# SHocks: structure, AcceleRation, dissiPation

## Work Package 4
## Exploring acceleration in astrophysical shocks through broadband emission

## Deliverable D4.1
## Technical report on X-ray synchrotron model completion and implementation

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# 1 Summary

It is now well established that the X-ray emission from young supernova remnants (SNRs) emit continuum radiation caused by the synchrotron process. This component is spatially distinct from the thermal X-ray emission, as it is spectroscopically featureless, and confined to regions close to the shock front. In addition, this component extends to the hard X-ray band and has been detected for SNR Cassiopeia A up to at least 100 keV . The current theory to explain the synchrotron radiation is based on the theory of diffusive shock acceleration (DSA), and in order to produce synchrotron radiation in X-rays a highly turbulent magnetic field $(*\delta B/B)^2 \sim 1)$ is required. However, the emission models applied to the data still rely on using a static magnetic field. The turbulence can be tested with the future IXPE mission [Weisskopf et al., 2016], measuring polarisation. But here we explore the practical—i.e. measurable—consequences of a highly turbulent magnetic field on the broad-band X-ray emission.

We summarise the existing theory for synchrotron radiation in a turbulent magnetic field, which predicts that the synchrotron spectrum has an additional power law component, whose photon index $\Gamma$ is directly proportional to the turbulent spectrum $P(k) \propto k^{-s}$, resulting in $\Gamma = s + 1$.

We briefly discuss the consequences for Cas A, and then explain a simple model that we developed and which can be called from with the open software *XSPEC* and its Python version *PyXspec*.

# 2 Introduction

*This report summarizes X-ray synchrotron model completion and its implementation, and serves as a basis for the upcoming tasks in Work package 4.*

The discovery of X-ray synchrotron emission from regions immediately downstream of the shocks of young SNRs [Koyama et al., 1995, Vink and Laming, 2003, Völk et al., 2005, Bamba et al., 2005, Helder et al., 2012] has had important implications for our understanding of cosmic-ray acceleration. First of all, the high photon energy of X-ray synchrotron emission implies a rather efficient charged particle acceleration, understood to be caused by diffusive shock acceleration [DSA, eg. Malkov and Drury, 2001]. For example, in case that the maximum electron energy is determined by radiative losses balancing energy gains through DSA one can derive for the typical photon energy [e.g. Aharonian and Atoyan, 1999, Zirakashvili and Aharonian, 2007, Vink, 2020]:

$$h\nu_{\rm c} \approx 3\eta^{-1} \left( \frac{V_{\rm s}}{5000\ {\rm km\,s^{-1}}} \right)^2\ {\rm keV}, \tag{1}$$

with $V_{\rm s}$ the shock velocity and $\eta$ the level of magnetic turbulence, important for the diffusion of the relevant electrons:

$$\eta \equiv \left\langle \frac{\delta B}{B} \right\rangle^{-2}. \tag{2}$$

Given that the evidence for X-ray synchrotron emission is typically identified in the 4-6 keV band, which is typically devoid of X-ray line emission, this equation implies that the level of magnetic field turbulence must be high, $\eta \approx 1$–5, and close to the so called Bohm limit of $\eta = 1$, for which typical mean free path of the particles is roughly the gyroradius—i.e. $\lambda_{\rm mfp} \approx r_{\rm g} = E/eB$. This level of turbulence implies that protons may be accelerated up to $10^{13}$–$10^{14}$ eV [Lagage and Cesarsky, 1983], provided the magnetic field is amplified. Secondly, the morphology of the X-ray synchrotron emitting region, seems to be confined to regions close to the shock front, implying relatively large magnetic fields [Vink and Laming, 2003, Bamba et al., 2005, Völk et al., 2005], indicative of magnetic-field amplification near the shock, as theorised in [Bell, 2004] for example. The reason is that strong radiative cooling of the maximum electrons implies that they lose energy once they are advective too far downstream of the shock. The stronger the magnetic field, the shorter the time scale ($\tau$) over which the electron population is cooled. Assuming an observed length scale ($l_{\rm obs}$) that is a combination of the advection length scale ($l_{\rm adv} = \Delta v \tau$) and the diffusion length scale (i.e. $l_{\rm diff} = D/\Delta v$) one finds

$$B_2 \approx 110 \eta^{1/3} \left( \frac{l_{\rm obs}}{10^{17}\ {\rm cm}} \right)^{-2/3}\ \mu{\rm G}, \tag{3}$$

with $B_2$ the average magnetic-field strength downstream (i.e. in the shock-heated plasma). For young SNRs one typically finds $B_2 \approx 50$–$500\ \mu$G [Helder et al., 2012], which is more than one would expect from simple compression of the typical magnetic field in the interstellar medium $B_1 \approx 5\ \mu{\rm G} \rightarrow B_2 \lesssim 20\ \mu$G.

So although the X-ray synchrotron emission strictly tells us about the ultra-relativistic electrons, the evidence for turbulent magnetic fields ($\eta \sim 1$) and magnetic-field amplification has had a profound impact of our general understanding of DSA in SNRs. However, one important aspect is often overlooked in the modelling of X-ray synchrotron spectra from young SNRs: our general understanding uses the turbulence of the magnetic field to describe DSA (see the use of $\eta$), but neglects the impact magnetic-field turbulence has on the shape of the X-ray synchrotron spectra.

# 3 The current standard model for X-ray synchrotron emission and its limitations

It is customary to assume that the electron spectrum shaped by DSA and radiative losses, or losses due to a limited time of acceleration, is given by

$$N(E) \propto K E^{-q} \exp\left[ -\left( \frac{E}{E_{\rm cutoff}} \right)^{a} \right], \tag{4}$$

with $q \approx 2$ the particle index, $E_{\rm cutoff}$ the cutoff energy and $a$ a parameter governing the steepness of the cutoff, with $a = 1$ inferred for age-limited distributions [Reynolds, 1998] and $a = 2$ for radiative-loss-limited distributions [Zirakashvili and Aharonian, 2007], see also [Yamazaki et al., 2014].

For a uniform magnetic field this gives rise to a synchrotron spectral shape of

$$n(h\nu) \propto (h\nu)^{-\Gamma} \exp\left[ -\left( \frac{h\nu}{h\nu_{\rm c}} \right)^{\beta} \right], \tag{5}$$

with $\Gamma = (q+1)/2$[1]. An additional complication is that radiative cooling result in an additional cooling break steepening the power law from $\Gamma \rightarrow \Gamma + \frac{1}{2}$ [Zirakashvili and Aharonian, 2007]. However, we limit ourselves here to spectra close to the shock front where the break frequency is very close to $h\nu_{\rm c}$. According to [Zirakashvili and Aharonian, 2007] $\beta \approx 0.5$ for $a = 2$, but the popular *xspec*[2] model *srcut* [Reynolds, 1998] uses a different approximation. This *xspec* model in particular has been popular to determine the relevant cutoff photon energy of the synchrotron spectra [e.g. Bamba et al., 2005]. In general the X-ray synchrotron spectra below 10 keV have spectra of $\Gamma \approx 3$.

In that light it is interesting that for a few young SNRs, notably Cas A and Tycho's SNR, X-ray synchrotron emission has been measured well above 10 keV [Favata et al., 1997, Allen et al., 1997, The et al., 1996, Vink, 2008, Grefenstette et al., 2015], and these hard X-ray spectra are best described by a power-law spectrum that appears a continuation of the soft X-ray spectrum. The description of the spectrum around the cutoff also seems puzzling in light of the standard theory explained in the introduction. For example, the cutoff photon energy should according to (1) scale with $V_{\rm s}^2$, but NuStar observations of Tycho's SNR appears to suggest that $h\nu_{\rm c} \propto V_{\rm s}^4$ or even a steeper dependency [Lopez et al., 2015].

There may be some second order effects in DSA that we do not yet understand—for example $\eta$ could also be dependent on $V_{\rm s}$. But it may also be that the fitting models used—i.e. (5)— are incorrect. *One important aspect ignored in the fitting models ignored up to now is the fact that the magnetic-field turbulence must have some affect on the synchrotron spectrum not incorporated in (5).* As part of the SHARP project we would like to make the next step and investigate whether indeed the spectra are influenced by magnetic-field turbulence and what the consequences are for understanding the underlying electron energy distribution and the implications for understanding DSA in SNRs.

*Taking this next step involves two aspects: describing the effects of the magnetic-field turbulence on the spectrum, and then quantitatively measuring these effects in observed synchrotron spectra. The reward is hopefully also that the results will inform us quantitatively about the magnetic-field turbulence spectrum, as already pointed out in [Yamazaki et al., 2014].*

# 4 The next step: synchrotron spectra from turbulent plasmas

In surveying the literature we found out that quite some relevant literature exist on the effects of magnetic-field turbulence on the spectral distribution of synchrotron emission, the outcome of which we briefly review here. We note that here that any form of turbulence has the tendency to soften the impact of the electron cutoff on the resulting spectral shape. Recently the effect of a Gaussian distribution of magnetic-field strengths was investigated in [Derishev and Aharonian, 2019], who found that an electron cutoff governed by a shape parameter $a$ results in a

[1] This corresponds to the synchrotron radiation spectral index $\alpha = \Gamma - 1 = (q-1)/2$ used for radio spectra

[2] `https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html`

spectrum with spectral cutoff shape

$$\beta = \frac{2a}{3a+4}, \tag{6}$$

which for $a = 2$ gives $\beta = 0.4$ slightly less sharp than $\beta = 0.5$ inferred in [Zirakashvili and Aharonian, 2007].

However, in reference [Derishev and Aharonian, 2019] one has simply integrated the expected synchrotron shape for a uniform magnetic-field configuration over a Gaussian distribution. This is only valid if the magnetic-field fluctuations have a characteristic length scale larger that the gyroradius of the electrons near the cutoff energy—i.e. $l_{\mathrm{B}} > E_{\mathrm{cutoff}}/e < B >$.

More interesting is the case in which one considers the spectrum of magnetic-field turbulence as a function of turbulence wavelength $k$:

$$P(k) \propto k^{-s}, \tag{7}$$

which results in a diffusion parameter [Yamazaki et al., 2014]

$$D \propto E^{2-s}. \tag{8}$$

For the theory of DSA there are three interesting cases: $s = 5/3$ for Kolmogorov turbulence, $s = 3/2$ for Kraichnan turbulence, and $s = 2$ which is required for Bohm diffusion independent of particle energy, $\eta = 1$ for all $E$.

The resulting synchrotron spectra have been theoretically investigated in [Toptygin and Fleishman, 1987] and [Kelner et al., 2013], and the resulting radiation is sometimes referred to *"jiiter radiation"*. For an underlying electron spectrum with a power-law distribution given by (4) one finds two broad regimes in the radiation spectrum depending on the critical photon energy [Toptygin and Fleishman, 1987]

$$\nu_* \equiv \left(\frac{\omega_{\mathrm{B}\perp}}{2\pi}\right)\gamma^2_{\mathrm{cutoff}} \approx \left(\frac{eB_\perp}{2\pi m_{\mathrm{e}}c}\right)\left(\frac{E_{\mathrm{cutoff}}}{m_{\mathrm{e}}c}\right)^2 \Lambda, \tag{9}$$

with $\omega_{\mathrm{B}\perp} = eB_\perp/m_{\mathrm{e}}c^2$ the electron cyclotron frequency for the large scale magnetic field, and $\Lambda$ a logarithmic factor[3] [Toptygin and Fleishman, 1987]. In addition to a large-scale (quasi uniform) magnetic field, one also needs to consider the magnetic-field energy density in turbulent magnetic field $\sqrt{< B_t^2 >}$, and its associate cyclotron frequency $\omega_{\mathrm{t}} = e\sqrt{< B_{\mathrm{t}}^2 >}/m_{\mathrm{e}}c$. This field is taken to be static, i.e. the time variation is relatively slow and is neglected for the purpose of calculating the synchrotron radiation. Finally, there is a frequency $\omega_0 = ck_0$ associated with the wave number of the smallest magnetic-field turbulence mode,

$$k_0 = 2\pi/l_{\mathrm{min}}. \tag{10}$$

Within this framework *the two frequency regimes are now*:

[3]This is given by

$$\Lambda = \frac{3}{2}\ln\left[\frac{3^{s+3/2}(s+2)\Gamma(s/2-1/2)}{2^{2s+5/2}\Gamma(s/2)}\frac{\omega_{\mathrm{B}\perp}^{s+1}}{\omega_{\mathrm{st}}^2\omega_0^{s-1}}\right].$$

1. $\nu \ll \nu_*$: The photon spectrum has a shape similar to the traditional synchrotron spectrum, a power law corresponding to $N(h\nu) \propto (h\nu)^{-(q+1)/2}$,

2. $\nu \gg \nu_*$: The photon spectrum has also a power-law shape but with a shape reflecting the index of the magnetic turbulence spectrum: $N(h\nu) \propto (h\nu)^{-(s+1)}$,

with $s$ corresponding to (7). In the spectral region for which $\nu \approx \nu_*$ we have an exponential decline, and then a connection to the power-law with $\nu^{-(s+1)}$. We refer here to regime 1. as the synchrotron regime and 2. as the jitter regime.

So an important conclusion is that *if jitter radiation is (partially) responsible for the hard X-ray emission from young SNRs, the power-law slope in hard X-rays directly informs us about the power-law slope of magnetic-field fluctuations.* The jitter regime should extend to a maximum frequency

$$\nu_{\max} \approx \frac{c}{2\pi l_{\min}} \left(\frac{E_{\rm cutoff}}{m_{\rm e}c^2}\right)^2. \tag{11}$$

The luminosity in the the two regimes separated by $\nu_*$ also depends on the factors of an order unity and the ratios of several frequencies [Toptygin and Fleishman, 1987]:

$$\frac{P_2}{P_1} = \frac{2^{s+1}(q+1)\Gamma(s/2)}{3^{1+q/2}\pi^{1/2}(s+1)(2s+1-q)\Gamma(s/2-1/2)\Gamma(q/4-1/12)\Gamma(q/4+19/12)} \times \frac{\omega_{\rm t}^2\omega_0^{s-1}}{\omega_{B\perp}^{s+1}}, \tag{12}$$

with $P_2$ the jitter regime and $P_1$ the synchrotron regime.[4]

**To summarise: including magnetic-field fluctuations in the calculations of broad band synchrotron radiation results at the very basic level in 1) a softening of the exponential synchrotron cutoff spectrum [Derishev and Aharonian, 2019], but more likely, in the case $\delta B/B \sim 1$ in "jitter radiation" [Toptygin and Fleishman, 1987] which produces a power-law with a slope that directly relates to the magnetic-field spectrum!**

# 5 An example: Implications of jitter radiation for Cas A

In order to estimate the effects of jitter radiation and implication we provide here as an example Cas A. Cas A is the second youngest SNR in the Galaxy and the brightest radio source in the sky. This SNR has been crucial for our general understanding of SNRs in general, and particle acceleration by SNRs in particular.

Here we use the observed characteristics of the X-ray synchrotron emission of Cas A to put constraints on the properties of the turbulent plasma in the framework of the jitter radiation theory, based on the hard X-ray properties described

[4] We change the labeling with respect to [Toptygin and Fleishman, 1987] in order to go from low to high frequency and preserve the labeling used above.

in the literature. These are based on measurements with RXTE [Allen et al., 1997], BeppoSAX-PDS [Favata et al., 1997, Vink and Laming, 2003, Vink, 2008], INTEGRAL-ISGRI [Renaud et al., 2006], and NuStar [Grefenstette et al., 2015], all with detections from $\sim$ 10–100 keV, as well as Chandra at lower energies [e.g. Helder and Vink, 2008]. In addition there is evidence for emission above 100 keV by CGRO-OSSE [The et al., 1996]. These studies show that the hard X-ray data are consistent with a power-law spectrum with index $\Gamma \approx 3.2$.

The question is now whether the broad-band X-ray synchrotron radiation from $\sim 1$–$\sim 150$ keV is just the trailing of the synchrotron radiation, i.e. an extension of the radio spectrum with an exponential decay, or a signature of a jitter component to the synchrotron radiation?

As discussed above for jitter radiation we expect a power-law with exponential cut-off caused by the largest scale magnetic fields, plus an additional power-law component ending at potentially hard X-ray energies?

For jitter radiation we need the first power-law component with $\Gamma = \alpha + 1$, which is expected to be $\Gamma = 1.6$ for Cas A, followed by an exponential cutoff at (9)

$$h\nu_* = 2.8 \left(\frac{B_\perp}{100\ \mu\mathrm{G}}\right)\left(\frac{E_{\mathrm{cutoff}}}{10\ \mathrm{TeV}}\right)^2 \Lambda\ \mathrm{keV}, \quad (13)$$

with $B_\perp$ the magnetic-field of the large scale component.

Beyond $\sim h\nu_*$ the jitter component takes over with $\Gamma_2 = s + 1$. Since observations for Cas A suggest $\Gamma \approx 3.2$, the observed component could be indeed due to a turbulent magnetic-field with $s = \Gamma - 1 \approx 2.2$. This is much steeper than Kolmogrov turbulence ($s = 5/3$), but consistent with Bohm diffusion. This makes jitter radiation a promising explanation!

The ratio between the jitter and synchrotron component around $h\nu_*$ (12) cannot be too small, whilst than the hard X-ray emission would not be observable. According to (12) the ratio depends on the ratio between the large scale magnetic-field strength $B_\perp$ and the turbulent magnetic field $B_\mathrm{t} = \sqrt{< B^2 >}$, which is expected to be relatively high for efficient cosmic-ray acceleration. Taking $B_\mathrm{t} = f B_\perp$, the ratio $P_2/P_1$ depends on

$$\frac{\omega_{\mathrm{st}}^2 \omega_0^{s-1}}{(\omega_{B\perp})^{s+1}} = f^2 \left(\frac{\omega_0}{\omega_{\mathrm{B}\perp}}\right)^{s-1}, \quad (14)$$

with $\omega_0 = k_0 c$, with $k_0 = 2\pi/l_{\mathrm{max}}$, and likely $f \sim 1$. Here $l_{\mathrm{max}}$ indicates the maximum scale for turbulence.

So jitter radiation, once positively identified, provides information on the turbulent spectrum through $\Gamma_2$, $\omega_0$ — and thus the largest turbulence scale $l_{\mathrm{max}}$—and $B_\mathrm{t}/B_\perp$ through (12), and finally on the minimum turbulence scale $l_{\mathrm{min}}$ as it determines $h\nu_{\mathrm{max}}$ (1). For Cas A, there is evidence that $h\nu_{\mathrm{max}} \gtrsim 100$ keV, suggesting $l_{\mathrm{min}} \sim 10^4$ cm.

The nice thing is that the archive for NuStar, SWIFT and Integral contains sufficient data to test the jitter model for Cas A, as well as for some other young SNRs.

# 6 XSPEC models for exploring X-ray synchrotron emission from turbulent plasmas

## 6.1 Practical issues

The theory of ”jitter radiation” promises to be important for our understanding of the non-thermal X-ray emission from young SNRs, and on top of that offers us an opportunity to explore the magnetic-field turbulence spectrum. In that sense it will be complementary to X-ray polarisation which will measured once the NASA mission IXPE [Weisskopf et al., 2016] has been launched (expected in December 2021).

In practical terms the theory suggests that the synchrotron spectrum can be described by a minimum of six, but more safely by eight parameters:

1. `norm1`: synchrotron normalisation
2. `PhoIndex1`: synchrotron power-law slope ($\Gamma_1$)
3. `break1`: synchrotron cutoff energy ($h\nu_*$)
4. `PhoIndex2`: jitter-radiation power-law slope ($\Gamma_2$)
5. `break2`: jitter-radiation cutoff energy ($h\nu_{\rm max}$)
6. `jratio`: ratio between flux in regime 1 and regime 2 ($P_2/P_1$)

   The additional parameters are not described in Toptygin and Fleishman [1987]:
7. `beta1`: shape of the exponential cutoff around `break1` ($\propto \exp[-(\nu/\nu_*)^{\beta_1}]$)
8. `beta2`: shape of the exponential cutoff around `break2` ($\propto \exp[-(\nu/\nu_{\rm max})^{\beta_2}]$)

Not all these parameters can be fitted. The photon index 1 is best set to the value obtained from the radio measurements ($\Gamma_1 = \alpha + 1$) and the shape functions $\beta_1$ and $\beta_2$ can be best fixed to $\beta_1 = \beta_2$ following Yamazaki et al. [2014].

Another practical issue is that $h\nu_*$ may fall outside the X-ray band, in which case `norm1` and `break1` can be best set to educated guesses, and fitting is limited to `PhoIndex2` and `jratio`. This case is not that interesting as it is equal to fitting a simple power-law function. However, the model as given allows the flexibility of testing various theoretical expectations, from simple synchrotron radiation (fit only `norm1`, `PhoIndex1`, `break1` with `jitterratio` set to zero).

## 6.2 Implementation in xspec

XSPEC is the standard X-ray spectral fitting package [Arnaud and Raymond, 1992] maintained by NASA[5]. The software comes with standard emission models, fitting algorithms and display options. More recently, Python interfaces for XSPEC have been developed under the form of the PyXspec[6] package. This Python version allows the same options than the standard XSPEC, most notably the implementation of user defined models. We take this approach here and implement our jitter radiation model using the `addPyMod` method from PyXspec. For

[5] `https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html`
[6] https://heasarc.gsfc.nasa.gov/xanadu/xspec/python/html/index.html

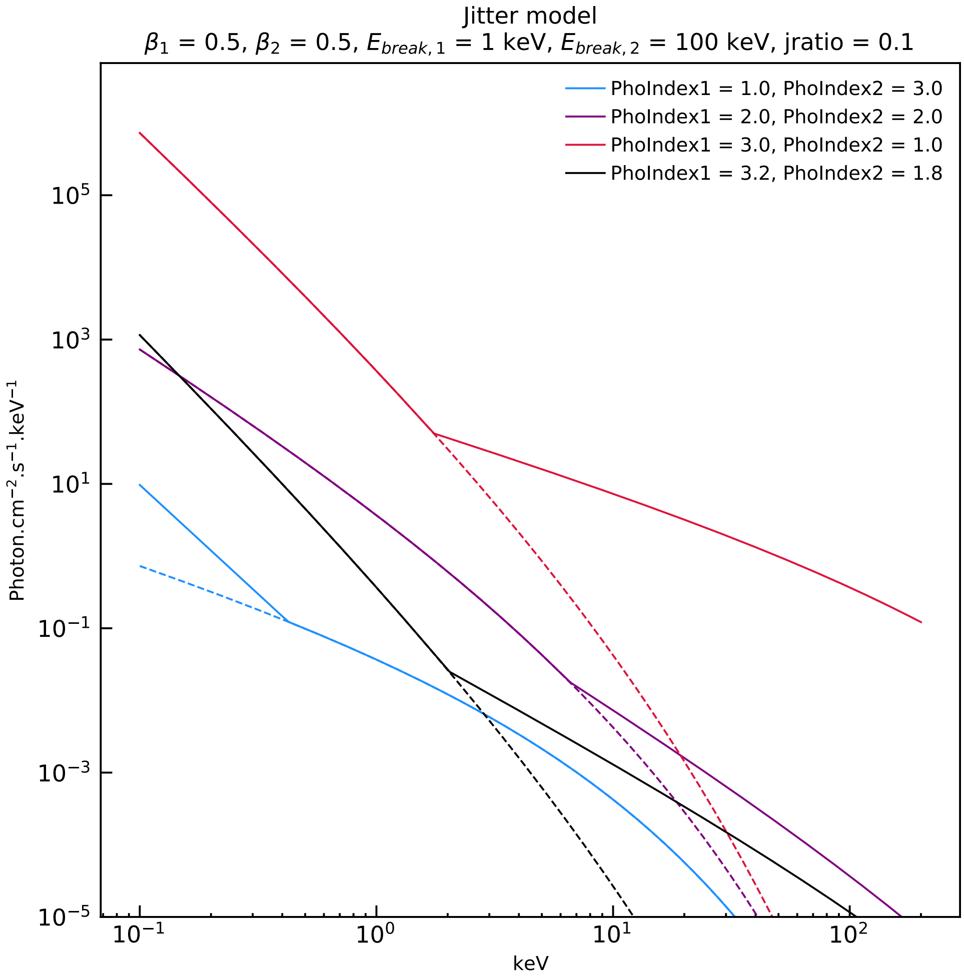


Figure 1: Jitter radiation spectra with different sets of arbitrary parameters (full curves). The black curve roughly corresponds to a Cas A like X-ray spectrum. The associated synchrotron spectrum without jitter radiation is also displayed (dashed curves).

now, the model can only be used through PyXspec, but a future Fortran version will be developed to be used by regular Xspec users. The codes as well as example scripts can be found at the following link: https://github.com/aellien/sharp.

# 7 Conclusion

We showed that turbulent magnetic fields are predicted to alter the standard synchrotron spectrum: instead of a power-law spectrum with exponential cutoff, an additional power-law component extends beyond the cutoff.

We explained the theory behind this, which is sometimes referred to as jitter radiation, and developed an *xspec* model to test the jitter radiation on archival X-ray data.

Our next step will be to indeed explore jitter radiation using the available archival data. This new data analysis will provide information on the turbulence of the magnetic field that will be complementary to what IXPE [Weisskopf et al., 2016] is likely to find based on X-ray polarisation measurements.

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