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DARK MATTER LINE EMISSION CONSTRAINTS FROM NuSTAR OBSERVATIONS OF THE BULLET CLUSTER


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ABSTRACT

Some dark matter candidates, e.g., sterile neutrinos, provide observable signatures in the form of mono-energetic line emission. We present the first search for dark matter line emission in the 3–80 keV range in a pointed observation of the Bullet Cluster with NuSTAR. We do not detect any significant line emission and instead we derive upper limits (95% CL) on the flux, and interpret these constraints in the context of sterile neutrinos and more generic dark matter candidates. NuSTAR does not have the sensitivity to constrain the recently claimed line detection at 3.5 keV, but improves on the constraints for energies of 10–25 keV.

Key words: dark matter – line: identification – X-rays: galaxies: clusters

1. INTRODUCTION

Dark matter searches are a key pursuit of both astrophysics and particle physics. The scenario where dark matter is in the form of particles that provide gravity, but otherwise interact very weakly with ordinary matter or photons, is the most compelling (e.g., Taoso et al. 2008). The most promising astrophysical objects for searches for dark matter are clusters of galaxies, along with the Galactic Center and dwarf galaxy satellites to the Milky Way. Here, we consider the top end of the mass scale, galaxy clusters, with total masses—most of it in the form of dark matter—often exceeding $10^{14} M_\odot (\approx 2 \times 10^{47}$ g). Most cluster mass estimates are inferred from X-ray observations (Vikhlinin et al. 2009; Mantz et al. 2010). Under the assumption of hydrostatic equilibrium, X-ray data provide a reasonably accurate model of the mass distribution and imply cluster masses that are roughly consistent with masses measured via gravitational lensing, albeit both types of data are available for only a limited number of objects. Their total masses are roughly five times greater than the baryonic masses inferred from X-ray luminosities (von der Linden et al. 2014).

One possible particle candidate for dark matter is the sterile neutrino (described in the reviews Boyarsky et al. 2009; Kusenko 2009; Drewes 2013, and references therein). In the framework of this minimally neutrino extension of the standard model (νMSM), the lightest of the three sterile neutrinos provides the dark matter. The mass is basically unbound from theory, but some astrophysical constraints apply. The mass is firmly bound from below through the phase space density of nearby dwarf galaxies. The Tremaine–Gunn bound (Tremaine & Gunn 1979) gives a model-independent lower mass of roughly 0.4 keV (Boyarsky et al. 2008b). This limit can be increased if the production method is known; e.g., for resonant production the boundary is approximately 1 keV (Boyarsky et al. 2008b; Destri et al. 2013). An upper limit of a few hundred keV comes from a combination of production mechanisms and line emission searches. The sterile neutrino can, in principle, decay spontaneously via mixing with the standard model neutrinos to two photons of equal energy, with the decay probability given by the mixing angle $(\sin^2(2\theta))$. The resulting signature would be a narrow emission line, corresponding to an energy of $E_\gamma = m_\nu c^2/2$, where $m_\nu$ is the mass of the sterile neutrino. Both the mass and mixing angle are in principle unknown but tied to each other for a given model (Pal & Wolfenstein 1982). The line width would be determined roughly by the velocity dispersion of dark matter particles, which for clusters is of the order of $v \sim 1000$ km s$^{-1}$, which is smaller than the instrumental resolution of current observatories.

If we can limit the X-ray flux of a line at a specific energy and know the distance, we right away have a limit on the luminosity of the line from the cluster. Since we know the total mass of the cluster, we know how many sterile neutrinos there must be at a given assumed energy to provide the total mass of the cluster. Since we have a limit on the line luminosity, the ratio of the two is basically the limit on the decay rate. A number of authors have reported searches for such emission lines in the soft X-ray band (Abazajian & Koushiappas 2006; Boyarsky et al. 2006a, 2006b, 2007b, 2008a, 2008b; Riemer-Sørensen et al. 2006; Riemer-Sørensen et al. 2007; Loewenstein et al. 2009; Riemer-Sørensen & Hansen 2009; Loewenstein & Kusenko 2010; Leccardi & Molendi 2012), with a few claims of potential detections that are yet to be confirmed (Leccardi & Molendi 2012; Boyarsky et al. 2014; Bulbul et al. 2014). For an unambiguous detection, the searches must avoid the spectral regions with line emission associated with atomic (or nuclear) transitions from the cluster gas,
corresponding to any elements with an expected appreciable cosmic abundance.

Bulbul et al. (2014) recently reported a possible signature for such a sterile neutrino at $E_s \approx 3.5$ keV in stacked spectra of galaxy clusters observed with the XMM-Newton satellite; the result was confirmed at lower significance in a couple of individual clusters (Boyarsky et al. 2014), but it remains to be independently confirmed in other types of dark matter objects, or using different instruments such as Suzaku (Anderson et al. 2014; Malyshnev et al. 2014; Riemer-Sørensen 2014; Sekiya et al. 2015; Tamura et al. 2015). Regardless, since there is no theoretical expectation as to the mass of the dark matter sterile neutrino beyond the broad range described above, one should search for its signature in all accessible X-ray spectral bands.

Here, we report on a search extending the energy range to the hard X-ray band, and thus the mass of the putative sterile neutrino to twice the upper end of the NuSTAR’s bandpass, $m_s = 156$ keV. Prior to the launch of NuSTAR, there were no sensitive spectral measurements beyond 10 keV, mainly because sensitive measurements require focusing optics (Harrison et al. 2013). While these energies have been searched for line emission previously using the cosmic background (Boyarsky et al. 2006a, 2008b), this is the first search in a pointed observation with focusing optics. The $E_s > 10$ keV energy range is particularly interesting for entropy-diluted sterile neutrinos (Asaka et al. 2006; Patwardhan et al. 2015).

Recently the NuSTAR team observed and reported the results on one well-studied cluster—the “Bullet Cluster” (Wik et al. 2014). There are many previous observations covering its X-ray and lensing properties (Markevitch et al. 2002, 2004; Clowe et al. 2006; Paraficz et al. 2012). This galaxy cluster, at $z = 0.296$, is perhaps best known for the detailed comparison of the distribution of dark matter as inferred from gravitational lensing to the X-ray-emitting gas. The lack of spatial alignment between the two distributions reported in Clowe et al. (2006) on the basis of a weak lensing analysis and in Bradač et al. (2006), using a joint weak and strong lensing analysis, is often considered to be one of the strongest arguments for the existence of dark matter particles. Bradač et al. (2006) estimate the total mass of the cluster to be $5 \times 10^{14} M_\odot$ within the central 500 kpc. Due to the offset between the mass and X-ray-emitting gas, the Bullet Cluster provides an excellent low-background environment for dark matter searches.

The Chandra X-ray data of the Bullet have been searched for isolated X-ray emission lines out to 10 keV (Riemer-Sørensen et al. 2007; Boyarsky et al. 2008c) but here we extend the range to $\sim$80 keV by using the NuSTAR observations from Wik et al. (2014).

Our approach (described in Section 3.1) is to fit the data with an adequate model describing the emission by the hot gas in the cluster, and then search for the improvement to the fit by adding an isolated emission line of varying energy but with fixed width (determined by the instrumental resolution). The detection (or limit on the flux of the line) provide the measurement (or limit) of the flux and thus luminosity of decay photons, yielding the volume-integrated decay rate of the putative dark matter particle (presented in Section 4).

2. OBSERVATIONS

The Bullet Cluster was observed by NuSTAR in two epochs (see Wik et al. 2014 for details) for a total combined exposure of 266 ks. To filter the events, standard pipeline processing (HEASoft v6.13 and NuSTARDAS v1.1.1) was applied along with strict criteria regarding passages through the South Atlantic Anomaly (SAA) and a “tentacle”-like region of higher activity near part of the SAA, i.e., in the call to the general processing routine that creates Level 2 data products, nupipeline, the following flags were included: SAAmode = STRICT and TENTACLE = yes. No strong fluctuations are present in light curves culled from the cleaned events, suggesting a stable background, so no further time periods were excluded.

From the cleaned event files, spectra and response files were created using nuproducts. The call to nuproducts included extended = yes, most appropriate for extended sources, which weights the response files based on the distribution of events within the extraction region, assuming that to be equivalent to the true extent of the source. We extracted spectra for each of the regions shown in Figure 1 (details in Table 1). The regions were chosen to maximize the amount of dark matter within the field of view while minimizing gas emission. The “Peak” region contains the leading mass peak but excludes the shock front. It is identical to the analyzed region in Boyarsky et al. (2008c) and Riemer-Sørensen et al. (2007), while for the “Half Peak” region, the extracted area is larger to compensate for the lower spatial resolution of NuSTAR compared to Chandra. The “Left” region

Figure 1. Image of the NuSTAR observations of the Bullet Cluster, with the X-ray contours from Chandra overlaid in black (Riemer-Sørensen et al. 2007), and the weak lensing contours in green (Clowe et al. 2006). The white circles illustrate the source regions with the second circle excluded to avoid gas emission. The magenta circles are the background regions chosen to have similar gas emission as the source regions, but much less mass.
contains the trailing mass peak with the exclusion of the main
gas emission. For each region we chose an offset background
region of identical shape at a location with similar gas emission
but less mass as inferred from the lensing map. The resulting
spectra for all three regions are shown in Figure 2.

3. ANALYSIS

3.1. Spectral Modeling

We fit the spectra of both observations and both detectors
simultaneously using the Xspec spectral fitting package
(Arnaud 1996) and explored two different approaches to
background modeling and subtraction. The spectra were binned
to contain at least three counts per bin, and we assume the
background to be Poisson distributed and consequently use
Cash-statistics (C) to optimize the parameter values
(Cash 1979). The Cash-statistics is similar to χ² but generally
regarded as more suitable for analyzing spectra with a few
counts per channel (Nousek & Shue 1989; Arzner et al. 2007)
and less biased than χ² (Leccardi & Molendi 2007). The
magnitude of C depends on the number of bins included in the
fit and the values of the data themselves, and consequently one
cannot analytically assign a goodness-of-fit measure to a given
value of C. However, for large number counts (>5) the C-
distribution is similar to the χ²-statistics and ΔC can be used
instead of Δχ² for model comparison tests.

In the first method of background treatment we simply
subtract the spectrum of the dark matter offset region from the
spectrum of the source region. Since the spectra are almost
identical we can fit any residual with a single power law (the
statistics for each region are given in Table 1). Subsequently,
we added a Gaussian to represent a single emission line at a
fixed energy and flux to the best-fit model above, and searched
for the improvement of C as a function of line energy and
intensity, allowing for simultaneous variation of the power-law
parameters and the Gaussian normalization. We consider line
intensities from 0 to 10⁻⁵ photons cm⁻² s⁻¹ and line energies
of 3–80 keV in steps of ΔE = 0.1 keV. We assume that the line
is narrow compared to the detector resolution, fixing the intrinsic
line width at 0.001 keV and noting that as long as the assumed
width is less than ~0.03 keV, our results do not change.

The reduction of the C parameter by the extra line is shown
as a function of line energy in the upper panel of Figure 3. At
most energies, the additional Gaussian does not lead to any
significant improvement (∆C < 9 for 1105–3821 degrees of
freedom), and instead we constrain the flux by increasing the

![Figure 2. Spectra of the three different regions: Peak (blue), Half Peak (green),
Left (red). The individual exposures have been stacked and rebinned for
visualization purposes. The bump around 30 keV comes from instrumental
lines and only affects the background modeling method, not the background
subtraction.](https://example.com/figure2.png)

Gaussian normalization and refitting all other parameters until
ΔC = C – C_base = 2.71, corresponding to the one-sided 95%
confidence level marginalized over the power-law normal-
izations. These flux levels are shown in Figure 3 for the Peak
and Left regions as well as for the combined analysis.

In the second approach we model the background instead of
subtracting it. In Wik et al. (2014) the background emission in
the Bullet Cluster was thoroughly investigated and we use their
results as a baseline model for the background, and check if
there is room for any line emission above this model. The
model consists of four components: (i) the aperture background
(smooth gradient across the detector with a normalization
uncertainty of 10%); (ii) a focused cosmic ray background from
unresolved sources (smooth with a normalization uncertainty of
10%); (iii) instrumental continuum (we use a 10% normal-
ization uncertainty even though the systematic uncertainty is
probably much smaller); and (iv) the thermal solar continuum
and instrumental lines from reflections (smooth component
with a normalization uncertainty of 10% plus known detector
emission lines). Additionally we fit a line-free plasma model
(apec; Smith et al. 2001) to account for any gas emission from
the cluster. The redshift and abundances of the plasma model
are kept fixed at z = 0.296 and A = 0.2, respectively (consistent

<table>
<thead>
<tr>
<th>Region</th>
<th>Peak</th>
<th>Half Peak</th>
<th>Left</th>
<th>Peak+Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Included center (R.A., decl.) (degrees)</td>
<td>104.56825, −55.941758</td>
<td>104.56825, −55.941758</td>
<td>104.64978, −55.951826</td>
<td>...</td>
</tr>
<tr>
<td>Included radius (arcmin)</td>
<td>0.66</td>
<td>0.66</td>
<td>1.00</td>
<td>...</td>
</tr>
<tr>
<td>Excluded center (R.A., decl.) (degrees)</td>
<td>104.58827, −55.942086</td>
<td>104.59071, −55.994209</td>
<td>104.62326, −55.944488</td>
<td>...</td>
</tr>
<tr>
<td>Excluded radius (arcmin)</td>
<td>0.375</td>
<td>0.66</td>
<td>1.00</td>
<td>...</td>
</tr>
<tr>
<td>Mass (M_☉)</td>
<td>5.7 × 10^{13}</td>
<td>4.5 × 10^{13}</td>
<td>1.0 × 10^{14}</td>
<td>1.6 × 10^{14}</td>
</tr>
<tr>
<td>Power law c-parameter/ dof</td>
<td>1460.3/1355</td>
<td>1195.6/1105</td>
<td>1967.4/1889</td>
<td>3405.2/3221</td>
</tr>
<tr>
<td>Background model c-parameter/ dof</td>
<td>1610.0/1646</td>
<td>1411.6/1347</td>
<td>2380.3/2315</td>
<td>3990.3/3933</td>
</tr>
</tbody>
</table>

**Note.** The first section provides the coordinates of the regions illustrated in Figure 1. The second section gives the dark matter mass within each field of view based on weak gravitational lensing. The third section contains the fit statistics for each of the regions for the two methods of background subtraction and modeling. The spectra were binned to a minimum of three counts per bin before the analysis.
with the value found in Wik et al. 2014), while the temperature is required to be the same for both detectors and both observations, but with individual normalizations.

The 3–150 keV energy interval is well fitted by the background model with the statistics given in Table 1. As before, for each energy between 3 and 80 keV in steps of \( \Delta E = 0.1 \) keV we add a Gaussian and determine the best-fit normalization considering line intensities from \(-10^{-5}\) to \(-10^{-5}\) photons cm\(^{-2}\) s\(^{-1}\). The line intensities are allowed to be negative to account for overestimation of the background. The normalization is then increased until \( C > 2.7 \) is reflected in weaker constraints at those energies. While \( |\Delta C| > 9 \) would appear to imply a significant detection, we need to take the look-elsewhere effect into account (Gross & Vitells 2010). The energy of the line is unknown and by scanning over energy we perform a number of independent searches that increase the chance of seeing statistical outliers. Consequently the probability of detection is degraded by the number of independent attempts (given the spectra resolution of NuSTAR we search of the order of 150 independent energies).

Line-like features may arise from fluorescent and activation-induced instrumental lines if imperfectly modeled, or due to statistical/systematic fluctuations between target and background regions (see appendix of Wik et al. 2014). These lines are strongest between 20 and 30 keV, and may explain the region of larger \( C \) values at those energies.

The flux limits from the two approaches for the background subtraction are compared in Figure 3. The solid lines show the results of modeling the background of the nearby dark matter offset region, and the dotted lines show the results of subtracting the nearby dark matter offset region. The results from the individual regions are consistent with each other and the constraints tighten by combining the regions. The background modeling generally provides slightly stronger constraints, but with gaps where the preferred flux is negative.
model was constructed. This is unlikely to be the case for direct background subtraction.

3.2. Mass within the Field of View

The weak lensing shear maps12 from Clowe et al. (2006) can be integrated to provide the masses within the three regions for a fiducial cosmology of $\Omega_m = 0.3$, $\Omega_b = 0.7$, $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The map contours are shown in Figure 1 and the obtained region masses are given in Table 1. Paraficz et al. (2012) presented a mass map of the Bullet Cluster based on strong lensing rather than weak lensing. This map provides region masses that are almost twice as big as for the weak lensing map. This indicates an uncertainty on the matter mass within the field of view, and $D_L$ is the luminosity distance. Equation (2) is only concerned with the decay of the sterile neutrinos and applies regardless of how they were formed. Theoretically, the sterile neutrino can have any mass, but as explained in Section 1 observations restrict the range to approximately 1–100 keV.

As illustrated in Figure 4, very large mixing angles will lead to overproduction of dark matter and are consequently ruled out. Similarly, the resonant production mechanisms require a primordial lepton asymmetry (Boyarsky et al. 2008b), which may affect Big Bang nucleosynthesis and cosmic element abundances. This gives a lower limit on the mixing angle. As mentioned in Section 1, the mass range is limited from below by the Tremaine–Gunn bound (Tremaine & Gunn 1979; Boyarsky et al. 2008b) and from above by line emission searches. The NuSTAR Bullet Cluster constraints from the Peak region alone are weaker than previously existing constraints from the diffuse cosmic background, but provide an important cross-check.

4. RESULTS

4.1. Sterile Neutrinos

Assuming all of the dark matter to be Majorana-type sterile neutrinos, we can interpret the flux constraints from Figure 3 in terms of the sterile neutrino parameters of mass, $m_\nu$, and mixing angle, $\sin^2(2\theta)$, where the latter describes the mixing probability with the lightest of the active neutrinos. The constraints are converted as (Riemer-Sørensen et al. 2006; Boyarsky et al. 2007b):

$$\sin^2(2\theta) \leq 10^{13} \left( \frac{F_{\text{obs}}}{\text{erg cm}^{-2} \text{s}^{-1}} \right) \left( \frac{m_\nu}{\text{keV}} \right) \left( \frac{M_{\text{fov}}}{M_\odot} \right) \left( \frac{D_L}{\text{Mpc}} \right)^2$$

where $F_{\text{obs}}$ is the observed flux limit, $M_{\text{fov}}$ is the total dark matter mass within the field of view, and $D_L$ is the luminosity distance. Equation (2) is only concerned with the decay of the sterile neutrinos and applies regardless of how they were formed. Theoretically, the sterile neutrino can have any mass, but as explained in Section 1 observations restrict the range to approximately 1–100 keV.

As illustrated in Figure 4, very large mixing angles will lead to overproduction of dark matter and are consequently ruled out. Similarly, the resonant production mechanisms require a primordial lepton asymmetry (Boyarsky et al. 2008b), which may affect Big Bang nucleosynthesis and cosmic element abundances. This gives a lower limit on the mixing angle.

4.2. Generic Dark Matter Constraints

In Figure 5 we present the constraints on generic dark matter decays leading to photon emission for two photons per decay. For one-photon interactions, the constraints are weaker by a

12 http://flamingos.astro.ufl.edu/1e0657/index.html
5. DISCUSSION

5.1. Possible Detections

Unfortunately, the claims of possible line detections (Loewenstein & Kusenko 2010; Boyarsky et al. 2014; Bulbul et al. 2014) all lie below the lower sensitivity cutoff for NuSTAR of 3.89 keV introduced by the redshift of the Bullet Cluster.

5.2. Possible Improvements

The Milky Way halo has provided strong constraints on line emission in the X-ray range (Riemer-Sørensen et al. 2006; Riemer-Sørensen 2014). The advantage of local constraints is that the dark matter source is nearby and there exists a wealth of observations, but the disadvantage is the number of sources of non-thermal “background” radiation and the uncertainty of the inner mass profile. The background radiation issue can be reduced significantly by point source removal if one has sufficient spatial resolution. This is now becoming possible with NuSTAR, and will be investigated further in future work. The profile uncertainty problem can be mitigated somewhat by excluding the center of the halo from the analysis.

6. SUMMARY

We have searched NuSTAR observations of the Bullet Cluster for exotic line emission over the 3–80 keV interval. No significant line flux was found and we have derived upper limits on the possible line emission flux. While the constraints are similar to previous constraints from the cosmic background emission, this is the first time a search has been performed in this energy interval using a pointed observation. The constraints can be improved by longer observations or by using different targets, e.g., the Milky Way halo (as in Riemer-Sørensen 2014).

This research made use of data from the NuSTAR mission, a project led by the California Institute of Technology, managed by the Jet Propulsion Laboratory, and funded by NASA, and it also made use of the NuSTAR Data Analysis Software (NuSTARDAS) jointly developed by the ASI Science Data Center (ASDC, Italy) and the California Institute of Technology (USA).

Facility: NuSTAR

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