Measurement of dispersion measure variations and solar wind effect by millisecond pulsars

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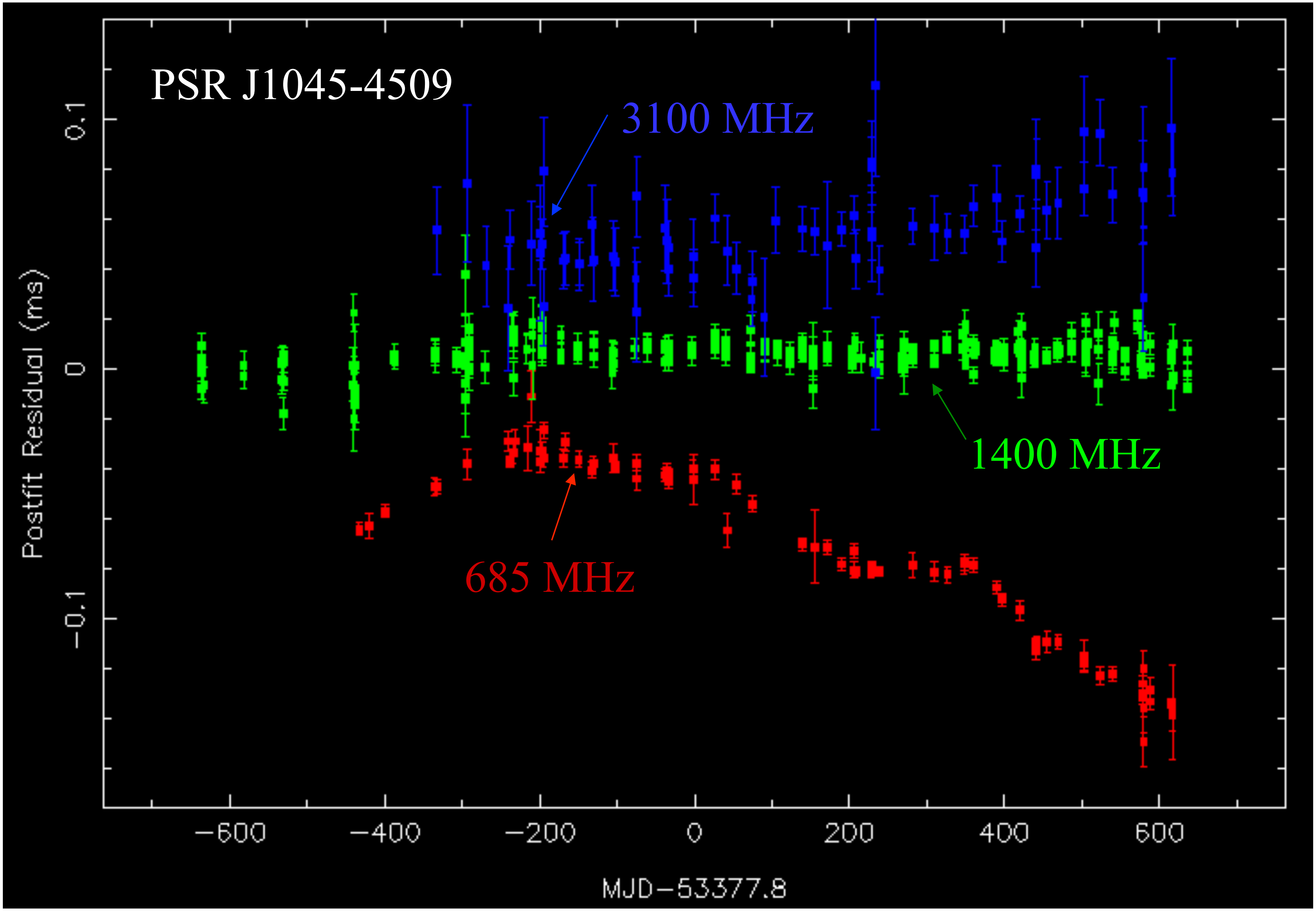
2012 IPTA Conference, Kiama

DM variations mentioned yesterday

- Dick’s talk
- Maura’s talk
- Ben’s talk
- David’s talk
- Gemma’s talk
- Bill’s talk
- KJ’s advertisement for poster
- Paul’s talk tomorrow maybe?

PPTA

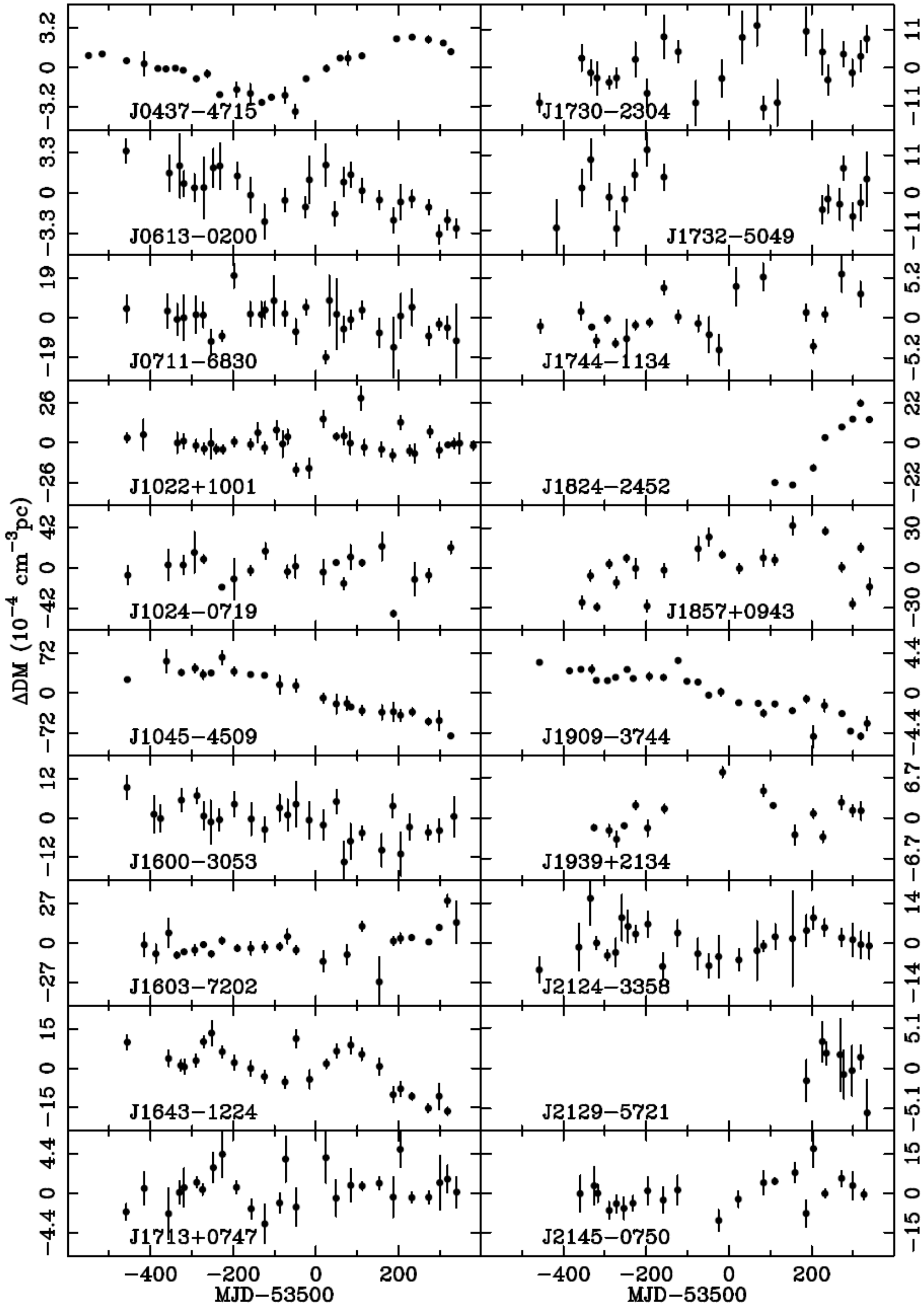

PSR J1045-4509
3100 MHz
1400 MHz
685 MHz
Postfit Residual (ms)
0.1
0
−0.1
−600
−400
−200
0
200
400
600
MJD−53377.8

DM variations from ISM

20 millisecond pulsars

(You et al., 2007)

PPTA



Smoothing method to improve pulsar timing residuals

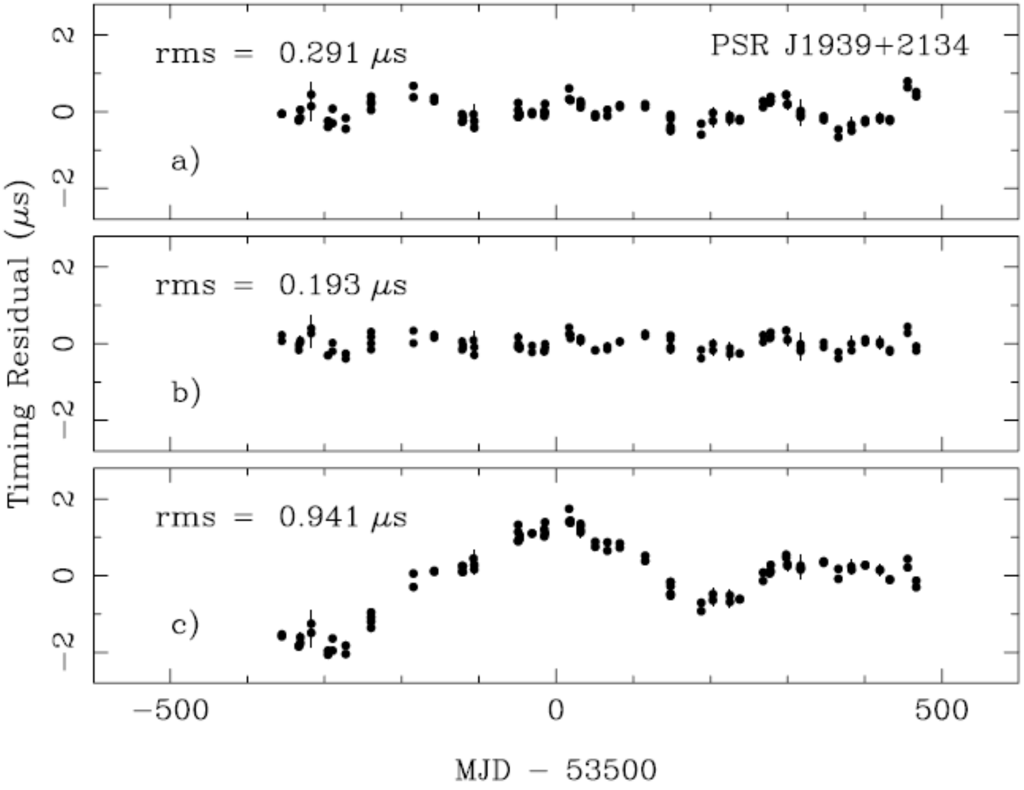
- 6 pulsars’ residuals improved

PSR Name	T_{sm}^{theory} (d)	$T_{sm}^{simu.}$ (d)	σ_{orig} (μs)	$\sigma_{\text{cor.}}$ (μs)	$\sigma_{\text{uncor.}}$ (μs)
J1939+2134	100	71	0.291	0.193	0.941
J1824−2452	54	51	0.937	0.883	4.111
J0437−4715	243	91	0.396	0.316	0.509
J1909−3744	163	211	0.192	0.186	0.605
J1045−4509	116	201	3.862	3.800	9.386
J1643−1224	281	361	2.770	2.732	3.200

- Timing parameters changed

	J1939	J1045
P	28 σ	10 σ
dp/dt	28 σ	6 σ
PM	17 σ	no

(You et al., 2007)



DM Variations and Correction

- DM offsets solved for along with pulsar parameters and frequency-independent (“common-mode”) signal using Cholesky algorithm in Tempo2 on PPTA three-band data sets

$$\boxed{t_{o,i} = t_c + t_d(\lambda_i/\lambda_r)^2 + t_{w,i}}$$

- DM offsets measured at intervals through data sets with linear interpolation between values
- Interval size taken to be inverse of modulation frequency where red (DM) signal is same power as white noise
- Mean DM offset constrained to be zero
- Effectiveness of algorithm tested using simulations

(Keith et al. 2012)

(From Dick’s talk yesterday)

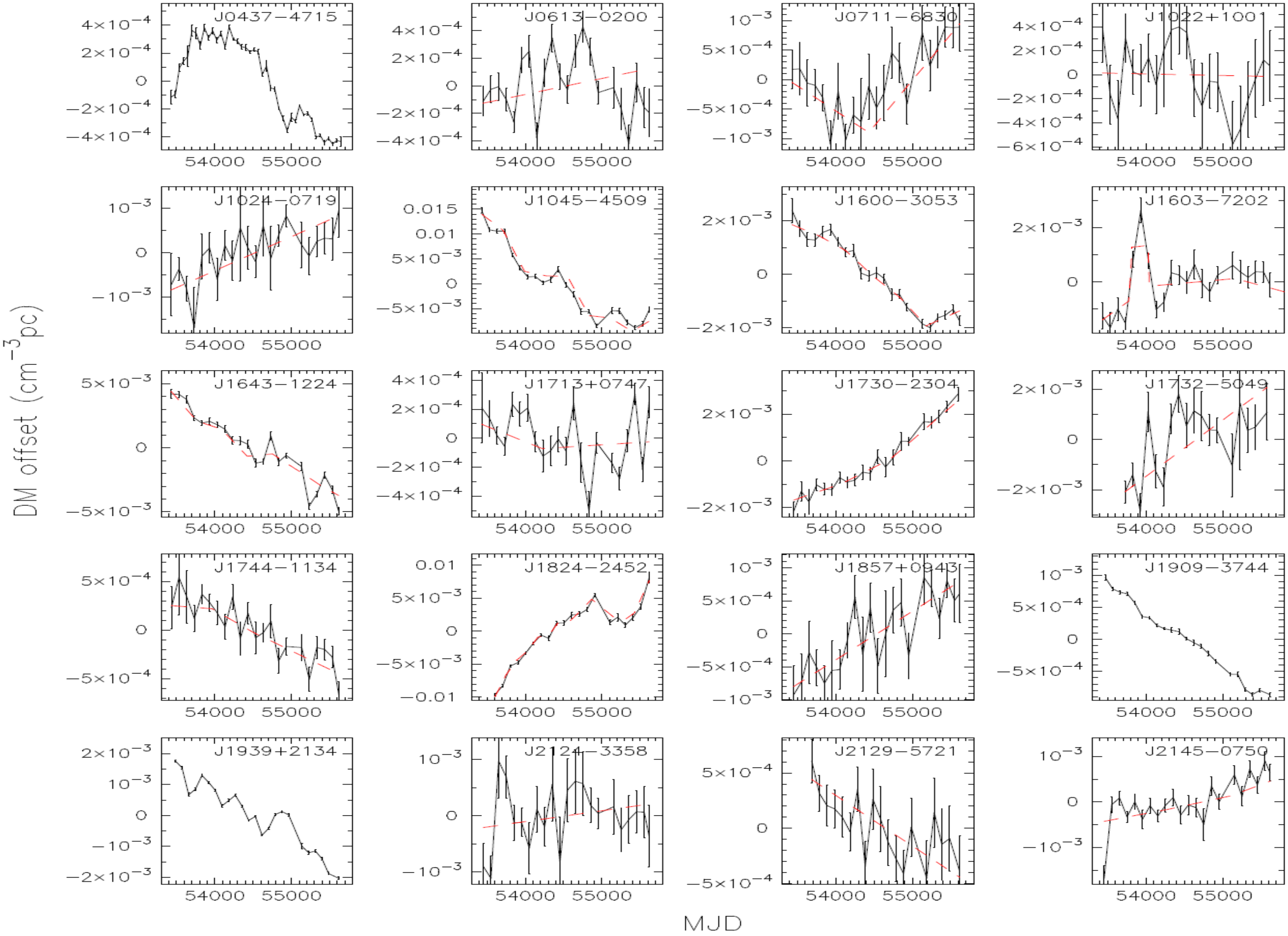
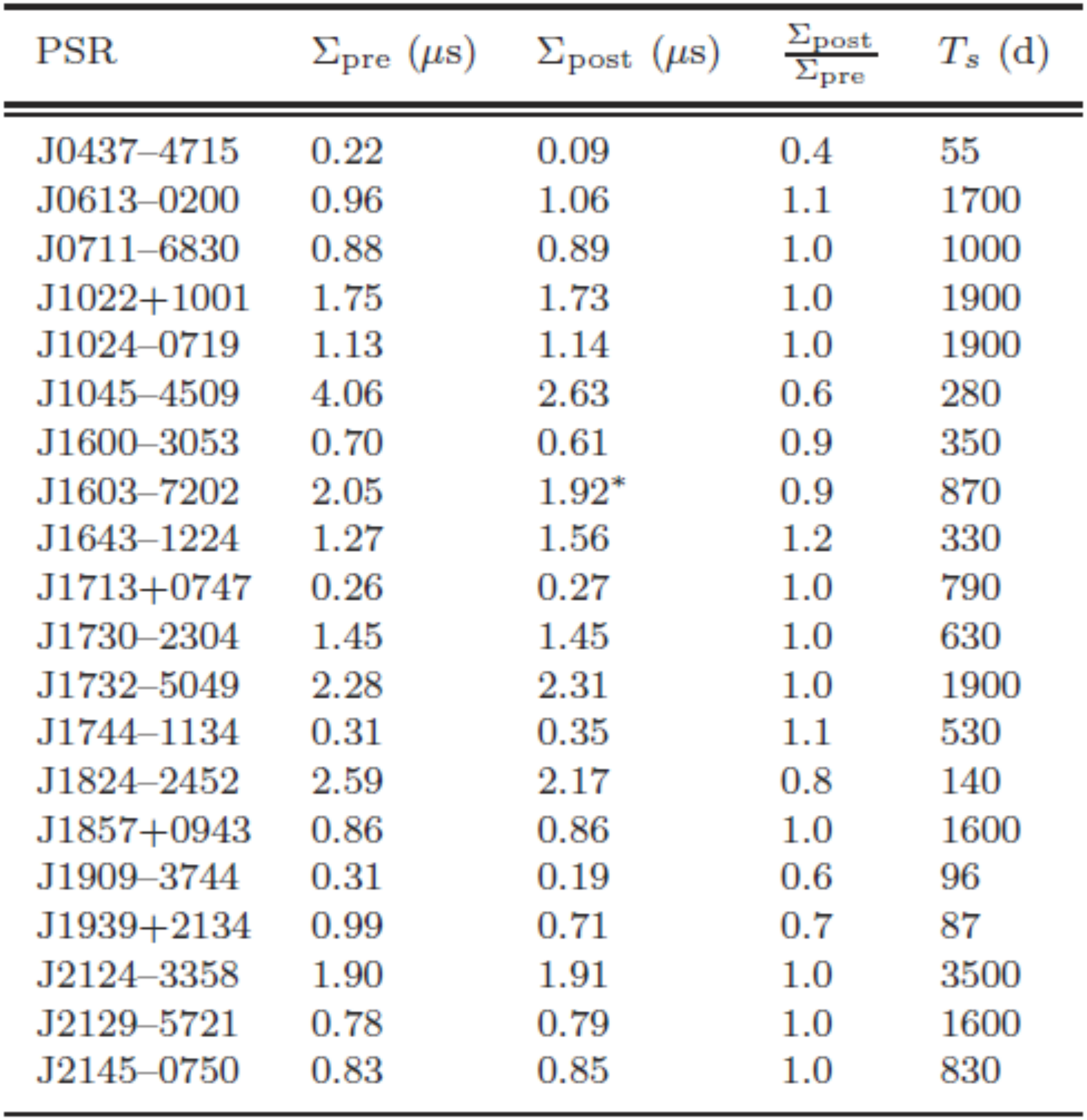


Figure 6. DM as a function of time for 20 PPTA pulsars. Solid lines show values measured at 100 day intervals, or T_s if shorter. Dashed lines show values measured with sampling interval T_s.

(Keith et al. 2012)

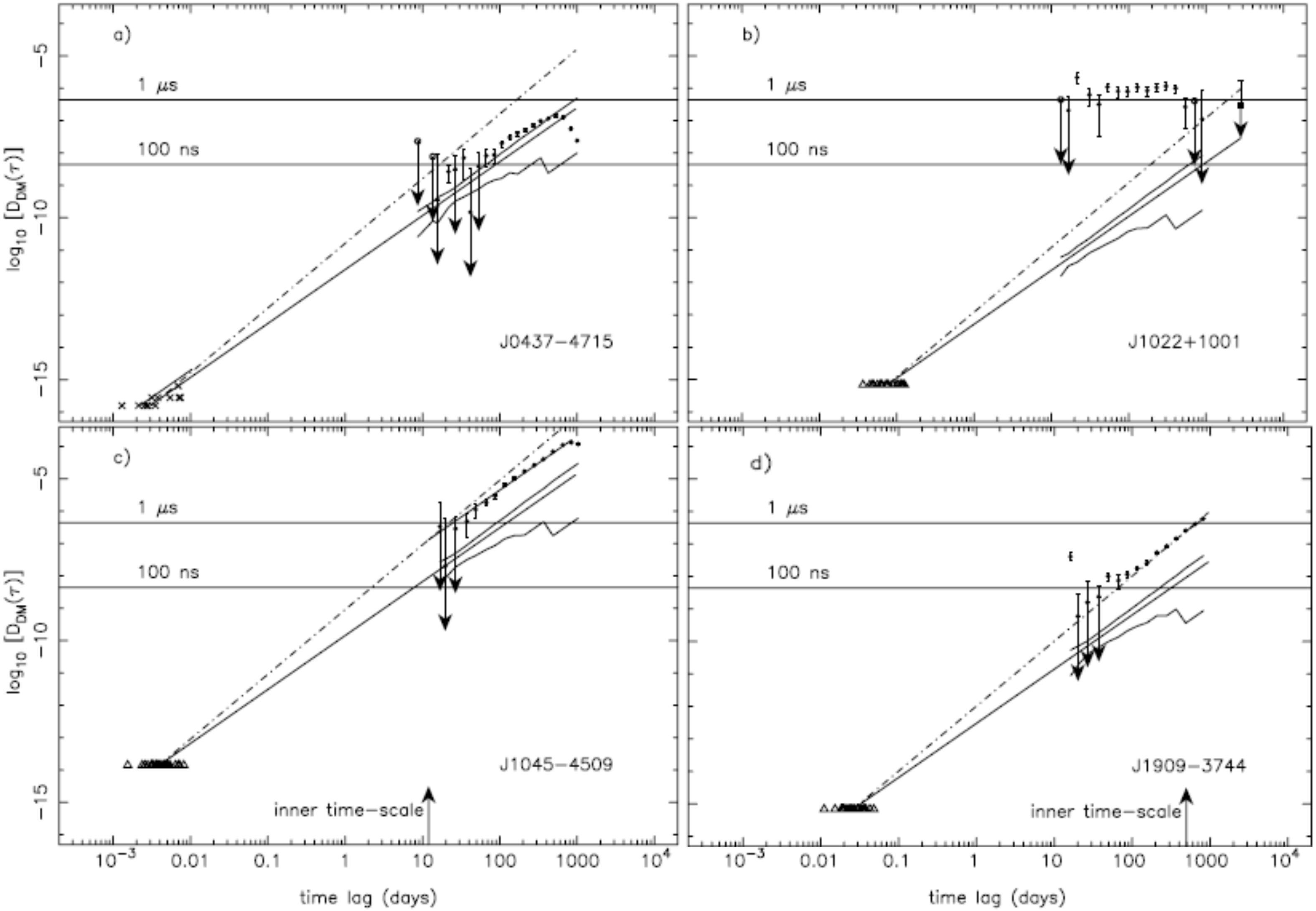
7 pulsar’s residual improved

(Keith et al. 2012)

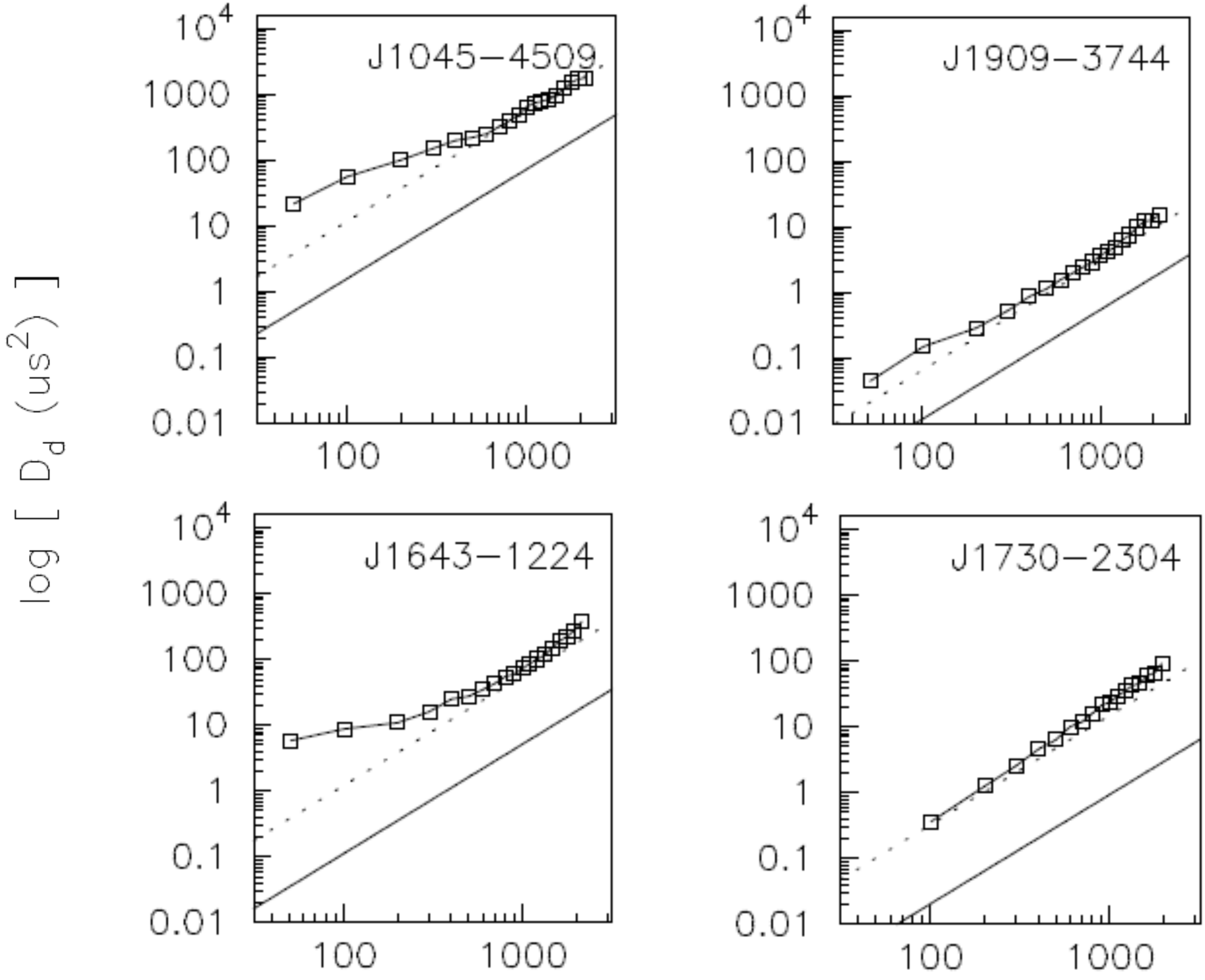


PSR	$\Sigma_{\rm pre}$ (μs)	$\Sigma_{\rm post}$ (μs)	$\frac{\Sigma_{\rm post}}{\Sigma_{\rm pre}}$	T_s (d)
J0437–4715	0.22	0.09	0.4	55
J0613–0200	0.96	1.06	1.1	1700
J0711–6830	0.88	0.89	1.0	1000
J1022+1001	1.75	1.73	1.0	1900
J1024–0719	1.13	1.14	1.0	1900
J1045–4509	4.06	2.63	0.6	280
J1600–3053	0.70	0.61	0.9	350
J1603–7202	2.05	1.92*	0.9	870
J1643–1224	1.27	1.56	1.2	330
J1713+0747	0.26	0.27	1.0	790
J1730–2304	1.45	1.45	1.0	630
J1732–5049	2.28	2.31	1.0	1900
J1744–1134	0.31	0.35	1.1	530
J1824–2452	2.59	2.17	0.8	140
J1857+0943	0.86	0.86	1.0	1600
J1909–3744	0.31	0.19	0.6	96
J1939+2134	0.99	0.71	0.7	87
J2124–3358	1.90	1.91	1.0	3500
J2129–5721	0.78	0.79	1.0	1600
J2145–0750	0.83	0.85	1.0	830

Study spectrum of turbulence of ISM



(You et al., 2007)



(Keith et al. 2012)

Summary

- Researching DM variations is very important both for improving pulsar timing residuals and studying properties of interstellar medium

Brief introduction of the solar wind

Solar wind --- plasma with speed ~ 400 km/s, complex structure

Quasi-static and transient component

- quasi-static ： co-rotating with the Sun；

- Transient component：changes very quickly，coronal mass ejections (CME)

- Our work, concentrate on quasi-static component

The magnetic field of the solar wind

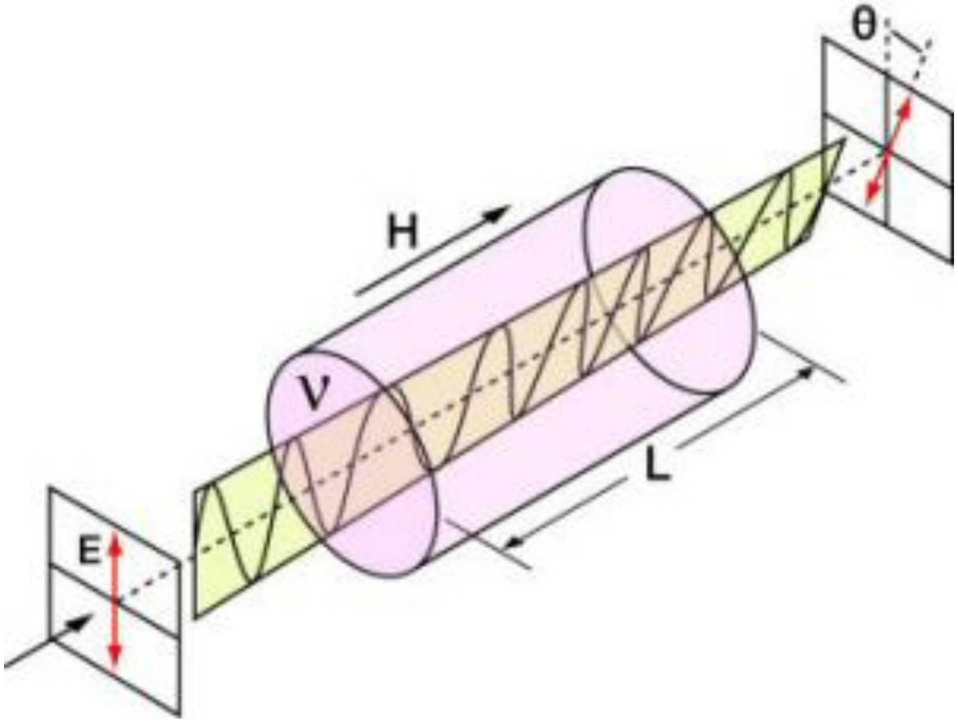
- Very important, control structure and dynamics of the coronal and solar wind plasma
- Difficult to measure
- The most reliable method is:

  Faraday rotation of linearly polarized radio background sources

$$\Delta\psi = \mathrm{RM}\lambda^2$$

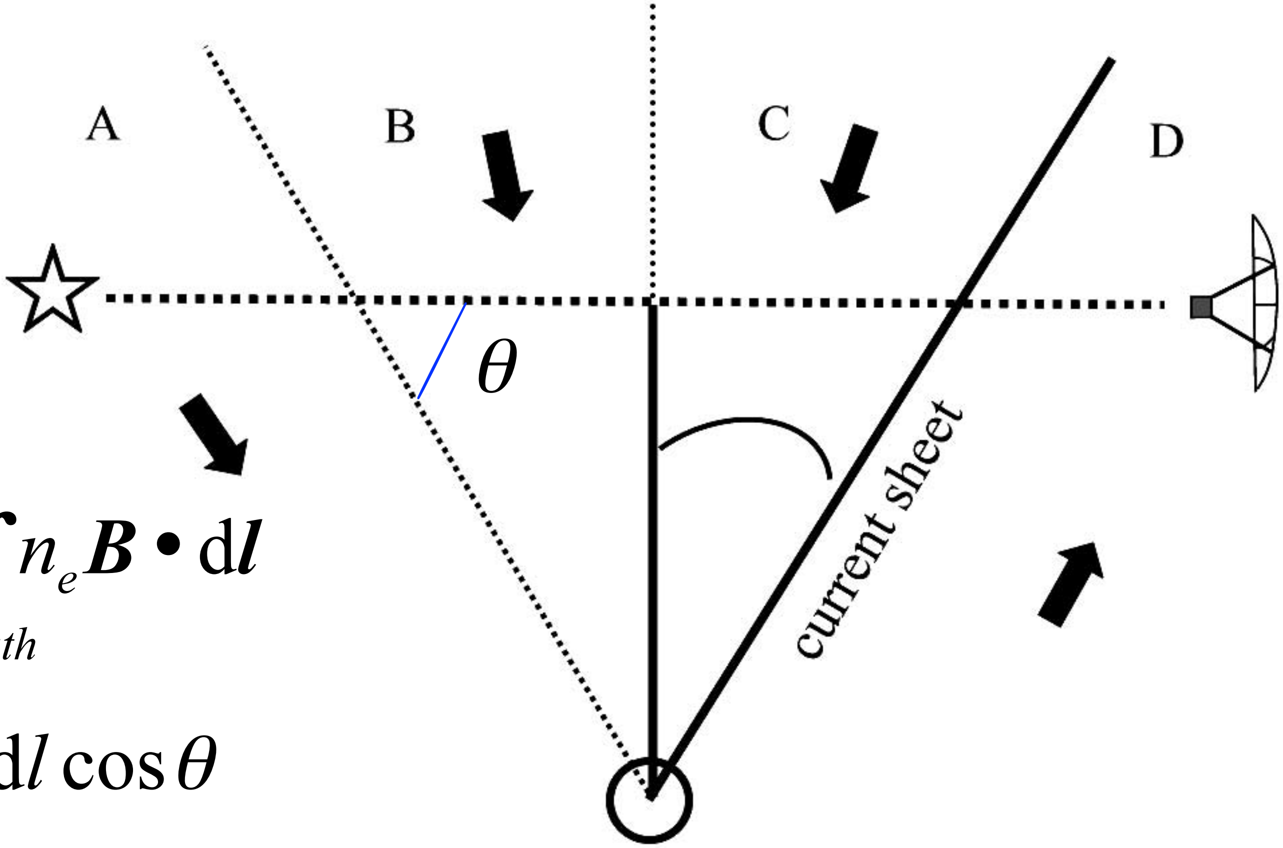
$$\mathrm{RM} = \frac{e^3}{2\pi m_e c^4} \int_{path} n_e \boldsymbol{B} \bullet d\boldsymbol{l}$$

$$= 0.810 \int_{path} n_e \boldsymbol{B} \bullet d\boldsymbol{l}$$



The magnetic field of the solar wind

- Radial Magnetic field close to the Sun
- Importance of “current-sheet”, radial component of field change sign.



$$\mathrm{RM} = 0.810 \int_{path} n_e \boldsymbol{B} \bullet \mathrm{d}\boldsymbol{l}$$

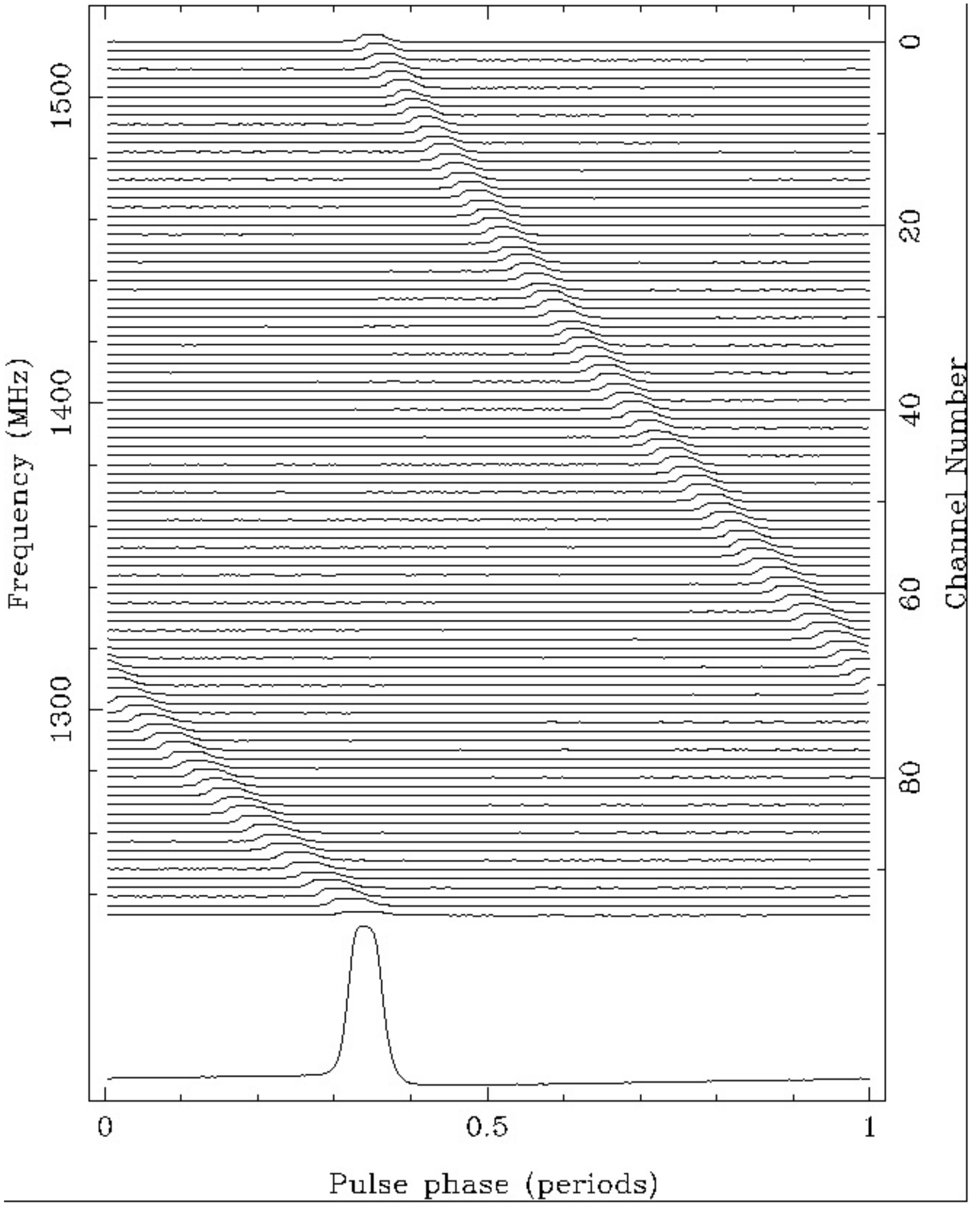
$$= 0.810 \int_{path} n_e B \mathrm{d}l \cos\theta$$

The problem of n_e

- Pulsars as an unique source to get information of n_e
- Dispersion Measure（DM）

$$\tau_g = \frac{e^2}{2\pi m_e c \nu^2} \int_{path} n_e \mathrm{d}l$$

$$\mathrm{DM} = \int_{path} n_e \mathrm{d}l$$



Group delay from the solar wind

- Simultaneously getting group delay and rotation measure is important
- Comparing with ISM, group delay from the solar wind is very small
- Only high precise timing can measure it
- Need millisecond pulsars.

Previous work

- Using extragalactic radio sources
  - Ingleby et al 2007, 30-34 mG at 6.2 R_s
  - Spangler 2005, 39mG at 6.2 R_s
- Using normal pulsars
  - Ord et al, 2007, RM changes 170 rad m^2
- Both of them can NOT measure DM from the solar wind

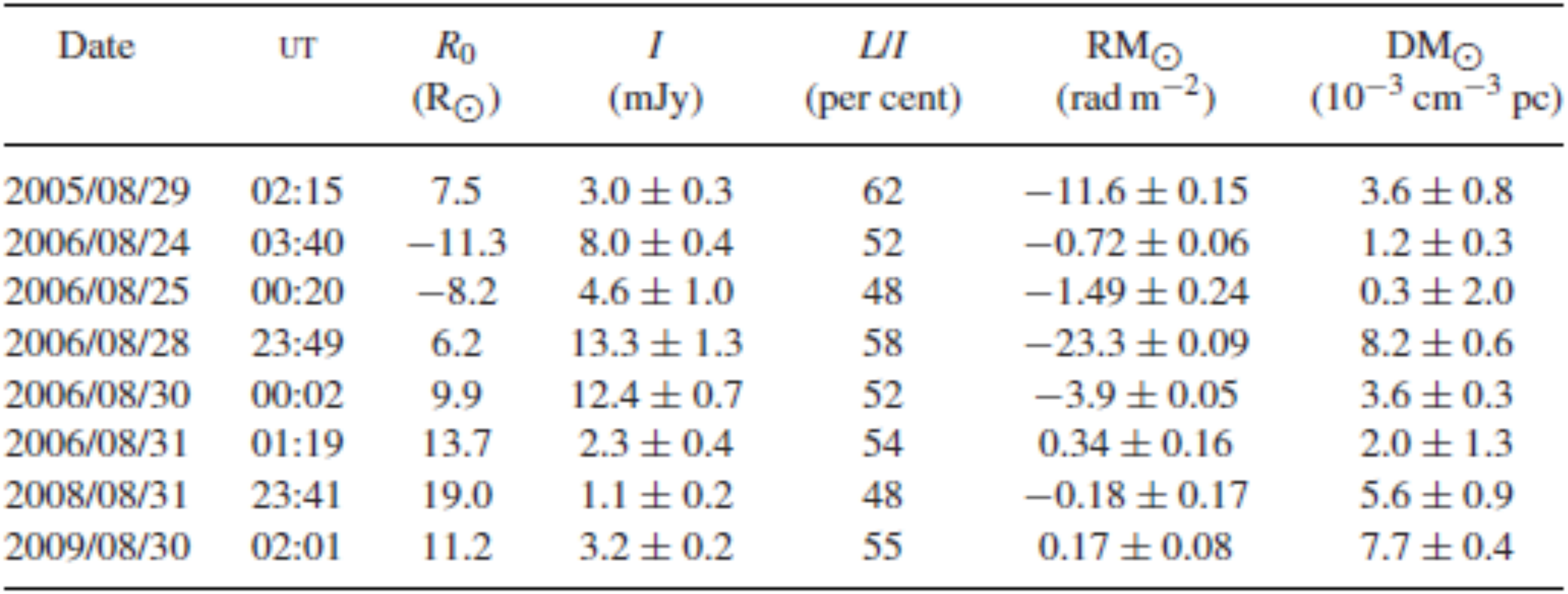
Our work

- Using a millisecond pulsars PSRs J1022+1001 (b_e=-0.06^o)
- Obtain both RM and DM from the solar wind
- Model fitting our measurement to obtain magnetic field of solar wind

(You et al., 2007)

Observation and data process

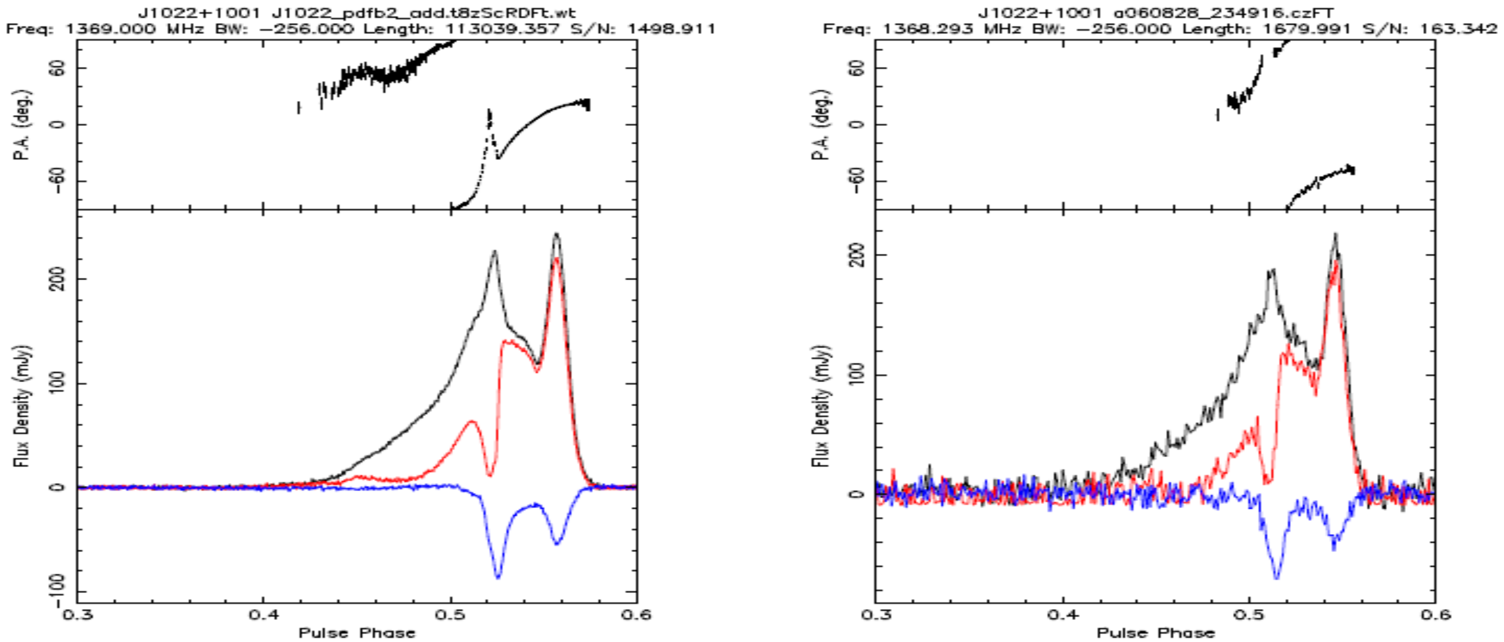
- Part of the PPTA project
- Using the observations when the line of the pulsar close to the Sun.
- Frequency, ~1400 MHz , bandwidth, 256MHz
- Full flux and polarization calibrated



Date	UT	R_0 ($R_\odot$)	I (mJy)	L/I (per cent)	$\mathrm{RM}_\odot$ (rad m^{-2})	$\mathrm{DM}_\odot$ (10^{-3} cm^{-3} pc)
2005/08/29	02:15	7.5	3.0 ± 0.3	62	-11.6 ± 0.15	3.6 ± 0.8
2006/08/24	03:40	−11.3	8.0 ± 0.4	52	-0.72 ± 0.06	1.2 ± 0.3
2006/08/25	00:20	−8.2	4.6 ± 1.0	48	-1.49 ± 0.24	0.3 ± 2.0
2006/08/28	23:49	6.2	13.3 ± 1.3	58	-23.3 ± 0.09	8.2 ± 0.6
2006/08/30	00:02	9.9	12.4 ± 0.7	52	-3.9 ± 0.05	3.6 ± 0.3
2006/08/31	01:19	13.7	2.3 ± 0.4	54	0.34 ± 0.16	2.0 ± 1.3
2008/08/31	23:41	19.0	1.1 ± 0.2	48	-0.18 ± 0.17	5.6 ± 0.9
2009/08/30	02:01	11.2	3.2 ± 0.2	55	0.17 ± 0.08	7.7 ± 0.4

Obtain RM from the Sun

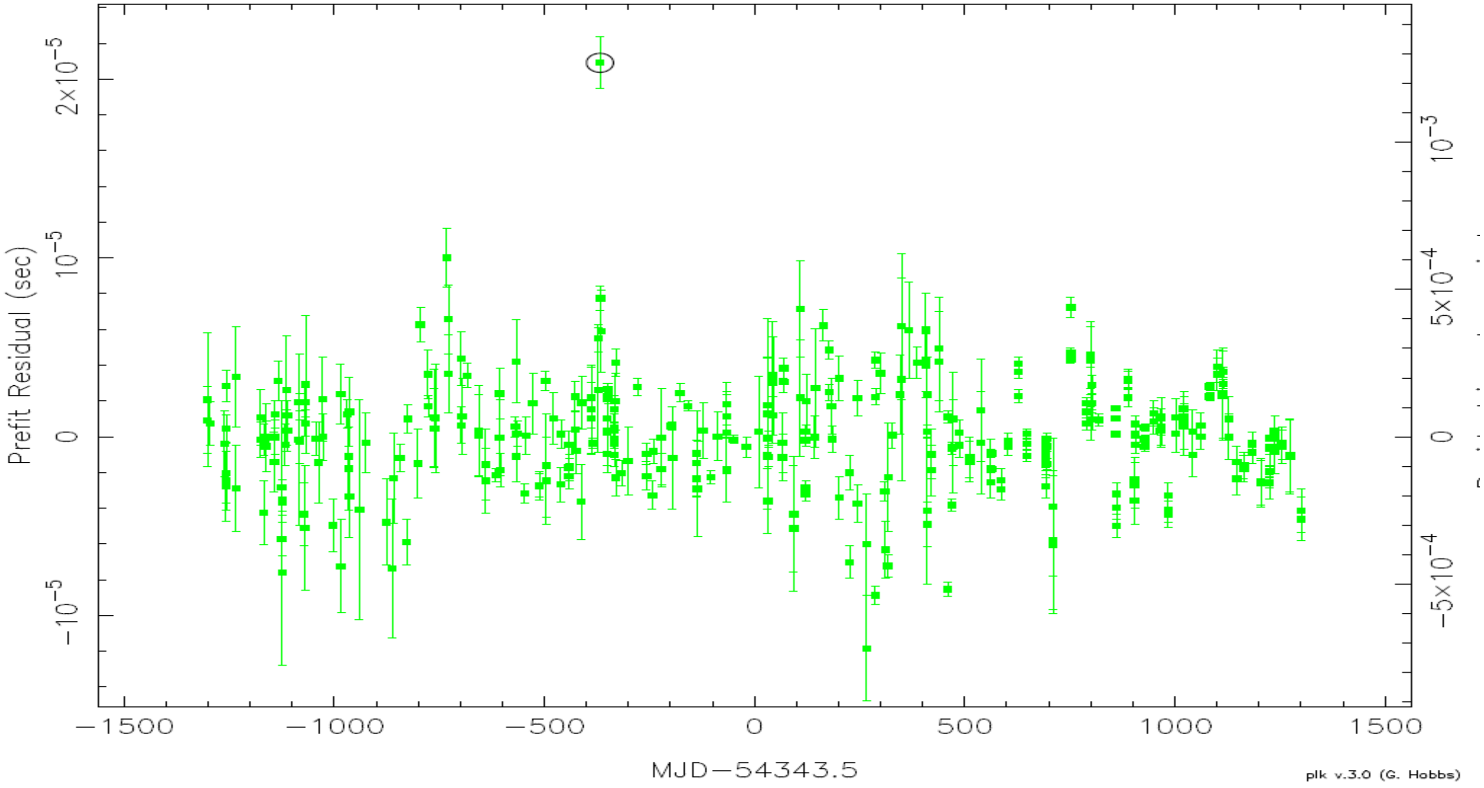
- Adjust RM to optimize the linearly polarized intensity, depolarization
- Separate the each observation into two halves
- Calculating PA difference close and far from the Sun (taking weighted average of the difference between PAs across an individual observation profile and the PAs across the grand average profile)
- Subtracting the contribution from ionosphere (IRI model)



060828:23:49 R0=6.2 Rs PA=-68.5^o, RM_sun=-23.7 rad m^2

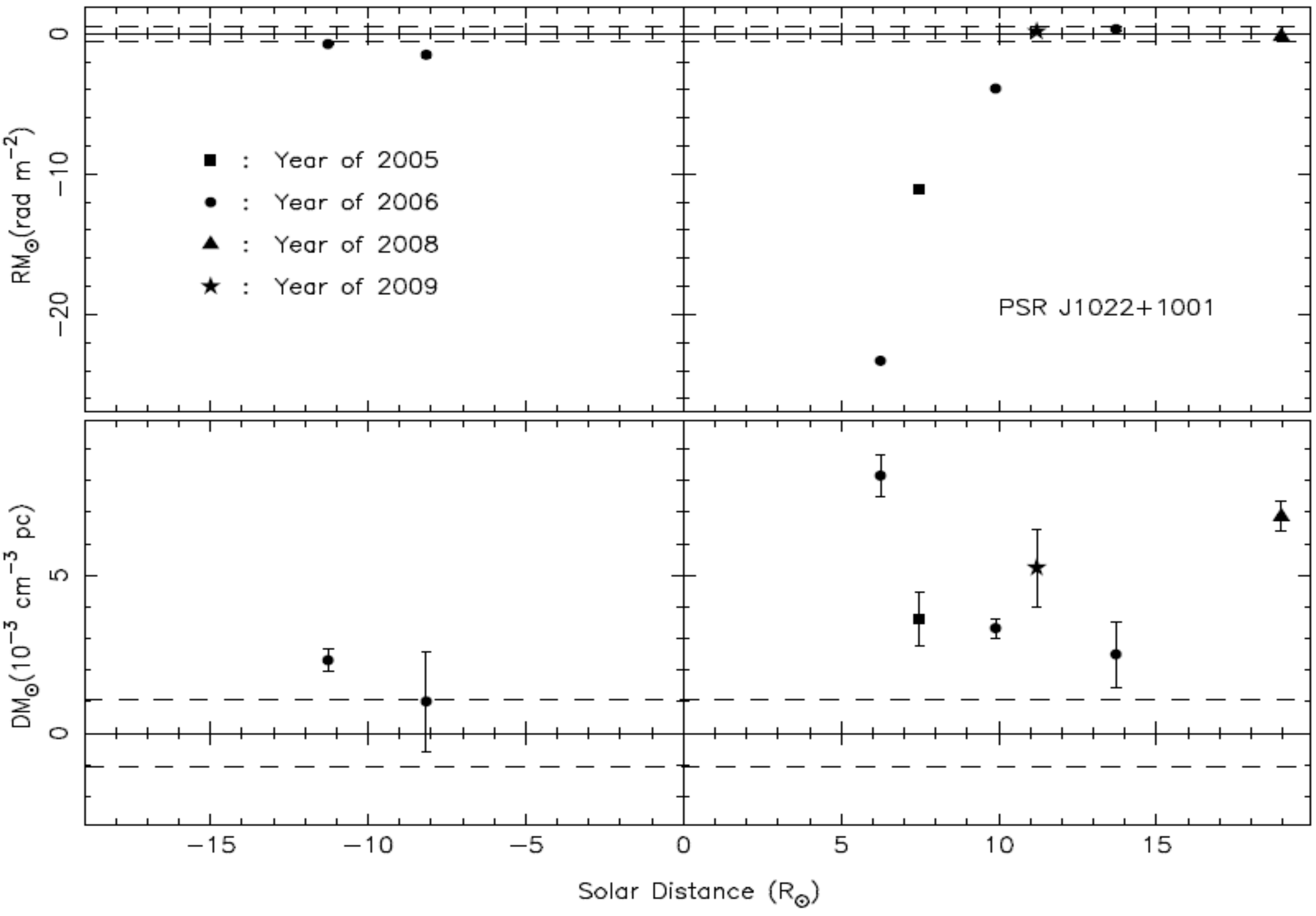
Obtain DM from the Sun

- Fitting timing model
- Obtain extra timing residual from the Sun



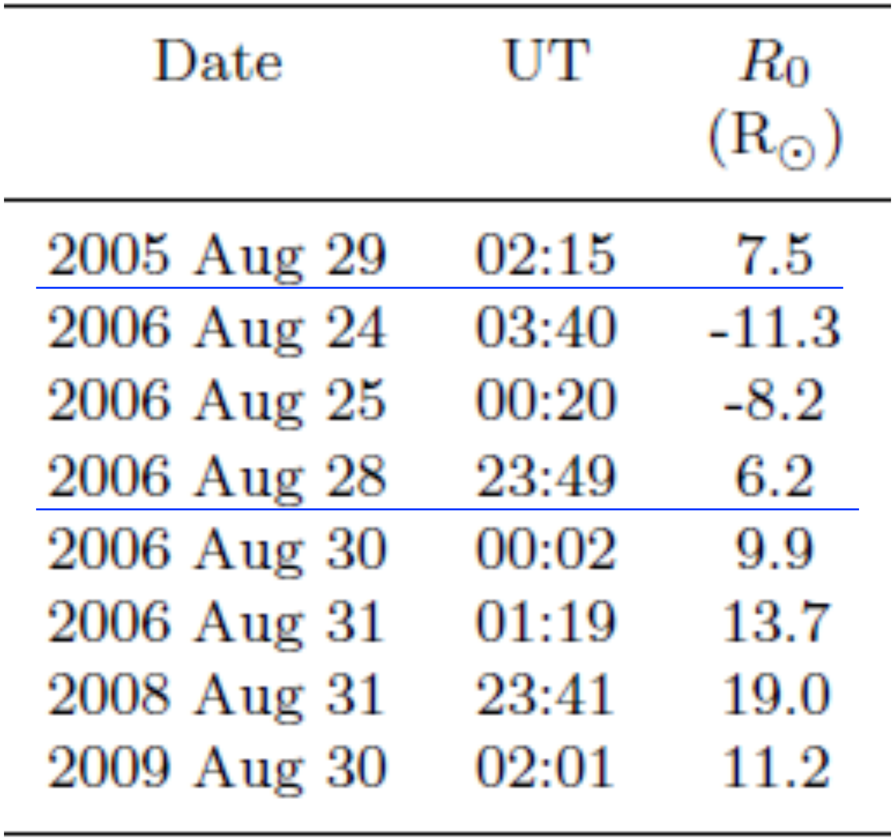
060828:23:49   R0=6.2 Rs t=20.5 μs, DM_sun=8.2X10^{-3} cm^{-3}pc

Observational results

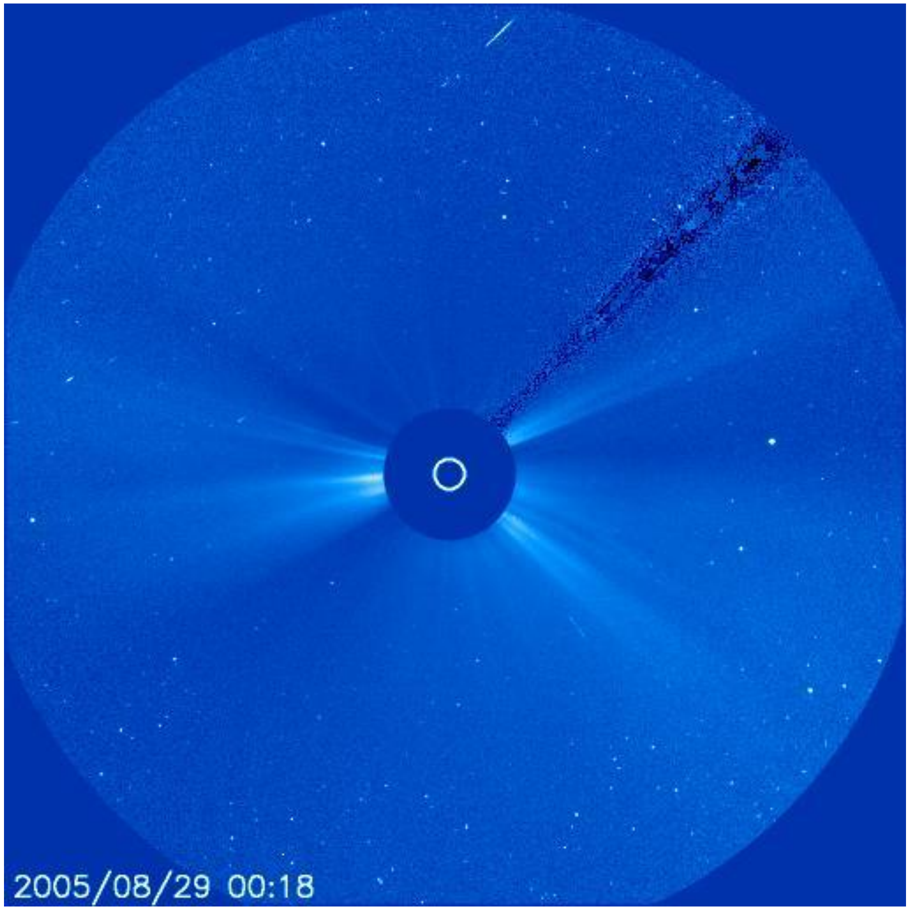


Model fitting

- Step 1, check there is no transient event
- Using LASCO C3 movie



Date	UT	R_0 ($R_\odot$)
2005 Aug 29	02:15	7.5
2006 Aug 24	03:40	-11.3
2006 Aug 25	00:20	-8.2
2006 Aug 28	23:49	6.2
2006 Aug 30	00:02	9.9
2006 Aug 31	01:19	13.7
2008 Aug 31	23:41	19.0
2009 Aug 30	02:01	11.2



Step 2: modelling electron density Two-state model：fast and slow wind

- **Fast wind**：lower density, originate in active regions at high latitude

$$n_e = 1.155\times10^{11} R_\odot^{-2} + 32.3\times10^{11} R_\odot^{-4.39} + 3254\times10^{11} R_\odot^{-16.25} \quad (m^{-3}) \qquad (3)$$

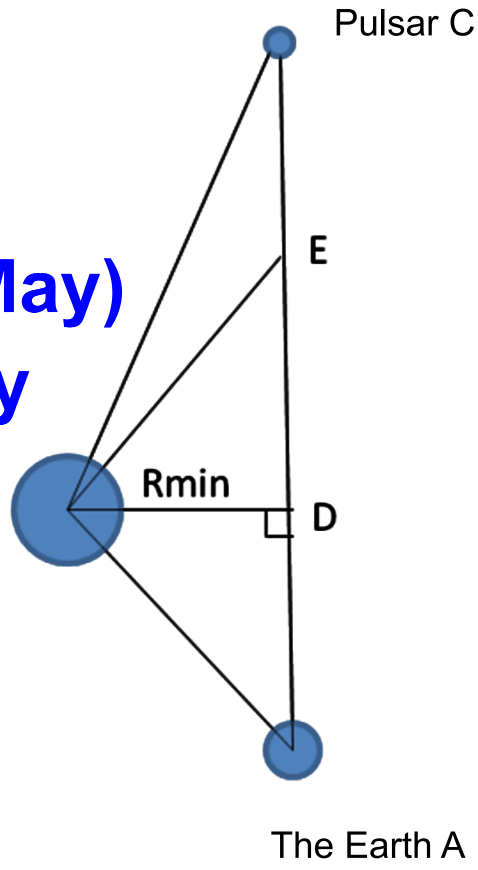
- **Slow wind**：relatively high density, originate in active regions at low or middle latitude

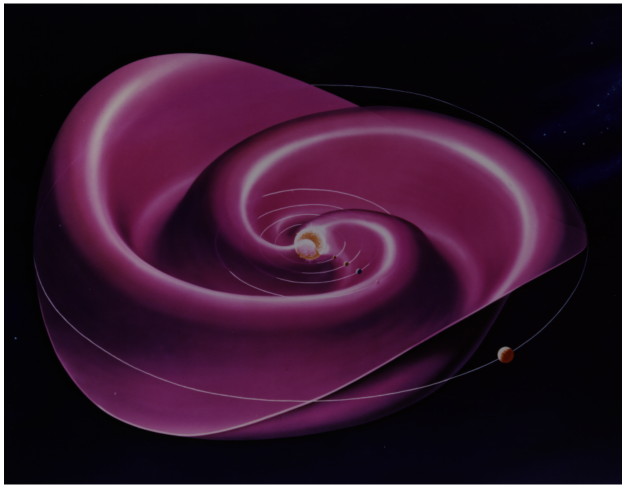
$$n_e = 2.99\times10^{14} R_\odot^{-16} + 1.5\times10^{14} R_\odot^{-6} + 4.1\times10^{11}(R_\odot^{-2} + 5.74R_\odot^{-2.7}) \quad (m^{-3}) \qquad (4)$$

- Assume slow wind occupies the zone within 20° of the magnetic neutral line and outside this is dominated by the fast wind and that both winds flow radially.

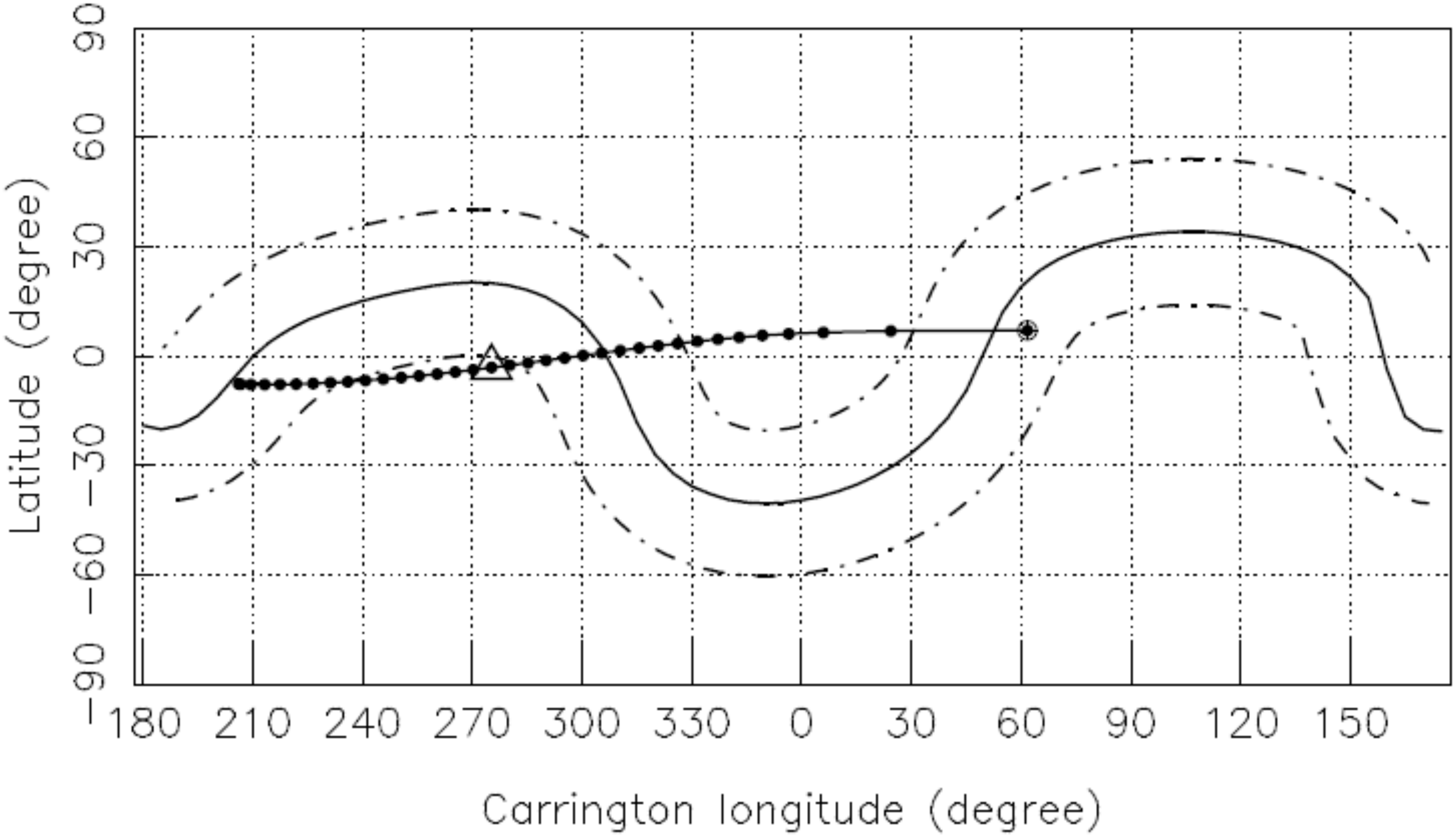
obtain the current-sheet

- Position of pulsars → relatively positions of the pulsar, the Sun and the Earth
- Observing time → make sure the Carrington rotation (starting 1976, May)
- Data from Wilcox Solar Observatory
- According the data, determine the position of the current-sheet



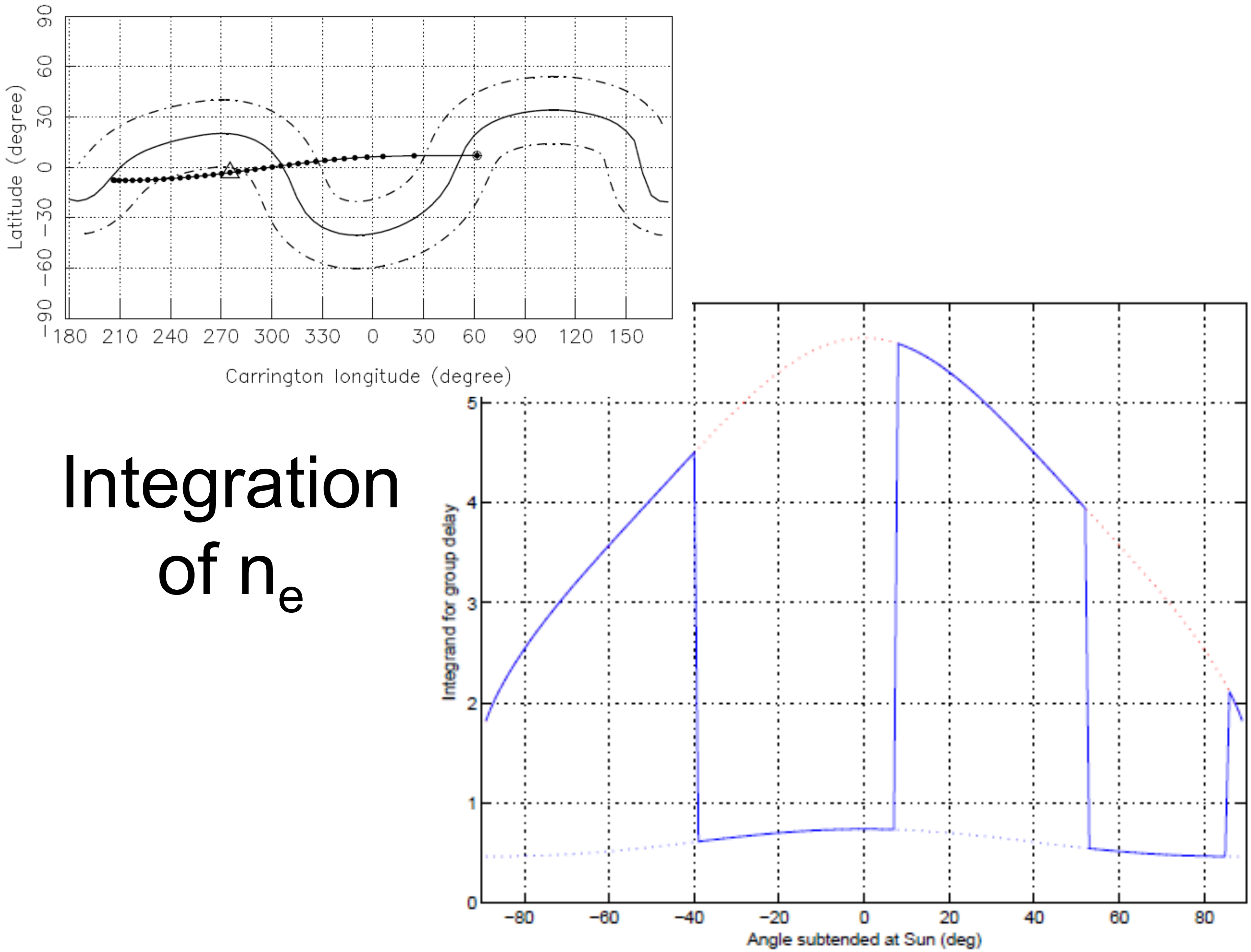


Projection onto a sphere at 2.5 Rs

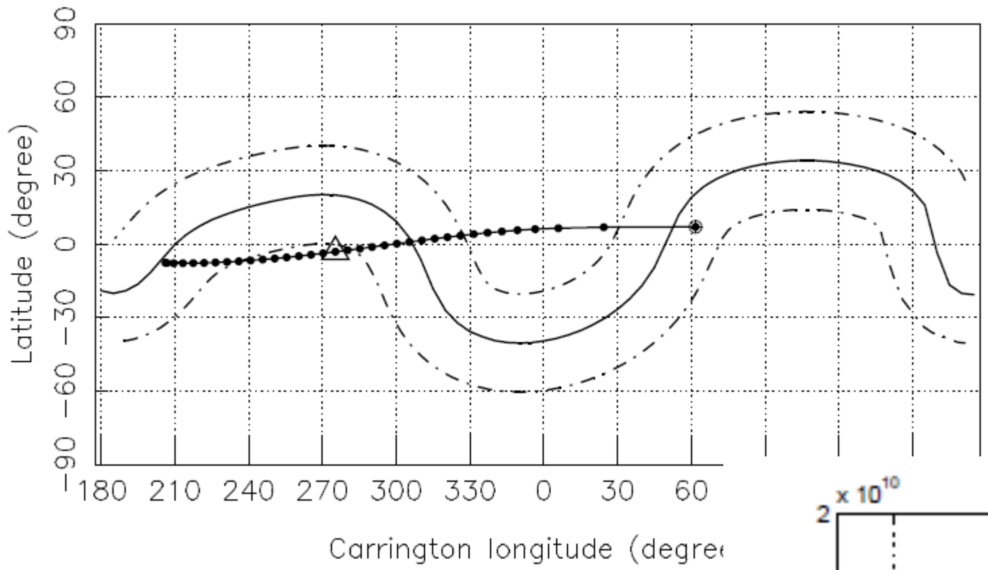


PSR J1022+100, Aug 25th, 2006

Integration of n_e



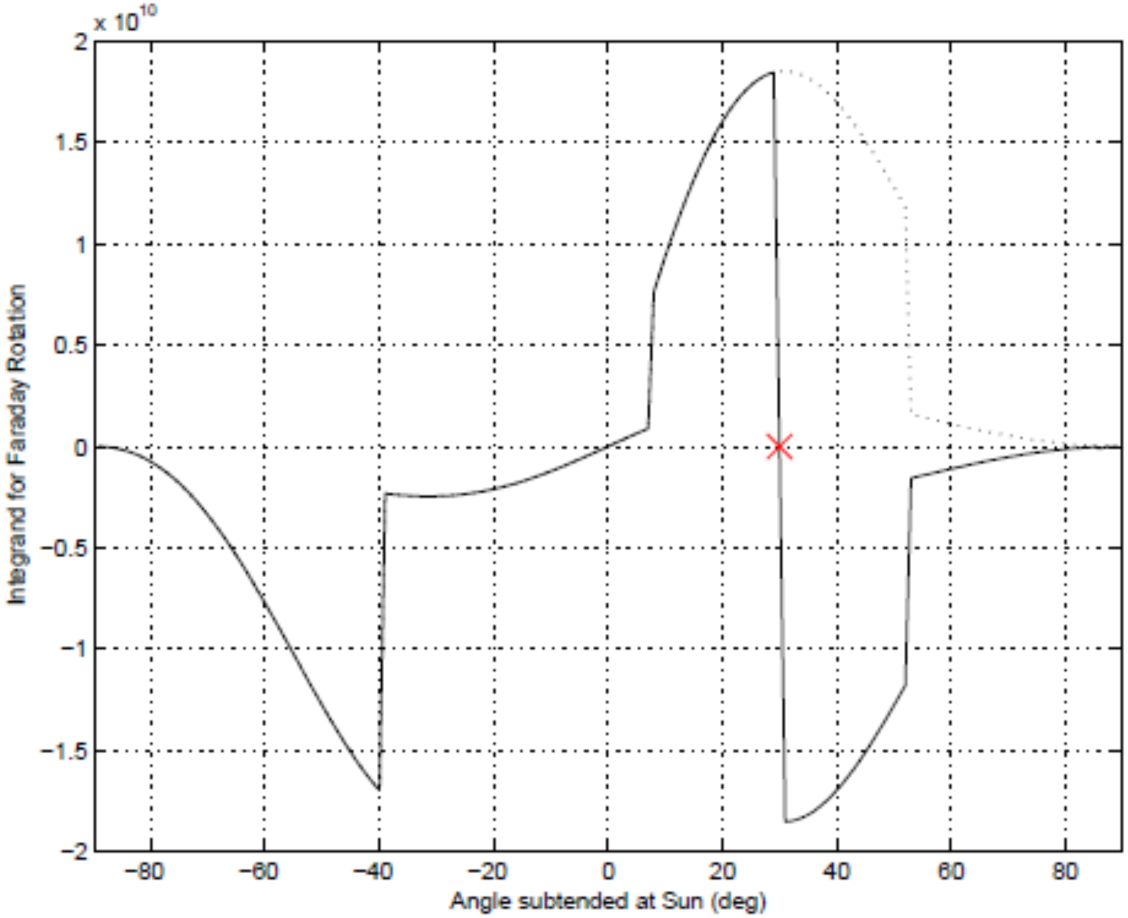
Step 3: modeling B



- Assuming B is radial,
- sign reversal at current-sheet
- quadratic decrease with distance

$$B(R) = B_0(R/R_0)^{-2}$$

Integration of n_e B



Three WSO models

- Classic model, Radial 250 model, Radial 325 model
- Boundary of slow and fast wind is not clear

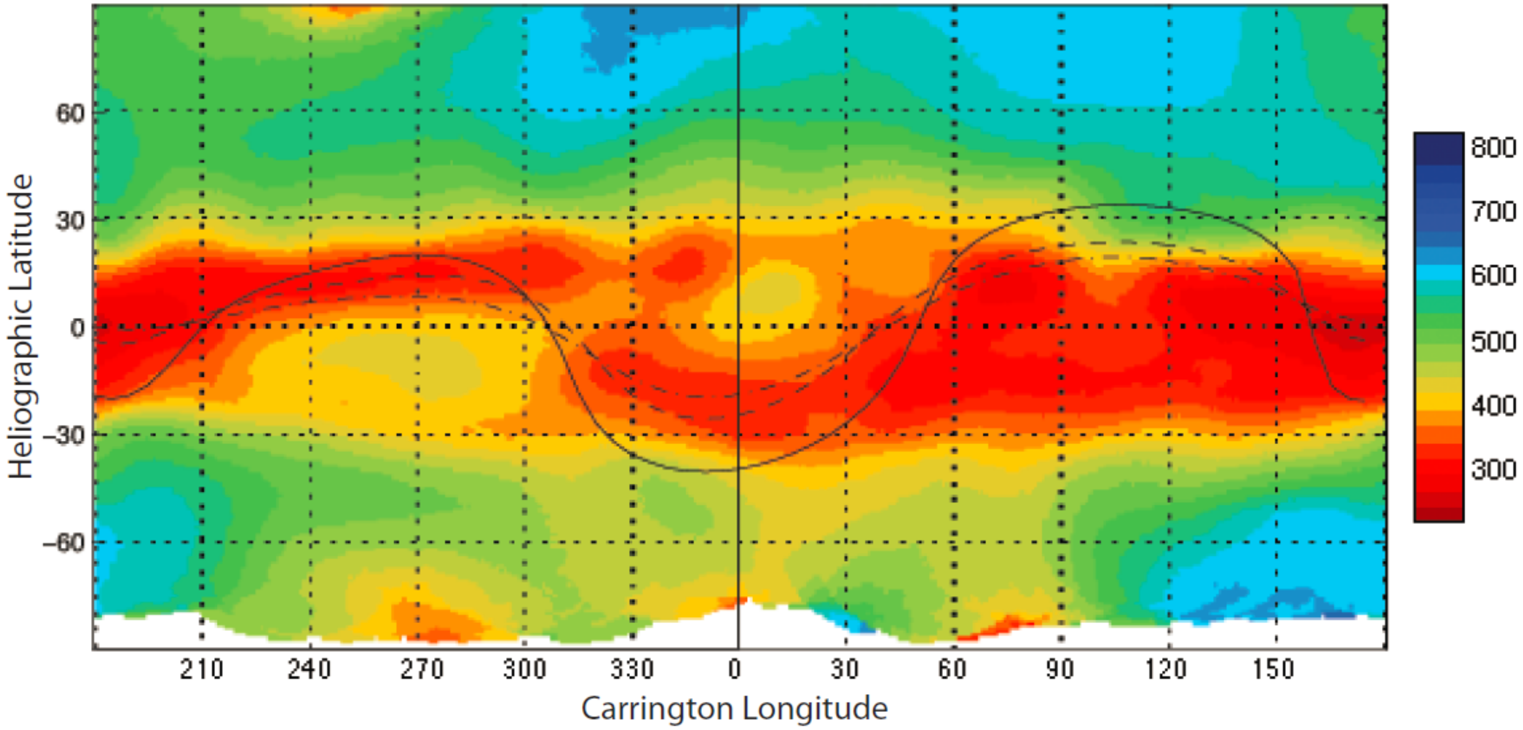


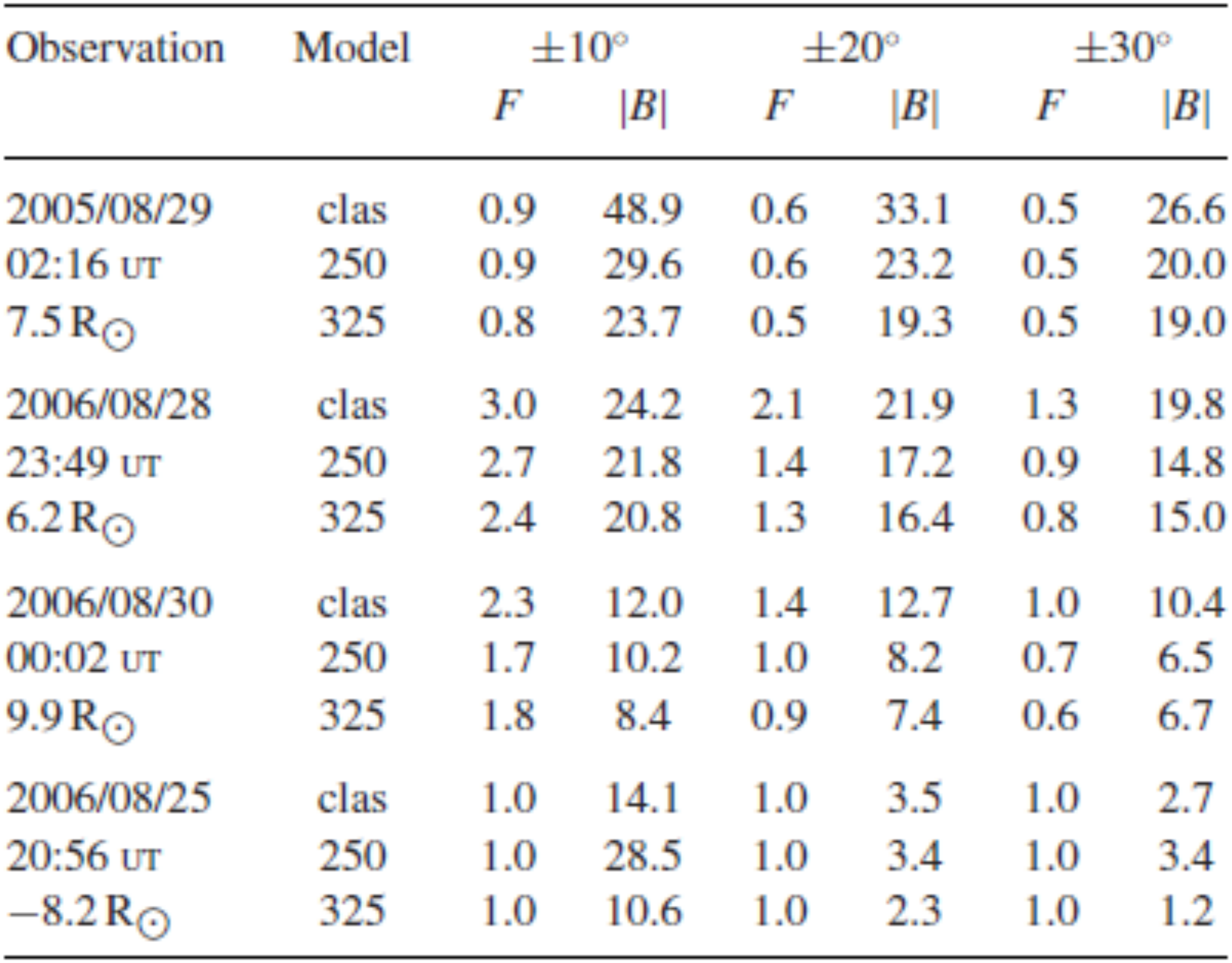
Figure 3. Solar wind velocity from STELAB, Nagoya U. This figure has been rotated in longitude to match Figure 4. The current sheet location from the three WSO models have been overlaid. Solid line is the "Classic" model, dashed line is the "SS250" model, dash-dotted line is the "SS325" model.

Solar-Terrestrial Environment Laboratory, Nagoya University

Completely modeling for three observations

- DM modeling:
  - Width of slow wind is not clear, 10^o, 20^o, 30^o
  - Three different extrapolation model
  - Times a factor *F* for both slow and fast wind to match the observation
- RM modeling:
  - Find |B| to match the observation
  - Check the sensitivity of the model

Result of model sensitivity



Observation	Model	±10°		±20°		±30°	
		F	$\|B\|$	F	$\|B\|$	F	$\|B\|$
2005/08/29	clas	0.9	48.9	0.6	33.1	0.5	26.6
02:16 UT	250	0.9	29.6	0.6	23.2	0.5	20.0
7.5 $R_\odot$	325	0.8	23.7	0.5	19.3	0.5	19.0
2006/08/28	clas	3.0	24.2	2.1	21.9	1.3	19.8
23:49 UT	250	2.7	21.8	1.4	17.2	0.9	14.8
6.2 $R_\odot$	325	2.4	20.8	1.3	16.4	0.8	15.0
2006/08/30	clas	2.3	12.0	1.4	12.7	1.0	10.4
00:02 UT	250	1.7	10.2	1.0	8.2	0.7	6.5
9.9 $R_\odot$	325	1.8	8.4	0.9	7.4	0.6	6.7
2006/08/25	clas	1.0	14.1	1.0	3.5	1.0	2.7
20:56 UT	250	1.0	28.5	1.0	3.4	1.0	3.4
−8.2 $R_\odot$	325	1.0	10.6	1.0	2.3	1.0	1.2

Three observations in 2006 are less model sensitive than the one in 2005

Estimated error

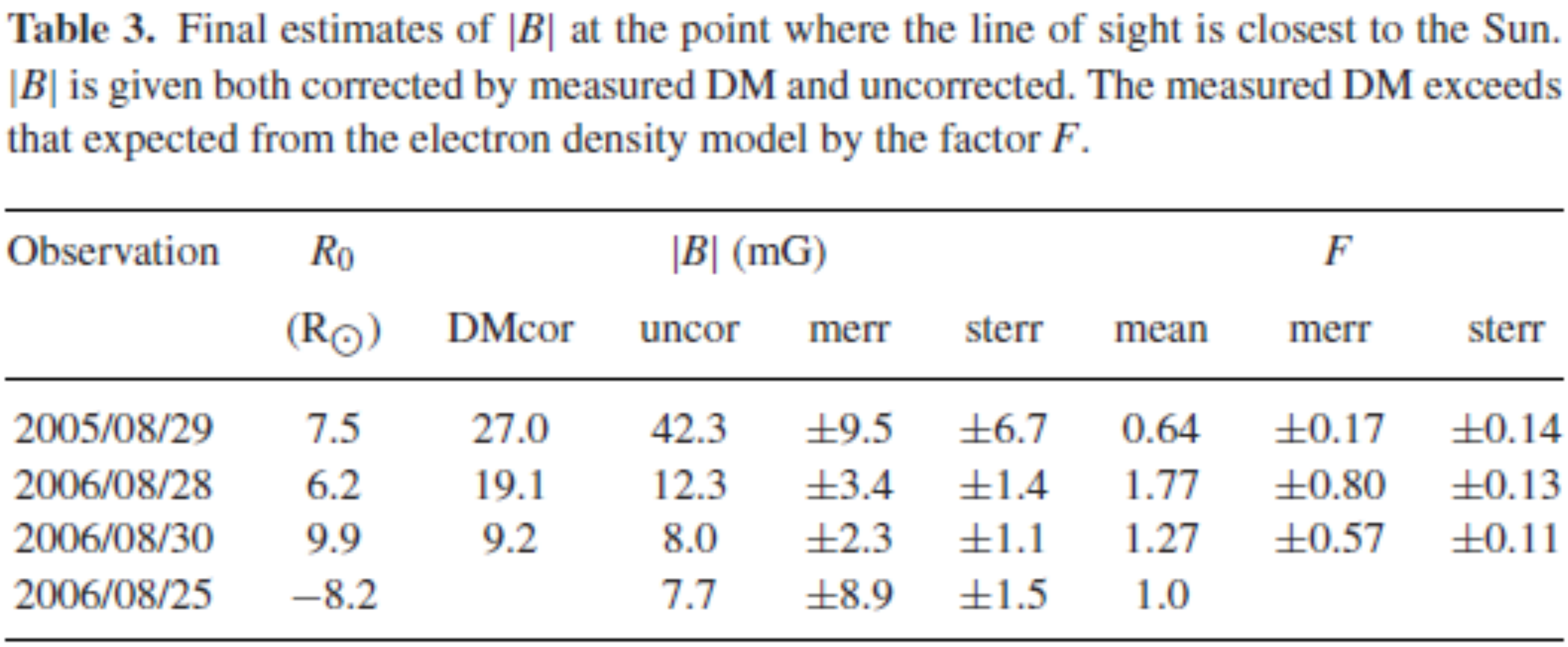
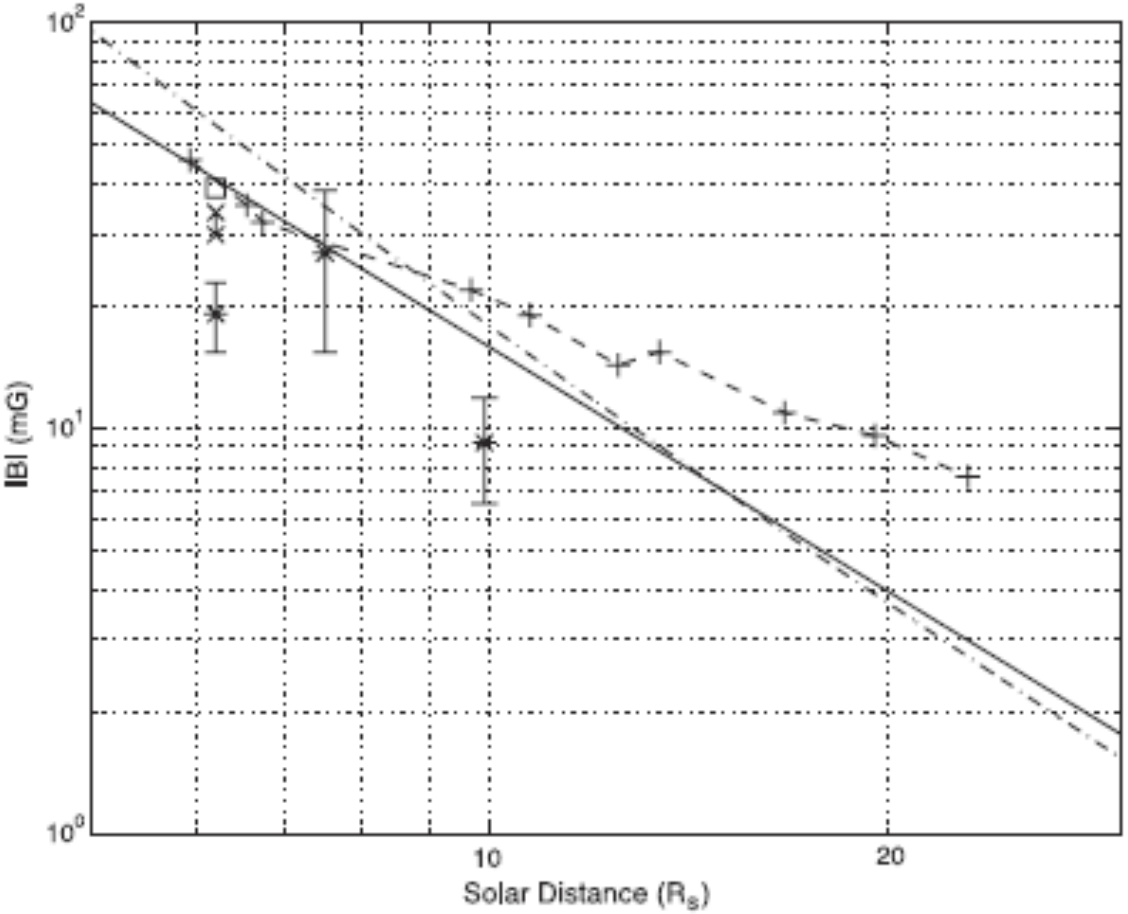


Table 3. Final estimates of $|B|$ at the point where the line of sight is closest to the Sun. $|B|$ is given both corrected by measured DM and uncorrected. The measured DM exceeds that expected from the electron density model by the factor F.

Observation	R_0	$\lvert B\rvert$ (mG)				F		
	($R_\odot$)	DMcor	uncor	merr	sterr	mean	merr	sterr
2005/08/29	7.5	27.0	42.3	±9.5	±6.7	0.64	±0.17	±0.14
2006/08/28	6.2	19.1	12.3	±3.4	±1.4	1.77	±0.80	±0.13
2006/08/30	9.9	9.2	8.0	±2.3	±1.1	1.27	±0.57	±0.11
2006/08/25	−8.2		7.7	±8.9	±1.5	1.0		

Comparing with previous results



(1) The extrapolated mean |B| from Helios of 0.38mG at 64.5 Rs (Burlaga 2001)

(2) B=1000($6R^{-3}$+$1.18R^{-2}$) (Patzold 1987)

(3) Estimate if the field in a CME shock (Gopalswamy and Yashiro 2011)

(4) Ingleby et al. (2007) 30 -34 mG at 6.2 Rs

(5) Spangler (2005) 39 mG at 6.2 Rs

Our result broadly consistent with Helios space craft observations

Model error depends on 1) current sheet, 2) width of slow and fast region

Analysis must include a range of model variation to estimate model error

Conclusion and summary

- We have the observation both of DM and RM near the Sun.
- The technique to measure the magnetic field of the solar wind is very important
- Using our model, we can estimate the B when our model prediction match the observation
- Error strongly depend on the geometry of current sheet and region of slow and fast wind
- Relatively weaker pulsar J1730-2304 and J1824-2452 could be modeled by larger telescope