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PULSAR FLUCTUATION SPECTRA AND THE GENERALIZED DRIFTING-SUBPULSE PHENOMENON. II.

D. C. BACKER*
Goddard Space Flight Center, Greenbelt, Maryland
J. M. RANKIN
Department of Physics and Astronomy, University of Iowa
AND
D. B. CAMPBELL
National Astronomy and Ionosphere Center, Arecibo, Puerto Rico
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ABSTRACT

Pulsar observations at meter wavelengths have been analyzed to investigate pulse-to-pulse variations and to identify regions of the pulse profile which display distinct statistical properties. Fluctuation spectra of eight recently discovered pulsars are presented along with a description of the drifting-subpulse phenomenon in several objects with *quasi*-periodic responses in their fluctuation spectra. A quantitative analysis of the drifting-subpulse phenomenon in PSR 0031−07 and PSR 0809+74 is given which emphasizes the broad-band nature of the phenomenon. A summary of the memory exhibited by pulsars with time scales of ~50 periods is given.
Subject heading: pulsars

I. INTRODUCTION

The pulse-to-pulse intensity variations in pulsars have been described concisely by fluctuation spectrum analyses for many years. The description has been used both to study interstellar scintillation of pulsar signals (Lovelace and Craft 1968; Lang 1971) and to identify *quasi*-periodic variations (Lovelace and Craft 1968; Taylor, Jura, and Huguenin 1969). One of us (Backer 1970*a*, 1973) has developed a longitude[1] resolved, fluctuation-spectrum analysis procedure which was shown to be useful in quantifying the properties of the drifting-subpulse phenomenon.

Several recent studies (Taylor and Huguenin 1971; Backer 1973 [hereafter referred to as Paper I], Schönhardt and Sieber 1973) have dealt with pulse-to-pulse variability in a number of the stronger pulsars at meter wavelengths. Following the pattern of Paper I we present below fluctuation spectra both for eight relatively weak pulsars using Arecibo 430-MHz observations and for two well-known objects, PSR 0031−07 and PSR 0809+74, using data recorded at the National Radio Astronomy Observatory (NRAO).[2] In several cases it is possible to describe aspects of the drifting-subpulse phenomenon quantitatively, while in others the significance of nonrandom features in fluctuation spectra is interpreted in terms of correlations in sequences of pulses.

II. OBSERVATIONS

The experimental procedures employed in an individual-pulse polarization survey carried out at the Arecibo Observatory during 1971–1974 will be discussed in detail in a forthcoming paper, and thus only a few relevant details will be given here. The measurements were made with the new 430-MHz, aberration-correcting, wave-guide feed which produced both senses of circular polarization. The two circularly polarized signals were passed through narrow, band-limiting filters, detected, smoothed, and sampled by an on-line computer which recorded the data on magnetic tape. Off-line processing produced calibrated, total-intensity sequences of individual pulse profiles on tape which were then sent to NRAO for computer analysis.

Observations at the NRAO were made in 1972 employing a 250- to 500-MHz radiometer with a circularly polarized feed on the traveling mount of the 92-m transit telescope. Four independent radiometer channels were defined within the 250- to 500-MHz band and were individually band-limited, detected, and passed to a signal averager which smoothed the data and acted as a rapid acquisition storage buffer prior to transferring the data to magnetic tape under the control of an on-line computer. Additional observational details are given in table 1.

III. RESULTS

Average pulse profiles for 10 pulsars are given in figure 1. Fluctuation spectral analyses for these objects are divided into three groups below: (*a*) four objects which display different spectral properties in distinct sections of their pulse profile, (*b*) three objects whose spectra do not vary over the width of their profile; and (*c*) three objects with narrow, stable features in their spectra. Since the various effects considered below are for the most part well known

* NAS/NRC Resident Research Associate.

[1] 360° longitude = 1 pulsar period.

[2] NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

PULSAR OBSERVATIONS

PSR	Date	Pulses	Frequency (MHz)	Bandwidth (MHz)
0031−07.........	1972 Apr. 19	1792	283/325	1.0
			495	3.0
0301+19.........	1972 Jan. 01	1536	430	2.0
0540+23.........	1973 Feb. 07	4608	430	0.1
0611+22.........	1973 Feb. 07	4608	430	0.1
0809+74.........	1972 Apr. 18	2048	290/325	1.0
			430/495	3.0
0943+10.........	1972 Jan. 02	1024	430	2.0
1604−00.........	1973 Feb. 11	3584	430	2.0
1915+13.........	1972 June 29	2560	430	0.5
1944+17.........	1972 June 13	2560	430	2.0
2020+28.........	1972 June 29	2560	430	0.5

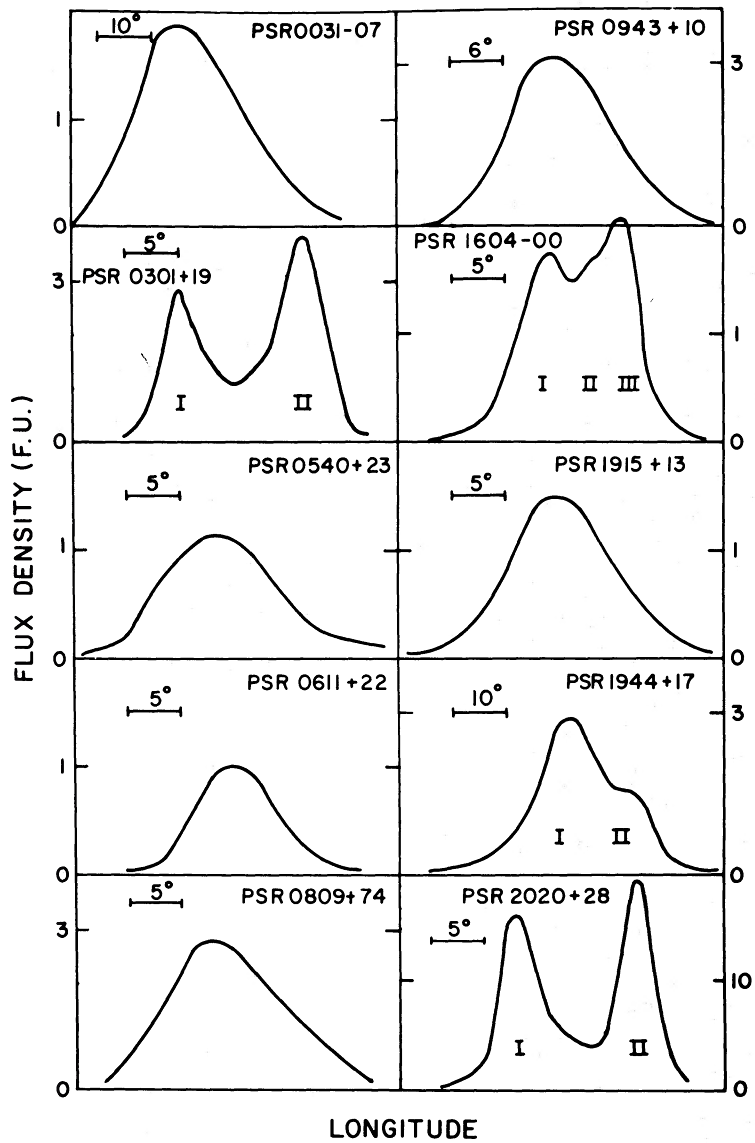

FIG. 1.—Average pulse profiles for 10 pulsars. Components of the profiles are noted by roman numerals. Abscissa scales are in degrees of longitude, and ordinate scales are in janskys (10^{-26} W m^{-2} Hz^{-1}) as indicated in each plot.

and since typical sequences of pulses will be given in a forthcoming article, the fluctuation spectra are discussed entirely in terms of the properties of individual pulse groups without displaying the observations. The fluctuation spectra were calculated from data which were recorded at intervals of longitude of approximately 1/20 of the overall pulse width and over blocks of 512 pulses (Arecibo data) or 256 pulses (NRAO data).

In all cases studied, the longitude resolution (as determined by the time constant and the bandwidth [dispersion] smearing) of the data was a small fraction of the overall pulse width. Each spectrum was normalized by the square of the level of the average profile so that it represents a normalized second-moment (variance density) spectrum[3] and averaged over the total length of data available. For display purposes the spectra were smoothed over several resolution cells in frequency and over two or more resolution cells in longitude. Zero levels are not specified in the displayed spectra since our interest is in deviations from a "white" or nearly "white" continuum, i.e., nonrandom behavior. As discussed in Paper I, the area under a spectral feature, and above the continuum, is proportional to the contribution by the *quasi*-periodic process to the total variance of the signal about its mean, while the square root of this quantity is a fractional modulation index. Thus the level of correlated fluctuations within a given range of time scales can be directly discerned from the spectra.

Interstellar scintillation is an important factor in the fluctuation spectra of many pulsars. At about 400 MHz it has the effect of producing a "tail" at low frequency which cannot vary with pulse longitude. Fluctuations due to scintillation are suppressed by use of bandwidths which are large compared with the correlation bandwidth of the phenomenon and are not apparent in spectra which have been calculated coherently over intervals short compared with the correlation time. Examples of both types of suppression are encountered below.

Fluctuation spectra for PSR 0301+19 are given in figure 2*a*. A broad feature occurs in the spectrum of component I centered near 0.15 cycles per pulse period (c/P_1) while in component II the feature appears to be spread from 0.1 to 0.35 c/P_1 and lacks a central peak. In both cases the feature is related to linearly drifting subpulses (Schönhardt and Sieber 1973) with $P_3 \sim 6.4\,P_1$ and a drift rate of about $-1°$ of longitude per pulse period ($°/P_1$). The difference of the spectrum in the two components indicates that, while subpulses seem to drift across the full width of the pulse, they appear more erratic in component II than in component I. A similar difference in the subpulses between

[3] In the notation of Paper I the normalized spectra are written as $P'(\phi_j, f_m) = P(\phi_j, f_m)/\langle I(\phi_j, t_k)\rangle_k^2$, where ϕ is the pulsar longitude (arbitrary zero), f is the fluctuation frequency, t is time, P is the unnormalized spectrum, I is the total intensity data, and $\langle\ \rangle_k$ denotes an average over k; $\theta(\phi_j, f_m)$ is the set of phases associated with the complex spectra.

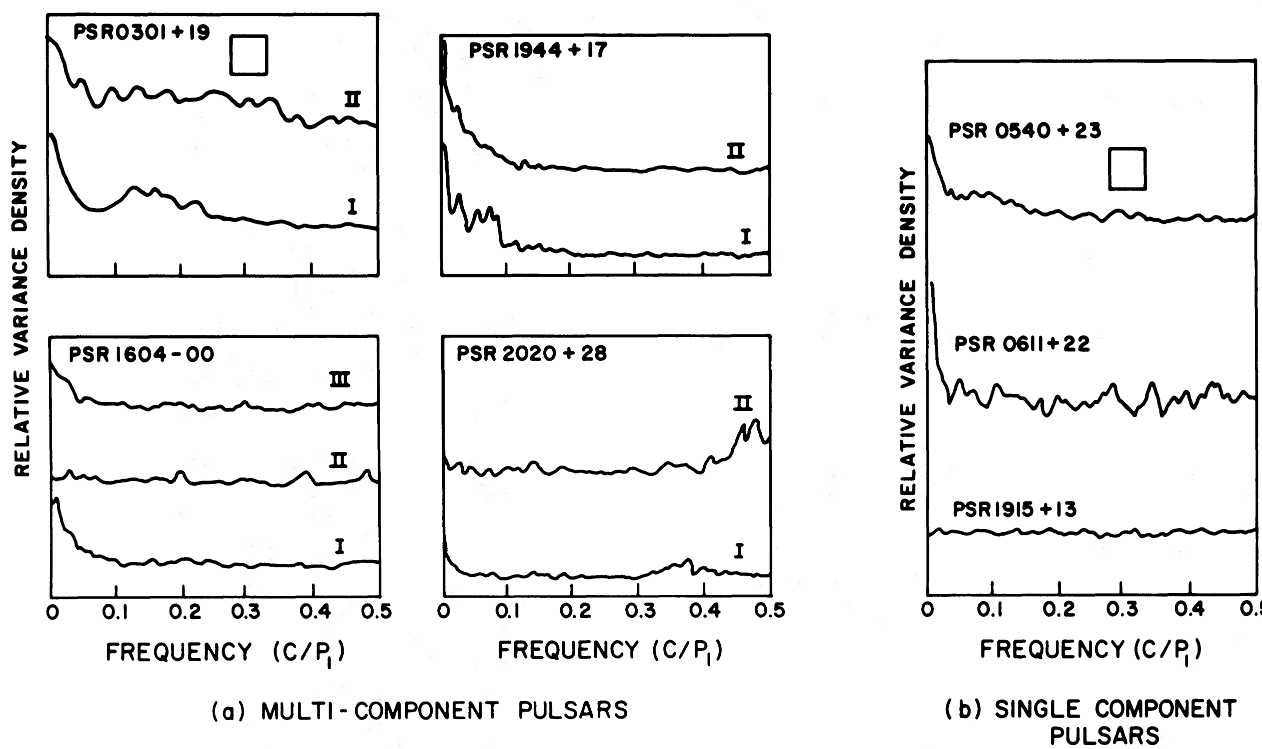

FIG. 2.—Fluctuation spectra for seven pulsars. Four sets of spectra are given in (*a*) for objects with more than one component; a single spectrum is given in (*b*) for three objects with one component. Abscissa scales are in cycles per pulse period (c/P_1). The area of the box in each figure corresponds to a fractional modulation index (see text) of 0.10, 0.10, 0.50, and 0.25 for PSRs 0301+19, 1604−00, 1944+17, and 2020+28, respectively, in (*a*); and 0.25, 0.05, and 0.25 for PSRs 0540+23, 0611+22, and 1915+13, respectively, in (*b*).

two halves of the average wave form is also found in PSR 2016+28 (Paper I). Both interstellar scintillation and pulse nulling phenomena (Backer 1970*b*) probably contribute to the enhancement of the spectra below 0.05 c/P_1.

PSR 1604−00 appears to have three components in its total intensity profile at the positions indicated in figure 1. The fluctuation spectra for components I and III both exhibit a substantial low-frequency feature which is absent in component II. The apparent absence of scintillation in component II then implies that the low-frequency fluctuations are intrinsic to the pulsar. (The pulsar's small dispersion measure is suggestive of a scintillation correlation time which exceeds the length of the transform.) Displays of the data reveal that the pulsar's emission is characterized by two principal modes: one in which components I and II are enhanced and III is quiet, and a second with radiation predominantly in components II and III. While the object appears to spend comparable amounts of time in each mode, it is given to shorter bursts in the first (components I and II) mode, which may account for the low-frequency enhancement in the spectrum of component I.

The fluctuation spectra for PSR 1944+17 at frequencies below 0.2 c/P_1 also depend on longitude. In component I the spectrum consists of a number of features superposed on an inverse-frequency "tail," while in component II there is only the inverse-frequency "tail" (see fig. 2*a*). The spectra for the leading and trailing edges of the profile display some but not all of the low-frequency properties of the component I spectrum in figure 2*a*. PSR 1944+17 data exhibits an unusual variety of phenomena: the pulsar generally emits bursts of pulses with a separation of 50–100 P_1 and a duty cycle of less than 0.25. Since the bursts usually start and stop abruptly, a substantial part of the low-frequency excess evident in figure 2*a* is the result of variations in the emitted radiation, and not of interstellar scintillation. Within some bursts linearly drifting subpulses are observed with $P_3 \sim 20\, P_1$, a value which is consistent with the several features in the component I spectrum, and with drift rates near $-0\overset{\circ}{.}85/P_1$. Within other bursts the drifting-subpulse behavior does not occur—often there are subpulses at the longitudes of one or both of the unresolved components in the average profile.

The two components of PSR 2020+28 exhibit quite different features in their fluctuation spectra near 0.5 c/P_1 (see fig. 2*a*). In component II the features near 0.47 c/P_1 are strong and narrow while the feature near 0.36 c/P_1 in component I is less well defined (see also Schönhardt and Sieber 1973). Data displays show repeated bursts of subpulses spaced by 2 to 3 P_1 which in component I exhibit no systematic drift direction while in component II resemble the even-odd emission of PSR 2303+30 as described in Paper I and by Rankin, Campbell, and Backer (1974). Although the two-component pulse profile of PSR 2020+28 resembles that of PSRs 0301+19, 0525+21, 1133+16, and others, the independence of the fluctuation properties in the two components suggests that it should not be classified with the PSR 0301+19 type pulsar. In fact, both the present discussion and the polarization properties, which will be discussed in a later paper, suggest that in PSR 2020+28 we are observing two independent regions of radiation, which individually behave as typical single-component objects.

Both the average wave form and the fluctuation spectra of PSR 0540+23 indicate a single component. The excess of fluctuations below 0.03 c/P_1 in figure 2*b* is presumably due to interstellar scintillation while that between 0.03 and 0.16 c/P_1 is probably the result of subpulse modulation. The solar elongation angle was greater than 90° at the time of the observations and hence the modulation index due to interplanetary scintillation at comparable fluctuation frequencies for this ecliptic plane object should be less than 0.05 (Harris, Zeissig, and Lovelace 1970). The object is not strong enough to facilitate investigation of subpulse phenomena in detail. The spectrum of PSR 0611+22 is similar to that of PSR 0540+23 except that there is no indication of correlated subpulse activity (see fig. 2*b*); the low-frequency enhancement is again presumably the result of interstellar scintillation. Finally, it may be seen in figure 2*b* that PSR 1915+13 exhibits a completely featureless spectrum. The absence of scintillation probably results from use of a bandwidth in excess of the correlation bandwidth.

The fluctuation spectrum of PSR 0943+10 in figure 3 exhibits a prominent feature at 0.461 ± 0.010 c/P_1 as well as a weak feature at 0.078 ± 0.020 c/P_1 which is precisely where the alias response of the second harmonic of the prominent feature is expected. In the discussion below it is shown that the prominent feature arises from linearly drifting subpulses and hence that a second harmonic response is expected. Since the feature at 0.461 c/P_1 is strong and narrow, the phase of the drifting subpulses as a function of longitude can be investigated.

In figure 4 an average phase function $\theta(\phi_j)$ for the feature at 0.461 c/P_1 is given along with the average pulse profile. The phase was averaged over frequencies f_m between 0.457 and 0.465 c/P_1 weighting the phasor $\exp\{i\theta(\phi_j, f_m)\}$ according to the average quantity $\langle P'(\phi_j, f_m)\rangle_j$. Figure 4 shows that the phase (or equivalently, the time origin of the periodic fluctuations) increases uniformly across the pulse indicating the existence of linearly drifting subpulses with $P_3 \sim 2.2\, P_1$ and a drift rate of $+4\overset{\circ}{.}2/P_1$. This result contrasts sharply with the interpretation of Taylor and Huguenin (1971) who suggested both that P_3 is associated with the weak feature in their fluctuation spectrum at 0.065 ± 0.005 c/P_1 and that there is an additional "alternate pulse modulation" which is related to the prominent spectral feature at 0.477 ± 0.003 c/P_1. Perhaps the center frequencies and widths of the features vary with time and/or radio frequency as observed in other objects (§ IV). It is not possible to further resolve the discrepancy between the two sets of measurements. Taylor and Huguenin's spectrum does not appear to exhibit a harmonic relation between the two features, while in our own case it is possible to

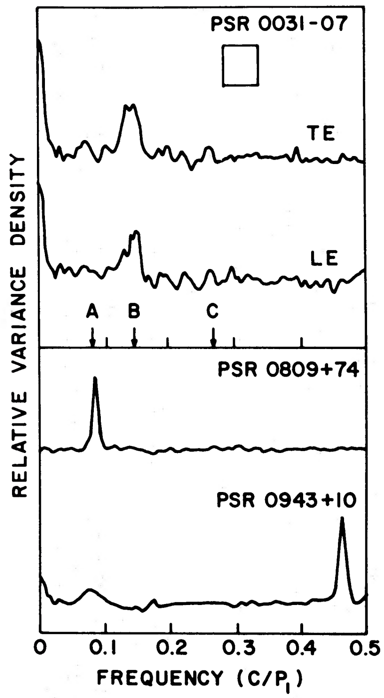

FIG. 3.—Fluctuation spectra for three pulsars. Spectra for both the leading (LE) and trailing (TE) halves of the pulse are given for PSR 0031−07, and the frequencies of the three drifting-subpulse modes are noted on the abscissa axis (A, B, C). The abscissa scale is in cycles per pulse period (c/P_1). The area of the box at the top of the figure corresponds to a fractional modulation index (see text) of 0.50, 0.50, and 0.25 for PSRs 0031−07, 0809+74, and 0943+10, respectively.

avoid the conclusion of a harmonic relation only by assuming that the relationship is fortuitous.

PSR 0031−07 fluctuation spectra for both the leading half (LE) and the trailing half (TE) of the pulse at 283 MHz are given in figure 3. The width of the feature at 0.15 c/P_1 is somewhat different in the spectra from the two halves of the pulse. Simultaneous observations were recorded at three frequencies (see table 1) to investigate the radio frequency dependence of the subpulse patterns. Figure 5 gives phase functions which have been corrected for dispersion at each of the three radio frequencies. (The phase data are plotted only when their corresponding amplitudes are statistically significant relative to the "white" continuum level.) The set of functions is typical of fluctuation frequencies between 0.123 and 0.162 $c/P_1(B)$; the phase behavior demonstrates that the feature is produced by linearly drifting subpulses with $P_3 \sim 6.9\ P_1$ and with a drift rate of $-3^\circ.1/P_1$, values which are in agreement with direct measurements by Huguenin, Taylor, and Troland (1970). Furthermore, there is no obvious dependence of the drift rate on radio frequency between 283 and 490 MHz. The other modes of P_3 discussed by Huguenin *et al.* (*A*, *C*) do not appear clearly in the spectra of figure 3.

Figure 3 also gives a typical fluctuation spectrum for PSR 0809+74; the fluctuation properties are found to be independent of pulse longitude. The feature has a period, P_3, of $10.9 \pm 0.2\ P_1$, which agrees with measurements in 1969–1970 by Sutton *et al.* (1970) and Taylor and Huguenin (1971). Phase functions for one block of data recorded simultaneously at 290, 325, 430, and 495 MHz are given in figure 5: no averaging proved necessary in that the

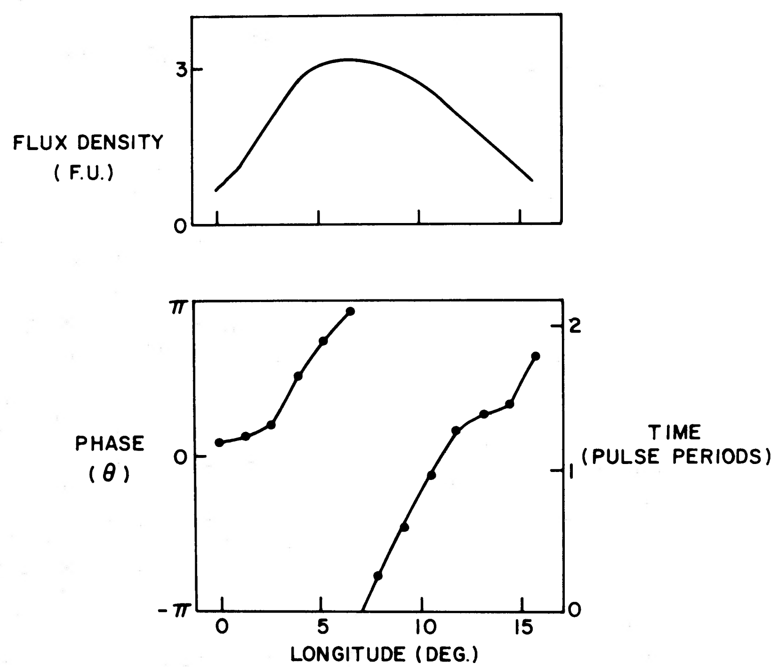

FIG. 4.—Pulse profile (*top*) and phase function (*bottom*) for PSR 0943+10. The phase function has been averaged over the spectral feature at 0.461 c/P_1. Time is related to phase by a constant factor $2\pi/0.461\ c/P_1$.

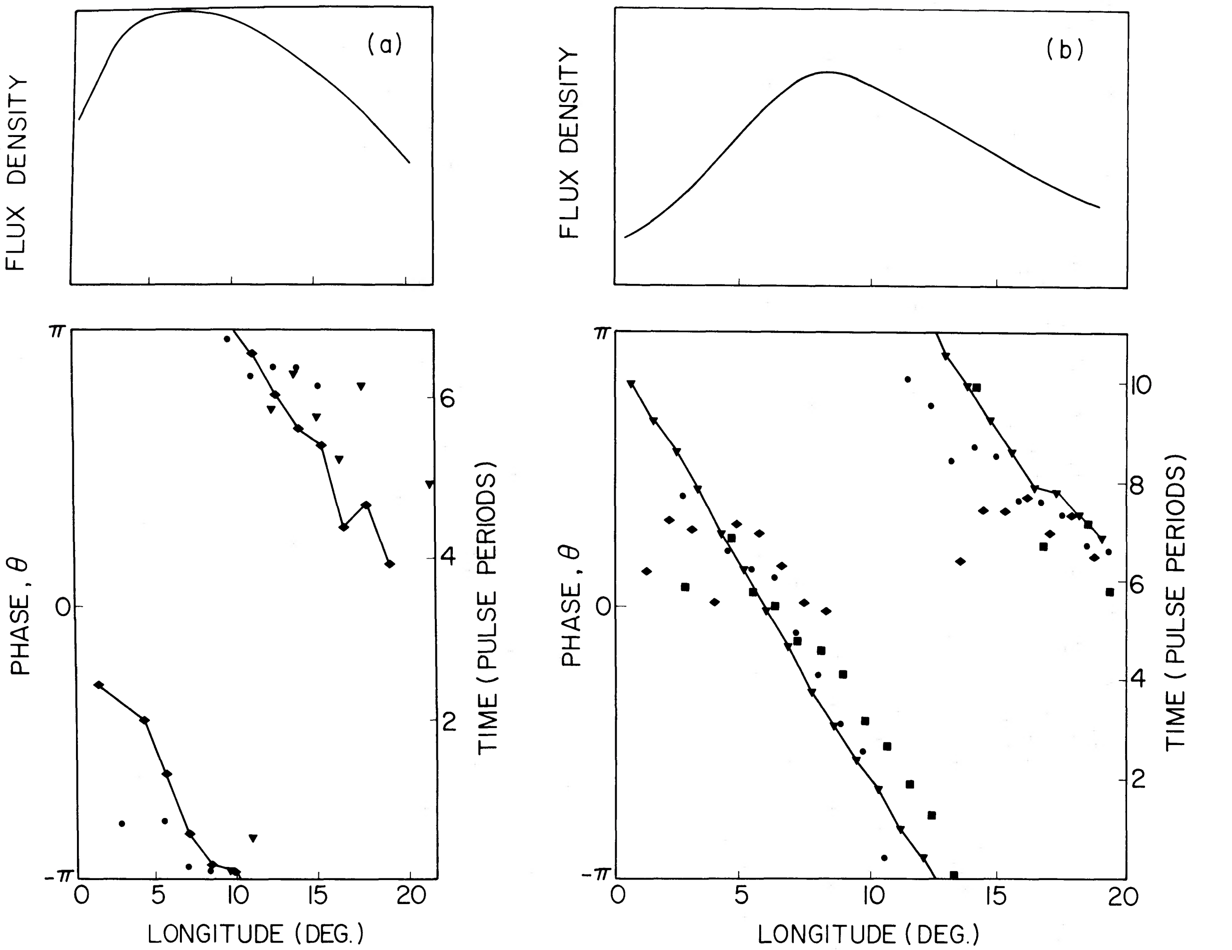

FIG. 5.—Average pulse profiles (*top*) and phase functions (*bottom*) for (*a*) PSR 0031−07 and (*b*) PSR 0809+74. The symbols refer to simultaneous data at the following frequencies: ◇, −290 MHz; ○, 325 MHz; □, 430 MHz; ▽, 495 MHz. Time is related to phase by constants $2\pi/0.142$ c/P_1 and $2\pi/0.092$ c/P_1 in (*a*) and (*b*), respectively.

feature is strong and extends over only a few resolution cells. The behavior of the phase with longitude is clearly indicative of linearly drifting subpulses with $P_3 \sim 10.9\, P_1$ and a drift rate of $-1.^\circ2/P_1$—which implies a longitude spacing of subpulses (P_2) of $13^\circ \pm 2^\circ$ or 47 ± 6 ms. This value of P_2 disagrees with direct measurements at an earlier epoch, and at a lower radio frequency, by Sutton *et al.* and Cole (1970), who find typical P_2 values of 55 ms. While the discrepancy is not excessive in that systematic variations of the pulsar's fluctuation properties have been discussed both by Cole and by Page (1973), a secular change or a dependence on radio frequency of P_2 cannot be eliminated. The phase function results for both PSR 0031−07 and PSR 0809+74 above further emphasize the broad-band nature of the subpulse emission process (i.e., a bandwidth of about 200 MHz at about 400 MHz); a similar situation was found to obtain for PSR 1919+21 and PSR 0834+06 in Paper I and for PSR 0809+74 by Page (1973).

IV. DISCUSSION

The foregoing investigation has provided further examples of well-known subpulse modulation phenomena as well as several new results. Of particular note are pulsars PSR 0943+10 which exhibits highly organized subpulse emission and PSR 1915+13 and PSR 0611+22 which show no evidence of ordered emission whatsoever. More typical are the remainder of the objects which show correlated subpulse structure but not all the time nor always at a conspicuous level. Two objects exhibited unusual subpulse properties: PSR 1944+17 switches abruptly between a drifting-subpulse mode and a more chaotic mode; and PSR 2020+28 has a total-intensity profile similar to PSRs 0301+19, 0525+21, and others, yet exhibits fluctuation properties in its two components which are totally different, unlike any object heretofore encountered. The phase information from fluctuation spectra has been used to quantitatively study the drifting-subpulse structure in PSR 0943+10 and two further objects, PSR 0031−07 and PSR 0809+74. The availability of multifrequency observations in the case of the latter two objects has again demonstrated the broad-band nature of the subpulse emission morphology.

Pulsars exhibit a variety of fluctuation phenomena in the domain of 100 P_1. PSRs 1237+25, 0329+54, and perhaps 1604−00 abruptly change their mode of emission and remain in a second mode for 10–1000 P_1 (Backer 1970*c*; Lyne 1971; Hesse 1973; this paper). PSRs 0525+21, 1133+16, 1237+25 and 1919+21 have periodic pulse-energy modulations with characteristic periods of 40–100 P_1 (Lang 1969; Backer 1973). Random bursts of pulses with durations and/or spacings of several tens of periods occur in PSRs 0031−07 (Huguenin *et al.* 1970), 0950+08 (Paper I), 0540+23, 1944+17 (this paper), and others. Finally, P_3, the spacing in time of drifting-subpulse sequences, has been found to jump on time scales of 100 P_1 between closely spaced values in PSR 1237+25 and PSR 1919+21 (Paper I) and between multiples of the predominant P_3 in PSR 0031−07 (Huguenin *et al.* 1970). Because the time scales of these varied phenomena are similar, it is possible that they are different manifestations of a single physical process. This suggestion is supported by the fact that each of the effects involves a form of memory having a characteristic duration: memory of how strong the emission will be, memory of the orientation of the emitted beam, or memory of the repetition period of the drifting subpulses. In objects with more random subpulse behavior it is possible that these long period effects extend down to intervals shorter than 10 P_1 and hence destroy correlated subpulse activity. Without a specific model in mind, it is not possible to attribute the memory exhibited in sequences of pulses to any definite plasma–electromagnetic-field configuration.

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D. C. Backer: Code 693, Radio Astronomy Branch, Goddard Space Flight Center, Greenbelt, MD 20770

J. M. Rankin: Department of Astronomy, Cornell University, Ithaca, NY 13850

D. B. Campbell: Haystack Observatory, Westford, MA 01886