A breath of fresh air from the old Swan

A detailed Suzaku study of an evolved SNR, the Cygnus Loop

July 21, 2011
Suzaku2011@SLAC

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The Cygnus Loop Observations with Suzaku & XMM-Newton

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Number</th>
<th>Obs. Date</th>
<th>Eff. Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suzaku</td>
<td>72</td>
<td>Nov 2005 – Jun 2011</td>
<td>1676.7 ks</td>
</tr>
<tr>
<td>XMM-Newton</td>
<td>9</td>
<td>Nov 2002 – May 2006</td>
<td>93.5 ks</td>
</tr>
</tbody>
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We completely covered this remnant with Suzaku (and XMM) by the AO6 phase.

First Detection of Ar XVI Kα (Uchida+2010)
Outline

• **Introduction**
  – Classical fit with a conventional thin thermal model

• Panoramic X-ray View of the Cygnus Loop
  – Metallicity structures of the ejecta
  – North-South inhomogeneity of the heavy element

• “Deep” Observation of the Cygnus Loop
  – Unknown excess at 0.7keV
  – 1.2keV (missing) line problem

• Summary
Basically, the spectra are well fitted with a two-component NEI model.
Swept-up ISM and Ejecta Structures of the Cygnus Loop

Flux distribution of ISM component

Flux distribution of Ejecta component

Uchida+2009a
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• Summary
Abundance vs. Abundance Plot

ISM abundance
Ejecta abundance
The ISM and the ejecta components are clearly separated.

Uchida+ in prep
"Onion-like" Structures of the Cygnus Loop

Uchida+2009b

Mass fraction of $15M_{\odot}$ star before SN

Elemental Distributions in a pre-explosion $15M_{\odot}$ star
The heavy elements blew out to South?

We have observed the blowout region with Suzaku (in AO5 and AO6 phases).

Si (and Fe) distribution Center shifts toward the South?
North-South Inhomogeneity of the Heavy Element

Si Abundance: 0.41±0.05
Si/O: ~1
Fe/O: ~0.5

The Si abundance in the southernmost region is ten times higher than that in the northernmost region.

Si Abundance: 4.2 ±0.6
Si/O: 10-30
Fe/O: 2-3


Many theories estimate that the heavy elements eject in one direction.

We are analyzing all the available data to reveal the whole picture of the ejecta structure.
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  – Unknown excess at 0.7keV – Possible charge exchange emission
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• Summary
Low abundance problem of the ISM component

- The ISM abundances are significantly lower than the solar abundances.
- Such low abundance ISMs have been reported from some other SNRs;

Puppis A: Hwang et al. 2008
RCW86: Yamaguchi et al. 2008
Vela SNR: Miceli et al. 2008
Abundance Enhancement in the Cygnus Loop Rim

Metal abundance map, Ne for the other elements

- Blue region: ~0.2 solar
- Orange region: ~1 solar

Why the abundance distributions are inhomogeneous?
What is the difference of the spectra between them?
Fitting problems @ 0.7 keV and 1.2 keV in the current NEI model

Katsuda+2011

Uchida+ in prep
Refit excluding the 0.7 keV excess (Katsuda et al. 2011)

- When we exclude the excess at around 0.7 keV, the values of the abundances decreased significantly.
- The abundance inhomogeneity is resolved. However, what is the origin of the excess which faked the abundance enhancement?

![Graph showing counts and energy levels with annotations for Northeast and Excluded regions.]

- Refit excluding the 0.7 keV excess (Katsuda et al. 2011)
  
  \( \chi^2/\text{dof} = 758/463 \)
What is the origin of the excess @0.7 keV?

- Thermal Origin?
  - Fe XVII L (3s→2p: 730eV)
  - He-like O Kγ+Kδ+… (e.g., SN1006; Yamaguchi+2008)

→ Hey / Heα ratio (~0.045) requires a very high temperature.

Flux ratio of X to O Heα: 0.041-0.049

OHeγ/OHeα line ratio map in a kT_e - log(n_e t) plane (based on a NEI model)
Abundance vs. EW@0.7 keV Plot in the Cygnus Loop

- No correlations are found.
- The observed excess is not likely to be a thermal origin.
What is the origin of the excess @ 0.7 keV?

- Thermal Origin?
  - Fe XVII L (3s→2p: 730eV)
  - He-like O Kγ+Kδ+… (e.g., SN1006; Yamaguchi+2008)

→ Heγ / Heα ratio (~0.041-0.049) requires a very high temperature.

Flux ratio of X to O Heα: 0.041-0.049
What is the origin of the excess @0.7 keV?

• Thermal Origin?
  – Fe L lines (3s→2p: 730eV, 3d→2p: 820eV)
  – He-like O Kγ+Kδ+… (e.g., SN1007;)

• He-like O K cascade?
  – Recombining Plasma (Yamaguchi-san’s talk)
    → No RRC feature is found in the Cygnus Loop spectra.
  – Photoionized Plasma (e.g., Cyg X-3; Kawashima & Kitamoto 1996)
    → There are no strong X-ray sources around the Cygnus Loop.
  – Charge Exchange (Katsuda et al. 2011)

Lallement (2004) claimed that charge exchange emission could be significant at narrow regions just behind shocks.
The excesses at 0.7 keV are found only in some rims and only their outermost part.

We propose that the excess at 0.7 keV is due to a charge-exchange emission. (Katsuda et al. 2011)
Fitting problems @ 0.7 keV and 1.2 keV in the current NEI model
The missing line problem at 1.2 keV is often seen in many spectra with many detectors. Most of their sources are “Fe-rich”, which strongly suggests that these lines originate from a missing F-L line.
Correlations between the EW@1.2 keV and elemental abundances

- The EW@1.2keV correlate with the Fe (and Si) abundances (Uchida+ in prep).
- Astro-H will identify such missing lines which are not included in current plasma codes.
Summary

• We have observed the Cygnus Loop with Suzaku and XMM-Newton. The total exposure time reaches into ~1.7Ms.
• The ejecta structure show a clear “onion-like” structure. The heavy elements such as Si and Fe are much more abundant in the south toward the blowout region.
• We found that the spectra obtained from the enhanced-abundance regions have an excess at 0.7 keV.
• By considering various possibilities, we concluded that the excess at 0.7 keV originates from the charge-exchange emission at the outermost rim of the Loop.
• We also found a line-like feature at 1.2 keV and concluded the line originates from a missing Fe L line which is not included in the current plasma code.
• Astro-H SXS will be a key instrument to confirm the presence of charge exchange emission and a missing Fe L line at 1.2 keV.