A repeating fast radio burst residing in a magnetar/Be star binary

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Fast radio bursts (FRBs) are mysterious cosmic sources emitting millisecond-duration radio bursts\textsuperscript{1}. Although several hundreds FRBs have been discovered\textsuperscript{2}, their physical nature and central engine remain unclear\textsuperscript{3–6}. The variations of Faraday rotation measure and dispersion measure, due to local environment, are crucial clues to understand their physical nature\textsuperscript{7,8}. The recent observations on the rotation measure of FRB 20201124A show a significant variation on a day time scale\textsuperscript{9}. The variable rotation measure demonstrates that FRB 20201124A is in a dynamic magneto-ionic environment\textsuperscript{9}. Intriguingly, the oscillation of rotation measure supports that the local contribution can change sign, which indicates the direction changes of the magnetic field along line of sight. Here we propose that this FRB resides in a binary system containing a magnetar and a Be star with a decretion disk. When the magnetar approaches the periastron, the propagation of radio waves through the disk of the Be star naturally leads to the observed varying rotation measure, depolarization, large scattering
timescale, and Faraday conversion. Searching for FRB signals from Be/X-ray binaries is encouraging.

FRB 20201124A was firstly detected by the Canadian Hydrogen Intensity Mapping Experiment (CHIME) on 24 November 2020\textsuperscript{[10]}. It has a dispersion measure (DM) of 413.52 pc cm\textsuperscript{−3}, larger than the Galactic DM contribution. This FRB is extremely active, with burst rate up to 50 per hour\textsuperscript{[9]}. Thanks to its repetition property, it was localized to a galaxy named SDSS J050803.48+260338.0 at $z = 0.098$ by Australian Square Kilometre Array Pathfinder (ASKAP)\textsuperscript{[11]}, the Five-hundred-meter Aperture Spherical radio Telescope (FAST)\textsuperscript{[9]}, VLA/realfast\textsuperscript{[12]}, and European VLBI Network\textsuperscript{[13]}.

FAST detected 1863 independent bursts in a total of 88 hours from 1 April to 11 June 2021, covering 1.0 GHz to 1.5 GHz\textsuperscript{[9]}. FAST observations discovered several previously unseen characteristics of repeating FRBs. First, this FRB shows dramatic Faraday rotation measure (RM) variations on a day time scale. The maximum variation of RM is about 500 rad m\textsuperscript{−2}. A small variation of RM ($\sim 1.8\%$) was also found from 20 bursts observed by the Effelsberg Radio Telescope\textsuperscript{[14]}. Second, it is the first repeating FRB that shows circular polarization. Third, it is the repeating FRB that has the widest mean burst width\textsuperscript{[15]}. These characteristics cannot be explained by current theoretical models. Interestingly, FRB 20201124A can be analogy to the pulsed emissions from the Galactic binary system PSR B1259-63/LS 2883\textsuperscript{[15]}, containing PSR B1259-63 and the Be star LS 2883. The pulsed emission of PSR B1259-63 also shows variations in its RM, DM, scattering timescale and polarized intensity on short time-scales when it approaches periastron (see Methods). We propose
that FRB 20201124A is produced by a magnetar orbiting around a Be star companion with a decretion disk. The interaction between radio bursts and the disk of Be star can naturally explain the observed unusual characteristics of FRB 20201124A. Interestingly, it has been argued that a highly magnetized neutron star in an interacting high-mass X-ray binary system can account for all of the observational phenomena of FRB 20180916B\cite{17}. A Be/X-ray binary system, which is composed of a neutron star and a Be star with a decretion disk can well explain the frequency-dependent active window of FRB 20180916B\cite{18}.

We attempt to explain the observed properties of FRB 20201124A using a physical model for the decretion disk of a Be star. It has generally been accepted that the presence of an equatorial disk of a Be star, supported by many observational evidences\cite{19}, such as double-peaked Balmer emission lines and infrared continuum excess (see Methods). We consider the rotationally supported, geometrically thin disk model with isothermal hydrogen gas. The density profile of a Be star disk can be described as\cite{19}

\[ \rho(r, z) = \rho_0 \left( \frac{r}{R_\star} \right)^{-\beta} \exp[-z/H(r)], \]

(1)

where \( r \) is the distance from the star, \( \rho_0 \) is the disk density at the stellar radius \( R_\star \), \( \beta \) is the density slope, \( z \) is the height, and \( H(r) \) is the scale height of the disk. Observational properties of Be stars are well described by the above disk model and the density slope \( \beta \) is constrained in the range \( 2 - 4 \)\cite{19}. The competition between the viscous torque and the resonant torque can result in disk truncation. For our model parameters, we find that the spread of the disk material can make the truncation inefficient in the classical viscous disk model (see Methods)\cite{20}.
The magnetic field, $B$, in the disk is poorly known. We assume that it is azimuthal and has a radial profile

$$B(r) = B_0(R_*/r),$$

with $B_0$ is the magnetic field strength at the stellar surface. This model can well explain the RM variation of PSR B1259-63/LS 2883\textsuperscript{16}. When the magnetar approaches the periastron, the emission of FRBs penetrates the free electrons in the disk. Given the above model, we can calculate the RM as a function of orbital phase. The RM contributed by the free electrons in the disk is

$$\text{RM} = 8.1 \times 10^5 \int_{\text{LOS}} n_e B_\parallel dl \text{ rad m}^{-2},$$

where $n_e$ is the free electron density in unit of cm$^{-3}$, $B_\parallel$ is the magnetic field along the line of sight in unit of Gauss, and $l$ is in unit of parsec. For the simple azimuthal magnetic field described above, we expect the RM contribution from the disk to change sign when the magnetar passes in front of the Be star, which is supported by FAST data.

Our model is shown in Figure 1. The Be star locates at the disk center. For the coordinate system, we set the Be star as the origin and fix the $x$-axis and $y$-axis on the disk. The orbit has an inclination $\phi$ with respect to the disk. Generally, magnetars are formed by supernova explosions. Supernova explosions are usually asymmetric and give large kicks to the newly formed magnetars\textsuperscript{21}. Due to the natal kick of the magnetar, the orbital plane and the disk plane is misaligned\textsuperscript{22}. From observations, the inclination angles have a wide range in Be star/X-ray binary systems, from 25$^\circ$ to 70$^\circ$\textsuperscript{23}. In our model, after the companion dies as a supernova, a magnetar is formed, leading to FRBs generated in the magnetar magnetosphere\textsuperscript{5,24}, which is supported by the FAST observations\textsuperscript{9}.
As the orbital motion of the binary, radio bursts from the magnetar pass through different components of the disk to reach the observer, which causes the variation of RM. When the pathway of radio bursts does not intersect the disk, a non-evolving RM is expected.

For the binary system PSR B1259-63/LS 2883, significant RM changes were observed both in magnitude and in sign before and after the 2004 periastron passage\textsuperscript{25}. Compared to the Galactic PSR B1259-63, the RM variation of FRB 20201124A is small. A thin disk is considered. We assume the density of the disk at the stellar surface $\rho_0 = 3 \times 10^{-14} \text{ g cm}^{-3}$ and $\beta = 4$, which are the typical value for disks of Be stars\textsuperscript{19}. The orbital period is assumed to be 80 days with orbital eccentricity $e = 0.75$. Using the disk model in equation (1) and the magnetic field profile in equation (2), we can reproduce the overall RM variation with time (see Methods). The derived RM variation is shown as the red line with magnetic field $B_0 = 10 \text{ G}$ at the stellar surface in Figure 2. This magnetic field strength is consistent with those derived from RM variation and Faraday conversion\textsuperscript{9}. The blue points is the mean observed RM variation $\Delta RM = \text{RM-RM}_c$ in a day. The value of $\text{RM}_c$ is taken as the constant RM value observed after MJD 59350. The blue shadow region is the range of $\Delta RM$.

Some dips and peaks of $\Delta RM$ are not well reproduced. The possible reason is that the disk is very clumpy both in density and/or magnetic field. From observations, a clumpy disk was required to explain the multi-wavelength observations of the Galactic binary system PSR B1259-63/LS 2883\textsuperscript{26,27}. The clumpy disk is also supported by numerical simulations. For example, a two-armed spiral density enhancement caused by the tidal interaction was found using three-dimensional
smoothed particle hydrodynamics simulation\cite{28}. From observations, stellar winds from massive stars are clumpy, with the clumping filling factor of \( f_c \sim 0.1 \).\cite{29} At present, there is no constraints on disk clumps. For simplicity, we assume that they are similar to the clumps in stellar winds, with no magnetic field clumps. The disk density inside the clumps is \( 1/f_c \) times that of the smooth disk. Because the space between the clumps is not empty, a process with the rate proportional to the \( n_e^2 \) can be described by the clumping factor \( f_c = \langle n_e^2 \rangle / \langle n_e \rangle^2 \). The detailed form of clumpy disk remains unknown, in particular, the spatial distribution of clumps. Using ad hoc clumps to fit the RM variation is less productive. So we discuss the effect of clumps on RM quantitatively. For the RM peak near MJD 59340, the observed value is about ten times larger than the prediction of the smooth disk. This implies the value of \( f_c \) is about 0.1 if only density clumps are considered, similar to that in stellar winds.

The disk also affect the DM and detection of radio bursts. In Figure 3 we show the DM and the optical depth due to the free-free absorption contributed by the disk (see Methods). The DM change shown as the blue line is small. The maximal change is 0.12 pc cm\(^{-3}\). FAST found no significant DM variation in a 95%-confidence-level\cite{9}, with an upper limit \( \Delta \text{DM} \leq 4.9 \text{ pc cm}^{-3} \). Therefore, the model prediction is consistent with FAST observations. Next, we consider the free-free absorption as a function of orbital phase. The optical depth \( \tau \) due to free-free absorption shown as the red line is less than unity. For typical parameters of the stellar wind, the DM and free-free absorption contributed by the stellar wind can be ignored (see Methods). The presence of disk clumps also affects the interaction with radio bursts. The dispersion measure and free-free absorption are enhanced by a factor of \( 1/f_c \sim 10 \) with respect to the case of a smooth disk\cite{30}. 
Form Figure 3 in the clumps, the maximum DM contribution is 4 pc cm$^{-3}$, which is less than the observed DM variation$^{29}$. After considering the disk clump, the optical depth of free-free absorption is less than 1. So the clumpy disk does not affect the detection of radio bursts. The induced Compton scattering could also affect radiation from sources with high brightness temperature$^{31}$. The induced Compton scattering due to the disk is also estimated to be small, and does not affect FRB detection (see Methods). Therefore, the disk is transparent to the radio signal, and has no effect on the detection of FRBs.

The observations show that some bursts have low polarization (e.g., $P/I < 40\%$) before MJD 59350. After this time, all the bursts have large polarization. The observed pulse depolarization is attributed to random fluctuations in the magnetic field and/or electron density in the disk, which can cause differential Faraday rotation along different paths of the light rays$^{32}$. If the Faraday dispersion function is well described by a Gaussian distribution with variance $\sigma^2 = k^2 \langle \delta(RM)^2 \rangle$, the measured polarized intensity can be parameterized as

$$P(\lambda^2) = P_i \exp[-2k^2 \langle \delta(RM)^2 \rangle \lambda^4],$$

where $P_i$ is the intrinsic polarized intensity, $\lambda$ is the observing wavelength, $k = 0.81$ is a constant, and $\langle \delta(RM)^2 \rangle^{1/2}$ is the variance in $\Delta RM$. For simplicity, we assume that $\langle \delta(RM)^2 \rangle^{1/2}$ arises from fluctuations in free electron density $n_e$. Furthermore, we assume that the variance of electron density $n_e$ satisfies $\langle \delta n_e^2 \rangle^{1/2} \propto n_e$ in the disk$^{33}$, which is similar to the small-scale turbulence in the interstellar medium. Letting $\langle \delta(RM)^2 \rangle^{1/2} = f \Delta RM$, the stochastic Faraday rotation leads to the depolarization when $|\Delta RM| > f^{-1} \lambda^{-2}$. From the FAST observation, the value of $|\Delta RM|$ is about 200 rad m$^{-2}$ at frequency 1.25 GHz. Therefore, $f \sim 0.1$ is derived. We conclude that stochastic
Faraday rotation may be responsible for the observed depolarization.

The mean burst width of FRB 20201124A is larger than the widths of other known repeaters. From the CHIME observation, the largest scattering timescale of FRB 20201124A is 14 ms. The fluctuations of the electron density in the disk can cause scatter broadening of the pulses. The electron plasma with density fluctuations of $\delta n_e$ and spatial scale $a$ produces a typical scattering angle at wavelength $\lambda$ of

$$\theta_s = \frac{1}{2\pi} \left( \frac{L}{a} \right)^{1/2} r_0 \lambda^2 \delta n_e,$$

where $r_0$ is the classical electron radius and thickness of the screen $L$ is assumed to be roughly equal to its distance $d$ from the magnetar. If the scattering is due to a thin screen at a distance $r_s$ from the magnetar, the scattering angle $\theta_s$ is $(2\tau_s c / r_s)^{1/2}$, with the scattering time $\tau_s$. We use the burst 20210405B with scattering time $\tau_s = 12.17$ ms detected by CHIME to estimate the spatial scale $a$. The distance between the burst and the screen is about 42 solar radius. Therefore, the scattering angle is $\theta_s \sim 0.9^\circ$. From equation (5), the density fluctuation of electron plasma in the disk is $\delta n_e = 80a^{1/2} \text{ cm}^{-3}$. If we set $\delta n_e$ equal to the total electron density $n_e$ in the scattering region. From the disk model, this is $3.9 \times 10^6 \text{ cm}^{-3}$, implying that $a \sim 2.4 \times 10^9 \text{ cm}$.

For non-repeating FRBs, variations in both linear and circular polarization have been observed. However, previous observations show that repeating FRBs only have high degrees of linear polarization. FRB 20201124A is the first one showing high circular polarization. For the Galactic binary system PSR B1259-63/LS 2883, the linear and circular polarizations varied rapidly in an hour timescale near the periastron. Physically, besides Faraday rotation, FRBs propagate through...
magneto-ionic environment can also lead to Faraday conversion. In addition, a fraction of circular polarization of FRB 20201124A is produced by radiation mechanism. There are two mechanisms to generate Faraday conversion. The first case is that radio signals propagate into a relativistic plasma. The second case is that the magnetic field quasi-perpendicular to the wave vector is large, which had been used to interpret the circular polarization observed in solar radio bursts.

For the first case, interactions between the relativistic wind of the magnetar and the low-velocity wind from the Be star can form a termination shock, which accelerates electron and positron pairs from the magnetar wind to relativistic velocities. Because electrons and positrons contribute with the opposite sign to the circularly polarized component, the different distributions of electrons and positrons are required to generate circular polarization. In our model, weak magnetar wind is considered. Therefore, the termination shock may be absent. For the binary system PSR B1259-63/LS 2883, the minimum Lorentz factor of the shocked electrons is estimated as $10^5$. From the accurate calculations, the exact Faraday conversion is found to approach zero with the increasing electron energy, because ultra-relativistic electrons hardly interact with radiation field. When the magnetar is in front of the Be star, FRB signals cannot interact with the plasma shocked by the termination shock, leading to no conversion. So, the Faraday conversion due to relativistic plasma is hard to account for the observed circular polarization (see Methods).

Next we use the magnetic field quasi-perpendicular to the wave vector to explain the origin of circular polarization. When the cyclotron frequency is approaching the observation frequency, the Faraday conversion will take effect. From the FAST observations, the required magnetic field $B_\perp$ is about 7 Gauss for Faraday conversion, which is the same order of the parallel magnetic
field $B_\parallel$. This mechanism naturally explains the circular polarization of FRB 20201124A. FAST observations indicate that the Faraday conversion occurs in the RM variation stage (e.g., bursts 779 and 926). When the RM variation stopped, the circularly polarized bursts lack quasiperiodic structures (e.g. Burst 1472). There is no Faraday conversion. This is consistent with the prediction of our model. For the above orbital parameters, the observed Faraday conversion appears when bursts’ paths penetrate the disk. When the pathway of radio bursts does not intersect the disk, the RM variation stopped. Meanwhile, there is no perpendicular magnetic field required for Faraday conversion.

Using a model for a Be star disk with a power-law radial dependence on the electron density and magnetic field, we can naturally explain the mysterious features of the FRB 20201124A. We conclude that the disk density is $\rho_0 = 3 \times 10^{-14}$ g cm$^{-3}$ close to the star and has a steep-decay index $-4$ as a function of radius. This model provides a good fit to the variation of RM with a magnetic field of 10 Gauss at the stellar surface. This field, together with the strong electron density fluctuations implied by the scattering observations, accounts for the observed depolarization of the pulses by differential Faraday rotation along different scattering paths. The magnetic field perpendicular to the wave vector in the disk, having the same order of the magnetic field along the line of sight, can generate the observed circular polarization. Recent observations show that the RM of FRB 20190520B is rapidly varying with two sign changes\cite{19,19}, with magnitude similar to that of PSR B1259-63/LS 2883. The sinusoidal-like form of RM variation emerges. A dense magnetized screen near the FRB source can account for the RM variation and depolarization\cite{19}. In our model, the distance of the screen is of order the separation of the two stars. For orbital period $P = 600$ d,
our model can well explain the RM variation of FRB 20190520B, which is shown in supplementary figure 1 (see Methods). The semimajor axis can be derived as \( a = \left( \frac{G M_T P^2}{2\pi} \right)^{1/3} \sim 8.5 \text{ AU} \), where \( M_T \sim 30M_\odot \) is the total mass of the binary. Our model predicts the RM evolution would be quasi-periodic. When enough number of RM detections spanning a long timescale is accumulated, the orbital period could be derived from these RM data by the timing analysis. LS I + 61°303 is a Be gamma-ray binary with similar orbital period and eccentricity as our model. Recent observations indicates that it may be a magnetar/Be star binary\[^{40,41}\]. Our work will encourage searching for FRB signals from it.

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Author Contributions  
F.Y.W. conceived the idea. G.Q.Z. performed the RM fit with the help of F.Y.W. . Z. G. D. and K. S. C. joined the model discussion. F. Y. W. wrote the draft, with contributions from G.Q.Z., Z. G. D., and K. S. C.

Data availability  
The data that supports the findings of this study are available from the corresponding
authors on reasonable request.

**Competing Interests**  The authors declare that they have no competing financial interests.
Figure 1: A schematic diagram of the magnetar/Be star binary model. (a) The Be star locates at the center of the disk. The magnetar is shown as the red point. The stellar disk is inclined to the orbital plane with the angle $\phi = \pi/12$. The purple dash line is the major axis of the magnetar’s orbit. When the pathways of radio bursts pass through the disk, the interaction between bursts and disk can reproduce the observed variable rotation measure, depolarization, large scattering timescale, and Faraday conversion. (b) The face-on view of the Be star’s disk. The magnetic field is assumed as azimuthal (or toroidal) in the disk. This model predicts that the RM contribution from the disk changes sign when the magnetar passes in front of the Be star. The RM variation discovered by FAST supports this scenario.
Figure 2: **The fit of RM using the binary model.** The blue scatter is the mean of observed $\Delta RM$ in day, and the red line is the predicted evolution of our model. The blue shadow region is the range of observed RM. In the calculation, the disk density is $\rho_0 = 3 \times 10^{-14}$ g cm$^{-3}$ close to the star and has a steep-decay index $\beta = 4$. The orbital period is taken as 80 days with orbital eccentricity $e = 0.75$. Our model can reproduce the main structure of RM evolution. However, there are some minor structures can not be reproduced. These minor structures may be caused by the clumps in the disk.
Figure 3: The DM and free-free absorption optical depth $\tau$ contributed by the disk. The same model parameters as Figure 2 are used. The DM variation shown as the blue line is small, which is consistent with the FAST observation. The optical depth due to free-free absorption by the disk denoted as the red line is much less than 1. So the existence of disk has no effect on the detection of radio bursts.
Methods

**PSR B1259-63/LS 2883** PSR B1259-63/LS 2883 is a binary system hosting a radio pulsar and a high-mass \((M_\star \geq 10M_\odot)\) Be star LS2883. The pulsed radio emission gives the spin period of the pulsar is \(P = 47.76\) ms with a spin-down power of \(L_{\text{sd}} \approx 8 \times 10^{35}\) erg/s\(^{42}\). It lies at a distance of 2.6 kpc away from the Earth\(^{33}\). The pulsar is in a highly eccentric \((e \sim 0.9)\) orbit around the LS2883 with a period of 1237 days\(^{32,44}\) ranging from 13\(^{\circ}\) to 64\(^{\circ}\). The LS2883 is an early Be type star that possesses a significant stellar wind and an equatorial excretion disk\(^{42}\). There is evidence that the Be-star disc is highly inclined to the orbital plane both from the pulsed emission\(^{33,16}\), the unpulsed emission\(^{47}\), and timing measurements\(^{48}\).

The pulsar generates a powerful pulsar wind that interacts with the stellar wind or disk near the periastron, emitting non-thermal, unpulsed radiation, in radio\(^{42}\), X-rays\(^{49}\), GeV\(^{50,51}\), and TeV \(\gamma\)-rays\(^{52}\). The light curves show double-peak profiles in the radio, X-ray, and TeV \(\gamma\)-ray bands, which are believed to be attributed to the pulsar radiation passage through the dense disk regions\(^{53}\).

There are four pulsed radio observations near periastron passages in the year of 1994\(^{16}\), 1997\(^{30}\), 2000\(^{54}\) and 2004\(^{25}\). When the pulsar approaches the periastron, the pulsed emissions of PSR B1259-63 show large changes in its flux, degree of linear polarization, dispersion measure and rotation measure on short time-scales\(^{16,25,54}\). These parameters’ variations can be well understood in the model that the pulsed emissions interact with the Be star disk\(^{16,33}\). The properties of pulsed emissions, such as degree of linear polarization, dispersion measure and rotation measure, are similar for the four periastron passages\(^{35}\).
**Disk properties** There is spectral-line evidence for disks around Be stars in general\(^{55}\) and LS 2883 in particular\(^{55}\). By combining interferometry with polarimetry data, an upper limit of 20° for the disk opening angle of Be stars is derived\(^{56}\). The physical size of a Be disk is hard to be measured from observations. From optical long baseline interferometry observations, the disk size is from a few star radius to a few tens star radius\(^{19}\). Observational properties of Be stars can be well described by a radial power-law density form. The density of the disk near stellar surface lies in the range between about 10\(^{-13}\) to a few times 10\(^{-10}\) g cm\(^{-3}\)\(^{19}\). In order to interpret the DM and RM evolution of the 1994 periastron passage of PSR B1259-63/LS 2883, a low value \(\rho_0 \sim 10^{-16}\) g cm\(^{-3}\) was found\(^{33}\).

The classical formation channel of Be/X-ray binaries (or magnetar/Be star binaries) is as follows. In an interacting binary, the B type star accretes matter and angular momentum from the companion star. Therefore, the B star is spun up to nearly break-up velocity, leading to the formation of a decretion disk, which is supported by observations\(^{57}\). At this stage, the orbit and disk are very close to co-planar, such as seen in the classical Be+sdO system phi Per\(^{58}\). In magnetar/Be star binaries, the companion is a compact magnetar, which is usually formed by supernova explosion. Supernova explosions are asymmetric and give very large kicks to the newly formed magnetars\(^{21,59}\). Due to the natal kick of the magnetar, the orbital plane and the disk is misaligned. Besides, the kick from the supernova also makes the orbit eccentric, and even unbinds the binary\(^{23,60}\).

From observations, some Be/X-ray binaries have been found to be high misaligned\(^{23}\). For the Galactic binary PSR B1259-63/LS 2883, there are many works to estimate the inclination angle between the orbital plane and the disk plane via several methods from observations. The
inclination angle is found to be $10^\circ \sim 40^\circ$ by fitting to the observed variations in DM and RM of PSR B1259–63\textsuperscript{13}. Using the XMM–Newton and ASCA X-ray data of PSR B1259-63, the derived inclination angle is about $70^\circ$\textsuperscript{61}. The inclination angle of PSR B1259-63/LS 2883 system is about $25^\circ$ from the optical spectra of LS 2883\textsuperscript{62}. Using the 23 yr of pulsar timing data, the inclination angle is found to be $35^\circ$\textsuperscript{44}.

**The effect of tidal forces on the disk.** The tidal force of magnetar could affect the disk\textsuperscript{63}. The process of disk truncation in Be/X-ray binaries was first discussed in 1997 from the orbital period-H$\alpha$ equivalent width diagram\textsuperscript{64}. From observations, 26 Be stars with sufficient data show disk truncation signature\textsuperscript{65}. Among them, six Be stars are known to have close binary companions in circular orbits\textsuperscript{65}. In the classical viscous disk model\textsuperscript{20}, the criterion for disk truncation at a given resonance radius can be written as

$$T_{\text{vis}} + T_{\text{res}} \leq 0,$$

where $T_{\text{vis}}$ and $T_{\text{res}}$ are the viscous torque and the resonant torque, respectively. Using standard formulae of $T_{\text{vis}}$ and $T_{\text{res}}$\textsuperscript{66}, the criterion $T_{\text{vis}} + T_{\text{res}} \leq 0$ is met for $\alpha$ (viscosity parameter) smaller than a critical value. For subsonic outflows, the drift time-scale is $\tau_{\text{drift}} \sim \Delta r/v_r$, where $v_r$ is the radial velocity, and $\Delta r$ is the gap size between the truncation radius and the radius where the gravity by the magnetar begins to dominate. The spread of the disk can make the truncation inefficient for a system with $\tau_{\text{drift}}/P_{\text{orb}} = \Delta r/0.1c_sP_{\text{orb}} < 1$. For a typical value $\alpha = 0.1$, $\tau_{\text{drift}}/P_{\text{orb}} \sim 0.1$ in our model, which supports the truncation effect is inefficient. This conclusion is consistent with that of Okazaki & Negueruela (2001). In their paper, they concluded that disk truncation is inefficient in systems with high orbital eccentricity. This conclusion has been confirmed by
numerical simulations. For misaligned Be/X-ray binary systems, the SPH simulations show that Be star disks are not truncated in highly eccentric binaries, unlike truncated Be disks in binaries with circular orbits\(^2\(^8\)\). In addition, the disk may be warped by the tidal force\(^2\(^8\)\), leading to non-smooth distributions of density and magnetic field in the disk. This is the possible reason to cause some dips and peaks in RM variation (Figure 2). The spread of the disk could cause the density of the disk outer part thinner, compared to last periastron. Therefore, the variation of RM will become smaller in magnitude over time.

Besides the tidal force, the magnetar wind may also affect the disk. In our model, the radio bursts can be powered by the magnetic-energy release of the magnetar. The magnetar wind may be weak, similar to that of Galactic magnetars (i.e., SGR 1935+2154). Strong magnetar winds can produce a bright, compact persistent radio source associated with FRB\(^6\(^7\)\(^8\)\), which has been observed in FRB 20121102A\(^5\(^9\)\) and FRB 20190520B\(^7\(^0\)\). However, there is no compact persistent radio emission associated FRB 20201124A\(^1\(^3\)\). The extended radio emission around FRB 20201124A is attributed to star-formation activity\(^1\(^1\)\(^1\)\(^2\)\).

**RM evolution** Compared to the Galactic PSR B1259-63, the RM variation of FRB 20201124A is small. We consider a thin disk by assuming \(\rho_0 = 3 \times 10^{-14} \text{ g cm}^{-3}\), and \(\beta = 4\). The radius and mass of Be star is taken as \(R_\star = 5R_\odot\) and \(M_\star = 8M_\odot\). Typical velocities of the plasma in the disk are \(v_d \sim 150 – 300 \text{ km s}^{-1}\). The vertical scale height is derived from

\[
H(r) = c_s \left( \frac{r}{GM_\star} \right)^{1/2} r, \tag{7}
\]
where $c_s$ is the sound speed and $M_*$ is the mass of the Be star. For isothermal gas, the sound speed is $c_s = (kT/\mu m_H)^{1/2}$, where $T$ is the isothermal temperature, $\mu$ is the mean molecular weight, and $m_H$ is the proton mass. We assume the disk is pure hydrogen disk $\mu = 1$ and the isothermal temperature is $T = 10^4$ K. The circular polarization may be caused by Faraday conversion, which requires a strong magnetic field. We assume the magnetic field $B_0 = 10$ G. As shown in Figure 2, the RM variation is very complex. In order to prevent that the disk is significantly truncated by tidal forces, we consider a large eccentric orbit with $e = 0.75$. In our model, the RM variation is largely affected by the orbital motion. We assume the orbit period is $P = 80$ days. Then the semi-major axis can be derived from

$$a_0 = \left( \frac{G(M_* + M_{NS})P^2}{4\pi^2} \right)^{1/3}, \quad (8)$$

where $M_{NS} = 1.4M_\odot$ is the mass of magnetar. To match the observed RM evolution, we assume that the inclination angle is $\phi = \pi/12$ and the observer’s direction is $\theta = 3.08, \phi = 2.18$. From observations, the surface magnetic field of Be stars has been measured. The magnetic field in the longitudinal direction is between 2 and 300 Gauss for 15 Be stars\textsuperscript{73}. From a large sample of 60 Be stars, the maximal surface magnetic field 4000 Gauss was derived\textsuperscript{74}. Therefore, the value of $B_0 = 10$ G is well in the allowed range.

The corresponding DM contribution of the disk is

$$\text{DM} = \int_{\text{LOS}} n_e dl. \quad (9)$$

In the observations, FAST can detect FRB signals. Therefore, the optical depth due to free-free
absorption

\[ \tau = 8.2 \times 10^{-2} T^{-1.35} \nu^{-2.1} \int_0^d n_e^2 dl \]  

(10)
of free-free absorption must be less than unity. In the above equation, \( T \) is the temperature in Kelvin, \( \nu \) is the observing frequency in GHz, and \( d \) is the distance to the pulsar (in pc) and \( n_e \) is the free electron density along the line of sight. The same parameters for the disk is used to calculate the DM and optical depth. The results are shown in Figure 3. The variation of DM is so small that we can ignore it safely. Because we use a sparse disk, the optical depth is also very small. It doesn’t affect the detection of FRBs.

The induced Compton scattering is crucial for high brightness temperature source. In our model, the scattering occurs in the nearest vicinity of the source. For a single narrow beam of uniform brightness and solid angle \( \Delta \Omega \), the effective optical depth is

\[ \tau_{\text{ind}} = \frac{kT_B}{m_e c^2} (\Delta \Omega^2) \tau_t, \]  

(11)
where \( T_B \) is the brightness temperature, and \( \tau_t = n_e(r) \sigma_T r \) is the Thompson scattering optical depth. For radio bursts with millisecond duration \( w \) and Jy flux \( S \) occurring at redshift \( z = 0.098 \), the brightness temperature is

\[ T_B = S d^2 / 2k(\nu w)^2 \sim 6.6 \times 10^{30} \frac{S}{\text{Jy}} \left( \frac{\nu}{\text{GHz}} \right)^{-2} \left( \frac{w}{\text{ms}} \right)^{-2} \left( \frac{d}{450 \text{Mpc}} \right)^2. \]  

(12)
The radiation subtends a solid angle \( \Delta \Omega = \left( c w / r_d^2 \right) \sim 10^{-10} \) with the distance \( r_d = 50R_\odot \) between the magnetar and the disk. If we assume radio bursts travel at distance \( 2R_\star \) away from the Be star, using the base density \( 5 \times 10^{-14} \) g cm\(^{-3} \) of the disk and equation (11), we can estimate \( \tau_{\text{ind}} \) is 0.025, which is much less than one. Therefore, the radio bursts can escape from the disk.
We also use our model to explain the RM variation of FRB 20190520B. The fitting result is shown in supplementary figure 1. The change-sign RM variation can be well reproduced. The parameters are $\rho_0 = 8 \times 10^{-13} \text{ g cm}^{-3}$, and $\beta = 3$. The radius and mass of the Be star is taken as $R_\star = 10R_\odot$ and $M_\star = 30M_\odot$. The magnetic field strength at the surface of the Be star is 100 G. These values are allowed from observations of Be stars. The period of orbit is 600 d and the eccentricity is $e = 0.75$. The period is similar as that of the binary PSR B1259-63/LS 2883. Other parameters are the same as those used in figure 2.

**The effect of stellar wind** Massive stars usually have large wind mass loss, which strongly depends on the stellar effective temperature. We also consider the effect of stellar wind on DM and free-free absorption. For isotropic winds, the number density of the wind is given by

$$\rho_{\text{wind}} = \rho_{0,\text{wind}} (r/R_\star)^{-2}, \quad (13)$$

where $r$ is the radial distance from the center of the Be star. The stellar surface density is $\rho_{0,\text{wind}} = \dot{M}/4\pi R_\star^2 v_w$ with mass loss rate $\dot{M}$ and wind velocity $v_w = 3 \times 10^8 \text{ cm s}^{-1}$. From observations, the mass loss rate of Be stars has been estimated to be $10^{-11} - 10^{-8} M_\odot \text{ yr}^{-1}$. A typical value $\rho_{0,\text{wind}} = 4.18 \times 10^{-17} \text{ g cm}^{-3}$ is adopted, which corresponds the mass loss rate $3 \times 10^{-10} \text{ M}_\odot \text{ yr}^{-1}$. The ratio of the mass flux density in the disk over the stellar wind is

$$\frac{\rho_{0\nu_d}}{\rho_{0,\text{wind}} v_w} \sim 80, \quad (14)$$

which is well in range of 30-100.

Because of adiabatic cooling, the wind temperature decreases slowly with radial distance from the star. The temperature of stellar wind follows a power-law evolution due to adiabatic
cooling\textsuperscript{80}

\[ T_{\text{wind}} = T_{0,\text{wind}} (r/R_*)^{-\beta_1}. \]  

(15)

In our calculation, we use the effective temperature of star \( T_{0,\text{wind}} = 3 \times 10^4 \) K and \( \beta_1 = 2/3 \). In this case, the maximum DM\(_w\) and \( \tau_w \) contributed by the stellar wind are 0.54 pc cm\(^{-3}\) and 0.005, respectively. Based on these results, the contribution of stellar wind can be safely ignored. We are not aware of magnetic field measurements in the winds of massive stars. For the Galactic PSR B1259-63, the RM variation cannot be explained by the contribution from stellar wind\textsuperscript{33}. The geometry of magnetic field in stellar winds may be toroidal\textsuperscript{33,81}. Therefore, the radio burst propagates orthogonally to the toroidal magnetic field in a significant fraction of the orbit, which contradicts the observed RM evolution.

Below, we compare the magnetic field in the pulsar wind and in stellar disk. Since the magnetic field is dipolar inside the magnetar light cylinder, \( r_{\text{LC}} = 5 \times 10^9 P_{m, s} \) cm, and toroidal (\( \propto r^{-1} \)) in the wind, the magnetic field strength at a distance \( r \) is

\[ B_{\text{wind}} = 230 B_{14} P_{s}^{-3} (5 \times 10^9/r) \text{ G}, \]  

(16)

for the period of magnetar \( P_m = 2 \) s. We make the comparison at the same radius \( r = 2R_* = 10R_\odot \). \( B_{\text{wind}} = 0.9 \) G is less than the magnetic field in the disk. Therefore, the magnetic field in the disk dominates.

**Origin of circular polarization** FRB 20201124A is the first repeating FRB with significant circular polarization as discovered by FAST\textsuperscript{9} and Parkes\textsuperscript{82}. Two possible mechanisms can cause Faraday conversion: linearly polarized light is converted to circularly polarized one and vice versa.
The polarization measurement of FRB 121102 has been used to constrain the local magneto-ionic environment using Faraday conversion\(^8\).  

First, we consider that the circular polarization arises from the propagation through mildly relativistic plasma. For the PSR B1259–63/LS 2883, X-ray, GeV gamma-ray and Tev gamma-ray radiations have been observed. The natural physical mechanism for these high-energy emissions are as follows. The interactions between the relativistic wind of the pulsar and the low-velocity wind from the Be star will form a termination shock. The electron and positron pairs from the pulsar wind are accelerated to relativistic velocities by the terminal shock and emit broadband non-thermal emission through synchrotron radiation and inverse Compton scattering. In our model, a terminal shock may be not exist, due to the weak magnetar wind.  

If only the relativistic plasma is considered, the change of polarization angle is

\[
\Delta \phi = \frac{1}{2} \text{RRM} \lambda^3, \quad (17)
\]

where RRM is the relativistic rotation measure (RRM), and \(\lambda\) is the observed wavelength. We assume a power-law distribution for accelerated particles

\[
N(\gamma) = N_0 \gamma^{-p}, \quad \gamma_{\text{min}} \leq \gamma \leq \gamma_{\text{max}},
\]

(18)

where \(\gamma_{\text{min}}\) and \(\gamma_{\text{max}}\) are minimum Lorentz factor and maximum Lorentz factor, respectively. For the power-law index \(p \neq 1\), the normalization factor is \(N_0 = n_r(p - 1)(\gamma_{1}^{1-p} - \gamma_{2}^{1-p})^{-1}\) with the number density \(n_r\) of the relativistic particles. The definition of RRM is\(^8\)

\[
\text{RRM} = \frac{\varepsilon_0 e^4}{4\pi^3 m_e^3 c^4} \frac{p - 1}{p - 2} \int n_r(B \sin \theta)^2 \gamma_{\text{min}} ds. \quad (19)
\]
The fraction of circular polarization is $\Pi_c = \text{RRM} \lambda^3$ for the relativistic plasma dominated case. For relativistic plasma, the definition of DM is $\text{DM} \times D^{86}$, with Doppler factor $D = [\gamma(1 - v/c \cos \theta)]^{-1}$. $\theta$ is the angle between the line of sight and the direction of plasma motion. The RRM effect should require $n_e \ll n_r \gamma_1 \ln(\nu/f_c \gamma_1)$.

For the 1994 periastron passage of PSR B1259-63, the changes of DM and RM can not be explained in the termination shock model. The observed changes of DM in four periastron passages of PSR B1259-63 is roughly consistent with the contributions from the disk and wind of Be star, with the disk component dominated. Therefore, the cold plasma dominates the wave properties. The RRM effect is very weak. When the magnetar is in front of the Be star, radio bursts cannot interact with the plasma shocked by the termination shock. Therefore, there is no Faraday conversion, which is disfavored by the FAST observations.

Numerically, the approximated Faraday conversion coefficient is

$$\rho_Q = 8.5 \times 10^{-3} \frac{2}{p - 2} \left[ \frac{\omega}{f_c \sin \theta \gamma_{\min}^2} \right]^{(p-2)/2} - 1 \left[ \frac{p - 1}{\gamma_{\min}^{1-p}} \left( \frac{f_c \sin \theta}{\omega} \right)^{\frac{p+2}{2}} \frac{2\pi}{\omega} \right]^2,$$

where $\omega = 2\pi \nu$, $f_c = eB/m_e c$ is the cyclotron frequency, $\theta$ is the angle between wave vector and the line of sight. This approximation approaches zero if $\gamma_{\min} \geq 200$. In supplementary figure 2, the approximation of Faraday conversion coefficient $\rho_Q$ as a function of $\gamma_{\min}$ is shown. In the calculation, $\theta = \pi/4$ and $p = 2.3$ are used. The exact Faraday conversion coefficient is found to approach zero when $\gamma_{\min}$ is large. In order to explain the high-energy emission from the Galactic binary system PSR B1259-63/LS 2883, an extreme large $\gamma_{\min} \sim 10^5$ is required. Therefore, the relativistic plasma is hard to generate the observed circular polarization, unless the minimum
Lorentz factor is less than 100.

Next we consider the Faraday conversion occurring when the magnetic field is perpendicular to the wave propagation direction. The required magnetic field for Faraday conversion is about $7 \, \text{G}^{[9]}$, which is the same order of the magnetic field strength along the line of sight. The Be star disk can provide the required vertical magnetic field. This is the most natural way to explain the production of circular polarization.

Candidates of magnetar/Be star binary. There are two candidates of magnetar/Be star binary. The first one is LS I + 61° 303$^{[10]}$. The second questionably one is SGR 0755-2933, which is also referred to as 2SXPS J075542.5-293353$^{[10]}$. LS I + 61° 303 is a Be gamma-ray binary, with period about 26.496 d and a high eccentric orbit ($e=0.537^{[10]}$). The mass of the Be star in this binary is about 13 $M_{\odot}$. Some energetic, magnetar-like bursts have been plausibly ascribed to it$^{40,91}$. More recently, using observations with FAST, transient radio pulsations from the direction of LS I + 61° 303 were found$^{[11]}$. The pulsation period is 269 ms, which strongly supports the existence of a rotating neutron star in this binary$^{[11]}$. So the magnetar/Be binary used in this paper is close to LS I + 61° 303. They have similar orbital period and eccentricity. Searching for FRBs from LS I + 61° 303 is attractive. From FAST observation, the pulsations are not present in three out of four observations, which indicates a rapid change of the plasma properties along the line of sight. Possible reasons include interstellar scintillation, intrinsic nulling of the pulsar and changes in the stellar wind properties$^{[11]}$. Because the brightness temperatures of FRBs are much higher than that of pulsations$^{[1]}$, the induced Compton scattering may be significant$^{[11,75]}$.  

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However, no FRB-like signal from the two systems has been reported. The possible reasons are as follows. Firstly, FRBs are rare phenomena. They may be highly beamed and have narrow spectra, making them hard to discover. For example, more than 20 magnetars have been discovered in our Galaxy. Only FRB 200428 emitted from SGR 1935+2154 has been discovered. A bright X-ray burst is associated with FRB 200428, which has a strikingly different spectrum from other X-ray bursts. FAST observed SGR 1935+2154 for eight hours in its active phase. 29 X-ray bursts are detected, but no FRBs coincident with the bursts. Secondly, the high brightness temperatures of FRBs require that the emission process mechanism must be coherent. The physical conditions required to produce coherent radiation in magnetars may be hard to satisfy. Thirdly, the burst rate of FRBs deviates from Poissonian and varies significantly. For FRB 20201124A, FAST found a sudden quenching of burst activity. No burst is detected during the 9 hr of observations after 2021 May 29. If similar active properties of FRBs generated in magnetar/Be star binaries, enough and proper-time observations should be performed to search FRB signals from them.
Supplementary Figure 1: The fit of RM evolution for FRB 20190520B using the binary model. The blue points are the observed RM, and the red line is the fit. The RM is dominated by the disk, and other parts’ contributions are assumed to be zero. In the model, the disk density is \( \rho_0 = 8 \times 10^{-13} \text{g/cm}^3 \) with a steep-decay index of -3. The mass of the Be star is assumed to be \( 30 M_\odot \) with radius \( R_* = 10 R_\odot \). The magnetic field at the stellar surface is 100 G. The orbital period is taken as 600 d with orbital eccentricity \( e = 0.75 \).
Supplementary Figure 2: Faraday conversion coefficient $\rho_Q$ distribution as a function of minimum Lorentz factor $\gamma_{\text{min}}$. An electron column density of $N_e = 1$ pc cm$^{-3}$ is assumed. The plot uses $\nu = 1.25$ GHz, $\theta = \pi/4$ and $p = 2.3$. Faraday conversion only takes effect for $\gamma_{\text{min}} < 200$. 
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