Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
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Probing magnetar formation channels with high-precision astrometry: The progress of VLBA astrometry of the fastest-spinning magnetar Swift J1818.0−1607

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Abstract. Boasting supreme magnetic strengths, magnetars are among the prime candidates to generate fast radio bursts. Several theories have been proposed for the formation mechanism of magnetars, but have not yet been fully tested. As different magnetar formation theories expect distinct magnetar space velocity distributions, high-precision astrometry of Galactic magnetars can serve as a probe for the formation theories. In addition, magnetar astrometry can refine the understanding of the distribution of Galactic magnetars. This distribution can be compared against fast radio bursts (FRBs) localized in spiral galaxies, in order to test the link between FRBs and magnetars. Swift J1818.0−1607 is the hitherto fastest-spinning magnetar and the fifth discovered radio magnetar. In an ongoing astrometric campaign, we have observed Swift J1818.0−1607 for one year using the Very Long Baseline Array, and have determined a precise proper motion as well as a tentative parallax for the magnetar.

Keywords. radio continuum: stars, pulsars: individual (Swift J1818.0−1607), stars: neutron, techniques: interferometric, techniques: high angular resolution

1. Introduction

As the most magnetized objects in the universe, magnetars may account for at least 12% of the neutron star population (Beniamini et al. 2019). However, only roughly 30 magnetars have been identified (Olausen & Kaspi 2014) in our Galaxy or in the Magellanic Clouds. This discrepancy can be explained by short-lived energetic electromagnetic activities of magnetars.

Magnetars sit at the intersection of multiple research topics. Their postulated link to fast radio bursts (FRBs) has been strengthened by the FRB-like bursts recently observed from a Galactic magnetar (Andersen et al. 2020; Bochenek et al. 2020). But it remains unclear whether all FRBs are originated from magnetars. Magnetars are also strongly connected to γ-ray bursts (GRBs) through the detection of giant magnetar flares from nearby galaxies (e.g. the one in NGC 253, Roberts et al. 2021; Svinkin et al. 2021), and newborn magnetars from double neutron star mergers (e.g. Sarin & Lasky 2021). On the other hand, the formation mechanism of magnetars is yet not well understood. A few distinct magnetar formation theories have been proposed, including normal core-collapse supernovae (CCSN) of magnetic massive stars (Schneider et al. 2019), accretion-induced collapse (AIC) of white dwarfs Duncan & Thompson (1992) and double neutron star mergers (Giacomazzo & Perna 2013; Xue et al. 2019). Most magnetar formation channels require magnetars to be born with millisecond spin periods. The only exception is the normal CCSN formation channel, where a new-born magnetar simply inherits the magnetic fields from its magnetic progenitor star (Schneider et al. 2019).

While almost all magnetars are identified with their soft γ-ray and X-ray activities, $\approx 40\%$ of them are also visible at optical/infrared or radio frequencies (Olausen & Kaspi 2014). This visibility allows precise astrometry for the magnetars. Historically, 7 magnetars have been precisely measured astrometrically, including 4 infrared-bright magnetars (Tendulkar et al. 2013) and 3 radio magnetars (Deller et al. 2012; Bower et al. 2015; Ding et al. 2020b). The primary motivations of previous astrometric campaigns of magnetars are to **1)** establish supernova remnant associations and **2)** test whether magnetars receive extraordinary kick velocities ($\gtrsim 1000\,\mathrm{km\ s^{-1}}$) as predicted by Duncan & Thompson (1992). With growing numbers of Galactic magnetars precisely measured astrometrically, new research opportunities start to emerge.

The small sample studied by Tendulkar et al. (2013), entailing 6 astrometrically measured magnetars, offers no indication that magnetar space velocities (magnetar velocity with respect to the neighbourhood of the magnetar) follow a distribution different from that of normal pulsars (Hobbs et al. 2005). This rough consistency may imply that most magnetars in spiral galaxies are born in normal CCSN similar to the ones that create typical neutron stars. The CCSN origin of magnetars is also supported by few SNR associations of magnetars (e.g. Borkowski & Reynolds 2017, GCN circular 16533). On the other hand, the DNS merger origin is not favored by the Galactic magnetar sample, as all Galactic magnetars are found near the Galactic plane (see Figure 1). For other formation channels (e.g., the AIC channel), it remains an open question if they contribute to the formation of the Galactic magnetar population, or more generally magnetars in spiral galaxies. This question can be approached with a refined magnetar space velocity distribution, to be established with $\gtrsim$10 Galactic magnetars precisely measured astrometrically. As different formation channels may lead to distinct magnetar space velocity distributions (e.g., the AIC channel would probably give rise to relatively small magnetar space velocities), the averaged magnetar space velocity distribution could turn out to be bi-modal or even multi-modal (if there are more than one formation channel of magnetars).

Astrometry of Galactic magnetars would also play a role in the FRB study. On one hand, FRBs have been localized to specific environments (i.e., spiral arms) of spiral galaxies (Mannings et al. 2021). On the other hand, magnetar astrometry could potentially pinpoint the 3-D magnetar location (Ding et al. 2020b) in the Galaxy. Hence, comparing the Galactic magnetar distribution against FRB sites (localized to spiral galaxies) can test the link between FRBs and magnetars. However, Galactic magnetars precisely measured astrometrically are usually limited to the vicinity of the Solar system. To better infer magnetar distributions in spiral galaxies, one needs the knowledge of contributing formation channels of magnetars in the spiral galaxies (which, again, can be approached by magnetar astrometry). This is because magnetars formed in one channel are expected to follow a specific spatial distribution (e.g., magnetars born via the CCSN and DNS-merger channel are expected to be associated with, respectively, star-forming regions and stellar mass of a galaxy).

2. The progress of astrometry of Swift J1818.0−1607

Swift J1818.0−1607 is the fifth discovered radio-bright (Karuppusamy et al. 2020) magnetar (GCN circular 27373), which is also the hitherto fastest-spinning magnetar with a spin period of 1.4 s (Enoto et al. 2020). Its short spin period and high spin-down rate correspond to a characteristic age of around 500 yr (Champion et al. 2020),

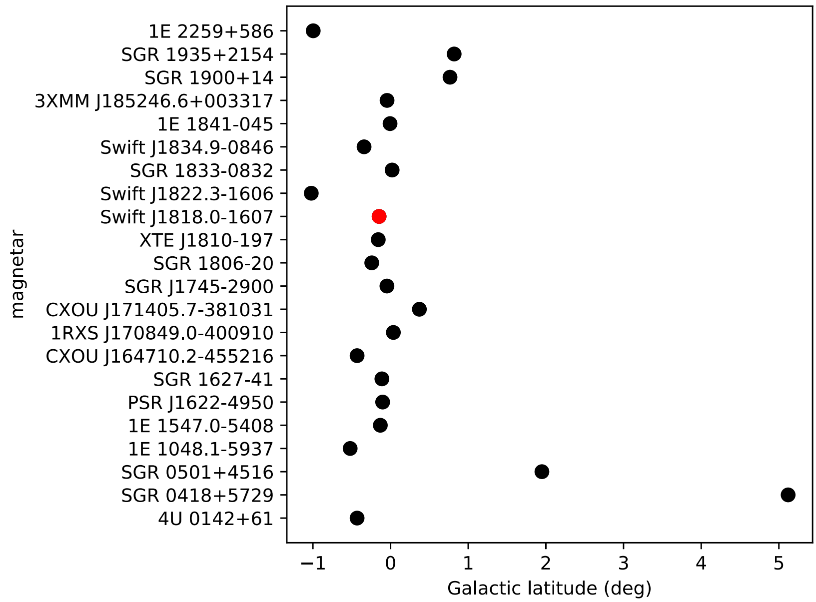

Figure 1. Galactic latitudes of Galactic magnetars calculated from their equatorial positions provided by Olausen & Kaspi (2014), where Swift J1818.0−1607 is highlighted in red.

implying its great youth. Right after the radio detection of Swift J1818.0−1607, we launched an astrometric campaign of the magnetar using the Very Long Baseline Array (VLBA). The first VLBA observation was made at 1.6 GHz on 20 April 2020, which did not lead to a detection (Ding et al. 2020a). In response to the spectral flattening (of Swift J1818.0−1607) first noticed in July 2020 (e.g. Majid et al. 2020), we raised the observing frequency to 8.8 GHz, and managed to detect Swift J1818.0−1607 with VLBA on 19 August 2020 (Ding et al. 2020a).

At the time of writing, more than a year has passed since the first VLBA detection. During this period, 5 more VLBA observations have been made, all resulting in detections at sub-mas positional precision. We applied pulsar gating to improve image S/N, where the pulse ephemerides were generated from ongoing Parkes monitoring of Swift J1818.0−1607 (Lower et al. 2020). To enhance astrometric accuracy of our observations, we have employed the 1-D interpolation tactic (e.g. Fomalont & Kopeikin 2003; Ding et al. 2020b) for all the 6 VLBA observations. After data reduction and analysis, we obtained a compelling proper motion $\mu_\alpha = -3.54 \pm 0.05\,\mathrm{mas\ yr^{-1}}$, $\mu_\delta = -7.65 \pm 0.09\,\mathrm{mas\ yr^{-1}}$, alongside a tentative ($5\,\sigma$) parallax (see Figure 2). Here, in order to roughly account for the systematic errors caused by atmospheric propagation effects, the uncertainty of the proper motion (as well as parallax) has been scaled by $1/\sqrt{\chi^2_\nu}$, where χ^2_ν stands for reduced chi-square of direct parallax fitting. The final astrometric results with thorough error estimation will be obtained and discussed in a future publication, following the completion of the whole astrometric campaign that spans at least 2 years.

3. Future prospects

For Swift J1818.0−1607, with 6 more VLBA observations to be made in the following year, the parallax measurement is likely to become substantial ($>7\,\sigma$), which would simplify the conversion of parallax to distance (without needing to take into account the Lutz-Kelker effect, Lutz & Kelker 1973). With regard to the whole magnetar category, to

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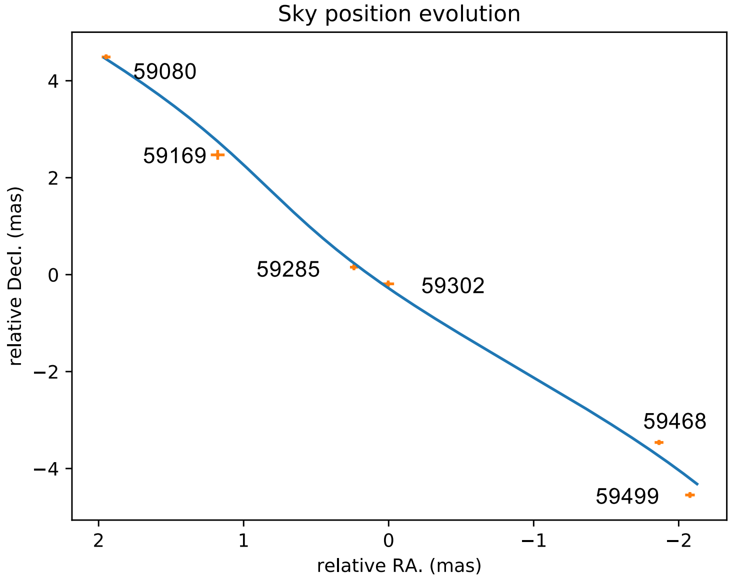

Figure 2. Sky positions of Swift J1818.0−1607 relative to the reference position $18^{\mathrm{h}}18^{\mathrm{m}}00\overset{\mathrm{s}}{.}19327$, $-16°07'53\overset{''}{.}0095$. The positions are labeled with the observing dates in MJD. We note that the positional uncertainties presented here only reflect random errors caused by image noises. The blue curve represents the best-fit astrometric model.

establish the magnetar space velocity distribution is mainly limited by the small sample of (≈ 11, Olausen & Kaspi 2014) radio or optical/infrared magnetars. To expand this sample and hence accelerate the establishment of the magnetar space velocity distribution, new candidates of radio or optical/infrared magnetars, such as the newly discovered ultra-long-period sources (e.g. Hurley-Walker et al. 2022), are desired.

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