THE DRIFTING SUB-PULSE PHENOMENON
N PSR 0809 + 74

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SUMMARY

PSR 0809 + 74 has been observed simultaneously at 81·5 MHz and 151 MHz in order to study drifting sub-pulses and the effects of pulse nulling. It is found that drifting sub-pulse bands are generated with a periodicity which is stable to at least 1 part in $10^8$ when allowance is taken of a characteristic jump of sub-pulse phase associated with nulls. The overall behaviour is similar at both frequencies, apart from an increased sub-pulse width at 151 MHz, although the mean pulse envelope is substantially broader at 81·5 MHz. The relevance of these observations to pulsar models is briefly discussed.

1. INTRODUCTION

Many pulsars exhibit quasi-periodic intensity variations on a time scale several times longer than their fundamental period (Taylor, Jura & Huguenin 1969). In certain cases, e.g. PSR 0031−07, PSR 0809 + 74, these variations are clearly associated with a sub-pulse structure which shifts systematically from the trailing to the leading edge of a time window defined by the mean pulse profile. This phenomenon of 'drifting sub-pulses' has only been found to occur distinctly in the oldest pulsars and it is notable that PSR 0809 + 74, which exhibits the most stable sub-pulses, also has the greatest age ($P/P = 2·5 \times 10^8$ yr) of any pulsar yet measured. The sub-pulse process evidently plays an important role in controlling the radiation from these pulsars since characteristic nulls, during which the pulse switches off, are usually associated with sudden reductions in the drift rate of the sub-pulses (Cole 1970; Backer 1970a; Taylor & Huguenin 1971).

In an attempt to understand these effects more fully, extended observations of PSR 0809 + 74 have been made at 81·5 MHz and 151·5 MHz simultaneously. The observing system is described in Section 2 and measurements of the drift rate and occurrence of sub-pulses are presented in Section 3. The radio frequency dependence of sub-pulses is described in Section 4 and a discussion of all the observations is given in Section 5.

2. THE OBSERVING SYSTEM

The observations were made at the Mullard Radio Astronomy Observatory between 1970 December and 1971 October at frequencies of 81·5 and 151·5 MHz. At 81·5 MHz the '4-acre' phased array (Hewish & Burnell 1970) was used which enabled the source to be observed for up to 15 min per day. The bandwidth of 30 kHz resulted in a smearing of 2·6 ms due to pulse dispersion. The signals could
also be received simultaneously at 151.5 MHz with a cylindrical paraboloid antenna of 5800 m² area (Collins & Scott 1969) which has a phasing mechanism enabling the source to be tracked for over an hour around meridian transit; a bandwidth of 200 kHz was normally used which also gave about 2.6 ms dispersion smoothing. Both antennas were linearly polarized in the east–west direction.

The detected outputs of the receivers were amplified, integrated in a single stage C–R unit, digitized, and recorded on magnetic tape. One channel could be recorded at 500 samples per s in which case a 2.2 ms time constant was used in the integrator; alternatively two channels could be recorded simultaneously at 250 samples per s with a time constant of 5 ms. The records were analysed by an IBM 360/44 computer.

3. SYSTEMATIC SUB-PULSE BEHAVIOUR

3.1 Nomenclature

The terminology of drifting sub-pulses can be confusing and we now define clearly the quantities which will be discussed. Consider an idealized diagram, sketched in Fig. 1, in which the intensity within a given pulse is plotted horizontally, with the leading edge to the left, and successive pulses at the fundamental pulsar period $P_1$ are arranged vertically downwards. Addition of intensities in vertical columns yields the mean pulse envelope. Position within this time window will be defined in terms of longitude $\phi$ taking the centre of the window as origin. (This coordinate has been called pulse phase by some authors.) For convenience the longitude $\phi$ will be measured in milliseconds. The separation in longitude of sub-pulse maxima within the same pulse is called $P_2$; the time interval between the crossing of longitude zero by successive sub-pulse bands is called $P_3$. The drift rate $D$ of sub-pulse bands in longitude is $d\phi/dt$ and will be given in units of ms/$P_1$; for a stable pattern $D = d\phi/dt = P_2/P_3$. Since each band is well defined it is also useful to define a sub-pulse number $N$ as in Fig. 1.

3.2 The sub-pulse drift rate

A typical observation of PSR 0809+74 is shown in Fig. 2. This was made directly from the computer output where numerical symbols have been replaced by dots of appropriate size. A glance at this plot shows that the simultaneous observations at 81.5 and 151.5 MHz show strongly correlated sub-pulse behaviour.

In order to make an accurate measurement of the mean drift rate as a function of longitude we have used Backer's method (1970a) and carried out a Fourier analysis of pulse to pulse intensity variations at a series of longitudes. Fourier analysis naturally gives a prominent component at a frequency of $P_3^{-1}$ and if the phase angle of this component is $\theta$, the drift rate $D$ is given by

$$D = 2\pi \frac{d\phi}{d\theta} P_3^{-1}.$$ 

Values of drift rate as a function of longitude are shown in Fig. 3 where the analysis was carried out on 8 min of data at 151 MHz. There are small but significant variations of $D$ with longitude and it has been found that the form of the curve stays substantially the same for periods of up to an hour but not from one day to the next. Since $P_3$ exhibits no significant longitude variation, the variation of $D$
implies a corresponding small variation of $P_2$ with longitude. The mean drift rate always remains within $\pm 1$ ms/$P_1$ of its mean value right to the wings of the mean pulse envelope. There is no evidence for the drift rate tending to become large at the leading edge as has been reported for PSR 1919+21 (Backer 1970a). The drift rates for individual sub-pulse bands were determined by eye from the computer printed longitude—time plots (Fig. 2) and small deviations from a linear drift such as those shown by Fig. 3 are not readily distinguishable. The best-fitting linear drift for each sub-pulse band can be determined to better than $0.5$ ms/$P_1$ and this is also found to vary significantly from one sub-pulse band to the next. This agrees with the observations by Taylor & Huguenin (1971) of PSR 2016+28, a pulsar which sometimes exhibits, simultaneously, two sub-pulse bands which maintain constant but different drift rates.

Measurements of the drift rate for a succession of sub-pulse bands are plotted in Fig. 4(a). Small irregular variations, not due to uncertainties of measurements, occur between adjacent bands and a significant reduction takes place immediately following a null. The data in Fig. 4 show rather more nulls than usual, the median interval between nulls in all observations being approximately $300 P_1 = 27 P_3$. When the results for 12 nulls are superposed, as shown in Fig. 4(b), the average behaviour indicates that the sudden fall in drift lasts for less than $40 P_1$ after which the rate has returned to its normal value.
Fig. 2. Typical longitude–time plot of PSR 0809 + 74 at 81 MHz and 151 MHz. The dispersion delay, amounting to two periods, has not been removed; the intensity within each 4-ms sample is represented by a dot of appropriate size.
Fig. 3. Mean drift rate $D$ of sub-pulses at $151\, MHz$ as a function of longitude. (a) 1971 April 16 (600 pulses), (b) and (c) 1971 Sept. 22 (400 pulses).

Fig. 4. (a) Drift rates of successive sub-pulses. (b) Average behaviour of $D$ near a null. (c) Sub-pulse phase as a function of time. (d) Sub-pulse phase allowing for a phase-jump of $11\, P_\lambda$ at each null.
3.3 The stability of $P_2$ and $P_3$

It can be seen from Fig. 2 that bands of sub-pulses occur with great regularity. A quantitative measure of the stability of $P_3$ is obtained from the Fourier spectrum of the pulse to pulse intensity variations discussed in the previous section. Typical values of $P_3/\Delta P_3$ of about 100 are obtained and values of up to 500 have occasionally been found. Since $P_3$ exhibits its greatest variations in the vicinity of nulls it is of interest to study these regions in detail.

The mean value of $P_3$ derived from several months data is $P_3 = 10.97 P_1$. To study the short term variations of $P_3$ we adopt a rounded value of $11 P_1$ for convenience. Counting sub-pulse bands from some arbitrary zero we define the phase of the $N$th band as $\psi(N)$

$$\psi(N) = t(N) - 11 NP_1$$

where $t(N)$ is the time at which this band crosses zero longitude. When the observed sub-pulse phase is plotted as a function of sub-pulse number, as in Fig. 4(c), it is seen that the phase undergoes a discontinuity immediately following a null. The step-like character of the variation suggests that nulls may be associated with a systematic phase-jump having a magnitude of the order of $11 P_1$. The same data are replotted in Fig. 4(d) with a phase jump of $11 P_1$ subtracted at each null and it is apparent that, with this modification, the phase returns to the slowly varying trend that existed before the null occurred. This shows that the mechanism responsible for generating sub-pulses has a far greater fundamental stability than is suggested by the typical value of $P_3/\Delta P_3 = 100$. When allowance is taken of the slow phase perturbation the basic stability is entirely limited by our observation time and we obtain $P_3/\Delta P_3 \approx 700$. Unfortunately the slow perturbations do not allow the day to day phases to be related, but continuous observations for one day or more might indicate a far higher stability for the sub-pulses in this source. Some typical observations on other occasions are shown in Fig. 5.

The parameter $P_3$ may be obtained from direct measurements of the separation, in longitude, of adjacent sub-pulse bands. The mean value is, however, more accurately obtained from the gradient $d\theta/d\phi$ discussed in Section 2.1 using the relation

$$P_3 = 2\pi \frac{d\phi}{d\theta}.$$

In Table I we summarize the mean values of all the sub-pulse parameters, where $\sigma_1$ denotes the short-term standard deviation of samples from the half-hourly mean, and $\sigma_2$ is the standard deviation of the half-hourly mean from the long-term value. It is evident that $P_3$ is the most stable parameter, not only from sub-pulse to sub-pulse, but also from day to day.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\mu$</th>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$ ms/$P_1$</td>
<td>4.83</td>
<td>0.5</td>
<td>0.42</td>
</tr>
<tr>
<td>$P_2$ ms</td>
<td>53.1</td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>$P_3$ periods</td>
<td>10.97</td>
<td>0.5</td>
<td>0.22</td>
</tr>
</tbody>
</table>
4. RADIO FREQUENCY DEPENDENCE OF SUB-PULSE PROPERTIES

4.1 Pulse shapes

Fig. 2 clearly illustrates the close correspondence between sub-pulses observed simultaneously at 81.5 MHz and 151.5 MHz and no significant frequency dependence of the parameters listed in Table I has yet been found. Sub-pulses do, however, drift over a much wider range of longitude at 81.5 MHz and Fig. 2 also suggests that the instantaneous width, in longitude, of sub-pulse bands is smaller at 81.5 MHz. The first point is related to the greater width of the mean pulse envelope at the lower frequency as shown in Fig. 6. The asymmetry of the pulse envelope at 81.5 MHz suggests that the increased width may result from a second hump which becomes more prominent at low frequencies, as has already been observed for PSR 0950+08 (Lyne, Smith & Graham 1971). A comparison of the two sources is illustrated in Fig. 6 and it is seen that a second hump at a longitude separation of about 13° could account for the envelope profile. The radio frequency spectrum of this component must vary more rapidly than $f^{-0.8}$ if this explanation is correct. The half-power width of the envelope at various frequencies is plotted in Fig. 7 from the present data and the results of Lyne et al. (1971) and Vitkevitch & Shitov (1970). The break in the curve near 150 MHz is difficult to explain other than by a second component with a steep radio spectrum.

To measure the average width, in longitude, of sub-pulse bands their profile was assumed to be gaussian and a least squares fit was carried out on occasions when the intensity was large at both frequencies. Instantaneous variations of width and
height of the best fitting gaussian profiles were highly correlated between 81 and 151 MHz. After making a correction for dispersion and time constant smoothing (see Section 2), the mean values obtained for the half-power sub-pulse width were $9 \pm 1$ ms at 151 MHz and $5.5 \pm 1$ ms at 81 MHz.

Little information is currently available on the frequency dependence of sub-pulse structure in other pulsars, but the present result differs from earlier work by Smith (1969) who reported no frequency dependence over 151–1420 MHz in PSR 0329+54.

Since both antennas are linearly polarized it is possible that our result could be due to the changing polarization of the sub-pulses since Taylor et al. (1971) have shown that each sub-pulse is linearly polarized with the plane rotating through more than 90° through each sub-pulse band. We measure one linear component only which could lead to an apparently narrower sub-pulse at 81 MHz if the rate of
rotation of the plane of polarization was faster at 81 than 151 MHz. The evidence from other pulsars (Lyne et al. 1971; Komesaroff, Morris & Cooke 1970) is that the rate of rotation is not frequency dependent and it is therefore unlikely that our result can be explained in this way.

4.2 Irregular intensity variations

The steady drift of the sub-pulses is accompanied by rapid and irregular pulse to pulse intensity variations. The time scale and frequency correlation of these was studied by autocorrelation and cross-correlation analyses. In order to minimize periodic variations associated with $P_3$ the intensity of each pulse was taken to be the mean energy inside a time window of width $P_3$ centred on the maximum of the mean pulse envelope. The autocorrelation functions at each frequency are shown in Fig. 8(b) and (d); the small maxima at a lag of $\sim 11 P_1$ show the residual effect of $P_3$, but the dominant variations indicate no correlation beyond a lag of $2 P_1$. Cross-correlation of the data at 81 MHz and 151 MHz given in Fig. 8(c) shows a significant correlation of $0.4$ at a lag of $2 P_1$ corresponding to the dispersion delay. Hence the rapid variations must be similar over a wide range of radio frequency. Similar results have been reported for PSR $\phi 329+54$ by Rickett (1970).

![Image](https://example.com/image.png)

**Fig. 8.** (a) Cross-correlation of pulse to pulse intensity variations at 81 MHz and 151 MHz. (b) Autocorrelation at 81 MHz. (c) Cross-correlation between adjacent sub-pulse bands at 81 MHz. (d) Autocorrelations at 151 MHz.

The fluctuation index $F$ given by $F^2 = \langle I^2 \rangle / \langle I \rangle^2$, where $I$ is the pulse intensity gave values $F_{81} = 0.85$ and $F_{151} = 0.7$. A slightly higher value for $F_{81}$ would be expected due to interplanetary scintillation but it does not seem possible to account for all of the difference in this way.

In order to see whether adjacent sub-pulse bands suffer the same intensity variations, or vary independently, the data were also analysed using a pair of adjacent time windows of width $P_3$ symmetrically arranged about the centre of the mean pulse envelope. Adjacent sub-pulses therefore had the same relative position in each window. The cross-correlogram, shown in Fig. 8(c) indicates significant correlation of $0.28$ at zero time lag for the short duration fluctuations together with a component at $P_3$. The irregular variations are thus partially correlated in adjacent sub-pulse bands within the same main pulse. This result confirms the
impression gained from inspection of typical pulse sequences (cf. Fig. 2) on
occasions when adjacent bands are observed simultaneously. The rapid pulse to
pulse variations often show detailed correlation in each band, but the mean strength
of a given band varies randomly from one band to another. It is also clear from
the appearance of pulse sequences that there is a systematic modulation of sub-pulse
intensity with longitude which corresponds to the mean pulse envelope. This
implies that two beaming mechanisms are involved; a primary process which
defines the sub-pulses and a secondary process to modulate their intensity as a
function of longitude.

5. DISCUSSION

The following conclusions can be drawn from the results which have been
described for PSR 0809 + 74:

1. The fact that sub-pulse bands maintain their individual drift rates and mean
intensity suggests that pulsar emission originates in physical entities which can
last for at least 17 s, corresponding to 13 rotations for the usual neutron star
model.

2. Sub-pulses are generated at regular intervals of about 14 s by some mechan-
ism which, when a slow phase drift is allowed for, maintains this period with a
stability of at least 1 part in 10³.

3. The pulsar ‘switches off’ at regular intervals separated typically by 200–
600 s, and this event is associated with the absence of a complete sub-pulse band.

4. For about 60 s following such a null, the timing of sub-pulses is disturbed
but it eventually returns to the stable pattern which existed beforehand.

5. Nulls are associated with a characteristic reduction in the longitude drift
rate of sub-pulses which lasts for 2 or 3 further sub-pulse bands.

6. In addition to the above systematic effects, PSR 0809 + 74 is subject to
rapid irregular intensity variations characteristic of many pulsars which do not
exhibit drifting sub-pulses.

In comparing the above behaviour with that of PSR 0031 – 07, the only other
pulsar known to have sub-pulses of comparable stability, it is notable that \( P_2 \) for
this source is \( \sim 57 \) ms (Huguenin, Taylor & Troland 1970) which is similar to our
value of \( P_2 = 53.1 \) ms for PSR 0809 + 74. On the other hand the drift rate is
normally double that of PSR 0809 + 74, whilst it varies above and below this value
by a factor of 2. Another similarity is that the nulls are associated with a decrease
of drift rate. It would be interesting to carry out a sub-pulse phase analysis for
PSR 0031 – 07 although it is evident from typical pulse sequences that the phase
variations are considerably larger and lead to an apparent frequency modulation of
\( P_3 \).

Possibly the most interesting feature of our present observations is the stability
of \( P_3 \). The origin of this periodicity is currently unknown and it may be related
to changes at the neutron star surface, or in its magnetosphere. Torsional and
vibrational modes of the magnetosphere have periods which are probably too short
to explain \( P_3 \), but azimuthal particle drifts might yield circulation periods of the
right order for particles near the light cylinder (Ruderman 1972).

Following Gold (1969) and Smith (1970) it may be that sub-pulse bands are
related to beamed radiation from localized plasma regions. If these regions are
generated near the light cylinder it is difficult to understand the underlying phase
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stability of $P_3$. It seems more likely that some process within or near the neutron star is involved. In a purely schematic model we might suppose that plasma blobs are released at intervals $P_3$ near the base of some magnetic field line and then travel outwards along it. The blobs begin to radiate as they approach the light cylinder and continue to travel outwards until they are lost in the stellar wind zone. Relativistic beaming would then produce drifting sub-pulses which advance from the trailing to the leading edge of the mean pulse envelope. This model demands some mechanism to maintain a constant spacing between the blobs, while a variable outward velocity could account for the observed changes of drift rate. The total removal of a blob is required to account for the nulling phenomenon.

The stability of $P_3$ may be of crucial importance in identifying the physical processes underlying such a model. The sub-pulse phase jumps associated with nulls, described in Section 3, are reminiscent of the behaviour of a relaxation oscillator synchronized to some higher frequency, which occasionally falls out of step and slips one complete cycle before regaining synchronism. The slow phase drifts, on the other hand, could arise from systematic variations of the mean outward velocity of the blobs along field lines.

Our result, described in Section 4.2, that the sub-pulses are substantially narrower at 81 MHz than at 151 MHz does not agree with the hypothesis that sub-pulse width is simply related to the relativistic beaming process as has been suggested by Smith (1970, 1971). The results of Hankins (1971) have, however, revealed frequency-independent sub-pulses on a much finer time scale in PSR 0950 + 08 and PSR 1133 + 16 and it is possible that these correspond to the primary relativistic beaming process.

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REFERENCES