GC Galactic disk
Sun
ROSAT X-ray All-sky Survey

- Red – 1/4 keV band
- Green – 3/4 keV band
- Blue – 1.5 keV band

EW ~ 0.36 eV along the sightline to LMC X-3, comparable to that to Mkn 421

LMC X-3
Distance = 50 kpc
Vs = 310 km/s
z = -120--70 km/s

AGNs
X-ray binaries

100 ks Chandra LETG/HRC

Red - 1/4 keV band
Green - 3/4 keV band
Blue - 1.5 keV band
4U1820-303

Distance = 7.6 kpc

(a) NeIX Kα

(c) OVII Kα

Similar or greater EWs to several Galactic LMXBs

See also
Futamoto et al. 2003
Correlation with diffuse $\frac{3}{4}$-keV band intensity

There is no compelling X-ray observational evidence for the large-scale warm-hot IGM!

Diagnostics of diffuse interstellar hot gas:

- X-ray absorption and emission lines
- FUV absorption and emission lines
- Broad-band diffuse X-ray emission
  → thermal, ionization, and chemical states of the hot ISM.
Extra-planar Diffuse Hot Gas Along the Hubble Sequence: Normal Disk Galaxies

Diffuse X-ray properties (compared to nuclear starburst galaxies):

• Less concentrated toward Galactic central regions
• Elongated along the major axes
• Characteristic $T < 1$ keV, even in central regions
Why interesting

- External perspectives of our own Galaxy
- Most of present galaxies are not nuclear starbursters
- Phenomena that would be otherwise overwhelmed
  - Disk/halo interaction
  - Bulge wind driven by Type Ia SNe
  - Accretion from the IGM

Subtle, but enduring → strongly affect the evolution of galaxies
Sample of normal disk galaxies

<table>
<thead>
<tr>
<th>Galaxy Name</th>
<th>Hubble Type</th>
<th>D (Mpc)</th>
<th>Incl. ang. (deg)</th>
<th>Exp. Time (ks)</th>
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<tbody>
<tr>
<td>N4244</td>
<td>Sd/LSB</td>
<td>3.6</td>
<td>85</td>
<td>60</td>
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<tr>
<td>N4631</td>
<td>Sd</td>
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<td>85</td>
<td>60</td>
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<tr>
<td>N3556</td>
<td>Sc</td>
<td>14.1</td>
<td>80</td>
<td>60</td>
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<td>N4565</td>
<td>Sb</td>
<td>13.4</td>
<td>87</td>
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<tr>
<td>N4594</td>
<td>Sa</td>
<td>8.9</td>
<td>84</td>
<td>19</td>
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</tbody>
</table>

All with low Galactic foreground absorption \( (N_H < 3 \times 10^{20} \text{ cm}^{-2}) \)
SFR = 0.04 \, M_{\text{sun}}/\text{yr}

0.3-1.5 \, \text{keV}
Chandra Images of NGC 4631

1.5 - 7 keV band

0.3 - 1.5 keV band

SFR = 3 Msun/yr

Wang et al. (2001)
X-ray Halo Spectrum of NGC 4631

Two-temperature thermal plasma fit:

- $T_1 \sim 2 \times 10^6$ K; $T_2 \sim 7 \times 10^6$ K
- $P/k \sim 4 \times 10^4$ K cm$^{-3}$ (inner halo) - $5 \times 10^3$ K cm$^{-3}$ (outer halo)

Total diffuse X-ray luminosity $\sim 3 \times 10^{39}$ ergs/s

< 1% of the expected SN energy input!

Where does the energy go?
Hot gaseous corona

Otte et al. 2003

Wang et al. 2001

Red: farUV

Blue: 0.3-1.5 keV

NGC 4631

HST/WFPC2 Hα
Chandra 0.9-1.5KeV
Chandra 0.3-0.9KeV

OVI

Wavelength (Å)

Otte et al. 2003

Wang et al. 2001
NGC 4631 in Radio

NGC 4631 22cm VLA Total Intensity + Magnetic Field

Copyright: MPIfR Bonn (R. Beck & G. Golla)
NGC 3556: radio vs. X-ray

Wang et al. 2003
NGC 3556: optical vs. X-ray

Red - optical
Green - 0.3-1.5 keV band
Blue - 1.5-7 keV band
NGC 3556: structure of the diffuse X-ray emission

0.3-1.5 keV band
Energy balance in late-type disk galaxies

- Outflows driven by massive stars in form of galactic fountains
- Much of the SN energy can in principle be dissipated in disk
- Large portion of the energy could be consumed by OVI-bearing gas in halos and by escaping cosmic rays
Sb galaxy NGC 4565


Red - optical
Green - 0.3-1.5 keV band
Blue - 1.5-7 keV band

Very low specific SFR
No sign for any outflows from the disk in radio and optical
NGC 4565: Diffuse hot gas properties

- Within ~ 10 kpc radius in the disk
- Extends ~ 15 kpc into the halo
- Strongly asymmetric relative to the Galactic plane
- Mean T ~ a few \( \times 10^6 \) K
- \( L_x \sim 3 \times 10^{39} \) erg/s

![X-ray intensity plot with SW and NE regions highlighted](image)
No correlation with radio!
NGC 4594: X-ray vs. optical

ACIS-S 0.3-1.5 keV intensity contours

Diffuse 0.3-1.5 keV intensity contours

Hα ring
NGC 4594: X-ray spectra

- Average $T \sim 6 \times 10^6$ K
- Slight softening in the disk and in the outer bulge
- Strong Fe -L complex
- $L_x \sim 4 \times 10^{39}$ erg/s

NGC 4631

Normalized counts/sec/keV

Channel energy (keV)
Comparison with the predictions

Toft et al. (2003)
Missing energy in early-type disk galaxies

- For NGC 4594, hot gas radiative cooling rate ~ 2% of $L_{SN} \sim 2.4 \times 10^{41}$ ergs/s from Type Ia SNe alone
- Not much cool gas to hide or convert the SN energy
- Mass and metals are also missing!
  - Mass input rate of evolved stars
    $\sim 1.3 \ M_{\odot}/yr$
  - Each Type Ia SN $\rightarrow$ 0.7 Msun Fe

Gone with the wind!
Bulge wind model

- Spherical, steady, and adiabatic
- NFW Dark matter halo + stellar bulge
- Energy and mass input follows the stellar light distribution
- CIE plasma emission
- Implemented in XSPEC for both projected spectral and radial surface brightness analyses

Li & Wang 2004, also see the poster in this meeting
Data vs model

Consistent with the expected total mass loss and SN rates as well as the Fe abundance of $\sim 4 \times$ solar!
The best-fit model density and temperature profiles of the bulge wind
Consistency check: timescales

\[ \frac{T}{dT/dt} \]

Radiative cooling

O recom.

T/(dT/dt)

Fe recom.
~ $10^{55}$ erg, or ~ $10^4$ Type Ia SNe over the past ~ a few $\times 10^7$ years.

Snowden et al. 1997
Summary

The extra-planar diffuse hot gas has been detected unambiguously in normal galaxies ranging from Sd - Sa types!

- **X-ray luminosity**
  - Proportional to SF rate and to stellar mass
  - Accounting for < a few % of SNe energy input

- **Spectral shape**
  - Apparently thermal (steep spectrum and emission lines)
  - $T \sim a$ few $\times 10^6$ K,
  - Typically with abnormally low metal abundances (< 10% solar), if fitted with one- or two-T plasma

- **Morphology**
  - Elongated along major galactic axises
  - Dependence on galaxy type, SFR, and environs
“Missing” Energy Problem and Plausible Solutions

• Late-type (Sd-Sc):
  - Cooling due to OVI-bearing gas and possibly to escaping cosmic rays

• Early-type (Sb-S0):
  - Little evidence for X-ray emission from accretion flow from the IGM
  - Energy loss in a Type Ia SN-driven bulge wind

• In general
  - A lot of mass, energy, and metals could be in massive galactic halos

But we still have little idea about the thermal, ionization, and chemical states of the diffuse hot gas.