THE BIRTH PROPERTIES OF NEUTRON STARS

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INTRINSIC VS. OBSERVED PROPERTIES

Selection effects,

- beaming
- propagation of signal through ISM
- motion away from Galactic disk
- turn-off at late times,

depend on unknown properties of the sources.

⇒ Need a combined source and detection model.

Past efforts differ primarily in their treatments of selection effects.
How to combat observational selection? Simulate everything!

Generate *Monte Carlo* pulsars, complete with “observables,” and compare against catalogued real pulsars.

Parameterize assumptions about neutron star birth and evolution

Choose one set of parameters

Create & evolve neutron stars

"Detect" pulsars with real-world surveys

Compare detected PSRs with known population, compute a likelihood

Solving the *forward problem* is computationally intensive.
THE MODEL

Parameterize initial conditions and the equations that govern rotational, kinematic, and luminosity evolution.

Birth.

- Constant rate, in uniform disk with scale height $z_0$
- Log-normal initial $P$ and $B$ distributions
- Orientations of $\Omega$ and $\hat{B}$ assumed random at birth, with no evolution with time
- Velocity vectors randomly oriented, with magnitudes drawn from 1- or 2-component 3D Gaussian distributions.

Evolution.

- Assume canonical magnetic dipole spindown law, $n = 3$ and no torque decay
- Trace trajectories in Galactic potential.
Detection.

- Deterministic luminosity law,
  \[ L_r = P^\alpha \dot{P}^\beta 10^\gamma \text{ erg s}^{-1}, \]
  \( \Rightarrow \) i.e., assume pulsars are standard candles, and observed spread is due to viewing geometry alone.

- “Death band” implemented as probability that a pulsar’s emission has turned off

- Phenomenological beaming model used to create a pulse profile for each object given \( P, L_r \), viewing geometry, distance, and assumed spectral behavior

(Rankin 1983)
- Fourier amplitudes of dispersed and scattered profiles are compared with detection thresholds of relevant surveys.

430 MHz Radio Pulsar Surveys

- STWD (NRAO, 300°)
  15° ≤ |l| ≤ 210°
  -15° ≤ b ≤ 15°

- FCWA (AO)
  195° ≤ α ≤ 270°
  10° ≤ δ ≤ 28°

- VLT (Molonglo)
  0° ≤ α < 360°
  0° ≤ δ ≤ 20°

- TDK (AO)
  120° ≤ α ≤ 195°
  19° ≤ δ ≤ 76°

- DIWS (NRAO, 300°)
  0° ≤ α ≤ 360°
  30° ≤ δ ≤ 90°

- CNI (AO)
  320° ≤ α ≤ 15°
  8° ≤ δ ≤ 30°

- NFT (AO)
  36° ≤ |l| ≤ 68°
  -8.5° ≤ δ ≤ 8.5°

- Parkeś
  0° ≤ α < 360°
  -90° ≤ δ ≤ 0°
**LIKELIHOOD FUNCTION**

In all, 14 model parameters:

\[ \alpha, \beta, \gamma, \tilde{D}L, \sigma_{DL}, \sigma_{v_1}, \sigma_{v_2}, w_1, P_0, \sigma_{P_0}, B_0, \sigma_{B_0}, z_0, \hat{N} \]

**Bayesian treatment:** “posterior” probability of a model is likelihood of data \( \mathcal{L} \) times any “prior” information. We assume flat priors, so most probable model is the one that maximizes the likelihood.

\( \mathcal{L} \) is formed through the usual product of probabilities that individual data points will occur within the model, for 6 observable properties simultaneously.

Likelihood of measuring observables for pulsar \( D_i \) from a given simulated star \( \tilde{D} \),

\[ \mathcal{L}_{D_i}(\tilde{D}) = \prod_{j=1}^{l_q} \delta(q^j - \tilde{q}_j) \prod_{j=1}^{l_s} \mathcal{L}_{s^j}(\tilde{s}_j) \]

so probability that \( D_i \) arises in the model is

\[ \rho(D_i) = \int d\tilde{D} \mathcal{L}_{D_i}(\tilde{D}). \]
IMPLEMENTATION

A novel method of evaluating the likelihood function.

In the limit of small bins, precisely estimates formal likelihood.

- Advantages: compares joint distributions in many dimensions. Computationally efficient!

- Disadvantages: for small bins (or large dimensionality) need enormous number of MC points. We use $10^{10}$ simulated pulsars. Computationally inefficient!
## RESULTS

### SUMMARY OF MODEL PARAMETERS ($n = 3$).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Peak posterior probability value</th>
<th>Range searched</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$-1.3$</td>
<td>$-2$ to $0.5$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$0.4$</td>
<td>$0$ to $1$</td>
</tr>
<tr>
<td>$\gamma$ (erg s$^{-1}$)</td>
<td>$29.3$</td>
<td>$27.5$ to $30.5$</td>
</tr>
<tr>
<td>$DL$</td>
<td>$0.5$</td>
<td>$-1.2$ to $1.2$</td>
</tr>
<tr>
<td>$\sigma_{DL}$</td>
<td>$0.8$</td>
<td>$0$ to $3.2$</td>
</tr>
<tr>
<td>$\langle \log P_0 [s] \rangle$</td>
<td>$-2.3$</td>
<td>$-2.6$ to $-1.6$</td>
</tr>
<tr>
<td>$\sigma_{\log P_0}$</td>
<td>$0.25$</td>
<td>$0.1$ to $0.4$</td>
</tr>
<tr>
<td>$\langle \log B_0 [G] \rangle$</td>
<td>$12.35$</td>
<td>$12.0$ to $12.4$</td>
</tr>
<tr>
<td>$\sigma_{\log B_0}$</td>
<td>$0.4$</td>
<td>$0.25$ to $0.5$</td>
</tr>
<tr>
<td>$z_0$ (pc)</td>
<td>$160$</td>
<td>$80$ to $250$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Two comp. vel. dist.</th>
<th>One comp. vel. dist.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{v_1}$ (km s$^{-1}$)</td>
<td>$90^{+20}_{-15}$</td>
<td>$290 \pm 40$</td>
</tr>
<tr>
<td>$\sigma_{v_2}$ (km s$^{-1}$)</td>
<td>$500_{-50}^{+100}$</td>
<td>$-400$</td>
</tr>
<tr>
<td>$w_1$</td>
<td>$0.4 \pm 0.1$</td>
<td>$-0$</td>
</tr>
</tbody>
</table>

### Luminosity.

- Spin Dependence: $L_r \propto P^{-1.3}$ $\dot{P}^{0.4}$ (uncertainties $\sim 10\%$). We find scaling roughly with $\sqrt{E}$

- Birthrate: $\dot{N} > 1/750$ yr$^{-1}$
**BIRTH VELOCITY RESULTS**

Velocity.

- Two-component model preferred $10^4 : 1$
- 15% have $v > 1000 \text{ km s}^{-1}$
- Larger mean but more distinct high/low separation than previous estimates, result of (1) unbiased analysis, (2) inclusion of deep, high-latitude surveys
- No very low velocity component, $< 5\%$ contribution of $v < 50 \text{ km s}^{-1}$. 
COMPARISON WITH EARLIER RESULTS

For 49 young pulsars with proper motion measurements, Cordes & Chernoff (1998; CC98) report

\[
\begin{align*}
\sigma_{v_1} & = 175 \, \text{km s}^{-1} \\
\sigma_{v_2} & = 700 \, \text{km s}^{-1} \\
w_1 & = 86\%.
\end{align*}
\]

Simulating selection of their sample,

⇒ implications of selection important for spatially bounded samples, but not for deep, high-latitude searches.

Same pitfalls of volume-limited samples befall most previous velocity determinations.

From formation rates of LMXBs, HMXBs, and isolated PSRs as function of birth kick, Fryer et al. (1998) report

- 30% receive no kick, 70% receive 500–700 km s\(^{-1}\) (true) kick.

⇒ Very similar result, but unlikely that our low-velocity component is relic orbital velocity, so two physical kick mechanisms suggested.
**IMPLICATIONS**

**Kick Mechanisms.**

Strong observational evidence for kicks, but few clues to the nature of the mechanism. No viable mechanism for kicks $> 1000 \text{ km s}^{-1}$ known.

- No clear correlation with other pulsar parameters: Chandra shows aligned spin & velocity vectors for Crab, Vela, but NS binaries require kicks perpendicular to spin

- Kick duration less than orbital timescale, but perhaps long on rotational timescale

- Our result further evidence for large kicks, but apparent need for two mechanisms is puzzling. Perhaps there’s an energy or rotation rate trigger?

Global hydrodynamic asymmetry likely.
Implications (cont.)

Escape from Galaxy & cluster potentials.

In solar vicinity, Galactic escape speed is $\sim 430 \text{ km s}^{-1}$ ⇒ half of all NS born in the disk may be escaping.

Cluster escape speeds are $\lesssim 30 \text{ km s}^{-1}$, and at least 10\% of NS must be retained. Our 2-component model improves over Lyne & Lorimer (1994)'s 4\%, but neither may apply to clusters.

Populations of Isolated Pulsars.

- Dearth of low-velocity objects may explain shortage of old isolated NS accreting from the ISM

- If SGRs/AXPs are isolated NSs, and if radio results apply, large kicks strengthen some proposed SNR associations, but no overlap between populations in most respects.
IMPLICATIONS (CONT.)

LIGO & GRB Rates.

Number and orbits of post-SN binaries depend on kick
distribution: birthrates decrease with increasing kick,
but high-$e$ and short $P_b$ endstates merge.

- Largest source of rate uncertainty is characteris-
tic kick: 3–12 Myr$^{-1}$ for large kicks, $\times 10$ for small
  kicks. For our preferred model, low-velocity com-
ponent dominates the rate, $\sim 30$ Myr$^{-1}$

- Similar implications for GRB rate in coalescence
  models, disfavored because host galaxy offsets too
  small. Disruption filter prevents large kicks from
  producing large offsets.

Black Holes.

Systemic velocities of BHC LMXBs smaller than those
of NS LMXBs—no apparent need for black-hole kicks,
and none expected in prompt collapse.

Delayed collapse and short-lived NS stage possible. X-
ray Nova Sco 1994 has high peculiar velocity, and birth
kick simplifies formation scenarios. Also, elemental abund-
cances in companion support SN origin.

$\Rightarrow$ small number of BHs do perhaps arise through SN
explosions and are kicked.

Velocity constraints from binaries select against high ve-
locities because of disruption.