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

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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 multplies 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.

While many models obtained from studying this correlation have been proposed to explain this phenomena, few have focused their study 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 categories of pulsars we will be working with for this study. Here, we focus exclusively on rotation powererd pulsar (RPPs) where rotational energy is the dominant source of X-ray emission. We exclude magnetars (AXPs and SGRs), as their X-ray properties are not linked to rotational activities. We also concentrate on isolated pulsars specificaly, which is not enough studied.

We also point out that our study include isolated MSPs, which consist of ?? % of known MSPs (source). We precise this fact as the existence of isolated MSPs is itself surprising (source, potentiellemtn [Lee et al., 2018]).

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

2.1. Pulsars and basics definitions

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

Period P.

Spin-down rate $\dot{P}$:. Representing the rate at which a pulsars pulse decrease, it is generally very slow, but it is it which provides energy to generate electromagnetic waves.

Intrinsic X-ray luminosity L_X. 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, ROSAT : 0.1–2 keV, ASCA : 0.4–10 keV, XMM-Newton : 0.2–12 keV, Chandra : (0.110 keV)

Spin-down power $\dot{E}$. Also refered as spin-down luminosity, rotational loss etc.... It is defined as $\dot{E} = 4\pi^2 I\dot{P}/P^3$ with I the NS momentum of inertia, typically assumed in the literature as $I = 10^{45} g\ cm^2$.

Dispersion measurement (DM). lalala faut expliquer c'est quoi et a quoi ça sert

While thermal emissions of X-ray can be derived from the black body emission, the non-thermal one is still subject to debate. 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. It is a helpful starting point for understanding the diverse subclasses of pulsars and their connections, the intrinsic properties of neutron star formation, evolution, magnetic field, and age (Huang et al. 2022)

2.2. A brief history of the correlation study

Here, we present the articles considered as the basis of the subject, considering their citation number and being cited in most articles discussed in the next section. 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 pulsars hidden in remnants which show evidence for a central compact object or associated nebular emission, but no clear pulsed signal from the neutron star itself. Using the 22 known isolated pulsar (or 9 ? (2021)) from Einstein data at the time, they first established $L_X(0.2 - 4kev) = 10^{1.39}\dot{E}$ or $\log L_X = 1.39 \log \dot{E} - 16.6$. The uncertainties mostly came from the distances, as they were not well known at the times. Furthermore, these pulsars were mostly young and powerful, and there were nos disction of the pulsars luminosity from the one of its synchrotron nebula.

The study of this correlation was not limited to isolated pulsars. In 1997, "Although ordinary field pulsars and millisecond pulsars form well-separated populations in the $L_X(\tau)$ diagram they obey the same $L_X \propto \dot{E}$ correlation" (Becker and Trümper, 1997). "Using the 27 pulsars avaiable from the ROSAT data, they interpreted this correlation as suggesting that most of the observed X-rays are produced by magnetospheric emission originating from the co-rotating magnetosphere". They reported $L_X(0.1 - 2.4keV) \propto 10^{-3}\dot{E}$. The data was from 1997. « The strong correlation suggests that the prime energy source of the X-ray emission is the pulsar's rotational energy ». « Although ordinary field pulsars and millisecond pulsars form well-separated populations in the $L_X(\tau)$ diagram they obey the same $L_x \propto \dot{E}$ correlation. »

With the increasing amount of data, (Possenti et al., 2002) studied the empirical relation between the X-ray luminosity (in the 2–10 keV band) and the rate of spin-down energy loss Lsd of a sample of 39 pulsars.

While this previous study focused on the soft energy band (0.1 - 2.4 keV), it was theorized later on that a harder energy interval seems preferred to explore the nature of the X-ray emission resulting from the rotational energy loss: at energies above 2 keV the contribution from the neutron star cooling and the spectral fitting uncertainties due to interstellar absorption are reduced.

In 2002, the study of rotation powered pulsars excludes accretion powered pulsars and magnetars (AXPs) from the study, as we will later on. Considering the 39 sources usable, with MSPs, old pulsars, Geminga-like, Vela-like and Crab-like, theyr found $\log L_{X,(2-10)} = 1.34 \log(\dot{E}) - 15.34$ with a reduced $\chi^2 \sim 7.0$ and for the slope 1.34 ± 0.03 and 14.36 ± 1.11 for the constant term for the non-thermal emissions. We do have a reduced chi^2, as a consequence of very uncertain distances.

In 2008, (Li et al., 2008) presented a statistical study of the non-thermal X-ray emission of 27 young rotation powered pulsars (RPPs) and 24 pulsar wind nebulae (PWNe) by using the Chandra and the XMM-Newton observations, which with the high spatial resolutions enable us to spatially resolve pulsars from their surrounding PWNe, and does not includes MSPs. It found, accouting for the uncertainties $L_{X,psr(2-10)kev} = 10^{-0.8\pm1.3}\dot{E}^{0.92\pm0.04}(\chi^2 = 2.6)$. Because of the large scatter this relation must only be seen as an empirical average trend and not suitable for predicting the luminosity of any specific source.

Later on, those work continued using bigger data catalog.. We present those work below.

3. State of the art

3.1. Mesures de flux X des pulsars isolés

Accurate estimates of absorption and distance, upon which the derived luminosity depends strongly, are seldom available.

Here we start with the 2021 article (Hsiang and Chang, 2021). Considering that we are interested in the properties coming from the rotation of pulsars, we will use the $L_{X,psr}$ fit and not the one from the PWNe, as it is not a pulsating parameters (genre ça provient pas de la pulsation du pulsars). The article finds the correlation

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

In (Chang et al., 2023), they found the correlation for non-thermal emissoin

$$L_P \propto \dot{E}^{0.88\pm0.06}(\chi^2_\nu = 3.98)$$

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 we use X-ray luminosities in 0.3–10.0 keV range for XMM-Newton and in 0.5–7.0 keV range for Chandra, further categorizing the data into SX band (<2 keV), hard X-ray (HX) band (>2 keV)

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

which is consistent with the findings of (Chang et al., 2023) within the error margins.

(Lee et al., 2018) studied specifically isolated MSPs, but only 6 are isolated MSPs out of the 35 studied in the sample. Only one correlation is given, and even if they are comparable to other classes of non-isolated, it is not limited to isolated, so debatable

$$L_X = 10^{31.05}(\dot{E}/10^{35})^{1.31} erg/s (2 - 10keV)$$

where $\dot{E}$ is the spin-down power 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 . . .

Another group studied this correlation : in 2016, (Shibata et al., 2016) they used a sample from the ANTF exclusing MSPs and magnetars and puslar in binary system, so only isolated pulsars;

$$L_x(0.5 - 10keV) = 10^{31.69}(L_{rot}/L0)c_1$$

with $c_1 = 1.03 \pm 0.27$ and $L_0 = 10^{35.38}$

Also (Enoto et al., 2019)

(Malov and Timirkeeva, 2019) found

$$L_X = 3.47 \times 10^{-10}(dE/dt)^{1.17}$$

(Prinz and Becker, 2015) found

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

comparing with (Possenti et al., 2002)

3.2. *Distances defined in previous studies*

Most of these studies adopted a 40% uncertainties on distances, using ANTF catalog.

4. Conclusion

Most data is old, and the impact from the distances uncertainties is too impactful on data. We propose to use a more adapted DM model and more recent data, and also use Gaia

Considering data from the ANTF being updated since 2024 (citer les versions ?), we now have (nombre) new potential data to study

For our upcoming study, we can base ourself on the 2025 article to compare our results.

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

5. Discussion and future work

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.

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