X-RAY EMISSION DUE TO CHARGE EXCHANGE IN THE CYGNUS LOOP?

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Outline

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  • Cascade
  • Cross Sections
  • Spectra
• XSPEC Modelling
  • Shock Model
  • CX Model
  • Future model
• Summary
**Cygnus Loop**

- Supernova Remnant
- Cygnus Constellation
- Distance: ~1500 ly
- Size: ~90 ly
- Age: ~5000- 8000 years
- Shock Speed ~300 km/s

Katsuda et al. 2011
SNR: Cygnus Loop

Part of NE Rim
Significant neutral H fraction

Katsuda et al. 2011

Suzaku ObsID 500023010
Charge Exchange Process

\[ X^{q+} + Y \rightarrow X^{q-1}(nl^{2S+1}L) + Y^+ \]

- Collision of
  - Highly charged ion \( X^{q+} \)
  - Neutral atom \( Y \)
- Produces highly excited, high charge state ions \( X^{q-1}(nl^{2S+1}L) \)
  - Cascade to lowest energy
    - Produce x-rays
Cascade Model

- Low-density steady state cascade
  - Rigazio et al. (2002)
  - Initial state population proportional to CX cross sections
  - Cascade to lowest E-level results in X-rays
Ne$^{10+} + \text{H} \rightarrow \text{Ne}^{9+} + \text{H}^+ \text{ Cross Sections}

Not included in Cygnus Loop Model
Methods for Calculating Cross Section

- Multi-Channel Landau Zener
  - Fully stripped atoms:
    - Statistical I-distribution
    - Low-energy I-distribution
- Classical Trajectory Monte Carlo
- Atomic Orbital Close Coupling
- Quantum-Mechanical Molecular Orbital Close Coupling
  - Best method
  - Time consuming
$\text{Ne}^{10+} + \text{H} \rightarrow \text{Ne}^{9+} + \text{H}^+$

- MCLZ Low Energy
- 1 keV/u collisional energy
- 10 eV Gaussian FWHM

Not included in Cygnus Loop Model
XSPEC Model

- Initial Model without CX spectra (SNR Shock)
  - VpShock Model
  - 2 APEC thermal Plasma Models
  - 2 broken power laws (X-ray background)
- CX Model (SNR + CX)
  - 35 separate emission lines
    - Tie separate lines together based on line ratios
  - Electron Temperature = 0.21 keV
  - Line intrinsic widths much smaller than instrumental line width
  - Collisional Energy of 1 keV/u
- Input:
  - Line Energy
  - Line Ratios
Cygnus Loop: Shock Model

- Initial Model
- Background + VpShock
- Reduced $\chi^2 = 8.9$ with 592 dof
- FI and BI fitted Simultaneously

**Fig 2a**

- Front-illuminated
- Back-illuminated
- $+:$ Observation
- $\ldots:$ Individual Models
- $-:$ Total Model
Astrophysical Modeling: Using Xspec

- $^{5+}$C +H
  - (Nolte et al. 2012)
- $^{6+}$C +H
  - (Janev et al. 1993)
- $^{6+}$N +H
  - (Wu et al. 2011)
- $^{7+}$N +H
  - (Harel et al. 1998)
- $^{7+}$O +H
  - (Nolte et al. 2013)
- $^{8+}$O +H
  - (Janev et al. 1993)

X-ray Energy (keV)

Normalized Counts s\(^{-1}\) keV\(^{-1}\)

Relative Intensity

Normalized Counts s\(^{-1}\) keV\(^{-1}\)

X-ray Energy (keV)

Cygnus Loop
$\text{O}^{8+} + \text{H} \rightarrow \text{O}^{7+} + \text{H}^{+}$

Collision Energy: 1 keV/u

(Janev et al. 1993)
$\text{C}^5^+ + \text{H SEC}$

C V cascade emission spectrum (10 eV FWHM)

 stick plot at 20 keV/u
 lines normalized to $1s2p^1P \rightarrow 1s^2^1S$

(Nolte et al. 2012)
C$^{5+}$ + H SEC

C V cascade emission spectrum (10 eV FWHM)

Ly $\beta$

stick plot at 20 keV/u
lines normalized to 1s2p $^1P \rightarrow 1s^2 \, ^1S$

(Nolte et al. 2012)
C$^{6+} + \text{H}$

(Janev et al. 1993)
C$^{6+}$ + H

(Janev et al. 1993)
$N^{6+} + H$

(Wu et al. 2011)
N^{6+} + H

(Wu et al. 2011)
$\text{N}^7+ + \text{H}$

(Harel et al. 1998)
$\text{N}^7^+ + \text{H}$

(Harel et al. 1998)
$\text{O}^{7+} + \text{H}$

(Nolte et al. 2014)
$O^{7+} + H$

(Nolte et al. 2014)
Cygnus Loop: Free normalizations

Model with CX
Background + VpShock + 33 CX lines
- Intensities vary independently
- No line ratios
Reduction \( \chi^2 = 1.36 \) with 533 dof.

Unphysical Line Ratios
Cygnus Loop: With CX Data

- Model with CX
- Background + VpShock + 33 CX lines
  - Tied to respective Kα line
- Reduced $\chi^2 = 3.95$ with 555 dof.
- Physically Reasonable Line Ratios
Cygnus Loop: With CX Data + Fe Lines

Figure 4

- Model with CX
- Background + VpShock + 35 CX lines
  - Tied to respective Ka line
- + .725 keV & .826 keV Fe lines
- Reduced $\chi^2 = 1.83$ with 553 dof.
Ne$^{10+}$ + H $\rightarrow$ Ne$^{9+}$ + H$^+$
Ne$^{10+}$ + He $\rightarrow$ Ne$^{9+}$ + He$^+$
Mg$^{12+}$ + H $\rightarrow$ Mg$^{11+}$ + H$^+$

MCLZ
Low Energy Distribution

To be included in Cygnus Loop Model
$\text{Fe}^{26+} + \text{N}_2 \rightarrow \text{Fe}^{25+} + \text{N}_2^+$

Wargelin et al., 2005
Electron beam ion trap

Wargelin et al., 2005

150 eV resolution

Relative Intensity (arb. Units)

Energy (eV)

L-shell

K-shell

Wargelin (10 eV/u)
MCLZ 10 eV/u
MCLZ 100 eV/u
MCLZ 1 keV/u
$\text{Fe}^{26+} + \text{N}_2 \rightarrow \text{Fe}^{25+} + \text{N}_2^+$

**Ionization Energy $\text{Fe}^{26+}$**

![Graph showing ionization energy](image)
$C^6^+ + H_2 \rightarrow C^5^+ + H_2^+ : CTMC$
Summary

- CX often invoked in observations with anomalous X-ray features
  - Often with unrealistic CX data

- Cygnus Loop:
  - Can improve spectrum from NE4 with CX model
  - 0.7 keV region still difficult to model
  - Consider only ion interactions with Neutral H
    - Would like to consider He
  - Need more:
    - Ions: Ne, Mg, Fe, si
    - Ionization stages
    - Neutral species (he, H₂)
  - Future: Apply to other Observations
In the Future

M82

Liu et al. 2012

Comet Linear: Beiersdorfer et al., Science, 200