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J/MNRAS/458/3341 42 millisecond pulsars high-precision timing (Desvignes+, 2016)

High-precision timing of 42 millisecond pulsars with the
European Pulsar Timing Array.

Desvignes G., Caballero R.N., Lentati L., Verbiest J.P.W., Champion D.J., Stappers B.W., Janssen G.H., Lazarus P., Oslowski S., Babak S., Bassa C.G., Brem P., Burgay M., Cognard I., Gair J.R., Graikou E., Guillemot L., Hessels J.W.T., Jessner A., Jordan C., Karuppusamy R., Kramer M., Lassus A., Lazaridis K., Lee K.J., Liu K., Lyne A.G., Mckee J., Mingarelli C.M.F., Perrodin D., Petiteau A., Possenti A., Purver M.B., Rosado P.A., Sanidas S., Sesana A., Shaifullah G., Smits R., Taylor S.R., Theureau G., Tiburzi C., Van Haasteren R., Vecchio A.

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Keywords: proper motions - stars: distances - pulsars: general

Abstract:
We report on the high-precision timing of 42 radio millisecond pulsars (MSPs) observed by the European Pulsar Timing Array (EPTA). This EPTA Data Release 1.0 extends up to mid-2014 and baselines range from 7-18yr. It forms the basis for the stochastic gravitational-wave background, anisotropic background, and continuous-wave limits recently presented by the EPTA elsewhere. The Bayesian timing analysis performed with TEMPONEST yields the detection of several new parameters: seven parallaxes, nine proper motions and, in the case of six binary pulsars, an apparent change of the semimajor axis. We find the NE2001 Galactic electron density model to be a better match to our parallax distances (after correction from the Lutz-Kelker bias) than the M2 and M3 models by Schnitzeler. However, we measure an average uncertainty of 80 per cent (fractional) for NE2001, three times larger than what is typically assumed in the literature. We revisit the transverse velocity distribution for a set of 19 isolated and 57 binary MSPs and find no statistical difference between these two populations. We detect Shapiro delay in the timing residuals of PSRs J1600-3053 and J1918-0642, implying pulsar and companion masses $mp=1.22^{+0.5}_{-0.35}M_{\odot}$, $mc=0.21^{+0.06}_{-0.04}M_{\odot}$ and $mp=1.25^{+0.6}_{-0.4}M_{\odot}$, $mc=0.23^{+0.07}_{-0.05}M_{\odot}$, respectively. Finally, we use the measurement of the orbital period derivative to set a stringent constraint on the distance to PSRs J1012+5307 and J1909-3744, and set limits on the longitude of ascending node through the search of the annual-orbital parallax for PSRs J1600-3053 and J1909-3744.

Description:
This paper presents the EPTA data set, up to mid-2014, that was gathered from the 'historical' pulsar instrumentations at EFF, JBO, NRT and WSRT with, respectively, the EBPP (Effelsberg-Berkeley Pulsar Processor), DFB (Digital FilterBank), BON (Berkeley-Orleans-Nancay) and PuMa (Pulsar Machine) backends. The data recorded with the newest generation of instrumentations, e.g. PSRIX at EFF (Lazarus et al., 2016MNRAS.458..868L) and PuMaII at WSRT (Karuppusamy, Stappers & van Straten 2008PASP..120..191K), will be part of a future EPTA data release.

File Summary:

FileName	Lrecl	Records	Explanations
ReadMe	80	.	This file
table1.dat	89	42	Summary of the 42-pulsar data set
tab2-12.dat	517	42	Timing model parameters
table13.dat	95	42	Summary of pulsar parallaxes and distance estimates
table14.dat	58	19	Summary of the transverse motion of the isolated MSPs
table15.dat	58	57	Summary of the transverse motion of the binary MSPs
table17.dat	74	7	Table of pulsar and companion masses
tablea1.dat	79	257	Summary of the EPTA data set
refs.dat	107	55	References

Byte-by-byte Description of file: table1.dat

Bytes	Format	Units	Label	Explanations
1- 10	A10	---	PSR	PSR name (JHHMM+DDMM)
11	A1	---	n_PSR	[+] Note on PSR (1)
13- 31	A19	---	Obs	Observatories that contributed to the data set
33- 36	I4	---	NTOAs	Number of TOAs
38- 41	F4.1	yr	Tspan	Time span of the data set
43- 47	F5.2	us	e_TOA	Median TOA uncertainty taking into account the

Bytes	Format	Units	Label	Explanations
				white noise parameters 'EFAC' and 'EQUAD'
49- 53	F5.2	us	rms	rms timing residual (2)
55- 58	F4.1	ms	PSpin	Spin period
60- 65	F6.2	d	POrb	?=- Orbital period
67- 70	F4.2	mJy	S1400	Median flux density of the pulsar at 1400MHz (3)
72- 89	A18	---	Ref	References for the last published timing solution, in refs.dat file

Note (1): + indicates pulsars that are also named following the B1950 coordinate system, with the names B1855+09, B1937+21 and B1953+29, respectively.
Note (2): The quoted rms values are obtained from keeping the noise parameters, DM and red noise models at the maximum likelihood value while subtracting the DM signal from the residuals. Because of the degeneracy between the DM and red noise models, especially where no multifrequency data are available, the resulting rms quoted here can be biased towards smaller values (when the removed DM signal absorbed part of the red noise signal).
Note (3): see Section 2.3 for more details about the flux measurements.

Byte-by-byte Description of file: tab2-12.dat

Bytes	Format	Units	Label	Explanations
1- 10	A10	---	PSR	PSR name (JHHMM+DDMM)
12- 16	I5	d	MJD1	MJD range
17	A1	---	---	[-]
18- 22	I5	d	MJD2	MJD range
24- 27	I4	---	NTOAs	Number of TOAs
29- 33	F5.2	us	rms	rms timing residual
35- 39	I5	d	EpochR	[55000] Reference epoch (MJD)
41- 42	I2	h	RAh	Right ascension (J2000) (2)
44- 45	I2	min	RAm	Right ascension (J2000) (2)
47- 56	F10.7	s	RAs	Right ascension (J2000) (2)
58- 65	F8.7	s	e_RAs	rms uncertainty on Right ascension (1)
67	A1	---	DE-	Declination sign (J2000) (2)
68- 69	I2	deg	DEd	Declination (J2000) (2)
71- 72	I2	arcmin	DEm	Declination (J2000) (2)
74- 82	F9.6	arcsec	DEs	Declination (J2000) (2)
85- 91	F7.6	arcsec	e_DEs	rms uncertainty on Declination (1)
93- 99	F7.3	mas/yr	pmRA	Proper motion in RA
101-105	F5.3	mas/yr	e_pmRA	rms uncertainty on pmRA (1)
107-113	F7.3	mas/yr	pmDE	Proper motion in DE
115-120	F6.3	mas/yr	e_pmDE	rms uncertainty on pmDE (1)
122-139	F18.15	ms	Per	Period
141-148	E8.4	ms	e_Per	rms uncertainty on Per (1)
150-158	F9.6	10-2	dP/dt	Period derivative, dP/dt
160-166	F7.6	10-2	e_dP/dt	rms uncertainty on dP/dt (1)
168-171	F4.2	mas	plx	?=- Parallax
173-175	F3.2	mas	e_plx	?=- rms uncertainty on Parallax (1)
178-185	F8.4	pc/cm3	DM	Dispersion measure (2)
187-191	F5.4	pc/cm3	e_DM	rms uncertainty on DM (1)
193-200	F8.5	pc/cm3/yr	DM1	First dispersion measure derivative
202-207	F6.5	pc/cm3/yr	e_DM1	rms uncertainty on DM1 (1)
209-217	F9.6	pc/cm3/yr2	DM2	Second dispersion measure derivative
219-225	F7.6	pc/cm3/yr2	e_DM2	rms uncertainty on DM2 (1)
227-242	F16.12	d	Pb	? Orbital period
244-254	E11.4	d	e_Pb	? rms uncertainty on Orbital period (1)
256-266	F11.5	d	T0	? Epoch of periastron, T0 (MJD)
268-273	F6.5	d	e_T0	? rms uncertainty on T0 (1)
275-285	F11.8	---	x	? Projected semimajor axis, x, of the pulsar orbit (in lt-s unit)
287-295	F9.8	---	e_x	? rms uncertainty on projected semimajor axis (in lt-s unit)
297-304	F8.4	deg	Omega0	? Longitude of periastron
306-312	F7.4	deg	e_Omega0	? rms uncertainty on Omega0 (1)
314-323	E10.6	---	e	? Orbital eccentricity, e
325-329	E5.2	---	e_e	? rms uncertainty on e (1)
331-339	E9.4	---	kappa	? kappa = e x sin(Omega0) parameter
341-348	E8.4	---	e_kappa	? rms uncertainty on kappa (1)
350-359	E10.5	---	eta	? eta = e x cos(Omega0) parameter
360-363	F4.1	---	E_eta	? Error on eta, upper value (1)
366-371	E6.3	---	e_eta	? rms uncertainty on eta or error lower value (1)
373-387	F15.9	d	Tan	? Time of ascending node (MJD)
389-395	E7.4	d	e_Tan	? rms uncertainty on Tan (1)
397-401	F5.1	deg	GLON	Galactic longitude (3)
403-407	F5.1	deg	GLAT	Galactic latitude (3)
409-412	I4	pc	d	? Parallax distance corrected from the LK bias (3)
413	A1	---	---	[+]
414-417	I4	pc	E_d	? Error on d (upper value)
418	A1	---	---	[-]
419-421	I3	pc	e_d	? Error on d (lower value)
423-428	F6.3	mas/yr	CPM	Composite proper motion, μ (3)
430-435	F6.3	mas/yr	e_CPM	rms uncertainty on CPM (1)
437-443	F7.5	10-20	dP/dtSHK	SHK contribution to period derivative
445-451	F7.5	10-20	e_dP/dtSHK	? rms uncertainty on dP/dtSHK (1)
453-462	F10.7	10-20	dP/dtKZ	KZ contribution to period derivative
464-471	F8.7	10-20	e_dP/dtKZ	? rms uncertainty on dP/dtKZ (1)
473-480	F8.5	10-20	dP/dtDGR	DRG contribution to period derivative

Bytes	Format	Units	Label	Explanations
482-486	F5.4	10-20	e_dP/dtDGR	? rms uncertainty on dP/dtDGR (1)
488-494	F7.4	10-10	dP/dtInt	Intrinsic period derivative
495-499	F5.3	10-10	e_dP/dtInt	? rms uncertainty on dP/dtInt (1)
501	A1	---	l_Age	Limit flag on Age
502-506	F5.2	Gyr	Age	? Characteristic age, τc (Gyr)
508	A1	---	l_B	Limit flag on B
509-512	F4.1	10+8gauss	B	? Surface magnetic field
514-517	F4.2	Msun	M2min	? Minimum companion mass (4)

Note (1): 68.3 per cent confidence uncertainties and come from the one-dimensional marginalized posterior distribution of each parameter.
Note (2): The position, spin period and DM are given for the reference epoch of MJD=55000.
Note (3): The derived parameters show the Galactic longitude (l) and latitude (b), the parallax distance corrected from the LK bias (d), the composite proper motion (mu).
Note (4): For binary pulsars, the minimum companion mass, assuming a pulsar mass of 1.2 $M_{\odot}$.

Byte-by-byte Description of file: table13.dat

Bytes	Format	Units	Label	Explanations
1- 10	A10	---	PSR	Pulsar name (JHHMM+DDMM)
12- 17	F6.2	pc/cm3	DM	Dispersion measure
19- 22	F4.2	kpc	Dist1	Distance based on the NE2001 electron density model DNE2001 (Cordes & Lazio, 2002astro.ph..7156C)
24- 27	F4.2	kpc	DistM2	Distance based on the M2 model
29	A1	---	l_DistM3	Limit flag on DistM3
30- 34	F5.2	kpc	DistM3	Distance based on the M3 model
36	A1	---	l_Dist	Limit flag on Dist
37- 41	F5.2	kpc	Dist	?=- Upper limit on the distance DdP/dt (only indicated when this limit is <15kpc; see text)
43- 46	F4.2	mas	plxP	?=- Previously published parallax value (reference in table 1)
48- 51	F4.2	mas	e_plxP	? rms uncertainty on plxP
53- 56	F4.2	mas	plx	?=- our new measurement of the parallax
58- 61	F4.2	mas	e_plx	? rms uncertainty on plx
62	A1	---	n_plx	[*] Note on plx (1)
64- 67	F4.2	mas	plxCorr	?=- LK-bias-corrected parallax
69- 72	F4.2	mas	E_plxCorr	? Error on plxCorr (upper value)
74- 77	F4.2	mas	e_plxCorr	? Error on plxCorr (loper value)
78	A1	---	n_plxCorr	[*] Note on plxCorr (1)
80- 83	F4.2	kpc	DistPlx	?=- Distance corresponding to plx and plxCorr
85- 88	F4.2	kpc	E_DistPlx	? Error on DistPlx (upper value)
90- 93	F4.2	kpc	e_DistPlx	? Error on DistPlx (lower value)
94	A1	---	n_DistPlx	[*] Note on DistPlx (1)
95	A1	---	Note	[a] Note (2)

Note (1): * : updated or new parallax measurements as part of this work.

Note (2): a: For PSR J0218+4232, the parallax was obtained through VLBI observations (Du et al. 2014ApJ...782L..38D) but the inferred large distance was later corrected by Verbiest & Lorimer (2014MNRAS.444.1859V) for the LK bias.

Byte-by-byte Description of file: table1[45].dat

Bytes	Format	Units	Label	Explanations
1- 10	A10	---	PSR	Pulsar name (JHHMM+DDMM)
12- 19	F8.4	mas/yr	CPM	Composite proper motion
21- 27	F7.4	mas/yr	e_CPM	rms uncertainty on CPM
28	A1	---	n_CPM	[n] n for new proper-motion measurement
30- 35	F6.1	pc	Dist	Best distance estimates available (1)
37- 42	F6.1	pc	e_Dist	? rms uncertainty on Dist
43	A1	---	n_Dist	[*] * for NE2001 distance
45- 49	F5.1	km/s	vt	Transverse velocity corresponding to distance Dist (2D velocity)
51- 55	F5.1	km/s	e_vt	rms uncertainty on vt
57- 58	A2	---	Ref	Reference with published proper motion and distance measurements, in refs.dat file

Note (1): The distances refer to the best distance estimates available, either the parallax when uncertainties are given or the NE2001 distance (indicated by *) where a 80 per cent error is assumed.

Byte-by-byte Description of file: table17.dat

Bytes	Format	Units	Label	Explanations

```
  1- 10  A10    ---      PSR       PSR name (JHHMM+DDMM)
 12- 15  F4.2   Msun     MpPrev    ? Previous pulsar mass
 17- 20  F4.2   Msun     e_MpPrev  ? rms uncertainty on previous pulsar mass
     21  A1     ---      n_MpPrev  [+] Note on MpPrev (1)
 23- 27  F5.3   Msun     McPrev    ? Previous companion mass
 29- 33  F5.3   Msun     e_McPrev  ? rms uncertainty on previous companion mass
     34  A1     ---      n_McPrev  [*] Note on McPrev (1)
 36- 37  A2     ---      Ref       Reference for previous masses, in refs.dat file
 39- 42  F4.2   Msun     Mp        New pulsar mass
 44- 48  F5.3   Msun     E_Mp      Error on Mp (upper value)
 50- 54  F5.3   Msun     e_Mp      Error on Mp (lower value)
 56- 60  F5.3   Msun     Mc        New companion mass
 62- 67  F6.4   Msun     E_Mc      Error on Mc (upper value)
 69- 74  F6.4   Msun     e_Mc      Error on Mc (lower value)
```

```
Note (1): Note as follows:
  + = the pulsar masses were not reported by Verbiest et al.
       (2009MNRAS.400..951V) so we quote the pulsar mass value based on the
       mass function and their companion mass.
  * = Nice et al. (2008, AIP Conf. Proc. Vol. 983, 453) did not report on the
       companion mass in their proceedings.
```

Byte-by-byte Description of file: tablea1.dat

```
   Bytes Format Units  Label    Explanations

  1- 10  A10    ---    PSR      PSR name (JHHMM+DDMM)
 12- 13  I2     ---    Nj       Nmber of JUMPs included in the timing solution
 15- 20  F6.2   ---    ARN      Maximum likelihood results for the red noise
                                 model, dimensionless amplitude A
 22- 25  F4.2   ---    gammaRN  Maximum likelihood results for the red noise
                                 model, spectral index gamma
 27- 32  F6.2   ---    ADM      Maximum likelihood results for the DM model,
                                 dimensionless amplitude A
 34- 37  F4.2   ---    gammaDM  Maximum likelihood results for the DM model,
                                 spectral index gamma
 39- 42  A4     ---    Obs      Observatory
 44- 49  F6.1   MHz    Freq     Frequency band
 51- 56  F6.1   yr     Year1    Year range
     57  A1     ---    ---      [-]
 58- 63  F6.1   yr     Year2    Year range
 65- 68  I4     ---    NTOAs    Number of TOAs
 70- 73  F4.2   ---    Ef       Maximum likelihood values for the EFAC parameter
 75- 79  F5.2   [s]    Eq       Maximum likelihood values for the EQUAD
                                 parameter, in log10-base
```

Byte-by-byte Description of file: refs.dat

```
   Bytes Format Units   Label     Explanations

  1-  3  A3     ---     Ref       Reference code
  5- 23  A19    ---     BibCode   BibCode
 25- 54  A30    ---     Aut       Author's name
 56-107  A52    ---     Com       Comments
```

History:
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