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

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Abstract

Pulsars correspond to rapidly rotating and highly magnetized neutron stars (NSs), which emit a strong electromagnetic beam in direction of their magnetic axis from radio waves to gamma-rays. If this radiation happens to be directed towards Earth, it can be detected thanks to its period P, which ranges from milliseconds (for millisecond pulsars (MSPs)) to seconds (for 'normal' pulsars (NPs)).

While around 4351 pulsars (version 2.7.0, Manchester et al. (2005)) have been discovered 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 luminosity and spin-down power of isolated pulsars can give us helpful information toward reaching an explanation.

The aim of this literature review is to present the current state of the art on 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 Institut of Planetology and Astrophysics of Grenoble and the Astroparticles and Cosmology team at the Laboratoire d'Annecy-le-Vieux de Physique Théorique. We will establish an up-to-date catalog of known isolated pulsars using databases from spatial missions such as Chandra, XMM-Newton, Swift/XRT, and SRG/eRosita, and set their distances as precisely as possible using parallaxes from the Gaia mission and dispersion measurements from radio observations.

1. Introduction

Ever since their discovery in 1967 by Jocelyn Bell (Hewish et al., 1968), more than 4,000 pulsars have been discovered. Their physical properties have been extensively studied, but while some models propose an explanation for the origin of pulsed emissions in radio and gamma rays, that for X-ray emissions has not yet been completely formulated.

A possible explanation for their X-ray luminosity properties is thought to be correlated to their rotational properties, and more specifically to their spin-down power $\dot{E}$. This correlation has been thoroughly studied since 1988 (Seward and Wang, 1988), with the amount and precision of the data growing exponentially each year.

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

In the next section, we begin by introducing pulsars and their relevant parameters, and present a brief history of the study of the intrinsic X-ray luminosity and spin down power correlation. In the third section we review recent studies of the correlation and discuss their limitations. Finally, in the last section, we present how we wish to further continue this work.

2. Presentation of the subject

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

2.1. Population of pulsar studied

NSs can be classed in differents subclasses, depending on their main powering source and mangetic properties. We distinguish *pulsars*, with rotation-powered pulsars and accretion powered pulsars from *magnetars*.

Here, we focus exclusively on rotation-powered pulsar (RPPs), which consist of 90% of the pulsars population (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. Moreover, since we will focus on isolated pulsars specificaly, we will exclude accretion-powered pulsars, as they are only found in binary systems. 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 be working.

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 rotational axis, and ranges from seconds (NPs) up to milliseconds (MSPs). Its rotational axis is not necessarily aligned to its magnetic axis, which results in the observed pulsed emission. It is measured from radio observations, and its 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 particularly slow rate at which the period P decrease. It is this decay which provides the energy to generate electromagnetic waves, and 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 measured for a specific bandwidth. Depending on the catalog used, the measured flux can be from different energy band. We list below the main X-ray missions, and their energy band :

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

Mission	Operating period	Energy band (keV)
Einstein	1978–1981	0.2–4
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 ($> 2\,\mathrm{keV}$) and the soft X-ray band ($< 2\,\mathrm{keV}$). We precise this as we will later present the distinction between thermal and non-thermal emission.

Spin-down power $\dot{E}$ Also refered as spin-down luminosity, rotational luminosity, 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 luminosity L_{sd} as $\dot{E} = -L_{sd}$ (Enoto et al., 2019), some also choose to consider it the same, with $\dot{E} = L_{sd}$ (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 (e.g. 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 measuread fluxes into intrinsic luminosities. We point out that while DM are used to determine pulsars distances in general, parallax method are usually preferred when avaiable, as they are more precise.

In our case, we are particularly interested in studying the correlation between the intrinsic X-ray luminosity L_X and the spin-down power $\dot{E}$ of pulsars, as it might help us define the origins of the X-ray emissions of pulsars, as they are thought to be linked to their rotational properties.

2.3. A brief history of the correlation study

The $L_X/\dot{E}$ correlation for isolated RPPs 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

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

The study of this correlation was not limited to isolated pulsars. In 1997, (Becker and Trümper, 1997) found from the 26 detected RPPs (including 7 MSPs) available from the July 1997 ROSAT data that even if MSPs and NPs 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 uncertainties on L_X, resulting from the errors on the X-ray fluxes and on the unwell known distances of most pulsars at the time. Not only that, but it was later thought that working in the hard X-ray band rather than the soft X-ray band to study specifically the non-thermal emission was preferrable, as to reduce the contribution of thermal emission and the impact of interstellar absorption (Possenti et al., 2002). Indeed, the thermal component is thought to be explained from differents models, and not from the rotational properties of pulsars.

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 power $\dot{E}$ of a sample of 39 pulsars, which exclude accretion-powered pulsars and AXPs. They found

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

In 2008, (Li et al., 2008) presented a statistical study of the non-thermal X-ray emission of 27 young RPPs (excluding MSPs, as their non-thermal X-ray emissions may come from a different mechanism from NPs) 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. Since previous studies considered L_X as the total emission due to the pulsars plus PWNe, the goal was to study them separatly, as to remove the non-pulsed synchrotron emission. It found, accouting for uncertainties

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

However, even with a high correlation coefficient of $r_s = 0.82$ and $p_s < 0.0001$ between L_X and $\dot{E}$, the resulting χ^2 is statistically unacceptable.

For both of these previous work, the resulting χ^2_ν and χ^2 implies that these relation can not be considered as law, and can not be used to predict the luminosity of any specific source, as it was initially thought in (Seward and Wang, 1988).

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) of separating the RPPs luminosity from PWNe, with a larger set of data. The article finds the correlation for the non-thermal luminosity L_X and $\dot{E}$

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

In (Chang et al., 2023), while also excluding MSPs, they found the correlation for non-thermal emission with data up to 2008 (Li et al., 2008) (which does not distinguish $L_{X,\mathrm{psr}}$ from $L_{X,\mathrm{pwn}}$):

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

In 2025, with the data set representing the largest sample of X-ray counterparts ever compiled, including 98 NPs and 133 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 was strong in the hard X-ray band, but no significant in 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 :

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

(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 galactic field (GF) (excluding the pulsars in globular clusters (GCs)), considering MSPs as RPPs with period $P < 20$ ms, but not necessarily isolated.

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

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

For GF (outliers excluded):

$$\begin{cases} L_X(0.3-8\,\mathrm{keV}) \propto \dot{E}^{0.86\pm0.16} \\ L_X(2-10\,\mathrm{keV}) \propto \dot{E}^{1.03\pm0.26} \end{cases}$$

For GC :

$$\begin{cases} L_X(0.3-8\,\mathrm{keV}) \propto \dot{E}^{0.56\pm0.14} \\ L_X(2-10\,\mathrm{keV}) \propto \dot{E}^{0.77\pm0.18} \end{cases}$$

In (Malov and Timirkeeva, 2019), which excludes magnetars, they found by uniting data from (Possenti et al., 2002) and (Prinz and Becker, 2015) resulting in 61 pulsars :

$$L_X(0.1-10\,\mathrm{keV}) \propto \dot{E}^{1.17\pm0.08}$$

(Prinz and Becker, 2015), consider the spin down luminosity as $\dot{E} = -4\pi^2 I\dot{P}/P^3$, which using a larger sample, tested the results from (Becker, 2009)

$$L_X(0.1-2\,\mathrm{keV}) \propto \dot{E}^{0.997^{+0.008}_{-0.001}}$$

$$L_X(2-10\,\mathrm{keV}) \propto \dot{E}^{1.336^{+0.036}_{-0.014}}$$

3.1. Distances defined in presented studies

While the data for some studies did 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.

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) used the 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 appendix, 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 of the data used in the presented studies date from more than 5 years, which with the amount of new data implies for a more updated study. Not only that, but the consequence 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 specific to isolated pulsars in recent studies, implying for a updated study on the subject.

5. Discussion and future work

The aim of our work is to establish an up-to-date catalog of isolated RPPs, using existing databases from different X-ray space missions such as Chandra, XMM-Newton, Swift/XRT, and SRG/eRosita from the ANTF catalog (Manchester et al., 2005). After extracting X-ray fluxes from each pulsar, we will calculate their intrinsic luminosity L_X by defining their distance as precisely as possible, using parallaxes from the Gaia mission and dispersion measurement established from radio observations. From that, we will try to establish if a correlation exists between their L_X and their spin-down power $\dot{E}$. Using the parallax method, we do have to consider the low brightness of MSPs in optical, making it harder to determine distances. This method could also be impacted by a potentially important amount of dust. We will restrict our work to a specific energy interval, as most of the presented data studies the correlation for different energy bands.

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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