On the correlation between X-ray luminosity and spin down-power of isolated pulsars

Laly Boyer[a], Laura Pulgarin-Castaneda[a], Maïca Clavel[b], Francesca Calore[c]

[a] *Université Grenoble Alpes, Grenoble, France*
[b] *IPAG, Grenoble, France*
[c] *LAPTh, Annecy, France*

Abstract

Pulsars correspond to rapidly rotating and highly magnetized neutrons star (NSs), which emit a strong electromagnetic radiating in their magnetic axis direction from radio waves to gamma-rays. If this radiation happens to be in the direction of the Earth, can be detected thanks to their period P, which range from millisecond (for millisecond pulsars MSPs) to second (for 'normal' pulsars).

While around 4351 pulsars (version 2.7.0, Manchester et al. (2005)) have been discovered up to date, the X-ray emission mechanism for isolated pulsars can still not be properly explained. However, the study of the correlation between X-ray luminosty and spin-down power of isolated pulsars can give us helpful informations toward reaching an explanation.

The aim of this literature review is to present the current state of the art as for the study of this correlation, and present the aim of our future work with Maïca CLAVEL and Francesca CALORE, respectively in the SHERPAS team at the Grenoble Institut of Planetology and Astrophysics and the Astroparticles and Cosmology team at the Laboratoire d'Annecy-le-Vieux de Physique Théorique, establishing an up-to-date catalog of known isolated pulsars using database from spatial missions such as Chandra, XMM-Newton, Swift/XRT and SRG/eRosita, and setting their distances as precisely as possible using parallaxes from the Gaia mission and dispersion mesuremnet from radio observations, and determine if we can conclude a correlation between their X-ray luminosity and spin-down power.

Keywords: keyword 1, keyword 2, keyword 3, keyword 4

1. Introduction

Ever since their discovery in 1967 by Jocelyn Bell (Hewish et al., 1968), more than 4000 pulsars have been discovered; their physical properties have been throughly studied and are reaching toward better modelisation. Among them, X-ray pulsars, are still very misunderstood. While the origin of pulsar emission is the subject of observational and theoretical research, with emission models proposed to explain the pulsed emission detected in radio and gamma rays. but the origins of their X luminosity can not be completely formulated.

While multiples possible explanation of X-ray luminosity from binary pulsars has been made, that for isolated pulsars, is still very unclear. A possible explanation for their X-ray luminosity properties is thought to be correlated to their rotational properties, and more specifically their spin down power, $\dot{E}$. This correlation has been throughly studied since 1988 (Seward and Wang, 1988), and continue to be studied, with the amount and precision of the data exponantially growing each year.

But while many studies of this correlation have been made on pulsars, few have been focused on isolated pulsars, which limit our understanding for this specific population.

In the second section, we present pulsar and their pertinent parameters and present a brief history of the subject, then in the third section we present how this correlation has been recently studied and their limits, and in our last section we present how we wish to keep going with this work.

2. Presentation of the subject

We start off by defining the properties of pulsars, and the categories of pulsars we will be working with for this study.

2.1. Population of pulsar studied

Here, we focus exclusively on rotation-powered pulsar (RPPs) where rotational energy is the dominant source of X-ray emission. They consist of 90% of the pulsars populations (Xu et al., 2025). We exclude magnetars (Anomalous X-rays Pulsars (AXPs) and Soft Gamma Repeaters (SGRs)), as their X-ray properties are not linked to rotational activities, and also implicitely exclude accretion-powered pulsars, as they are only found in binary systems. More specifically, we will focus on isolated pulsars specificaly, whose population have not been througly studied recently.

We also point out that our study include isolated MSPs, which consist of around 30% of known milliseconds pulsars (Manchester et al., 2005).

Next, we define the parameters with which we will work with.

2.2. Pulsars and basics definitions

From the many physical properties of pulsars, we define those of which we need :

Period P A pulsar period corresponds to its *rotation period* along its axis, and ranges from second (normal pulsars) up to millisecond (millisecond pulsars, called MSPs). Its rotation axis is not necessarely aligned to its magnetic axis, which results in the observed pulsed emission. It is measured from radio observations. It stability makes it a very interesting tool for high-precision measurement, comparable to that of atomic clocks.

Spin-down rate $\dot{P}$ It is the rate at which they decrease, and is generally very slow, it is this decay which provides the energy to generate electromagnetic waves. Similarly to the period P, it is measured from radio observations

Intrinsic X-ray luminosity L_X It is defined as $L_X = 4\pi d^2 f_x$, with d the distance between the observer and the pulsar, and f_x the x-ray flux mesured for a specific bandwidth. Depending on the catalog used, the measured flux can be from different energy band. We list below the principal X-ray missions, and their energy band :

Table 1: Main X-ray missions and corresponding energy bands

Mission	Operating period	Energy band (keV)
ROSAT	1990–1999	0.1–2
ASCA	1993–2001	0.4–10
XMM-Newton	1999–ongoing	0.1–12
Chandra	1999–ongoing	0.1–10

We distinguish inside the X-ray band the hard X-ray band (> 2 keV) and the soft X-ray band (< 2 keV).

Spin-down power $\dot{E}$ Also refered as spin-down luminosity, rotational luminosity, bracking energy, or rate of loss of rotational energy, it is defined as $dE/dt = 4\pi^2 I\dot{P}/P^3$ with I the pulsar momentum of inertia, typically assumed in the literature as $I = 10^{45}\mathrm{g\ cm}^2$. We note that while some distinguish $\dot{E}$ from the spin-down L_{sd} as $\dot{E} = -L_{sd}$ (Enoto et al., 2019), some also choose to consider it the same : $\dot{E} = L_{sd}$ (Possenti et al., 2002), (Shibata et al., 2016).

Dispersion measure (DM) Used to determine pulsars distance, it corresponds to the intergrated electron column density along the pulsars photon path, it is defined following (Yao et al., 2017)

$$\mathrm{DM} = \int_0^d n_e dl = 2.410 \times 10^{-16} \times (t_2 - t_1)/(\nu_2^{-2} - \nu_1^{-2})\ \mathrm{cm}^{-3}\mathrm{pc}$$

where t_1 and t_2 are observed pulse arrival times at frequencies ν_1 and ν_2, respectively.

By knowing the electron density along a path, we can retrieve a pulsar distance d from this formula. The electron density is previously mesuread using this same formula but for pulsars whose distance are well-known (i.e. using the parallax method with *Gaia*), and then can be used to know the distance of other closely located pulsars, considering they have a similar electron density along their path. Distance are then used to convert mesuread fluxes into luminosities.

In our case, we are particularly interested in studying the correlation between the x-ray luminosity and the spin-down rate of pulsars, as it might help us distinguish differents classes of pulsars.

2.3. A brief history of the correlation study

The $L_X/\dot{E}$ correlation for isolated rotation-powered pulsars has been studied since the 1988 (Seward and Wang, 1988), and initially was used to "derive the characteristics of possibly unseen pulsars in detected supernova remnant". Using 21 known isolated pulsar from the *Einstein* mission, they first established

$$L_X(0.2 - 4\ \mathrm{keV}) = \dot{E}^{1.39}$$

The study of this correlation was not limited to isolated pulsars. In 1997, (Becker and Trümper, 1997) found from the 26 detected pulsars (including 7 MSPs) available from the July 1997 ROSAT data that even if MSPs and 'normal' pulsars differ in characteristics, they both follow the same $L_X/\dot{E}$ correlation :

$$L_X(0.1 - 2.4\ \mathrm{keV}) \propto \dot{E}^{1.03\pm0.08}$$

with a correlation coefficient $r = 0.946$.

Those two previous studies did not include the statistical and systematic uncertainties on L_X resulting from the errors on the X-ray fluxes and on the poorly known distances of most pulsars. Not only that, but their studies were done in the soft X-ray band, when it was later on theorzied that working in the hard X-ray band was preferrable to reduced the contribution from surface thermal emission and correctly explore the nature of the X-ray emission resulting from the rotational energy loss. Soft X-ray fluxes are also more sensitive to the uncertainties due to interstellar absorption (Lee et al., 2018).

Those considerations were included in (Possenti et al., 2002), which with the increasing amount of data studied the empirical relation between the non-thermal X-ray luminosity and the rate of spin-down energy loss L_{sd} of a sample of 39 pulsars, which explicitly exclude accretion-powered pulsars and AXPs. They found

$$L_X(2 - 10\mathrm{keV}) = (14.36 \pm 1.11)\dot{E}^{1.34\pm0.03} \quad (\chi^2_\nu = 7.0)$$

The high reduced χ^2 implies that this relation must only be seen as an empirical average trend and not suitable for predicting the luminosity of any specific source, as explained by (Li et al., 2008), due to the observationnal uncertainties.

They also found for ten known MSPs at the time :

$$\log L_{X,MSP}(2 - 10\mathrm{keV}) = (1.38 \pm 0.10) \log \dot{E} - (16.36 \pm 3.64)$$

In 2008, (Li et al., 2008) presented a statistical study of the non-thermal X-ray emission of 27 young RPPs and 24 pulsar wind nebulae (PWNe) by using the Chandra and the XMM-Newton observations, which with the high spatial resolutions enable to spatially resolve pulsars from their surrounding PWNe, and does not includes MSPs. Since previous studies considered L_X as the total emission due to the pulsars plus PWNe, it studied them separatly, as to test the consistence of their emission properties with proposed models at time. It found, accouting for the uncertainties

$$L_{X,psr}(2-10\,\text{keV}) = 10^{-0.8\pm1.3}\dot{E}^{0.92\pm0.04}(\chi^2 = 2.6)$$

$$L_{X,pwn}(2-10\,\text{keV}) = 10^{-19.6\pm3.0}\dot{E}^{1.45\pm0.08}(\chi^2 = 2.7)$$

However, both the fits are statistically unacceptable. Later on, those work continued using bigger data catalog, as none of the regression lines are statistically acceptable. We present those work below.

3. State of the art

Here we start with the 2021 article (Hsiang and Chang, 2021). Its goal was to continue the work done in (Li et al., 2008), with a larger set of data from the March 2005 version of the McGill PWN catalog and Li, Lu and Li (2008). The article finds the correlation for the non-thermal luminosity

$$L_{X,psr}(0.5-8\text{keV}) \propto \dot{E}^{1.15\pm0.11}, \quad (\chi^2_\nu = 3.43)$$
$$L_{X,pwn}(0.5-8\text{keV}) \propto \dot{E}^{1.32\pm0.13}, \quad (\chi^2_\nu = 4.38)$$

In (Chang et al., 2023), while also excluding MSPs, as their non-thermal X-ray emissions may come from a way different from normal pulsars, because of their weak magnetic field, they found the correlation for non-thermal emission with data up to 2008 (Li et al., 2008) (which does not disintguish $L_{X,psr}$ and $L_{X,pwn}$):

$$L_X(0.5-8\text{keV}) \propto \dot{E}^{0.88\pm0.06}(\chi^2_\nu = 3.98)$$

In 2025, with the data set representing the largest sample of X-ray counterparts ever compiled, including 98 normal pulsars (NPs) and 133 millisecond pulsars (MSPs), (Xu et al., 2025) found by fitting accross the entire X-ray band :

$$L_X \propto \dot{E}^{0.85\pm0.05}$$

which is consistent with the findings of (Chang et al., 2023) within the error margins. While they did this study for the whole X-ray band, they found that the correlation is strong in the hard X-ray band, but no significant correlation has been found for the soft X-ray, likely due to the presence of mixed thermal and nonthermal components. They also fitted for 83 MSPs and 93 NPs separatly :

$$\begin{cases} L_{X,MSPs} \propto \dot{E}^{0.87\pm0.17} \\ L_{X,NPs} \propto \dot{E}^{0.83\pm0.06} \end{cases}$$

(Lee et al., 2018) studied specifically isolated MSPs, but only 6 are isolated MSPs out of the 35 studied in the sample, and only in GF (excluding the pulsars in globular clusters), considering MSPs as RPPs with period $P < 20ms$. Only one correlation is given, and even if they are comparable to other classes of non-isolated, it is not limited to isolated,

$$L_X(2-10\text{keV}) \propto \dot{E}^{1.31\pm0.22}$$

where $\dot{E}$ is the spin-down powe r in units of 10^{35} erg/s.

In 2022, a study for MSP in GC was done, which found (Zhao and Heinke, 2022)

In 2023, this study was reconducted by (Lee et al., 2023) but accouting for MSPs in GC and GF. The results was

For GF (outliers excluded):

$$\begin{cases} \log L_X(0.3-8) = (0.86\pm0.16)\log\dot{E} + (1.36\pm5.36) \\ \log L_X(2-10) = (1.03\pm0.26)\log\dot{E} + (-4.92\pm8.91) \end{cases}$$

For GC (Group C):

$$\begin{cases} \log L_X(0.3-8) = (0.56\pm0.14)\log\dot{E} + (11.43\pm4.90) \\ \log L_X(2-10) = (0.77\pm0.18)\log\dot{E} + (3.96\pm6.17) \end{cases}$$

(Malov and Timirkeeva, 2019), which excludes magnetars found

$$\log L_X = (1.17\pm0.08)\log\dot{E} - 9.46\pm2.89$$

It also found that by uniting the range from 0.1 to 10 keV

$$L_X(0.1-10\text{keV}) = 3.47\times10^{-10}\dot{E}^{1.17}$$

(Prinz and Becker, 2015) found (it consider 'the spin down luminosity' $\dot{E} = -4\pi^2 I\dot{P}/P^3$)

$$L_{X(0.1-2\,\text{keV})} = 10^{-3.24^{+0.26}_{-0.66}}\,(\dot{E})^{0.997^{+0.008}_{-0.001}}$$

in 2009, Becker found

$$L_X(0.1-2\text{keV}) = 10^{-3.24^{+0.26}_{-0.66}}\dot{E}^{0.997^{+0.008}_{-0.001}}$$

$$L_X(2-10\text{keV}) = 10^{-15.72^{+0.7}_{-1.7}}\dot{E}^{1.336^{+0.036}_{-0.014}}$$

comparing with (Possenti et al., 2002)

3.1. Distances defined in previous studies

While the data for some studies could consider more accurate pulsars distance d using parallax measurement or data from calculation with associated supernova remnants (Possenti et al., 2002)(Lee et al., 2018), most of these studies adopted a 40% uncertainties on distances derived from DM (Xu et al., 2025), (Lee et al., 2023), (Hsiang and Chang, 2021), (Li et al., 2008), (Possenti et al., 2002), (Lee et al., 2018), (Lee et al., 2023). The most recent study from 2025 considered distances of most pulsars as are acquired from he ATNF catalog (Manchester et al., 2005), using the YMW16 electron distribution model, which still adopt a 40% uncertainties. (Malov and Timirkeeva, 2019) used distance and uncertainties from (Prinz and Becker, 2015) and (Possenti et al., 2002).

(Prinz and Becker, 2015) estimated distance estimate based on the work by Verbiest et al. (2012), where they present a detailed analysis of all measured distances to pulsars. For all other sources we used the NE2001 model of Cordes and Lazio (2002) to transform the measured DM to a distance. We apply a distance error of 20% to 120% depending on their Galactic coordinates.

3.2. *Dates from used catalogs*

Most of these articles used older, stable data from catalog. (Hsiang and Chang, 2021) used the March 2005 version of 'The Pulsar Wind Nebula Catalog' and Chandra and the XMM-Newton data from (Li et al., 2008). While the (Lee et al., 2023) also reused (Li et al., 2008), their most recent data are considered as from the table of (Potekhin et al., 2020). The most recent analysis from 2005, used the ATNF pulsar catalog v2.3.0, dating from 2024.

(Lee et al., 2018) used April 2017 version of ATNF pulsar catalog, and successing (Lee et al., 2023) 204 radio GC MSP : P. Freire for GC MSPs and online catalogue West Virginia university for GF MSP, dating as latest possible from 2023.

(Prinz and Becker, 2015) sued ATNF pulsar database (version 1.54) with archival XMM-Newton and Chandra observations publicly released by July 1st 2016, and (Malov and Timirkeeva, 2019) "used data from Possenti et al. (2002) and Prinz and Becker (2015) for X-ray loud pulsars only", so probably also July 2016 and data as of 2002.

In the table in annex, we summarize for each article cited the type of data used, its date, pulsars types studied, date of most recent data used and distance considered

4. Conclusion

Most data is old, and the impact from the distances uncertainties is too impactful on data. Most sources used DM and a 40% associated uncertainties, which results in a error ~ 0.3 in $\log L_X$ (Possenti et al., 2002).

We can also observe a lack of study of isolated pulsars in recent studies,

5. Discussion and future work

For our upcoming study, we can base ourself on the 2025 article to compare our results. The aim of our work is to update and For this, we will first etablish an updated catalogue of isolated pulsars using existing databases coming from differents space mission in X ray such as Chandra, XMM-Newton, Swift/XRT et SRG/eRosita. Then after extracting their X-ray flux from them, we will determine their distance as precisely as possible using paralaxes from Gaia mission and dispersion mesurement establisehd from radio observations. Using those two parameters, we will try to establish if a correlation exists between the luminosity in X-ray L_X of those source and their spin-down power $\dot{E}$. We note that with the Gaia catalog having been released in ???, it was not common practice to use it up to (?)

We will also restrict our work to a specific energy interval, as most of the presented data studies the correlation for high or low energy.

We do have to consider the low brightnest of MSPs in optical, impacting the Gaia method. Not only that but an important amount of dust also makes it unable to use Gaia.

Appendix A. Appendix title 1

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Table A.2: Census of most recent articles and associated data

Articles	Pulsars type/excluded	luminosity type	Year of most recent data	Distance used and
(Xu et al., 2025)	RPP (MSPs in GC and NPs with PWNe)	T+NT(0.3-10)	2024	0.00
(Chang et al., 2023)	RPPs (PWNe w/ assoc. pulsar)/MSPs	NT (0.5-8)	2020	0.00
(Hsiang and Chang, 2021)	Pulsar w/ detect. X-ray/MSPs	NT	2008	0.00
(Lee et al., 2023)	204 MSPs in GC and GF	T+NT	2023	0.00
(Lee et al., 2018)	47 MSPs (6 Iso) in GF/MSPs in GC	T+NT	2017	0.00
(Malov and Timirkeeva, 2019)	RPPs (impl. Iso)/magnetars	NT	2016	0.00
(Prinz and Becker, 2015)	RPPs	NT	2016	0.00

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