0945070133 – 10

Source Identification, Counterparts and Properties

STONKS alert

- Type of Alert: High Flux State,
- Long-term Variability = 8.1,
- No short-term Variability.

Simbad

https://simbad.cds.unistra.fr/simbad/sim-id?Ident=%4013058032&Name=2MASS%20J03332989-2714334&submit=submit

The source is identified on *Simbad* as a Star: 2MASS J03332989-2714334.

ESASky

https://sky.esa.int/esasky/?target=53.37579166666667%20-27.242833333333333&hips=XMM-Newton+EPIC+color&fov=1&projection=SIN&cooframe=J2000&sci=true&lang=fr

The source has multiple counterparts on *ESASky*:

- EPIC Stack (Soft X-ray)
- XMM-SUSS 6.2 (UV to Optical)? Slightly off.
- Gaia DR3 (Optical)
- Euclid MER Q1 (Optical to Near-IR)
- 2MASS (Near-IR)
- AllWISE (Near-IR to Mid-IR)

Gaia DR3 gives the following useful information:

- Parallax: $P = 1.9836\ mas \rightarrow d \approx 504\ pc$,
- Magnitude: $G = 17.5984$.

There are 1 publication: Kado-Fong, E. et al., M Dwarf Activity in the Pan-STARRS1 Medium-Deep Survey: First Catalog and Rotation Periods, December 2016 (https://ui.adsabs.harvard.edu/abs/2016ApJ...833..281K/abstract).

3DNH-tool

http://astro.uni-tuebingen.de/nh3d/nhtool

3DNH-tool suggests a column density of $n_H \approx 2 * 10^{20}\ cm^{-2}$, which is relatively low, typical of a Galactic source. However, this value might not be reliable as it does not account for the distance of the source.

X-ray Variability and Periodicity

Only the data from the PN instrument observation show a periodicity. As the results differ between instruments, we chose to consider only those from the instrument with the highest maximum likelihood.

According to the STONKS alert document, the maximum likelihood for PN is $DetML = 94.8$, while for M2 it is $DetML = 33.3$, supporting our decision to rely solely on the PN data.

The source exhibits an extremely short period of $P = 0.337\ s$, characteristic of a rotating compact object, like:

- A pulsar (e.g., rotation-powered neutron star),
- A magnetic white dwarf (e.g., DQ Her-type),
- Or possibly a flaring low-mass star, although this is unusually fast.

But since the source is identified as stellar, this heavily favours a compact object binary (e.g., X-ray emitting white dwarf or neutron star).

Nevertheless, the STONKS alert document mention a long-term variability of 8.1 (what does this value mean?) but no short-term variability which contradict with our results. We consider the information provided by STONKS to be more reliable than our own results (because obviously I am only a student).

The presence of long-term variability is consistent with the M-dwarf hypothesis mention in the publication of Kado-Fong et al.

X-ray Spectral Properties

Xspec models

The main models that we are using are: Black body, Bremsstrahlung, Apec and Powerlaw, or a combination of two components: Black body and Powerlaw, Bremsstrahlung and Powerlaw and, Apec and Apec.

Black body

When an X-ray spectrum is well fitted by a black body model, it suggests that the X-ray emission is coming from a hot, dense surface or region that radiates like an ideal thermal emitter (i.e. a black body). A black body emits radiation with a spectrum that depends only on its temperature, and this emission is:

- Smooth and has a characteristic peak at a certain energy,
- Thermal, meaning it reflects a state of thermal equilibrium,
- Strongly dependent on temperature (the hotter the black body, the more it emits and the higher the peak energy).

A black body model fit generally implies that the X-rays are emitted by a compact and hot surface (not by diffuse gas). Likely sources include:

- The surface of a neutron star,
- The boundary layer in a white dwarf system (e.g., in cataclysmic variables),
- The accretion disk's inner region (if dense and hot enough),
- Or even a hot stellar photosphere.

Bremsstrahlung

When a bremsstrahlung model (also known as thermal bremsstrahlung or free-free emission) fits an X-ray spectrum well, it suggests that the X-ray emission is primarily produced by hot, ionized gas (i.e. plasma) through a specific process: Bremsstrahlung (German for "braking radiation") occurs when electrons are decelerated as they pass near atomic nuclei. This deceleration causes them to lose energy in the form of X-ray photons. This type of emission is thermal, meaning the spectrum depends on the temperature of the plasma. A good fit with this model indicates that:

- The X-ray source likely contains hot plasma (temperatures typically in the range of millions of Kelvins, so $\sim 10^{-2} keV$ to $\sim keV$).
- The X-ray spectrum is smooth and continuous, without strong emission lines (although lines may still be present if other processes are involved).

It is common in environments like:

- Accretion shocks (e.g., in cataclysmic variables, where infalling material heats up).
- Stellar coronae (like in active M-dwarfs).
- Supernova remnants or galaxy clusters.

Source of the plasma temperature: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/plasma-temperature.

Astrophysical Plasma Emission Code (APEC)

When an X-ray spectrum is well fitted by an Apec model, it indicates that the emission is coming from a hot, diffuse, optically thin plasma in collisional ionization equilibrium. It models emission from a plasma that contains a mix of elements (H, He, Fe, etc.) at a certain temperature, where:

- Electrons collide with ions, exciting them,
- The ions then de-excite by emitting photons, often in the X-ray range,
- Both continuum emission (mainly bremsstrahlung) and emission lines are included in the model.

Thus, when Apec fits the spectrum, it suggests that:

- We are observing a thermal plasma (like bremsstrahlung, but with line emissions),
- The plasma is optically thin (photons escape without being absorbed),
- The plasma is in collisional ionization equilibrium, meaning the ionization state is stable and set by the temperature.

It is common in environments like:

- Stellar coronae (like in active M-dwarfs),
- Supernova remnants,
- Hot gas in galaxy clusters,
- Accretion disks or shocks in systems like cataclysmic variables (CVs),
- Flares, where gas is suddenly heated and emits thermal X-rays.

Powerlaw

When an X-ray spectrum is well fit by a powerlaw model, it means that the emission is of non-thermal origin, meaning that it doesn't come from a hot gas or a thermal surface like in blackbody or bremsstrahlung models. Instead, it points to processes involving high-energy particles, such as acceleration or scattering. Mathematically, a powerlaw has the form:

$$F(E) \propto E^{-\Gamma}$$

With $F(E)$ the flux of photon at energy E and Γ the photon index (PhoIndex in *Xspec*) typically between 1 and 3. A steeper index (higher Γ) means the spectrum drops off faster with energy.

A good powerlaw fit implies non-thermal emission mechanisms, such as:

- Synchrotron radiation (relativistic electrons spiralling in magnetic fields),
- Inverse Compton scattering (high-energy electrons boosting low-energy photons),
- Emission from accretion flows, like in black holes or neutron stars,
- Emission from magnetically active stars (e.g. in the tail of a flare event).

We might see a powerlaw spectrum from:

- Active Galactic Nuclei (AGN) because of the non-thermal emission from jets or corona,
- X-ray binaries because of the accretion-powered emission with comptonization,
- Pulsars or magnetars because of the synchrotron and curvature radiation,
- Some flare stars or M-dwarfs because of high-energy particles in flare tails,
- Cataclysmic variables (CVs) if there is a strong magnetic activity or shock jets.

Fit statistic

Chi-squared

The chi-squared fit statistic assumes that each bin contains enough events to approximate the Poisson distribution with a normal distribution. If some bins have under 20 counts, this test becomes unreliable. In order to be more secure, we will consider that if the bins have less than 100 counts, C-statistic should be used instead. Here, we have about 95 counts which under 100 but still close, so we will do both Chi-squared and C-statistic.

The Chi-squared χ^2 is the sum of the squared residuals, weighted by the errors in the data. The reduce Chi-squared χ_ν^2 (reduced by the number of degrees of freedom) is:

$$\chi_\nu^2 = \frac{\chi^2}{n_{bins} - n_{parameter}}$$

- $\chi_\nu^2 \approx 1$: Good fit.
- $\chi_\nu^2 \gg 1$: Bad fit.
- $\chi_\nu^2 \ll 1$: Overfitting?

Here, the number of bins is: $n_{bins} = 5$. The number of parameters $n_{parameter}$ depends on the model:

Model	$n_{parameter}$	Main parameters
tbabs*bbody	3	nH, kT, norm
tbabs*bremss	3	nH, kT, norm
tbabs*apec	4	nH, kT, abondance, norm
tbabs*powerlaw	3	nH, PhoIndex, norm
tbabs*(bbody+powerlaw)	5	nH, kT, norm (bbody), PhoIndex, norm (powerlaw)
tbabs*(bremss+powerlaw)	5	nH, kT, norm (bremss), PhoIndex, norm (powerlaw)
tbabs*(apec+apec)	6	nH, temp1, abondance, norm1, temp2, norm2

Let's compare the most promising models (i.e. with the chi-squared closest to 1):

Criteria	Bremsstrahlung	Powerlaw	Black body + Powerlaw	Bremsstrahlung + Powerlaw
Chi-squared χ^2	1.1526	1.1882	1.1923	0.2076

Reduce Chi-squared χ_v^2 (5 bins)	0.5763	0.5941	nan	nan
Column density n_H $(10^{22}\ cm^{-2})$	7.584e-02 ± 0.103	0.225 ± 0.185	0.215 ± 0.403	0.366 ± 8.051
k_T (keV)	1.096 ± 0.75	X	199.355 ± 2.381e+14	0.568 ± 3.353
PhoIndex Γ	X	3.20 ± 1.15	3.137 ± 3.943	9.5 ± 246.635
Norm	2.428e-05 ± 2.082e-05	1.931e-05 ± 1.211e-05	3.106e-11 ± 665.837 (bbody), 1.873e-05 ± 1.491e-05 (powerlaw)	1.051e-04 ± 2.246e-03 (bremss), 6.118e-07 ± 1.656e-04 (powerlaw)
Null hypothesis probability	5.6196e-01	5.5205e-01	nan	nan
Degrees of freedom	2	2	nan	nan

In the case of **Black body + Powerlaw** and **Bremss + Powerlaw** models, $n_{bins} = n_{parameter}$. Therefore, we cannot calculate the reduced chi-squared, because that would amount to dividing by zero. This means that:

- The model has too many parameters compared to the data,
- The models are fitting the data exactly (overfitting),
- The χ^2 may be close to zero, but no longer has any statistical significance, because there is no room for error to assess the quality of the fit.

We generally prefer that $n_{bins} \gg n_{parameter}$. Ideally, we want at least a few dozen degrees of freedom for the χ^2 to be reliable.

Moreover, for the **Bremsstrahlung + Powerlaw** model:

- The spectral index is very poorly constrained $(PhoIndex = 9.5 \pm 246)$. This shows that either the model is too flexible, the powerlaw component is not necessary or the data are insufficient to constrain this part of the spectrum.
- The value of k_T is quite low $(\sim 0.57\ keV)$, which is still in soft emission.

For the **Black body + Powerlaw** model k_T is extremely poorly constrained. The very large errors on both of these models show that degeneracy remains a problem.

Thus, we will only retain **Bremsstrahlung** and **Powerlaw** models as promising:

- Both have a χ_v^2 very close to 1, indicating that they fit the data well (over 5 bins).
- The column density value given by the **Bremsstrahlung** model is the closest one to what 3DNH-tool suggest with $n_H \approx 7.58 * 10^{20}\ cm^{-2}$. The value of the column density of the **Powerlaw** model is: $n_H \approx 2.25 * 10^{21}\ cm^{-2}$, indicating a farer source but still coherent. Both imply a Galactic source.
- The **Bremsstrahlung** model has a temperature $k_T \approx\ 1\ keV$, which is consistent with hot plasmas, indicating possible coronal activity or accretion.

- The **Powerlaw** model yields a high photon index ($\Gamma \approx 3.2$), which is rather soft, and therefore more typical of certain non-thermal sources or a spectrum dominated by the diffuse background (synchrotron, inverse Compton).
- The uncertainties are significant in both cases, but slightly smaller for **Powerlaw**.
- The probabilities of the null hypothesis are equivalent ($\sim 0.55 - 0.56$), so neither is statistically better.

Based solely on the statistical quality of the fit, the **Bremsstrahlung** model is slightly better. However, the final choice depends on the astrophysical context of your source:

- If the source is thermal, then the **Bremsstrahlung** model is more relevant.
- If the source is non-thermal (e.g., AGN, pulsar, synchrotron), then the **Powerlaw** model is more appropriate.

C-statistic

In general, we can compare the value of C-statistic to $n_{bins} \pm \sqrt{2 * n_{bins}}$ as an order of magnitude. Here, the expected C-statistic value of a "perfect" fit is: C-statistic ≈ 129 ± 16 (with $n_{bins} = 129$). So, a C-statistic value between 113 and 145 approximately.

Let's compare the most promising models (i.e. with C-statistic between 113 and 145):

Criteria	Bremsstrahlung	Apec	Powerlaw	Apec + Apec
C-statistic	135.7132	132.8102	134.7690	130.2412
Column density n_H $(10^{22}\ cm^{-2})$	4.62e-04 ± 2.63e-02	1.918e-09 ± 2.62e-02	4.503e-02 ± 5.008e-02	4.105e-16 ± 0.359
k_T (keV)	2.70 ± 1.5	1.87 ± 0.345	X	1.733 ± 0.514 (1), 57.464 ± 1323.80 (2)
PhoIndex Γ	X	X	2.135 ± 0.425	X
Norm	1.32e-05 ± 3.086e-06	1.999e-05 ± 5.289e-06	1.089e-05 ± 2.606e-06	1.707e-05 ± 1.257e-05 (1), 1.222e-05 ± 7.439e-05 (2)
Null hypothesis probability	2.607e-01	7.998e-01	2.698e-01	2.753e-01
Degrees of freedom	126	126	126	124

- The C-statistic values of all models fall within the expected range (113 to 145) to be considered a good fit.
- Only the column density values of **Bremsstrahlung** and **Powerlaw** ($n_H \approx 10^{18} - 10^{20}\ cm^{-2}$) could be coherent and would imply a Galactic source, although the **Bremsstrahlung** one is quite low.
- The **Bremsstrahlung** and **Apec** models have a temperature $k_T \approx 2 - 3\ keV$, which is consistent with hot plasmas, indicating possible coronal activity or accretion.
- The **Powerlaw** model yields a quite high photon index ($\Gamma \approx 2.1$), which is rather soft, and therefore more typical of certain non-thermal sources or a spectrum dominated by the diffuse background (synchrotron, inverse Compton).
- The uncertainties are significant in all cases, but slightly smaller for **Powerlaw**.

- The probabilities of the null hypothesis are equivalent ($\sim 0.26 - 0.27$) for all models except **Apec** (~ 0.80). Apec's p-value show a stronger support for the null hypothesis. Thus, the other models are more statistically significant.

Supported by the Chi-squared results, **Bremsstrahlung** and **Powerlaw** appear to be the best-fitting models. Although the C-statistic suggests that the **Apec** model may also be viable, the unreliability of its n_H value and its higher p-value make it less promising.

X-ray Flux and X-ray-to-Optical Flux Ratio

The source is detected by Gaia DR3 with a magnitude $G = 17.5984$, a faint object which is consistent with a low-mass star at $500\ pc$.

The G-band corresponds to the wavelength interval of: 330 nm to 1050 nm (https://gaia.obspm.fr/la-mission/les-resultats/article/les-observations-spectro-photometriques).

The optical flux is calculated as follow:

$$F_{optical} = F_0 * 10^{-0.4*G}$$

With $F_0 = 1.05 * 10^{-5}$ Gaia zero-point magnitude.

Here, we have an optical flux of $\boldsymbol{F_{optical} \approx 9.59 * 10^{-13}\ erg/cm^2/s}$.

Chi-squared

From *Xspec* AllModels.calcFlux(".2 12.0") we obtain the X-ray flux:

- Bremsstrahlung model: $F_X \approx 3.06 * 10^{-14}\ erg/cm^2/s$.
- Powerlaw model: $F_X \approx 3.29 * 10^{-14}\ erg/cm^2/s$.

So, an X-ray flux of $\boldsymbol{F_X \approx 3 * 10^{-14}\ erg/cm^2/s}$ regardless of the model.

Then, we calculate the X-ray to optical flux ratio:

- Bremsstrahlung model: $\frac{F_X}{F_{optical}} \approx 0.032$.
- Powerlaw model: $\frac{F_X}{F_{optical}} \approx 0.034$.

So, an X-ray to optical flux ratio of $\boldsymbol{\frac{F_X}{F_{optical}} \approx 0.03}$ regardless of the model.

C-statistic

From *Xspec* AllModels.calcFlux(".2 12.0") we obtain the X-ray flux:

- Apec + Apec model: $F_X \approx 4.56 * 10^{-14}\ erg/cm^2/s$.
- Apec model: $F_X \approx 3.41 * 10^{-14}\ erg/cm^2/s$.
- Bremsstrahlung model: $F_X \approx 5.23 * 10^{-14}\ erg/cm^2/s$.
- Powerlaw model: $F_X \approx 4.72 * 10^{-14}\ erg/cm^2/s$.

So, an X-ray flux between $\boldsymbol{F_X \approx 3 * 10^{-14}\ erg/cm^2/s}$ and $\boldsymbol{F_X \approx 5 * 10^{-14}\ erg/cm^2/s}$ regardless of the model; which is coherent with the value found with chi-squared.

Then, we calculate the X-ray to optical flux ratio:

- Apec + Apec model: $\frac{F_X}{F_{optical}} \approx 0.048$.
- Apec model: $\frac{F_X}{F_{optical}} \approx 0.036$.
- Bremsstrahlung model: $\frac{F_X}{F_{optical}} \approx 0.055$.
- Powerlaw model: $\frac{F_X}{F_{optical}} \approx 0.049$.

So, an X-ray to optical flux ratio between $\sim \mathbf{0.03}$ and $\sim\mathbf{0.06}$ regardless of the model; which is coherent with the value found with chi-squared. This range of values is typical for active late-type stars, cataclysmic variables (CVs), or magnetic white dwarfs.

Luminosity and Distance

In order to calculate the luminosity L in erg/s, the source is assumed to be spherical:

$$L = 4\pi F_X d^2$$

With F_X the X-ray flux calculated previously in $erg/cm^2/s$ and d the distance to the source in cm. This distance is calculated from value of the parallax given by Gaia: $P = 1.9836\ mas$.

We get a distance of $\boldsymbol{d \approx 1.56 * 10^{21}\ cm}$.

Chi-squared

Finally, the luminosity of the source is:

- Bremsstrahlung model: $L_X \approx 9.31 * 10^{29}\ erg/s$.
- Powerlaw model: $L_X \approx 10^{30}\ erg/s$.

So, a luminosity of $\boldsymbol{L_X \approx 10^{30}\ erg/s}$ regardless of the model.

C-statistic

Finally, the luminosity of the source is:

- Apec + Apec model: $L_X \approx 1.39 * 10^{30}\ erg/s$.
- Apec model: $L_X \approx 1.04 * 10^{30}\ erg/s$.
- Bremsstrahlung model: $L_X \approx 1.44 * 10^{30}\ erg/s$.
- Powerlaw model: $L_X \approx 1.59 * 10^{30}\ erg/s$.

So, a luminosity of $\boldsymbol{L_X \approx 10^{30}\ erg/s}$ regardless of the model; which is coherent with the value found with chi-squared.

This luminosity could correspond to:

- An active M stars, flaring,
- A cataclysmic variable in quiescence,
- Polars / Intermediate Polars (magnetic CVs),
- Young pulsars if in a binary (though this would normally be brighter in X-rays).

Possible Classifications

Active M-dwarf (flare Star)

M-dwarfs are active stars that exhibit variability in chromospheric emission and photometry at short and long timescales, including long cycles that are related to dynamo processes.

https://arxiv.org/abs/2303.03998

Strongest candidate due to:

- Simbad identification as a star,
- Multiwavelength detection
- Publication from Kado-Fong, E. et al. M Dwarf Activity in the Pan-STARRS1 Medium-Deep Survey: First Catalog and Rotation Periods, December 2016,
- Long term variability (STONKS alert document),
- Bremsstrahlung, Apec (only with C-statistic) and Powerlaw fit,
- Soft powerlaw index and/or thermal emission,
- Low-to-moderate absorption,
- Galactic source,
- Low X-ray flux $F_X \approx 10^{-14}\ erg/cm^2/s$,
- X-ray to optical flux ratio and luminosity values match flaring M-dwarfs.

However, if the short periodicity we found is actually right, therefore it would not be typical for flares or rotation of M dwarfs (which is hours to days).

https://iopscience.iop.org/article/10.3847/1538-3881/acd6a2/pdf

Cataclysmic Variable (CV)

Also, candidate (not strong candidate at all but why not) due to:

- Short periodicity of $\sim 0.3\ s$ (but the results are not really reliable),
- Multiwavelength detection,
- Bremsstrahlung, Apec (only with C-statistic) and Powerlaw fit,
- Low-to-moderate absorption.
- Galactic source,
- X-ray luminosity $L_X \approx 10^{30}\ erg/s$.