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Radio Pulsar Timing for Fermi: The Second Half-decade

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1. Introduction

The *Fermi* Pulsar Timing Consortium (PTC) can be proud: we achieved both of the goals that we established before launch, which were 1) to not mess up the "obvious, guaranteed" science foreseen for CGRO-like pulsars, and 2) to remain as open as possible to the discovery potential of the LAT's high-sensitivity all-sky survey (see the MoU's, Smith & Thompson 2008a,b) and (Smith et al. 2008). The good working relation established between PTC and the LAT team smoothed the way for the successes of the Pulsar Search Consortium (PSC), including discovery of some of the faintest-ever radio signals from some blind-search pulsars (e.g. Pletsch et al. 2012), and use of the LAT's "treasure map" of unidentified, steady sources to significantly increase the number and variety of known millisecond pulsars (Ray et al. 2012).

Now, after five years on orbit, with the Second *Fermi* Pulsar Catalog behind us (2PC, Abdo et al. 2013), and with 148 gamma-ray pulsars in the bag, it's time to update our timing strategy. This document will mostly discuss target lists, but will also address author lists. The 15 December 2013 Parkes proposal deadline is our goal, with the 5 November 2013 Nançay deadline being good preparation.

2. What we've been looking at so far

The PTC agreement was to time all possible pulsars with spindown power $\dot{E} > 10^{34}$ erg s^{-1}. The ones that ultimately got timed are shown as green, red, and black symbols in Figure 1. The number of gray dots (ones we haven't gamma phase-folded) above 10^{34} is small. For most, some good reason explains why we 'missed' it. "All_gt1E34unfolded" lists them[1]. Table 1 summarizes the different lists of pulsars.

PTC later agreed to share as many non-MoU ephemerides as possible with the LAT team:

[1]The longer lists of pulsars discussed in this memo will be files attached to `https://confluence.slac.stanford.edu/display/GLAMCOG/Year+6+Pulsar+Timing`. If you can't get them, ask one of the authors to send you a .tar file. Links there to "Timing" and "Year 2 Timing" are worth reading.

these appear as the six hundred or so green, red, and black symbols with $\dot{E} < 10^{34}$ erg s^{-1} in Figure 1. Thus, we have discovered that the gamma-ray deathline for young pulsars is about 10x lower than what we thought from EGRET ; and apparently another 10x lower for MSPs (Guillemot & Tauris 2014). We have also, alas, been able to confirm the prejudice that if any old, low-power pulsars emit gamma rays, that they are not bright, or not common, or neither. The spreadsheet file "results_wSearchPulsation.xls" contains the results of Lucas' phase-folding for most of the > 800 black, green, and red dots.

"As many as possible" is highly latitude-dependent, as illustrated in Figure 2, right-hand panel. In the northern sky, roughly half of the $\dot{E} < 10^{34}$ erg s^{-1} pulsars have been folded. LAT does not have ephemerides for the other half[2]. Nançay, Westerbork and Urumqi round out the TOA samples for some pulsars. Effelsberg has not been used for routine timing for Fermi in the past. (Shall we tabulate how many each of the latter observatories times? Shall we tabulate which pulsars are timed by multiple observatories? In many cases multiple observatories is actually useful, e.g. observation rate vs TOA accuracy.) In the Parkes' sky, nearly none of the $\dot{E} < 10^{34}$ erg s^{-1} pulsars have been gamma phase-folded. In particular, gamma phase-folding the remaining southern MSPs should become a priority.

GBT and Arecibo provided timing for some key, interesting, radio weak pulsars earlier in the mission, no longer necessary on a routine basis: either they are now timed by the LAT, or remain undetected by the LAT. Similarly, a few PTC members were devoted to providing X-ray ephemerides to the LAT team. Except for Geminga, none of these were detected, and in the future can probably be studied on a case-by-case basis. Hartebeesthoek helped us see Vela immediately after launch, but was unable to contribute steadily thereafter.

[2]We believed that Andrew Lyne at JBO tries to time all northern pulsars, and intended to share the timing solutions for all that he times with the LAT team. A quick look at the 400 or so 'missing' northern pulsars in ATNF suggests that they have S1400 < 0.5 or so, so perhaps many are too weak for routine timing at JBO.

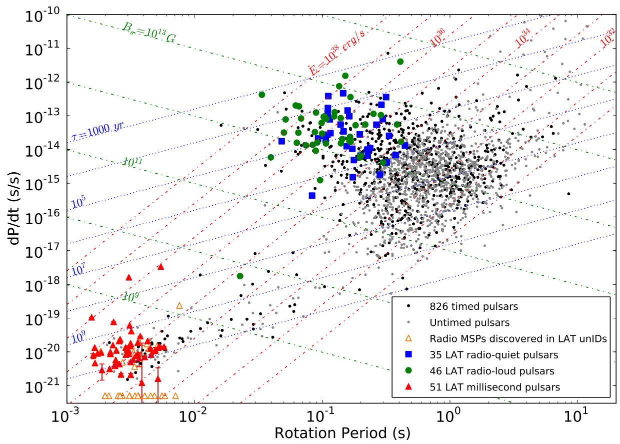

Fig. 1.— The rate of period increase $\dot{P}$ vs. rotation period P for pulsars outside of globular clusters. Large colored markers show the 132 publically announced gamma-ray pulsars, of the 148 detected, including over half of the 59 pulsars discoverd by the PSC, as of Oct 2013. "Timed" means that we phase-folded the gamma-rays using a radio or X-ray rotation ephemeris, but gamma pulsations were not seen, except for the black dots hidden by green or red. The $\dot{P}$ uncertainties visible for some MSPs come from the Shklovskii correction. New MSPs for which the spindown rate is unavailable are plotted at $\dot{P} = 5 \times 10^{-22}$.

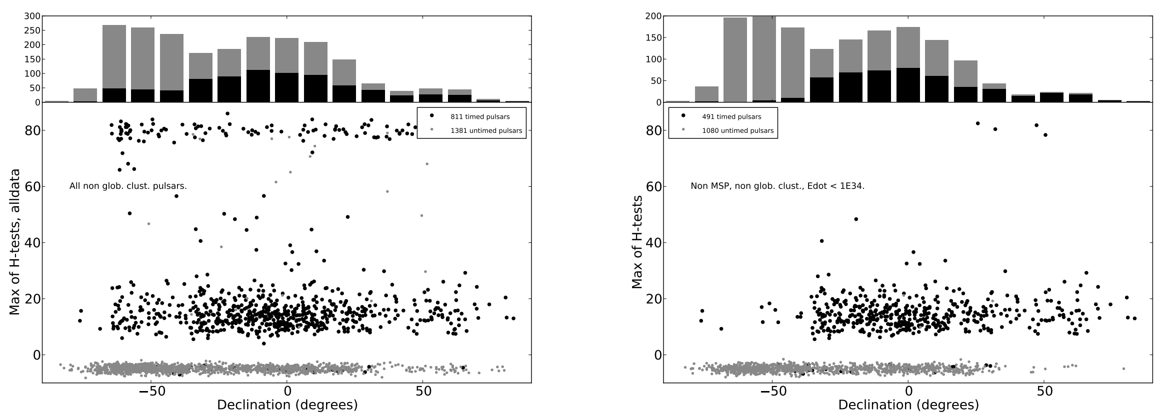

Fig. 2.— Maximum of ≤ 4 H-test values versus pulsar declination. The four values use either 5 years of LAT data vs only the ephemeris validity interval ; and either the value at the end of the interval vs the peak during the interval. For clarity, large maxima are smeared to 80 ± 2, and unfolded pulsars are smeared at -5 ± 1. H-test is not corrected for the 855 trials over the "cookie-cutter" energy and angular radius cuts. Left: All field pulsars. Right: Only low power, non-recycled pulsars. Half (nearly zero) of those in the north (south) aren't gamma-folded.

Table 1: Summary of the pulsar lists. The files are attached to `https://confluence.slac.stanford.edu/display/GLAMCOG/Year+6+Pulsar+Timing`. "South" or "North" means a cut at $\delta = -35°$. Except for "all", "results", or "MSP" files, MSPs (P0$<$ 10 ms) are excluded. Globular clusters are excluded from all lists.

File name	Purpose	Cuts	How many
results_wSearchPulsation.xls	Folding results	PKS, NAN, JBO .par's	805^a
All_gt1E34unfolded.txt	Round up stragglers	$\dot{E} > 10^{34}$ but no .par	≈ 20
gt1E34noPulse.txt	Get rid of deadbeats	$\dot{E} > 10^{34}$ folded, but never H-test > 20	62 south, 68 north.
DeathNotFolded.txt	Probe the deathline	$10^{33} < \dot{E} < 10^{34}$, $\vert b\vert > 3°$, $d < 5$ kpc.	37 south, 12 north.
MSPsNotFolded.txt	Fold all possible MSPs	P0 < 30 ms	11 (36) south, 3 (57) north[b]
WeakNearOffPlane.txt	Sample more of the old population	see note *c*.	111 south, 88 north
ATNF_LATmatches.txt	Maybe *not* just spatial coincidence	angsep $<$ Conf_95_SemiMajor	~ 30 boil down to $\lesssim 10$
InterpulsarsPTC2014.txt	23 of 27 already folded!	Weltevrede & Johnston (2008)	< 4
PTCpeople.txt	Current list of names		34 PTC + 4 PSC

Note. — a) Primarily the pulsars routinely timed by PKS NAN JBO. These include most γ-detected pulsars, and exclude many pulsars where the ephemerides originally came from GBT, RXTE, etc, detected or not. The number is thus a bit different than the 826 in Figure 1.

b) 11 (3) is the number in ATNF with a pre-launch reference date, and 36 (57) is the number of known MSPs that the LAT team hasn't folded. The difference is due to PSC etc recent discoveries, where either a timing model good enough for gamma folding doesn't exist yet ; or the discoverers prefer to do it independently of the LAT team. *All_gt1E34unfolded.txt* includes comments about some of these.

c) Cuts for the WeakNearOffPlane sample: $\dot{E} < 10^{33}$, $|b| > 3°$, $d < 3$ kpc, P0$>$ 10 ms, not folded. In addition, one should require a not-too-small S1400, and also ask: will we be able to back-trapolate to launch?

3. What to look at in the future

MSP minimum observed $\dot{E}$ for gamma emission keeps going down. We should phase-fold them *all*, regardless of prejudice: science arguments abound. "MSPsNotFolded" (see Table 1) shows that few have been neglected.

There are far too many young "boring" pulsars to time them all, especially in the South, and the Science arguments are speculative[3]. We now list guidelines to help us pick which to time.

- "gt1E34noPulse" lists the $\dot{E} > 10^{34}$ erg s^{-1} for which, after 5 years of devoted phase-folding, no hint of pulsations has been seen. From the LAT's point of view, we could stop timing these, to free up radio telescope time. Parkes may wish to continue monitoring them for other Science goals. We certainly favor continued radio timing of weak gamma-detected pulsars. Brighter ones could perhaps be timed with the LAT, with only occasional radio observations, to ensure phase coherence.

- "ParkesTimesNorth" *would* list pulsars that Parkes times, that are accessible by the Northern telescopes. (DAS didn't make the list.) In 2009, Simon suggested dropping these. It doesn't seem to have happened, possibly due to those 'other Science goals'. Well?

- "DeathNotFolded" focusses on the $10^{33} < \dot{E} < 10^{34}$ erg s^{-1} range, to study whether the gamma-ray deathline is gradual or sharp. Figure 1 shows 247 (!) gray dots in the zone. We can tune the number of targets by tweaking the thresholds on latitude, distance, and S1400.

- "WeakNearOffPlane" aims to increase the number of black dots amongst the overall population. Latitude and distance cuts favor reasonable gamma signal-to-noise even for low luminosity. Gamma-ray detection of the low spindown power pulsars is a worthwhile, maybe, longshot (Hou & Smith 2013) although we'll need to be sure we're able to back-trapolate to launch. (If we favor high S1400 pulsars to make life easier for the radioastronomers, will that introduce an unwanted beaming bias?) Matthew started listing archival Parkes observations of some of these, and was starting to think about sky temperature.

- "ATNF_LATmatches" lists a dozen unfolded pulsars that fall within the error ellipse of weak (TS> 10) 4-year LAT sources. We could time all or some of these (e.g. the ones with the highest $\sqrt{\dot{E}}/d^2$, or ones with not-too-small latitude $|b|$, et cetera).

- "InterpulsarsPTC2014". This turns out to be a non-issue: we already phase-fold all but four of the 27 radio interpulse pulsars studied by Weltevrede & Johnston (2008). Their geometry

[3]Suppose that the electrons responsible for the radio beams also radiated a weak, collimated gamma beam. We might only see it for high-latitude, nearby pulsars with a small range of orientations. And perhaps with low or no modulation. The theorists dis-predict this. But if it were true, it would change our ideas about pulsar contributions to the diffuse emission. Look a little harder?

is particularly well-known, using polarization data. We solidly detect three. A few more give a glimmer of hope, and we should keep at them. We could add J1126−6054. J1806−1920 is probably too low latitude, too low $\dot{E}$, and too far. J1852−0118 has low S1400 = 350 μJy in addition to those handicaps. The fourth, J1713−3844, has P0 = 1 s and low $\dot{E}$ and is probably beyond the scope of PTC.

- "Slowpokes" would be a sample of P0 > 1 s pulsars. Off hand, none of us expect or believe that these emit gamma-rays. But when I explore for dodgy stuff, I stumble over these. Probably "dodgy" is the key word.

A strawman summary of all of the above considerations could be this:

1. Leave no MSP unturned (a dozen more).

2. Try to γ-phase-fold pulsars co-located with weak DC source candidates (a dozen).

3. Add the extra interpulse pulsar or three.

4. Add lots of deathline pulsars, $10^{33} < \dot{E} < 10^{34}$ erg s^{-1}, to the timing list. We'll probably only detect few, if any, but it could provide useful information. The theorists will probably contradict me. The cuts in the Table give 50-ish.

5. More black dots in the middle of the $P\dot{P}$ plane, especially those that we will be able to fold over the mission's first half-decade. The number is potentially very large.

6. All telescopes can free up time by abandoning the 60 or so high $\dot{E}$ pulsars per "hemisphere" with no gamma signal. Parkes can free up time by offloading Northern pulsars to the north.

CONCLUSION: We would thus add about 80 new pulsars to the campaign, without counting extras in the middle of the $P\dot{P}$ plane, and could remove over a hundred.

4. Author lists

The MoU lists observatory PI's as the 'responsable person' for each pulsar, and Patrick Weltevrede as the overall coordinator. We thank Patrick for leading this effort during the early years. Since some time, Lucas Guillemot has taken over. We propose to make that Official.

We further propose significant pruning of the PTC list that the LAT team uses to generate the emailings leading to sign-in on the author lists for PTC papers. The GBT, Arecibo, and Xray efforts that were so important in 2009 are essentially over. Studies of specific pulsars not in the list we propose here should be organized outside of the PTC. The updated author list would favor the people at the key radiotelescopes who actively participate in the observations and data reduction.

Table 1 includes "PTCpeople.txt" naming the current crowd. PSC appears small, with 4 people, because of the hierarchical, one-name-only-once structure of the Pub Board pages. That is, the rest of the PSC people were already in other lists when we added PSC. The 34 PTC names include e.g. Peter Michelson, that is, people who do other things in addition to PTC. There are a few names of people who have moved on.

As stated in the introduction, PTC has been working great and we certainly don't want to spoil that! We will circulate this memo to the PTC *and* the PSC, so as not to leave out anyone willing and able to contribute timing solutions for large numbers of pulsars. We hope that the new, improved PTC will be people involved in the timing of many exciting pulsars, but also many putatively boring pulsars. The LAT team encourages and welcomes cooperation with people working on specific projects, so if you're not a part of this specific timing campaign you can still write great papers with us.

Thus, we suspect that consensus will mainly be with the PI's from the large radio telescopes, who will speak for their groups.

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