A precessing magnetar model for GLEAM-X J162759.5-523504.3

K. Yavuz Ekşi and Sinem Şasılmaz

1Istanbul Technical University, Faculty of Science and Letters, Physics Engineering Department, 34469, Istanbul, Turkey, ekşi@itu.edu.tr

11 February 2022

ABSTRACT
We propose a precessing transient magnetar model for the recently discovered radio source GLEAM-X J162759.5-523504.3. We identify the observed period of \( \sim 1 \) ks as the precession period of the magnetar deformed due to its strong \((B_0 \sim 10^{16} \text{ G})\) toroidal field. The resulting deformation of order \( 10^{-4} \) implies a spin period of \( P_s = 0.1 \) s. Assuming a strong dipole field of \( B_d \sim 10^{14} \text{ G} \) we predict a period derivative of \( \dot{P}_s \sim 10^{-11} \text{ s s}^{-1} \). We also predict that the precession period of the magnetar can be observed in the hard X-ray band just as the other three galactic magnetars exhibit precession.

Key words: stars: neutron – stars: individual:GLEAM-X J162759.5-523504.3 – radiation: radio

1 INTRODUCTION
The recent detection of a transient radio source with coherent emission in the radio band and high fractional polarization (88\%) clearly indicates to a neutron star magnetosphere as the origin (Hurley-Walker et al. 2022). The radio emission is modulated with a period of 18.18 min (\( \sim 1 \) ks). This is interpreted as the spin period of a rotationally-powered pulsar or a magnetar (Hurley-Walker et al. 2022).

The spin period of rotationally-powered pulsars range between \( P_s = 10 \text{ ms} \) to \( P_s = 20 \text{ s} \) (see Manchester et al. 2005, for the ATNF Pulsar Catalogue\(^1\)). The spin period of galactic magnetars (see Kaspi & Beloborodov 2017, for a review) range between \( P_s = 2 \) – 12 s (see Olausen & Kaspi 2014, for the catalogue of galactic magnetars\(^2\)). The \( \sim 1 \) ks period of the GLEAM-X J162759.5-523504.3 is unusual as the period of a pulsar or a magnetar with sufficient resources to exhibit the observed phenomena.

More recently, a fallback disc model was suggested for this source by Ronchi et al. (2022). Such discs were proposed to exist around anomalous X-ray pulsars (AXPs) (Chatterjee et al. 2000) and all enigmatic young neutron stars (Alpar 2001). Such a disc was discovered around 4U 0142+61 by Wang et al. (2006).

Some of the galactic magnetars are observed to exhibit precession periods observed in the hard X-ray band: 4U 0142+61 with \( P_s = 55 \text{ ks} \) (Makishima et al. 2014, 2019), 1E 1547–54 with \( P_s = 35 \text{ ks} \) (Makishima et al. 2016, 2021) and SGR 1900+14 with \( P_s = 40.5 \text{ ks} \) (Makishima et al. 2021). Makishima (2021) notes that AXP IRXS J170849.0–400910 and SGR 0501+4516 likely exhibit the same behaviour. Such precession occurs owing to the deformation of the star by the strong toroidal magnetic fields (Thompson & Duncan 1995; Dall’Osso et al. 2009; Braithwaite 2009). Recently, precessing magnetars are proposed as central engines in short gamma-ray bursts (Suvorov & Kokkotas 2021) and repeating fast radio bursts (Sob’yanin 2020; Zanazzi & Lai 2020; Levin et al. 2020; Wasserman et al. 2021). In this letter we interpret the 1.091 ks modulation of GLEAM-X J162759.5-523504.3 as the precession period of a young transient magnetar with a spin period of \( P_s \sim 0.1 \) s. In the next section we introduce the model equations, and in the final section, we discuss the implications of this model and some predictions.

2 MODEL EQUATIONS
Assuming the object is spinning-down by magnetic dipole radiation torques its dipole field would be related to its period and period derivative as
\[ B_d = 6.4 \times 10^{19} \sqrt{P_r P_s} \]  
\[ (\text{Gunn & Ostriker 1969}) \] and for a typical magnetar dipole field of \( B_d = 10^{14} \text{ G} \) one obtains the period derivative of the object as
\[ \dot{P}_s = 2.4 \times 10^{-11} B_d^2 / P_{s,14} \]  
where we use the notation \( X \equiv 10^{-4} X_0 \). The spin-down power of the object is
\[ L_{\text{sd}} = 4\pi^2 I P_s^3 \]  
where \( I \sim 10^{45} \text{ g cm}^2 \) is the moment of inertia. This can be expressed as
\[ L_{\text{sd}} \sim 10^{39} I_{45} B_d^2 / P_{s,14}^4 \]  
This is compatible with the brightest radio pulses of the object being \( L = 4 \times 10^{31} \text{ erg s}^{-1} \) (Hurley-Walker et al. 2022) since typically radio luminosity of pulsars are orders of magnitude smaller than

---

\(^1\) See https://www.atnf.csiro.au/research/pulsar/psrcat/.
\(^2\) See http://www.physics.mcgill.ca/~pulsar/magnetar/main.html.
their spin-down power. Given the upper bounds on X-ray luminosity of the object \( L_X < 10^{32} \) erg s\(^{-1}\) as obtained by Swift (Hurley-Walker et al. 2022) this renders the source as a rotationally powered magnetar! This oxymoron is to mean that although the spin-down power is presently greater than the magnetic power of the object, when the source slows down sufficiently, its magnetic power will dominate over the spin-down power just as the typical galactic magnetars. The source is considered as a magnetar simply because of its strong toroidal field.

Magnetars are expected to have strong toroidal magnetic fields \( B_\phi \sim 10^{16} \) G (Thompson & Duncan 1995; Dall’Osso et al. 2009; Brailtwaite 2009). Given the presence of magnetars with low dipole magnetic fields (Rea et al. 2010), it is possible that this strong toroidal field that makes a magnetar different from a rotationally powered pulsar. Magnetic stresses deform such a neutron star into a prolate spheroid (Ioka 2001; Cutler 2002; Ioka & Sasaki 2004; Haskell et al. 2008; Mastrano et al. 2011, 2013, 2015; Frieben & Rezzolla 2012; Frederick et al. 2021; Zamani & Bigdeli 2021; Soldateschi et al. 2021) with asphericity

\[
\varepsilon = \frac{I_3 - I_1}{I_3} \sim 10^{-4} B_{\phi,16}^2
\]  

(5)

where \( I_3 \) is the moment of inertia around the magnetars symmetry axis and \( I_1 \) is that around the axis orthogonal to this. As a result a magnetar will exhibit free precession with a period of

\[
P_p = P_s/\varepsilon
\]  

(6)

(see e.g. Heyl & Hernquist 2002). In Figure 1 we show the relation between the spin period and precession period of the three galactic magnetars together with GLEAM-X J162759.5–523504.3. Assuming asphericity range of \( \varepsilon = (0.6 - 1.6) \times 10^{-4} \), as suggested by \( P_s/P_p \) values of 1E 1547–54 (Makishima et al. 2016) and of 4U 0142+61 (Makishima et al. 2014), we obtain a spin period in the range \( P_p \approx (0.6 - 0.2) \) s.

3 DISCUSSION

We proposed a precessing magnetar model for the GLEAM-X J162759.5–523504.3 identifying the observed period of \( \sim 1.1 \) ks as the precession period. Assuming a typical toroidal magnetic field of \( \sim 10^{16} \) G this implies a proloid deformation of order \( \varepsilon \sim 10^{-4} \) implying a spin period of \( P_s = 0.1 \) s. This implies that the object is likely to be a magnetar on the basis of its strong toroidal field, but presently, due to its small spin period owing to its small age, its rotational power dominates over the X-ray luminosity.

The upper bounds on the X-ray luminosity is 3 orders of magnitude smaller than the persistent X-ray luminosity of mature magnetars, \( L_X \sim 10^{35} \) erg s\(^{-1}\), but similar to quiescent state of transient magnetars. This implies that, assuming the above picture is correct, the source may show X-ray enhancement in the future.

Association of the object with galactic transient magnetars that show X-ray modulation due to precession (Makishima et al. 2014), we predict that the object might be brighter in hard X-rays compared to the soft X-ray band.

We predicted that the source should have a period derivative of \( \dot{P} \sim 10^{-11} \) s s\(^{-1}\) and spin-down power of \( L_{sd} \sim 10^{30} \) erg s\(^{-1}\). If the spin period of the source is 0.2 s, instead of the 0.1 s as assumed throughout the text, this luminosity drops 16 times owing to the strong dependence on the period given in Equation 4.
DATA AVAILABILITY

No new data were analysed in support of this paper.

ACKNOWLEDGEMENTS

We acknowledge support from TÜBİTAK with grant number 118F028.

REFERENCES

Alpar M. A., 2001, ApJ, 554, 1245
Braithwaite J., 2009, MNRAS, 397, 763
Chatterjee P., Hernquist L., Narayan R., 2000, ApJ, 534, 373
Cutler C., 2002, Phys. Rev. D, 66, 084025
Dall’Osso S., Shore S. N., Stella L., 2009, MNRAS, 398, 1869
Frederick S. G., Thompson K. L., Kuchera M. P., 2021, MNRAS, 503, 2764
Frieben J., Rezzolla L., 2012, MNRAS, 427, 3406
Gunn J. E., Ostriker J. P., 1969, Nature, 221, 454
Haskell B., Samuelsson L., Glampedakis K., Andersson N., 2008, MNRAS, 385, 531
Heyl J. S., Hernquist L., 2002, ApJ, 567, 510
Hurley-Walker N., Zhang X., Bahramian A., McSweeney S., O’Doherty T., Hancock P., Morgan J., Anderson G., Heald G., Galvin T., 2022, Nature, 601, 526–530
Ioka K., 2001, MNRAS, 327, 639
Ioka K., Sasaki M., 2004, ApJ, 600, 296
Kaspi V. M., Beloborodov A. M., 2017, ARA&A, 55, 261
Levin Y., Beloborodov A. M., Bransgrove A., 2020, ApJ, 895, L30
Makishima K., 2021, in American Institute of Physics Conference Series Vol. 2319 of American Institute of Physics Conference Series, Observations of magnetic deformation of magnetars. p. 040003
Makishima K., Enoto T., Hiraga J. S., Nakano T., Nakazawa K., Sakurai S., Sasano M., Murakami H., 2014, PRL, 112, 171102
Makishima K., Enoto T., Murakami H., Furuta Y., Nakano T., Sasano M., Nakazawa K., 2016, PASJ, 68, S12
Makishima K., Enoto T., Yoneda H., Odaka H., 2021, MNRAS, 502, 2266
Makishima K., Murakami H., Enoto T., Nakazawa K., 2019, PASJ, 71, 15
Makishima K., Tamba T., Aizawa Y., Odaka H., Yoneda H., Enoto T., Suzuki H., 2021, ApJ, 923, 63
Manchester R. N., Hobbs G. B., Teoh A., Hobbs M., 2005, AJ, 129, 1993
Mastrano A., Lasky P. D., Melatos A., 2013, MNRAS, 434, 1658
Mastrano A., Melatos A., Reisenegger A., Akgün T., 2011, MNRAS, 417, 2288
Mastrano A., Suvorov A. G., Melatos A., 2015, MNRAS, 447, 3475
Olausen S. A., Kaspi V. M., 2014, ApJS, 212, 6
Rea N., Esposito P., Turolla R., Israel G. L., Zane S., Stella L., Mereghetti S., Tiengo A., Götz D., Göğüş E., Kouveliotou C., 2010, Science, 330, 944
Ronchi M., Rea N., Graber V., Hurley-Walker N., 2022, arXiv e-prints, p. arXiv:2201.11704
Sob’yain D. N., 2020, MNRAS, 497, 1001
Soldateschi J., Bucciantini N., Del Zanna L., 2021, arXiv e-prints, p. arXiv:2106.00603
Suvorov A. G., Kokotkas K. D., 2021, MNRAS, 502, 2482
Thompson C., Duncan R. C., 1995, MNRAS, 275, 255
Wang Z., Chakrabarty D., Kaplan D. L., 2006, Nature, 440, 772
Wasserman I., Cordes J. M., Chatterjee S., Batra G., 2021, arXiv e-prints, p. arXiv:2107.12911
Zamani M., Bigdeli M., 2021, Astronomische Nachrichten, 342, 633
Zanazzi J. J., Lai D., 2020, ApJ, 892, L15