A GENERIC MODEL FOR PERSISTENT RADIO SOURCE AROUND FAST RADIO BURSTS

Yushan Chen, Hao Tong
School of Physics and Materials Science - Guangzhou University - China
603358079@qq.com, tonghao@gzhu.edu.cn

Introduction

The repeated fast radio bursts FRB 121102A and FRB 190520B have been reported to be spatially consistent with a compact, extended persistent radio source (PRS)[1; 2]. Although the origin of PRSs remain unclear, their high luminous emission indicate a dense and strong-magnetized environment around these FRBs. We present a parameterized one-zone model of PRS with energy injection from central engine, and show how to fit the observed spectra of PRS and constraint the parameters through observation regardless of energy budget and physical model, which may reveal the information of central engine that generates both FRB and PRS.

Analytical One-zone Model

Synchrotron Radiation for One-zone Model

We consider a basic scenario in which a relativistic magnetized wind from the central engine (probably magnetar) sweeps up the surroundings, e.g. freely expanding supernova ejecta, giving rise to a power-law distribution of electron between the forward shock and the termination shock. With the presence of magnetic field, the relativistic electrons emit synchrotron radiation which is bright enough to account for observation data. We use a piecewise function with a few parameters, to fit the observed spectra of PRSs, where the spectra depend on three break frequencies, i.e. the synchrotron cooling frequency $\nu_{\rm c}$, the typical synchrotron frequency $\nu_{\rm m}$, the synchrotron self-absorption frequency $\nu_{\rm a}$[3].

$$L_{\circ} = \begin{cases} L_{\circ,\rm max}(\frac{\nu_{\rm a}}{\nu_{\rm m}})^{-\frac{p-1}{2}}(\frac{\nu}{\nu_{\rm a}})^{\frac{5}{2}},\ \nu < \nu_{\rm a}, \\ L_{\circ,\rm max}(\frac{\nu}{\nu_{\rm m}})^{-\frac{p-1}{2}},\ \nu_{\rm a} < \nu < \nu_{\rm c}, \\ L_{\circ,\rm max}(\frac{\nu_{\rm c}}{\nu_{\rm m}})^{-\frac{p-1}{2}}(\frac{\nu}{\nu_{\rm c}})^{-\frac{p}{2}},\ \nu \geq \nu_{\rm c}. \end{cases} \tag{1}$$

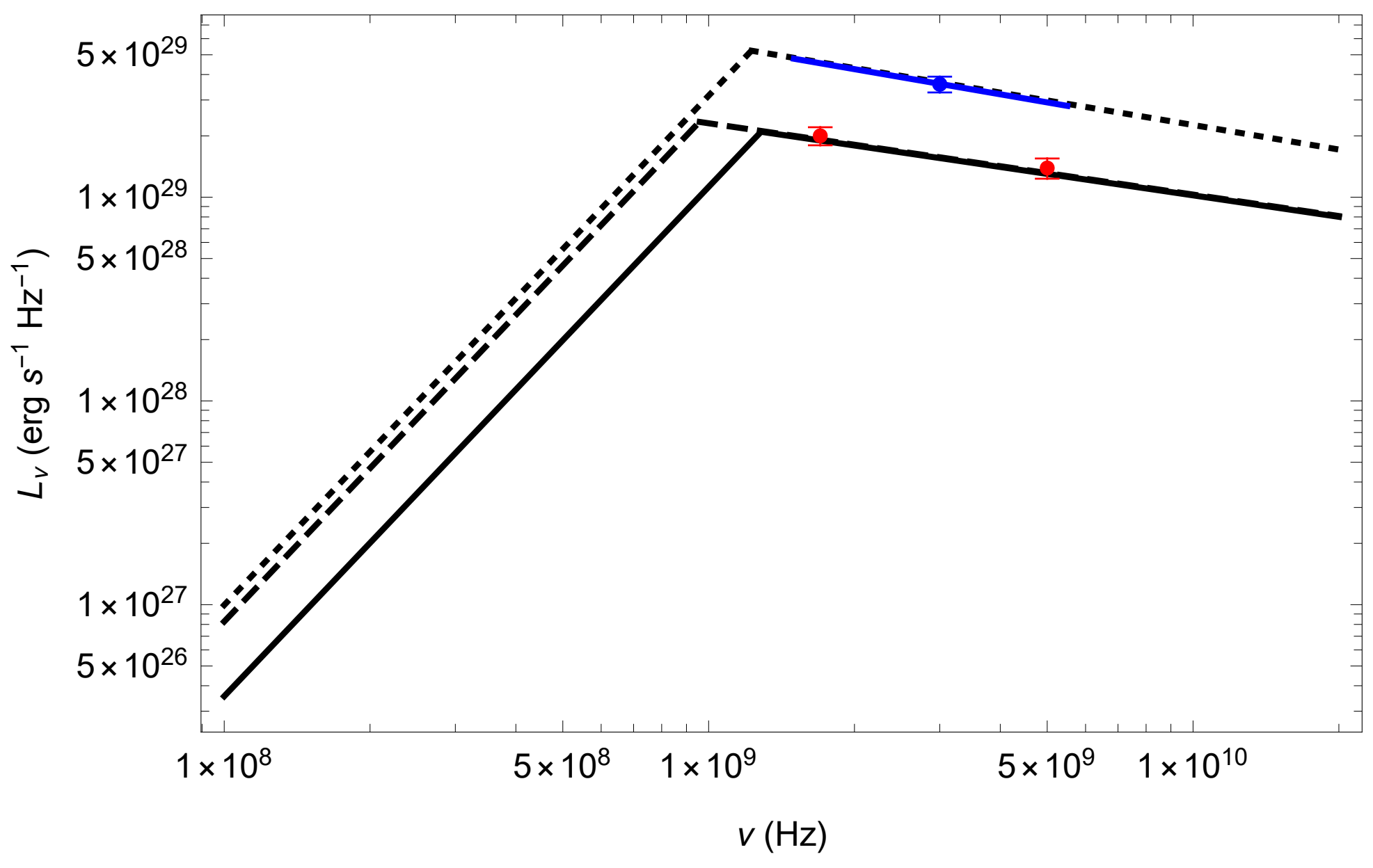

Figura 1: Fitting the spectra of both PRSs. Here we focus on the hard electron spectrum when $\nu < \nu_{\rm c}$.

Dynamical Evolution

We assume the PRS is a pulsar wind nebulae (PWN) embedded in a free expanding supernova remnant (SNR), and assume the dynamical evolution and radiation are in the same zone. Under the approximation of the PWN as a spherical bulk, the size of PWN $R_{\rm PWN} \propto t^{\rm m}$ is a function of time. With conservation law of energy

$$\begin{aligned} L_{\rm w} &= \frac{d(4\pi R_{\rm PWN}^3 P_{\rm PWN})}{dt} + P_{\rm PWN} 4\pi R_{\rm PWN}^2 \frac{dR_{\rm PWN}}{dt} \\ &= P_{\rm PWN} 16\pi R_{\rm PWN}^2 \frac{dR_{\rm PWN}}{dt} + 4\pi R_{\rm PWN}^3 \frac{dP_{\rm PWN}}{dR_{\rm PWN}} \frac{dR_{\rm PWN}}{dt}. \end{aligned} \tag{2}$$

where the energy injection $L_{\rm w}$ is a constant, and the law of motion

$$M_{\rm cd} \frac{d^2 R_{\rm PWN}}{dt^2} = 4\pi R_{\rm PWN}^2 P_{\rm PWN}, \tag{3}$$

where $M_{\rm cd}$ is the swept-up mass of the supernova ejecta, we apply the self-similar method ($P_{\rm pwn} \propto R_{\rm PWN}^{\alpha}$ and $R_{\rm PWN} \propto t^{\rm m}$) to obtain $R_{\rm PWN} \propto t^{\frac{6}{5}}$. The PWN is dynamical along with its radiation properties, so we can obtain any time-varying quantities (including DM and RM) as long as they are related to dynamical timescale.

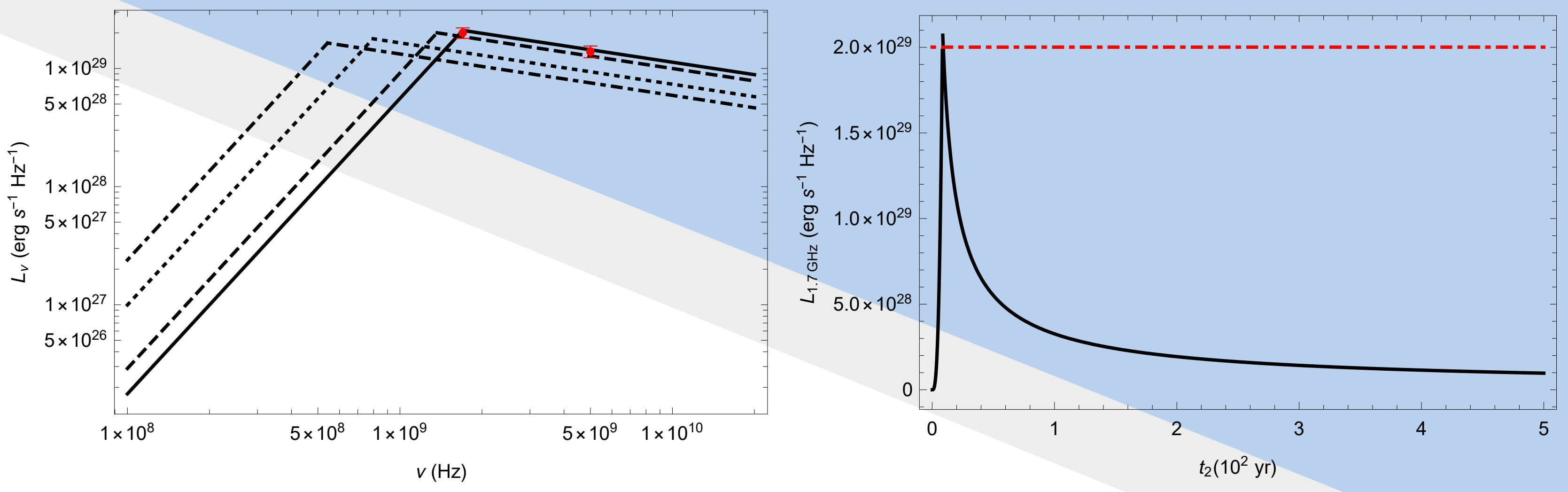

Figura 2: The time variation of the spectrum of PRS 121102 (left) and the luminosity of PRS 121102 in 1.7 GHz (right).

Parameter constraints

For our dynamical one-zone scenario of PWN, we have eight parameters: $L_{\rm w,41}, t_2, n_{0,2}, \epsilon_{\rm e}, \epsilon_{\rm B}, \gamma_{\rm max}, \gamma_{\rm min}, p$. We fix $n_{0,2} = 1, \epsilon_{\rm e} = 0.3, \epsilon_{\rm B} = 0.001, \gamma_{\rm max} = 10^3, \gamma_{\rm min} = 5, p = 1.7$ for PRS 121102, and obtain the constraints on the source parameters $L_{\rm w,41}$ and t_2 through constraints from observation data (1) $\nu_{\rm a} \sim 1.7$ GHz (black line), (2) $L_{\rm 1.7GHz} \sim 2 \times 10^{29}$ ergs^{-1}Hz^{-1} (black dot-dashed line), (3) the upper limit of PWN size ~ 0.66 pc (black dotted line), (4) DM ~ 565.8 pc cm^{-3} (black thick line), (5) RM $\sim 10^5$ rad m^{-2} (black dashed line). The final permitted parameter space is surrounded by five lines and pointed out by black arrow. for PRS 190520, we fix $n_{0,2} = 1, \epsilon_{\rm e} = 0.3, \epsilon_{\rm B} = 0.001, \gamma_{\rm max} = 10^3, \gamma_{\rm min} = 5, p = 1.8$ and apply the same constraints as (1) $\nu_{\rm a} \sim 1.5$ GHz (black line), (2) $L_{\rm 1.5GHz} \sim 4.8 \times 10^{29}$ ergs^{-1}Hz^{-1} (black dot-dashed line), (3) the upper limit of PWN size ~ 4.5 pc (black dotted line), (4) DM ~ 1204.7 pc cm^{-3} (black thick line), (5) RM $\sim 1.8 \times 10^5$ rad m^{-2} (black dashed line), (6) decrease of DM ~ 0.09 pc cm^{-3} day^{-1} (black thick dashed line). The final permitted parameter space is surrounded by six lines and pointed out by black arrow as well.

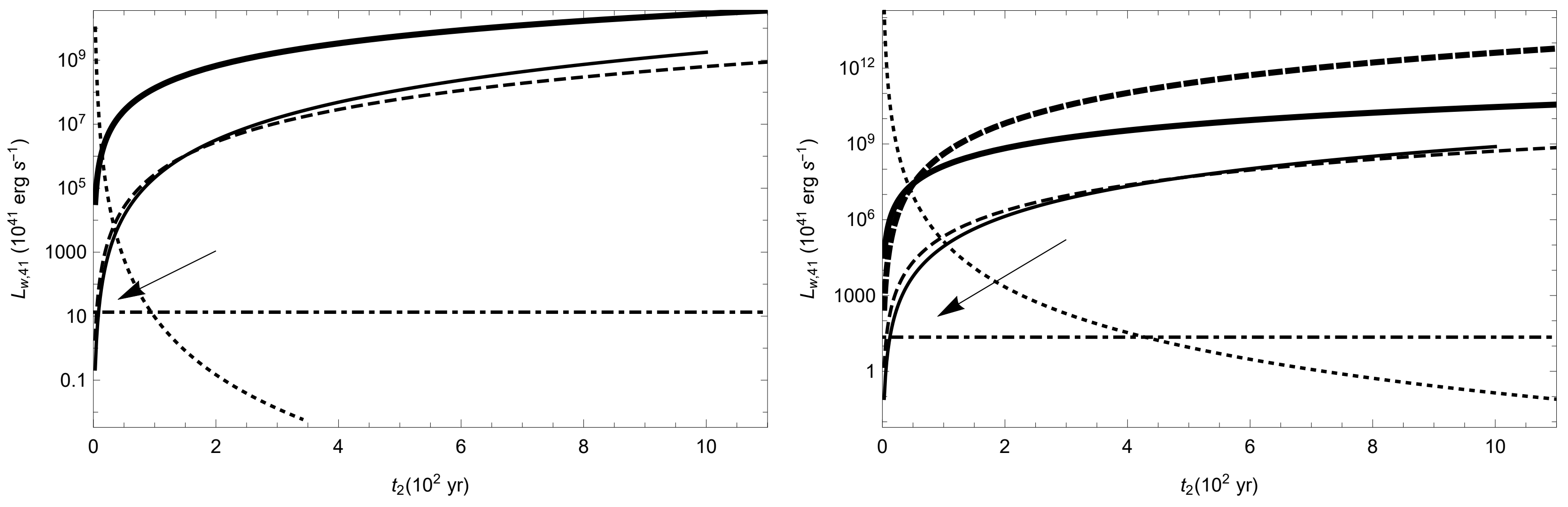

Figura 3: The permitted parameter spaces of PRS 121102 (left) and PRS 190520 (right).

Conclusion

One-zone model is a practical and most simple method to obtain properties, e.g. the spectra or evolution, for PRSs. It can demonstrate the constraints via observation and test the relation between parameterized physical quantities. As PRS 121102 is seemed, the source ages between about 8.5∼100 yr, which is consistent with the assumption of our scenario that the whole system is at its early age; meanwhile, the energy injection rate ranges from about 10^{42} erg s^{-1} up to 10^{44} erg s^{-1}, which might indicate that the central engine is significantly energetic at its early age, more likely leading to the magnetars. The case of PRS 190520 is even more extrem than that of PRS 121102. However, the DM constraints from both PRSs do not constrain the permitted parameter space any better than the other parameters, which may indicate that the generating and the decreasing of DM could originate from different “zones”rather than the “zone”where the radiation and RM are generated.

References

[1] Marcote, B., Paragi, Z., Hessels, J. W. T., et al. 2017, ApJL, 834, L8, doi: 10.3847/2041-8213/834/2/L8
[2] Niu, C. H., Aggarwal, K., Li, D., et al. 2022, Nature, 606, 873, doi: 10.1038/s41586-022-04755-5
[3] Sari, R., Piran, T., & Narayan, R. 1998, ApJL, 497, L17, doi: 10.1086/311269