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Abstract. I review studies of the hot gaseous medium in and around nearby normal disk galaxies, including the Milky Way. This medium represents a reservoir of materials required for lasting star formation, a depository of galactic feedback (e.g., stellar mass loss and supernovae), and an interface between the interstellar and intergalactic media. Important progress has been made recently with the detection of X-ray absorption lines in the spectra of X-ray binaries and AGNs. The X-ray absorption line spectroscopy, together with existing X-ray emission and far-UV O VI absorption measurements now allows for the first time to characterize the global spatial, thermal, and chemical properties of hot gas in the Galaxy. The results are generally consistent with those inferred from X-ray imaging of nearby edge-on galaxies similar to the Milky Way. Observed diffuse X-ray emitting/absorbing gas does not extend significantly more than ~ 10 kpc away from galactic disks/bulges, except in nuclear starburst or very massive galaxies. The X-ray cooling rate of this gas is generally far less than the expected supernova mechanical energy input alone. So the bulk of the energy is "missing". On the other hand, evidence for a large-scale ($\gtrsim 10^2$ kpc) hot gaseous halo around the Milky Way to explain various high-velocity clouds is mounting. The theoretical argument for ongoing accretion of intergalactic gas onto disk galaxies is also compelling. I discuss possible solutions that reconcile these facts. In particular, large-scale hot gaseous halos appear to be low in metallicity, hence X-ray emission. The metal enrichment in the intergalactic medium may be substantially non-uniform; fast-cooling clumps of relatively high metallicity may have largely dropped out and may partly account for high-velocity clouds. In addition, ongoing galactic mechanical energy feedback is likely important in balancing the cooling of the halos and may be strong enough to produce galactic winds in bulge-dominated galaxies.

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1 Introduction

It is widely believed that disk galaxies were formed and are still evolving from the mist of large-scale diffuse gas. Around reasonably massive galaxies like the Milky Way, such gas can be heated to X-ray-emitting temperatures at the so-called virial shocks (at galactocentric distances of $\sim 200-300$ kpc) and through subsequent gravitational compression (e.g., Birnboim & Dekel 2003). This gas, cooling radiatively, can maintain lasting star formation in galactic disks. But there are serious problems with this pure accretion scenario. Primary among these is the so-called "over-cooling" problem (e.g., Navarro & Steinmetz 1997). This refers to the fact that structure formation simulations consistently over-predict the cooled gas content in galactic disks. Essentially the accreted gas, with a "typical" metallicity, would cool too quickly in the forming galactic halos. Observationally, the mass of all stars and the interstellar medium (ISM) in a galactic disk typically accounts for only about half of the baryon matter expected from the accretion. The remaining matter, if having not been blown away, presumably resides in the galactic halo, most likely in a hot phase (e.g., Fukugita & Peebles 2006). In reality, the accretion is not only sensitive to the galaxy mass, but is also affected by various feedback processes such as the pre-heating and metal enrichment of the IGM as well as the ongoing energy release from stars and/or active galactic nuclei (AGNs; e.g., Toft *et al.* 2002; Mo & Mao 2002; Davé & Oppenheimer 2006). However, it is not clear which of these processes is more important. Energetically, the ongoing galactic feedback typically provide enough energy to balance the cooling. Indeed, much of the expected mechanical energy feedback from supernovae (SNe) is "missing", at least not observed in X-ray emission (Wang 2005, Li *et al.* 2006a,b), and could meet the energy need for heating the halo. But the problem is how to transport the energy from inside a galactic disk/bulge into a large-scale gaseous halo. All these problems are related to the behavior of the global diffuse hot gas in and around the galaxies. So let me first review the status of characterizing the spatial, thermal, and chemical properties of the hot gas and then discuss possible solutions to the problems.

2 Hot Gas in and around the Milky Way

2.1 Diagnostics

Half a century ago, Spitzer (1956) postulated the presence of a Galactic corona to provide the confinement for H I clouds observed at high Galactic latitudes. This corona, different from the large-scale hot gaseous halo as expected from the IGM accretion, was thought to be heated by the Milky Way, similar to the relationship between the Sun and its corona. Direct evidence for the Galactic corona at a temperature of $\sim 10^6$ K, of course, needs to come from X-ray and far-UV observations. Various broad-band X-ray observations have indeed revealed an extensive diffuse soft ($\lesssim 1$ keV) X-ray background (SXB; e.g., Fig. 1, Snowden *et al.* 1997; 2000). High spectral resolution X-ray emission data, made with sounding rockets and accumulated from large swaths of the sky (McCammon *et al.* 2002), have further shown emission lines such as C VI, O VII, and O VIII, confirming the thermal origin for much of the SXB. X-ray emission observations alone, however, give little distance information. One may infer the location of X-ray-emitting plasma relative to X-ray-absorbing cool gas, by comparing their relative distributions in the sky, though often with great uncertainties. A substantial part of the SXB, even in the 1/4-keV band, appears to arise from regions beyond the immediate solar neighborhood, or the so-called Local Bubble (LB). In particular, there is a general intensity enhancement towards the inner region of the Galaxy in the 3/4-keV and 1.5-keV bands. This enhancement is at least partly due to the emission from the Galactic bulge and possibly from a hot gas outflow from the Galactic center. The intensity distribution is substantially patchier in the 1/4-keV band than in the 3/4-keV band, which cannot be entirely due to absorption by cool gas (e.g., Kuntz & Snowden 2000). There is also no intensity correlation between the two bands. These differences strongly suggest the presence of gas components at quite different temperatures (e.g., $\sim 10^6$ K vs. $\sim 3 \times 10^6$ K); the hotter gas with a longer cooling time scale tends to be more abundant and diffuse than the cooler one. But, it is still not clear whether the Milky Way actually has a smoothly distributed Galactic corona, which may explain the bulk of the 3/4-keV diffuse emission (Wang 1997; Pietz et al. 1998), or just a composite of various discrete hot gas outflows or Galactic fountains from the Galactic disk as well as the bulge.

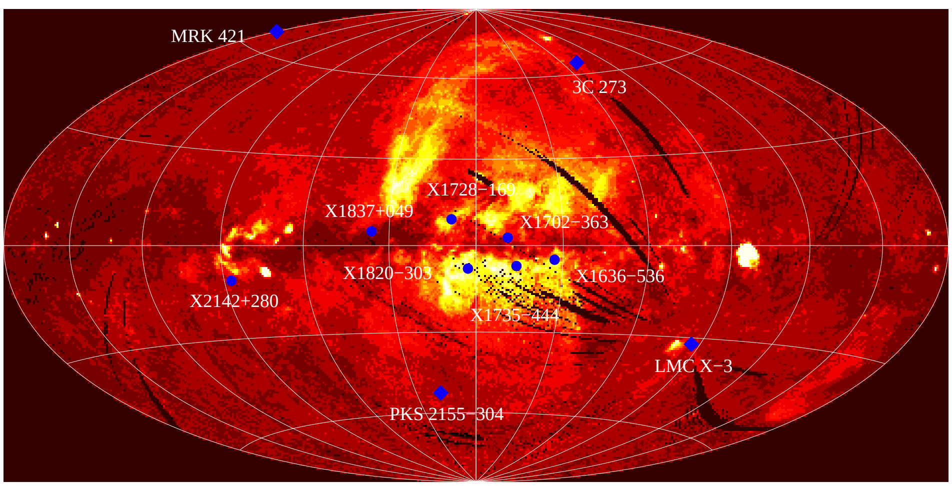

Fig. 1. *ROSAT* all-sky survey map of the diffuse 3/4-keV-band background intensity (in the Aitoff projection; Snowden *et al.* 1997). The blue symbols mark the directions of X-ray sources toward which X-ray absorption lines by Galactic hot gas have been detected (e.g., Yao & Wang 2005; Wang *et al.* 2005).

Hot gas in the Galaxy is also traced by far-UV absorption/emission lines, mostly observed in absorption. The vertical scale heights of O VI, N V, C IV, and Si IV absorptions, as inferred from their distributions across the sky, are ~2.3, 3.9, 4.4, and 5.1 kpc, respectively (e.g., Savage *et al.* 2000; Savage *et al.* 2003), clearly showing a trend toward lower ionization states at larger distances from the Galactic plane. This trend may be understood as a result of Galactic fountains, in which hot gas heated primarily by SN blastwaves in the Galactic disk cools off on the way to the Galactic halo. While the populations of C IV and Si IV could be largely due to photon-ionization, O VI, sensitively probed with *FUSE* as the 1031.9 and 1037.6 Å resonance line doublet, should originate predominantly in collisionally ionized plasma. Indeed, the doublet has also been detected in diffuse emission, which requires very long exposures with *FUSE* because of its small aperture ($30'' \times 30''$). Unlike the absorption, however, the emission intensity is subject to extinction, the correction of which can be rather uncertain. Existing emission observations are also typically not taken in close vicinities of the absorption sight-lines. Therefore, the comparison between the absorption and emission data has been difficult. Furthermore, the inference of the relevant physical parameters from the far-UV data alone requires an assumption of the gas temperature, often taken to be $\sim 3 \times 10^5$ K, at which the O VI ionic fraction peaks in collisionally ionized gas. Under this assumption, one neglects the O VI contribution from thermally more stable and thus more abundant gas at higher temperatures.

The most direct and powerful tool to study the *global* properties of hot gas in the Galaxy is the X-ray absorption line spectroscopy (e.g., Yao & Wang 2005, 2006a,b). The X-ray bandpass contains all the K-shell transitions of carbon through iron and the L-shell transitions of silicon through iron (Paerels & Kahn 2003). The grating instruments aboard *Chandra* and *XMM-Newton* X-ray Observatories, with a spectral resolution of ~ 500 km s^{-1}, now enable us to study the hot gas by detecting its line absorption in the spectra of bright background X-ray sources. The strongest lines are produced by ions such as O VII, O VIII, and Ne IX, which sample the entire expected temperature range of the hot gas ($\sim 10^{5.5} - 10^{6.5}$ K) in collisionally ionization equilibrium (CIE; Yao & Wang 2005). Unlike X-ray emission, which is sensitive to the volume density, the absorption lines trace the column density, which is proportional to the mass of the hot gas. Detection of multiple lines along the same sight-line can further provide sensitive diagnostics of the thermal, chemical, and kinematic properties of the hot gas. These diagnostics are independent of ionization-edge (photo-electric) absorption dominated by abundant interstellar cool gas ($T \lesssim 10^4$ K) and are therefore ideal for studying the global hot ISM. Comparison of the absorption lines detected along two or more sight-lines further allows to examine the differential properties of the hot ISM. Combining the absorption and emission measurements, we can even estimate the effective depth of hot gas along individual sight-lines. Existing results from using these capabilities are reviewed in the following.

2.2 Recent Results

- Spatial Extent

The X-ray absorption lines produced by local hot gas ($cz \sim 0$) are first detected in the spectra of several bright AGNs (e.g., Fig. 2). Typically only the O VII Kα line is detected, often marginally, except for PKS 2155–304, 3C 273, and Mrk 421 (e.g., Rasmussen *et al.* 2003; McKernan *et al.* 2004; Williams *et al.* 2005; Fang *et al.* 2006 and references therein). Early analyzes all assume a single temperature for the absorbing gas, which is certainly an over-simplification. Williams *et al.* (2005) show that the one-temperature assumption is only consistent with an extragalactic origin of the gas along the sight-line toward Mrk 421 (e.g., in the Local Group). However, the detection of the O VII Kα line with a similar equivalent width in the spectrum of LMC X-3 at a distance of 50 kpc strongly suggests that the absorption is primarily Galactic in origin (Wang *et al.* 2005). Stronger absorptions are also detected in the spectra of Galactic low-mass X-ray binaries (LMXBs), when the signal-to-noise ratios of the *Chandra* observations are reasonable high (Futamoto *et al.* 2004; Yao & Wang 2005). Most of the observations were taken for the study of the objects themselves (therefore the use of the high-energy transmission grating; HETG) and were not necessarily optimized for the ISM study. The HETG spectra most commonly show the Ne IX Kα absorption line. A joint analysis of the detected absorption lines along the Galactic and extragalactic sight-lines further suggests that the absorbing gas is located around the Milky Way and with effective scales no more than a few kpc, depending on the assumed overall morphological shape, disk- or sphere-like (Yao & Wang 2005; Juett *et al.* 2006). This, of course, does not exclude the presence of hot gas in a substantially larger region around the Galaxy (see §4.2 for more discussion). But it is clear that the bulk of the observed X-ray emission and absorption arises in the immediate vicinity of the Galactic disk/bulge.

• Temperature and Density Distributions

Along the sight-line to Mrk 421, Yao & Wang (2006b) find that the measured absorption line strengths of O VII and O VIII (Fig. 2) are *inconsistent* with the diffuse emission line ratio of the same ions, if the hot gas is assumed to be isothermal in a CIE state. But all these lines as well as the diffuse 3/4-keV broad-band background intensity in the field can be jointly fitted with a plasma with a power-law temperature distribution, which can be derived from a vertical exponential disk model of hot gas. The joint fit gives the exponential scale heights of the density and temperature as $\sim 1.0/f$ kpc and $1.6/f$ kpc and their mid-plane values as 2.8×10^6 K and 2.4×10^{-3} cm^{-3}, respectively. The filling factor of the hot gas f is still very uncertain, although a preliminary multi-phase column density comparison for the 4U 1820–303 sight-line indicates that the filling factor of hot gas is $\gtrsim 0.8$.

• Metal Abundances

So far the most comprehensive study of interstellar X-ray absorption lines is for the sight-line toward the Galactic bulge LMXB 4U 1820–303, located in a globular cluster (Galactic coordinates $l, b = 2°.79, -7°.91$ and distance = 7.6 kpc). The *Chandra* grating spectra of the source show absorption lines produced by O I, O II, O III, O VII, O VIII, Ne IX, and Fe XVII. The detection of these lines allows us to

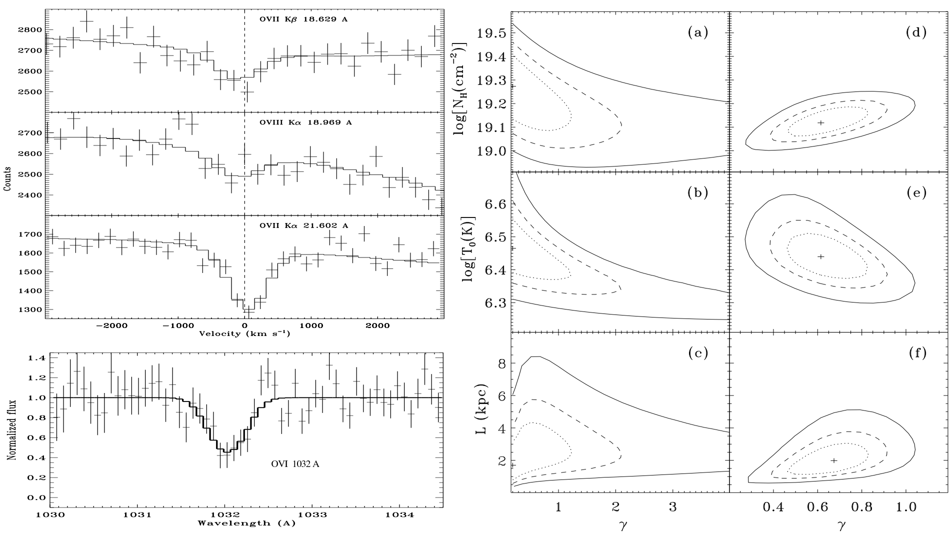

Fig. 2. Left panels: *Chandra* detection of O VII Kα and Kβ and O VIII Kα absorption lines and the *FUSE* detection of the O VI 1031.9 Å absorption line along the Mrk 421 sight-line. The histograms represent the fitted model, assuming a power-law hot gas temperature distribution ($dN_{\rm H}/dT \propto T^{\gamma-1}$; Yao & Wang 2006b). Right panels: The 68%, 90%, and 99% confidence contours of the model parameters: the total hot hydrogen column density $N_{\rm H}$, the maximum (mid-plane) temperature T_0, and the effective path-length L versus γ. The constraints are obtained from the joint fits to the X-ray absorption data and the O VII and O VIII emission line measurements from McCammon *et al.* (2002) with (d-f) or without (a-c) the inclusion of the O VI absorption line (Yao & Wang 2006b).

measure the column densities of the cold, warm, and hot atomic phases of the ISM through much of the Galactic disk (Yao & Wang 2006b, Yao *et al.* 2006). The hot phase of the ISM accounts for about 6% of the total atomic oxygen column density 8.0×10^{17} cm^{-2} along the sight-line. By comparing these measurements with the 21 cm hydrogen emission and with the pulsar dispersion measure along the same sight-line, we have further estimated the mean oxygen abundances in the neutral and ionized (warm plus hot) phases as 0.3(0.2, 0.6) and 2.2(1.1, 3.5) solar (90% confidence intervals). We have also obtained the Ne/O and Fe/Ne abundance ratios of the hot phase as 1.4(0.9, 2.1) and 0.9(0.4, 2.0) solar. The results indicate a substantially increased molecule/dust grain destruction and/or enhanced metal enrichment in the warm and hot phases of the ISM.

• Relationship between O vi- and O vii-bearing gases

A hint about this relationship comes from the similar kinematic properties of O vi- and O vii-bearing gases. Although the X-ray absorption lines are not resolved in the existing grating spectra, we can estimate the velocity dispersion of the absorbing gas from the O vii Kα/Kβ ratio. The estimated average dispersion is $\sim 85(74, 116)$ km s^{-1} for the LMC X-3 and Mrk 421 sight-lines, which sample the local hot gaseous disk/halo at high Galactic latitudes (Wang *et al.* 2005; Yao & Wang 2006b), and $\sim 255(165, 369)$ km s^{-1} for 4U 1820–303 toward the Galactic bulge (Yao *et al.* 2006). The high velocity dispersion of the hot gas along this latter sight-line is probably due to the large differential rotation, which would occur mostly in the Galactic Center region (Clemens 1985), and/or to the enhanced bulk/turbulent motion expected in the Galactic bulge region. Even the dispersion in the local disk/halo is significantly greater than the value expected from the thermal motion of the O VII ions ($\sim$ 36 km s^{-1}) and is consistent with those ($\sim 80 - 90$ km s^{-1}; e.g., Wang *et al.* 2005) directly resolved in the *FUSE* O VI absorption line observations with a resolution of $\sim$ 20 km s^{-1}. The O VI and X-ray absorption lines further show little offset from the local standard of rest. These similarities and consistencies indicates that the O VI absorbers are dynamically mixed with the X-ray-absorbing hot gas and originate mostly in a thick rotating hot disk with a weak bulk/turbulent motion, probably due to a Galactic fountain (Bregman 1980; Wang *et al.* 2005). So it is reasonable to assume that at least part of the O VI-bearing gas arises from the cooling X-ray-absorbing hot gas and hence may be characterized with a single temperature distribution. The inclusion of the *FUSE* O VI absorption data can greatly tighten the constraints on the temperature distribution of the hot gas (Yao & Wang 2006b). Fig. 2 (a-f) compares the confidence contours of the parameter constraints with or without the inclusion of the O VI absorption line in the fit for the Mrk 421 sight-line.

We may further explore the relationship between the O VI- and O VII-bearing gases by comparing the absorption lines with the measurements of the background O VI line emission. A preliminary comparison shows that the temperature distribution inferred from the absorption line fits for the local disk/halo sight-lines predicts an O VI emission intensity that is substantially smaller (by a factor of ~ 4) than $\sim$ 4000 photons s^{-1} cm^{-2} str^{-1}, typically measured with *FUSE* observations of high S/N ratios and at high Galactic latitudes (e.g., Shelton 2002; Dixon *et al.* 2006). Therefore, the bulk of the O VI emission likely arises from an additional component with a characteristic temperature of $\sim 3 \times 10^5$ K. This component, most naturally representing the combined contribution from conductive interfaces around cool gas clouds (e.g., Borkowski *et al.* 1990), should have a relatively high mean density or a small volume filling factor, compared to the diffuse hot gas in which they are embedded. The presence of this discrete component of O VI-bearing gas also helps to explain its large column density variation from one sight-line to another. But more studies of existing and upcoming far-UV/X-ray emission and absorption observations are needed to quantify the component. Now assuming that only part of the observed O VI absorption is associated with the diffuse hot gaseous disk, the contours shift primarily to the right in Fig. 2 (d-f).

Clearly, the existing characterization of the global hot ISM is still very limited. Much more can be learned even with the existing capabilities of *Chandra*, *XMM-Newton*, *Suzaku*, and *FUSE*. Detailed studies of individual sight-lines and their differential properties will ultimately enable us to characterize the dependence of the thermal, chemical, and kinematic properties of the global hot ISM on the Galactic radius as well as the vertical off-plane distance. Of course, our inside view of the hot gas in and around the Milky Way is further complemented by various external perspectives we now have on nearby disk galaxies of various types.

3 Hot Gas around Nearby Disk Galaxies

Thanks largely to *Chandra* and *XMM-Newton* X-ray observatories, much progress has also been made recently in the study of hot gas around nearby normal spiral galaxies, especially edge-on ones (Wang *et al.* 2001, 2003; Wang 2005, Li *et al.* 2006a,b). With superb spatial resolution, *Chandra* observations in particular allow to cleanly detect extraplanar diffuse hot gas and to explore its relationship to other galactic components. About 10 such edge-on galaxies have been observed with relatively deep exposures ($\gtrsim 50$ ks), although only a few of them have been adequately analyzed. Some preliminary characterizations of the diffuse X-ray emission from the galaxies are as follows:

• Morphological Properties

The diffuse X-ray emission appears to consist of two main components: one is correlated with the star formation (SF) rate and the other with the mass of a galaxy. The SF component tends to have an elongated morphology along the galactic disk (Fig. 3). Both the overall morphological shape and extent are similar to those observed in $H\alpha$ and in radio continuum. The mass-related component is readily seen in early-type disk galaxies (Type Sb-Sa) with little SF. Examples are NGC 4565 (Wang 2005) and M104 (Sombrero; Fig. 4a). The morphology of the X-ray emission resembles the stellar light distribution, typically concentrated toward galactic bulges. But the X-ray emission can be far more extended than the stellar light (e.g., Fig. 4b). Also little correlation is found between X-ray and radio emission of such galaxies. The X-ray-emitting gas is most likely heated by Type Ia SNe. A quantification of the exact spatial scale of the relatively faint diffuse X-ray emission around normal disk galaxies is difficult and has hardly been done consistently, due to uncertainties in the component separation, discrete source subtraction, background removal, and 2D-to-3D de-projection. Nevertheless, the effective (exponential) scales of the emission all seem to be in a range of 1-4 kpc (e.g., Li *et al.* 2006, Strickland *et al.* 2004).

The extraplanar hot gas, responsible for the diffuse X-ray emission, appears to have substantial substructures, which are best appreciated in disk galaxies that are moderately inclined. Fig. 3b shows that the diffuse X-ray emission arises primarily from the inner galactic disk of the Sb galaxy NGC 2841, and extends chiefly toward the southwest. This morphology is apparently a result of various hot gas plumes sticking out from the disk (with its northeast portion tilted toward us) and into the halo of the galaxy. These X-ray-emitting plumes extend vertically up to a few kpc and most likely represent blown-out hot gas heated in the galactic bulge and massive star forming regions in the disk.

• Spectral Properties

The diffuse X-ray spectrum can be characterized typically with a thermal plasma. The characteristic temperature is in the range of $(1-7)\times 10^6$ K, depend-

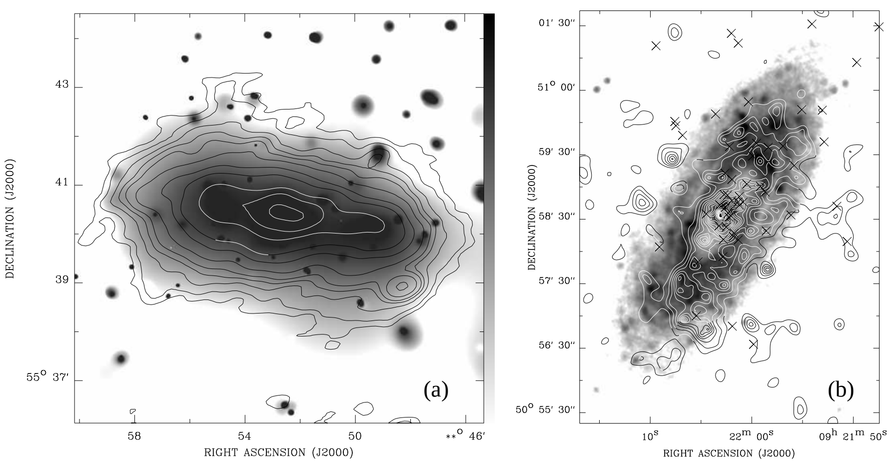

Fig. 3. (a) *Chandra* ACIS-S 0.5–1.5 keV intensity image of NGC 3556 with overlaid radio continuum contours (Wang *et al.* 2003). (b) ACIS-S 0.5–1.5 keV intensity contours, overlaid on an optical blue image of NGC 2841.

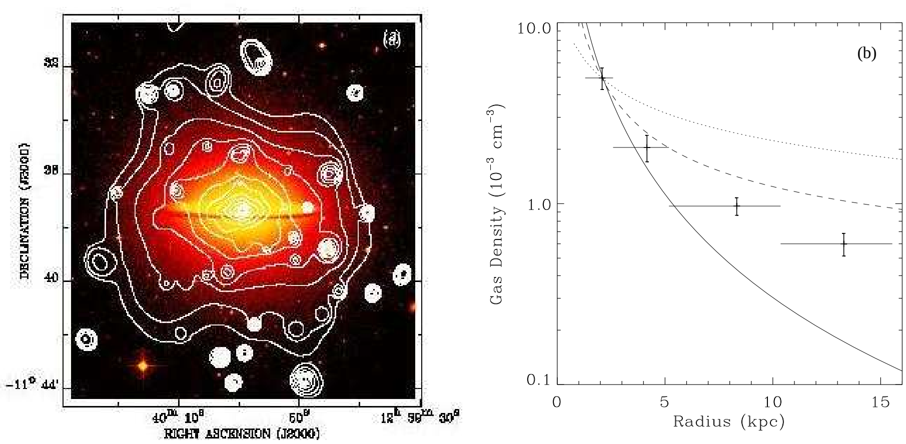

Fig. 4. (a) *XMM-Newton* EPIC-PN 0.5-2 keV intensity contours overlaid on the digitized sky-survey blue image of M 104. (b) De-projected radial density distribution of hot gas (*crosses*), compared with the model predictions, assuming an adiabatic (dotted curve) or isothermal (dashed) gaseous corona in hydrostatic equilibrium or a 1-D steady galactic wind (solid).

ing on both the SF rate and mass of individual galaxies. The metal abundances of the thermal plasma appear to be enhanced: O-like elements in late-type spirals and Fe-like elements in early-type spirals. But in general, the metal abundances are not well constrained, subject to uncertainties in the background subtraction and the assumed temperature distribution of the plasma.

• Energetics

The X-ray luminosity of the diffuse X-ray emission is proportional to the SF rate and to the stellar mass, as traced by the far-IR and K-band luminosities of a galaxy. But the luminosity typically accounts for only a few percent of the SN mechanical energy input expected from simple empirical estimates. This missing energy problem becomes particularly acute in so-called low L_X/L_B bulge-dominated galaxies (typically Sa spirals, S0, and low mass ellipticals). In a relatively deep *Chandra* observation, the bulk of the X-ray emission from such a galaxy is resolved into point-like sources (e.g., LMXBs); the remaining "diffuse" X-ray component generally shows a soft spectrum, indicating a primarily thermal origin (Irwin *et al.* 2002; O'Sullivan *et al.* 2003; Wang 2005). But the luminosity of this component accounts for no more than a few percent of the expected Type Ia SN mechanical energy input alone.

In principle, much of the mechanical energy input could be released by gas at lower temperatures and hence is not observed as X-ray emission. In a pilot study, Otte *et al.* (2003) detected the O VI 1031.9 Å emission line in two regions of the NGC 4631 halo. Follow-up observations have detected the line in several other regions of the halo (E. Murphy, private communications). The line centroids of the detected O VI emission appear to match the underlying disk rotation velocities reasonably well, indicating an origin in cooling galactic fountains or chimneys (Otte *et al.* 2003). The velocity widths of the O VI lines are considerably greater than the expected thermal broadening, but could be accounted for by the line-of-sight velocity dispersion of the galactic disk and/or by the turbulent motion of the gas. The inferred cooling rate of the O VI-bearing gas does not seem to be greater than the thermal X-ray luminosity of the galaxy. Interestingly, O VI line emission is not detected from NGC 891 and from superwinds around nuclear starburst galaxies such as M82 (Otte *et al.* 2003; Hoopes *et al.* 2003). This non-detection may, however, be explained by the relatively high foreground extinctions and short *FUSE* exposures of these targets. Deeper observations are clearly desirable to understand the role that O VI-bearing gas plays in the thermal evolution of hot gas.

4 Discussion

The results summarized above represent a basic characterization of hot gas in and around nearby normal disk galaxies. Two outstanding problems become apparent: 1) The observed far-UV/X-ray emitting/absorbing gas close to the galactic disks/bulges is heated primarily by SNe; but the inferred radiation luminosity of the gas accounts for only a few percent of the expected mechanical energy input. 2) There is little evidence for the large-scale X-ray emission or 'over-cooling" of the accreted IGM, as predicted in galaxy formation simulations. In the following, I discuss possible solutions to these two problems.

4.1 The Missing Stellar Feedback Problem

One possibility is that the missing stellar energy feedback is gone with galactic winds. In early-type spirals or elliptical galaxies with little SF, such winds are likely driven by Type Ia SNe. Theoretical studies of galactic-scale gas flows have had a long history (Mathews & Brighenti 2003 and references therein). Various solutions, mostly 1-D, have been examined, ranging from steady to time-dependent ones and from inflow to outflow, depending on the mass of an individual galaxy. But, comparisons of these solutions with observations are so far very much limited to such integrated quantities as the galaxy-wide X-ray luminosities. There has been little direct confrontation of the model-predicted spectral and spatial properties of diffuse hot gas with current X-ray observations.

We have been conducting both 1-D and 3-D studies of Type Ia SN-driven galactic bulge winds. We have first constructed a simple spherically symmetric wind model (Li & Wang 2007). We assume that the mass and energy inputs are proportional to the K-band intensity distribution and account for the galactic gravitational potential of stellar and dark matters in determining the gas dynamics. This model is a function of three basic parameters: the stellar mass loss and energy input rates as well as the galactic bulge size. A preliminary comparison of the predicted density profile with a de-projection measurement based on *Chandra* and *XMM-Newton* data is shown in Fig. 4b (Li *et al.* 2006b). The measurement assumes that the gas is in CIE. The apparent deviation of the measurement from the wind model prediction indicates that this assumption may not be valid. Indeed, one may expect that the fast adiabatic cooling of the wind results in delayed recombination (Breitschwerdt & Schmutzler 1999; Ji, Wang & Kwan 2006). This non-ionization equilibrium (NIE) effect can naturally lead to both a hardened X-ray spectrum and a relatively flat X-ray surface intensity distribution at large radii, compared to the CIE predictions. We are currently carrying out quantitative NIE calculations of the bulge winds.

We also test the suitability of the 1-D model and possibly calibrate it, by conducting 3-D simulations for representative galactic bulges. These simulations are used to characterize the effects of key 3-D physical processes and phenomena (e.g., discrete SNR heating and turbulence), which should not be sensitive to the exact global galactic properties assumed. The characterization of the 3-D density, temperature, and chemical structures is particularly important for comparison with X-ray observations and for determining the fate of SN chemical enrichment. We have already had a basic setup for such simulations. We use the parallel, adaptive mesh refinement FLASH hydro-code to cover a large dynamic range of the structures and to effectively capture shocks. SNe are randomly generated in time and according to the spatial distribution of stellar light. Our simulations (e.g., Fig. 5a) clearly show that the hot gas is full of dynamic structures, which could not be studied in the 1-D wind model. A preliminary comparison shows that the corresponding 1-D solutions substantially underestimate the X-ray fluxes at both low and high photon energies, due to the lack of the broad temperature distribution shown in the 3-D simulations. Furthermore, only massive galactic

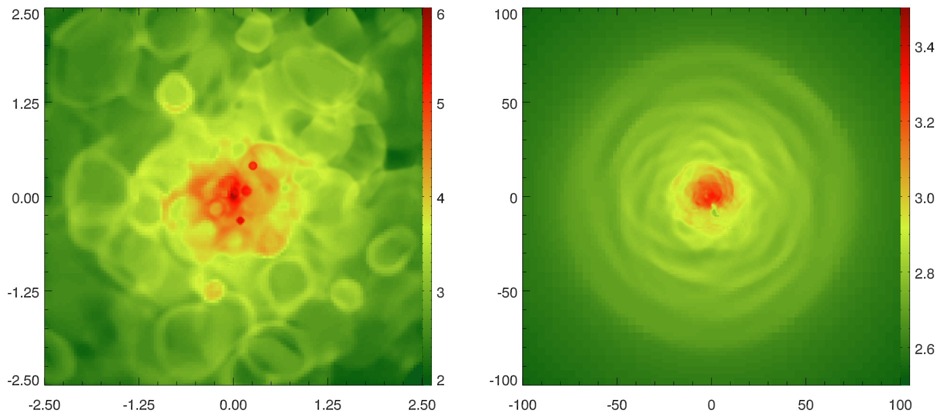

Fig. 5. *Left panel:* A slice of a 3-D simulated gas thermal pressure distribution in a galactic bulge similar to the one in the Milky Way or M31, assuming a wind solution. This slice across the galactic center shows various shell structures that correspond to enhancements caused by SNe. Weak shocks are seen as light green rings. The highest spatial resolution is 6 pc. *Right panel:* A similar pressure slice on a large scale from a test run, assuming a pre-existing hydrostatic halo. The ring patterns show that weak waves excited in the bulge propagate into the halo. The X and Y axes are all in units of kpc.

bulges are able to generate winds that are energetic enough to overcome both the gravity of the galaxies and the in-fall of the IGM.

For a small galactic bulge such as the one in the Milky Way, one instead expects convective flows, mixing outflows with accreted IGM. Much of the ongoing galactic feedback energy can also propagate outward in waves (Fig. 5b; Tang & Wang 2005, Tang *et al.* 2007), which can steepen into dissipative shocks, especially in and around cooling gas clumps (with decreasing sound speeds) formed in the hot gaseous halos. Such intra-halo "tsunamis" provide a promising mechanism for substantially slowing down the cooling of the accreted gas.

4.2 The Over-cooling Problem

While no significant observational evidence is found for the "over-cooling" of hot gas in and around galactic disks/bulges on scales of $\lesssim 10$ kpc, there is also little sign for diffuse X-ray-emitting halos on larger scales (Wang 2005; Li *et al.* 2006b). One probable exception is the claim made by Pedersen *et al.* (2006) for the detection of an apparent X-ray-emitting halo ($r \sim 20$ kpc) around the quiescent galaxy NGC 5746, based on a moderate exposure (37 ks) with the *Chandra* ACIS-I. They interpret this halo as the evidence for the hot gas from the IGM accretion. However, a careful re-analysis of the same *Chandra* data shows no significant detection of such a halo, after accounting for the position (mainly radial) dependence of the soft X-ray detection sensitivity due to the ice-building on the optical blocking filter of the ACIS-I detector, which was not corrected for in the early version of the analysis software used by Pedersen *et al.* (2006). In addition, part of the claimed halo may also be due to an inadequate removal of point-like sources. Of course, even if a truly diffuse X-ray-emitting gaseous halo is convincingly detected, it may still be due to the ongoing galactic feedback, SF- and/or stellar mass-related, as discussed above. On the other hand, the presence of a large-scale hot gaseous halo, though apparently very weak in X-ray emission, is required to confine high-velocity clouds seen at large distances from the Galactic disk and to explain their apparent ram-pressure stripping morphologies and conductive interfaces (e.g., detected in O VI absorption lines; Peek *et al.* 2006 and references therein).

A scenario that may reconcile these observations with the galaxy formation theory is that much of the halo gas is very low in metallicity. Metals are known to be present in the IGM; the intra-cluster medium with a typical metal abundance of $\sim 1/3$ solar is often used as an example. But this view of the metal enrichment is strongly biased, and the average metal abundance of the IGM in the field and in galaxy groups is expected to be significantly lower (Davé & Oppenheimer 2006). Most importantly, the enrichment is probably very non-uniform even on scales substantially smaller than the sizes of individual galaxies. Unlike in a galactic disk, where shear flows due to differential rotation can lead to efficient gas mixing, the IGM is not expected to be very turbulent. The mixing or diffusion of metals from early galactic feedback into the IGM has to be complete on microscopic scales to affect its cooling. Therefore, one may expect that the metal enrichment is highly clumpy in the IGM. Such medium, after being accreted into the Galactic halo, would cool in a rate proportional to the local metallicity. While metal-rich gas quickly condense into clouds and fall toward the Galactic disk, the remaining medium tends to have zero or low metallicity, especially in inner regions of the Galactic halo. This scenario qualitatively explains the lack of a giant X-ray-absorbing/emitting hot halo, which would otherwise have resulted from the IGM accretion; the observed X-ray emission and absorption in the immediate vicinities of the Galactic disk/bulge (§ 2.2) apparently arise from metal-rich gas, or the product of the ongoing stellar feedback. The low-metallicity (hence radiation inefficient) gaseous halo further alleviates the theoretical over-cooling problem of the IGM accretion. A detailed modeling of the scenario will be presented elsewhere.

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