The movement of pulsars in the Galaxy and determination of their kinematic ages

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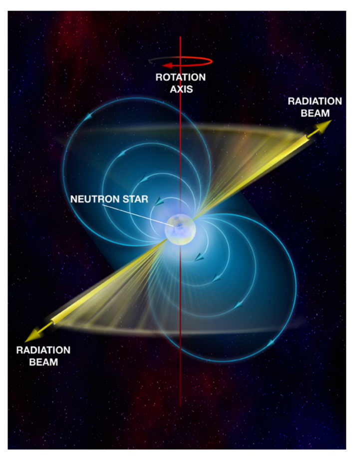
Motivation

Knowing neutron star (NS) ages is important to better understand the Galactic NS population. The commonly used characteristic age (spin-down age) is based on questionable assumptions like pure magnetic dipole braking and a negligible birth period. Therefore we search for independent age estimates, for which we trace back the trajectories through the Galactic gravitational potential, until we find the birth places. If individual birth associations, like supernova remnants (SNRs), stellar clusters or runaway stars can be found, we obtain a precise age, and also current parameters like the radial velocity can be determined. But this method is not applicable for older NSs, because the number of possible birth associations increases with the length of the trajectories. In a more general attempt we can also assume a range of ± 100 Parsec around the Galactic plane as the birth place, where most NSs are born. We use a kinematic simulation for 162 pulsars to search for intersections with the Galactic plane and find unambiguous age estimates for 92 of them. The distribution of logarithmic ages roughly follows a Gaussian with a peak at about 10^6 years. We discuss the advantages and disadvantages of the method for young and old pulsars and compare the results to Tetzlaff (2013) [14], who identified individual birth associations for young NSs. We also present a recent discovery of a runaway star and our current attempt to find more such cases.

Neutron Star ages

- The spin-down age:
  - Deceleration law: $\dot{P} = kP^{2-n}$
  - Integration gives expression for age: $t = \frac{P}{(n-1)\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right]$
  - Simplifications: $n = 3$ (magnetic dipole model) and $P_0/P = 0$

  $\Rightarrow$ characteristic age $\tau_c = P/2\dot{P}$



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- Association with a Supernova remnant:
  - Expansion time of a SNR [7]
  - Pulsar's outward movement from SNR centre [6], [3]
- Identification of further parent associations [14]
  - Stellar clusters
  - Runaway stars
- Neutron star cooling models

The kinematic method

Basic steps:

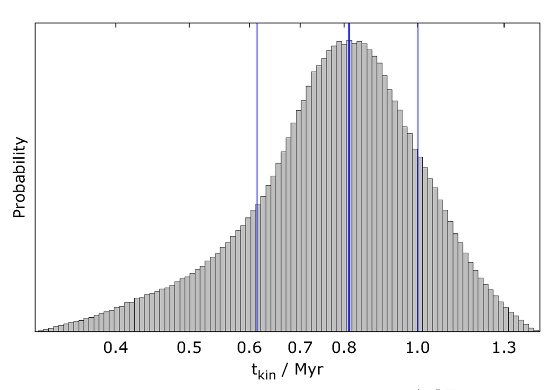
- Calculation of a pulsar's trajectory through the Galactic gravitational potential [10]
- Search for intersections with the Galactic plane, where most pulsars are born ($\sim 90\,\%$, [11])
- Kinematic age: Travel time from intersection to current position

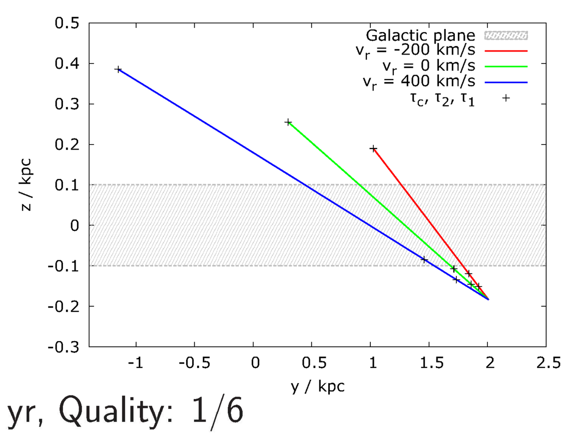
This concept was first discussed by [8] and used by [9] in a work about pulsar spin-velocity alignment. They were restricted on pulsars with polarization data and obtained ages for 33 pulsars. Our aim was to increase this number by using a larger initial sample.

Sample selection:

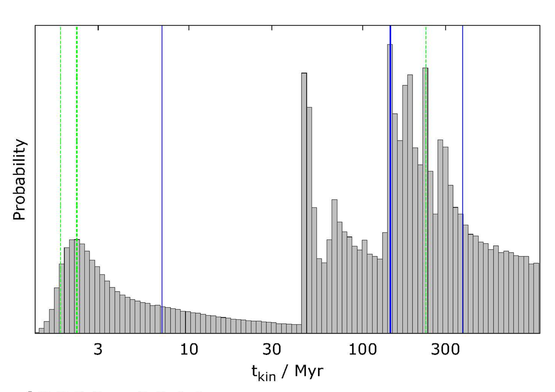
- Position, proper motion [4] and distance needed
- Search in ATNF pulsar catalogue yields 162 non-recycled pulsars
- Probability density distribution functions (PDFs) created with the program from [9]

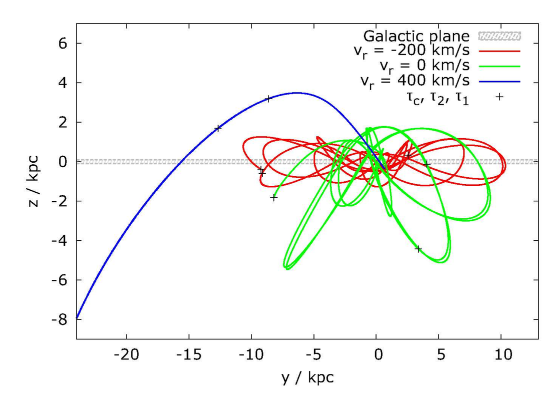
Examples





J0139+5814: $t_{kin} = 8.13^{+1.87}_{-1.96} \times 10^5$ yr, Quality: 1/6

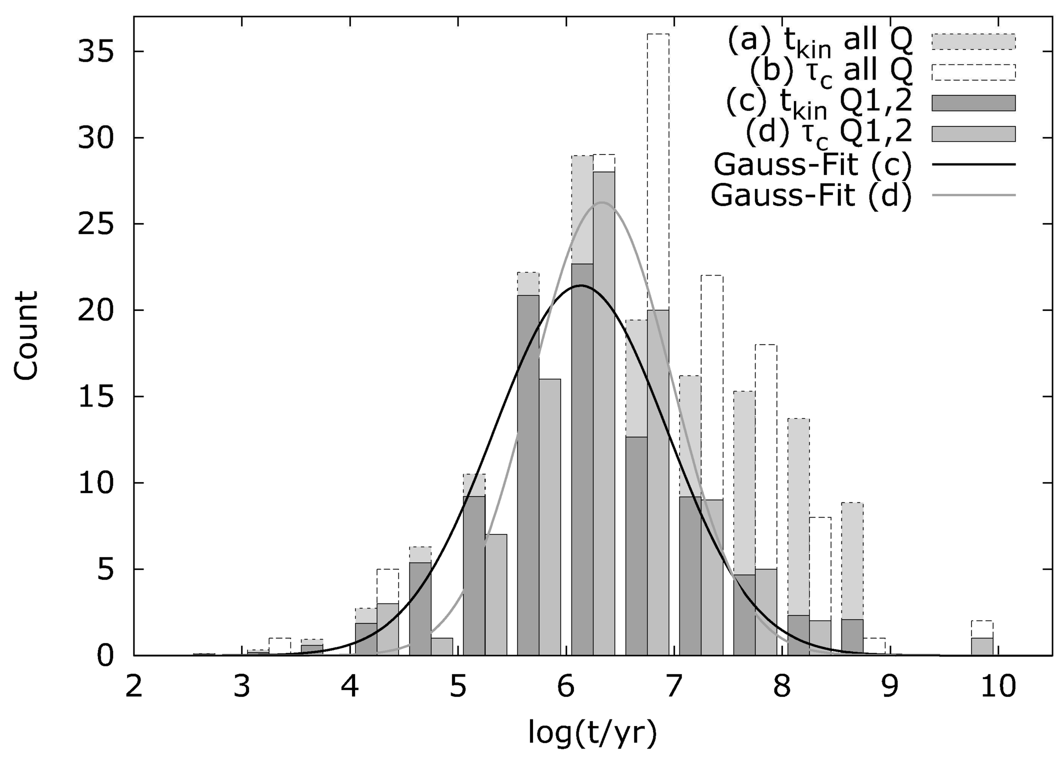




J0323+3944:
$t_{kin} = 1.44^{+2.32}_{-1.37} \times 10^8$ yr (blue) or $2.26^{+229}_{-0.44} \times 10^6$ yr (green)

$\Rightarrow$ uncertain, Quality: 4/6

The distribution of ages



$N_{Q1/2} = 92$, $N_{all} = 146$

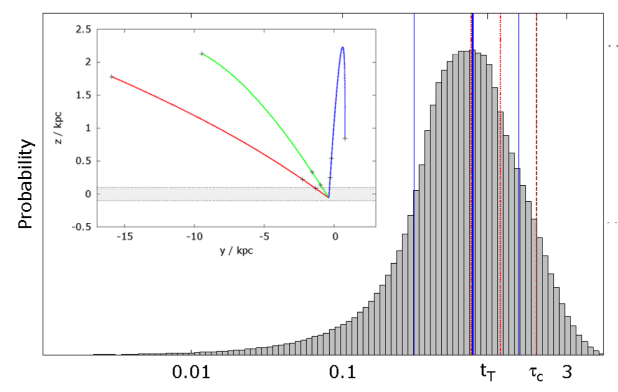
The distribution of logarithmic kinematic ages roughly follows a Gaussian with a peak at 10^6 years. The kinematic ages are smaller on average than the characteristic ages. In many cases characteristic and kinematic ages are not consistent with each other.

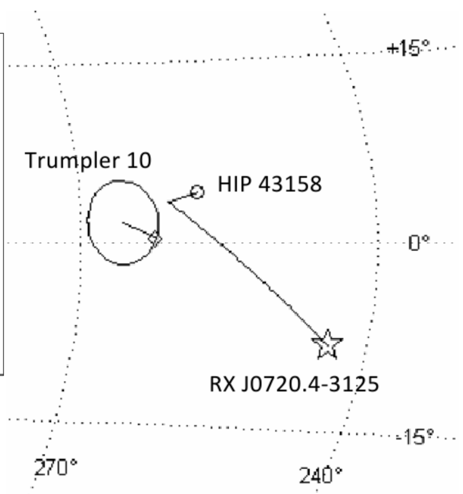
Young and old pulsars

- Young pulsars (e.g. the Crab pulsar, $t = 963$ yr, SN observed in 1054 AD) often did not have time to intersect with the Galactic plane $\Rightarrow$ no solutions (quality 6)
- High fraction of good qualities (1 & 2) (60–70%)
- Old pulsars: Fewer pulsars with quality 6
- Low fraction of good qualities (20–40%), additional intersections increase complexity of PDFs

Comparison with Tetzlaff 2013

[14] found 18 kinematic ages for young pulsars from identifying birth places like OB associations [12] or runaway stars as former companion candidates. In 15 cases her results can be directly compared to ours.



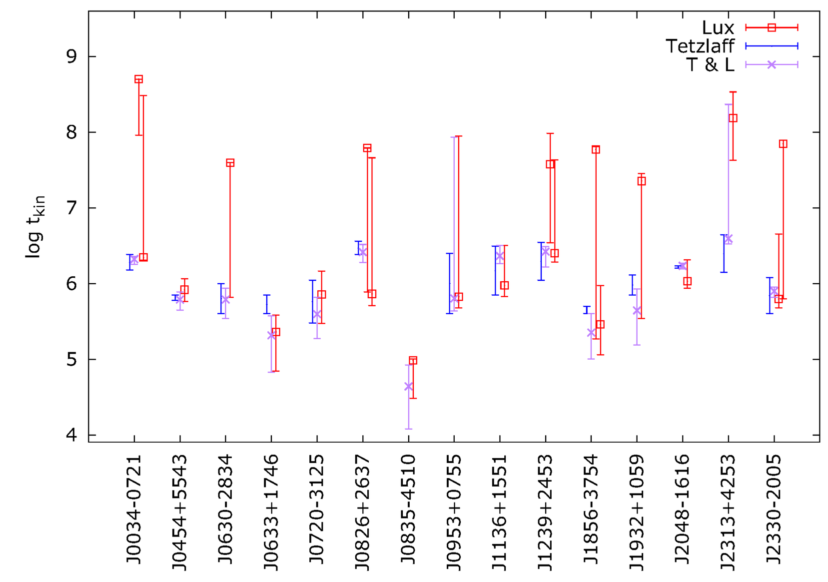


J0720−3125: $t_{kin} = 0.7^{+1.2}_{-0.5}$ Myr

Tetzlaff et al. (2011) [13]
$t = 0.9^{+0.2}_{-0.2}$ Myr

J1856−3754:
$t_{kin} = 0.3^{+0.6}_{-0.2}$ Myr or $52.3^{+9.5}_{-52.1}$ Myr

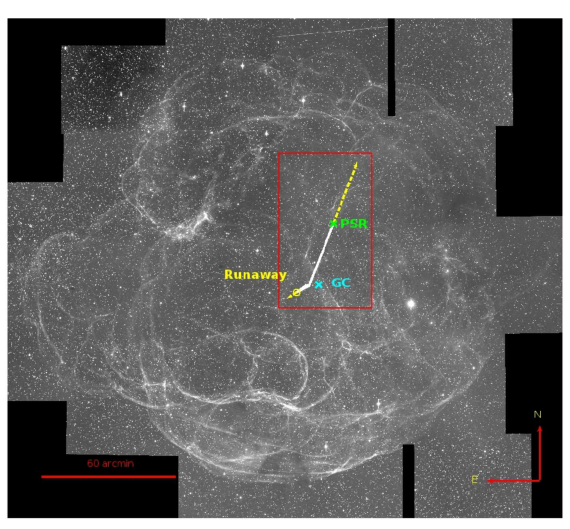
Tetzlaff: $t \approx 0.5$ Myr



Direct comparison: The ages shown by the purple crosses were obtained by performing our kinematic simulation with constrained radial velocities. These were found by [14] by assignments to birth associations. We see that Tetzlaff's method and the combined method are much more precise for young pulsars.

Discovery of a Runaway Star

- [3]: Discovery of B-type runaway star HD 37424 as former companion of PSR J0538+2817 in SNR S147
- Runaway was located at the geometrical center of the SNR 30 ± 4 kyr ago, consistent with the age and former location of the PSR as given by [6]
- Proving the binary SN ejection scenario [1]



Dinçel et al. 2015

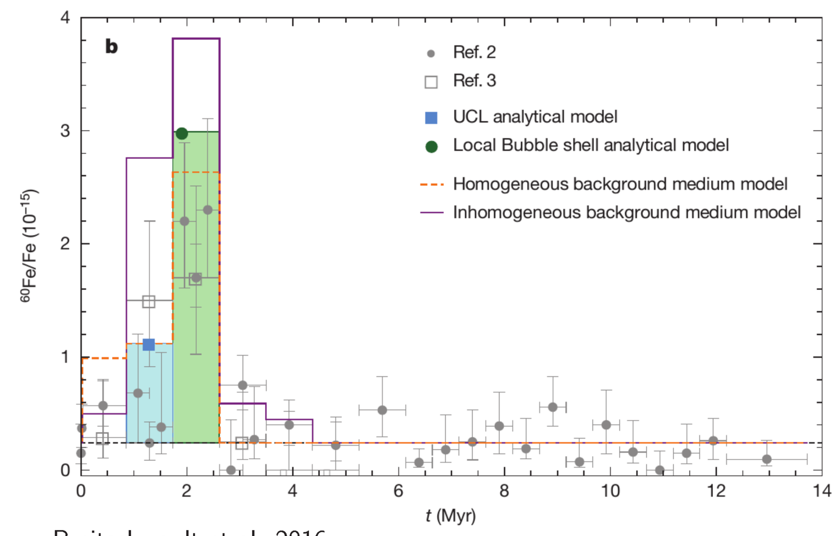
Current Work

Runaway stars in supernova remnants:

- Consider 24 closest SNRs, distance up to ~ 1.6 kpc
  $\Rightarrow$ should allow identification of all runaways with spectral classes earlier than M4
- Higher precision with Gaia data $\Rightarrow$ Runaway candidates from position, proper motion and parallax
- Spectroscopy with VLT/UVES and Subaru/HDS will reveal the properties of our candidates:
  - Are they young, i.e. do late-type stars show Lithium 6708 Å absorption?
  - Does the radial velocity fit to the expected 3D motion, away from the geometric center of the SNR?

The pulsar that placed ^{60}Fe onto the earth

- Unusual high amounts of ^{60}Fe detected in earth crust, dated ~ 2 Million years ago [5]
- [2] identified two Supernovae as most probable explanation, which happened at distances of 91 and 96 parsecs
- Which neutron stars are the remnants of these events?



Breitschwerdt et al. 2016

Conclusions

- Determinations of 92 pulsar kinematic ages from intersections with the Galactic plane
  - No need for questionable assumptions
  - Age determinations also for older pulsars
- But:
  - Large errors, individual t_{kin} can differ a lot from independent age estimates
  - Problems for very young (no solutions) and old (complicated PDFs) pulsars
  - Not applicable for millisecond pulsars or pulsars in clusters
- Take into account individual pulsar properties, e.g. birth associations like SNRs or runaways, to obtain more precise ages and insights into massive binary evolution and SN kick mechanisms
- The method can be applied further: Search for the pulsar that placed ^{60}Fe onto the earth crust

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