showing the pulsations. Virtually every radio telescope around the world was observing pulsars in 1968. Many of the important parameters of pulsars like the exact period, the period derivative, pulse shape, the polarization and spectrum were determined in the earliest papers already. Also the Galactic distribution of pulsars was found after the discoveries with the Molonglo telescope (Large et al. 1968a) increased rapidly the number of known objects. The Pulsar – Supernova correlation was suggested by the discovery of PSR 0833−45 near the Vela X SNR (Large et al. 1968b) and conclusively confirmed by the discovery of the pulsar in the Crab nebula (Clonella et al. 1969; Zeissig & Richards 1969). This gave the theory of pulsar formation great impulse. The measurement of the pulsar polarization in PSR 0833−45 by Radhakrishnan & Cooke (1969), that showed a vector sweep, finally clinched the argument that we were observing the magnetic poles of a rotating neutron star. Further important discoveries at radio frequencies were the binary pulsar (Hulse & Taylor 1975), the millisecond pulsar (Backer et al. 1982) and the planets around a pulsar (Wolszczan & Frail 1992).

The early discoveries made way to large search programmes and to surveys of pulsar characteristics. All the large radio telescopes have been involved in finding new objects. In particular, the recent Parkes multibeam survey (e.g. Manchester et al. 2001), led to the discovery of more than 600 new pulsars. To determine the pulsar spectra we require the collection of data over a wide frequency range. In this area the Effelsberg radio telescope was most prominent since it was the only instrument able to observe pulsars at high radio frequencies. Pulsar polarization is a very important parameter that has to be known for any serious emission theory discussion. This was observed by many telescopes but also in particular in Effelsberg. Pulsar emission shows many details, like drifting sub-pulse emission, pulsar modes or microstructure. I will not discuss these details because of lack of time. I will concentrate on pointing out what I consider to be the important connections of known pulsar parameters. Towards the end of this talk I will describe some promising new avenues of observational pulsar research.

2. Pulsar period

The periods of pulsars are remarkably stable, in the range 0.0015 sec to 8.51 sec. The pulsar period has been found to change (increase) as a result of loss of rotational energy. This period derivative P(dot) is a very important parameter for the determination of the pulsar age. The ‘normal’ pulsars are found in the period range of 0.03 sec for the Crab pulsar and up to 8.51 sec for PSR J2144−3933 (Young et al. 2000). The peak of the period distribution of pulsars lies around 0.7 sec. A second population of pulsars, the millisecond pulsars, is to be found in the period range 1.558 millisec to 20 millisec. These objects have very small period derivative and are considered to be ‘recycled’ pulsars. These are the best clocks in the universe.

3. Pulse shapes

One of the very characteristic parameters of a radio pulsar is its pulse shape. The pulse shape is due to the emission region that is close to the magnetic pole in a dipolar magnetic field of the rotating neutron star. This emission region sweeps past the observer giving, depending on the
Fig. 1. Pulse shape of PSR B0355+54 aligned by timing

Fig. 2. Pulse shape of PSR B1642−03. Note the unusual frequency evolution of this pulsar

giving multiple (non-integral) periodicities. The description of all these effects becomes even more complicated when one considers the evolution of pulse shape with radio frequency. The general evolution is to a narrower pulse shape at higher radio frequencies that is often cited as the Radius–to–Frequency mapping. At higher radio frequencies emission is thought to come from regions closer to the neutron star surface. A large collection of pulse shapes is to be found in Seiradakis et al. (1995) and in Kijak et al. (1998). The evolution of pulse shape with frequency is documented in Sieber et al. (1975), Kramer et al. (1997) or Kuzmin et al. (1998). I present the pulse shapes for the pulsars 0355+54 (Fig. 1) and 1642−03 (Fig. 2) to illustrate the different evolutions of pulse shape with frequency. Finally there are moding pulsars where a stable pulse shape changes for some time to an abnormal mode, returning to normal after an unpredictable length of time.
4. Pulsar spectra

Observing at five frequencies (four of them simultaneously) with the Parkes telescope, Robinson et al. (1968) established the spectrum of CP1919+21 from 85 MHz to 2.7 GHz. This ‘classical’ spectrum showed a steep spectral index at decimeter wavelengths (\(\alpha \sim 1.5\)) with a spectral break with the spectral index increasing to \(\alpha \sim 3.0\) at the highest frequencies. The continuation of gathering of data at many frequencies was a prerequisite of determining pulsar spectra. Here a serious problem must be mentioned, namely that there are huge flux variations due to interstellar scattering, but possibly also due to internal variations in the pulsar emission. Pulsars with high dispersion measure exhibit particularly strong ‘fading’ at high radio frequencies. To determine a flux of a pulsar at a frequency repeated observations are necessary. In spite of these difficulties several large data sets are available (e.g. Malofeev et al. 1994; Lorimer et al. 1995; Toscano et al. 1998; Maron et al. 2000). The older data on pulsar spectra were derived for flux density measurements in the frequency range 85 MHz to 1400 MHz. The newer data have extended the spectra of hundreds of pulsars up to 4.8 GHz and down to 102 MHz. For the strongest objects data are available at 10 GHz and even at mm wavelengths. Here a surprise has been found: the spectrum of some pulsars did not continue fall but showed a surprising ‘flattening’ or even ‘turn-up’ (e.g. Wielebinski et al. 1993; Kramer et al. 1997). The spectra of eight strongest pulsars with detected flux values at mm wavelengths are shown in Figure 3. One pulsar could be detected at 87 GHz (Morris et al. 1997). A change in the pulsar emission mechanism?

5. Pulsar polarization

The earliest observations (e.g. Lyne & Smith 1968) showed that sub-pulse components had very high degree of polarization. At first it was only the linear polarization that was studied showing the characteristic position angle sweep that indicated rotating objects. Later circular polarization was also detected (e.g. Manchester 1971). A surprising result was the observation by Manchester et al. (1973) that pulsar polarization remains high up to some critical frequency and then falls rapidly. Orthogonal polarization modes were postulated (e.g. Manchester 1975) based on the observation that in some pulsars the position angle sweep has jumps of \(\sim 90^\circ\). Recent surveys of integrated polarization of pulsars at many frequencies (e.g. von Hoensbroech & Xilouris 1997; Gould & Lyne 1998; Weisberg et al. 1999; von Hoensbroech 1999) showed us the great diversity in polarization morphology. A type of pulsar has been discovered (von Hoensbroech 1999) in which the linear polarization falls to high frequencies with a corresponding increase of circular polarization. This was interpreted as a propagation effect (von Hoensbroech & Lesch 1999). The early conclusion that the linear polarization drops suddenly after reaching some critical frequency has been confirmed. This is shown in Figure 4. This drop in linear polarization seem to occur when the spectrum (compare Figures 3 and 4) of the pulsar changes. Does the loss of coherence (polarization) occur when another emission mechanism (incoherent one) begins to dominate?

6. Discussion

In this talk many of the integral characteristics of pulsars were discussed. I presented a summary about pulsar periods, their spectra, the polarization and pulse shapes. I have not dealt with the characteristics of millisecond pulsars since they are presented elsewhere in this volume. I want to bring to your attention the importance of studying single pulses at many frequencies simultaneously. Such observations require the use of many telescopes simultaneously. A contribution by Karastergiou (this volume) describes recent four-station experiments. The single pulse data, with full polarization, taken over a wide frequency range may hold the key to understanding the pulsar emission process. Also the extension of pulsar observations to yet higher radio frequencies (into the sub-mm wavelength range) may finally allow us to ‘join’ the radio to infrared spectra and hence understand how pulsars work.

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Fig. 3. The spectra of eight pulsars detected at mm-wavelengths

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Fig. 4. The polarization of the eight pulsars shown in Figure 3. Note the sudden break in polarization and the corresponding change in the spectrum