# What's powering the magnetar wind nebula around Swift J1834.9-0846?

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## Introduction

The confirmation of the first-ever wind-nebula[1] around the magnetar Swift J1834.9−0846 presents a rare opportunity to study the global energetics of magnetars and the properties of their particle wind or outflows, both in quiescence and during outbursts. X-ray bright wind-nebulae are often observed around young pulsars, with spin-down power $L_{\rm sd} = f B_s^2 R_{\rm NS}^6 \Omega^4 c^{-3} \gtrsim 10^{36.3}$ erg s$^{-1}$ [$f \sim O(1)$], that are still embedded in their host supernova remnants (SNRs).They radiate over a broad energy range (radio to TeV $\gamma$-rays) part of the power injected by their central pulsars in the form of a relativistic MHD wind.

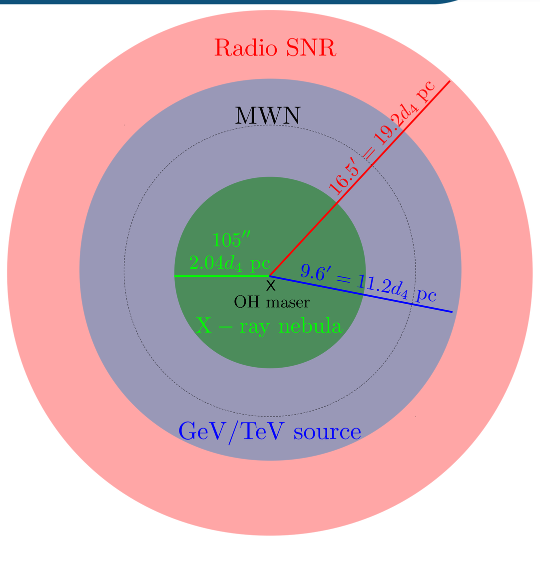



Fig. 1: Physical setup of the system

Magnetars are slowly rotating NSs, with periods $P \sim 2-12$ s and period derivatives $\dot{P} \simeq 10^{-13} - 10^{-11}$ $s\,s^{-1}$, but with high inferred surface dipole magnetic fields $B_s \simeq 10^{14-15}$ G. Although their small characteristic ages ($\tau_c \sim 10^{3-5}$ yr), would suggest otherwise, their low spin-down power ($L_{\rm sd} \simeq 10^{30-34}$ erg s$^{-1}$) cannot power a canonical pulsar wind-nebula (PWN).

Swift J1834.9−0846 has emerged as a unique case where X-ray observations unequivocally show it to be the underlying source powering the surrounding X-ray nebula. At a distance of $d = 4d_4$ kpc it is located very close to the center of the SNR and also a Fermi/H.E.S.S detected GeV/TeV region[2] (see Fig. 1). In this work, we argue that the high X-ray efficiency ($\eta_X = L_{X,\rm MWN}/L_{\rm sd} \simeq 0.13 d_4^2$) of the magnetar wind nebula (MWN) can only be supported if the power supplied by the magnetar's quiescent MHD wind is heavily supplemented by outflows during bursts. From its measured rotational properties ($P = 2.48$ s, $\dot{P} = 7.96 \times 10^{-12}$ $s\,s^{-1}$), the inferred surface field $B_s = 1.16 \times 10^{14} f^{-1/2}$ G and $L_{\rm sd} = 2.05 \times 10^{34}$ erg s$^{-1}$. Its characteristic age, assuming magnetic dipole radiation spindown, $\tau_c = 4.9$ kyr is smaller by a factor $\sim 2-20$ as compared to the age of its host SNR W41, $t_{\rm SNR} \approx 10-100$ kyr.

## Energetics of the X-ray Nebula

The relativistic electrons injected into the MWN cool via synchrotron emission, producing X-rays detected (by NuSTAR) up to $E_X = 30$ keV from the MWN. The confinement condition for accelerating electrons in the inner nebula gives a maximal energy corresponding to the voltage across the open field lines emanating from the neutron star's polar cap, yielding a strong constraint on the nebular magnetic field

$$B > B_{\rm min} = \frac{m_e^3 c^6 f E_X}{\hbar e^3 L_{\rm sd}} \simeq 11\, f E_{30\rm keV}\ \mu{\rm G}\,. \qquad (1)$$

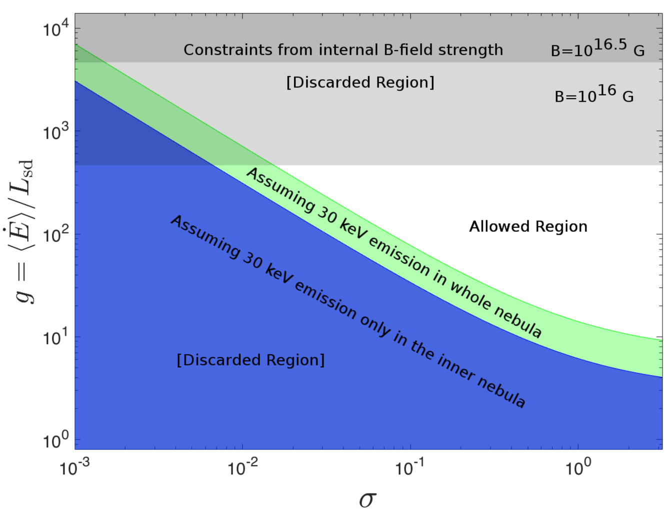



Fig. 2: $g-\sigma$ parameter space

The synchrotron cooling time for $2E_2$ keV X-ray emitting electrons in a 15 $\mu$G field is $t_{\rm syn} \simeq 1 B_{15\mu\rm G}^{-3/2} E_2^{-1/2}$ kyr $\ll t_{\rm SNR}$. Then the assumption of a steady-state implies that the mean rate of energy injection into the MWN is

$$\langle \dot{E} \rangle = g L_{\rm sd} = \frac{(1+\sigma)}{\epsilon_e \epsilon_X} L_{X,\rm MWN} \longrightarrow g = \frac{(1+\sigma)}{\epsilon_e \epsilon_X}\eta_X \xrightarrow[\text{using } B_{\rm min}]{} g > g_{\rm min} = 3.07\left(\frac{1+\sigma}{\sigma}\right) d_4^3 E_{30\rm keV}^{7/2} f^{7/2} \qquad (2)$$

where a fraction $(1+\sigma)^{-1}$ of the total energy injected into the MWN goes into particles, a fraction $\epsilon_e$ of that goes into power-law electrons, and a fraction $\epsilon_X$ of that goes into electrons radiating observed X-rays. Here $\sigma \ll 1$ is the magnetization of the nebular plasma. Our result that $g \gg 1$ implies that total energy injection far exceeds $L_{\rm sd}$, and is likely dominated by outflows from bursts or giant flares powered by the decay of the magnetar's magnetic field.

## The GeV/TeV Emission

There are three different channels, falling under either leptonic or hadronic, that can give rise to the extended GeV/TeV emission. (i) Energetic electrons injected into the MWN by the quiescent magnetar MHD wind can inverse-Compton (IC) scatter soft seed CMB or near-infrared (NIR) Galactic background photons to GeV energies. The required energy in GeV emitting electrons to produce the measured $(0.1-100)$ GeV luminosity $L_{\rm GeV} \simeq 1.45 \times 10^{35} d_4^2$ erg s$^{-1}$ peaking at $\sim 2$ GeV is

$$E_e = L_{\rm GeV} t_{\rm IC} = \begin{cases} 3.6 \times 10^{50} d_4^2 U_{\rm NIR,-13}^{-1} E_{2\rm GeV}^{-1/2}\ {\rm erg} & (E_{\rm soft} = E_{\rm NIR} \simeq 0.1\ {\rm eV}) \\ 6.9 \times 10^{48} d_4^2 U_{\rm CMB,-12.37}^{-1} E_{2\rm GeV}^{-1/2}\ {\rm erg} & (E_{\rm soft} = E_{\rm CMB} = 0.63\ {\rm meV}) \end{cases} \qquad (3)$$

where $t_{\rm IC}$ is the IC cooling time. However, the MWN's total energy is not enough to support either IC channel, especially when considering the larger size of the GeV/TeV region. (ii) Alternatively, electrons accelerated to TeV energies at the SNR forward blast wave can explain the GeV emission through non-thermal relativistic Bremsstrahlung emission (CR$e + p \rightarrow e + p + \gamma$). (iii) Likewise, cosmic-ray protons can explain the TeV emission through the production of neutral pions (CR$p + p \rightarrow p + p + \pi^0$) followed by their decay to hard photons ($\pi^0 \rightarrow 2\gamma$). Both of these channels require high target proton/ion density ($n \gtrsim 10^2$ cm$^{-3}$), which is supported by the fact that the SNR is in close proximity to a giant molecular cloud[3] and directly interacting with it, as inferred from OH (1720 MHz) maser emission observed at the center of the SNR.

## References

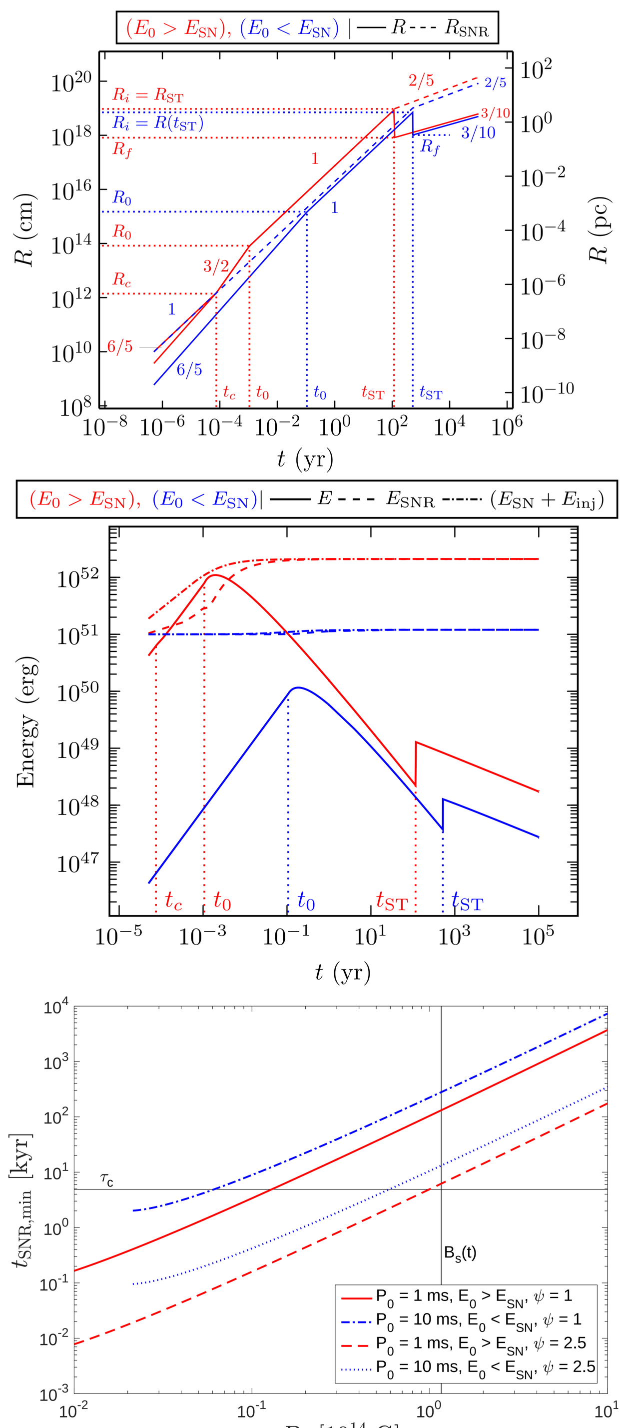
[1]Younes, G. et al. 2016, ApJ, 824, 138 [2] Aharonian et al. (H.E.S.S Collab.) 2015, A&A, 574, 10 [3] Tian, W. W. et al. 2007, ApJ, 657, L25, [4] **Granot et al. 2017, MNRAS, 464, 4895**

## MWN Dynamics

A wind nebula is a bubble of relativistically *hot* particles containing the shocked relativistic MHD wind from the central neutron star. It serves as an excellent calorimeter that tracks the energy injection and adiabatic cooling history of the system while it expands into the unshocked SN ejecta. The magnetar injects a rotationally powered wind into its MWN with a power

$$L_{\rm sd} = L_0\left(1 + \frac{t}{t_0}\right)^{-m} \approx L_0 \times \begin{cases} 1 & t < t_0 \\ (t/t_0)^{-m} & t > t_0 \end{cases} \qquad (4)$$

where most of its initial rotational kinetic energy $E_0 = \frac{n-1}{2} L_0 t_0 = \frac{1}{2} I \Omega_0^2 \simeq 2 \times 10^{52} P_{0,\rm ms}^{-2}$ erg is injected over its initial spin-down time $t_0$; here $m = (n+1)/(n-1)$ where $n$ is the braking index, and $\Omega_0 = 2\pi/P_0$ where $P_0$ is the initial spin period. We consider two cases: (i) when $P_0 = 1$ ms ($E_0 > E_{\rm SN}$) the magnetar injects more energy than the kinetic energy of the expanding SN ejecta, thus seriously affecting the dynamical evolution of the SNR+MWN system, and (ii) when $P_0 = 10$ ms ($E_0 < E_{\rm SN}$) the magnetar is dynamically unimportant and the SNR+MWN system is similar to canonical PWNe.

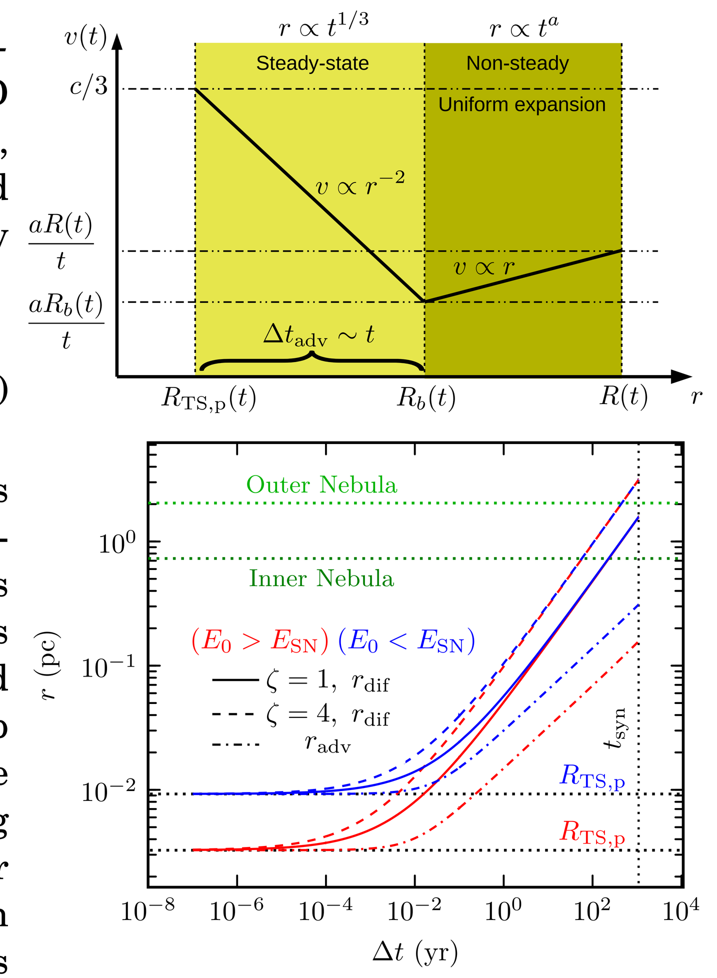


**Figures**: (*Top*) Dynamical evolution of MWN and SNR's radius $R(t) \propto t^a$ in a uniform density ISM and assuming initial surface dipole magnetic field $B_0 = 10^{14}$ G. Labels of line segments show temporal power law indices $a$ in the different expansionary phases separated by dotted lines that punctuate the transition radii corresponding to the transition times: $t_c$ – SN ejecta density core crossing time by the MWN, $t_{\rm ST}$ – Sedov-Taylor onset time where the MWN is compressed by the reverse shock; (*Middle*) Total injected energy ($E_{\rm SN} + E_{\rm inj}$), energy in the MWN ($E$) and SNR ($E_{\rm SNR}$); (*Bottom*) Minimum age of the MWN for it to have expanded after reverse-shock crushing to the size of the observed X-ray nebula; shown here for a range of $B_0$ and the parameter $\psi$, which encodes oscillations in the equilibrium radius due to reverberations: $R(t) = \psi(t) R_{\rm eq}(t)$. Other parameters are: $n = 3$, $n_{\rm ISM} = 1$ cm$^{-3}$, $M_{\rm ej} = 3M_\odot$.

## Synchrotron Cooling Length

Power-law electrons (or $e^\pm$ pairs) injected at the *termination shock radius* ($R_{\rm TS,p}$), where the cold MHD wind from the magnetar is shocked and thermalized, cool adiabatically (first term) and radiatively (second term) by emitting synchrotron photons. Their energy evolution is governed by

$$\frac{d\gamma_e}{dt} = -\frac{\dot{R}(t)}{R(t)}\gamma_e - \frac{\sigma_T B^2(t)}{6\pi m_e c}\gamma_e^2\,, \qquad (5)$$




where the nebular magnetic field evolves as $B(t) \approx \sqrt{6\sigma E_{\rm MWN}(t)/[(1+\sigma)R^3(t)]}$. Under the assumption of steady-state, the nebular flow advects with velocity $v \propto r^{-2}$ from $r = R_{\rm TS,p}$ until this assumption breaks down at $r = R_b(t)$, beyond which the flow expands uniformly (see Fig. - top panel). The electrons therefore travel a distance $\Delta r_{\rm adv} = r(\Delta t) \propto \Delta t^{1/3}$ over their synchrotron cooling time ($\Delta t = t_{\rm syn}$). However, $\Delta r_{\rm adv}$ can't account for the size of the X-ray nebula (see Fig. - bottom panel). Instead, diffusion of particles dominates throughout the nebula, with diffusion length $\Delta r_{\rm diff} \sim \sqrt{2D\Delta t}$ and diffusion coefficient $D = \zeta R_L c$; $R_L = \gamma_e m_e c^2/eB \simeq 4 \times 10^{-3} B_{15\mu\rm G}^{-3/2} E_2^{1/2}$ pc is the Larmour radius of $2E_2$ keV X-ray emitting electrons.

**Figures**: (*Top*) Velocity profile (log-log plot) of the advective flow in the nebula shown for both where it assumes a steady-state and where this assumption fails. The flow is launched at the termination shock radius $R_{\rm TS,p}(t)$ with velocity dropping quadratically with radius at a fixed temporal snapshot of the nebula. The steady-state region terminates at radius $R_b(t)$ beyond which the flow expands uniformly with radius out to the edge of the MWN at $R(t)$. (*Bottom*) Advection and diffusion distances, $r = R_{\rm TS,p} + \Delta r$. $\Delta r_{\rm diff}$ is shown for two cases: $\zeta = 1$ (Bohm diffusion) and $\zeta = 4$.

## Conclusions

The wind nebula around the magnetar Swift J1834.9−0846 is instrumental in understanding the properties of the magnetar's outflows. **Our analysis[4]** yielded the following conclusions:

- The X-ray nebula cannot be powered by the quiescent MHD wind alone, and needs an extra source of energy – most likely energy injection by the super-Eddington episodic outbursts.
- The energy source for the required outbursts cannot be the decay of the magnetar's dipole field alone, and is most likely the decay of its much stronger internal magnetic field.
- The GeV/TeV emission cannot be of IC origin and is more likely to come from hadronic emission of CR protons interacting with target protons in the nearby GMC.