High-energy processes in galaxies

- X-ray source population
- Galactic ridge X-ray emission
- Multi-phase ISM
- Galactic corona
- Stellar wind bubbles and superbubbles
- Disk/halo interaction
- Star burst phenomenon and superwinds
- Ultraluminous X-ray sources (ULXs)
- X-ray emission as a tracer of star formation rate
X-ray emission from galaxies

• AGN at the very center of a galaxy
  - Up to $10^{48}$ erg/s
  - Typically power law
• Low- and high-mass X-ray binaries
  - $10^{36} - 10^{40}$ erg/s
  - $\sim$ black body + power law
  - The most common bright source type
• SNe and very young SNRs
  - up to $\sim 10^{40}$ erg/s
  - optical-thin thermal
  - radio counterparts expected
  - very rare, < 1 per galaxy except for star burst galaxies
• SNRs
  - optical-thin thermal (soft) and nonthermal (hard)
  - up to $\sim 10^{37}$ erg/s
  - resolved optical and radio counterparts may be expected
• The hot ISM
  - Soft optically-thin thermal spectrum (T < 10^7 K)
  - Even softer (T < 2 x 10^6 K) in the galactic corona, if present.
• Other compact sources (e.g., CV, isolated pulsars)
  - < 10^{36} erg/s
  - hard spectra
• Normal stars
  - < 10^{32} erg/s each. Typically not detectable even in nearby galaxies
  - The total contribution is typically insignificant
  - Massive close binaries (colliding winds) → up to ~ 10^{34} erg/s

Contributions from bright X-ray binaries, SNRs + discrete sources, and “diffuse emission” are typically comparable in an active star-forming galaxy.

Don’t forget background interlopes
• AGNs – accounting for ~ 90% at high Galactic lat. sources
• Groups or clusters of galaxies - rare
• Nearby stars ~10%
Galactic corona?

Galactic disk

Sun

GC
ROSAT all sky survey (Snowden et al. 1997)
The HEAO-1 hard X-ray sky

Boldt et al.
The GRXE

• Discovered by Worrall et al. (1982)
• A composite of multiple components
• The nature of the emission is still a mystery
• Ginga view of 6.7-keV line distribution (Yamauchi & Koyama 1993):
Longitude distributions

The 1.1-18.5 keV band emission

Fe 6.7-keV line emission

Co intensity (|$b|$ < 2°)
Characteristics of the GRXE

- Scales: radius ~ 4 kpc, scale height ~ 0.1 kpc
- Luminosity: ~ $10^{38}$ erg/s in the 2-10 keV band
- ~ $6 \times 10^{36}$ erg/s in the 6.7-keV line alone.
- 6.7-keV line emission peaks strongly in the Galactic bulge ($12^\circ \times 5^\circ$): additional $3 \times 10^{36}$ erg/s
- Significant 6.4-keV fluorescent line appears only in the central region.
- Assuming an ionization equilibrium thermal plasma, the characteristic temperature is 10 keV! Problems (Tanaka 2002):
  - Substantially hotter than observed young SNRs.
  - Not bound by the gravity of the Galaxy
  - Inconsistent with the observed H-like to He-like K-line intensity ratios of Si, S and Fe.
  - Indication of a broad Fe 6.7-keV line, corresponding $v$ ~ a few $10^3$ km/s!
• Charge exchange (Tanaka): interaction of low-energy cosmic-ray heavy ions with cold gas to explain the Fe 6.7-keV line width; probably too inefficient to work. Need all SN mechanical energy!

• Nonthermal bremsstrahlung emission (Valinia et al. 2000): explaining the 6.4-keV line from cold gas, but is too inefficient to account for the continuum.

• In situ acceleration of electrons *in hot gas*: proposed to recycle the energy (Dogiel et al. 2002). But no specific mechanism is known.

• Supernova ejecta fragments (Bykov 2002): explain the line width.

• Possible point-like source contribution: unlikely even in deep Chandra images.

• SNRs in hot gas (my idea): no energy problem, but details need to be worked out.
The ISM

ISM phases
• Cold HI/H2 – T \( \sim 10^2 \) K, n \( \sim 10^2-10^4 \) cm\(^{-3}\)
• Warm HI - T \( \sim 10^3 \) K, n \( \sim 1 \) cm\(^{-3}\)
• Warm HII – T \( \sim 10^4 \) K, n \( \sim 0.1 \) cm\(^{-3}\)
• Hot gas – T \( \sim 10^6-7 \) K, n \( \sim 0.01-0.001 \) cm\(^{-3}\)

which emits X-ray and is subject to absorption.
All these phases can be studied, using absorption spectroscopy.

Evidence for the hot ISM:
• Our Sun is within a hot gas bubble
• Diffuse X-ray emission from massive star forming regions
• Numerous SNRs

Questions:
• How pervasive is the hot gas?
• What are the heating sources of the hot gas?
• How does the hot gas interplay with other galactic components?
NGC 3603: A massive star forming region
Chandra ACIS-I image
NGC 3603: ACIS-I spectrum
Stellar wind bubble

- Thin-shell approximation
- Momentum eq. \( \frac{d}{dt}\left\{\frac{4}{3}\pi R^3 \rho_0 V\right\} = 4\pi R^2 p \)
- Energy: \( E = \frac{3}{2}p \left(\frac{4}{3}\pi R^3\right) \)
- Energy balance: \( \frac{dE}{dt} = L_w - 4\pi R^2 p \left(\frac{dR}{dt}\right) \)

\[
R = \left\{\frac{250}{(308\pi)}\right\}^{1/5}\left\{\frac{L_w}{\rho_0}\right\}^{1/5} t^{3/5} = (267 \text{ pc})\left\{\frac{L_{38} t_7^3}{n_0}\right\}^{1/5}
\]

\[
V = (15.7 \text{ km/s}) \left\{\frac{L_{38} t_7^{-2}}{n_0}\right\}^{1/5}
\]

\[
P = \frac{7}{(3850\pi)^{2/5}} L_w^{2/5} \rho_0^{-3/5} t^{-4/5}
\]

- Thermal energy: \( E = 5/11 L_w t \)
- Kinetic energy: \( K = 15/77 L_w t \)
- Shell formation: 27/77 \( L_w t \)

Weaver et al. (1977)
**Bubble: internal structure**

**Assuming the classic thermal evaporation:**

- \( T = T_c (1-r/R)^{2/5} \) where \( T_c = (3.5 \times 10^6 \text{ K}) \{L_{38}^{8}n_0^{2}/t_7^{6}\}^{1/35} \)
- \( n = n_c (1-r/R)^{-2/5} \) where \( n_c = (4.0 \times 10^{-3} \text{ cm}^{-3}) \{L_{38}^{6}n_0^{19}/t_7^{22}\}^{1/35} \)
- \( F_\nu = \int \Lambda_\nu(T)n^24\pi r^2dr \)

• The model has been generalized to cases such as \( L_w(t) \) and/or \( n_0(r) \) have a power law distribution.

• The model can also be used approximately for relatively old superbubbles, since the average energy input from SNe is \( \sim \) constant for a typical IMF (McCray & Kafatos 1987; MacLow & McCray 1988).
DISK-HALO INTERACTION

Norman & Ikeuchi (1989)
Galactic Gaseous Corona

- **Evidence:**
  - Diffuse soft X-ray background (< 1 keV)
  - Soft X-ray shadows produced by distant clouds, indicating gas at $T \sim 10^6$ K if thermal.
  - Presence of absorption and emission lines of highly ionized species such as CIV, NV, and OVI, indicating gas at $T \sim a few \times 10^5$ K.

- **Questions:**
  - How far does the hot halo extend?
  - Is it really extraplanar?
30 Doradus Nebula

30 Dor Nebula: the brightest HII region in the Local Group of galaxies
30 Doradus Across the Spectrum

Red - X-ray
Green - Hα
Blue – Far-UV

This HII region is full of hot gas!
ASCA SIS Spectrum of 30 Doradus Nebula
M51

Optical (Boroson, NOAO)

X-ray (Chandra)
(Immler et al. 2002; Wilson et al. 2002)
NGC 4631 in Radio

Type: Scd
Distance: 7 Mpc
(1' = 2.2 kpc)
Chandra Images of NGC 4631

1.5 -10 keV band

0.3-1.5 keV band

Wang et al. (2001)
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)
- $\sim 5 \times 10^3$ K cm$^{-3}$ (outer halo)
- Metal abundance $\sim 10\%$ solar (?)

Total 0.2-3 keV luminosity $\sim 3 \times 10^{39}$ ergs/s < 1% of SN energy! Where does the energy go?

- Radiated at lower energies
- Lost in galactic winds
NGC 4631
UIT FUV
Chandra soft 0.3-1.5KeV
Chandra hard 1.5-7KeV
NGC 4631

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

Wang et al. 2001
Magnetic loops
Corona
Galactic disk
Luminous infrared galaxy: MRK 273

30″ ~ 60 kpc

0.3-1 keV

L(0.1-2.4 keV) ~ 2 \times 10^{41} \text{ ergs/s}

Xia et al. 2002
Elliptical galaxy NGC 4697

Sarazin et al. (2000)
Ultra-luminous X-ray sources

• X-ray sources outside galactic nuclei with apparent luminosities \( \sim 10^{39} - 10^{40} \) ergs s\(^{-1}\)
  - Assuming that the emission is isotropic.
  - Interlopers (background and foreground objects)
• Known for more than 20 years. But most are discovered recently.
• Now the arcsecond positions allow for multi-wavelength ID.
• Heterogeneous in origins
  - Very young SNRs (should be relatively strong radio sources)
  - X-ray binaries
    • High mass binaries (associated with SF regions)
    • Low mass binaries (globular clusters and galactic bulges)
SS433 as a Galactic example of the outflow from X-ray binaries
Nature of the BHs

- Intermediate-mass BHs ($M \sim 10^2$-$10^5 M_{\odot}$; Makishima et al. 2000):
  - Many ULXs do seem to have the expected hard/soft multi-color BH spectra.
  - However, the high Tin requires a fast rotating BH.
  - The formation of BHs in this mass range is difficult, except probably from the pop 3 stars
  - Some galaxies seem to have too many ULXs
  - They tend to be associated with SF regions
- Stellar Mass BHs with true super-Eddington emission (Begelman 2002)
  - Inhomogeneous adiation-pressure dominated accretion
  - Difficult to give a luminosity $> 10 \times$ the limit.
• Anisotropic emission or beamed jets (micro-quasar; King et al. 2001):
  - Only stellar mass BHs are needed
  - Predicted strong periodic variability has been detected for several ULXs
  - QPOs are observed from one M82 ULX, indicating the dominant disk emission, against the beaming model
  - Inconsistent with periodical variations as observed of two ULXs, if due to eclipsing
  - Most of ULXs have remained remarkably steady throughout their observed history, inconsistent with beaming
  - Many ULXs are located within shell-like optical nebulae, some of which show strong recombination radiation from HeII atoms. The ionization of the atoms requires a soft X-ray luminosity that is consistent with the isotropic emission
ULXs and optical nebulae
ULX M81 X-9

Hα

Super-energetic shells