

# ARECIBO MULTI-FREQUENCY TIME-ALIGNED PULSAR AVERAGE-PROFILE AND POLARIZATION DATABASE

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## ABSTRACT

We present Arecibo time-aligned, total intensity profiles for 46 pulsars over an unusually wide range of radio frequencies and multi-frequency, polarization-angle density diagrams and/or polarization profiles for 58 pulsars at some or all of the frequencies 50, 111/130, 430 and 1400 MHz. The frequency-dependent dispersion delay has been removed. In order to align the profiles for study of their spectral evolution and wherever possible the profiles of each pulsar are displayed on the same longitude scale. Most of the pulsars within Arecibo's declination range that are sufficiently bright for such spectral or single pulse analysis are included in this survey—and the calibrated pulse sequences are available by web download for further study.

*Subject headings:* pulsars:general — polarization

## 1. INTRODUCTION

As part of a program to study the geometrical constraints on the emission mechanism of pulsars, we have recorded a set of total intensity average profiles at a number of frequencies from 25 to 4800 MHz at the Arecibo Observatory. The data were time-tagged so that through use of a suitable timing model for the pulsar, we were able to shift the arrival times of the pulses, modulo one stellar rotation period, to the solar system barycenter. Then by assuming a dispersion measure  $DM$ , we shifted all the profiles to infinite frequency arrival time. In many cases the dispersion measure was the only free parameter for alignment. The techniques used were similar to those of Hankins & Rickett (1986). In addition we have observed a large overlapping group of pulsars at selected frequencies with full Stokes' parameters. We present these two sets of observations in a coordinated fashion, so that they can be used for studies of the pulsar magnetospheric structure.

## 2. OBSERVATIONS

The two main programs of time-aligned total-power (P868) and polarimetric (P1260) observations presented here were made at the Arecibo Observatory during a number of sessions between 1988 and 1992. A few observations from previous polarimetric surveys (P110 at 430 MHz and P467 at 21 cm), however, are also presented in order to extend the completeness of our coverage.

### 2.1. Multiple frequency total intensity profiles

For the total intensity observation program, circularly polarized feeds were used at 430, 1400, 2380, and 4800 MHz and crossed-dipole linearly polarized feeds (with circular hybrids) were used at 130/111, 49, and 26 MHz.

All profiles were obtained using the then existing Arecibo 40-MHz Correlator (Hagen 1987); the autocorrelation functions (ACFs) were accumulated into typically 1024 pulsar-synchronous phase bins spanning one pulsar period, and then dumped to tape every two minutes.

These ACFs were then Fourier transformed off-line to obtain power spectra, and the appropriate dispersion delays between adjacent spectral channels were removed. The profiles from all spectral channels were then co-added to produce a dedispersed average profile. The two-minute averages were edited to remove interference and other corruption, then synchronously added together to form (in many cases) a high-signal-to-noise ratio (hereafter S/N) average profile. The time-tag of the first sample was used to relate the times of arrival to the solar system barycenter in terms of the pulsar phase at infinite frequency. Thus if the dispersion delays strictly obey the cold plasma dispersion law, then the pulses align in pulse phase exactly as they would if the observer were in the immediate pulsar neighborhood. The dispersion measure  $DM$  is, however, a free parameter in the phase alignment, and we found that adjustments from the tabulated values (Taylor, Manchester & Lyne 1993, Manchester 2002) were required for optimal alignment for many of the pulsars. The dispersion measures and timing models used for alignment are listed in Table 1.

To test and monitor the timing stability of the system during each observing session, we recorded a reference profile from a strong pulsar using the same sampling parameters each time. From these profiles systematic timing offsets could be determined and applied to data from other pulsars. Since it was not possible to observe throughout the whole range of frequencies in a single observing ses-

sion, we recorded reference profiles for each pulsar, usually at 430 MHz, to confirm its tabulated timing model. In a number of cases we had to make minor adjustments in the timing model to achieve alignments among profiles recorded at the same frequency. After any timing issues were resolved, the dispersion measure was adjusted to obtain pulse-phase alignment among profiles at different frequencies. Since the change in pulse phase  $\phi$  as a function of radio frequency  $\nu$ ,  $d\phi/d\nu \propto \nu^{-3}$ , we used the lowest frequency pairs with good S/N to determine any adjustment to *DM*.

The fiducial point of a pulse profile to be used for inter-frequency alignment depends upon the pulse shape. Usually aligning core components works well for pulsars with odd numbers of components. We aligned either the peak of the core component or the (symmetrical) half-power points for these pulsars. For double profiles, where the separation between the main components is clearly frequency dependent, we used the centroid between the two components.

## 2.2. Polarimetry

Most of the primary polarimetry observations were carried out during a set of sessions in October 1992; a few, however, come from earlier observations in March 1992 and January 1990. All used the then existing Arecibo 40-MHz Correlator, such that the average polarimetry was carried out in a continuous mode, whereas the pulse-sequence observations entailed use of special programs which gated the correlator synchronously with the pulsar. In both cases the basic data recorded at the telescope were the auto- and cross-correlation functions of the left- and right-hand channel voltages. The 21-cm observations used a 20-MHz bandwidth and the lower a maximum of 10-MHz at 430 MHz, 2.5 MHz at 111/130 MHz, and 625 kHz at 49 MHz. A minimum of 32 correlation lags were retained in order to reduce the dispersion delay across the bandpass to usually negligible levels. The resolution was then often essentially the correlator dump time for the pulse-sequence observations and the averaging-bin size for the profile-polarization measurements. These parameters are tabulated in Table 2. The Arecibo 40-MHz Correlator is described by Hagen (1987) and the continuous and gated observing software by Perillat (1988, 1992). The measured correlation functions were scaled, 3-level-sampling corrected, and Fourier transformed to produce raw Stokes parameters, which were in turn corrected (channel by channel) for dispersion, Faraday rotation, instrumental delays, and all of the known feed imperfections as determined by full-sky tracks of pulsar B1929+10 and other sources. These methods are more completely described in the Appendix. During the course of our analyses, we discovered that the instrumental polarization is highly frequency dependent, particularly at 430 MHz; therefore, the most recent observations represent some of the best calibrated ever made at the Arecibo Observatory. For some few, however, not all of the calibration information was available for one reason or another. We found, for instance, that interference rather easily corrupted our continuum-source observations, which are needed to determine the relative left- and right-hand channel gains, so as to calibrate the circular polarization *V*. In any case, Table 2 indicates this gain calibration with a “c” when a continuum source was used and

“n” when computed from the off-pulse noise level. The correction of the Stokes parameters for cross-coupling in the feed is denoted by a “p”.

Profile and single-pulse polarimetry were also carried out during these three sessions at 111.5/130 MHz and near 50 MHz. The techniques were virtually identical to those described above except that additional corrections were required for the changing ionospheric Faraday rotation and many fewer of our efforts to obtain reliable feed cross-coupling data were successful.

The older 430-MHz observations were carried out in the early 1970s with a single-channel polarimeter using various bandwidths and integration times as indicated by the particular star being observed; these are tabulated in Table 2. The polarimetry scheme is described in Rankin *et al.* (1975); and while the nominal 0.25% voltage amplitude of the feed crosscoupling—which can produce spurious circular polarization at typical levels of about 10% of the linear polarization—was known from radar observations, correction of the Stokes parameters was then impossible because the cross-coupling phase was unknown.

The older 1400-MHz observations were carried out in October 1981, again with a single-channel, adding polarimeter. Here, the bandwidths ranged up to 40 MHz, with these and the integration times chosen to provide a resolution of about a milliperiod. A serious effort was made for the first time to correct the measured Stokes parameters for instrumental cross-coupling distortion using the “orthogonal” approximation described by Stinebring *et al.* (1984).

In all cases we make no effort to give absolute polarization position angles. Therefore, the position angles in our polarization displays are arbitrary within a constant value.

## 3. RESULTS

Our results are summarized in the tables and figures. Table 1 gives the period, period derivative, timing epoch and dispersion-measure value used for the multi-frequency alignments, and Tables 2 & 3 give the observations date, configuration, resolution and rotation-measure value used in the polarimetric analyses. Comments on Tables 1 & 2 are given in Table 4.

Rotation-measure values were generally taken from Manchester *et al.* (2002); however, those given in bold-face with errors in Tables 2 & 3 were determined in the course of our polarimetric analyses by fitting the polarization position-angle swing across the available bandwidth. The errors in the rotation-measure values were computed from the position-angle errors which in turn were computed from the off-pulse noise level and represent two standard deviations.

The combined multi-frequency and polarimetry results are presented in approximate Right Ascension order in Figures 1 through 17 in order to facilitate intercomparison. The multi-frequency profiles are normally positioned in the lefthand columns and the 430- and 1400-MHz polarization displays in the central (C) and righthand (R) columns, where they are available—and in the half-dozen cases where both 111/130- and 50-MHz polarimetry is also available, these are given in the center and righthand columns of the following row. Details of the multi-

TABLE 1  
ALIGNMENT PERIODS, PERIOD DERIVATIVES, REFERENCE EPOCH, AND DISPERSION MEASURES

Pulsar	$P$ (s)	$\dot{P} \times 10^{-15}$ (s/s)	Epoch (MJD)	$DM$ ( $\text{pc cm}^{-3}$ )	Reference	Note	Figure
B0301+19	1.3875836665891	1.29613	42325.500	15.650	C,C,C,C	<i>a.</i>	1
B0523+11	0.354437595275	0.07362	48382.000	79.294	M,M,M,M		1
B0525+21	3.74549702041	40.0565	41993.500	51.024	C,C,C,C	<i>b.</i>	1
B0540+23	0.2459740892957	15.42378	48382.000	77.698	M,M,M,M		2
B0611+22	0.33492505401	59.630	42881.000	96.86	M,M,M,H		2
B0626+24	0.476622653938	1.99705	48382.000	84.216	M,M,M,H	<i>c.</i>	2
B0656+14	0.384885025950	55.0134	48423.000	14.02	M,M,M,M	<i>d.</i>	3
B0751+32	1.44234944724	1.0802	43830.000	40.04	M,M,M,M	<i>e.</i>	3
B0820+02	0.864872751896	0.10366	43419.347	23.6	M,M,M,M	<i>f.</i>	3
B0823+26	0.53066061717618	1.714776	47165.705796	19.4750	Mc,Mc,Mc,H		4
B0834+06	1.273768080098	6.7995	48362.00	12.8579	H,M,M,H	<i>g.</i>	4
B0919+06	0.43061431085	13.7248	43890.786	27.3091	H,T,T,T	<i>h.</i>	5
B0940+16	1.08741772517	0.1	48500.00	20.5	M,M,M,H		5
B0943+10	1.097704890211	3.4884	45781.306	15.339	S,S,S,H	<i>i.</i>	6
B0950+08	0.253065180710	0.229314	47165.7973	2.9701	Mc,Mc,Mc,H		6
B1133+16	1.187913314434	3.7341	47177.902	4.8472	Mc,Mc,Mc,H	<i>j.</i>	7
B1237+25	1.38244915690	0.95954	47177.91	9.277	Mc,Mc,Mc,H	<i>k.</i>	7
B1530+27	1.124835519553	0.803	46387.700	14.67	H,M,M,H		8
B1541+09	0.74844817748	0.43030	42304.00	34.99	T,T,T,T		8
B1604-00	0.4218162717899	0.30610	48419.00	10.6831	H,M,M,H		8
B1612+07	1.2068002120	2.357	43891.065	21.5	M,M,M,M		8 <i>b</i>
B1633+24	0.490506485351	0.1195	46075.099	24.265	M,M,M,H		8 <i>c</i>
B1737+13	0.803049715913	1.454	43892.616	48.73	H,M,M,H		9
B1821+05	0.752906449119	0.225	43890.159	66.7827	H,M,M,H		9
B1839+09	0.38131888145508	1.0916	43890.169	49.132	H,M,M,H		9
B1842+14	0.375462510949	1.866	43986.911	41.6	H,M,M,M		10
B1900+01	0.72930163274	4.0322	42345.50	245.	M,M,M,H		10
B1907+00	1.01694545765	5.5151	42647.00	111.	M,M,M,M		10 <i>e</i>
B1907+03	2.330260471	4.53	43984.933	83.5	M,M,M,H		10 <i>f</i>
B1915+13	0.19462634149	7.20286	42302.00	94.494	T,T,T,M		11
B1918+19	0.82103460383	0.8952	42577.00	153.48	M,M,M,H		11 <i>g</i>
B1919+21	1.337301192269	1.34809	40689.95	12.4309	M,M,M,M		11
B1920+21	1.07791915514	8.1899	42547.00	217.1	M,M,M,M		11 <i>i</i>
B1929+10	0.226517153473	1.15675	41704.00	3.176	H,T,T,T		12
B1933+16	0.358736247894	6.00354	42265.00	158.53	H,M,M,M		12
B1944+17	0.44061846173	0.02404	41501.00	16.11	T,T,T,M		12
B1952+29	0.426676786488	0.00164	48415.00	7.86	M,M,M,H		13
B2016+28	0.557953408114	0.14720	40688.50	14.1965	C,C,C,H	<i>l.</i>	14
B2020+28	0.343401720116	1.8935	47018.182	24.623	H,M,M,H		14
B2044+15	1.1382856067	0.185	43890.254	39.71	M,M,M,H		14
B2110+27	1.202851149957	2.6225	46075.294	25.122	H,M,M,H		15
B2113+14	0.440152954660	0.290	43986.016	56.14	H,M,M,H		15
B2210+29	1.00459237450	0.4948	46074.83	74.6	M,M,M,H		16
B2303+30	1.575884744270	2.89567	42341.00	49.575	M,M,M,H	<i>m.</i>	16
B2315+21	1.444652673768	1.05	43987.099	20.865	H,M,M,H	<i>n.</i>	17

References. — C: Cordes, 1992, H: this work, M: Manchester, *et al.* 2002, Mc: McKinnon, 1990, T: Taylor, *et al.* 1993, S: Shibanova (1990)

frequency alignments and polarimetry are given in Tables 1 & 2. In several cases where no polarimetry was available, the multi-frequency results are interpolated into the sequence (Fig. 8 (top row), Fig. 10 center row, and Fig. 11

bottom left). Finally, Figures 18-19 give polarimetry results for those stars where only single-frequency observations were carried out, and these in turn are described in Table 3. The time resolution of the multifrequency profiles

TABLE 2

POLARIMETRY CONFIGURATION, CALIBRATION & ROTATION MEASURE INFORMATION FOR THE RESULTS IN THE CENTER (C)  
AND RIGHT (R) COLUMNS BELOW

Pulsar	Date C	Date R	Config C (MHz/ch)	Config R (MHz/ch)	Resol C (deg)	Resol R (deg)	$RM$ (rad-m <sup>2</sup> )	Note	Figure
B0301+19	05/01/74	20/10/92	2./1:c	20./32:cp	0.85	0.31	−8.3		1
B0523+11	17/10/92	20/10/92	1.25/32:cp	20./32:cp	0.41	0.41	78.7		1
B0525+21	01/04/74	11/10/81	2./1:c	20./1:cp	2.76	0.15	50.96		1
B0540+23	05/01/74	20/10/92	0.1/1:c	20./32:cp	1.19	0.38	77.58		2
B0611+22	19/10/92	20/10/92	5./32:cp	20./32:cp	0.85	0.38	67.		2
B0626+24	16/02/92	20/10/92	10./64:cp	20./32:cp	1.06	0.31	82.		2
B0656+14	12/02/92	17/02/92	10./32:cp	20./32:cp	0.43	0.37	22.		3
B0751+32	19/10/92	—	10./32:cp	—	0.32	—	−7.		3
B0820+02	19/10/92	20/10/92	10./32:cp	20./32:cp	0.36	0.36	13.		3
B0823+26	20/10/92	15/10/92	10./32:cp	20./32:cp	0.43	0.34	5.9		4
B0834+06	01/04/74	10/10/81	2./1:c	20./1:cp	0.76	0.22	3.9		4
	16/02/92	03/01/00	0.63/256:n	2.5/128:n	0.70	0.70		1.	4
B0919+06	20/10/92	11/10/81	10./32:cp	20./1:cp	0.74	0.68	27.25		5
	17/02/92	15/02/92	0.31/256:n	2.5/128:n	2.00	1.61		1.	5
B0940+16	17/10/92	—	10./32:cp	—	0.35	—	53.		5
B0943+10	17/01/00	19/10/92	2.5/64:	10./32:cp	1.18	0.33	13.3	1.	6
B0950+08	06/11/71	10/10/81	10./1:c	20./1:cp	0.88	0.28	2.969		6
	15/02/92	—	0.63/128:n	???:	1.99	—		1.	6
B1133+16	19/10/92	16/10/92	10./32:cp	20./32:cp	0.31	0.37	3.9		7
	16/02/92	17/01/90	0.63/128:n	1.25/128:n	0.50	0.70		1.	7
B1237+25	06/01/74	11/10/81	2./1:c	20./1:cp	0.50	0.10	9.296		7
	—	15/02/92	—	2.5/64:	—	0.35		1,2.	7d
B1541+09	14/02/92	17/01/00	2.5/256:	10./32:cp	1.15	1.45	21.	1.	8
B1604−00	14/02/92	11/02/73	2.5/128:	10./1:c	1.20	1.91	6.5	1.	8
B1737+13	20/10/92	24/10/92	10./32:cp	20./32:cp	0.71	0.36	73.		9
B1821+05	05/01/00	19/10/92	5./64:cp	20./32:cp	0.34	0.36	145.		9
B1839+09	—	23/10/92	—	20./32:cp	—	0.38	53.		9
B1842+14	—	23/10/92	—	20./32:cp	—	0.39	121.		10
B1907+10	21/10/73	24/10/92	0.05/1:c	20./32:cp	0.98	0.51	540.		10
B1915+13	07/09/73	22/10/92	0.1/1:c	20./32:cp	1.82	0.33	233.		11
B1919+21	05/01/00	22/10/92	10./32:cp	20./32:cp	0.19	0.33	−37.		11
B1920+21	—	19/10/92	—	20./32:cp	—	0.34	282.		11
B1929+10	24/12/74	18/10/92	2./1:c	20./32:cp	1.05	0.49	−6.1		12
B1933+16	24/07/73	—	0.1/1:c	—	1.66	—	−1.9		12
B1944+17	27/07/73	23/10/92	2./1:c	20./32:cp	2.78	0.33	−28.		12
B1946+35	08/05/74	18/10/92	0.25/1:c	20./32:cp	1.69	0.35	−78.		13
B1952+29	15/02/00	—	20./32:cp	—	0.35	—	−18.		13
B2002+31	28/07/73	22/10/92	0.25/1:	20./32:cp	1.04	0.34	30.		13
B2016+28	15/10/92	18/10/92	10./32:cp	20./32:cp	0.39	0.39	−34.6		14
B2020+28	16/10/92	18/10/92	10./32:cp	20./32:cp	0.43	0.37	−74.8		14
B2044+15	14/02/92	19/10/92	10./64:cp	20./32:cp	0.40	0.32	−101.		14
B2053+21	20/10/92	18/10/92	10./64:cp	20./32:cp	0.35	0.35	−100.±7.		15
B2110+27	14/02/92	22/10/92	10./32:cp	20./32:cp	0.35	0.30	−65.		15
B2113+14	29/10/92	23/10/92	5./32:cp	20./32:cp	0.74	0.37	−25.		15
B2210+29	16/10/92	23/10/92	10./32:cp	20./32:cp	0.43	0.36	−175.±15.		16
B2303+30	15/10/92	18/10/92	10./32:cp	20./32:cp	0.37	0.28	−84.		16
	—	22/10/92	—	2.5/128:c	—	0.84		1.	16
B2315+21	14/02/92	19/10/92	10./32:cp	20./32:cp	0.35	0.35	−37.		17

is indicated by a set of three horizontal bars plotted on the left side of the profiles. The upper bar denotes the phase shift which would result from a change of dispersion measure of 0.01, 0.1, or 1.0 pc cm<sup>−3</sup>. The middle bar, labeled

“BW” shows the time resolution limited by the dispersion sweep time,  $\tau_{DM} = DM \Delta\nu / (1.205 \times 10^{-16} \nu^3)$ , across the receiver bandwidth,  $\Delta\nu$ , tuned to frequency  $\nu$ . The bottom bar shows the integration time constant used for the



TABLE 3  
MISCELLANEOUS PULSAR POLARIMETRY DATA (FIGS. 18 & 19).

Pulsar	Date	Config (MHz/ch)	Resol (deg)	$RM$ (rad-m <sup>2</sup> )
B0045+33	16/10/92	10./32:cp	0.40	?
B0609+37	17/10/92	5./32:cp	0.53	8.5
B1845-01	24/10/92	20./32:cp	0.39	580.
B1859+03	18/10/92	20./32:cp	0.66	-237.4
B1900+05	24/10/92	20./32:cp	0.37	-113.
B1910+20	15/02/92	10./64:cp	0.35	148.
B1917+00	08/05/74	0.5/1:c	1.34	—
B1919+14	20/10/92	5./64:cp	0.44	<b>275.±60..</b>
B1923+04	06/01/00	5./32:	0.55	-37.
B1951+32	04/01/00	20./32:cp	2.81	-182.
B2000+32	20/10/92	5./64:cp	1.03	20.
B2028+22	26/10/92	5./64:cp	0.40	<b>-195.±25.</b>
B2034+19	26/10/92	10./32:cp	0.35	<b>-98.5±8.</b>
B2053+36	24/10/92	20./32:cp	0.66	-68.
B2122+13	16/10/92	10./32:cp	0.51	<b>-48.3±3.6</b>

TABLE 4  
NOTES TO TABLES 1 – 2

Pulsar	Note
B0301+19	<i>a.</i> 2380-MHz profile shifted by -6.17 ms to correct systematic offset.
B0525+21	<i>b.</i> 2380-MHz profile shifted by -7.32 ms to correct systematic offset.
B0626+24	<i>c.</i> 2380-MHz and 430-MHz profiles shifted by 9.25 and 40.91 ms to correct systematic offset. DM determined from 1408 to 111.5-MHz alignment. The “bump” preceding the 430-MHz pulse at longitude -18° is probably spurious.
B0656+14	<i>d.</i> 430-MHz profile shifted by -11.29 ms to correct systematic offset.
B0751+32	<i>e.</i> Arbitrary alignment by profile centroids.
B0820+02	<i>f.</i> Arbitrary alignment by profile centroids.
B0834+06	<i>g.</i> 2380-MHz profile shifted by 8.40 ms to correct systematic offset.
B0919+06	<i>h.</i> 4880 and 111.5-MHz profiles shifted by -1.42 and -9.93 ms to correct systematic offsets.
B0943+10	<i>i.</i> The two 111.5-MHz profiles, showing the two modes of B0943+10, were recorded 1 year apart. They align well using Shabanova’s (1990) timing model. The 430 and 24.8-MHz profiles, recorded 4 days apart, also align well, so the DM determination is based on this frequency pair. Then these two profiles were shifted by 5.92 ms to align with the 111.5-MHz profiles, and the 49.2-MHz profile is arbitrarily shifted by 26.1 ms to align its centroid.
B1133+16	<i>j.</i> 49.2-MHz profile shifted by -9.48 ms to correct systematic offset.
B1237+25	<i>k.</i> 4880-MHz profile shifted by 15.1 ms to correct systematic offset.
B2016+28	<i>l.</i> The dramatic pulse shape change between 111.5 and 430 MHz is consistently observed on different days. The DM used for alignment was adjusted to align the 49.2 and 111.5-MHz profile peaks, though if the profile is actually bifurcating at low frequencies, this alignment may be incorrect.
B2303+30	<i>m.</i> 4880 and 1408-MHz profiles shifted by -39.40 ms to correct systematic offset.
B2315+21	<i>n.</i> 2380-MHz profile shifted by -37.12 ms to correct systematic offset.
—	<i>1.</i> For the observations at 11/130 MHz and 50 MHz, a search was carried out over a large range of rotation measure to maximize the linear polarization before combining the individual frequency channels, and the successive two-minute scans were rotated to a common polarization angle before combining them. This was found necessary because of a changing effective (ionospheric?) rotation measure with time.
—	<i>2.</i> The 130-MHz polarization display for B1237+25 has been placed in the left column just above the corresponding multifrequency plot.

plot. On the left side of the multifrequency profile plots an error bar is plotted to show the range of 2 standard deviations of the off-pulse noise level.

For the polarization plots the total intensity, linear and

circular polarizations are depicted by solid, dashed and dotted lines, respectively. The solid vertical bars indicate the range of 3 standard deviations of the off-pulse noise. Where present, the time resolution, including the effects of

dispersion across the receiver band and the post integration time constant are shown by a horizontal bar. In the lower part of each polarization plot the average linear polarization position angle is shown wherever the linear polarization exceeds two times the off-pulse noise level. Error bars for the position angle are shown for  $\pm 2\sigma$  uncertainties due to the estimation error of the linear polarization. For many of the pulsars individual pulse records were available. For these pulsars the position angle of each sample which exceeded 2 times the off-pulse noise is plotted as a dot. This type of plot allows study of polarization moding behavior (Manchester, Taylor & Huguenin 1975, Backer & Rankin 1980).

We wish to acknowledge Dan Stinebring's assistance in making many of the profile observations as well as making available some of our 1981 polarimetry and that of

Amy Carlow, Vera Izvekova, N. Rathnasree, Svetlana Suleymanova, and Kyriaki Xilouris in carrying out some of the 1990/1992 observations. It is a pleasure to thank Phil Perillat without whose remarkable software for the Arecibo 40-MHz Correlator this work would have been impossible. We thank Mark McKinnon of NRAO for determining timing models for many of these pulsars, Dipanjan Mitra for alignment of some of the profiles, the Pushchino pulsar group of the Lebedev Physical Institute for 61 and 102-MHz profiles, and J. A. Phillips for the 25-MHz profiles. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University for the National Science Foundation. This material is based upon work supported by the National Science Foundation under Grant AST-8917722, AST-9618408, AST-9986754 and AST-0139641.

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The following is a list of the pulsars mentioned to comply with AAST<sub>E</sub>X§2.15.3. It doesn't print in the right place.  
 B0045+33 B0301+19 B0523+11 B0525+21 B0540+23 B0609+37 B0611+22 B0626+24 B0656+14 B0751+32 B0820+02  
 B0823+26 B0834+06 B0919+06 B0940+16 B0943+10 B0950+08 B1133+16 B1237+25 B1530+27 B1541+09 B1604-  
 00 B1612+07 B1633+24 B1737+13 B1821+05 B1822-09 !!!!! B1839+09 B1842+14 B1859+03 B1900+01 B1900+05  
 B1907+00 B1907+03 B1907+10 B1910+20 B1915+13 B1918+19 B1917+00 B1919+14 B1919+21 B1920+21 B1923+04  
 B1929+10 B1933+16 B1944+17 B1946+35 B1951+32 B1952+29 B2000+32 B2002+31 B2016+28 B2020+28 B2028+22  
 B2034+19 B2044+15 B2053+21 B2053+36 B2110+27 B2113+14 B2122+13 B2210+29 B2303+30 B2315+21

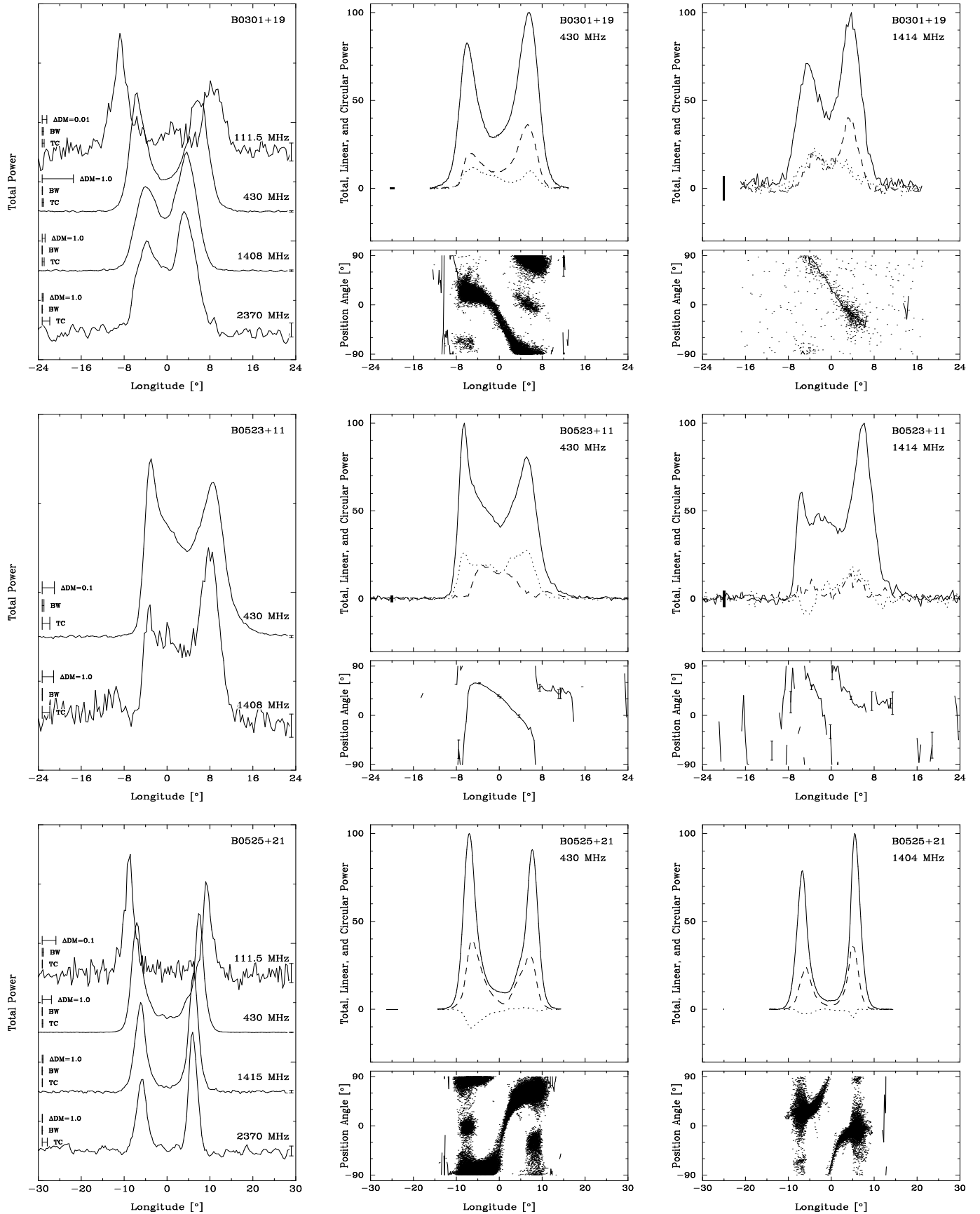


FIG. 1.— Multi-frequency and polarization profiles of B0301+19, B0523+11 and B0525+21.

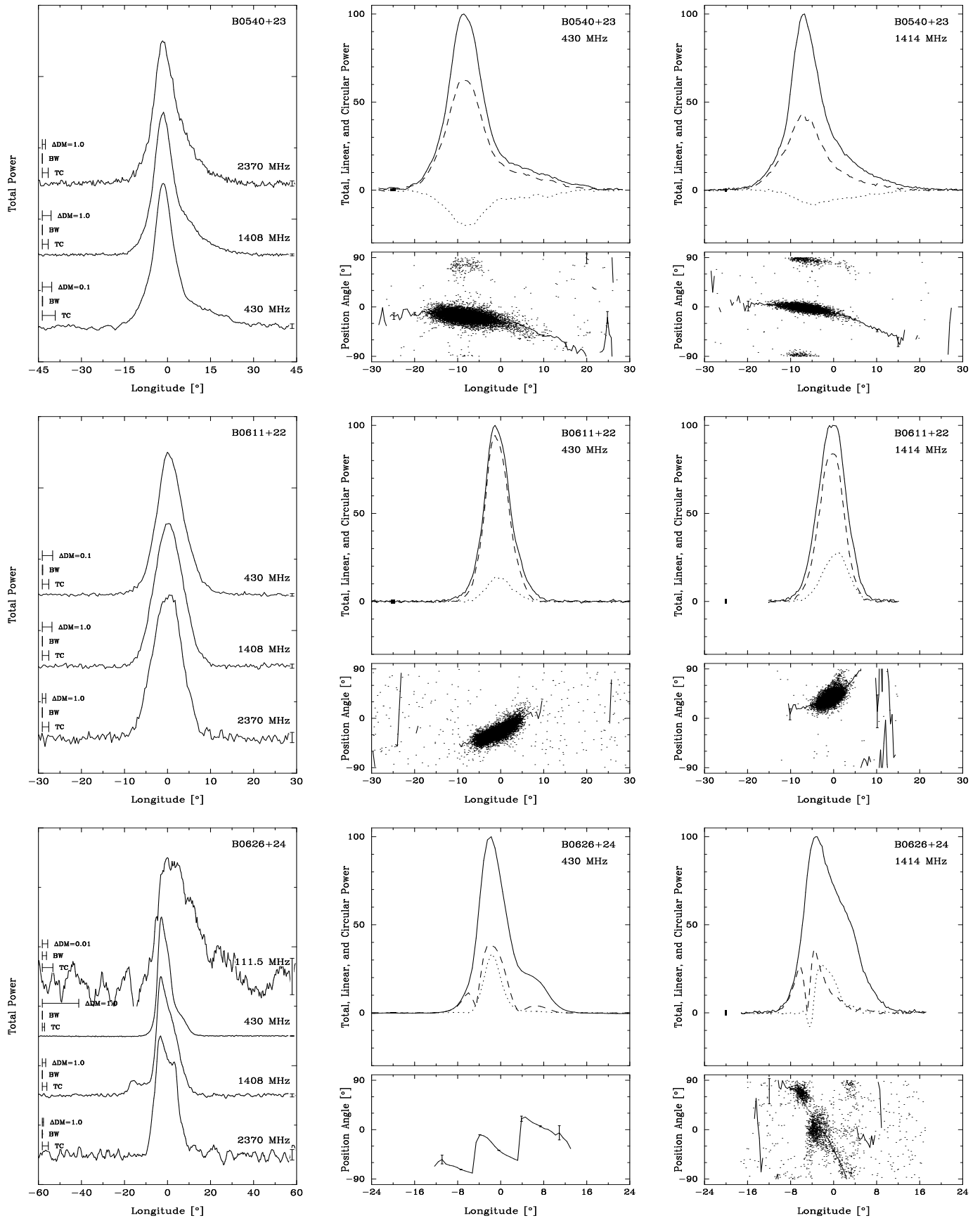


FIG. 2.— Multi-frequency and polarization profiles of B0540+23, B0611+22 and B0626+24.

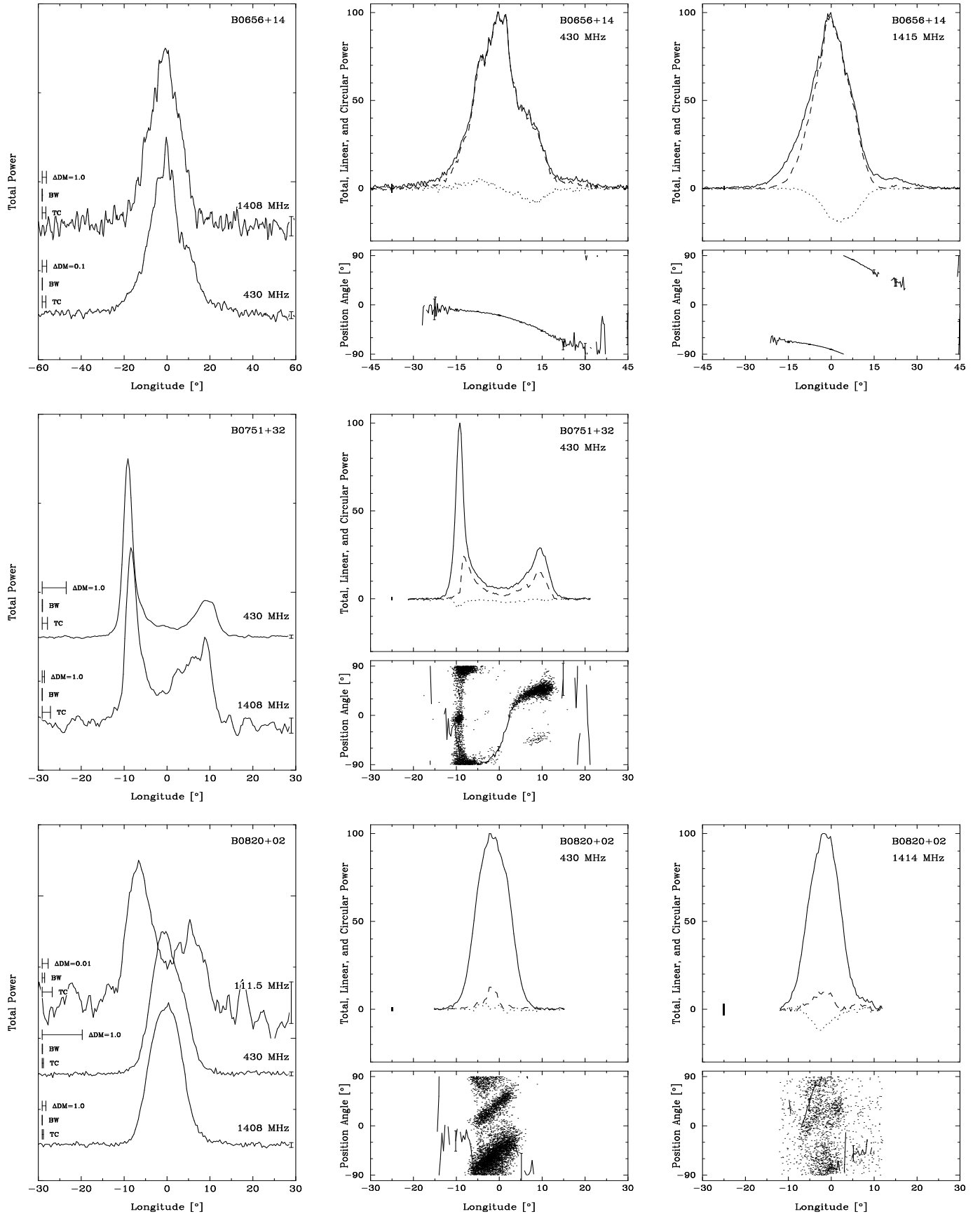


FIG. 3.— Multi-frequency and polarization profiles of B0656+14, B0751+32 and 0820+02.

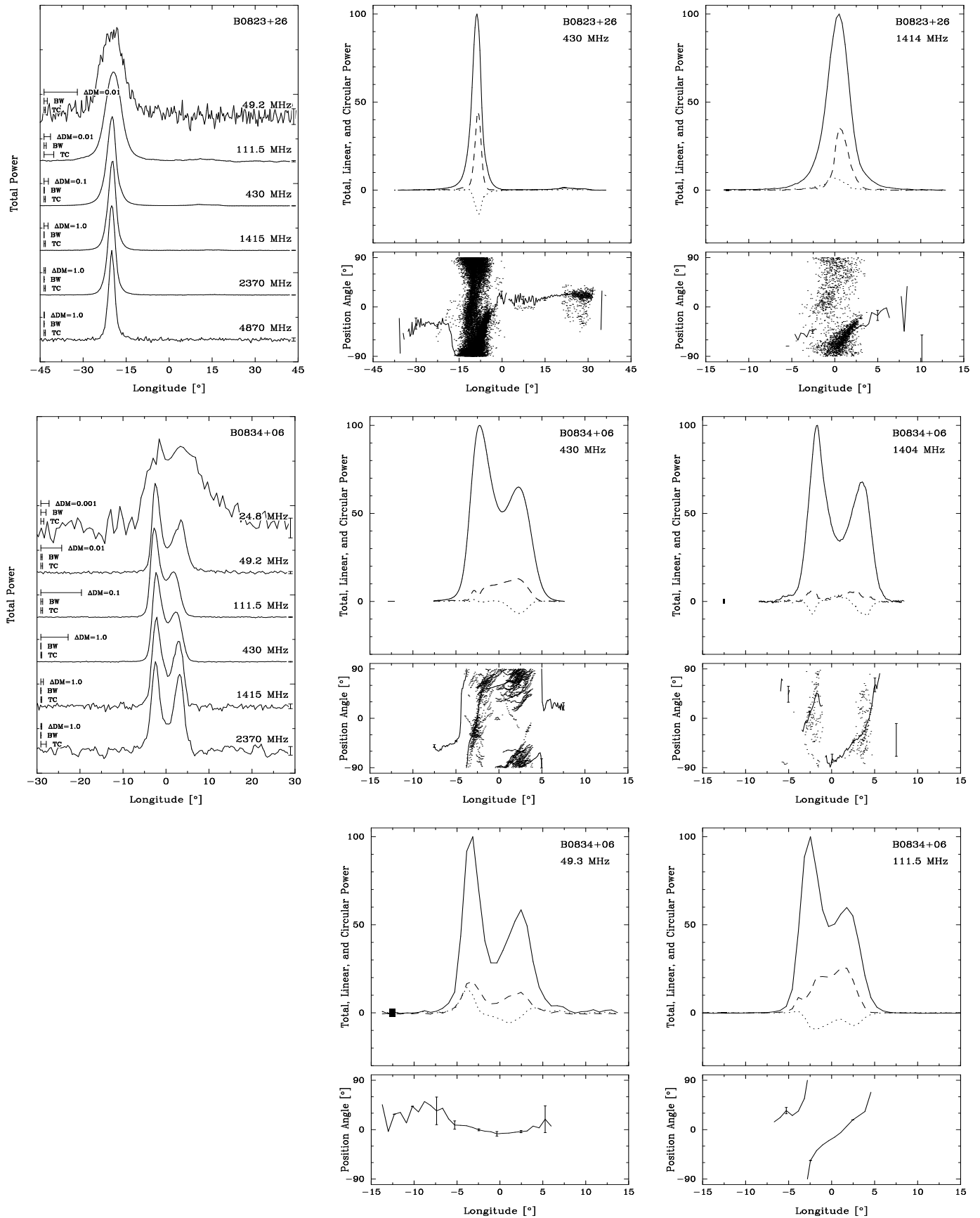


FIG. 4.— Multi-frequency and polarization profiles of B0823+26 and B0834+06.

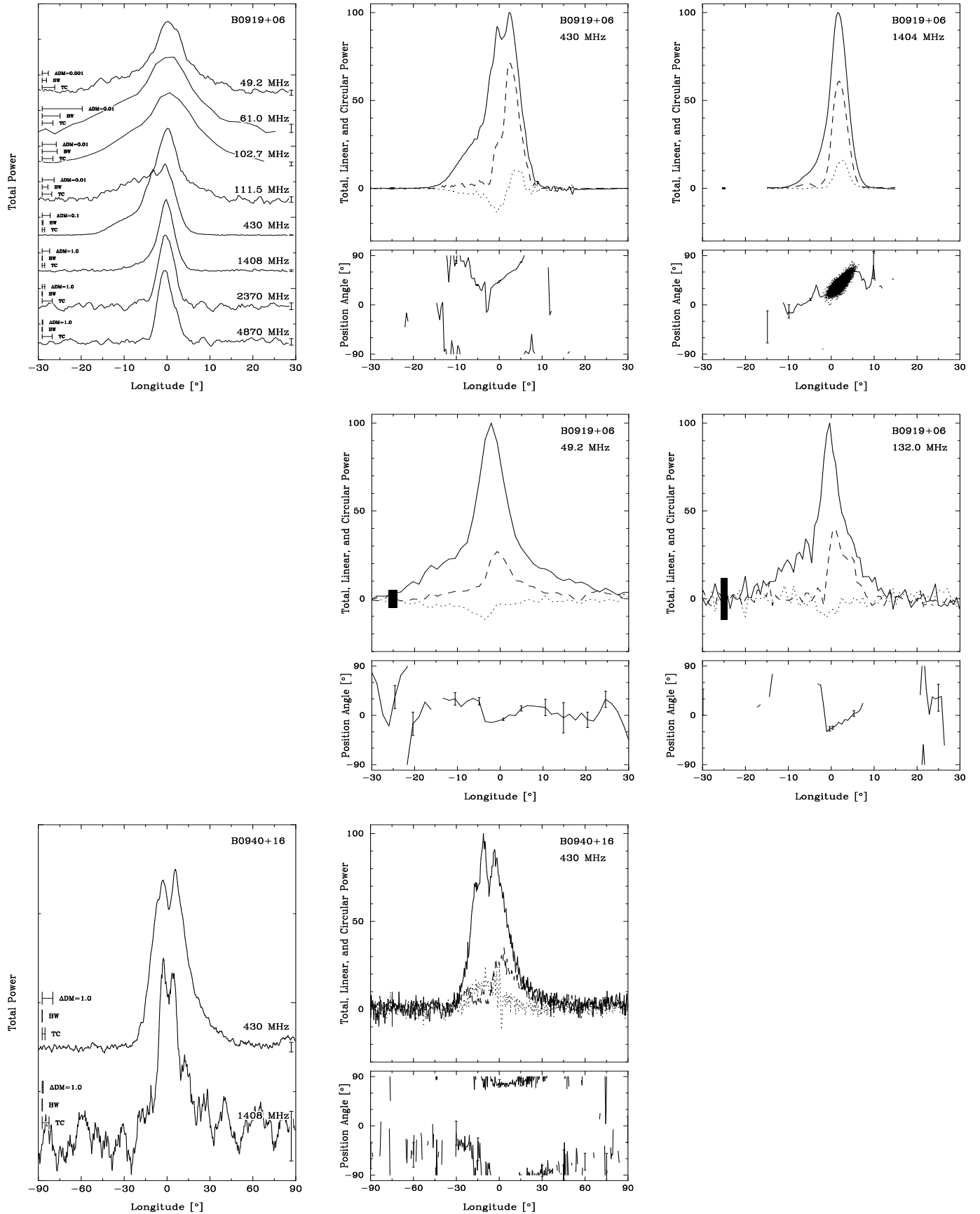


FIG. 5.— Multi-frequency and polarization profiles of B0919+06 and B0940+16.

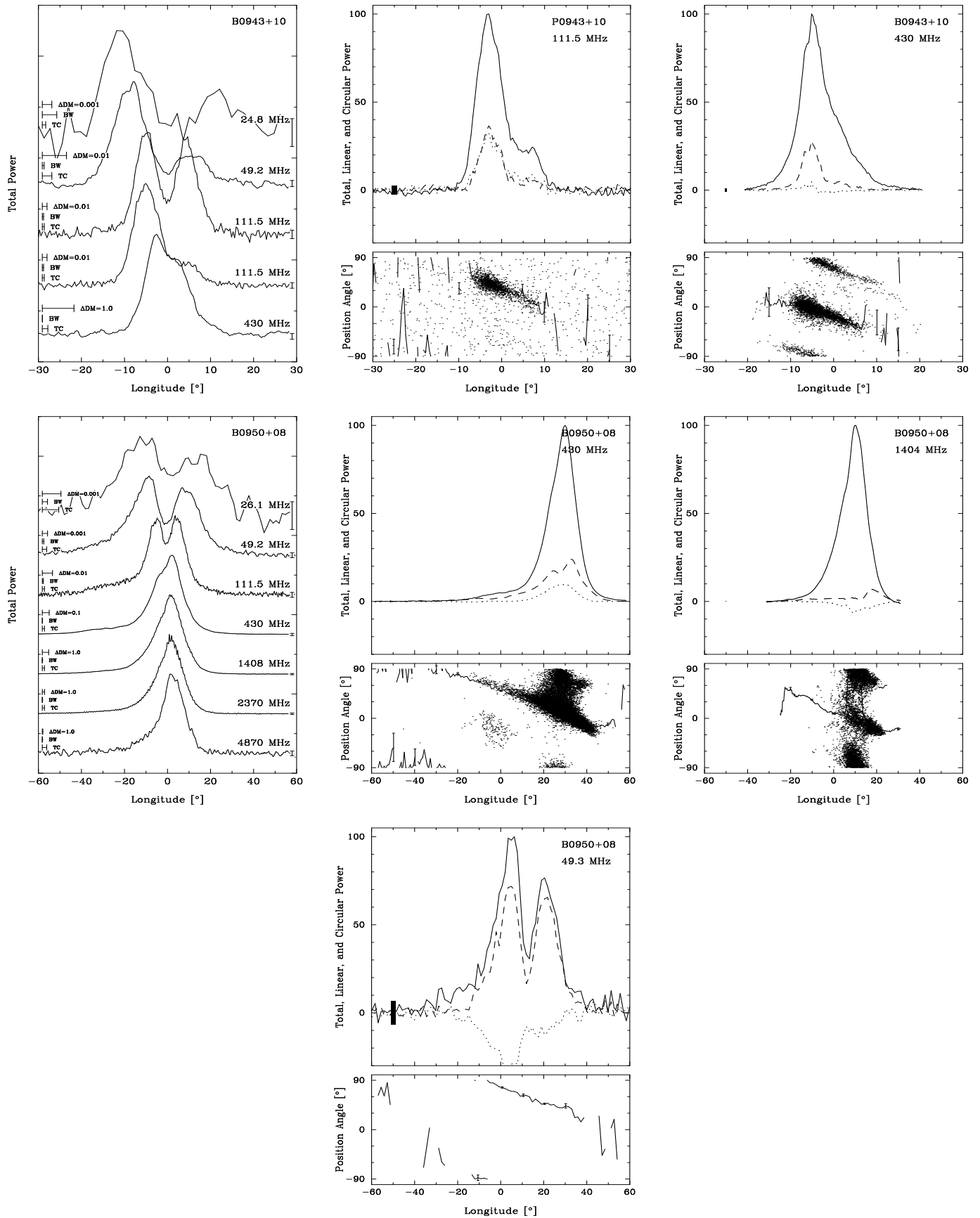


FIG. 6.— Multi-frequency and polarization profiles of B0943+10 and B0950+08.



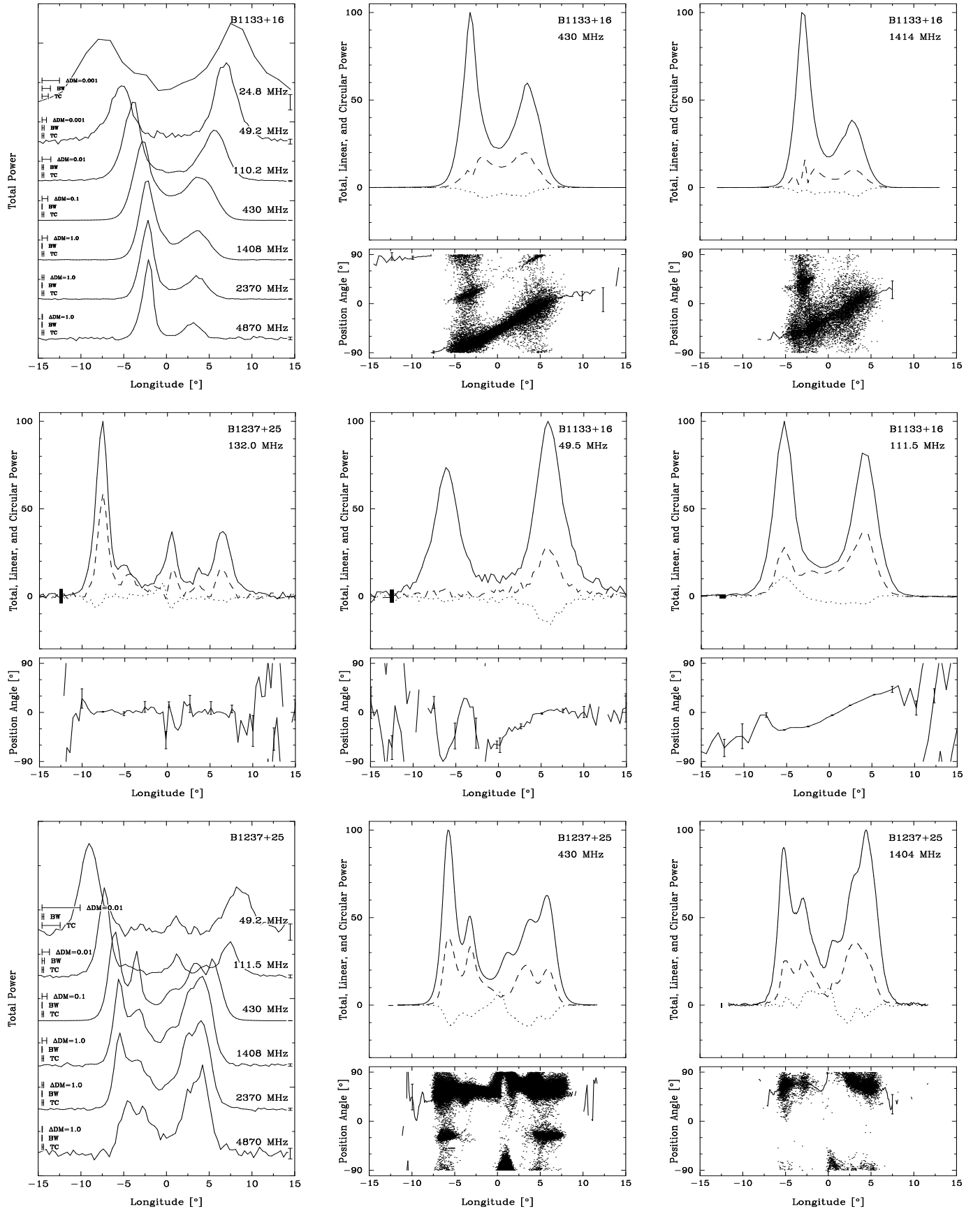


FIG. 7.— Multi-frequency and polarization profiles of B1133+16 and B1237+25.

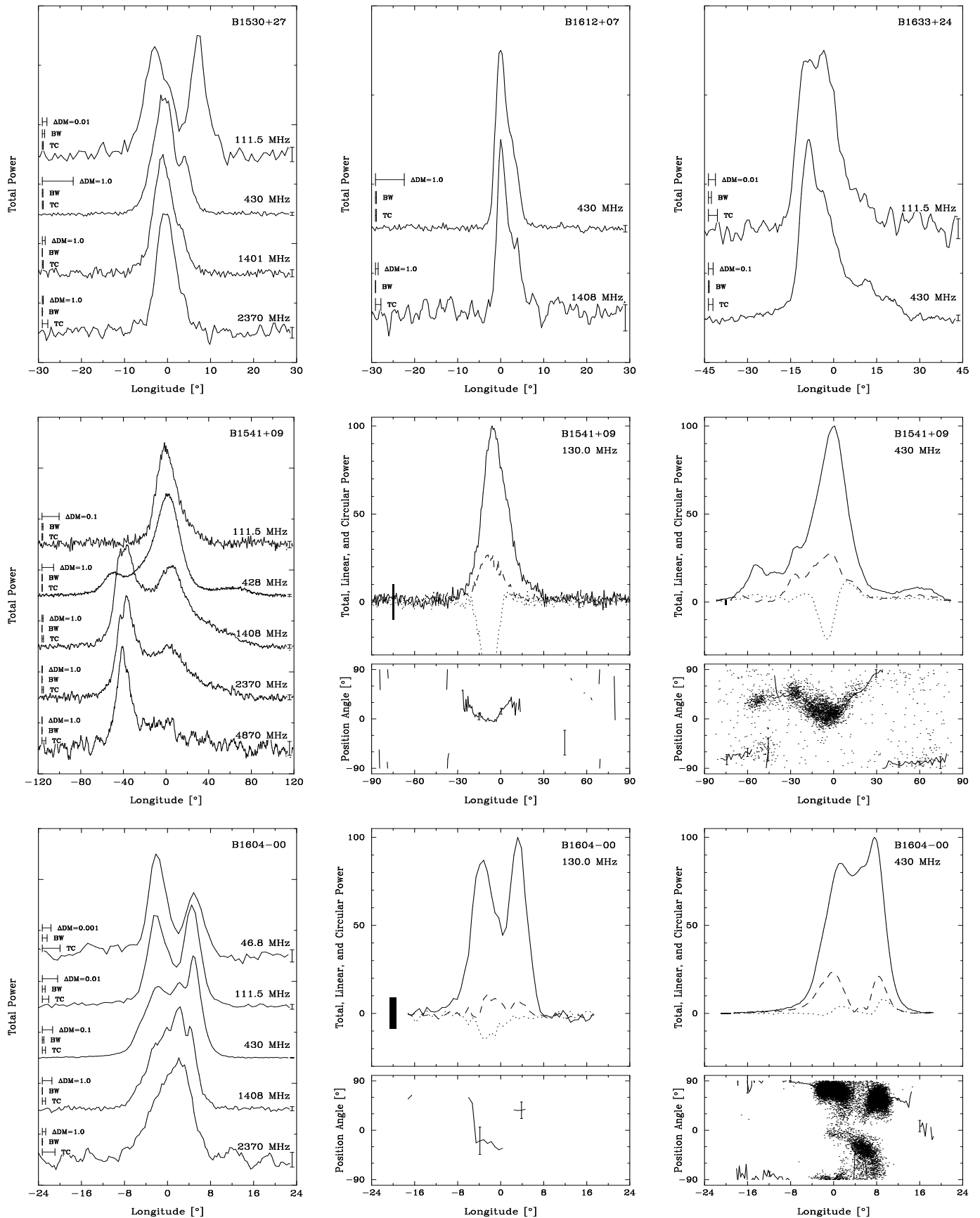


FIG. 8.— Multi-frequency profiles of B1530+27, B1612+07, B1633+24, B1541+09 and B1604-00, and polarization profiles of B1541+09 and B1604-00.

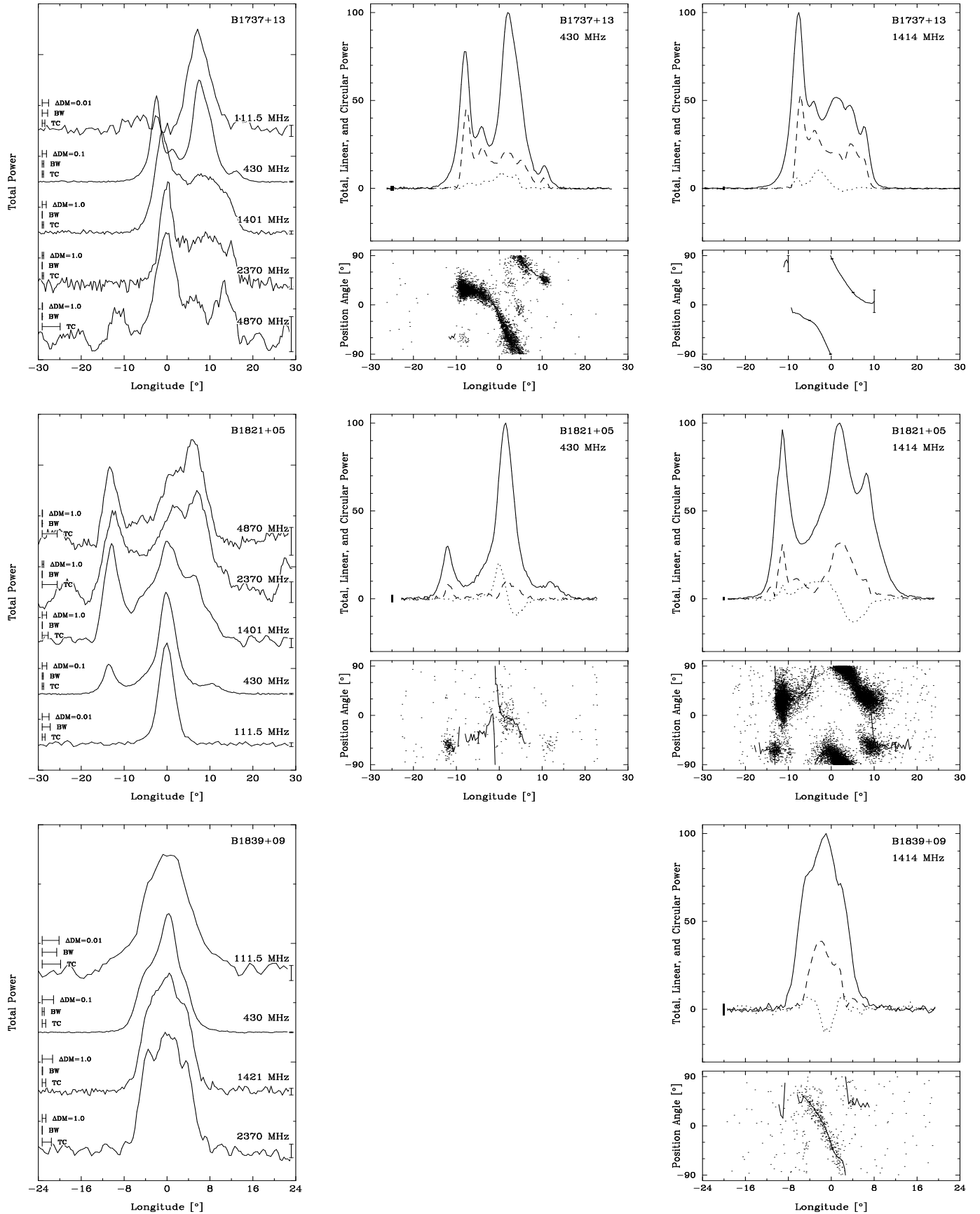


FIG. 9.— Multi-frequency and polarization profiles of B1737+13, B1821+05, and B1839+09.

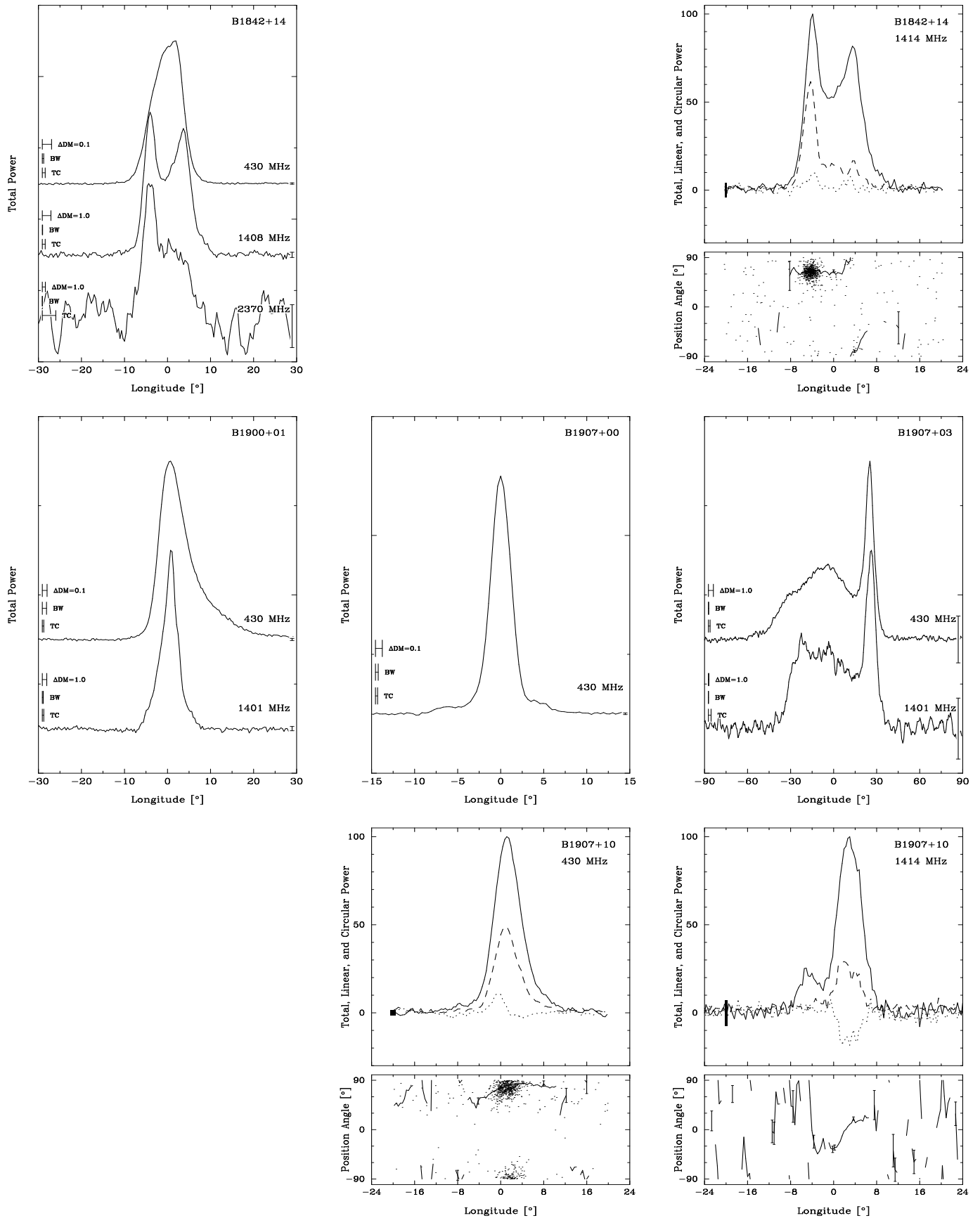


FIG. 10.— Multi-frequency profiles of B1842+14, B1900+01, B1907+00 and B1907+03, and polarization profiles of B1842+14 and B1907+10.

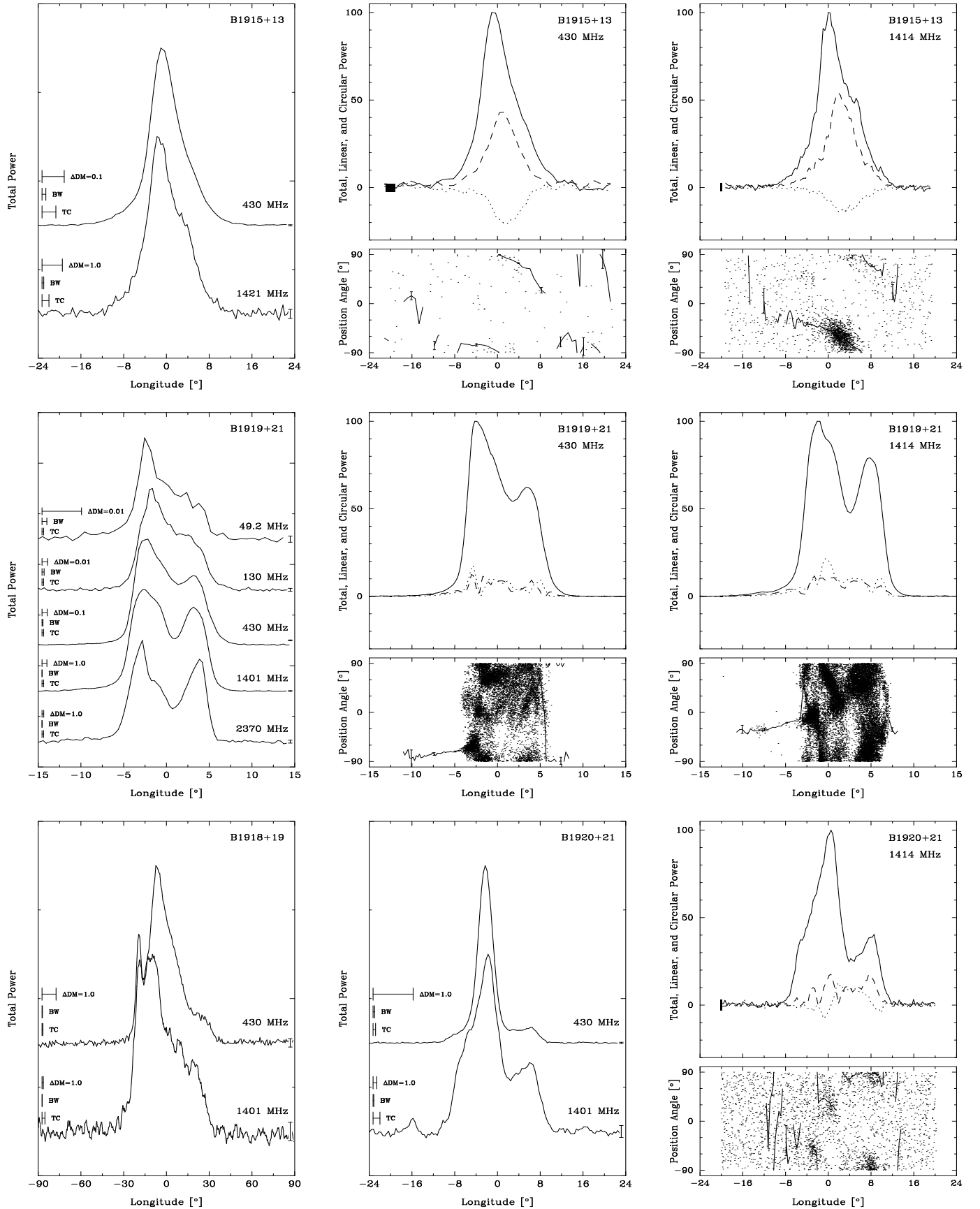


FIG. 11.— Multi-frequency profiles of B1915+13, B1919+21, B1918+19 and B1920+21, and polarization profiles of B1915+13, B1919+21 and B1920+21.

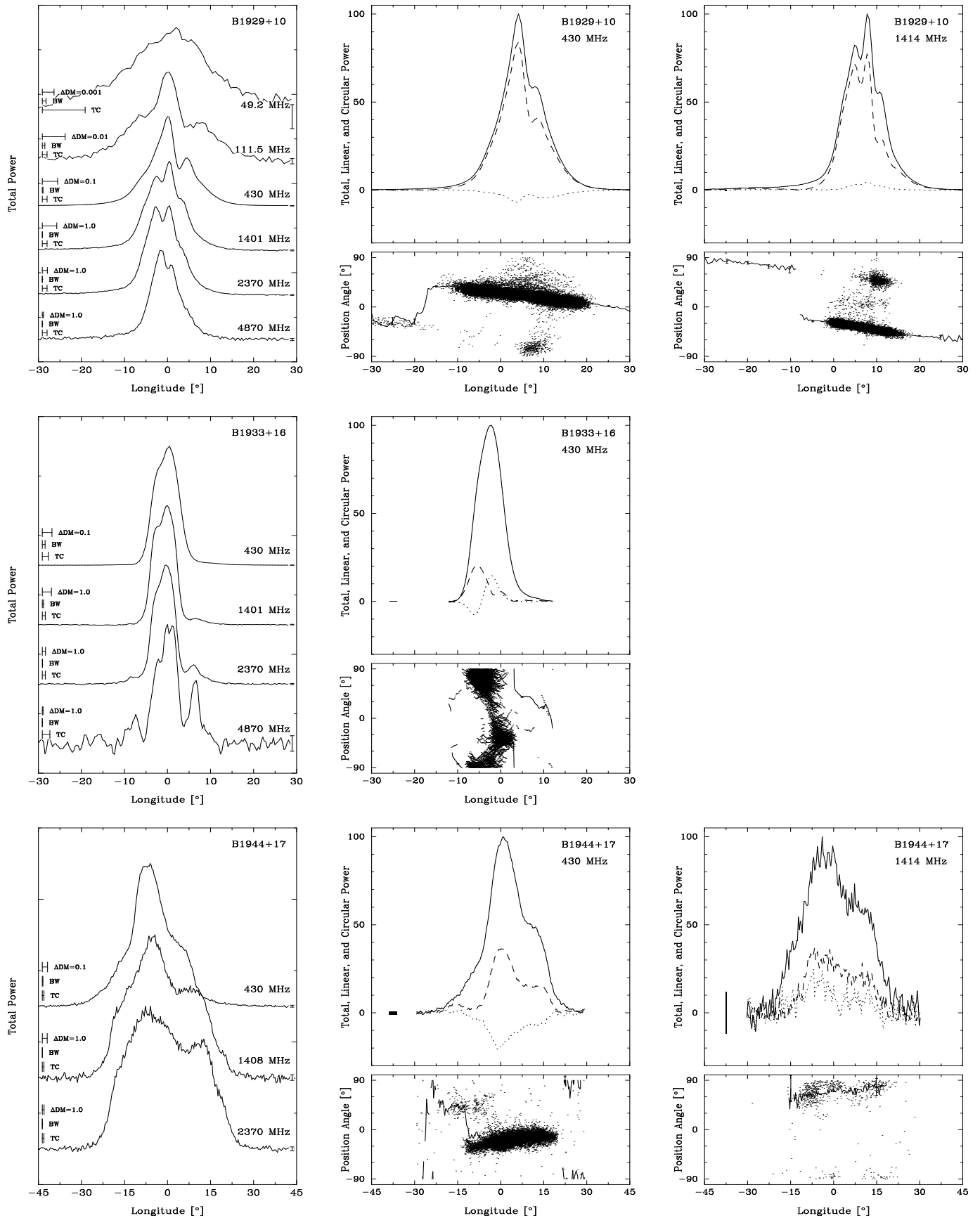


FIG. 12.— Multi-frequency and polarization profiles of B1929+10, B1933+16 and B1944+17.

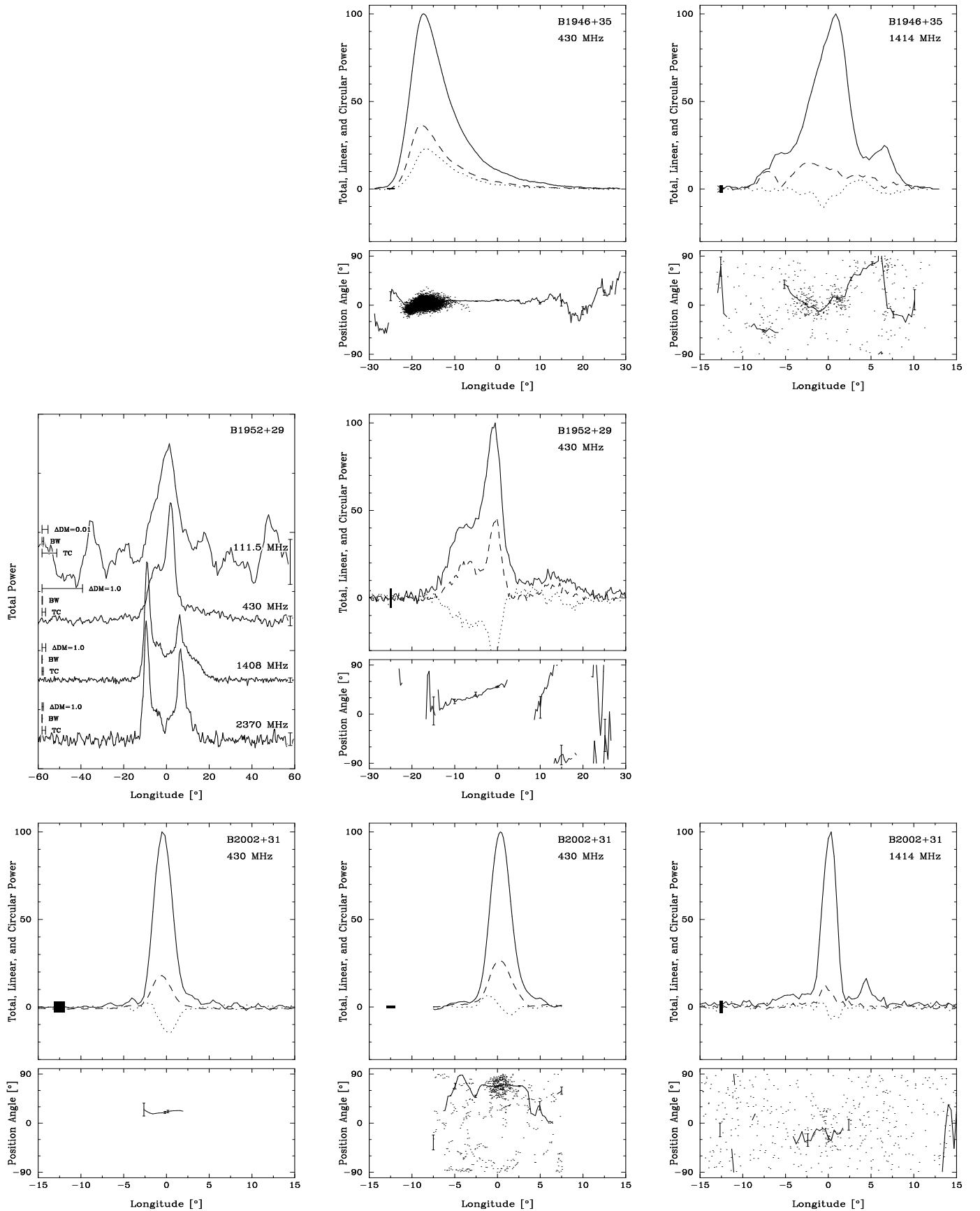


FIG. 13.— Multi-frequency and polarization profiles of B1946+35, B1952+29 and B2002+31.

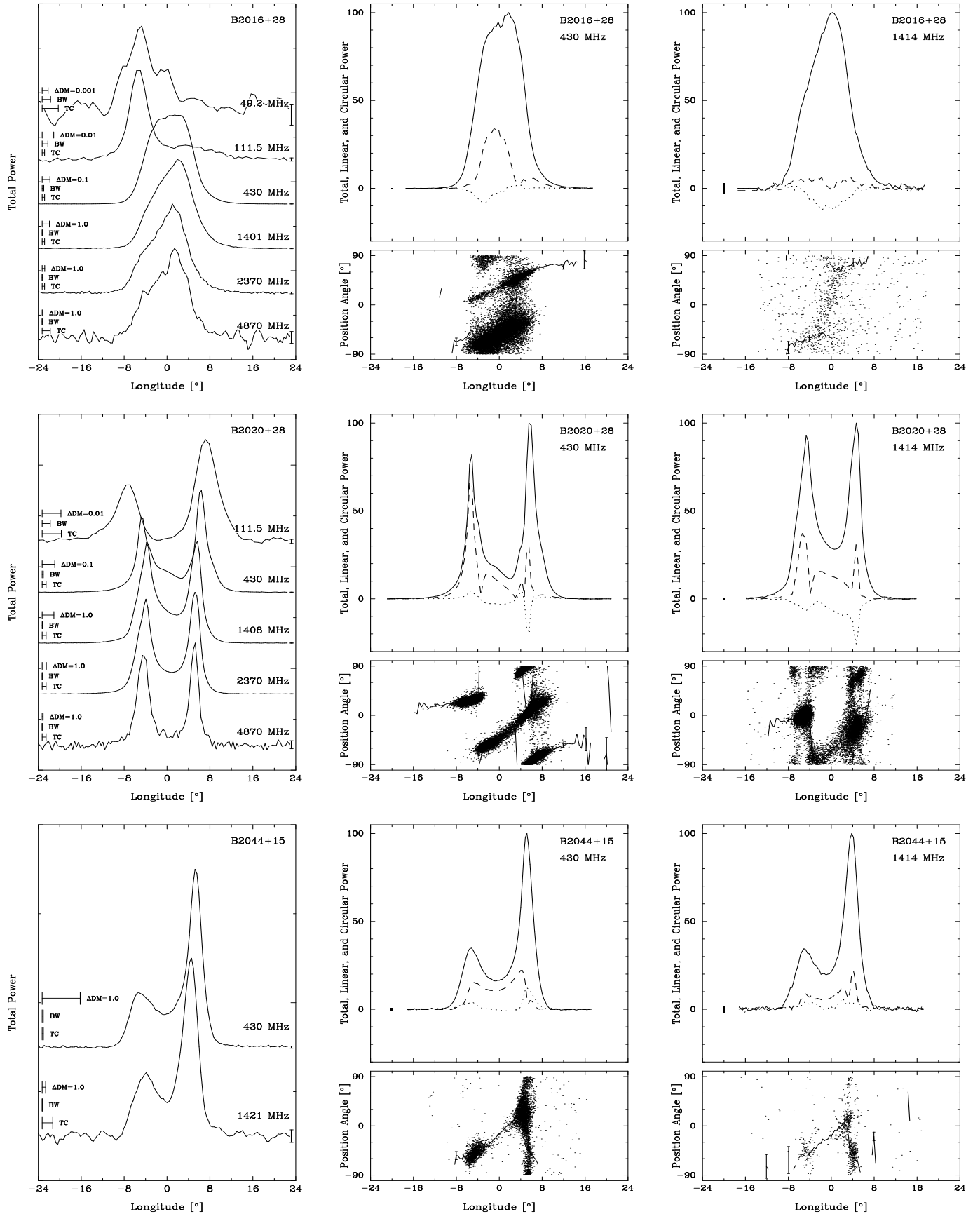


FIG. 14.— Multi-frequency and polarization profiles of B2016+28, B2020+28 and B2044+15.



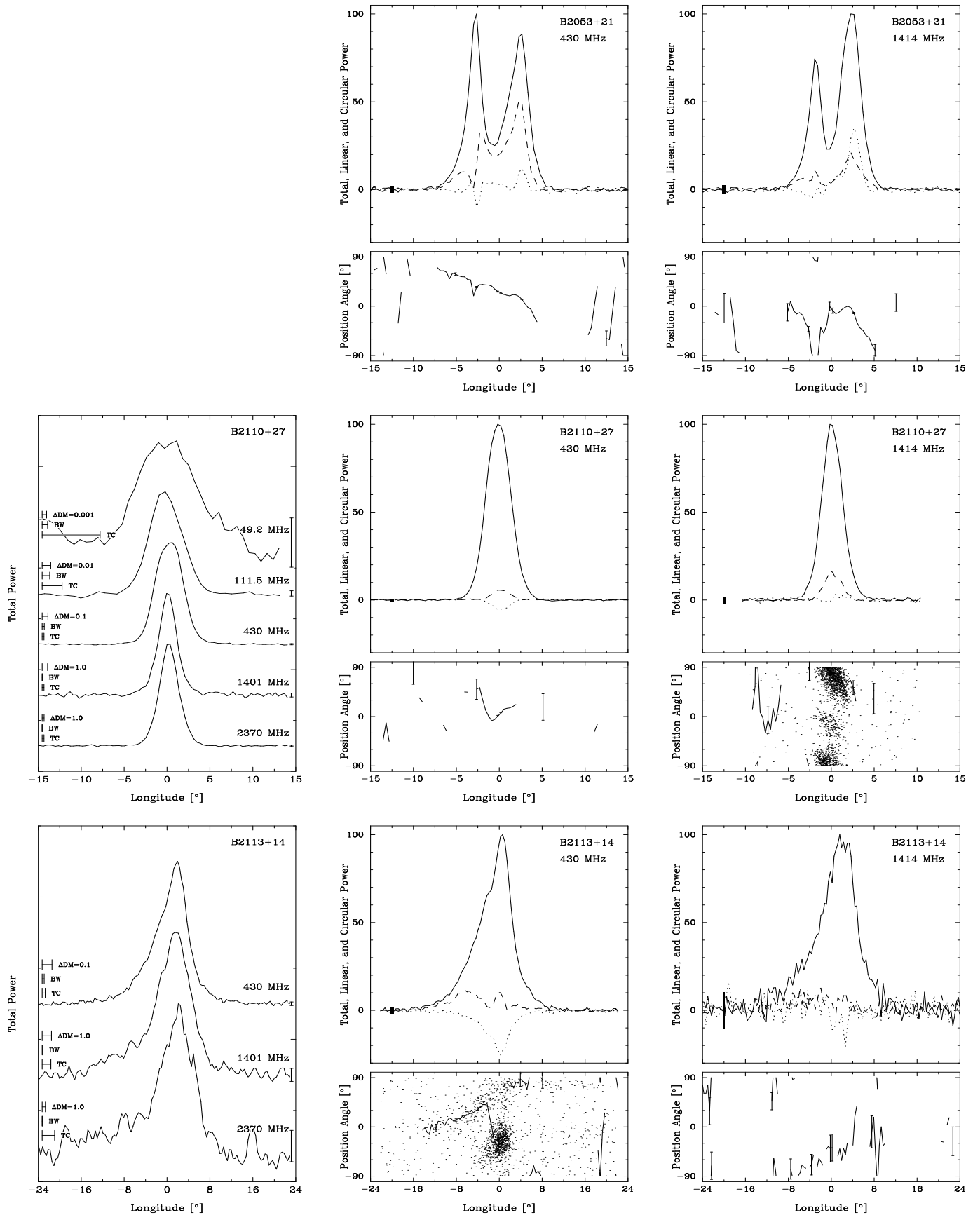


FIG. 15.— Multi-frequency and polarization profiles of B2053+21, B2110+27 and B2113+14.

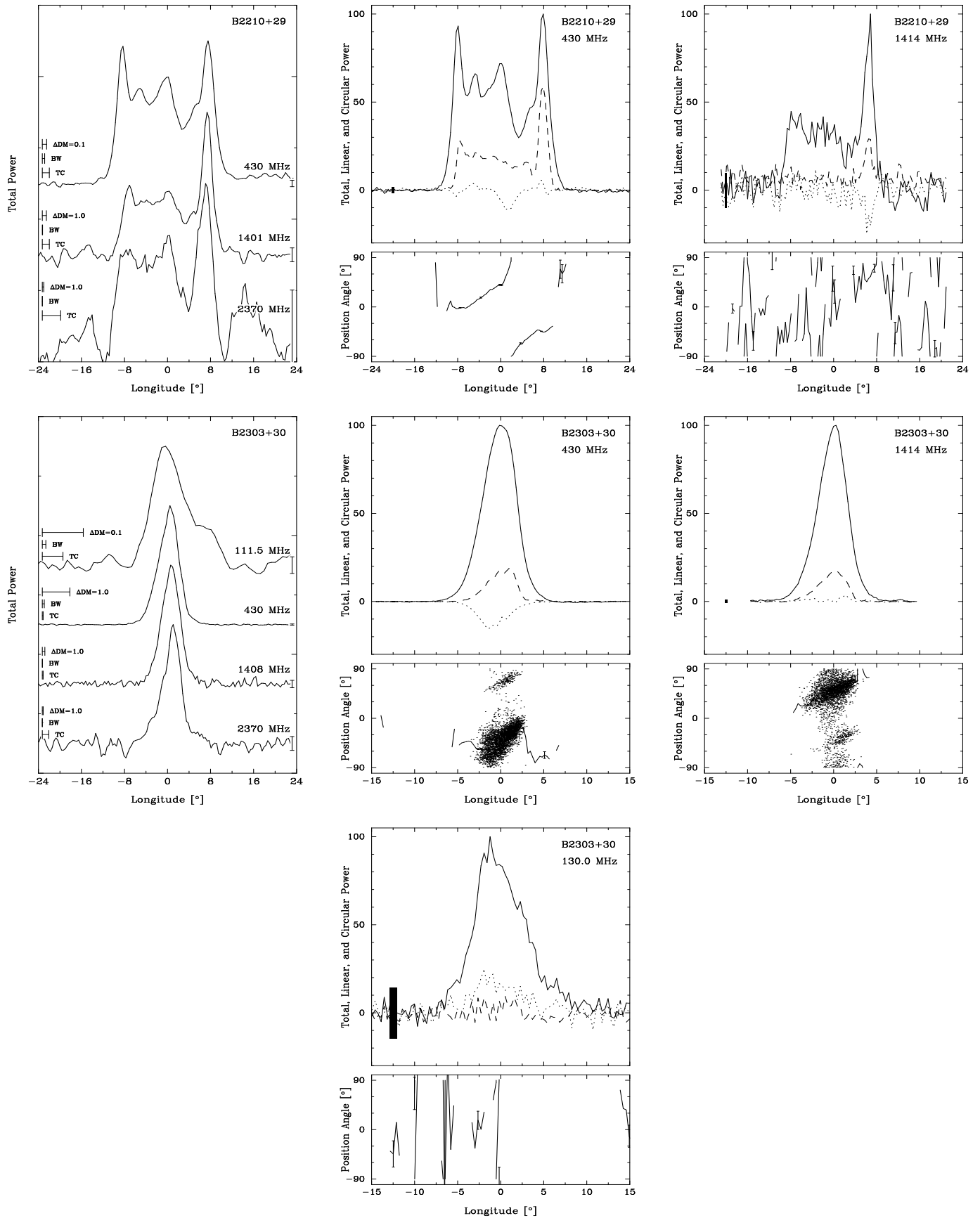


FIG. 16.— Multi-frequency and polarization profiles of B2210+29 and B2303+30.

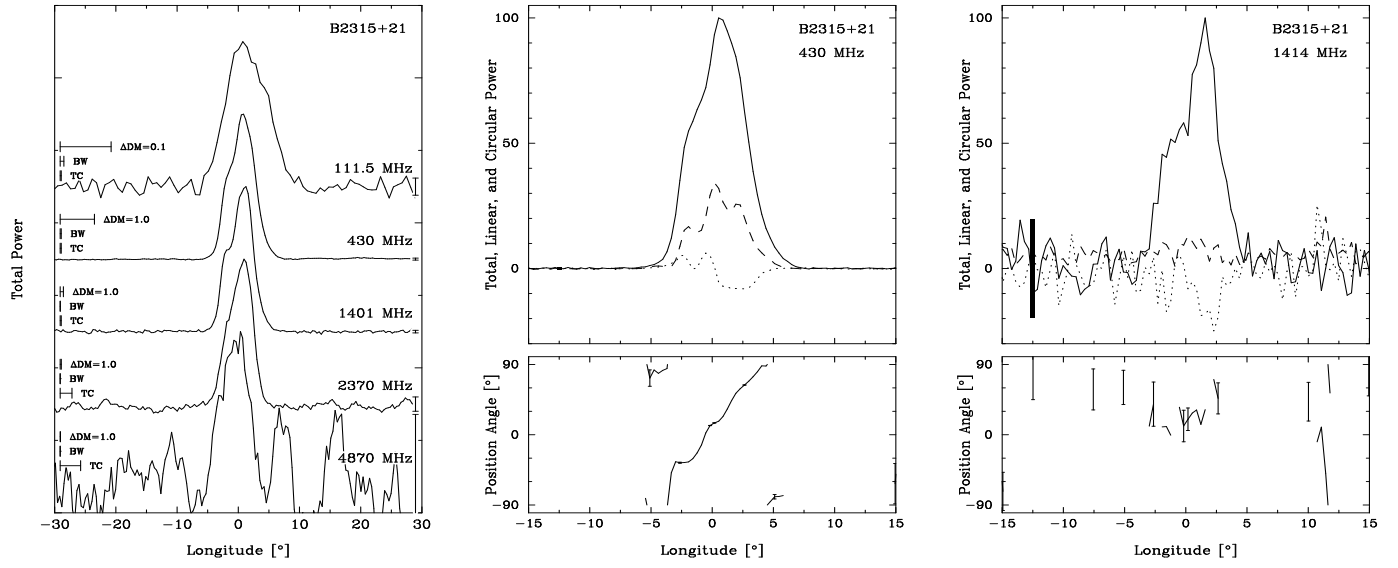


FIG. 17.— Multi-frequency and polarization profiles of B2315+21.

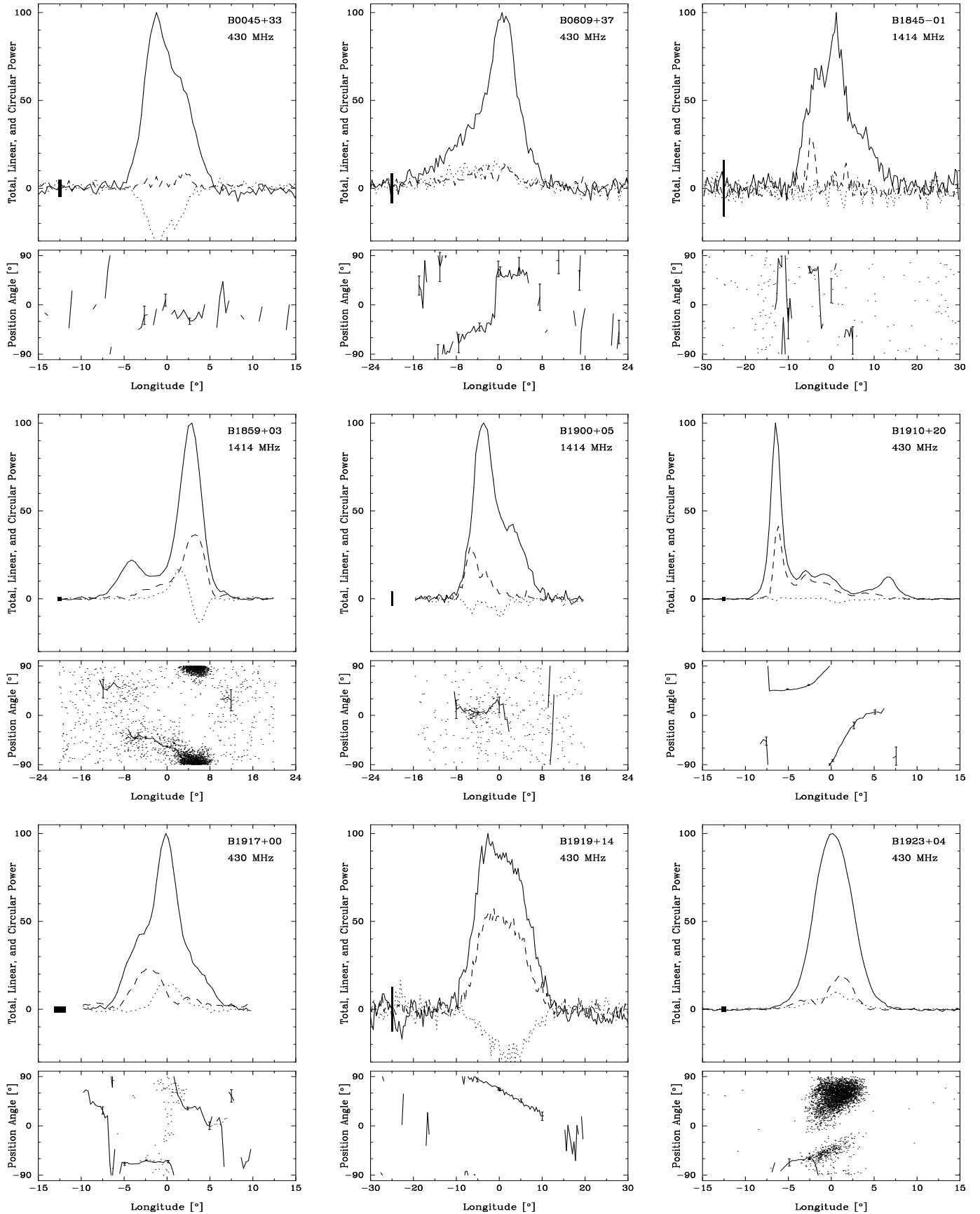


FIG. 18.— Polarization profiles of B0045+33, B0609+37, B1845-01, B1859+03, B1900+05, B1910+20, B1917+00, and B1919+14 and B1923+04.

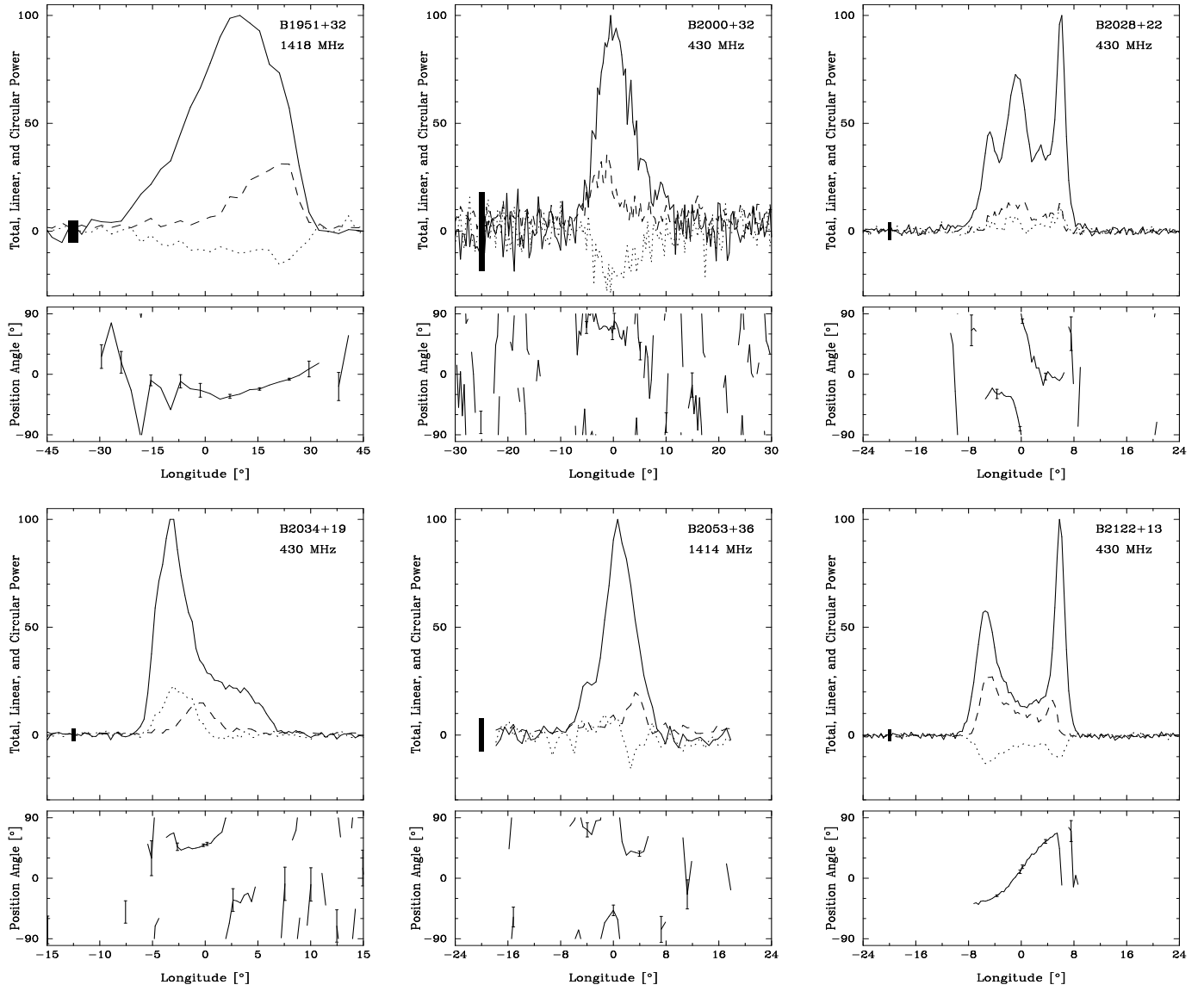


FIG. 19.— Polarization profiles of B1951+32, B2000+32, B2028+22, B2034+19, B2053+36, and B2122+13.

## APPENDIX: POLARIMETRIC CALIBRATION

Joanna M. Rankin, N. Rathnasree & Kyriaki Xilouris

While the Arecibo Observatory polarimetric feed systems were known to be imperfect from the 1970s, only slowly were techniques developed to measure these imperfections and ultimately to correct for them. The primary source of this imperfection results from the circumstance that some power is mutually cross-coupled between the two radiometers. At Arecibo in 1992 all of the polarimeter systems involved a pair of nominally left- and right-hand circularly polarized feeds, which were connected to a pair of matched receivers with coherent local oscillators and in turn connected to the Arecibo 40-MHz Correlator, which served as a multiplying polarimeter.

The basic effects of cross-coupling are well described in the Appendix of Stinebring *et al.* (1984). Indeed, this work reports not only the first technique for measuring the cross-coupling amplitude and phase using pulsar observations, but also shows how these measurements can be used to correct the measured Stokes parameters for the distorting effects of the cross-coupling.

Conceptually, we can understand that the cross-coupled power causes the nominally circularly-polarized feeds to have an elliptically polarized response. In other words, while a purely circularly polarized feed would have the same response to a linearly polarized signal at any orientation (or polarization angle), the ellipticity results in angles of maximum and minimum response  $90^\circ$  apart. In order to understand, then, the behavior of the polarimeter, we need to understand the axial ratio and orientation of the elliptical response of the left- and right-hand feeds.

Our analysis then extends that of the above paper in two significant ways: First, we have made no assumptions about the behavior of the feeds in terms of whether their response was “orthogonal” or “coincident” (see their eqs. A10 and A11), and second we have determined the cross-coupling amplitude and phase as a function of frequency over the entire usable band of the feed.

In order to carry out our analyses, we computed raw Stokes parameters for a pulsar with a region of nearly complete linear polarization; polarized average profiles comprising a few hundred pulses were computed over the full several hours that the pulsar could be tracked in order to obtain the largest possible excursion of parallactic angle. Pulsar B1929+10 has an almost fully polarized leading edge, which is excellent for this purpose as is virtually the entire profile of B0656+14, though the latter is substantially weaker. Then, we recovered the left- and right-hand channel responses  $\mathcal{L}$  and  $\mathcal{R}$  through use of the Stokes parameter definitions  $\mathcal{L} = (I + V)/2$  and  $\mathcal{R} = (I - V)/2$ . It was then possible to fit sinusoidal curves to the observed dependences of  $\mathcal{L}$  and  $\mathcal{R}$  as functions of raw instrumental linear polarization angle (rotated with respect to the feed by the changing parallactic angle with hour angle) in order to determine both the axial ratio and the orientation of the cross-coupling-distorted linear response.

This latter fitting procedure is nearly identical to that carried out by Stinebring *et al.* (1984) in their Fig. 39, except that we fitted to variations in  $\mathcal{L}/L$  and  $\mathcal{R}/L$  [where the total linear power  $L$  is  $\sqrt{Q^2 + U^2}$ ] rather than simply  $V/L$ . It is also worth pointing out that these fits are

to ratios of polarized intensities, so that any variations in the amplitude of the pulsar signal, due to scintillations or whatever, have no effect on the values, only their uncertainties.

The result then is that the fitted amplitudes determine the axial ratios of the elliptical response (complete circularity would produce no variation with raw feed position angle and imply an axial ratio of unity, whereas a completely linear response would imply an infinite axial ratio); whereas the phase of the variation determines the orientation of the elliptical response relative to the polarization-angle ( $PA$ ) origin of the polarimeter. In terms of Stinebring *et al.* (1984), this simple procedure results in the determination of the crucial four parameters, the respective cross-coupling amplitudes  $\varepsilon_1$  and  $\varepsilon_2$  and the cross-coupling phases  $\psi_1$  and  $\psi_2$  which first appear in their eq. (A2). In particular, these quantities are the only variables upon which the transformation between the intrinsic Stokes parameters and those measured by the imperfect polarimeter depend.

The results of our calibration efforts for the Arecibo 430-MHz line feed and for the 21-cm line feed are given in Figures A1 and A2. The left- and right-hand cross-coupling amplitudes are plotted in the top two panels and the left-hand phase in the bottom panel. In fact, we determined both cross-coupling phases and found that they were always orthogonal within our measurement errors, so that only one need be specified. The respective amplitudes, however, appear to exhibit subtle differences, though their overall behavior is very similar in the two cases.

During our October 1992 program observations we obtained several different sets of full-sky tracks on pulsars B1929+10, B0656+14, B1737+13 and B0525+21 as well as shorter tracks from which only the cross-coupling phase could be estimated. B1929+10 provided the most accurate results, and the two feeds appeared stable both from day to day in October 1992 as well as over the interval between several earlier preliminary observations in 1990 January and 1992 March, apart from the overall cross-coupling phase, which we believe results both from differences in our cabling setup for each observation as well (perhaps) as variations in the relative phase of the two receiver channels down from the platform to the control room. Therefore, we were careful to determine the cross-coupling phase for each observation and depend on its stability only over a few hours time.

Apparently, the 21-cm system exhibits a cross-coupling behavior common to many feed systems in use at various observatories—that is, it exhibits minimum cross-coupling amplitudes near the design band center and a progress rise in cross-coupled power toward the band edges. It was then surprising to see that the behavior of the 430-MHz system is very different, with minimum cross-coupled power near the lower band edge at 425 MHz and progressively rising cross-coupled power across the band. Indeed, the level of cross-coupling at the upper band edge is fully 15%, making it absolutely mandatory that observations at this frequency be corrected for the resulting distortion. This also apparently explains a strange phenomenon in our older AO polarimetry: we could not understand for many years why 430-MHz observations of B1929+10 in particular exhibited large variations in fractional circular polarization,

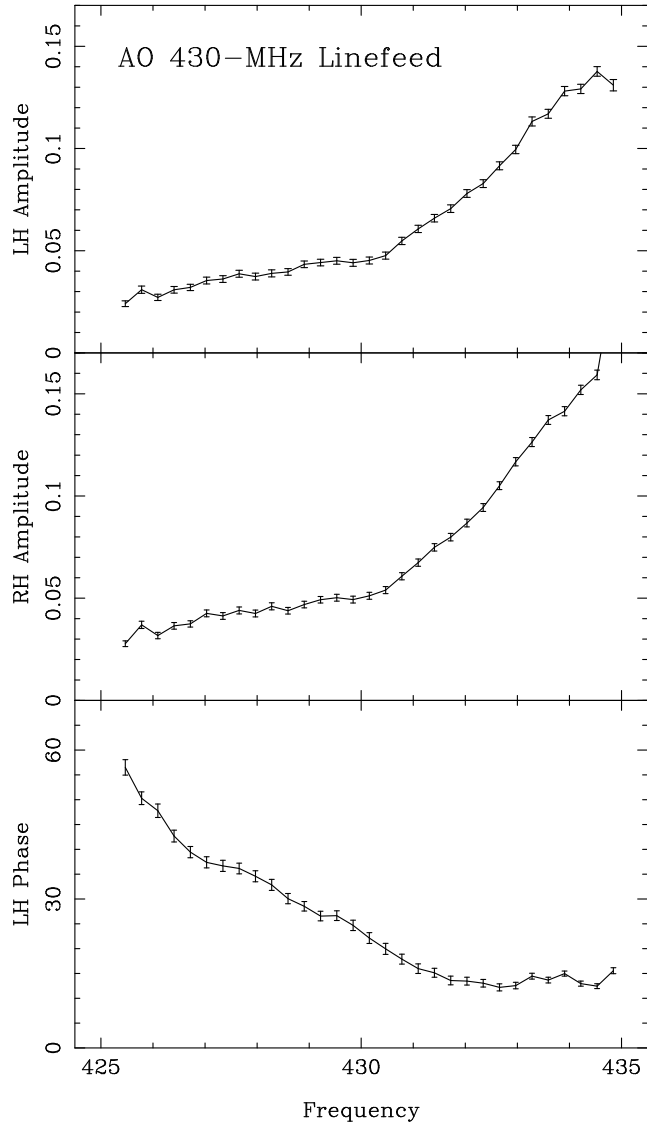


FIG. 20.— Left- (top panel) and right-hand (middle panel) cross-coupling amplitudes and the left-hand cross-coupling phase (bottom panel) as a function of frequency for the Arecibo Observatory 430-MHz line feed as determined from a full-sky track of pulsar B1929+10 in October 1992. The right-hand phase is orthogonal to the plotted left-hand phase within the observational errors, which represent one standard deviation.

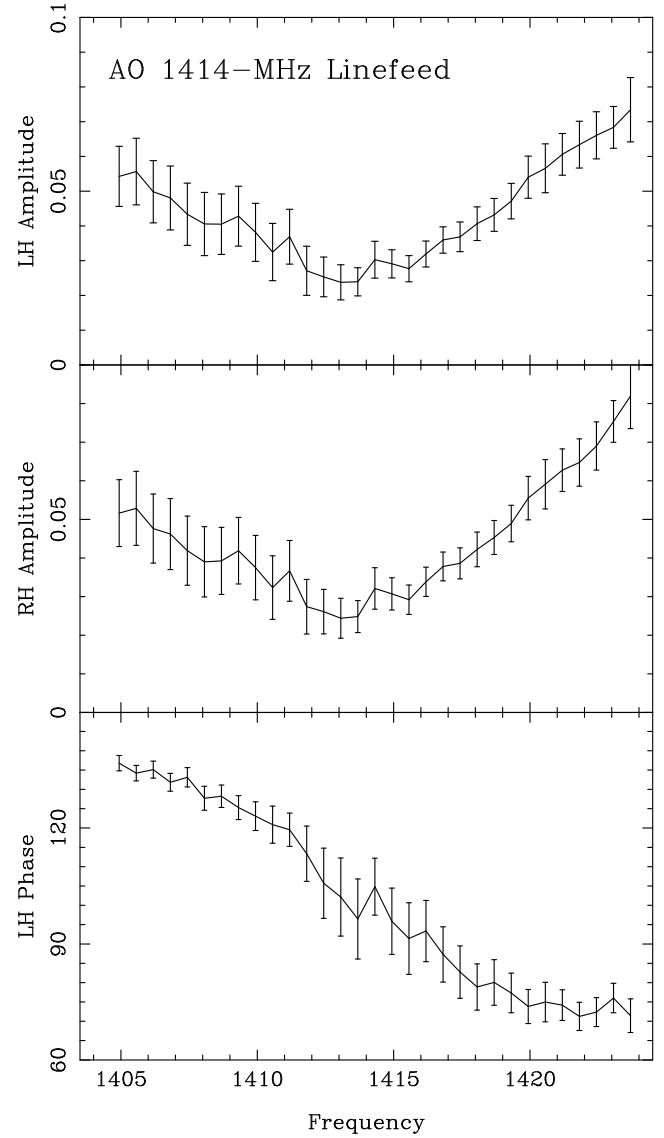


FIG. 21.— Cross-coupling amplitudes and phase for the Arecibo Observatory 21-cm line feed, determined from a full-sky track of pulsar B1929+10 in October 1992, as in Fig. A1.

between essentially zero and almost 40%. The reason we can now see is almost certainly that for such a low dispersion pulsar, the fractional circular would vary greatly depending upon how the scintillation-produced spectral variations excited the feed! More highly dispersed stars tend to have more bright scintiles within our passband, and thus the cross-coupling distortion tended to average across them.

Finally, we used the above cross-coupling information to correct the measured Stokes parameters whenever possible. If we write eq. (A5) of Stinebring *et al.* (1984) as  $\mathbf{S}' = \mathbf{M}\mathbf{S}$ , where  $\mathbf{S}$  is the true Stokes vector  $\mathbf{S}'$  the measured one, and  $\mathbf{M}$  is the  $4 \times 4$  Müller matrix relating the two, then our correction of the Stokes parameters took the form

$$\mathbf{S}(f) = \mathbf{M}^{-1}[\varepsilon_1(f), \varepsilon_2(f), \psi_1(f), \psi_1(f) \pm 90^\circ] \mathbf{S}'(f). \quad (1)$$

Despite these careful efforts, our calibrations vary considerably in quality. The great bulk of the 430- and 1400-MHz observations were fully calibrated both in terms of standard-source observations to determine the relative left- and right-hand channel gains as well as the cross-coupling distortion corrections outlined above. However, in some cases the standard-source pointings were corrupted by interference, and in a few cases, our shorter trackings to determine  $\psi_1$  were unsuccessful. We note these faults in Tables 2 & 3 above.