
Supplementary information

Lense–Thirring precessing magnetar engine drives a superluminous supernova

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Supplementary Information

Supplementary Information 1: Observing instruments

SN 2024afav was almost continuously observed since explosion by the Asteroid Terrestrial Last-Alert System (ATLAS) [68]. ATLAS is comprised of dual 0.5 m telescopes located on Mauna Loa and Haleakala in Hawaii which survey the entire night sky in at least one band daily. We used the ATLAS online photometry pipeline¹ to obtain forced photometry in the *o* (orange) and *c* (cyan) bands for SN 2024afav over the first ~ 180 days of its evolution. Calibration of the ATLAS forced photometry was done to the Pan-STARRS catalog.

Halfway through the “plateau,” we began observing SN 2024afav approximately daily with the Las Cumbres Observatory [69] 1 m and 2 m telescopes via the Global Supernova Project, as well as obtaining roughly weekly spectra with the wide-coverage (350 nm to 1 micron) FLOYDS spectrograph located on the northern 2 m LCO instrument at Haleakala Observatory. We obtained photometry in the *g*, *r*, and *i* bands, reduced the data using the `lcogtsnpipe` pipeline [70], and calibrated the extracted magnitudes to AB magnitudes [71] using the Sloan Digital Sky Survey catalog [72]. Spectroscopic data were extracted and reduced using the `floydsspec` pipeline [70].

We also obtained optical images of SN 2024afav in the *gri* filters with the Kepler-Cam imager on the 1.2 m telescope at FLWO. The data were reduced using standard IRAF routines, and we performed photometry with the `daophot` package. Instrumental magnitudes were measured by modeling the point-spread function (PSF) of each image using field stars and subtracting the model PSF from the target. To separate the flux of SN 2024afav from that of its host galaxy we perform image subtraction on each image with HOTPANTS [73], using archival PS1/ 3π images as reference templates. We estimate individual zero-points of each image by measuring the magnitudes of field stars and comparing to photometric AB magnitudes from the PS1/ 3π catalog

¹<https://fallingstar-data.com/forcedphot/>

[74]. The uncertainties reported for KeplerCam photometry are the combination of the photometric uncertainty and the uncertainty in the zero-point determination.

In addition to the LCO FLOYDS spectra, we obtained spectra using the Magellan telescope in Chile and the MMT instrument at the Fred Lawrence Whipple Observatory in southern Arizona. The data were reduced using the PyPeIt package [75] in a standard manner. The one-dimensional spectrum was extracted and flux-calibrated using a standard-star observation obtained with the same configuration.

Supplementary Information 2: Derivation of the precession

Following [Methods 3](#), we fit these oscillations with a two-component model, multiplying a time-evolving envelope $A(t)$ by a sinusoid,

$$\Delta L_{\text{LT}}(t) = A(t) \cos[\phi(t)]. \quad (3)$$

The choice of a sinusoid with a phase offset to represent the observed signal is well-motivated by the clearly sinusoidal modulations in the data. The phase function $\phi(t)$ is derived directly from the precession-frequency magnitude (Ω_p) in the weak-field approximation, which has both a Lense-Thirring component and a quadrupole-driven component. Given that the magnetar-disk system has an unknown orientation relative to the observer, we adopt a fully general prescription, following [21] and [76]. We choose $\hat{z}$ as the line of sight of the observer (with sky coordinates $\hat{x}, \hat{y}$). In the context of the orbit, we construct our unit triad $(\hat{i}, \hat{m}, \hat{h})$, following Equations 2–4 of [76], and magnetar spin vector $\hat{k}$. The spin axis $\hat{k}$ is defined by two spherical angles: the polar angle α' (primed to differentiate from α -disk characteristic parameter) between $\hat{k}$ and the observer's $\hat{z}$ axis, and the azimuthal angle δ between the projection of $\hat{k}$ onto the $(\hat{x}, \hat{y})$ plane and the $\hat{x}$ axis. Finally, the tilt between the spin axis and the disk is defined by $\cos \beta = \hat{k} \cdot \hat{h}$, since $\hat{h}$ is the unit orbital angular momentum vector (that is,

the normal of the disk). In this coordinate system, we find that the magnitude of the combined Lense-Thirring and quadrupole precession is

$$\Omega_p(r, \beta) = \Omega_{\text{LT}} + \Omega_{J_2} = \frac{2GJ}{c^2 r^3} + \frac{3}{2} J_2 \sqrt{\frac{GM}{r^3}} \left(\frac{R}{r}\right)^2 \cos \beta, \quad (4)$$

where J is the angular momentum of the magnetar, r is the characteristic radius of the accretion disk, R is the radius of the magnetar, and J_2 is the magnitude of the geopotential's quadrupole deviation from spherical symmetry. In theory, J_2 , J , and β are all free parameters. However, in practice, even at the theoretical upper limit of $J_2 \approx 10^{-3}$ [38] and assuming $\cos \beta \approx 1$ (unlikely as the tilt of the disk relative to the spin axis is not expected to be large), the ratio $\Omega_{\text{LT}}/\Omega_{J_2} \approx 10^2\text{--}10^3$ for all system parameters. Additionally, $J = I\Omega = (2\pi/P_{\text{spin}})kMR^2$ with $k \approx 0.35$ [77] is completely determined by the remaining free parameters (namely, M , R , P_{spin}). Thus, for simplicity, we restrict our analytic treatment to

$$\Omega_{\text{LT}} \approx \frac{2GJ}{c^2 r^3(t)}. \quad (5)$$

We tested this simplification by performing all fits with the full expression, and found that we indeed cannot constrain β or J_2 , as the quadrupole term is not sufficiently dominant to affect parameter constraints. This expression is consistent with similar derivations in the literature [e.g., 19], and is valid for a test-particle orbit or for a very thin annulus; however, the accretion disk will be composed of a range of orbits, resulting in a different precession frequency for the disk as a whole. Following [78], we model the disk with surface density $\Sigma = \Sigma_i(r/r_i)^{-\zeta}$, and find that for $\zeta = 3/4$ [55], the precession frequency derived above becomes

$$\Omega_{\text{LT}} = \frac{7}{5} \frac{1 - (r_o/r_i)^{-5/4}}{(r_o/r_i)^{7/4} - 1} \frac{2GJ}{c^2 r_i^3(t)}. \quad (6)$$

As the outer and inner radii (r_o and r_i) of the annulus often appear as a ratio, we treat r_o/r_i as a single parameter. For the purposes of our calculation, we assume r_o/r_i is constant; however, we test the validity of this assumption below.

The accumulated phase $\phi(t)$ is the integral of the angular frequency with time. The exact form of $r_i(t)$ depends on the mechanism driving the infall; however, most infall mechanisms can be approximated to first order as linear over the timescale of tens of days (see [Main Figure 3](#)). We assume $r_i(t) \propto t$ to first order; i.e., $r_i(t) = r_0 - \dot{r}_i(t - t_0) = \dot{r}_i(t_{\text{infall}} - t)$ where $t_{\text{infall}} = t_0 + r_0/\dot{r}_i$. Under this assumption, the phase function becomes

$$\phi(t) = \int \Omega_{\text{LT}} dt \approx -\frac{7}{5} \frac{1 - (r_o/r_i)^{-5/4}}{(r_o/r_i)^{7/4} - 1} \frac{GJ}{c^2 \dot{r}_i^3} (t_{\text{infall}} - t)^{-2} - \phi_0, \quad (7)$$

where the initial phase of the disk ϕ_0 is a free parameter, and t_{infall} and $\dot{r}$ are determined based on the assumed infall model. Next, we assume the accretion disk is supported by the magnetar-launched wind, which causes the disk to infall as the accretion rate decreases [\[17, 18\]](#). To approximate the equilibrium radius $r_w(t)$ (which we will identify with the inner radius r_i used above to obtain $r_i(t)$) where the disk pressure balances against the magnetar wind pressure, we consider the disk gas pressure [\[55\]](#)

$$P_g \propto \dot{M}^A r^{-b}, \quad (8)$$

where $\dot{M} \propto t^{-C}$ is the accretion rate through the disk, an approximation well-motivated for $C \approx 5/3$ at $\sim 10^6$ s by [\[29\]](#). We also consider the radiation pressure generated by the disk [\[55\]](#),

$$P_r \propto \alpha^{-0.8} \dot{M}_0^{A+0.7} t^{-C(A+0.7)} r^{-b-3/8}, \quad (9)$$

where $\dot{M}_0$ is a free parameter, corresponding to the accretion rate through the disk at a reference time t_0 (we take $t_0 = 30$ days). This combined disk gas and radiation pressure is balanced against the radiation pressure from the magnetar wind,

$$P_w \propto L(t)/r^2, \quad (10)$$

where $L(t) \propto (1+t/t_p)^{-2}$ as given by [4], which defines t_p as the spin-down timescale of the magnetar. We numerically solve for the disk radius $r_w(t)$ which satisfies $P_g + P_r \propto P_w$, where we adopt standard values of $A = 17/20$, $b = 21/8$, and $C = 5/3$ from [55], [29], and [33]. We use this radial infall function $r(t)$ to determine the phase function in Equation 7.

Supplementary Information 3: Investigation of alternative scenarios

We evaluate other mechanisms that could replicate the oscillating light curve, such as different precession modes and time-variable energy injection. For each mechanism, we compute a characteristic period and average period derivative over the timescale of the modulations observed in the SN 2024afav light curve. For each mechanism, we vary model parameters to fit the characteristic period P_c and calculate from those parameters a period derivative for comparison. For accretion disk precession-based mechanisms, we invoke wind-based radial infall to produce $\dot{P}_c < 0$ if the mechanism is not equipped with an evolving periodicity. Finally, we vary the MOSFiT magnetar model parameters and compute the corresponding P_c and $\dot{P}_c$ values to generate a Monte Carlo sampling of their possible range. We compare these to the SN 2024afav values of $P_c = 23 \pm 1.6$ days and $\dot{P}_c = -0.44 \pm 0.05$. A visualization of the period/period-derivative parameter space of the below scenarios is shown in Main Figure 3. For each scenario, we compute the precession period and period derivative

exactly, and compare to an analytic prediction based on assuming linear radial infall, to validate the assumption of [Supplementary Information 2](#). The analytic prediction is visualized for each mechanism as the gray dashed lines in [Main Figure 3](#).

Magnetic inclination angle precession: Ellipticity of the magnetar can lead to precession, causing modulations in the light curve [13]. We assume the model of [13] and compute the period of the magnetar versus time using their Equation 6. We adopt the MOSFiT magnetar parameters and find that a high deformation parameter of $\epsilon \approx 10^{-8}$ is required to obtain $P_c \approx 23$ days. However, the combination of parameters required to reproduce the periodicity observed in the data results in $\dot{P}_c \approx 0.1$, which implies an increasing periodicity. There is no mechanism in this model to create a decreasing period, and the magnitude of the predicted $|\dot{P}_c|$ is a factor of several too small. This model is disfavored.

Quadrupole-driven nodal precession: An oblate neutron star will cause orbits in the vicinity to precess in a manner which scales with the quadrupole coefficient of the neutron star J_2 and decreases with the square of the orbital radius [37]. We obtain the following expression for the quadrupole-driven nodal precession frequency of an annulus with inner and outer radii r_i and r_o ,

$$T_{\text{QDNP,annulus}} = \frac{4\pi}{3\sqrt{GM}J_2R_{\text{mag}}^2 \cos \beta} \frac{1 + \zeta}{5/2 - \zeta} r_i^{7/2} \frac{(r_o/r_i)^{5/2-\zeta} - 1}{1 - (r_o/r_i)^{-1-\zeta}}, \quad (11)$$

where R_{mag} is the magnetar radius, ζ parameterizes the surface density (i.e., surface density $\Sigma(r) \propto r^{-\zeta}$), and J_2 is a dimensionless coefficient which parametrizes the oblateness of the magnetar. There is no inbuilt mechanism for quadrupole-driven nodal precession to produce a decreasing period, so we invoke the radial infall of [Methods 4](#). We find that an accretion rate of $\dot{M} = 3.1 \times 10^{-6} M_\odot \text{ yr}^{-1}$ coupled with a high

$J_2 \approx 10^{-3}$ [38] produces $P_c = 18 \pm 2$ days. However, the accretion rate required to reproduce the period enforces $\dot{P}_c = -0.62 \pm 0.04$; thus, this model is disfavored.

Apsidal precession: If the disk has intrinsic ellipticity, it may experience apsidal precession due to relativistic effects [e.g., 79]. However, this effect is unlikely to be relevant on the timescale of the modulations observed in SN 2024afav. The disk circularizes on a timescale of roughly seconds to hours [35, 56, 80], whereas the bumps first appear ~ 2 months into the evolution of the SN. By this point, the accretion disk has circularized and does not experience apsidal precession.

Magnetic-warp precession: A diamagnetic accretion disk experiences a precessional torque with characteristic angular frequency given by [36]. We derive the following expression for the period of the magnetic-warp precession in the case of an annulus with thickness r_o/r_i :

$$T_{\text{MW,annulus}} = \frac{2\pi^3 \Sigma(r_i) \sqrt{GM}}{\mu^2 \cos \beta (3 \cos^2 \theta - 1)} \sqrt{\frac{2H}{r_m} \frac{9/4 + \zeta}{5/2 - \zeta} r_i^{11/2} \frac{(r_o/r_i)^{5/2-\zeta} - 1}{1 - (r_o/r_i)^{-9/4-\zeta}}}, \quad (12)$$

where θ is the obliquity angle (between the spin axis and magnetic moment of the magnetar), r_m is the magnetosphere radius, $\Sigma(r) \propto r^{-\zeta}$ is the surface density of the disk, H is the height of the disk (we assume $H/r > \alpha$), and μ is the magnetic moment of the magnetar. This magnetic-warp precession can give comparable periodicities if the disk surface density is unusually high ($\Sigma \gtrsim 10^7 \text{ g cm}^{-2}$), but the period is again likely to increase due to an induced disk-threading torque [36], conflicting with observations. If we instead modify the period by invoking radial infall, we can obtain $P_c = 13.4 \pm 6$ days using an accretion rate of $\dot{M} = 1.3 \times 10^{-3} \text{ M}_\odot \text{ yr}^{-1}$, which is somewhat high. However, this results in a best-fit $\dot{P}_c = -0.72 \pm 0.05$, which is once again inconsistent with the observations of SN 2024afav; thus, this model is disfavored.

Supplementary Information 4: Fits to other SLSNe-I

We consider previously studied SLSNe-I to which our model may be applicable. A majority of SLSNe-I have bumps or modulations of some kind [e.g., 7], and some appear to be periodic, motivating oscillating physical processes to explain them [13]. A variety of physical origins are plausible for SLSN-I modulations; we do not expect our model will be sufficient to describe all of them, especially those with nonsinusoidal or nonperiodic bumps. The magnetar+LT model can be considered when the early light curve is well described by the magnetar model and the modulations are clearly periodic or chirped in nature. We consider the following candidates which match these criteria to attempt to describe with our model.

1. SN 2018kyt: discovered [81] 2018 Dec. 19 by the Zwicky Transient Facility [ZTF; 82] at R.A. = $12^{\text{hr}}27^{\text{m}}56.240^{\text{s}}$, Dec. = $+56^{\circ}23'35.59''$. It was classified as an SLSN-I by ZTF based on a spectrum obtained on 2019 Jan. 29 [83]. SN 2018kyt had two clear peaks and possibly two dips at the same cadence as the peaks (~ 70 days). SN 2018kyt was previously considered as a possible candidate for modulation due to magnetic-inclination precession [13].
2. SN 2019unb: discovered [84] 2019 Oct. 20 at R.A. = $09^{\text{hr}}47^{\text{m}}57.010^{\text{s}}$, Dec. = $+00^{\circ}49'35.94''$ by ZTF. It was classified as an SLSN-I by ZTF based on a spectrum obtained on 2020 Feb. 22 [85]. SN 2019unb had two clear peaks and two clear dips with similar cadences (~ 45 days). SN 2019unb was previously considered as a possible candidate for modulation due to CSM interaction [7, 8].
3. SN 2021mkr: discovered [86] 2021 May 15 at R.A. = $1456^{\text{m}}52.570^{\text{s}}$, Dec. = $+60^{\circ}50'05.10''$ by ZTF. It was classified as an SLSN-I by ZTF based on a spectrum obtained on 2021 Aug. 09 [87]. SN 2021mkr had two clear peaks and one dip with a possible cadence of ~ 60 days. SN 2021mkr was previously considered as a possible candidate for modulation due to central-engine flares [12] or alternatively magnetic-inclination precession [13].

For each object, we downloaded publicly available ZTF data. The ZTF survey observes on a nightly basis using a dedicated camera mounted on the 48-inch Oschin Schmidt telescope at Palomar Observatory. We obtained subtracted and extracted magnitudes in the r and g bands preprocessed by the ZTF photometry reduction pipeline [88].

To model to these data, we incorporate the phenomenological magnetar+LT model constructed in [Methods 4](#). The procedure for fitting the candidate objects is identical to our method for fitting SN 2024afav.

The results of the fits are shown in [Main Figure 4](#). We find that our model is able to satisfactorily explain the modulations in the data with goodness-of-fit in the range of reduced $\chi^2 \approx 1.3\text{--}1.9$ ($N \approx 75\text{--}105$ data points, $k = 15$), and, as shown by [Extended Data Figure 5](#), estimates values for P_{spin} and B_{field} within normal ranges for SLSNe-I [51]. The key result is that the periodicity observed in the light curve for each object is well approximated by assuming Lense-Thirring precession of an accretion disk at the equilibrium radius, given the best-fit magnetar model parameters from the bulk behavior of the light curve. Successfully fitting the magnetar+LT model to legacy objects suggests SN 2024afav may not be a fluke or unique object, and this mechanism may be relatively common in young magnetars. However, multiple SLSNe-I have been followed to hundreds of days with moderate-cadence data [e.g., 89] without evidence of periodic modulations, which may have several explanations. First, the mechanism proposed here is not required to occur in every young magnetar system. Lack of fallback material or an insufficient accretion rate may prevent the formation of an accretion disk. Alternatively, an insufficient natal kick (or similar) may result in the disk forming with little to no tilt, resulting in no Lense-Thirring torque. Second, the intensity of the modulations is impacted by the diffusion timescale and inclination of the system relative to the observer line of sight, so for particular system configurations (e.g., spin axis parallel to the line of sight) no modulations will be visible. Additionally, our dataset is relatively unique in that, anticipating subsequent bumps, we maintained

the intense cadence across all LCO bands to capture them with a high signal-to-noise ratio and on a subdaily cadence. Had we only observed the first 2–3 bumps clearly—as is the case for most SLSNe-I with modulations (see, e.g., [\[7\]](#) or [\[13\]](#))—we would have been unable to disfavor completely periodic or aperiodic processes.

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