Part I

Structure of the magnetic field

Monday morning. Co-chairs: Tim Hankins and Arcadii Kuz'min

- What is the structure and orientation of the pulsar magnetic field?
    - ⋆ Structure of the magnetic field
        - ∗ Observations of pulsar profiles that pertain to the structure of the magnetic field.
        - ∗ Significance of microstructure-determined dispersion measures as a guide to the alignment of multi-frequency profiles.
        - ∗ Orientation of the magnetic field relative to the rotation axis.
        - ∗ Pulsar interpulses and other observations that pertain to the orientation of the magnetic field.

The first session of the Colloquium was opened by a review paper, entitled, **Observational constraints** on the pulsar magnetic field, *presented by the session co-chair, Dr. Arcadii Kuz'min.*

OBSERVATIONAL CONSTRAINTS ON THE STRUCTURE OF THE PULSAR MAGNETIC FIELD

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Introduction

The most widely adopted model of pulsar radio emission is the hollow cone model, which fits much of the experimental data. The pulsar radio emission in this model is curvature radiation of relativistic particles flowing from the magnetic poles of the neutron star along a cone of open magnetic lines. The curvature radiation is amplified at the plasma frequency, therefore different radio frequencies f originate at different radii r of the emitting regions. In a dipole magnetic field this dependence is

$$f(r) \propto r^{-3/2}. \tag{1}$$

The observed radio emission is pulsed because of the neutron star rotation; the emitting cone scans the observer like a rotating lighthouse. The temporal distribution across this scan represents the spatial longitude distribution of the emission sources across the emitting cone. So the observations of the shape of the pulses over a wide range of frequencies and their time alignment can be used to study the configuration of the magnetic field.

In a dipole magnetic field the emitting cone is straight and its axis is a straight line. Therefore the arrival time of pulses will be the same at all frequencies (after correction for dispersion delay). (See figure 1).

If the pulsar magnetic field has additional components which distort its axis, one can expect to observe a deviation of the time alignment from the straight line.

This is the general outlook and expectation. And what about the experiment?

Several multifrequency time alignment observations of the mean profiles and analysis of the structure of the pulsar magnetic field have been performed. The general conclusion is that the pulsar magnetic field is nearly dipolar at intermediate radii, where frequencies of about 100 to 1000 MHz are emitted. At lower radii multipole components of the magnetic field may add to the dipole and distort it. At larger radii the pulsar magnetic field may be twisted by the rotation of the star.

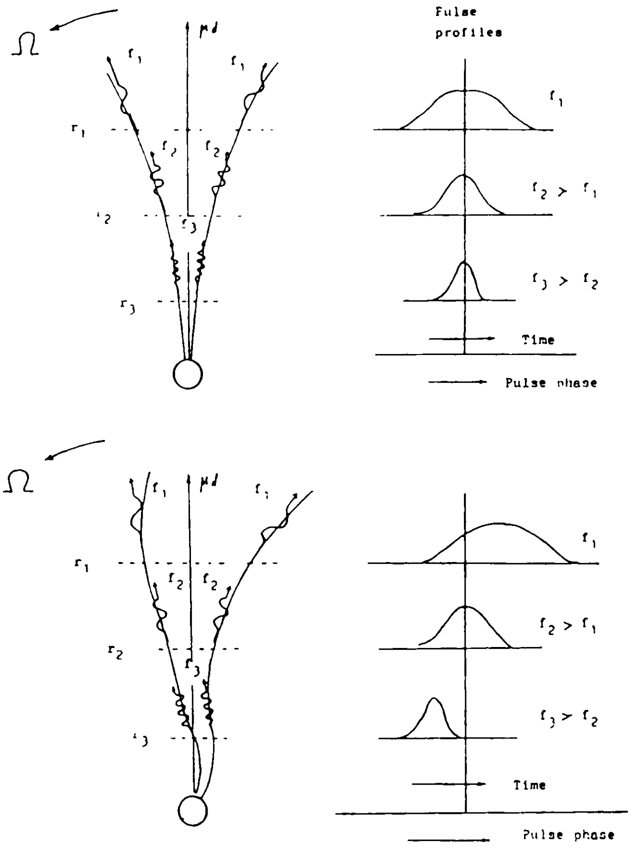

Figure 1 Schematic representation of the pulsar magnetic field and the expected alignment of pulse profiles at different frequencies.

The first multifrequency observations over a wide frequency band were undertaken in a Jodrell Bank-Pushchino collaborative experiment (Davis *et al.* 1984) at frequencies 39, 62, 102, 406 and 1400 MHz for the pulsar PSR 0809+74. The time aligned integrated profiles are shown in figure 2. One cannot align the profiles at all frequencies for any single value of the dispersion measure *DM*.

High-frequency time alignment: Multipole magnetic field

The most pronounced deviation from alignment takes place at the highest frequency of 1400 MHz, where the arrival time is 18 ms earlier than the lowest one. An attempt to align this profile required a *DM* change as large as 0.8 pc cm^{-3}, which led to a huge misalignment at frequencies below 400 MHz. Even such an unrealistically large error in the *DM* as 0.1 pc cm^{-3} will produce an error in time alignment of only 2.4 ms. Therefore Davis *et al.*, have

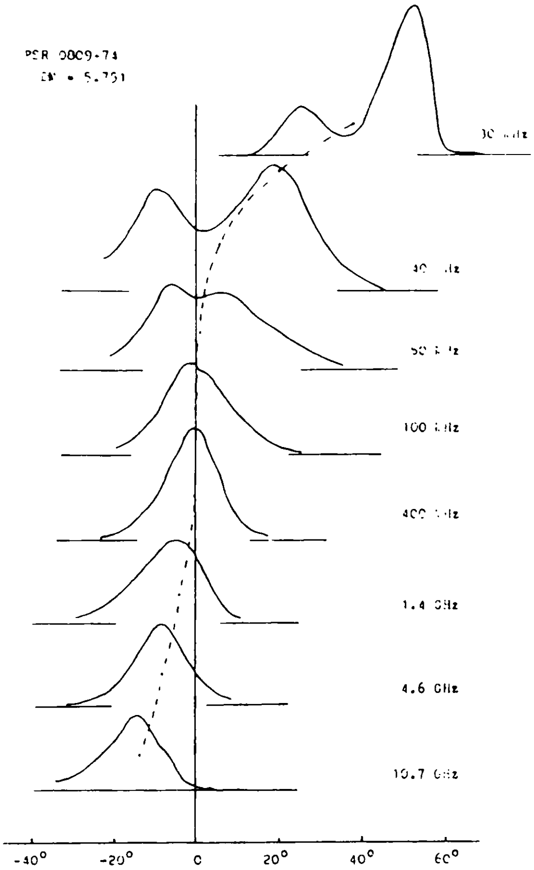

Figure 2 The time aligned mean pulse profiles of PSR 0809+74.

concluded that the pulses at 1400 MHz are emitted by the pulsar from an earlier rotation longitude of 5°. For an interpretation of this longitudinal shift of the pulse they have proposed a multipole magnetic field, in which at low radii a quadrupole component exists, which distorts the emitting cone of the open magnetic field lines. If this is the case, one may expect further shifting and consequent misalignment at higher frequencies.

High-frequency multifrequency time alignment observations were performed in an Effelsberg-Pushchino cooperative program (Kuz'min *et al.* 1986) at the frequencies 102 MHz, 4.6 GHz and 10.7 GHz. Observations have shown that the distortion of the emitting cone at higher frequencies increases: at 10.7 GHz the integrated profile of PSR 0809+74 is earlier than the profile at 4.6 GHz by 6 ms.

Thus, the emitting cone of PSR 0809+74 at high frequencies is curved and its deflection from a dipolar form increases at lower radii. Then it is reasonable to ask the question: Is high-frequency time misalignment and low-altitude distortion of the emitting cone a unique property of PSR 0809+74 only, or is it a common phenomenon for many pulsars? In the Effelsberg-Pushchino observations it was found that PSR 0809+74 is not unique. High-frequency misalignment was detected for a number of other pulsars. Some examples are shown in figure 3.

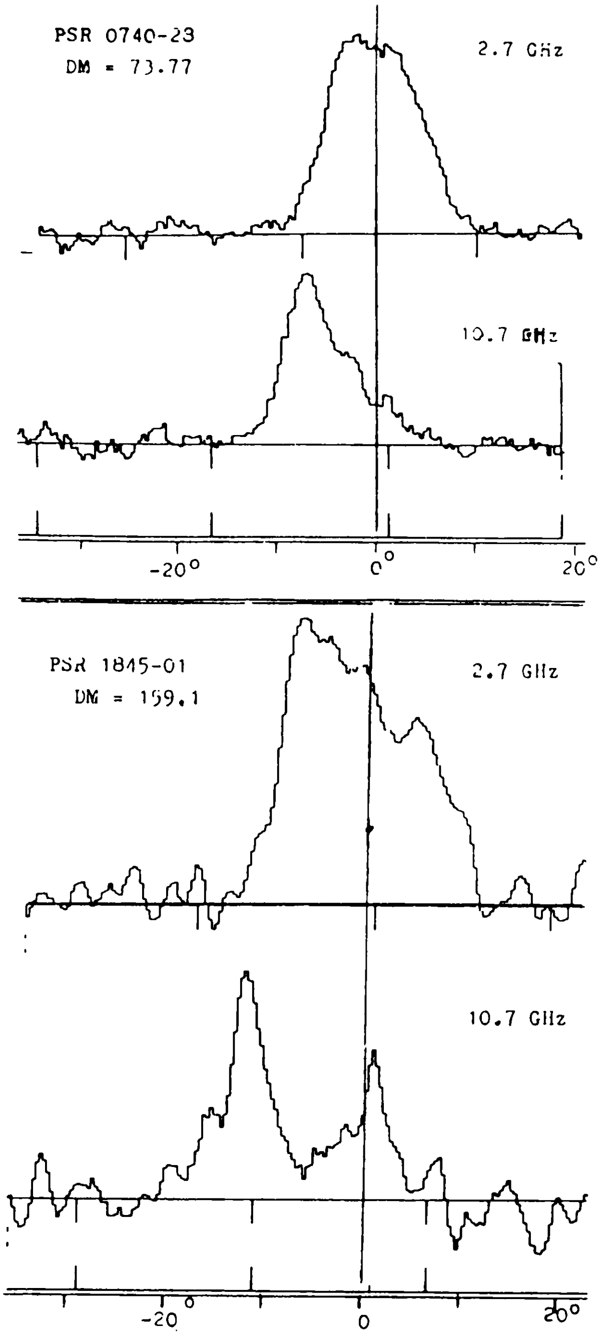

Figure 3 The high-frequency time alignment of mean profiles of PSR 0740−28 and PSR 1845−01.

The most natural interpretation of this high frequency misalignment, as was suggested by Davies *et al.* (1984), and by Kuz'min *et al.* (1986) is an effect of multipole components of the magnetic field of a neutron star at low altitude. In the region where multipoles are significant, the cone of the open magnetic field lines deviates from a pure dipolar form. An example of one of the configurations involving a dipole plus quadrupole magnetic field is presented in figure 4.

It is interesting to note that the total magnetic field is not as symmetrical as the strictly dipolar field. In one hemisphere, where the polarity of the dipole and the nearby quadrupole poles are the

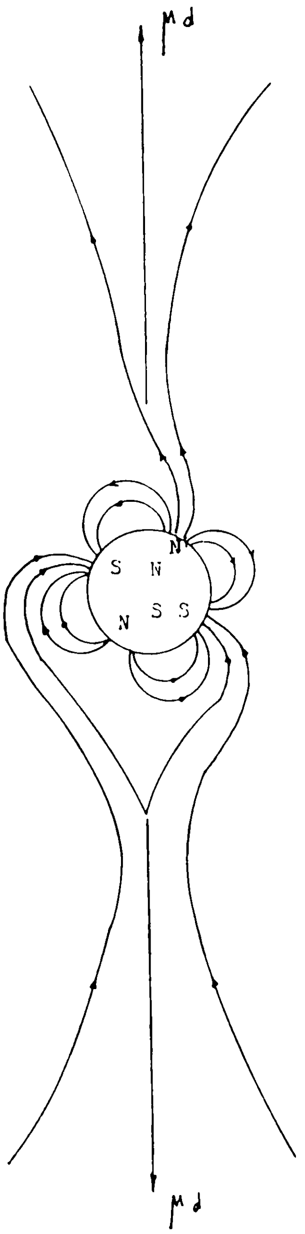

Figure 4 A schematic configuration of a dipole plus quadrupole magnetic field.

same, the open field line cone in the quadrupole region is a continuation of the dipole field region by a continuous bend if the locations of the dipole and quadrupole poles do not coincide. But in the other hemisphere, where nearby poles of the quadrupole are of opposite polarity to the dipole, the configuration of the magnetic field will be more complicated: at lower radii the single dipole cone of the open magnetic field lines will split into two separate cones, which will diverge with decreasing radius and touch the neutron star at two diametrically opposite poles of the quadrupole. Therefore one may expect that at very high frequencies the profiles of some pulsars may split in two parts like the main pulse and interpulse.

Some additional arguments that favor a multipole structure of the pulsar magnetic field are the high-frequency steepening of the pulse energy spectra and non $f^{-1/3}$ behavior of the frequency dependence of pulse widths (Kuz'min *et al.* 1986).

Low-frequency time alignment: Twisting of the magnetic field

The first indication of non-dipolar magnetic fields in low-frequency emitting regions was obtained by Shitov (1983) from polarization data and pulsar luminosity analysis and by Davies *et al.* (1984) from time alignment. Measuring the alignment of pulsar PSR 0809+74 in the 400 to 39 MHz frequency range, Davies *et al.* obtained a value of $DM = 5.762\,\mathrm{pc\,cm^{-3}}$, which is larger than the $5.752\,\mathrm{pc\,cm^{-3}}$ value obtained in the 400 to 100 MHz range and the $5.751\,\mathrm{pc\,cm^{-3}}$ measured by Smirnova *et al.* (1985) from microstructure. This deviation was interpreted as a twisting of the magnetic field by rotation braking reaction of the star (Shitov 1983).

Stronger evidence of low-frequency deviation of the magnetic field from a dipolar form was obtained in the very low-frequency time alignment observations of Shitov (1985) and Shitov *et al.* (1988). For PSR 0809+74, using $DM = 5.762\,\mathrm{pc\,cm^{-3}}$, they get an extra 30-MHz dispersion delay of 100 ms or 28° lag in longitude (figure 2). I noted earlier that PSR 0809+74 is not an exception: extra dispersion delay was detected in several other pulsars, PSRs 0031−07, 0320+39, 0329+54, 0823+26, 1508+55, 1604−00, 1642−03, 1929+10, 2016+28 and 2217+47 (Izvekova *et al.* 1989). Some examples of extra low-frequency dispersion delay are shown in figure 5.

Thus, there is much observational evidence for extra low-frequency dispersion delay. But these arguments are not widely accepted by the pulsar community. There is also an opposite opinion. Phillips and Wolszczan (1990), who recently performed multifrequency time-aligned observations in the 25 to 4800 MHz frequency range at Arecibo, claimed that pulsar arrival times obey the cold plasma dispersion law to high accuracy and that no deviation from the cold plasma dispersion delay and no extra dispersion delay has been detected in low-frequency time-aligned measurements.

But a more detailed analysis shows that the Phillips and Wolszczan data agree with the study of Shitov *et al.* and, in fact, even confirm the extra dispersion delay. In order to clarify this point, I would like to propose another approach for an objective way of analyzing the experimental data.

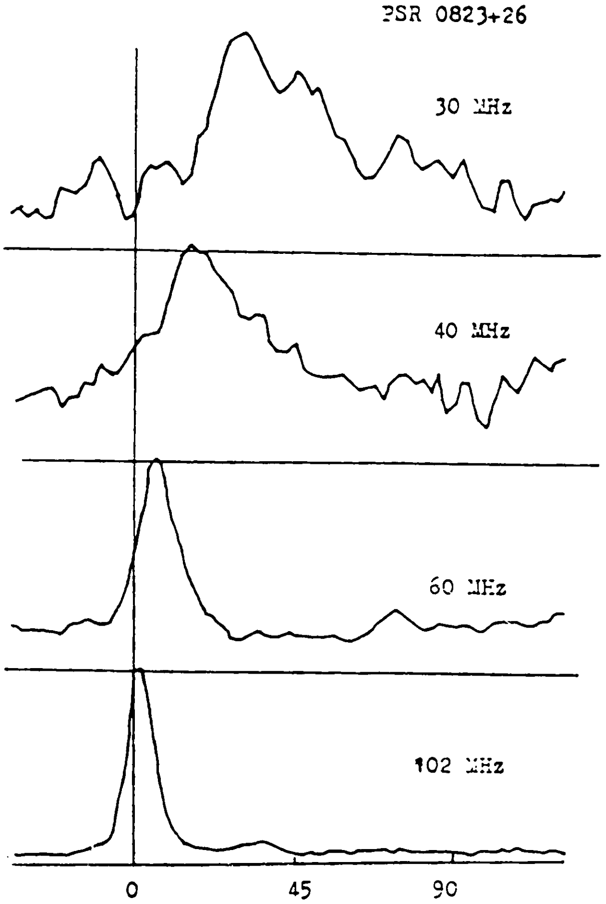

Figure 5a Low frequency time alignment of PSR 0823+26.

Let us see whether the measured value of *DM* is a constant independent of the frequency interval in which it was obtained, or whether it is frequency dependent. If a pulsar pulse's delay is only due to dispersion, the measured value of the *DM*, obtained from eq.(1) must be the same in any frequency interval. On the other hand, if some time delay exists in addition to the dispersion delay, it will increase the apparent measured value of the *DM*. Thus an excess in the measured value of the *DM* is evidence of extra dispersion delay.

The first analysis of the frequency dependence of the apparent measured value of the *DM*, performed by Kuz'min (1986), disclosed that the published values of the *DM*, measured at frequencies between 60 and 100 MHz, are systematically larger than those measured at higher frequencies. Today there are more studies available including the very recent data of Phillips and Wolszczan (1990). All the available data are presented in table 1. It can be seen that for all these pulsars, the value of the *DM* measured at low frequencies is systematically larger than at higher frequencies. Therefore, one may conclude that at lower frequencies some mechanism of pulse delay exists in addition to the dispersion delay. You can see also in the table that the experimental values of Phillips and Wolszczan (1990) agree very well with Shitov *et al.* (1988) and Izvekova *et al.* (1989). That is, we see no contradiction, but rather we see a good confirmation in support of the existence of extra dispersion delay at low frequencies.

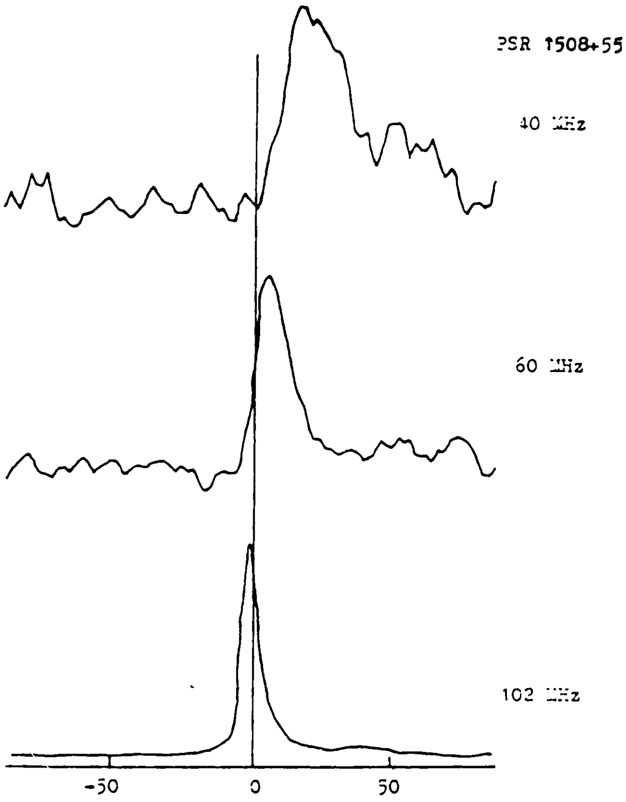

Figure 5b Low frequency time alignment of PSR 1508+55.

Table 1 Values of the *DM* as measured at high and low frequencies

PSR	$DM_{\rm HF}$	$DM_{\rm LF}$	$DM_{\rm LF} - DM_{\rm HF}$
0329+54	27.771[2]	26.785[11]	0.014
0809+74	5.751[10]	5.762[1]	0.011
		5.81[12]	0.059
0823+26	19.466[3]	19.475[13]	0.009
		19.475[9]	0.009
0834+06	12.856[2]	12.8579[9]	0.002
0919+06	27.286[7]	27.309[9]	0.023
0950+08	2.9696[10]	2.9702[9]	0.001
1133+16	4.8413[6]	4.8479[13]	0.007
		4.8471[9]	0.006
1508+55	19.599[2]	19.62[13]	0.021
1604−00	10.662[7]	10.687[5]	0.025
		10.6845[9]	0.023
1642−03	35.665[4]	35.736[13]	0.071

[1] Davies *et al.* 1984, [2]Goldstein and James 1969, [3]Hankins and Rickett 1986, [4]Hunt 1971, [5]Izvekova *et al.* 1989, [6]Kardashev *et al.* 1982, [7]Kuz'min *et al.* 1986, [8]Kuz'min 1986, [9]Phillips and Wolszczan 1990, [10]Popov *et al.* 1987, [11]Shitov 1971, [12]Shitov 1985, [13]Shitov *et al.* 1988

Conclusions

Finally I would like to summarize some conclusions for discussion and criticism:

1. There is a nondispersive time shift of the mean pulse profiles at high frequencies.
2. The nondispersive high-frequency time shift may be interpreted in the framework of a dipole plus a quadrupole (multipole) magnetic field configuration in the lower magnetosphere.
3. The apparent value of the *DM*, measured at lower frequencies (below 60–100 MHz), is larger than the value measured at higher frequencies.
4. The low-frequency apparent excess of *DM* is evidence that some factor exists which delays pulse times of arrival at low frequencies beyond the cold plasma dispersion delay.
5. This factor may be interpreted as a contra-rotation twisting of the pulsar magnetic field at large radii by the braking reaction.

A more detailed analysis of the low-frequency extra dispersion time delay and its interpretation will be presented in Shitov's report in this session.

I would like to invite you to present your pro and contra arguments and different approaches to these subjects.