“Equivalent” Views of the Cygnus Loop
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The XMM-Newton x-ray observatory performed 10 observations of the Cygnus Loop supernova remnant. Using these observations, we created images that show the strength of the various emission lines visible in the spectrum of this remnant. We found that the CVI, O and Mg lines are particularly strong towards the edge of the remnant while emissions from Ne, Fe, Si and S are concentrated towards the center. Ne and Fe in particular show highly asymmetrical structures.

§1. Introduction
The Cygnus loop is a middle aged supernova remnant located approximately 540 parsecs away [1]. XMM-Newton performed 10 observations of this remnant and using these observations we set out to investigate the spatial distribution of heavy elements within this remnant. To this end we created “equivalent width” images in a fashion similar to Hwang et al. [2].

§2. Analysis
In November 2002 XMM-Newton performed 8 observations of the Cygnus Loop, and another 4 in May 2006. The data were filtered for proton flares using the method developed by Nevalainen et al. [4] and we used the latest blank sky files to describe the x-ray background. Fig. 1 shows the three-color image of the merged XMM – Newton observations after filtering and background subtraction. The resulting exposure times are approximately 10 ks except for pos4, pos8 and pos9. In the case of these observations, due to severe flares, the total good time intervals are ~4 ks for pos4 and ~3 ks for pos8 and pos9. Severe flares also rendered 2 of the 4 observations performed in 2006 unusable. All the observations were performed using the medium filter except for the pn detector in the case of the XA knot observation, where the thin filter was used.

From the three-color image we see that on the outskirts of the remnant, low energy radiation dominates suggesting low temperatures and as we go towards the center the color shifts towards the blue. We then extracted the spectrum of the combined fields of view (fig. 2). This is a typical thermal spectrum from an optically
thin plasma and it shows several emission lines. In order to investigate the heavy element distribution in this remnant we created images in the energy bands of the various emission lines visible in the spectrum (depicted by the solid lines below the spectrum in fig. 2), and then created images in the bands to which we shall refer to as the “continuum” (solid lines above the spectrum in fig. 2). These bands of course do not correspond to the actual continuum emission for lines below and including Ne. This is because in this region of the spectrum, there are many weak unresolved emission lines and all of them dominate the continuum. For lines such as Mg, Si and S, the situation is somewhat better because these lines are isolated and the continuum dominates in this region of the spectrum however we have variable fluorescence lines between the Mg and Si lines. The resulting images were corrected for vignetting, smoothed and background subtracted.

The underlying “continuum” for each emission line was determined in the following way: In the case of the carbon and oxygen lines we assumed that the continuum level is that given by the images in the bands designated as $ccnt$ and $ocnt$ (fig. 2). For the rest of the emission lines, we calculated the continuum level by assuming that there is a power law relation between the “continuum” images to the left and to the right of the emission line and then interpolated these images pixel by pixel. Finally, in order to create the “equivalent width” images, we subtracted the “continuum” images from the line images and then divided the result with the “continuum” image.

§3. Results

The resulting images are shown in fig. 3 together with MOS2 spectra extracted from regions where the emission is strong and weak respectively. As mentioned above, since we do not know what the true continuum level is these are not equivalent width images per se and thus we shall refer to them as line strength images. We notice that the emission lines of lighter elements such as C, O, Mg, tend to be strong toward the edge of the remnant while those of the heavier elements such as Fe, Si, S are concentrated toward the center of the remnant. An interesting feature to notice is the high asymmetry in the distribution of Fe and Ne. This kind of asymmetry can be observed in other supernova remnants as well and it is believed that it arises as the result of the asphericity of the supernova explosion. We also notice a strange V shaped feature in the FOV of $pos2$ which marks a somewhat sharp boundary between the distribution of the lighter elements and the heavier ones. In this structure Fe and Ne emissions seem to be especially strong. The spectral analysis performed by Miyata et al. [3], Nemes et al. (in preparation) of the data from the region covered by $pos1$ shows that all the heavy element abundances are depleted. On the other hand Miyata et al. [3] showed that the plasma toward the center of this remnant is rich in Fe, Si and S, which is consistent with what we get from our images. This raises the question: could this V structure actually be the contact discontinuity? Further work needs to be done in order to fully answer this question.

Fig. 3: Line strength images together with spectra extracted from regions where the emission seems to be strong and weak respectively. The spectra for the C and O lines are plotted on a semi-logarithmic scale.
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Acknowledgements

This work was partly supported by a Grant-in-Aid for Scientific Research by the Ministry of Education, Culture, Sports, Science and Technology (16002004) and by the 21st Century COE Program “Towards a New Basic Science: Depth and Synthesis”.

References