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Extra-planar Diffuse Hot Gas Around Normal Disk Galaxies

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Abstract.

I review results from *Chandra* observations of nearby normal edge-on galaxies (Sd to Sa types). These galaxies have a broad range of star formation rate, but none of them is dominated by a nuclear starburst. The galaxies are all in directions of low Galactic foreground absorption ($N_{HI} \lesssim 4 \times 10^{20} \text{ cm}^{-2}$). Extra-Planar diffuse soft X-ray emission is detected unambiguously from all the galaxies, except for N4244 (Sd), which is low in both the stellar mass and the star formation rate. The thermal nature of the X-ray-emitting gas is well established, although its chemical and ionization states remain largely uncertain. The X-ray luminosity of the gas is proportional to the star formation rate and to the stellar mass of the galaxies. But the luminosity accounts for at most a few percent of the expected supernova mechanical energy input. Therefore, there is a “missing” energy problem for spiral galaxies. Much of the energy in late-type spirals may be converted and radiated in lower energy bands. But early-type ones most likely have outflows, which are powered primarily by Type Ia supernovae in galactic bulges. These galactic outflows may strongly affect both the dynamics and cooling of the intergalactic gas accretion, hence the evolution of the galaxies.

1. Introduction

It has long been theorized that a major, possibly dominant, phase of the interstellar medium (ISM) is gas at temperature $T \sim 10^6$ K in virtually all galaxies. This hot ISM is thought to be created and maintained primarily by supernova explosions (SNe; e.g., McKee & Ostriker 1977). If sufficiently energetic, the hot gas is expected to flow outward, creating a large-scale gaseous corona (e.g., Spitzer 1956; Bregman 1980a, Norman & Ikeuchi 1989) or even escaping as a galactic wind (e.g., Bregman 1980b). Therefore, the study of extra-planar hot gas is fundamentally important to our understanding of the mass, energy, and chemical evolution of a disk galaxy such as our own.

Observationally, although an understanding of the large-scale properties of the hot ISM in our own Galaxy is still elusive, the presence of large amounts of diffuse hot gas in nearby edge-on disk galaxies has been established. Much of this progress has been made with recent *Chandra* observations, which provide high-resolution and panoramic views of extra-planar hot gas and its interaction with other galactic components (e.g., Wang et al. 2001, 2003; Strickland et al. 2004). The arc-second resolution of these observations, in particular, allows for a clean separation of point-like sources from the diffuse emission, a step critical for

reliably determining both the content and physical condition of diffuse hot gas. Here I review key results from the observations and discuss their implications.

2. Summary of Existing *Chandra* Observations

Table 1. A Sample of Nearby Normal Disk Galaxies Observed with *Chandra*

Galaxy Name	Hubble Type	D (Mpc)	Incl. (deg)	L_{IR} ($10^{10}L_{\odot}$)	L_{60}/L_{100}	K_{tot}	Env.	Exp. (ks)	L_x ($10^{39}L_{\odot}$)
N4244	Sd	3.6	85	0.02	0.26	7.72	I	60	< 0.03
N4631	Sd	7.5	85	1.74	0.40	6.47	C	60	2
N3556	Scd	14	80	3.70	0.42	7.04	I	60	3
N3877	Sc	17	76	3.39	0.33	7.75	C	122	1
N5775	Sc	25	86	5.25	0.46	7.76	C	46	9
N4565	Sb	13	87	0.77	0.22	6.06	C	60	0.3
N4594	Sa	8.9	84	0.20	0.24	4.96	C	19	3

K_{tot} - K band magnitude from the 2MASS survey;

Env. - galaxy environment: I - isolated; C - with galaxy companions;

Exp. - *Chandra* ACIS-S exposure time;

L_x - Extra-planar diffuse 0.2-2 keV luminosity.

Table 1 lists a sample of nearby normal edge-on galaxies observed with the *Chandra* ACIS-S. They span a broad range of morphological types and star forming properties as judged by the $60\mu\text{m}$ to $100\mu\text{m}$ intensity ratios (L_{60}/L_{100} ; Table 1). But none of the sample galaxies is dominated by nuclear starburst or AGN activities. Both N4631 and N5775 are clearly disturbed by the interaction with their companions. Others seem to be rather isolated. N4244, an extremely quite and intrinsically low-surface brightness galaxy, presents little sign of diffuse X-ray emission (Strickland et al. 2004). The remaining six galaxies all show strong evidence for large-scale extra-planar diffuse X-ray emission (Fig. 1). Quantitative results have been reported only for N4631 and N3556 (Wang et al. 2001, 2003). The analysis of the other galaxies is still ongoing, although crude estimates of the extra-planar diffuse X-ray luminosities are included in Table 1.

It is interesting to compare the diffuse X-ray morphology of the normal galaxies with that of nuclear starburst galaxies (e.g., Fig. 2a; see also Strickland et al. 2004). The late-type (Sd-Sc) galaxies tend to show diffuse X-ray emission on scales comparable to, or even larger than, the optical sizes. The distribution of the galaxy-wide diffuse X-ray emission is relatively smooth and is more extended than H_{α} -emitting materials, which indicates that the bulk of the X-ray emission arises in galactic coronae — hot gas confined around the host galaxies. Interestingly, the nuclear starburst galaxy M82 (Fig. 2a) shows a similarly large-scale diffuse X-ray-emitting halo, in addition to an apparent bipolar outflow from the galactic central region (Strickland et al. 2004). The X-ray morphology of the halo is more vertically elongated than those in Fig. 1. This elongation is likely caused by the large momentum of the nuclear outflow.

In regions close to the galactic disks of both normal and nuclear starburst galaxies, the X-ray emission appears to be rather filamentary and shows a strong correlation with extra-planar H_{α} -emitting clouds, which are probably pushed out from the galactic disk (Wang et al. 2001, 2003; Strickland et al. 2004 and

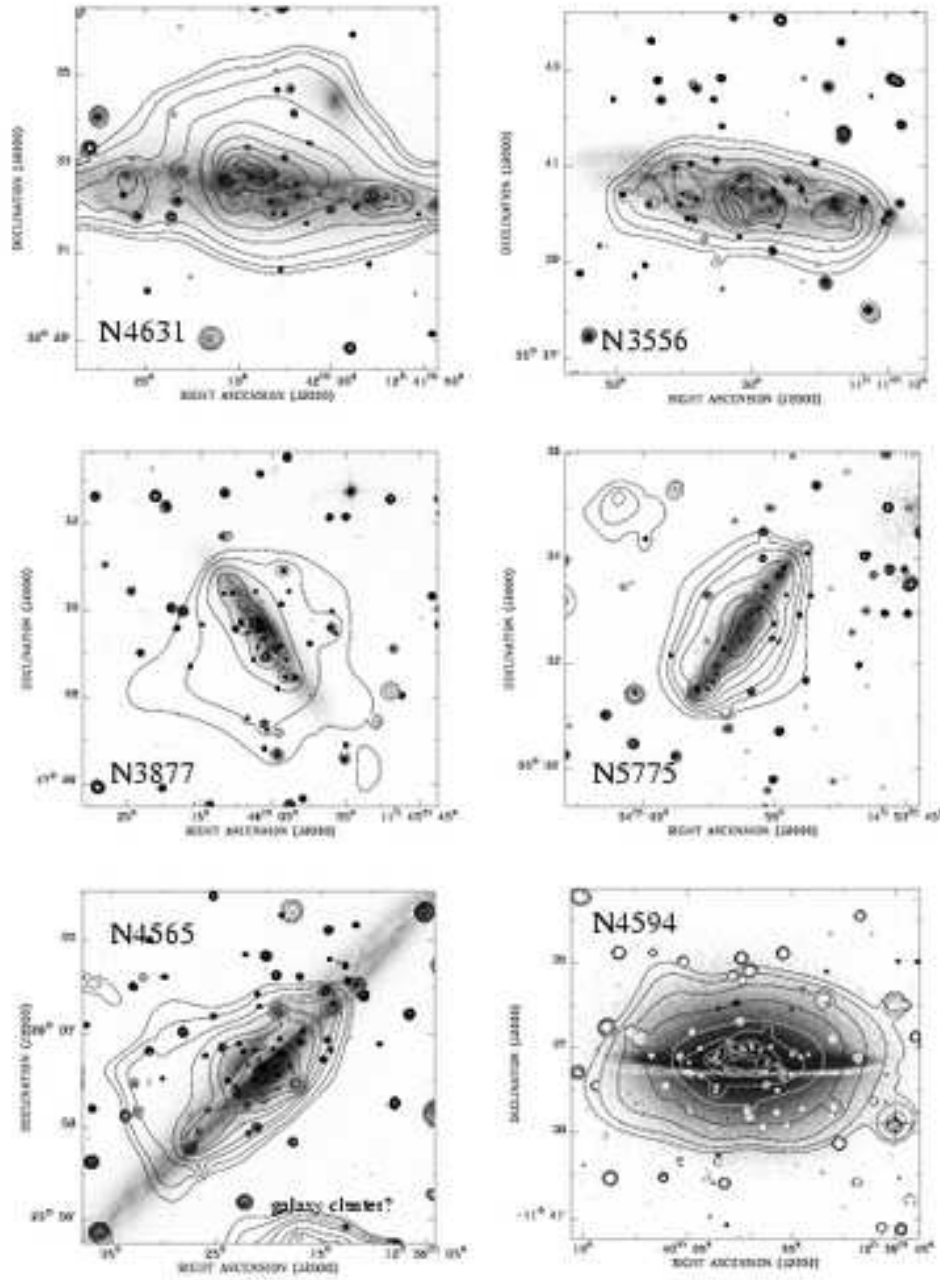


Figure 1. (a) *Chandra* ACIS-S intensity contours of nearby edge-on galaxies, overlaid on their optical B-band images.

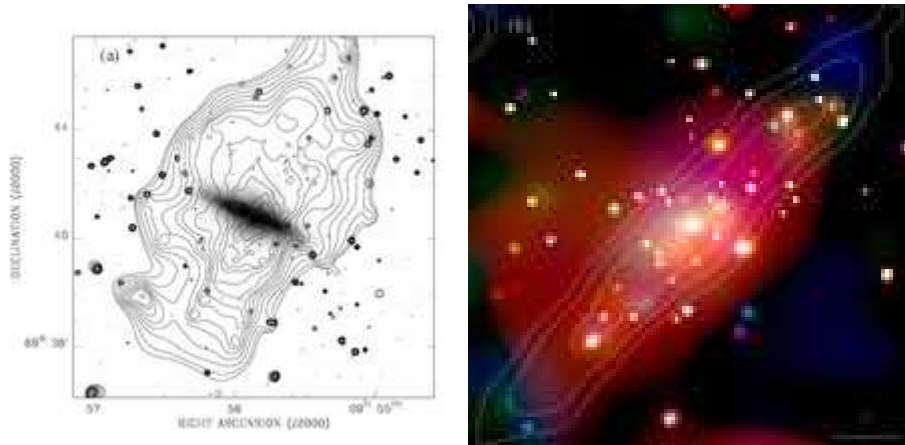


Figure 2. (a) *Chandra* ACIS-I intensity contours of the nuclear starburst galaxy M82, overlaid on an optical B-band image. The X-ray image is a mosaic of several existing observations; CCD readout streaks have been subtracted. (b) VLA 1.4 GHz continuum intensity contours overlaid on the tri-color *Chandra* ACIS-S image of N4565. The colors represent the intensities in the three energy bands: 0.3-0.7 keV (red), 0.7-1.5 keV (green), and 1.5-7 keV (blue).

references therein). Much of the X-ray emission may arise from freshly shocked cool gas clouds of small filling factor by fast-moving, low density outflows.

The diffuse X-ray emission seems to be more concentrated toward the inner regions of the early-type (Sb-Sa) galaxies. This concentration may be partly due to the fact that both N4565 and N4594 are very inactive in star formation. The gas heating by Type Ia SNe from the old stellar population becomes more important than core-collapsed SNe.

The diffuse X-ray spectrum can typically be characterized with a thermal plasma of a few times 10^6 K. The metal abundances appear to be enhanced in the diffuse hot gas: O-like elements in late-type spirals and Fe-like elements in early-type spirals (Fig. 3). But in general, both the ionization and chemical states of the X-ray-emitting plasma are not well constrained. The estimate of the absolute metal abundances, for example, depends strongly on the assumed plasma emission model, e.g., the temperature distribution. The X-ray luminosity estimate of a low-surface brightness corona is sensitive to the exact background subtraction. Nevertheless, we find that the luminosity appears to be proportional to the star formation rate and to the stellar mass, as traced by the far-IR and K-band luminosities of the galaxies, respectively. But the diffuse X-ray luminosity typically accounts for less than a few percent of the expected SNe energy input in each galaxy.

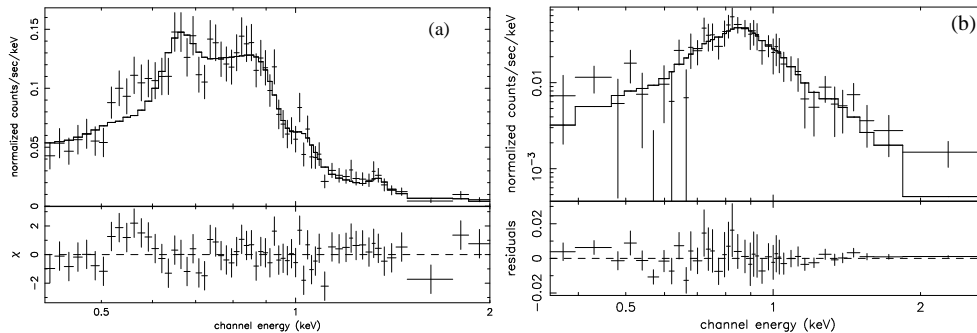


Figure 3. (a) The *Chandra* ACIS-S spectra of the diffuse emission from the central corona region of N4631. The histogram represents the best-fit thermal plasma plus a power law (photon index = 1.5; accounting for $\sim 10\%$ counts), constrained with a joint fit to an integrated spectrum of discrete sources. The best-fit temperature is ~ 0.4 keV, while the metal abundances are 0.8 and 0.2 solar for the O-like and Fe-like elements, respectively. (b) An ACIS-S spectrum of the extra-planar diffuse emission from N4594 and the best-fit galactic bulge-outflow model (histogram). Notice the strong and extended Fe-L bump at ~ 0.8 keV.

3. Implications

3.1. Mechanical Energy Balance

The mechanical energy balance in the ISM represents one of the basic and unsolved issues in galaxy evolution. A large fraction of SN blastwave energy is expected to be in the X-ray-emitting gas. But the energy is apparently not radiated in X-ray. Where does the SN energy go?

For late-type spirals with rich cool gas, the “missing” energy is perhaps radiated in a lower energy band than the X-ray, such as the UV or IR. In the N4631 corona, for example, a considerable fraction of the energy may be accounted for by the emission of the OVI 1032/1038 Å doublet (Otte et al. 2003). At temperatures of a few times 10^5 K, where gas of near-solar metallicity cools most efficiently, the OVI doublet is the dominant coolant. With some reasonable extrapolations, assuming an overall morphology and an extinction correction in these regions, the OVI-inferred cooling can account for a substantial fraction of the SN energy input. However, the nature of OVI-bearing gas remains uncertain. It may represent large-scale diffuse cooling gas or may only reside at the interfaces between diffuse hot gas and cool clouds of small filling factor. The existing X-ray CCD data (e.g., Fig. 3) have too limited spectral information content to uniquely determine the thermal state of hot gas, even under constrained assumptions about its ionization and chemical states. The estimate of the total radiative cooling rate, in particular, depends sensitively on the extrapolation of the assumed spectral shape. The link between the gas components observed in far-UV and X-ray is still missing.

Furthermore, N4631 may not be a typical normal galaxy. It is strongly interacting with its companions, as evidenced by both the presence of HI tidal arms and the enhanced star formation in the galactic disk. A more pristine environment for examining the disk/halo interaction can be found in the relatively

isolated edge-on Sc galaxy such as N3556, around which the extra-planar diffuse X-ray-emitting gas has also been detected (Wang et al. 2003; Fig. 1b). We have obtained 120 ksec *FUSE* observing time in the current cycle to further our investigation of the role that OVI-bearing gas might play in balancing the SN energy input.

A significant fraction of the SN energy may also be carried away by cosmic rays diffusing out of galaxies. Such outflows can be traced by extra-planar radio continuum emission and may be accompanied by outflows from galactic disks. Indeed, there is an overall morphological similarity between the extra-planar radio continuum and diffuse soft X-ray emission from late-type disk galaxies (Wang et al. 2001, 2003). But the similarity is absent in early-type disk galaxies. Take the Sb galaxy N4565 as an example (Fig. 2b). There is no evidence for significant extra-planar radio continuum emission, whereas the diffuse soft X-ray emission extends as far as ~ 15 kpc vertically. Therefore, the cosmic ray diffusion cannot be important. The missing energy problem remains. The total luminosity of the diffuse X-ray emission from the galaxy is $\sim 2 \times 10^{39}$ erg s $^{-1}$, only about 3% of the expected input from Type Ia SNe alone. A similar fraction is found for N4595. It is important to note that Type Ia SNe occur primarily in the galactic bulges or halos, in which there is too little cool gas to hide or convert the energy.

Most likely, galactic bulge outflows driven primarily by Type Ia SNe are responsible for much of the mass and energy balance in early-type disk galaxies, similar to the galactic winds proposed originally for elliptical galaxies (Mathews & Baker 1971; Bregman 1980b). We are quantitatively testing this idea, based on a simple spherically symmetric outflow model (Li & Wang 2004). We assume that the mass-loss and energy input rates are proportional to the near-IR star light and account for the galactic gravitational potential in determining the gas dynamics. We can now construct XSPEC models for both the surface brightness profile (in any selected energy band) and the projected spectrum (in any selected region), which can be analyzed in the same fashion. Preliminary fits to the X-ray data for N4595 show reasonably good fits (e.g., Fig. 3b). The fitted total mass and energy input rates are consistent with the values expected from the optical or near-IR luminosities of the galactic bulge. Most interestingly, the fits indicate that the outflow is particularly rich in iron; the abundance is $\sim 4 \times$ solar. However, there are some considerable discrepancies between the model and the data. The observed surface brightness seems to be systematically higher than predicted in outer regions of the galactic halo, which might indicate the limitation of the 1-D galactic outflow model and/or the importance of the interaction between the outflow and the accretion from the intergalactic medium (IGM).

3.2. ISM-IGM Connection Around Disk Galaxies

Ultimately, a comprehensive understanding of the extra-planar hot gas has to be put in the context of galaxy evolution. It is widely believed that disk galaxies are still accreting from the IGM, replenishing cold gas that is consumed by star formation (e.g., Toft et al. 2002 and references therein). Nevertheless, the gas around a massive galaxy may be heated to X-ray-emitting temperatures by an accretion shock and gravitational compression. But, the existing simulations

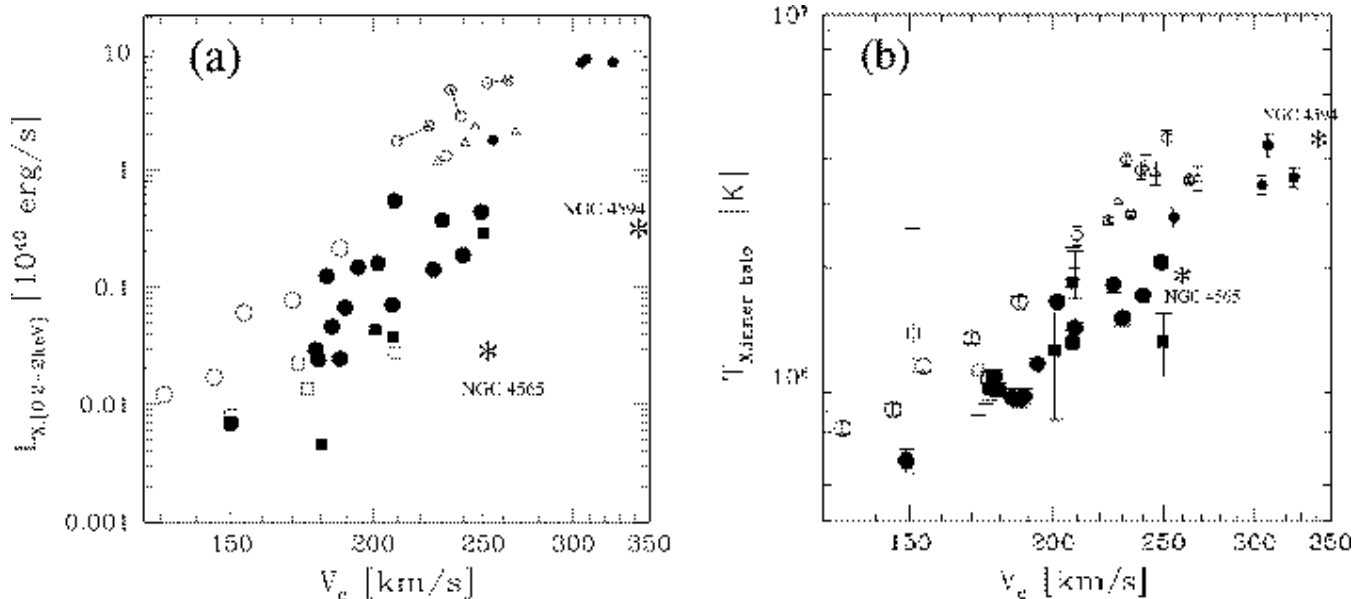


Figure 4. Observed diffuse X-ray properties of N4565 and N4594 (marked as *stars*), compared with the predictions from numerical simulations of disk galaxy formation (Toft et al. 2002): 0.2–2 keV band luminosity (a) and average inner halo hot gas temperature (b) versus galaxy characteristic circular speed. Various symbols represent simulations assuming different cosmologies. The large filled symbols, in particular, are from simulations with $(\Omega_\Lambda, \Omega_M) = (0.7, 0.3)$ cosmology with the baryon fraction $f_b = 0.1$: Circles correspond to primordial abundance, whereas squares to $Z = 1/3Z_\odot$.

do not adequately account for the energy feedback from the galaxies, especially the heating due to Type Ia SNe and the associated outflows discussed above. The predicted temperatures seem to be consistent with those inferred from the observations. But, there is a significant discrepancy between the observed extraplanar diffuse X-ray luminosities and the predictions from the simulations (Fig. 4). The observed X-ray luminosity of N4594, for example, is about a factor of ~ 30 lower than the predicted value.

The under-luminosity of the accretion may be due to the effect of the outflows from the galactic bulges, which tends to reduce the emission measure in the inner regions of the galaxies. The asymmetric morphology of diffuse extra-planar X-ray emission around N4565 may further suggest a complicated galactic outflow/accretion interaction. One may expect that the bulge outflow will eventually be stopped by the ambient medium. The reverse-shocked outflow materials may then accumulate around galaxies, responsible for much of the large-scale extra-planar diffuse soft X-ray emission. But if a galaxy has a motion relative to the ambient IGM, the outflow materials may be swept into a trail by the ram-pressure, which might be amplified by the gravitational focusing. In the case of N4565, the motion may be toward the northeast. The outflow in this direction may be confined in region close to the disk, enhancing the diffuse X-ray emission. But simulations need to be done to see whether or not such a

scenario may explain the observed morphological and spectral characteristics of the emission.

4. Future Prospect

Our ongoing systematic analysis of the existing *Chandra* data, together with the dedicated modeling, will give a more quantitative test of the various scenarios mentioned above. But a real breakthrough probably requires a new generation of observing tools. In the near future, *Astro-E2* high spectral resolution observations of edge-on galaxies can provide unique spectroscopic diagnostics of the thermal, chemical, and ionization states of the extra-planar hot gas, which will then allow a definitive test of various assumptions made in the analysis of X-ray CCD spectra and the role of extra-planar diffuse hot gas in both balancing the mechanical energy input from SNe and re-distributing chemical enriched materials in galaxies.

Another diagnostic tool that *Astro-E2* may offer is the measurement of emission line broadening. According to the ground calibration data, the width of a strong emission line can be determined to $\lesssim 0.5$ eV (~ 150 km s⁻¹). This resolving power results mainly from the fact that the line response profile of the instrument is almost perfectly Gaussian to 1 part in 10⁴. This capability raises the possibility to determine the velocity dispersion of extra-planar diffuse hot gas. Indeed, the supposedly much cooler OVI-bearing gas, as seen in the *FUSE* spectra of N4631, shows a substantial broadening with a *FWHM* ~ 200 km s⁻¹, corresponding to a thermal temperature of $\sim 10^7$ K (Otte et al. 2003). One may expect that the X-ray-emitting gas should have even broader lines. With a reasonable counting statistics, a line broadening of ~ 300 km s⁻¹ could easily be resolved. These new capabilities are essential to further the study of the heating, transferring, and cooling of extra-planar diffuse hot gas in galaxies.

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