X-ray timing analysis of six pulsars using ESA's XMM-Newton observatory

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• introduction
  – XMM-Newton
  – pulsars
• relative timing analysis
  – period searching
    • $\chi^2$, $Z^2$ and $H$ tests
    • accurate search: X-ray ephemeris
  – error analysis
  – Monte-Carlo simulations
• conclusions
• EPIC-pn camera provides two fast read out modes
• different time resolutions depending on the mode used: Small Window (6 ms), Timing (0.03 ms) and Burst (7 µs)
• 2 Crab observations per year
• various other pulsars
pulsars: general information

- neutron stars with high spinning velocities and strong magnetic fields
- radius \( \sim 10 \text{ km} \)
- density \( \sim 4 \times 10^{14} \text{ g cm}^{-3} \)
- temperature \( \sim 10^6 \text{ K} \)
- magnetic field \( \sim 10^{9-12} \text{ G} \)
- the periods of the pulsars analysed are between 15 ms and 200 ms
- PSR J0537-69: $p \sim 16$ ms
- Crab: $p \sim 33$ ms
- PSR B0540-69: $p \sim 51$ ms
- Vela: $p \sim 89$ ms
- PSR B1509-58: $p \sim 151$ ms
- PSR B1055-52: $p \sim 197$ ms
pulse profiles

rate vs phase

0.5 - 10 keV
• fold the data over a range of test periods, $P_1$:

First trial: radio period

• for each test period determine $\chi^2$ of the fit of the folded light curve vs. a uniform distribution:

Good period  High $\chi^2$  Bad period  Low $\chi^2$
• the weighted mean of the periods with $\chi^2$ gives the best X-ray period

\[
FWHM = \frac{P^2}{T}
\]
error analysis: approximation

• $\Delta P = P_X - P_R \rightarrow$ error of our observation

• assume that the radio period has no error

• the $\Delta P$ comes from the error of the X-ray period

• $\chi^2$ distribution can be approximated by a triangle

• approximation:

• compare the real and approximated errors of the periods
error analysis: comparison

• comparison between theoretical values (lines) and observational values (symbols)

• removing wrong observations:
  – observations inside circles have less reliable ephemeris and will not be considered
relative timing analysis: results

• left: results for all Crab observations => $\sigma = 5 \times 10^{-9}$
• right: results for all the pulsars => $\sigma = 7 \times 10^{-9}$
Monte-Carlo simulations (I)

• M-C simulation was done to some Crab observations using the IDL routine *epferror* from the aitlib of the IAAT

• estimate the error of a previous received period using the epoch folding approach

  1.) calculate a mean profile with given period.

  2.) compute the intensity for all times applying the period multiplied profile.

  3.) simulate an error for all times (standard: using Poisson statistics, or use the error for normal statistics).

  4.) perform epoch folding for that simulated lightcurve.

  5.) go to step 2.) Ntrial times, sum up the maximum of epoch folding found.

  6.) compute the standard deviation of the Ntrial maxima obtained and take these as the error.
Monte-Carlo simulations (II)

- black: ratio between $\Delta P$ calculated using the approximation formula divided by the M-C results
- red: ratio between the observed $\Delta P$ divided by the M-C results

![Graph showing ratios](image)

Mean: 1.34
Mean: 0.80
conclusions

• the relative time accuracy of the EPIC-pn camera considering 31 observations can be estimated as:

\[ \Delta P/P < 1 \times 10^{-8} \]

• in most of the cases the relative time accuracy obtained observationally is at least as good as the predicted by the approximation.

• the Monte-Carlo simulation errors of the period are smaller than the \( \Delta P \) obtained observationally.

• the difference between the X-ray and the radio period can be consider negligible.