Hunting dark matter with X-rays

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Radial Profile of the 3.55 keV line out to R_{200} in the Perseus Cluster
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6.1 Comment on "A novel scenario for the possible X-ray line feature at ∼3.5 keV: Charge exchange with base sulfur ions"

Recently, Gu et al. (2015) suggested that the unidentified ∼3.5 keV line could have originated from via charge exchange between bare sulfur and neutral hydrogen interacting with a relative velocity of ~ 200 km/s. New calculations of this interaction (Mullen et al., 2016) suggest that the dominant cross sections are to the $9p$ and $10p$ excited states of S XVI, leading to transitions at 3.45 keV and 3.46 keV, respectively. Although at lower energies, we agree that if present these transitions could affect the fits to the cluster spectra, as noted by Gu et al. (2015). However, Gu et al. (2015) also argues that these S XVI transitions are a "unique feature for probing CX in hot astrophysical plasmas," at least at CCD resolution. Although possibly true in the X-ray band, CX at the level implied by Gu et al. (2015) should also create detectable hydrogen Hα emission, although of course CX is not the only mechanism that could generate this line. The relationship between Hα and X-rays in clusters has been studied extensively; for example, Fabian et al. (2003) found that the Hα filaments in the Perseus cluster, which extend about 2 arcminutes in radius from the core, are associated with soft X-rays with a temperature of ~ 0.9 keV.

To calculate the possible Hα flux, we will assume a typical cluster sulfur abundance of 1/3rd solar, or [S/H] = 6.72. Between 2-4 keV, the fractional population of fully stripped S^{16+} varies between $\sim 0.42 - 0.84$; for concreteness, we use the value at 3 keV, 0.72, which also corresponds to the 200 km/s velocity where Mullen et al. (2016) find the

S^{16+} cross section peaks in the key $9p$ and $10p$ states. Inherent in the assumption that CX is occurring is that somehow the cluster contains a hot plasma mixing with a cool neutral plasma, possibly due to a cool infalling filament that is slowly "leaking" neutral hydrogen. In this case, the ionized hydrogen and neutral hydrogen can also interact, either via excitation or CX. To completely calculate the resulting Hα emission would require a complete level population calculation; we use a simpler approximation to this from McLaughlin (1999),

$$\sigma(H\alpha) = \sigma(1s \to 3s) + 0.118\sigma(1s \to 3p) + \sigma(1s \to 3d). \tag{6.1}$$

For the excitation and charge exchange cross sections, we use values from Table V of Winter (2009) at 3 keV, finding a total $\sigma(H\alpha) = 2.6 \times 10^{-18}\,\mathrm{cm}^{-2}$. Mullen et al. (2016) (via private communication) gives $\sigma(S^{16+} + H \to S^{15+}(9p, 10p) + H^{+}) \sim 3.3 \times 10^{-15}\,\mathrm{cm}^{-2}$. As the CX lines are at 3.45 keV, not 3.5 keV, they are not a one-for-one replacement for the $\sim$3.5 keV feature, but rather would impact the fits in this region in some complex fashion. It is reasonable to assume that any impact would become significant when the CX line had a similar flux as the $\sim$3.5 keV feature; in this case, we find:

$$F(H\alpha) = \frac{Ab(H)}{Ab(S)} \times \frac{\sigma(H\alpha) \times F_{3.5}}{\sigma(S^{16+} + H \to S^{15+}(9p, 10p) + H^{+})} \tag{6.2}$$

or $F(H\alpha) \approx 150 \times F_{3.5}$. For Perseus, Bu14 found a range of values for $F_{3.5}$ depending upon the analysis approach. We use here the *XMM-Newton* MOS values found after excluding the core 1 arcminute radius, $2.1(+1.1, -1.0) \times 10^{-5}$ ph cm^{-2}s^{-1} (90% errors). This implies that any potential cool plasma interaction would create Hα = $3.2(+1.8, -1.7) \times 10^{-3}$ ph cm^{-2}s^{-1}. Conselice et al. (2001) mapped all of the Hα filaments in Perseus, finding a total flux of 3.2×10^{-13} erg cm^{-2}s^{-1}, or 0.11 photons cm^{-2}s^{-1}. However, the majority of this emission was found within 1 arcminute (21 kpc) of the core. Excluding these points, however, reduces the observed flux to 9.5×10^{-3} photons cm^{-2}s^{-1}.

Most of the filamentary Hα emission in Perseus must be created by other mechanisms within the filaments (collisional excitation, recombination, or photoionization), and not CX; otherwise, the bare sulfur CX line at 3.45 keV would be orders of magnitude stronger than it is. Similar conclusions are reached by e.g. Fabian et al. (2011) through different methods. By the same token, in the core of Perseus, CX could create both a 3.45 keV line and trace Hα emission that could not be detected. In other words, the Hα emission in the core of Perseus does not exclude a CX interpretation of the $\sim$3.5 keV line in the core. However, neither does the Hα measurements necessarily indicate that CX has to be responsible for either (part of) the 3.5 keV line or the Hα emitted at a flux as calculated above. Rather, we notice that the filamentary flux drops off much more rapidly from the core (more than an order of magnitude at 1 arcminute radius) than the $\sim$3.5 keV line, which only drops by a factor of 2, and suggest that this may be a distinguishing characteristic to be used in the future. More work is needed, both in the laboratory to test the theoretical CX calculations, and observational to compare the radial distributions of Hα emission in other clusters with the core-excluded $\sim$3.5 keV line, to conclusively identify the impact of CX.

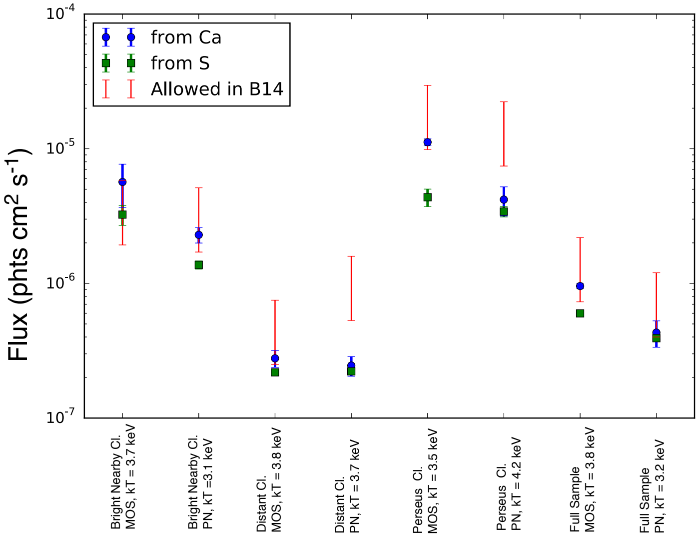

Figure 6.1: The estimated flux in the K XVIII triplet based on single temperature plasmas from the Bu14 samples. Blue - taken from Ca emission. Green - taken from S emission. Red - the calculated (lower end) and maximum allowed (upper end) flux of the triplet in Bu14.

6.2 Comment on "Discovery of a 3.5 keV line in the Galactic Centre and a critical look at the origin of the line across astronomical targets"

Jeltema & Profumo (2015) presented an analysis stating that if using a multi-component plasma and summing the fluxes from those using calcium to estimate the flux, the high temperature component would dominate, leading to a potentially large underestimate of the K XVIII triplet flux.

However, in our analysis we calculated the emissivity of the K XVIII triplet based on fluxes from both Ca and S, one of which peaks at a higher temperature, and one which peaks at a lower temperature. We have allowed for three times the maximum K XVIII flux permitted by either of these emissivity estimates as a safety margin. Crucially, the use of the S XVI emissivity, and not just the Ca, ensures that we have not underestimated the K XVIII triplet flux in the manner suggested by Jeltema & Profumo (2015).

To demonstrate this, we have estimated the flux of the K XVIII lines using another method, the results of which are shown in Figure 6.1. For each object listed in Bu14, the temperatures have been derived from the Ca XIX to Ca XX line ratio. These all lie in the range 3.1 keV to 4.2 keV. In those objects where we had extracted the S XV flux, the temperatures from the S XV to S XVI ratios were also found to lie in this range.

For each object, the emissivity of the K XVIII triplet has been calculated assuming that the plasma is a single temperature component plasma at the calculated temperature, and that S, Ca and K are in collisional ionization equilibrium and they all have solar photosphere abundance (Anders & Grevesse 1989). By comparing the predicted flux ratios with the observed flux in the Ca and S lines, we produce estimated fluxes for the K XVIII triplet based on the Ca and S observations. Error bars indicate the range of fluxes implied by the 90% uncertainty in the Bu14 line fluxes. The red lines in the same figure show the range between the upper limit for the K XVIII flux calculated in that paper and that value with the factor of 3 safety margin included.

As can be seen, in the case of the MOS observations of the brightest clusters (the sum of Coma, Centaurus and Ophiuchus), the data shows that we have been conservative in our estimates of the maximum K XVIII flux, with estimates from this technique consistently falling at least a factor of two below the allowed values in Bu14.

6.3 Comment on “Where do the 3.5 keV photons come from? A morphological study of the Galactic Center and of Perseus”

Carlson et al. (2015) presents a morphological investigation of the ∼3.5 keV signal in the Galactic Center (GC) and the Perseus cluster, concluding that in a template-based maximum-likelihood approach neither object prefers a dark matter-like contribution.

However, using templates that are derived directly from a few broad energy bands of the data essentially reduces the spectral information that is available. Since the ∼3.5 keV flux in clusters is of order 1% of the continuum at *XMM-Newton*’s spectral resolution, it is essential to determine the continuum emission to better than 1%. This is a non-trivial exercise even in a forward modeling approach as done in Bo14 and Bu14, and is impossible in the template approach. This can be seen from the broad brackets of continuum models in Figures 5 and 6 of Carlson et al. (2015). If a continuum template is incorrect by more than a percent at 3.5 keV (which is almost a certainty), the ∼3.5 keV line contribution to the residual signal would be very subdominant, the residuals will be dominated by astrophysical components and, of course, follow the spatial distribution of the astrophysical templates, biasing the results against dark matter-like behaviour.

It should be noted in addition that the detection of the ∼3.5 keV signal in Bu14, using the same *XMM-Newton* MOS data as Carlson et al. (2015), has a significance of only about 3.4σ for the integrated data of the entire field of view (excluding the $1'$ cluster core). Given such low significance for the whole cluster, it is difficult to see how it would be possible to subdivide the dataset and obtain statistically significant measurements of the spatial behaviour of the line signal, as is for example suggested by the size of the error bars in Figure 6 of Carlson et al. (2015) or by their discussion of the perceived ‘clumped nature’ of the residuals in Section 3.1. The errors on the actual ∼3.5 keV line contribution in various sub-regions are likely understated.

Lastly, the effect of absorption by the intervening interstellar medium on the GC analysis is strongly underestimated in Carlson et al. (2015). They use the HI data to estimate the absorbing column density, concluding that absorption at 3.5 keV is insignificant (a few percent effect). While these data are adequate over most of the sky, at low Galactic latitudes the true X-ray absorption is often higher. Indeed, using *Chandra* X-ray spectra for the GC fields, Muno et al. (2004) and Muno et al. (2004) measure the absorption column densities for various diffuse emission regions and for various point sources, respectively. They find median column densities close to 6×10^{22} cm^{-2}, while between 30 and 50% of the analyzed area has $N_H > 10^{23}$ cm^{-2}. This is much higher than the HI-based value; the excess can be due to molecular gas, etc. At 3.5 keV, such values of N_H correspond to attenuation by factor 2–3, not a few percent. These X-ray absorption measurements are directly applicable here, and were used in Bo14. This impacts any upper limits computed for dark matter decay. In addition, the absorption is likely irregularly distributed over the GC area (for example, the giant molecular clouds align with the Galactic plane), making an isotropic dark matter template inadequate.