2009

Global Hot Gas in and around the Galaxy

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Abstract.
The hot interstellar medium traces the stellar feedback and its role in regulating the eco-system of the Galaxy. I review recent progress in understanding the medium, based largely on X-ray absorption line spectroscopy, complemented by X-ray emission and far-UV O VI absorption measurements. These observations enable us for the first time to characterize the global spatial, thermal, chemical, and kinematic properties of the medium. The results are generally consistent with what have been inferred from X-ray imaging of nearby galaxies similar to the Galaxy. It is clear that diffuse soft X-ray emitting/absorbing gas with a characteristic temperature of $\sim 10^6$ K resides primarily in and around the Galactic disk and bulge. In the solar neighborhood, for example, this gas has a characteristic vertical scale height of ~ 1 kpc. This conclusion does not exclude the presence of a larger-scale, probably much hotter, and lower density circum-Galactic hot medium, which is required to explain observations of various high-velocity clouds. This hot medium may be a natural product of the stellar feedback in the context of the galaxy formation and evolution.

Keywords: the interstellar medium – X-ray
PACS: 98.38.Kx, 98.62.Ra, 98.35.Gi, 98.35.Nq

INTRODUCTION

An understanding of the Local Bubble (LB) must be in the context of the global interstellar medium (ISM). In particular, the very evidence for the presence of $\sim 10^6$ K gas in the LB is now questioned, because of the uncertainty in the contribution of the solar wind charge exchange (SWCX) to the observed diffuse soft X-ray background (e.g., see the contribution by Koutroumpa et al.; [1]). In the mean time, breakthrough observational progress has been made recently in characterizing the global hot ISM — a topic that I am reviewing here. I will further compare this characterization with the global perspectives obtained from observing hot gas in and around nearby galaxies. Finally, I will discuss the implications of the results, exploring the role of the global hot gas in regulating the Galactic ecosystem and the evolution of the Galaxy in general.

OBSERVATIONS

X-ray Emission

Until recently, our knowledge about the hot ISM ($T \gtrsim$ a few $\times 10^5$ K) came almost exclusively from various broad-band observations of the diffuse soft X-ray background. Maps generated from the ROSAT all-sky survey (RASS; [2]), for example, show the angular distribution of the background intensity in various energy bands. At energies $\lesssim 0.3$ keV, much of the background, if not due to the SWCX, should be produced by hot gas inside the LB. But as demonstrated in several measurements of X-ray shadows cast by cool gas clouds at known distances, a significant contribution of the background at high Galactic latitudes can have a more distant origin [e.g., 3]. In addition to an extragalactic component, consisting of mostly faint AGNs, a contribution is also expected from a thick hot gaseous Galactic disk and/or a large-scale circum-Galactic hot medium on scales $\gtrsim 10$ kpc. The distant contribution must dominate at higher energies. In particular, the X-ray background in the 0.5-2 keV range shows a general enhancement towards the inner part of the Galaxy. The nature of this enhancement is still greatly uncertain, but probably represents a combination of a nearby superbubble and an outflow from the Galactic nuclear region. Away from this inner region, the 0.5-2 keV background appears rather uniform, even across the Galactic plane. Such a uniformity provides the first indication for a Galactic disk contribution that more-or-less compensates the X-ray absorption by cool gas. This disk contribution most likely represents an accumulated contribution from stellar emission (primarily cataclysmic variables and coronally active binaries; [4, and references therein] as well as the hot ISM.

Spectroscopic observations have provided additional information about the nature of the soft X-ray background emission. For example, rocket experiments with instruments of sufficient spectral resolution have been used to detect individual lines or line complexes [e.g., 5]. At high Galactic latitudes, about 50% of the background in the RASS ~ 0.75 keV band is shown to be thermal in origin, while the rest can be accounted for by the nonthermal extragalactic AGN contribution. The spectra from such experiments were, however, accumulated from large swaths of the sky. More recently, reasonably good spectroscopic imaging data can be obtained from the X-ray CCDs on-board *Suzaku* with a much improved spectral resolution, compared with those on *Chandra* and *XMM-Newton*. Fig. 1c presents a *Suzaku* XIS diffuse X-ray spectrum obtained in a field adjacent to the sight line of LMC X-3 [6] — an X-ray binary for which both UV and X-ray absorption line spectroscopic data are available for comparison [7]. The emission spectrum clearly shows O VII, O VIII, and Ne IX Kα lines, suggesting the presence of an optically thin thermal plasma with an average temperature of $\sim 2.4 \times 10^6$ K.

The X-ray emission data alone, however, give little information on the global hot ISM. In particular, no kinematic and distance information can be extracted. The interpretation of the data very much depends on the assumptions of the density and temperature uniformity as well as of the relative cool (X-ray-absorbing) and hot gas distribution.

X-ray Line Absorption

Thanks to *Chandra* and *XMM-Newton*, we now have a new powerful tool — X-ray absorption line spectroscopy — to study the global hot gas. Unlike X-ray emission, which is sensitive to the emission measure of the hot gas, absorption lines produced by ions such as O VII, O VIII, and Ne IX directly probe their column densities, which are proportional to the mass of the gas and are sensitive to its thermal, chemical and kinematic properties. One also does not need to deal with the SWCX, because it contributes little to the line absorption. Furthermore, the line absorption, independent of photo-electric absorption by cool gas, samples hot gas unbiasedly along a sight line. Therefore, the absorption line spectroscopy, particularly in combination with the analysis of the emission data, now enables us to explore for the first time the global hot ISM in the Galaxy.

X-ray absorption lines produced by diffuse hot gas were first detected in the spectra of several bright AGNs (PKS 2155–304, 3C 273, and Mrk 421). While the very detection of such lines at non-zero redshifts remains to be controversial, the presence of the absorption by hot gas at $z \sim 0$ is firm [e.g., 8, 9, 10, and references therein] The spectral resolution of the grating observations, however, is still limited to about ~ 500 km s^{-1}, although with a sufficient counting statistics the centroid of a line can be determined to a much higher accuracy. Therefore, kinetically, the absorbing hot gas can be anywhere within a few Mpc around the Galaxy. But physically, it has been argued forcefully that the effective spatial scale of the gas cannot be on the Local Group scale of ~ 1 Mpc; otherwise, the amount of the baryon matter in the hot gas would exceed the expected baryon mass in the enclosed region [e.g., 11]. Furthermore, the hypothesis that the gas may represent the intra-group gas in the Local Group of galaxies may be ruled out because of the expected enhancement of the absorption in the M31 direction is not observed [12].

A more direct constraint on the location of the $z \sim 0$ hot gas comes from the absorption line spectroscopy of the sight line toward LMC X-3 [Fig. 1; 7]. The detected O VII and Ne IX Kα absorption lines have equivalent widths similar to those seen in the spectra of the AGNs. Most importantly, the absorption must occur within the source distance of 50 kpc and the line centroid is also inconsistent with the systemic velocity of the Large Magellanic Cloud. Indeed, similar interstellar absorption lines have been detected in the spectra of Galactic X-ray binaries [e.g., 13, 10]. It is now clearly that the hot ISM is present *globally* in the Galaxy and is the primary contributor to the observed $z \sim 0$ highly-ionized X-ray absorbers.

Far-UV Line Absorption and Emission

While the X-ray emission and absorption trace hot gas, far-UV spectroscopy is sensitive to gas at a few times 10^5 K. This so-called intermediate-temperature gas is particularly important for understanding the interplay between cool and hot gases. Far-UV spectroscopy also typically has spectral resolution higher enough to resolve individual emission/absorption lines, providing valuable kinematic information. So far most of such far-UV spectroscopy has been done in absorption for lines such as O VI and C IV [e.g., 14]. The bulk of such absorption is known to be in a Galactic disk with a vertical scale height of a couple of kpc. While the population of C IV could be partly 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. The doublet has also been detected in diffuse emission, typically based on 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. Also few emission observations were taken in close vicinities of the absorption sight lines [e.g., 15]. Therefore, the comparison between the absorption and emission data has been difficult. Furthermore, the inference of the relevant physical pa-

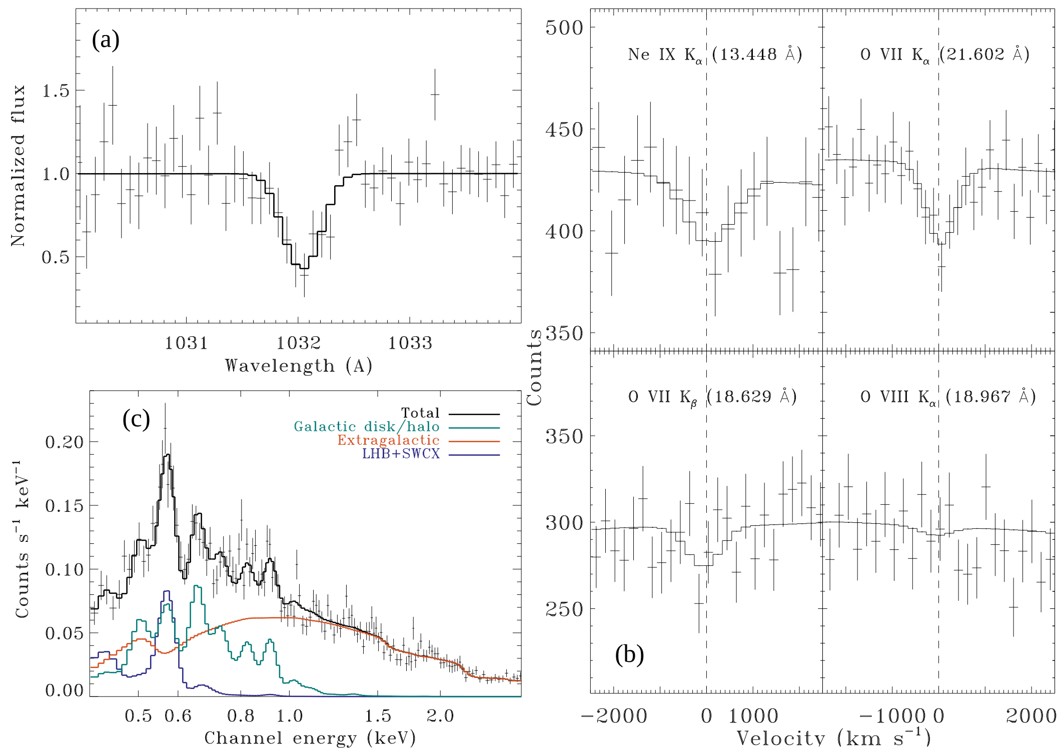

FIGURE 1. Spectroscopic data for the LMC X-3 sight line: (a) *FUSE* detection of the O VI absorption line, (b) the Neon and Oxygen absorption lines, as observed by *Chandra*, and (c) the local X-ray background spectrum from off-field *Suzaku* observations. The solid histograms in the plots represent a joint-fit of our non-isothermal model of the coronal gas to the data sets; panel (c) includes separately the contributions from the extragalactic background and the estimated charge exchange contribution, in addition to the hot ISM.

rameters 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, assuming a collisional ionization equilibrium. Under this assumption, one neglects the O VI contribution from thermally more stable and thus more abundant gas at higher temperatures.

CHARACTERIZATION OF THE GLOBAL HOT GAS

The rich data sets described above provide an excellent opportunity to characterize the global hot gas. An analysis tool has been developed to explore the data sets, especially the new X-ray absorption line spectroscopic capability [10, 6]. This tool allows us to joint fit multiple absorption lines (detected or not) as well as the emission measurements, spectroscopic or broad-band. Such joint fit maximizes the constraints from available data on spatial, thermal, chemical, and/or kinematic parameters of the hot gas with proper error propagation. Our analysis has so far assumed a collisional ionization equilibrium which is generally suitable for the global hot ISM. Here I highlight key results from such analysis for hot gas in the Galactic disk (defined to be within a few kpc of the Galactic plane), the Galactic bulge (a few kpc from the Galactic center), and the circum-Galactic medium (on scales beyond the Galactic disk and bulge, up to ~ 200 kpc or the virial radius of the Galaxy).

Hot Gaseous Disk

The sight-line/field of LMC X–3 (Galactic coordinates $l,b = 279^\circ, -46^\circ; D = 50$ kpc) provides an excellent sample of the hot gas away from the Galactic inner region. This bright black hole X-ray binary is located far outside the main body of the LMC [see Fig. 1 of 7]. The systemic velocity of the source ($+310$ km s^{-1}) further makes it relatively straightforward to distinguish any potential absorption that is local to the binary or to the LMC. The analysis of the comprehensive far-UV/X-ray data available for this sight-line/field (Fig. 1) has given the following key results [7, 6]: (1) Both far-UV O VI and X-ray O VII absorption lines show little offset from the local standard of rest, consistent with a Galactic interstellar origin; (2) Both X-ray emission and absorption data can be fitted well with a hot gaseous disk model with the temperature and density decreasing exponentially with the vertical distance from the Galactic plane, i.e., $n = n_0 e^{-z/h_n}$ and $T = T_0 e^{-z/h_T}$, where $n_0 \sim 1.4 \times 10^{-3}$ cm^{-3}, $h_n \sim 2.8$ kpc, $T_0 \sim 3.6 \times 10^6$ K, and $h_T \sim 1.4$ kpc; (3) This X-ray-data-constrained model can naturally account for all the observed far-UV O VI absorption. These results agree well with those obtained for the Mkr 421 sight line, which is also away from the Galactic inner region and is analyzed in a similar fashion [16].

Furthermore, a statistical analysis of the hot gas column densities along the sight lines toward a sample of Galactic and extragalactic sight lines gives a similar disk scale height for the hot gas. This scale height is also consistent with those inferred from similar statistical analyses of far-UV absorption lines and pulsar dispersion measures [10].

The sight line toward the low-mass X-ray binary (LMXB) 4U 1820-303 ($l,b = 3^\circ, -8^\circ; D = 8$ kpc), for example, presents a relatively low Galactic latitude view of the global ISM through the entire inner Galactic disk [13, 17]. *Chandra* grating observations show the presence of Fe XVII L transition as well as O I, O II, O III, O VII, O VIII, and Ne IXKα absorption lines, which are apparently interstellar in origin. The LMXB is super-compact; the large ionization parameter in the immediate vicinity of the binary greatly reduces the chance for a significant local contribution to the observed absorption lines, consistent with their constancy, moderate ionization state, and insignificant width/shift. Furthermore, the LMXB resides in the globular cluster NGC 6624, which also contains two radio pulsars with the dispersion measures giving a total free electron column density useful for an absolute abundance measurement of ionized gas. Based on these data, [17] obtain the column densities of the neutral, warm ionized, and hot phases of the ISM along the sight line. They find that the mean oxygen abundance in the neutral atomic phase is significantly lower than in the ionized phases. This oxygen abundance difference is apparently a result of molecule/dust grain destruction and recent metal enrichment in the warm ionized and hot phases.

Hot gas properties toward the Galactic inner regions seem to be significantly different from those in the solar neighborhood. Both the measured mean temperature and velocity dispersion are substantially higher along the sight lines toward LMXBs in the inner regions: $\sim 10^{6.3}$ K and 200 km s^{-1} vs. $\sim 10^{6.1}$ K and 50 km s^{-1}, respectively [10, 18]. While the X-ray absorption line profiles are not resolved with the existing grating observations, the velocity dispersion is inferred from the O VII Kα and Kβ ratio — a measure of the relative saturation that is sensitive to the line broadening. The substantially large velocity dispersion toward the inner regions indicates strong turbulent and/or large differential bulk motion of hot gas in and around the Galactic bulge.

Hot Gaseous Bulge

To probe the location dependence of the global hot ISM in the Galaxy, One can study the differential X-ray absorption/emission properties along multiple sight lines. Yao and Wang [18] have reported such a study of the soft X-ray background enhancement toward the inner region of the Galaxy. 3C 273 and Mrk 421 are two AGNs with their sight lines on and off the enhancement, but at similar Galactic latitudes. The diffuse 3/4 keV emission intensity is about 3 times higher toward 3C 273 than toward Mrk 421. *Chandra* grating observations of these two AGNs are used to detect X-ray absorption lines (e.g., O VII Kα, Kβ, and O VIII Kα transitions at $z \sim 0$). The mean hot gas thermal and kinematic properties along the two sight lines are significantly different. By subtracting the combined foreground and background contribution, as determined along the Mrk 421 sight line, they isolate the net X-ray absorption and emission produced by the hot gas associated with the enhancement in the direction of 3C 273. From a joint analysis of these differential data sets, they obtain the temperature, dispersion velocity, and hydrogen column density as 2.0 $\times 10^6$ K, 216 km s^{-1}, and 2.2 $\times 10^{19}$ cm^{-2}, which are significantly different from the measurements for hot gas away from the enhancement. The effective line-of-sight extent of the gas is also constrained to be in the range of $1-10$ kpc, strongly suggesting that the enhancement along the 3C 273 sight line is primarily due to a Galactic central phenomenon.

The difference between the Galactic disk and bulge regions also appears in the metal abundance of the hot gas. Irons are known to be strongly depleted in the local hot gas, probably by a factor of $\gtrsim 10$, based on X-ray emission line spectroscopy [5, 19]. This depletion is also consistent with the lack of a significant Fe XVII L transition line detection away from the Galactic central region (Y. Yao, private communications). Presumably the depleted irons reside in certain dust grains (or their sturdy cores), which have survived the thermal sputtering. The presence of such grains can be a very important energy sink of hot gas. However, along the sight line of 4U 1820-303, the estimated Fe/Ne abundance ratio is about solar. This ratio can be understood as the averaging of an extreme iron depletion in the disk and a large enhancement in the bulge. The iron enrichment in the bulge is expected because of frequent Type Ia SNe.

Circum-Galactic Hot Medium

One can further use the depth differences of multiple sight lines to constrain the hot gas column density of the large-scale Galactic halo. Yao et al. [6] have compared the detections of O VII and Ne IX Kα absorption lines along the sight line of 4U 1957+11 ($l, b = 51^\circ, -9^\circ; D = 10 - 25$ kpc), a persistent Galactic low-mass X-ray binary, and those toward extragalactic sight lines. They find that all the line absorptions can be attributed to the hot gas in a thick Galactic disk, accounting for the Galactic latitude-dependence. The O VII column density of the circum-Galactic hot medium is constrained to be $N_{O\ VII} < 5 \times 10^{15}$ cm^{-2} (95% confidence limit). A tighter constraint with $N_{O\ VII} < 2 \times 10^{15}$ cm^{-2} has been recently obtained with the comparison of the Cyg X-2 and the Mrk 421 sight lines (Yao et al. 2009 in preparation/private communication).

So far the most compelling, though indirect, evidence for the circum-Galactic hot medium comes from observations of high-velocity clouds [HVCs; e.g., 20]. HVCs in general represent a heterogeneous population, resulting from Galactic disk fountains, gas stripped from satellite galaxies, condensation from the hot medium, and possibly intergalactic clouds. A large sub-population of the HVCs (e.g., those detected in absorption lines produced by highly ionized ions such as O VI) appears to be located far away from the Galactic disk ($D \gtrsim 10$ kpc), although tight distance constraints are few. The velocity distribution of this sub-population indeed favors the circum-Galactic origin [21]. The HVCs also show a range of metallicity with the mean of ~ 0.1 solar, which is often used as a canonical value, although the number of good measurements is still very limited. The hot medium is required to provide the pressure confinement of the HVCs; otherwise they would be dispersed quickly. Also some of the HVCs, including those as part of the Magellanic Stream, show comet-like shapes, indicating stippling by the medium. The considerations of the survivability of the Magellanic Stream puts a limit on the density of the hot medium at $D \sim 50$ kpc from $\lesssim 10^{-4}$ cm^{-3} based on dynamical arguments to $\lesssim 10^{-5}$ cm^{-3} based on heating and evaporation arguments [22, and references therein]. The temperature of the hot gas is not constrained, observationally. But a temperature lower than a couple of 10^6 K would lead to a rapid cooling of the medium, for which no evidence is found in X-ray, and would be difficult to provide the pressure confinement. The presence of the hot medium is also necessary to produce the observed amounts of O VI, which resides mostly in a transitional phase between thermally more stable cool and hot phases and is typically found at conductive interfaces, turbulent mixing layers, and/or cooling flows.

In short, the current interpretation of the HVCs demands the presence of the circum-Galactic hot medium with a very low density. The high temperature and low density also naturally explain the lack of detectable X-ray emission and absorption from the medium and around other nearby galaxies similar to our own one.

DISCUSSION

Comparison with Hot Gas in Nearby Galaxies

To fully comprehend the global hot gas in and around the Galaxy, we need to complement our insider's view, presented above, with external perspectives from observing nearby galaxies of similar properties. To complement the study of the Galactic bulge, which is largely obscured in the wavelength range from optical to soft X-ray, one can examine hot gas in nearby galactic bulges. Based on a careful analysis of X-ray data on M31, Li and Wang [23] demonstrated that the properties of hot gas in a galactic bulge can be characterized if the contribution from X-ray binaries can be excised, which typically have individual luminosities $\gtrsim 10^{36}$ ergs s^{-1}; the collective X-ray emissivity of fainter sources can be tightly constrained, because they should spatially follow the stellar (K-band) light intensity [4].

The unambiguous detection of the diffuse hot gas in and around the M31 bulge helps to understand the soft X-ray enhancement observed toward the inner region of our Galaxy [23]. The temperature of the hot gas associated with the M31 bulge is similar to that with the Galactic bulge, as estimated from the RASS in regions with $|b| \gtrsim 10°$ [2]. But the X-ray emission of the Galactic bulge appears to be more extended and about a few times more luminous than that of the M31 bulge, presumably due to the feedback from recent extensive massive star formation at the Galactic center [e.g., 24, and references therein]. Within $|b| \lesssim 10°$, the interstellar absorption is severe, little can be inferred reliably about the properties of the hot gas. It is in this corresponding region in the M31 bulge that the diffuse soft X-ray intensity shows the steepest increase (by about one order of magnitude) toward the galactic center. Such a mid-plane enhancement of diffuse soft X-ray emission may also be present intrinsically in our Galactic bulge. The enhancement may be a result of the strong concentration of the SN energy input and the mass-loading from cool gas.

Wang [25] has reviewed recent work on the global hot gas around nearby normal galaxies, particularly edge-on ones. The results are generally consistent with the above characterization for the hot gas in our Galaxy. Observed diffuse X-ray emitting/absorbing gas typically does not extend significantly more than 10 kpc away from galactic disks/bulges, except in nuclear starburst or very massive galaxies. The morphology of the diffuse X-ray emission as well as its correlation with the star formation rate and the stellar mass clearly show that the detected extraplanar hot gas is primarily heated by the stellar feedback. In particular, recent analysis indicates that the hot gas may have multiple components of significantly different temperatures [26, 27]. Outflows from current and recent star forming regions (with stellar ages $\lesssim 10^7$ yrs) could be strongly mass-loaded, producing a lower temperature component, while those from older star forming regions in a galactic disk and from a galactic bulge may be responsible for the higher temperature component. But this scenario needs to be tested further with a systematic study of the relationship between the star formation and diffuse hot gas. Energetically, much of the expected stellar feedback seems to be "missing", at least not detected in X-ray emission [28, 29, 23]. The observed X-ray luminosity of diffuse hot gas is typically less than a few % of the energy input from SNe. This missing feedback problem is particularly acute in so-called low L_X/L_B bulge-dominated galaxies (typically Sa spirals, S0, and low mass ellipticals), in which little cool gas can hardly hide or radiate the energy in other wavelength bands. Most likely, the missing energy is gone with galactic outflows.

The Role of Global Hot Gas in Shaping the Circum-Galactic Medium

The presence of the global hot gas and its outflow can strongly affect its gaseous structure and evolution of a galaxy. According to the current theory of the structure formation, galaxies similar to the Milky Way were formed and are still evolving from the mist of the intergalactic medium (IGM). However, the actual formation and evolution process inside individual galaxies remains largely uncertain, critically depending on the treatment of the feedback from stars and AGNs. Therefore, it is important to understand the global hot gas as a tracer of the feedback in the context of galaxy formation and evolution.

One attempt in this direction is to understand the low density of the circum-Galactic hot medium. Tang et al. [30] demonstrate that the feedback from the stellar bulge can play an essential role in shaping the global hot gas. They have conducted 1-D hydrodynamical simulations of the hot gas evolution based on a feedback model consisting of two distinct phases: 1) an early starburst during the bulge formation and 2) a subsequent long-lasting mass and energy injection from stellar winds of low-mass stars and Type Ia SNe. An energetic outward blastwave is initiated by the starburst and is maintained and enhanced by the long-lasting stellar feedback. This blastwave can heat up the surrounding medium to a scale much beyond the virial radius of the halo, thus the hot gaseous accretion can be completely stopped. In addition, the long-lasting feedback in the later phase powers a Galactic bulge wind that is reverse-shocked at a large radius and maintains the circum-galactic hot medium. As the mass and energy injection decreases with time, the feedback may evolve to a subsonic and quasi-stable outflow, which is enough to prevent the development of a massive cooling flow. The two phases of the feedback thus re-enforce each-other's impact on the gas dynamics. The simulation results demonstrate that the stellar bulge feedback may provide a plausible solution to the missing stellar feedback problem and the over-cooling problem (over-predicting the amounts of cooled and cooling gas in and around a Milky Way-like galaxy).

To directly confront with the far-UV and X-ray emission/absorption measurements, one still needs to conduct more detailed modeling of the hot gas in and around the bulges and disks of our Galaxy, M31, and other similar galaxies. High spatial resolution 3-D simulations are necessary to account for density and temperature structures, which the emission is particularly sensitive to. Preliminary simulations have shown that the mass-loading from cool gas may play an important role in determining hot gas properties. Indeed, observational evidence is present for this process: a detailed analysis of the *Chandra* ACIS data shows enhanced X-ray emission around the nuclear cool gas spiral of the M31 bulge, while the detection of a strong OVI line absorption directly indicates the presence of large amounts of intermediate-temperature gas [31]. The magnetic field may also be important in shaping the outflow of hot gas, as indicated by the bi-polar morphology of the diffuse X-ray emission in and around the bulge of M31 [23]. These studies have demonstrated that detailed modeling of the X-ray and far-UV data can be very useful to the understanding of how the feedback works in and around galaxies.

ACKNOWLEDGMENTS

I thank the organizers of the workshop for the invitation to give this talk and am grateful to my students and collaborators (particularly Yangsen Yao, Zhiyuan Li, and Shikui Tang) for their contributions to the work as reviewed above, which is partly supported by NASA/CXC under grants NNX06AB99G, NNG05GC69G, and GO5-6078X.

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